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Ground Flash Density Dispersion from Ng

An observation based on 14 years of LIS data collected over Brazil

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Abstract — **In this work, the year-to-year variation of ground flash density (GFD) around its long-term average, Ng, is analyzed on specific areas encompassing the state capitals of Brazil, based on data from NASA's satellite borne lightning imaging sensor (LIS), collected in the 1998-2011 period (14 years). The ratio between GFD and Ng (GFD/Ng) was considered the most straightforward and proper to deal with the data in this work. The data set showed that from year to year the GFD/Ng ratio can vary widely, the variation ranging from 0 up to 14 in regions with low Ng values (Ng<2), and from 0 up to 6 for regions with higher Ng values (Ng>6). However, the data dispersion follows well-behaved probability distributions, particularly for GFD/Ng ratio greater than 1. For high Ng values (Ng>10) the probabilities for GFD/Ng to exceed 2, 3 and 4, are 12%, 3.5% and 0.6%, respectively. Other features about the data are discussed.**

Keywords—lightning; ground flash density; GFD; Ng; dispersion; variation; lightning protection.

I. INTRODUCTION

Ng is the average annual ground flash density (GFD), a quantity commonly used in lightning protection engineering and lightning related scientific studies. It is the number of lightning flashes to ground per square km, per year, averaged over a number of years (the longer the time, the better).

Ng "is a fundamental parameter, providing the basis for any estimation of the frequency of lightning effects upon electrical systems" [1]. Since it is a per unit area parameter, the average number of lightning flashes expected to hit a given flat area can be straightforwardly estimated by multiplying the area (in km^2) by Ng. For a structure on flat ground (building, tower, overhead power line etc), an equivalent area can be attributed to it, being this area not only defined by the structure footprint, but it extends outwards by a lateral distance that is function of the structure height. Such area then becomes the equivalent collection area of the structure, meaning that the structure is expected to collect (or intercept) all lightning that would otherwise hit the same area if the structure were not there.

The reality is obviously more complex in many respects. To make things easier, the standards assume some (normally conservative) simplifications so that the task of estimating the frequency of direct lightning strikes to a structure becomes as simple as described in the previous paragraph. To name a few standards, it is worth mentioning that Ng is a primary parameter of risk assessment in the international standard on lightning protection IEC 62305-2 [2] and standards derived from it, e.g. the Brazilian standard ABNT NBR 5419-2 [3], as well as in the American standard for lightning protection NFPA 780 [4].

As an average value taken on a yearly basis, Ng is more representative to studies involving long-term series of lightning events, affecting or expected to affect the structure under consideration. However, knowing that the GFD varies from year to year, what variation should one consider on the number of flashes to a structure with respect to the expected value based on Ng? This work intends to show some data in this respect, based on data collected by LIS over specific spot areas in Brazil.

II. DATA SET AND GENERAL OBSERVATIONS

The data used in this study come from LIS data collected and prepared by the Brazilian National Institute of Space Research (INPE) for the Brazilian Electric System National Operator (ONS) and for the Brazilian standard on lightning protection ABNT NBR 5419-2 [3]. A description of the application of LIS data for GFD maps in Brazil and further references can be found in [5] and [6].

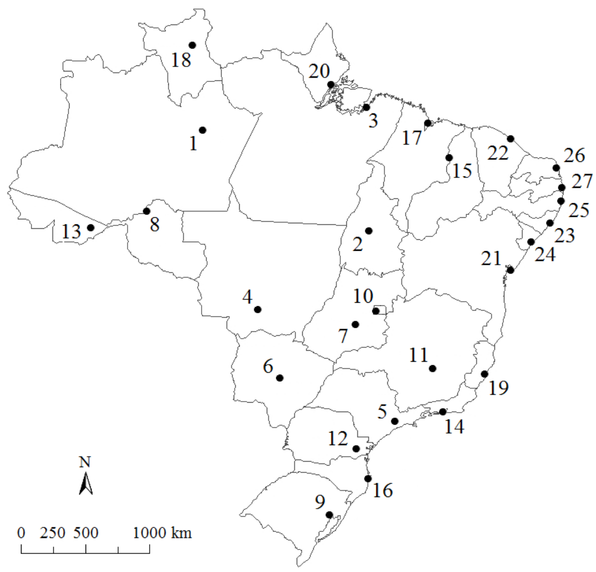

Fig. 1. Brazil and its 26 States and the Federal District (Brasília, #10). The State capitals and Brasília are indicated by numbers (1 to 27), ordered according to the Ng values in their respective district areas.

