Lightning density maps obtained by keraunic levels, lightning detection network data and satellite observations

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Abstract— **For decades, thunderstorm maps based on keraunic levels (number of thunderdays per year) have been used to estimate cloud-to-ground lightning density in the Brazilian standard ABNT NBR-5419. It is known that the thunderdays data were achieved in a small number of observations sites during the first half of the 20th century. In the last decade, two new advanced techniques have been used to provide cloud-to-ground lightning data over large areas: the lightning detection networks (on ground) and the space-born lightning instruments (on satellites). In Brazil, a LF lightning detection network (BrasilDAT) with more than 20 sensors have been collecting cloud-to-ground lightning data since 1999 for the mid-southern Brazil. By the other hand, a VLF network called World-Wide Lightning Location Network (WWLLN) was developed in the beginning of 2000's and have been collecting cloud-to-ground lightning data over the entire globe based on more than 30 sensors since 2005. A space-born technology for lightning detection is the Lightning Image Sensor (LIS) on board of the Tropical Rainfall Measuring Mission (TRMM) satellite launched in Nov/1997 by NASA. Due to its low orbit (350km of altitude) and the 35º latitude inclination, the LIS can record the lightning activity over the entire Brazil. This paper presents a comparative analysis of the cloud-to-ground lightning density maps obtained from the keraunic levels of ABNT NBR-5419, from 6 years of WWLLN data (2005-2010) and 12 years of LIS data (1998-2009). This study intends to investigate what are the uncertainties and/or errors of a lightning density map based on the keraunic level related to the lightning maps gathered from WWLLN data and LIS data. Since WWLLN presents a low DE over Southern and Southeastern Brazil compared to the other regions and LIS provides a measurement much less affected by DE, the lightning density map from LIS was used as a reference. The results suggest a revision of the standards in order to provide more realistic information for lightning protection.**

Keraunic level, lightning, ABNT NBR-5419, thunderdays, LIS, WWLLN, density maps

I. INTRODUCTION

Thunderstorm days (TD) are the first systematic way introduced to record the thunderstorm and lightning activity in the world [1]. Like any other observations, TD values are subjected to changes in the methods and/or changes in the boundary conditions related to the observations. In the case of thunderstorm day records, since they are man-made observations, the main limitations are related to the definition of a thunder day, changes in the operational procedure to make the observations and, finally, changes in the ambient around the observational site that can affect the process or even in the site location [2]. Regarding the definition of TD, almost all observations after 1897 consider a thunder day when an observer heard, at any time of the day, a thunder.

Depending on the frequency range of operation, different lightning detection networks can identify and locate cloud-to-ground (CG) lightning and/or intra-cloud (IC) discharges. A lightning detection network usually operates in 3kHz-300kHz frequency range (LF) and in general presents less than 1km of location accuracy (LA), about 80-90% of detection efficiency (DE) and about 1.000km of detection range. A long-range lightning detection network operates in 3Hz-30kHz frequency range (VLF) and generally present a detection range of about 5.000km, about 20km of LA and lower than 20% of DE. In Brazil, a LF lightning detection network (BrasilDAT) with more than 20 sensors have been collecting CG lightning data since 1999 for the mid-southearn Brazil [3]. By the other hand, a VLF network called World-Wide Lightning Location Network (WWLLN) was developed in the beginning of 2000's and have been collecting CG lightning data since 2005 over the entire globe based on more than 30 sensors [4][5].

A space-born technology for lightning detection is the Lightning Image Sensor (LIS) on board of the Tropical Rainfall Measuring Mission (TRMM) satellite launched in Nov/1997 by NASA [6][7]. Due to its low orbit (350km of altitude) and the 35º latitude inclination, the LIS can record the lightning activity over the entire Brazil. Since LIS travels around the Earth with a velocity greater than 7 km/s, the instrument can monitor individual storms and storm systems for lightning activity for almost 90s as it passes overhead. Thus, LIS needs about 49 days to collect lightning data at all times of the day over one particular region. However, since the instrument detects only the luminous pulses of the lightning events, it cannot discriminate between CG and IC discharges. Thereby, its information corresponds to the total lightning activity observed with an estimate DE of about 90-95%.

