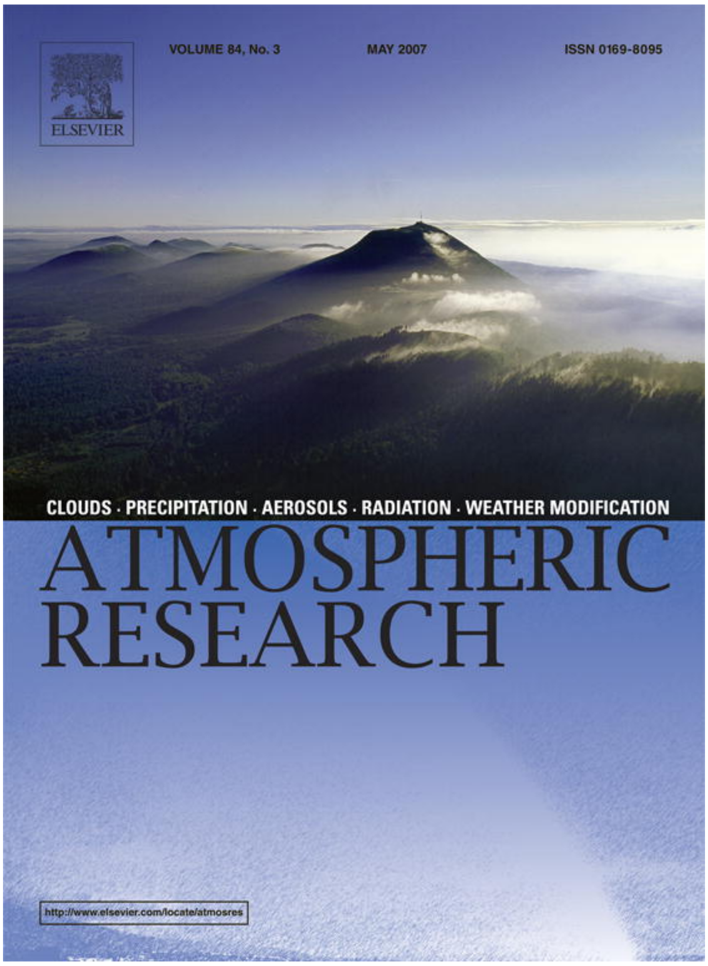
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Review Article

Maximum cloud-to-ground lightning flash densities observed by lightning location systems in the tropical region: A review

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Abstract

A comprehensive review of maximum cloud-to-ground (CG) lightning flash densities observed in the tropical region by different Lightning Location Systems (LLS) is presented. From the observed values, absolute maximum values for a spatial resolution of 1 km × 1 km are estimated, using an empirical curve relating flash density and resolution and correcting the data for differences in the detection efficiency and in the intracloud (IC) contamination of the different LLS. Maximum CG lightning flash densities are compared with total lightning observations by satellite in the same regions, for a spatial resolution of approximately 55 km × 55 km, to infer IC to CG ratios (IC/CG). It was found that absolute maximum CG lightning flash densities in the tropical region vary from 19 to 65 flashes km^{-2} year^{-1} and IC/CG ratios from 3.9 to 12.6. Absolute maximum CG lightning flash densities and the IC/CG ratios in the tropical region are then compared with similar values in the temperate region. Only the regions corresponding to the highest maximum CG lightning flash densities observed by LLS for each continent in the temperate region are considered. The comparison suggests that higher absolute maximum CG lightning flash densities occur in the tropical region and similar IC/CG ratios occur in both regions, with the exception of Colombia and Venezuela, where this ratio seems to be higher than in any other regions.

Keywords: Lightning; Lightning location systems; Cloud-to-ground lightning flash density; Tropical region

Contents

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1. Introduction

Most lightning on Earth occurs in the tropical region (Latham and Christian, 1998; Christian et al., 2003) and, since recent evidence suggests that the variation of the intracloud (IC) to cloud-to-ground (CG) lightning (IC/CG) ratio is more affected by local thunderstorm characteristics than by latitude (Boccippio et al., 2001; Rakov and Uman, 2003), the same is probably true for CG lightning.

The major part of the tropical region is formed by oceans, yet total lightning observations by satellite suggest that most tropical CG lightning occurs over the continents (Christian et al., 2003). In support of this fact, there is clear evidence indicating that thunderstorms over the ocean are less frequent both in space and time (Boccippio and Goodman, 2000) and produce less lightning than those over the continents (Williams et al., 1992; Zipser, 1994; Toracinta and Zipser, 2001; Toracinta et al., 2002). The physical reason for this pronounced contrast in lightning activity between continents and oceans is generally thought to be a result of the difference in their thermal heating by solar radiation, even though it has not been firmly established (Williams et al., 2004).

In addition, even though tropical CG lightning observations by Lightning Location Systems (LLS) are restricted to a small part of the tropical region, simultaneous total and CG lightning observations in the tropical region (Pinto et al., 2003a; Chisholm and Cummins, 2006) suggest that tropical CG lightning has a geographical distribution similar to total lightning. It is worth noting, however, that no LLS observations exist in the tropical region of the African continent, where the peak in the total lightning activity occurs over the equatorial Congo basin (Christian et al., 2003). Williams and Stanfill (2002), Williams and Sátori (2004) and Williams (2005) have addressed in details the reason for this peak in the global lightning activity.