In this work, more specifically, the data correspond to those adapted for the Brazilian standard [3], taken in the 1998-2011 period (14 years), with cell size of about 25 x 25 km. The presented Ng values in this work can be a bit different from those read in [3] or provided by INPE webpage [7], which provides Ng values over Google Maps, because the data in [3] and [7] were numerically interpolated to smaller cells of 12.5 x 12.5 km.

The study covers 27 separate areas in the country, arbitrarily chosen at the 26 state capitals of Brazil, and Brasília, the country capital. The 27 cities are located on the map in Fig. 1, numbered and ordered from the highest Ng (#1) to the lowest (#27). The considered areas are in fact the district areas governed by these cities, which are state capitals too. The cities (or districts) are listed in Table I, with their respective numbers of cells, ranging from 1 to 9 cells of 25 x 25 km (625 km^2) each, totaling 149 cells, or 93125 km^2, an area larger than many countries.

The cells have fixed size and they are disposed to cover the entire district area. The area covered by the cells will normally exceed the actual district area. As an example, the eight cells required to cover the São Paulo district area are shown in Fig. 2. Note that the district areas are not proportional to the city sizes or populations.

TABLE I. LIST OF CITIES, NO. OF CELLS AND NG

#	City (district)	Qty. cells	Ng[a]	Min – max Ng dispersion
1	Manaus	6	16.4	7.7 – 23
2	Palmas	6	12.5	8.7 – 17
3	Belém	6	12.2	5.2 – 16
4	Cuiabá	6	11.3	8.0 – 13
5	São Paulo	8	10.9	7.9 – 14
6	Campo Grande	8	10.8	6.2 – 18
7	Goiânia	6	7.9	6.8 – 9.7
8	Porto Velho	8	7.6	5.0 – 12
9	Porto Alegre	5	7.3	5.5 – 9.0
10	Brasília	9	7.2	4.5 – 11
11	Belo Horizonte	4	6.9	4.4 – 9.8
12	Curitiba	4	6.5	5.6 – 8.0
13	Rio Branco	8	6.5	4.5 – 8.4
14	Rio de Janeiro	4	5.7	2.8 – 10
15	Teresina	6	5.0	3.2 – 9.0
16	Florianópolis	6	4.5	2.7 – 7.4
17	São Luís	6	3.8	0.6 – 7.7
18	Boa Vista	8	3.6	2.0 – 5.4
19	Vitória	4	2.0	1.4 – 2.8
20	Macapá	7	2.0	0.8 – 3.3
21	Salvador	5	0.6	0.2 – 0.8
22	Fortaleza	4	0.34	0.2 – 0.6
23	Maceió	4	0.20	0.0 – 0.3
24	Aracaju	2	0.19	0.2 – 0.2
25	Recife	4	0.13	0.0 – 0.2
26	Natal	4	0.09	0.0 – 0.1
27	João Pessoa	1	0.00	0.0 – 0.0

a. Ng in this case is the average Ng among the cells covering the district area of the respective city/district (km^{-2} year^{-1}).

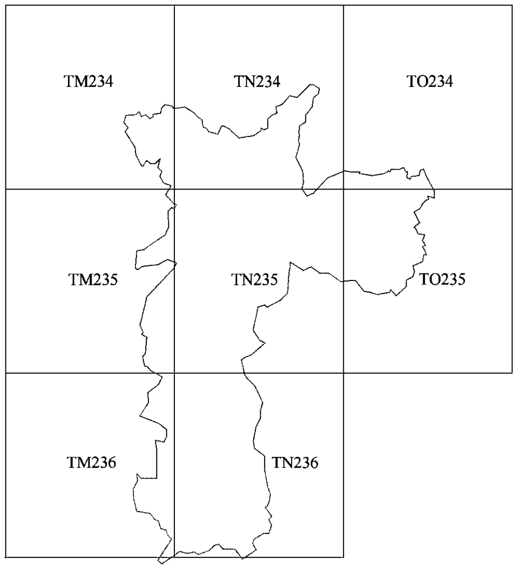

Fig. 2. Cells over São Paulo district. Distric area is 1521 km^2 while the area covered by the eigth cells is 5000 km^2.