This paper presents a comparative analysis of CG lightning density maps obtained from the keraunic levels of ABNT NBR-5419, from a 6-year WWLLN dataset (2005-2010) and from a 12-year LIS dataset (1998-2009). This study intends to investigate what are the uncertainties and/or errors of a CG lightning density map based on the keraunic level related to the CG lightning maps gathered from more precise and advanced technologies. Since WWLLN presents a low DE over Southern and Southeastern Brazil compared to the other regions and LIS provides a measurement much less affected by DE, the lightning density map from LIS was used as a reference. The results suggest a revision of the standards in order to provide more realistic information for lightning protection. They may also contribute to studies of performance of transmission lines and/or substations for power utility companies.

II. METHODOLOGY

A. ABNT NBR-5419 lightning flash density

The ABNT NBR-5419 lightning flash density map (given in flashes/km^2.year) was computed based on the isokeraunic level map and empiric equation provided by the respective standard [8] at page 30, figure B.1.a from Anexo B. The isokeraunic map is reproduced in Figure 1 for convenience.

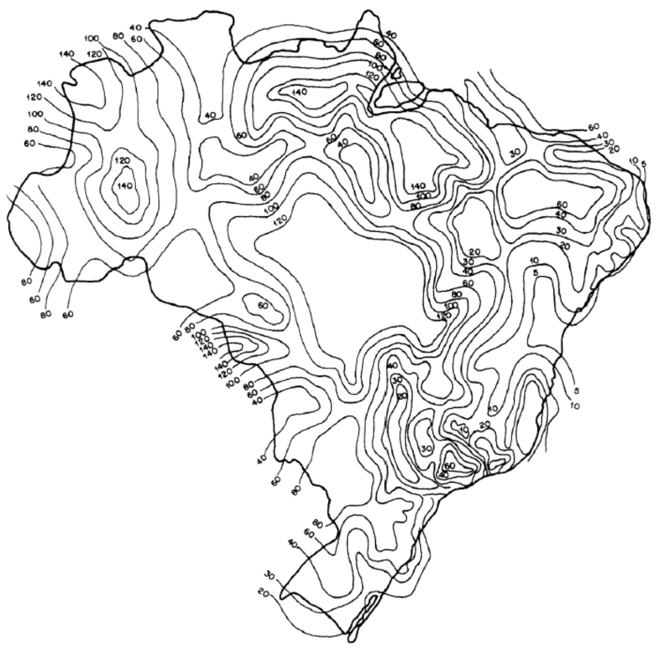

Figure 1. Isokeraunic level map (or number of TD) for Brazil provided by ABNT NBR-5419:2005

Equation (1) which is also provided by the standard is an empiric expression that correlates the CG flash density (flashes/km^2.year) and the TD values. Thus, based on the isokeraunic map from Figure 1 the correspondent CG flash density (Ng) map can be easily computed.

$$Ng = 0{,}04 \times Td^{\,1{,}25} \qquad (1)$$

B. WWLLN lightning flash density

The WWLLN has been operating since 2002 and throughout this period the processing algorithm responsible for the lightning location calculation had been changed a couple of times [9]. Thus, to assure employing the better CG lightning dataset (which was computed by the more recent processing algorithm), only the last 6 years (2005-2010) were used.

Since the WWLLN detects the VLF pulses irradiated from individual return strokes, the CG flash density map based on a 6-year dataset (2005-2010) was computed assuming that the overall CG flash multiplicity is 3 [10]. For the Paraiba Valley (in Southeastern Brazil), using high-speed cameras, the average CG flash multiplicity found was 3.8 [11]. Thus, it is reasonable to use multiplicity 3 as a first approximation for the whole country. It is also important to note that the WWLLN CG lighting dataset was not correct for the network DE variations. As a consequence, the spatial distribution of the CG lightning events is strongly biased by the network performance. Unfortunately, it is still not possible to precisely estimate the WWLLN DE over Brazil due to the absence of the detection efficiency model for VLF networks. There are some previous works available in the literature that estimates the network DE for the whole globe, however the computations were done only for a lower number of sensors over South America [12][13].