From a time perspective, tropical CG lightning presents variations on many scales. Such variations are linked to many phenomena, including semiannual variations in the low-level zonal wind (Petersen et al., 2002), 5-day global wave (Williams et al., 2001), intraseasonal Madden–Julian oscillation (Anyamba et al., 2000), interannual ENSO (Hamid et al., 2001; Pinto et al., 2003b), intertropical convergence zone annual oscillations (Moliníé and Pontikis, 1995) and regional meteorological phenomena, such as the South Atlantic Convergence Zone (Pinto et al., 2003b).

From a local perspective, tropical CG lightning may provide a key parameter as a forecast tool for intensification of tropical cyclones (Lyons and Keen, 1994; Molinari et al., 1994, 1999; Shao et al., 2005) and as a complementary tool for supporting studies of lightning related phenomena (Pinto et al., 2004a,c; Naccarato et al., 2003).

From a global perspective, in turn, tropical CG lightning may provide an indirect measure of temperature (Williams, 1992) and/or concentration of essential elements, such as nitrogen (Bond et al., 2002) and ozone (Ryu and Jenkins, 2005), contributing to our understanding of climate changes (e.g. Füllekrug and Fraser-Smith, 1997).

In this review, maximum CG lightning flash densities observed by LLS in the tropical region are revised for the first time, since the installation of the first LLS in the tropical region in 1988 in Brazil. The review is focused on maximum values of CG lightning flash density. Average values were not considered because they are more dependent on the variations in the LLS performance. While in most networks the detection efficiency in the region limited by the sensors changes from 60–90%, outside this region the detection efficiency falls off rapidly. This behavior has a large effect on average values of lightning flash density, since these values are strongly dependent on the region considered in the study with respect to the network configuration. Maximum values outside the region limited by the sensors were also not considered, since they are very sensitive to the details of the detection efficiency models to correct them.

From the maximum CG lightning flash densities observed, absolute maximum CG lightning flash densities for a spatial resolution of 1 km × 1 km are estimated, using an empirical curve relating flash density and resolution and correcting the data for differences in the detection efficiency and in the intracloud (IC) contamination of the different LLS. In the past, such values were not accessible due to the limited spatial coverage of the available methods and techniques (thunderstorm days or flash counters). The determination of absolute maximum CG lightning flash densities in different regions on Earth is important for lightning protection, as well as for many scientific applications, such as the validation of thunderstorm electrification models and the evaluation of the impact of global changes on lightning activity.

Absolute maximum CG lightning flash densities were then compared with total lightning observations by satellite to infer IC/CG ratios. The determination of the IC/CG ratios is important to better understand thunderstorm electrical characteristics.

Finally, both absolute maximum CG lightning flash densities and IC/CG ratios are compared with similar data in the temperate region.

In this review, the technical definition of the tropical region, which is the geographic region of the Earth centered on the equator and limited in latitude by the two tropics: the Tropic of Cancer (23.5° N latitude) in the north and the Tropic of Capricorn (23.5° S latitude) in the southern hemisphere, is adopted.

2. Cloud-to-ground lightning location systems in the tropical region

Although LLS to detect and locate CG lightning can operate at different frequency ranges from VLF to VHF, only in the VLF/LF range are the detection efficiency and location accuracy high (Rakov and Uman, 2003). VLF/LF LLS consists basically of several sensors, which determine the direction and/or the time to the lightning stroke at the sensor location, and a processing unit, which calculates stroke characteristics such as the strike point location and time, peak current, and others. For a comprehensive description of lightning locating techniques, see for example Cummins et al. (1998a,b) and Rakov and Uman (2003). VLF/LF LLS have collected a large number of CG lightning data, which have been used in many applications by power utilities, weather services, aviation, geophysical research and others.

LLS have been in operation (or have operated) in many countries in the tropical region: Brazil, Colombia, Venezuela, Java Island, China (South region of the country), Papua New Guinea, Australia and Malaysia.

The first LLS installed in the tropical region was in Southeastern Brazil (hereafter referred to as Brazil Southeast-1) in 1988. It operated initially with four and later 6 LPATS (Lightning Positioning and Tracking System) sensors. In 1996 it was upgraded to include IMPACT (Improved Accuracy from Combined Technology) sensors and also expanded to cover a larger region. The number of sensors increased gradually up to 24 sensors by mid-2005, when it became the largest LLS in the tropical region (hereafter referred to as Brazil Southeast-2). More details can be found in Pinto (2003, 2005), Pinto and Pinto (2003), Pinto et al. (1996, 1999a, b, 2003a,b, 2006a), Naccarato (2005) and Naccarato et al. (2003).

The LLS in the North region of Brazil began its operation in 1999 with the goal to provide ground truth data for the Lightning Imaging Sensor (LIS). It operated up to 2005 when it was integrated into the LLS in Southeastern Brazil (Pinto and Pinto, 2003; Pinto et al., 2003a; Blakeslee et al., 2003; Fernandes, 2005).

At the present time, only one network exists in Brazil and has more than 50 sensors (Pinto et al., 2006b), however, only a small data sample from this large LLS is available at the present time.