The data set contains the quantities of lightning discharges to ground on 149 cells over 14 years (2086 values). The total number of ground flashes is about 8.423 millions, which divided by the total area of 93125 km^2 and by 14 years results in an overall average GFD (mean value) of 6.46 km^{-2} year^{-1}. The median is 6.41 km^{-2} year^{-1}, very close to the mean value.

It is convenient to make a particular distinction between Ng and GFD in this study. Ng here implies GFD averaged along the 14-year period. GFD is more freely used. In the GFD/Ng ratio presented in Section III, the GFD abbreviation appears as a variable giving the individual GFD values (per cell and per year). All GFD and Ng values are in km^{-2} year^{-1}.

In order to assess the cloud to ground (CG) flash rates using the LIS data, it is required to correct the dataset considering the diurnal variation of the LIS detection efficiency (DE), which decreases to a minimum of about 70 % at noon and reaches a maximum of 88 % during the whole night. Furthermore, since the Tropical Rainfall Measuring Mission (TRMM) satellite has an orbit with 35º latitude inclination, the sampling time near the tropics is significantly higher than over the equator. This affects directly the number of lightning events detected by the sensor causing a spatial bias from south to north. In order to get the CG flash rate values from 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. The ratio was assessed comparing the LIS total lightning data and LF network CG data for two different regions of Brazil: Rondônia State (very closer to Amazon basin) and the Southeastern region. The results revealed that the IC/CG ratio did not present a significant difference between the two regions [8].

Fig. 3 and Fig. 4 show the distribution of Ng values among the 149 cells. The bars between 0-1, 1-2 and so on indicate the amount of cells having Ng values in the intervals 0-1, 1-2 etc. The intervals are separated by integers, and in this study the values were distributed by using their exact values from data set (not necessarily that accurate), for example, 0.999 falls into 0-1 interval while 1.001 falls in the 1-2 interval. All distributions presented in this study followed this procedure.

There is a high number of cells with low Ng values (Ng < 1), as it is evident in Fig. 3. In fact, there are many nulls in the data set, i.e. no lightning flash in a given cell in a given year, see TABLE II.

The cells were grouped in a few Ng ranges in order to show some characteristics of the data set according to this division, see TABLE II and TABLE III. These tables show, for example, that 71 % of data points in the range Ng < 2 are nulls. A few zeroes (1.5 %) also appear in the cells with Ng > 10, meaning that one or another cell experienced no lightning in a certain year (or, perhaps, no lightning was detected). The concentration of Ng values per cities/districts according to the Ng ranges defined in TABLE II is shown in Fig. 5.

An important information for this study is the lightning activity along the 14 years. The numbers of ground flashes along the years are presented in Fig. 6, the total and the ones in each of the defined Ng ranges (TABLE II). A steady decay of the activity for high Ng values is observed in the figure.

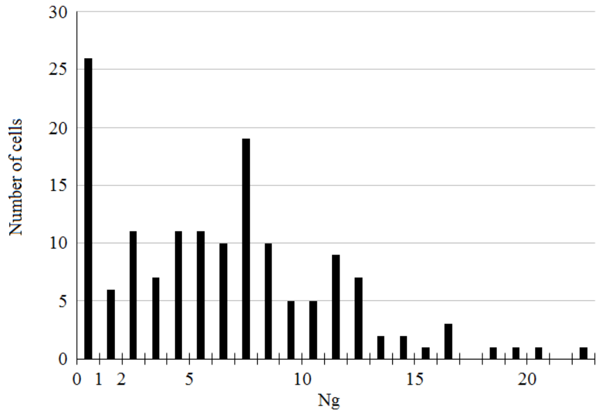

Fig. 3. Distribution of Ng values among the 149 cells. Mean value is 6.46 km^{-2} $year^{-1}$.