C. LIS lightning flash density

In order to assess a flash density map using the LIS data, it is required to correct the map considering the diurnal variation of the LIS DE, which decreases to a minimum of about 70% at noon and reaches a maximum of 88% during the whole night [7]. Furthermore, since the TRMM satellite has an orbit with 35º latitude inclination, the sampling time near the tropics is significantly higher than over the equator [7]. Thus, for the northern and northeastern Brazil, the total sampling time is almost one third of the sampling time for the mid-southern portion of the country [5]. This affects directly the number of lightning events detected by the sensor causing a spatial bias from north to south. Thus, the LIS dataset must be corrected by both the diurnal variation of the DE and the differential sampling view time between equatorial and tropical regions.

Since LIS does not discriminate between CG lightning and IC discharges, the dataset corresponds to the total lightning information. Thus, in order to get the CG flash densityfrom the total lightning information provided by LIS, the average IC/CG ratio of 1.5 (60% IC and 40% CG) was adopted for the whole country [5]. This ratio was assessed comparing the LIS total lightning data and LF network CG lightning data for two different regions of Brazil: Rondônia State (very closer to Amazon basin) and the Southeastern region.

III. RESULTS AND DISCUSSIONS

A. CG flash density map from WWLLN

Figure 2 shows the CG flash density map (with 0.25º resolution) for Brazil based on 6 years of WWLLN data (2005-2010). It is important to note that the WWLLN dataset was not correct for the network DE variations. As a consequence, it can be observed that the spatial distribution of the CG flash density is strongly biased by the network performance. Figure 2 clearly shows that the WWLLN presents a much higher DE over the northern Brazil compared to the southern portion [5]. Unfortunately, as already explained, it is still not possible to precisely estimate the WWLLN DE over Brazil.

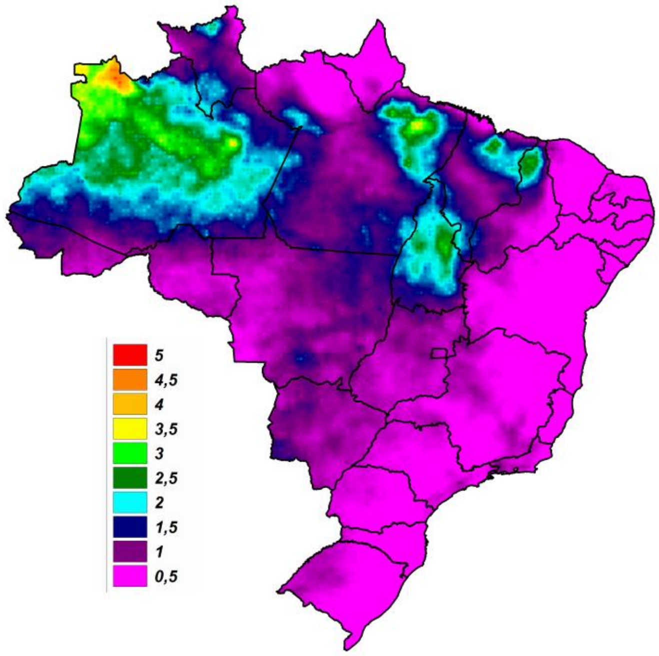

Figure 2. CG flash density over Brazil estimated by 6 years of WWLLN data (2005-2010) with 0.25º resolution. The values were not corrected for the network DE variations.