The LLS in Colombia was installed in 1997 with 6 LPATS sensors and operated up to 2003 (Torres et al., 2001; Younes et al., 2003, 2004). The LLS in Venezuela began its operation in 2000 with 12 IMPACT sensors, covering the whole country (Raizman et al., 2004; Tarazona et al., 2006). The LLS in Java Island began its operation in 1994, operating with four ALDF (Advanced Lightning Direction Finder) sensors (hereafter referred to as Java Island-1). In 1995, it was changed to 8 LPATS sensors (hereafter referred to as Java Island-2) and in 2004 it was upgraded with some IMPACT sensors; nevertheless, no data are available after 2004. More details can be found in Hidayat et al. (1996), Hidayat and Ishii (1998, 1999) and Berger and Zoro (2004).

Four other networks operate (or operated) in the tropical region: an LPATS LLS in Australia, an MDF (Magnetic Direction Finder) LLS in Malaysia, an MDF LLS in Papua New Guinea and an IMPACT LLS in the South region of China, which covers mainly a subtropical region. Data from the first three of these LLS were not included in this review for the following reasons: no data from the LLS in Australia is available (Sharp, 1999); the available data of the LLS in Malaysia are not reliable (Abidin and Ibrahim, 2003); the maximum CG lightning flash density observed by the 3-sensor MDF LLS in Papua New Guinea occurs outside the region limited by the sensors (Orville et al., 1997). Data from the 14-sensor IMPACT LLS in China will be considered in the comparison of the maximum CG lightning flash densities in the tropical and temperate regions, since the maximum CG lightning flash density observed by this LLS occurs outside the tropical region (Chen et al., 2002, 2004).

Table 1 summarizes the main characteristics of the LLS in the tropical region, indicating the countries where there are/were observations. It includes the period of the operation, number and type of sensors, detection technique, approximate latitude range of the observations in the tropical region and detection efficiency, that is, the percentage of flashes detected with respect to the total number of flashes occurring. It can be observed from this table that, even though only a small fraction of the tropical region is covered by LLS, almost all latitudes were partially covered. Data from Brazil and Java Island were divided in different data sets corresponding to different networks, regions and/or periods, as described before.

Table 1 indicates that only the Brazil Southeast-2 LLS detection efficiency was validated by independent

Table 1
Characteristics of LLS in the tropical region

Country	Period	Number of sensors	Type of sensors	Detection technique	Latitude range (degrees)	Average detection efficiency (%)
Colombia	1995–2003	6	LPATS	TOA	3–11 N	70–80 [a]
Venezuela	2000–2003	12	IMPACT	TOA/MDF	0–12 N	90 [a]
Java Island-1	1994–1995	4	ALDF	TOA/MDF	6–9 S	70 [a]
Java Island-2	1996–2001 [b]	8	LPATS	TOA	6–9 S	60 [c]
Papua New Guinea	1992–1994	3	ALDF	TOA/MDF	5 S – 2 N	70 [a]
Brazil Southeast-1	1988–1996 [d]	6	LPATS	TOA	16–22 S	70 [a]
Brazil Southeast-2	1997–2005	24	LPATS/IMPACT	TOA/MDF	13–23 S	80–90 [e]
Brazil North	1999–2005	4	ALDF	TOA/MDF	8–14 S	70 [a]

[a] Values were given by the manufacturers.
[b] IMPACT sensors were added to the network recently, but no data are available yet (Berger and Zoro, 2004).
[c] Value was estimated from the lowest peak current observed.
[d] The number of sensors changed from 4 to 6 in 1995 (Pinto et al., 2003b).
[e] Values were estimated by triggering lightning (Solorzano, 2003) and high-speed camera observations (Ballarotti et al., 2006).

observations. It was partially validated by triggering lightning (Solorzano, 2003) and by high-speed camera (Saba et al., 2004; Ballarotti et al., 2006) observations. The estimated detection efficiency is in reasonable agreement with the values predicted by the manufacturers. In the case of Java Island-2, the detection efficiency in Table 1 was estimated from the lowest peak current observed. For the other LLS, the values of the detection efficiency in Table 1 were provided by the manufacturers and are based on a model that assumes perfect operation of the system. In this sense, they should be considered as achievable values and might differ from real values.

3. Maximum CG lightning flash density observations with lightning location systems in the tropical region

This section concerns with just lightning flash density observations over the continents, since LLS observations over the oceans are outside the region where they have their best performance. As has been recently documented (Murphy and Holle, 2005), observations far away from the sensors, like those over oceans in this case, should be seen with caution if not adequately corrected for the detection efficiency of the LLS. The other lightning parameters observed by the LLS, such as peak current and multiplicity, were not considered in this review because, for most of the LLS in the tropical region, they are considerably affected by the low detection efficiency of the LLS to low peak current subsequent strokes (Schulz and Diendorfer, 1998, 2002). For this reason, in the majority of the LLS, mean peak current (multiplicity) values are overestimated (underestimated) considerably, making it very difficult to know if regional differences in these parameters are real or if they are mostly due to LLS performance (Pinto et al., 2004b). These parameters are also strongly affected by IC contamination, mainly for the LLS using only LPATS sensors (Cummins and Bardo, 2004).