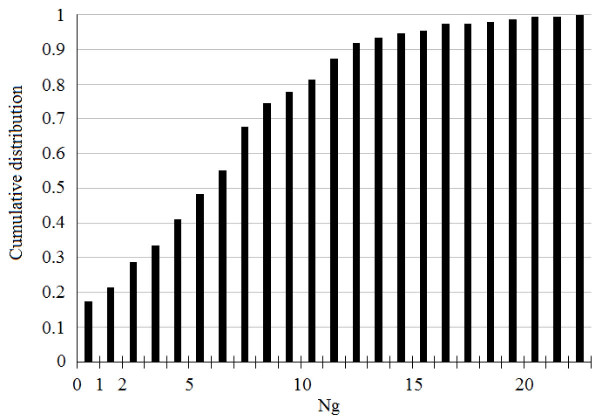

Fig. 4. Cumulative distribution of Ng values among the 149 cells. Median value is 6.41 km^{-2} $year^{-1}$.

TABLE II. DATA ACCORDING TO RANGES OF NG VALUES

Ng range	Cells	Data points	Ground flashes (thousands)	Nulls (no lightning)
< 2	32	448	147.0	319 (71 %)
2 – 5	29	406	887.7	60 (15 %)
5 – 10	55	770	3506.2	19 (2.5 %)
> 10	33	462	3882.4	7 (1.5 %)
Total	149	2086	8423.3	405 (19 %)

TABLE III. MEAN AND MEDIAN VALUES IN THE NG RANGES

Ng range	Cells	Data points	Ng mean	Ng median
< 2	32	21.5 %	0.53	0.27
2 – 5	29	19.5 %	3.50	3.32
5 – 10	55	36.9 %	7.29	7.26
> 10	33	22.1 %	13.4	12.4
Total	149	100 %	6.46	6.41

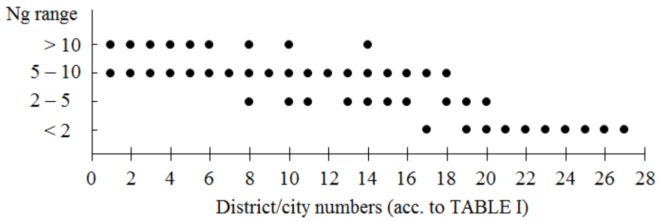

Fig. 5. Concentration of Ng values among the cells of the cities/districts, according to the Ng ranges defined in TABLE I.

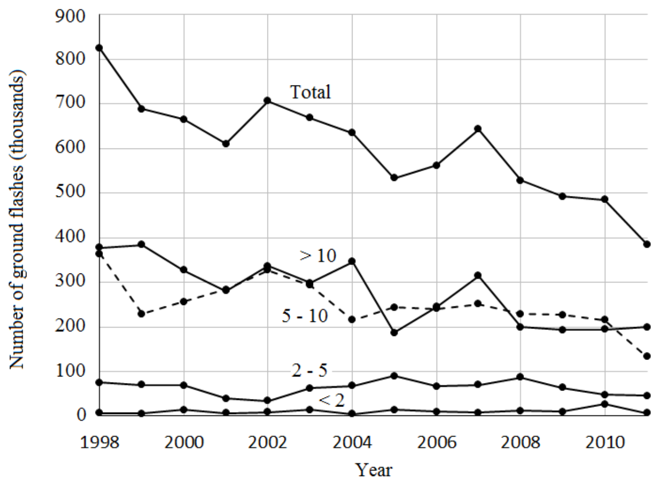

Fig. 6. Lightning activity in number of ground flashes (thousands) per year, for all cells (Total) and for the groups of cells with Ng in the indicated ranges.

III. GFD DISPERSION DATA

The 149 cells are sorted in increasing order according to their Ng values and plotted in Fig. 7 along with their corresponding minimum and maximum GFD found in the 14-year period.

The minimum and maximum GFD values of Fig. 7 are plotted in Fig. 8 as function of Ng. The minimum and maximum GFD/Ng ratios are plotted in Fig. 9 for the 149 cells ordered as in Fig. 7.