Due to the limitation in the WWLLN DE over Brazil which directly affects the lightning data, in a future work it is intended to first convert the WWLLN reports (which are actually lightning strokes) into thunderstorm days (TD) based on the definition of TD previously described. These TD values are then reconverted into CG flash density values based on Equation (1) thus recreating Figure 2. This procedure is expected to minimize the network effects over the final result since it is required to detect only one lightning stroke within 15km radius over all day to compute one TD. This new dataset is then supposed to be much less affected by the network DE.

B. CG flash density map from LIS

Figure 3 shows the CG flash density for Brazil (with 0.25º resolution) based on the 12 years of LIS data (1998-2009) applying all corrections discussed in section II. As already explained, since LIS provides a more DE-independent and continuous dataset, the map of Figure 3 was used as a reference in comparing to the CG flash density map derived from the TD values of ABNT NBR-5419.

Based on Figures 2 and 3, in fact the WWLLN DE is clearly lower over the southern Brazil related to the northern portion as previously stated by Naccarato et al. [14]. However, the main lightning features in the north part of the country are roughly reproduced by the WWLLN measurements.

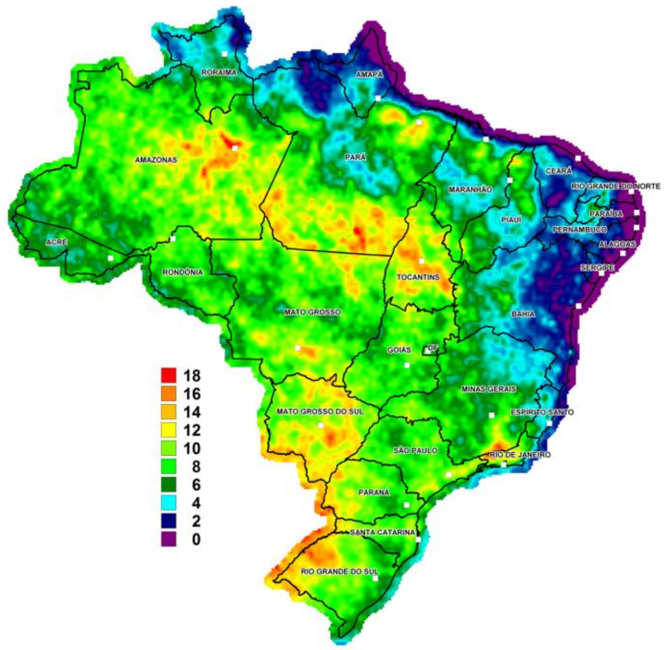

Figure 3. CG flash density over Brazil based on 12 years of LIS data (1998-2009) with 0.25º resolution applying all corrections.

From Figure 3, it can be observed that the CG lightning activity over Brazil presented four (among others) major lightning spots: (1) west portion of Rio Grande do Sul State; (2) the west portion of Rio de Janeiro and south of Minas Gerais states; (3) middle area of Mato do Grosso do Sul State; and (4) large part of the Amazon basin in the northern Brazil. A more comprehensive analysis of these lightning features in Brazil was done by Naccarato et al. [15].

A quick comparison of Figures 1 and 3 shows that the major spots of CG flash density and TD values are roughly coincident in both maps. However the TD map show some spots that are not present in CG flash density map and vice-versa. These features will be discussed in the next section.

C. CG flash density map from ABNT NBR-5419

Figure 4 shows the CG flash density map for Brazil (with 0.25º resolution) from LIS superimposed by the Ng values derived from the isokeraunic levels (or TD values) of ABNT NBR-5419. Table 1 presents the correlation between TD and Ng computed by Equation (1). These numbers are used to convert TD data into a color-coded Ng data in the map.