Fig. 1 shows, as an example, a map of the annual average CG lightning flash density for a spatial resolution of 10 km × 10 km observed in the tropical region, corresponding to the Brazil Southeast-2 LLS (Naccarato, 2005). Data in this figure are not corrected for detection efficiency of the LLS, following the format that is usually presented in the literature. At the present time, this is the large region mapped by an LLS in the tropical region. The regions in white in Fig. 1 correspond to densities larger than 7.5 flashes km^{-2} year^{-1}. The region of maximum CG lightning flash density in this figure around 23° S and 47° W, showed by a large white spot, is coincident with the urban area of the city of São Paulo. For the spatial resolution in Fig. 1, the maximum CG lightning flash density in this region is 9–10 flashes km^{-2} year^{-1}. Similar maps for the other LLS in the tropical region indicated in Table 1 can be found in: Younes et al. (2004) for Colombia, showing a maximum CG lightning flash density in the region around 8° N of latitude and 75.5° W of longitude; Tarazona et al. (2006) for Venezuela, showing a maximum CG lightning flash density in the region around 10° N and 72° W; Hidayat and Ishii (1998) for Java Island-1, showing a maximum CG lightning flash density in the region around 7° S and 107.5° E; Berger and Zoro (2004) for Java Island-2, showing (in a tabular form) a maximum CG lightning flash density in the region around 6.5° S and 108° E; Pinto et al. (2003a,b) for Brazil Southeast-1, showing a maximum CG lightning flash density in the region around 20° S and 44.5°

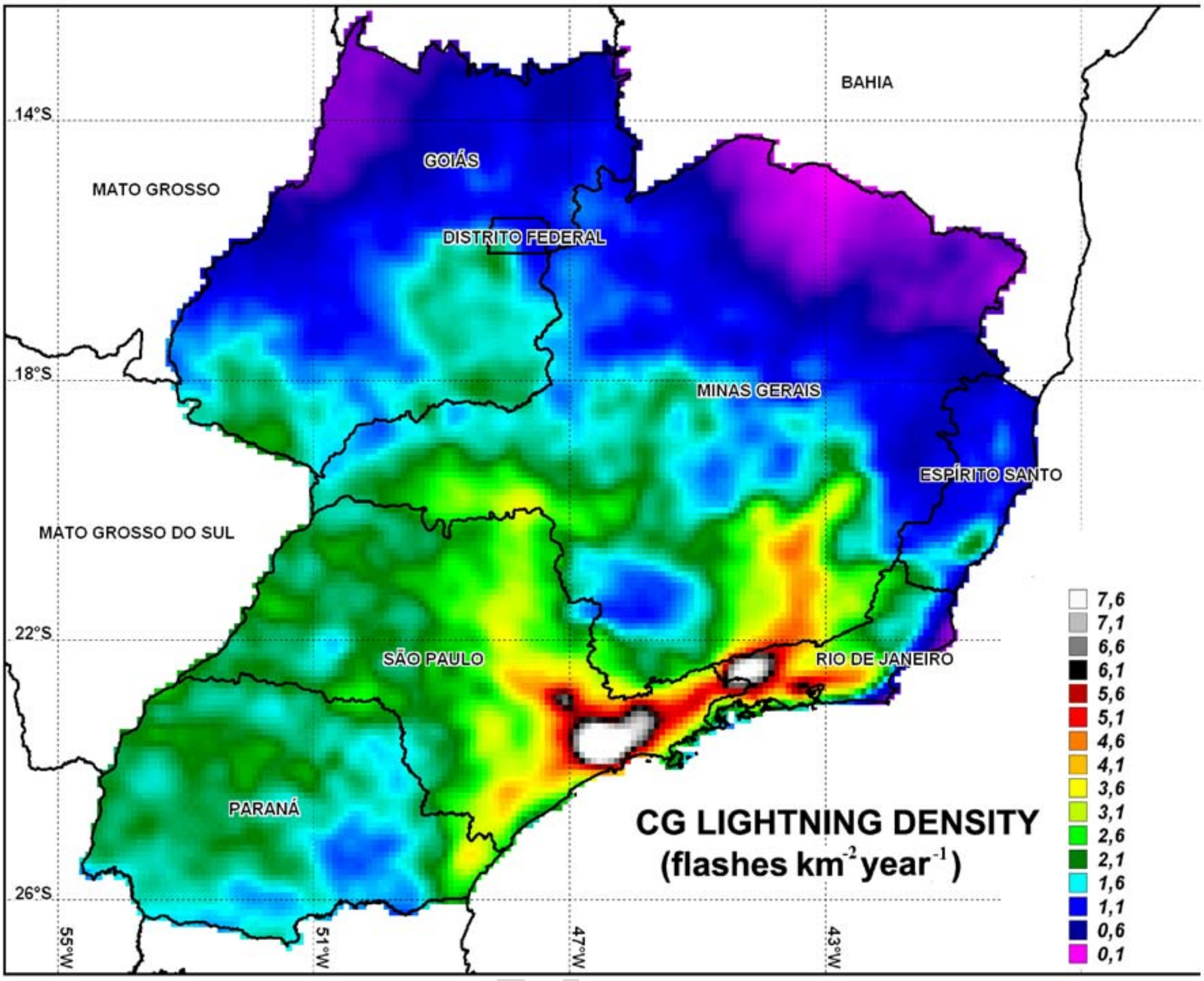

Fig. 1. Annual average CG lightning flash density in the Southeastern Brazil from 1999 to 2004 for a spatial resolution of 10 km × 10 km, as observed by a 24-sensor LLS. Regions in white correspond to densities larger than 7.5 flashes km^{-2} year^{-1}.