Figures 10 to 12 show discrete probability distributions, according to the Ng ranges as defined in TABLE II. The probabilities are related to the total number of ground flashes in each of the Ng ranges.

Fig. 10 shows the discrete probability distributions for GFD/Ng < 1, according to the Ng ranges defined in TABLE II, in 0.2 intervals from 0 to 1.

Fig. 11 shows the discrete probability distributions for GFD/Ng > 1, according to the Ng ranges defined in TABLE II, in the intervals 1-2, 2-3, 3-4…

Fig. 12 shows points of two distributions mingled together, with interleaved GFD/Ng intervals: values centered at 1, 2, 3, 4 and 5, correspond to intervals 1 ± 0.5, 2 ± 0.5, 3 ± 0.5, 4 ± 0.5 and 5 ± 0.5. Values centered at 1.5, 2.5, 3.5 and 4.5, correspond to intervals 1.5 ± 0.5, 2.5 ± 0.5, 3.5 ± 0.5 and 4.5 ± 0.5.

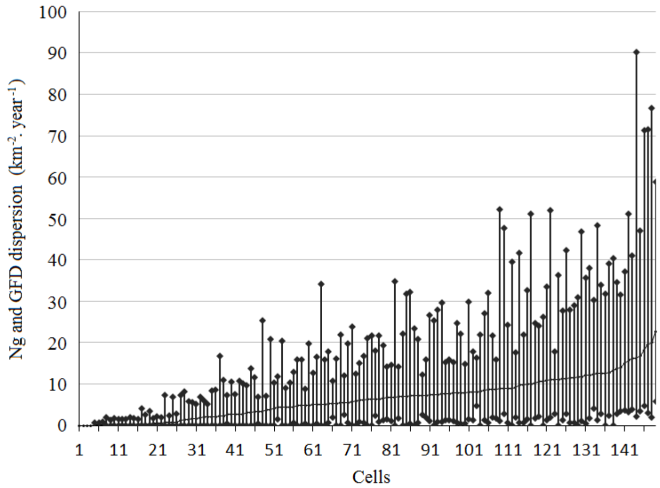

Fig. 7. Ng (solid line) of the 149 cells in increasing order and their respective maximum and minimum GFD values (vertical bars) in the 14-year period.

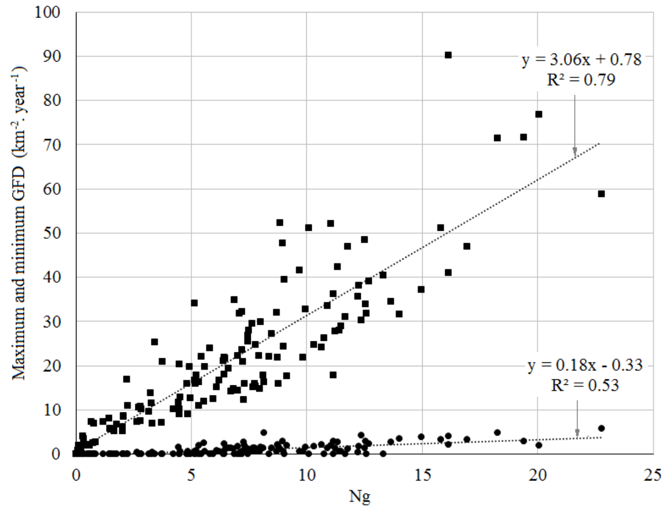

Fig. 8. Maximum and minimum GFD of the 149 cells as function of Ng.