TABLE I. CONVERTION OF TD INTO NG VALUES

TD	Ng	TD	Ng
5	0,3	60	6,7
10	0,7	80	9,6
20	1,7	100	12,6
30	2,8	120	15,9
40	4	140	19,3

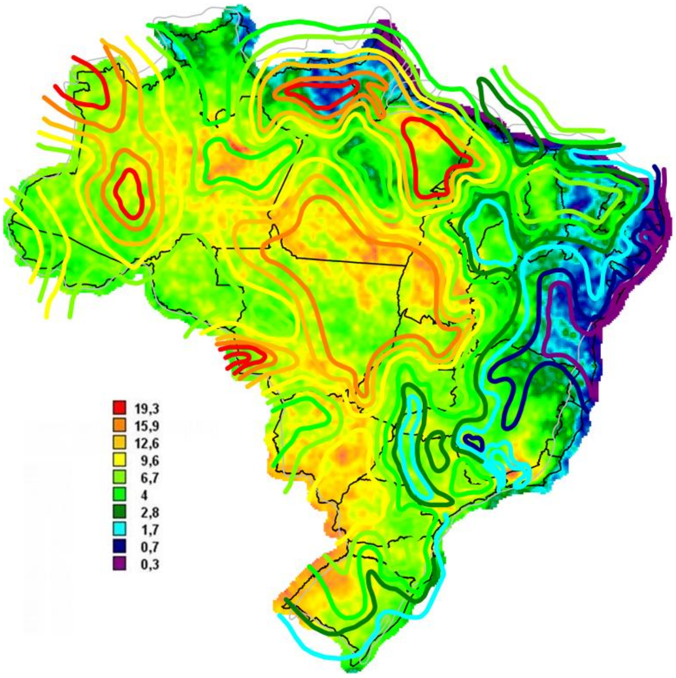

Figure 4. CG flash density for Brazil based on LIS data (12 years) and the TD values provided by ABNT NBR-5419 with 0.25º resolution.

It can be observed at Figure 4 that there are regions with very good correlation between LIS and TD-derived CG flash densities, mainly in northeast coast of Brazil and the center part of the country. By the other hand, there are some other regions with significant discrepancy between the maps, mainly the Amazon area and the southern part of Brazil. Two particular areas present a huge difference between CG flash densities: the north part of Pará State and a small area in the west of Mato Grosso State. Since this is a preliminary study, it is still not clear why the CG flash density derived from TD values over these regions are so high compared to the CG flash density derived from LIS. However, the most feasible explanation might be errors in the TD observations over those regions. Other areas also show differences in the CG flash densities but in a lower magnitude: west part of Amazon State, east part of Pará State, the overall Southeastern and Southern Brazil.

In a future work (in a similar way to the WWLLN data), the LIS data will be converted into TD and then reconverted into CG flash density values (Equation 1) to recreate Figure 3. This procedure requires some corrections of the LIS data due to the satellite sampling time difference between Equator and Tropic (as discussed in Section II-C). As a result, it is expected to achieve a much more reliable TD map that will be used as a reference to a more comprehensive evaluation / validation of the isokeraunic level map from ABNT NBR-5419.

IV. CONCLUSIONS

The results of this study indicate that the TD values (or isokeraunic levels) described in the Brazilian standard for protection of structures against lightning (ABNT NBR-5419) should be used with care. It was found regions with very good correlation between CG flash densities derived from TD and LIS data, mainly in northeast coast of Brazil and the center part of the country. However, some other regions show significant differences, mainly the Amazon area and the southern part of Brazil. These can be explained mainly because the TD measurements (Figure B.1.a at page 30) were made between 1910 and 1951 in a limited number of observational sites and then these data was extrapolated for the whole country.

The fact that the different data sets refers to different time periods should be taken into account in the interpretation of the results of this study. It is possible that the spatial distribution of thunderstorms in Brazil in the first half of the 20th century had been changed due to mainly the climate changes. However, this does not affect the conclusion of this study and further investigations are required.

In a future work, the LIS and WWLLN data will be converted into TD and then reconverted into CG flash density values (by using Equation 1) in order to recreate both CG flash density maps (Figures 2 and 3). As a result, it is expected to gather a much more reliable TD (and Ng) maps that will be used as a reference to a more comprehensive evaluation of the isokeraunic level map (and even Equation 1 itself) provided by ABNT NBR-5419.

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