W; and Fernandes (2005) for Brazil North, showing a maximum CG lightning flash density in the region around 11° S and 62.5° W.

Table 2 shows a summary of the maximum CG lightning flash densities observed by the different LLS described in Table 1. Values are not corrected for the detection efficiency of LLS and, when available, are presented for different spatial resolutions. The periods of the observations are also shown. CG Lightning flash densities were obtained by grouping strokes in flashes using different criteria. For LPATS LLS, in general, strokes were grouped assuming that all strokes belong to the same flash if they are located less than 10 km from the first stroke and occur less than 2 s from the first stroke, since at the same time consecutive strokes are separated by less than 500 ms. For hybrid (LPATS and IMPACT sensors) LLS or IMPACT LLS the criteria normally used is that suggested by Cummins et al. (1998a). Extreme values for specific years (1997 in Colombia, 1999 in Java Island and 2001 in Southeastern Brazil) are also included in Table 2. The values in Table 2 vary from 5 to 47 flashes km^{-2} year^{-1}. In general, the higher is the spatial resolution, the higher is the maximum lightning density. The maximum value observed for all LLS in Table 2 was in 1997 in Colombia, for a spatial resolution of 3 km × 3 km.

Table 2 also indicates the percentage of positive CG lightning flashes, which is considered later in this section, and the physical processes related to the maximum CG lightning flash densities observed by the different LLS. They include different meteorological systems and their interaction with different geographical features. In Colombia, the maximum CG lightning flash density occurs in the North of the country and is related to the seasonal variation of the trade winds associated with the oscillation of the Intertropical Convergence Zone and its interaction with local mountains. In Venezuela, the maximum CG lightning flash density

Table 2
CG lightning observations by LLS in the tropical region

Country	Maximum lightning density[a] (flashes km^{-2} year^{-1}) (Reference)	Spatial resolution (km × km)	Period of observation	Percentage of positive flashes (%) (Reference)	Physical-related process
Colombia	35 (Younes et al., 2004)	3 × 3	1997–2001	70 (Younes et al., 2003)	Trade winds and ITCZ[b]/ mountain interactions
	47 (Younes et al., 2004)	3 × 3	1997		
	16–17 (Younes et al., 2004)	30 × 30	1997–2001		
Venezuela	34–39[c] (Tarazona et al., 2006)	3 × 3	2000–2003	23 (Tarazona et al., 2006)	Trade winds and ITCZ/ mountain interactions
Java Island-1	16 (Hidayat and Ishii, 1998)	12 × 12	1995	–	Trade winds and ITCZ / sea–land interactions
Java Island-2	39 (Berger and Zoro, 2004)	1 × 1	1999	20 (Berger and Zoro, 2004)	Trade winds and ITCZ / sea–land interactions
	25 (Berger and Zoro, 2004)	8 × 8	1999		
Brazil Southeast-1	9 (Pinto et al., 2004c)	9 × 9	1988–1996	35 (Pinto et al., 1999a)	Cold front/mountain interactions
Brazil Southeast-2	24–25 (Naccarato, 2005)	1 × 1	2001	12 (Naccarato, 2005)	Cold front /sea–land/ Urban Area Interactions
	17–18 (Naccarato, 2005)	1 × 1	1999–2004		
	12–13 (Naccarato, 2005)	4 × 4	1999–2004		
	9–10 (Naccarato, 2005)	10 × 10	1999–2004		
Brazil North	12 (Fernandes, 2005)	10 × 10	2002–2003	20 (Blakeslee et al., 2003)	Trade winds and ITCZ / amazon forest interactions
	5 (Fernandes, 2005)	55 × 55	2002–2003		

[a] Values were not corrected for detection efficiency of the LLS.

[b] Intertropical Convergence Zone.

[c] Values were calculated from the stroke density of 55 strokes km^{-2} year^{-1}, assuming the negative multiplicity between 2 and 2.5 and the positive multiplicity equals to 1, typical values for IMPACT LLS.

occurs in the Northwest of the country, in a region close to the region of maximum CG lightning flash density in Colombia, and is related to the same processes that occur in Colombia. In Java Island, the maximum CG lightning flash density is also related to the seasonal variation of the trade winds associated with the oscillation of the Intertropical Convergence Zone. The same is valid for the North region of Brazil, although the presence of the Amazon forest has a considerable effect (Williams et al., 2002). Finally, in Southeast Brazil, in the case of Brazil Southeast-1, the maximum CG lightning flash density is related to the interaction of cold fronts and local mountains, while for Brazil Southeast-2 it is related to the interaction of cold fronts with an urban area of São Paulo in the presence of a sea breeze.