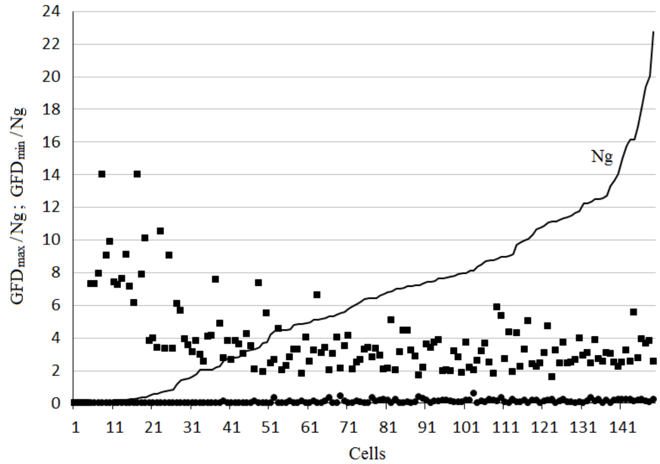

Fig. 9. Ng (solid line) of the 149 cells in increasing order and their respective maximum and minimum ratios to Ng (GFD_{max}/Ng and GFD_{min}/Ng).

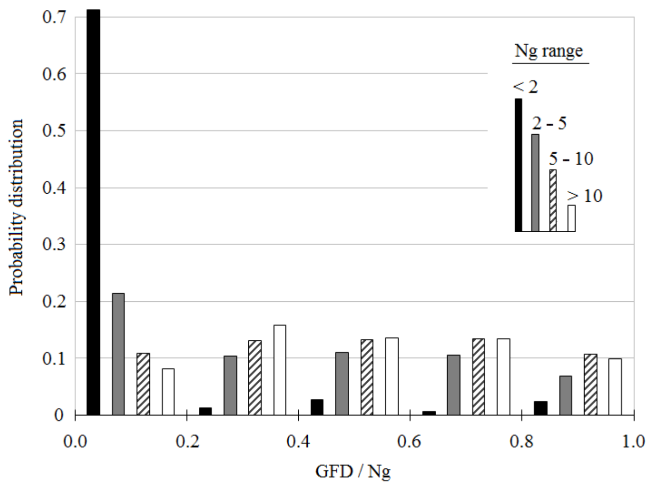

Fig. 10. Probability distributions of GFD/Ng < 1, for different Ng ranges.

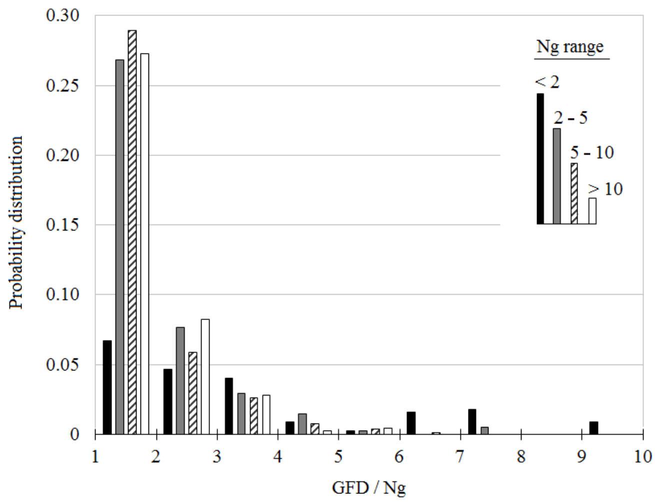

Fig. 11. Probability distributions of GFD/Ng > 1, for different Ng ranges.

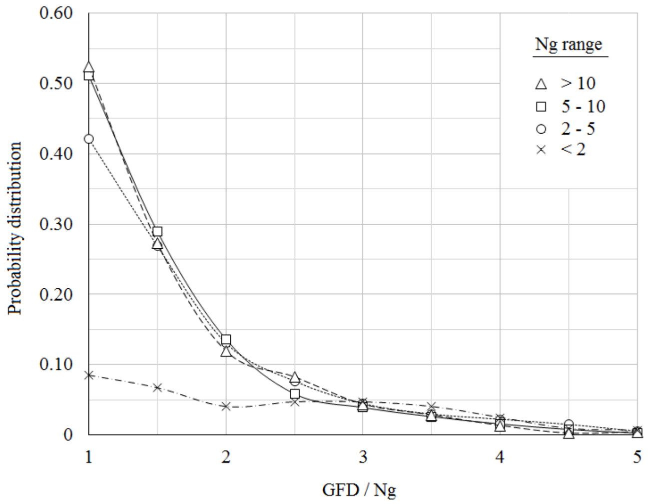

Fig. 12. Probability distributions of GFD/Ng for different Ng ranges. Two distributions are mingled together in the graph. The points on the curves are related to intervals centered at the GFD/Ng ratios ± 0.5 (see text).

IV. ANALYSIS AND DISCUSSION

Despite the inaccuracies involved in any method for obtaining GFD: thunderstorm days (TD), lightning flash counters (LFC) or in more sophisticated techniques such as lightning location systems (LLS) and satellite imaging (LIS), this study has the advantage of dealing with relative values from the same source (LIS). It is supposed that the inherent errors in the absolute values of this data set are at least partially cancelled out when ratios are taken. The particular characteristics of lightning detection based on LIS that could affect this work was not evaluated.

The results show considerable year-to-year variation of GFD around the average (Ng), see Figures 7 to 9. Of greater concern in most cases, the GFD_{max}/Ng ratio (Fig. 9) reaches values as high as 14 for very low Ng values, falling to values between 2 and 6 as Ng increases. Most values are however concentrated between 2 and 4 for high Ng values (say Ng > 5). Regarding the minimum GFD values (GFD_{min}/Ng), the values are frequently very low, with many nulls, particularly in the Ng < 2 range, see TABLE II.

Besides the wide data dispersion, Fig. 8 suggests that the maximum GFD values are concentrated around 3Ng (see linear interpolation in the figure). For the minimum values, the same figure suggests something around 0.2Ng (even removing the zeroes, the linear interpolation remains close to 0.2Ng). However, a more realistic approach should consider the probability of such dispersions to occur. Some probability distributions are shown in Figures 10 to 12.

The data set shows that about 2/3 of all GFD values is lower than Ng (GFD/Ng < 1) and, naturally, 1/3 is higher. The proportion is about 60/40 % for Ng > 2 and it is about 80/20 % for Ng < 2. TABLE IV presents such proportions. Note that while 78.3 % of GFD/Ng values are lower than 1 for Ng < 2, the number of nulls in this range is 71 %, see TABLE II.

The probability distributions have similar features for the Ng ranges above 2. The Ng < 2 range differ from the others. The probability to get, in any year, a GFD within Ng ± 50 % is around 50 % in regions where Ng > 5, and 42 % for areas with moderate Ng values (2 to 5). In areas with low Ng (Ng < 2), the probability is around 8 % only. Note in TABLE III (Ng mean and median) and in Fig. 10 that the distribution for range Ng < 2 is very skewed towards zero.

For Ng < 2, the probability of GFD/Ng > 1 is low, as shown in TABLE IV. However, it was in this range (Ng < 2) that the highest scattering of Ng data was observed, reaching 14 times Ng. For the other ranges (Ng > 2), the probabilities in the 0.2 intervals of Fig. 10 (GFD/Ng < 1) are so that no preferential GFD/Ng ratio is evident. The probabilities of GFD to exceed some values multiples of Ng are given in TABLE V.

It is worth noting that while GFD/Ng > 1 is normally of greater concern in the field of lightning protection, the GFD/Ng < 1 affects (negatively) those researchers seeking for lightning strikes on their experimental installations. The GFD variation has been experienced by researchers observations and measurements on P1P2 buildings in São Paulo [9], where lightning activity was more exciting in a particular year and somewhat frustrating in an other year. The author was also told about another case where the researcher noticed a great variation in lightning activity from year to year.

It is also worth noting that short term analysis about the performance of power transmission and distribution lines, for example, should preferably use the actual GFD along the study period, if available, otherwise wrong conclusions can be drawn from the results if the analysis is based on Ng. The GFD variations are also important when considering lightning protection for temporary installations, where Ng loses its long term significance.

There is a significant proportion of lightning discharges that hit the ground at more than one point [10]. This, together with other factors, mostly involving the accuracy of the available Ng values, have motivated the suggestion for the adoption of higher Ng values in the lightning protection standards, even doubling it [11]. The dispersion of GFD as presented here may also suggest an increase of Ng, at least under specific conditions or situations. The increasing factor, if applicable, should take into account proper probability distributions of GFD/Ng ratios.