In order to make a more reliable comparison among the values of maximum CG lightning flash densities in different countries in Table 2, three aspects should be considered: different spatial resolutions of the observations, different detection efficiency of each LLS and different contamination of each LLS by IC flashes. With respect to the spatial resolution, as observed before, the higher is the spatial resolution, the higher is the maximum lightning density. In consequence, in order to compare values at different spatial resolutions, it is necessary to know in detail the spatial distribution of the flash density in the different countries. Since this information is not available for most countries, this effect was estimated taking the available information of maximum CG lightning flash densities for different spatial resolutions in Colombia, Java Island-2, Brazil North and Brazil Southeast-2. Fig. 2 shows the variation of the maximum CG lightning flash density versus spatial resolution taking the values in Brazil Southeast-2 as reference. The values in Colombia, Java Island-2 and Brazil North were normalized to the values in Brazil Southeast-2 for the lower spatial resolutions available in these countries. The data from the different countries in Fig. 2 can be fitted to a logarithmic curve with a square

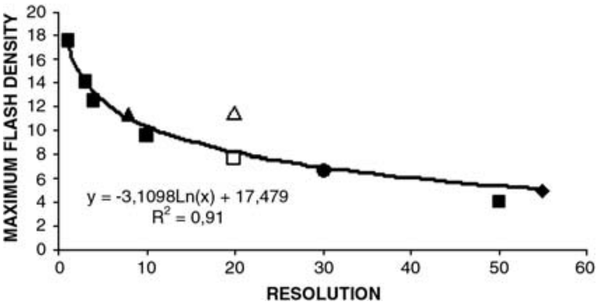

Fig. 2. Variation of the maximum CG lightning flash density, in flashes km^{-2} year^{-1}, as a function of the resolution (r), in km × km, based on data from the LLS in Brazil Southeast-2 (black square), Colombia (black dot), Java Island-2 (black triangle), Brazil North (black rhombus), Europe (white square) and North America (white triangle). The data are fitted by a logarithm equation with a square correlation coefficient (R^2) equals to 0.91.

correlation coefficient (R^2) equal to 0.91. The best fit in Fig. 2 also takes into account values from North America and Europe, normalized to the Brazil Southeast-2 values for a spatial resolution of 1 km × 1 km, so that this curve can be used in the comparison of tropical and temperate values of maximum CG lightning flash densities, as discussed in Section 5.

The detection efficiency of an LLS, in turn, depends on several aspects including distance and type of the sensors, network configuration, site characteristics, and others. For the LLS in Table 1, the detection efficiency varies from 60% in Java Island-2 to about 85% in Brazil Southeast-2. For the LLS for which values of detection efficiency in the region of maximum CG lightning flash density were available (Java Island-1, Brazil Southeast-1, Brazil Southeast-2 and Brazil North), the values were used to correct the data. Otherwise, average values inside the LLS were used.

The last aspect that should be considered when comparing data from different LLS is related to the possible influence of the IC contamination on the maximum CG lightning flash densities. The contamination is a result of misclassification of IC flashes as low peak current positive flashes. The resultant effect is an increase in the maximum CG lightning flash density. In order to investigate this aspect, it is necessary to consider the values of the percentage of positive CG flashes shown in Table 2. For all LLS this percentage is around 10%–20%, except for the LPATS LLS in Brazil Southeast-1 and Colombia, where they are 35% and 70%, respectively. In case of Brazil Southeast-1, later observations using also IMPACT sensors (Brazil Southeast-2) showed that this large percentage is a result of IC contamination, in agreement with observations outside the tropical region, suggesting that in this type of LLS positive flashes are more contaminated by IC flashes (e.g. Théry, 2001; Rakov and Uman, 2003). In the case of Colombia, no other observations exist to clarify this issue. However, considering the results obtained in Brazil Southeast-1 and considering that the large percentage of positive CG lightning observed in Colombia is not supported by indirect indications of the amount of positive flashes obtained from sprite and mesoscale convective system distributions (Toracinta and Zipser, 2001; Füllekrug and Price, 2002; Sato and Fukunishi, 2003; Cecil et al., 2006), it is assumed that it is probably also a result of IC contamination.

The aspects mentioned above were then applied to the values of maximum CG lightning flash densities shown in Table 2. First, the values of maximum CG lightning flash densities in Table 2 were normalized to the spatial resolution of 1 km × 1 km, following the equation shown in Fig. 2. Second, the values were corrected for variations in the detection efficiency, following the values described in Table 1. Finally, the values in Brazil Southeast-1 and Colombia were adjusted considering that their percentages of positive flashes are equal to those in Brazil Southeast-2 and Venezuela, respectively. This approach is based on the proximity of the regions and on the fact that the LLS in Brazil Southeast-2 and Venezuela are less subject to IC contamination due to the fact that they include IMPACT sensors. The resultant values were named absolute maximum CG lightning flash densities and are shown in Table 3. The main result of this table is that the absolute maximum CG lightning flash density in the tropical region ranges from 21 to 65 flashes km^{-2} year^{-1}, with the largest value occurring in Java Island-2 and not in Colombia as was the case for the maximum CG lightning flash densities observed.