The dispersion of GFD as presented in this study is coherent with the dispersions appearing in other works [1][12][13][14], as shown in Fig. 13.

TABLE IV. PROPORTIONS BETWEEN GFD/NG < 1 AND GFD/NG > 1 (%)

	All data	Ng range			
		< 2	2-5	5-10	> 10
GFD/Ng < 1	65	78.3	60.3	61.3	61.0
GFD/Ng > 1	35	21.7	39.7	39.7	39.0

TABLE V. PROBABILITIES OF GFD TO EXCEED MULTIPLES OF NG (%)

	All data	Ng range			
		< 2	2-5	5-10	> 10
GFD/Ng > 2	12	15	13	10	12
GFD/Ng > 3	5.4	10	5.2	3.9	3.5
GFD/Ng > 4	2.4	6.3	2.2	1.3	0.6
GFD/Ng > 5	1.6	5.4	0.7	0.5	0.4

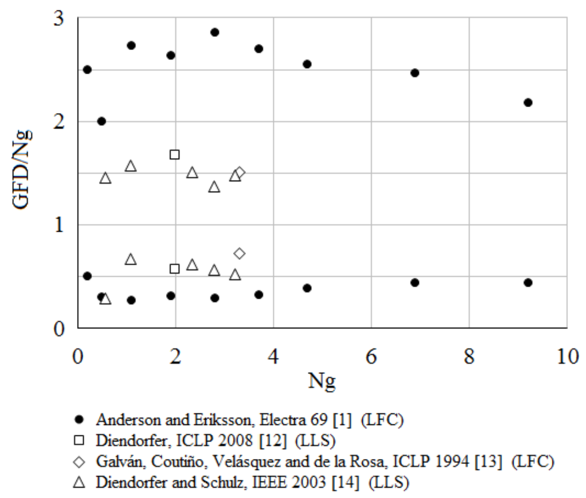

Fig. 13. Some GFD/Ng ratios adapted from referred works.

V. CONCLUSIONS

This study presents the year-to-year GFD dispersion around Ng, based on 14 years of accumulated data from LIS over 27 small areas in Brazil, corresponding to the district areas of the city capitals of the 26 Brazilian states and that of the country, totaling an area over 90 thousand km^2 from 149 cells, sized 25 x 25 km each. The data set contains 2086 GFD values (149 cells x 14 years), from which 149 Ng values are also taken.

The dispersions are presented in the form of GFD/Ng ratios, where the GFD abbreviation was assumed as a variable giving the individual GFD values (per cell and per year) and Ng is the GFD value of each cell averaged over the 14-year period. The GFD/Ng ratio revealed to be an interesting parameter to deal with the scattering of GFD data. The dispersion amplitudes are given as function of Ng, associated with probability distributions.

From year to year the GFD/Ng ratio can vary widely, with variations ranging from zero up to 14 in regions with low Ng values (Ng < 2), and from 0 up to 6 in regions with higher Ng values (Ng > 6). The analyzed data indicate that the dispersions follow well-behaved probability distributions, particularly for GFD/Ng ratio greater than 2 (GFD/Ng > 2).

The data set shows that about 2/3 of all GFD values is lower than Ng (GFD/Ng < 1) and, naturally, 1/3 is higher. The probabilities of GFD to exceed 2Ng, 3Ng and so on are given. On the lower side (GFD/Ng < 1), the probability distributions are somewhat flat from 0 to 1 (in 0.2 intervals), except for Ng < 2, in which the distribution is very skewed towards zero and the chances to get an year with no lightning is around 70 %.

The data is informative and useful for lightning protection designers and lightning researchers, and provide a more perceptive view about Ng and on how widely it can vary from year to year.

There are inaccuracies in any method of GFD determination. In this work, the author speculates that the inaccuracies may be reduced by the fact that the main results come from a ratio between quantities of the same kind, subject to the same errors (e.g. detection efficiency). On the other hand, this method (LIS) may have some peculiarities that can specially affect this kind of analysis, hence the need for an analysis in this respect and a more comprehensive study, possibly based on LLS data, on a much larger dataset, which is being considered as future work.

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