4. Comparison with total lightning observations by satellites in the tropical region

In this section maximum CG lightning flash densities observed by the different LLS in the tropical region are compared to total lightning densities (CG flashes plus IC flashes) obtained by optical sensors on board satellites for the same regions. The comparison is based on the values of the IC/CG ratio. This ratio, in turn, is associated with the thunderstorm characteristics (Williams et al., 1999). A combined data set from 1995 to 2005, including data from both the Optical Transient Detector (OTD) and the Lightning Imaging Sensor (LIS), kindly provided by Dr. Steve Goodman from Marshall Space Flight Center, was used. The data were corrected by variations in the view time and detection efficiency of the satellite sensors and corresponds to the spatial resolution of 0.5° × 0.5° (approximately 55 km × 55 km), due to limitations in the satellite

Table 3
Absolute maximum CG lightning flash densities in the tropical region

Country	Period of observation	Absolute maximum lightning flash density[a] (flashes km^{-2} year^{-1})
Colombia	1997–2001	34
	1997	46
Venezuela	2000–2003	56
Java Island-1	1995	33
Java Island-2	1999	65
Brazil Southeast-1	1988–1996	19
Brazil Southeast-2	1999–2004	21
	2001	29
Brazil North	2002–2003	34

[a] Values are referred to a spatial resolution of 1 km × 1 km.

Table 4
Total lightning densities observed in the tropical region from satellite and the inferred IC/CG ratios

Country	Total lightning flash density[a] (flashes km^{-2} year^{-1})	IC/CG ratio[b]
Colombia	99	11.0
Venezuela	181	12.6
Brazil Southeast-1	20	4.0
Brazil Southeast-2	26	4.9
Brazil North	25	3.9

[a] Values were kindly provided by Dr. Steve Goodman from Marshall Space Flight Center. They were corrected by variations in the view time and detection efficiency of the satellite sensors.

[b] Values were calculated for a spatial resolution of approximately 55 km × 55 km. Maximum CG density values for this spatial resolution were obtained from Fig. 2 (see text for details).

Table 6
Absolute maximum CG lightning flash densities in the temperate region

Continent	Period of observation	Absolute maximum lightning flash density[a] (flashes km^{-2} year^{-1})
North America	1996–2000	18
Europe	1992–2001	17
Asia	1997–2001	24
Africa	2001–2003	27

[a] Values were referred to for a spatial resolution of 1 km × 1 km.

sample rate. Both sensors can gather lightning data under daytime conditions as well as at night, providing a much higher detection efficiency and spatial resolution than has been attained by earlier satellite lightning sensors. The instruments record the time of the lightning events, measure their radiant energy, and determine the location of lightning events within its field-of-view. More details about the sensors can be found in Boccippio and Goodman (2000) and Christian et al. (2003).

Table 4 shows an estimate of the IC/CG ratio for the same regions of the maximum CG lightning flash densities shown in Table 3. The values were calculated using the total lightning density values from OTD and LIS shown in Table 4 and the maximum CG lightning flash densities shown in Table 3, converted to the spatial resolution of the total lightning data (approximately 55 km × 55 km) using the curve in Fig. 2. Only the LLS that operated for at least two years after 1995 were considered in the comparison, due to the limitations in the satellite sample rate. The values of IC/CG ratio obtained for the regions of maximum CG lightning flash densities observed by the different LLS in the tropical region show large variations, ranging from 3.9 to 12.6.

5. Comparison with maximum CG lightning flash densities and IC/CG ratios in the temperate region

In this section absolute maximum CG lightning flash densities and IC/CG ratios estimated by the different LLS in the tropical region are compared with similar data obtained in the temperate region. Due to the large number of LLS in the temperate region (more than 30), a comparison with data from all LLS is out of the scope of this review. For this reason, the comparison was limited to consider only the highest values of maximum CG lightning flash densities observed by LLS in each continent of the temperate region. Table 5 shows the highest values observed in each continent: in North America, the highest value was observed in Florida, United States (Orville and Huffines, 2001; Orville et al., 2002; Murphy and Holle, 2005); in Europe, the highest value was observed in the Northwest region of Italy (Schulz et al., 2005); in Africa, the highest value was observed in the Northwest region of South Africa

Table 5
Maximum CG lightning density observations in the temperate region

Continent (region)	Maximum lightning density[a] (flashes/km^2 year) (Reference)	Spatial resolution (km × km)	Period of observation
North America (Florida, United States)	16 (Murphy and Holle, 2005)	1 × 1	1996–2000
	9–12 (Orville et al., 2002)	20 × 20	1989–1998
Europe (Northwest region of Italy)	15 (Schulz et al., 2005)	1 × 1	1992–2001
	6–7 (Schulz et al., 2005)	20 × 20	1992–2001
Asia (South region of China)	7–8 (Chen et al., 2002)	30 × 30	1997–2001
Africa (Northwest region of South Africa)	19[b]	1 × 1	2001–2003

[a] Values were not corrected for the detection efficiency of the LLS.

[b] Data were obtained from SKA Site Selection South Africa, Report to the ISSC, Eskom, Dec. 2003. The number of flashes were obtained considering that strokes are part of a flash if the distance between successive strokes is less than 2.5 km and time between successive strokes is less than 100 ms.

(Ndlovu and Evert, 2006; Evert and Schulze, 2005; Bhikha et al., 2006); and, finally, in Asia the highest value was observed in the South of China (Chen et al., 2002, 2004).

Table 6 shows the absolute maximum CG lightning flash densities obtained from the observed values in Table 5. The following detection efficiency values, taken from the articles cited in the previous paragraph, were used to correct the observed densities: 90% for the regions in United States and Italy, 85% for the region in China and 80% for the region in South Africa. From a comparison of Tables 3 and 6 it can be observed that the absolute maximum CG lightning flash densities in the tropical region (19 to 65 flashes km^{-2} $year^{-1}$) are higher than in the temperate region (17 to 27 flashes km^{-2} $year^{-1}$). Considering that the most intense thunderstorms on Earth in terms of total lightning activity (and probably also in terms of CG lightning activity) occur in the temperate region (Zipser et al., 2006), the higher maximum CG lightning flash densities in the tropical region are probably a result of the fact that the lightning season in this region is longer than in the temperate region (Pinto et al., 2006b).

Finally, Table 7 shows an estimate of the IC/CG ratio for the same regions of maximum CG lightning flash densities in Table 5, obtained following the same procedure used to obtain the values in Table 4. The values vary from 2.1 to 8.7. This range is similar to that obtained in the continental United States by Boccippio et al., 2001 (1.0 to 9.0), based on observations from the National Lightning Detection network (NLDN) and the Optical Transient Detector (OTD), even though the value for the United States is lower than the value obtained by Boccippio et al. (2001) for the same region. The difference may be partially attributed to the different satellite data used in each case (only the OTD in Boccippio et al. (2001) and the OTD and LIS in Table 7), although the possibility that for Florida the dependence of the maximum CG lightning flash density on the spatial resolution follows a curve different to that indicated in Fig. 2 cannot be ruled out. From a comparison of Tables 4 and 7 it can be observed that the range of IC/CG ratio in the tropical region (3.9 to 12.6) is similar to that estimated for the temperate region (2.1 to 8.7), with the exception of the values in Colombia and Venezuela, where the IC/CG ratio seems to be larger than in all other regions. This fact supports recent evidence indicating that others factors than latitude can affect significantly this ratio (Rakov and Uman, 2003). In addition, it suggests that the IC/CG ratio in Colombia and Venezuela could be higher than in any other regions, what could explain the larger percentage of positive flashes observed in these countries compared to other countries with the same type of LLS.

Table 7
Total lightning densities observed in the temperate region from satellite and the inferred IC/CG ratios

Continent	Total lightning flash density (flashes km^{-2} $year^{-1}$)	IC/CG ratio[a]
North America	40	8.7
Europe	9[b]	2.1
Asia	36	5.8
Africa	30	4.3

[a] Values were calculated for a spatial resolution of approximately 55 km × 55 km. Maximum CG density values for this spatial resolution were obtained from Fig. 2 (see text for details).

[b] This value is based only on OTD data, since the region of maximum CG lightning flash density is outside the LIS coverage.

6. Summary

A comprehensive review of the maximum CG lightning flash densities observed by LLS in the tropical region is presented for the first time. From the observed values, absolute maximum values for a spatial resolution of 1 km × 1 km were estimated, using an empirical curve relating flash density and resolution and correcting the data for differences in the detection efficiency and in the intracloud (IC) contamination of the different LLS. Also IC/CG ratios were estimated using total lightning observations by satellites in the tropical region. The results were then compared with similar observations in the temperate region. The determination of absolute maximum CG lightning flash densities in different regions on Earth is important for lightning protection, as well as for many scientific applications, such as the validation of thunderstorm electrification models and the evaluation of the impact of global changes on lightning activity. The determination of the IC/CG ratios, in turn, is important to better understand thunderstorm electrical characteristics.

Some specific points emerging from this review are:

1. Maximum CG lightning flash densities observed by the different LLS for different spatial resolutions vary from 5 to 47 flashes km^{-2} $year^{-1}$, in response to processes involving different meteorological systems and their interaction with different geographical features. From the observed values, absolute maximum CG lightning flash densities for a spatial resolution of 1 km × 1 km were estimated, taking into account the differences in the detection efficiency and IC contamination of the LLS. Values from 19 to 65 flashes km^{-2} $year^{-1}$ were found.

2. IC/CG ratios were estimated for the same regions as the maximum CG lightning flash densities, for a spatial resolution of approximately 55 km × 55 km. It was found that they vary from 3.9 to 12.6.
3. Absolute maximum CG lightning flash densities in the tropical region were found to be higher than similar values in the temperate region (17 to 27 flashes km^{-2} year^{-1}). The highest maximum CG lightning flash density on Earth (65 flashes km^{-2} year^{-1}) occurs in Java Island. Considering that the most intense thunderstorms on Earth in terms of total lightning activity (and probably also in terms of CG lightning activity) occur in the temperate region (Zipser et al., 2006), the higher maximum CG lightning flash densities in the tropical region is probably a result of the fact that the lightning season in this region is longer than in the temperate region (Pinto et al., 2006b).
4. The range of values of the IC/CG ratio obtained for the regions of maximum CG lightning flash densities observed by the different LLS in the tropical region (3.9 to 12.6) is similar to that estimated for the regions of the highest maximum CG lightning flash density in each continent in the temperate region (2.1 to 8.7), with the exception of the values in Colombia and Venezuela. This fact supports recent evidence indicating that factors other than latitude can affect significantly this ratio (Rakov and Uman, 2003). In addition, it also suggests that the IC/CG ratio in Colombia and Venezuela could be higher than in any other regions, which could explain the larger percentage of positive flashes observed in these countries compared to other countries with the same type of LLS.

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