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A seven-year study about the negative cloud-to-ground lightning flash characteristics in Southeastern Brazil

Osmar Pinto Jr.[a,*], Iara Regina C.A. Pinto[a], Jose H. Diniz[b], Armando Cazetta Filho[b], Luiz C.L. Cherchiglia[b], Andre M. Carvalho[b]

[a] *National Institute of Space Research - INPE - Brazil*
[b] *Energetic Company of Minas Gerais - CEMIG - Brazil*

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Abstract

A seven-year study of negative cloud-to-ground (CG) lightning flash characteristics in southeastern Brazil is presented. The study is based on approximately 10 million flashes recorded by a Lightning Position and tracking system lightning detection network from November 1988 to December 1995. The data set is the longest ever obtained in the tropics using an almost constant network configuration. It provides a unique opportunity to study the long-term annual, monthly, and local time distributions of the number, intensity (peak current) and multiplicity of negative CG flashes in the tropics. The annual distribution of the number of flashes has variations as large as 80%. The variations does not show any clear relationship with any meteorological parameter, possibly indicating the complex interactions of different processes responsible for the lightning activity. The monthly and local time distributions seem to follow closely the related distributions of air temperature. The annual distribution of peak current shows an average value of 40.4 kA and has a significant decrease from 1991 to 1994, apparently related to an El Niño seasonal effect. The monthly distribution of peak current shows lower values in the winter, in contrast with the results recently reported for the United States, and seems to be related to the monthly distribution of the number of flashes. The local time distribution of the peak current seems also to be related to the local time distribution of the number of flashes; however, the dependency is less evident. The annual distribution of multiplicity has a systematic decrease during the period, with no apparent relationship with any of the variables studied. The monthly distribution of multiplicity is consistent with the hypothesis that the multiplicity is related to the average height of thunderstorms. The local time distribution of multiplicity, in turn, shows a sunrise/sunset effect. The results are compared to similar ones obtained in other regions of the world.

Keywords: Lightning; Climatology; LPATS; Brazil

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1. Introduction

Long-term characteristics of lightning flashes at large scales, that is, hundreds of thousands of square kilometers, have only recently been studied through the use of lightning detection networks, established for research field programs at the beginning of the 1970s (Orville et al., 1983; MacGorman et al., 1989). Since many lightning parameters show a large scatter for different storms, long-term data from lightning detection networks are usually more representative of average lightning characteristics than data derived from electric field measurements typically performed during a few thunderstorms (Rakov and Uman, 1990). The main difficulty found in the lightning network studies, however, is the frequent change in the network configuration, often including sensor locations, types and settings, and cloud-to-ground (CG) lightning discrimination criteria. As a consequence, the results of these studies seem to indicate a combination of natural observations free of instrumental effects and biased observations affected

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* Corresponding author. Instituto Nacional de Pesquisas, Divisao de geofisica Espacial (DGE), Espaciais (INPE), Av.dos Astronautas, 1758, Sao Jose dos Campos, SP CEP 12.227-010, Brazil.
E-mail address: osmar@dge.inpe.br (O. Pinto Jr.).

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by the characteristics of the network. Until now, the most comprehensive study was done by Orville and collaborators in the United States (Orville, 1991, 1994; Orville and Silver, 1997; Orville and Huffines, 1999a, b, 2001), spanning the period from 1989 to 1998. In the tropics, Orville et al. (1997) have reported monthly and local time variations for a 1-year study. Influences caused by changes in the lightning detection network configuration on the lightning characteristics have been discussed by several authors (Cummins et al., 1998a, b; Idone et al., 1998a,b; Diendorfer et al., 1998; Schulz et al., 1998; Orville and Huffines, 1999a, b; Pinto et al., 1999a, b, c; Wacker and Orville, 1999a, b).

In Brazil, the use of lightning detection networks to study CG lightning characteristics at large scales began in 1988 (see Diniz et al., 1996a, b). At that time, the network was concentrated in the state of Minas Gerais, in the southeastern part of the country. The first results obtained from this network were published by Pinto et al. (1996) and Pinto (1997). From November 1988 to December 1995, the network operated with the same configuration formed by four lightning position and tracking system (LPATS) sensors, except from July to December 1995, when two more sensors were included. In 1996, the network changed to the new advanced position analyzer APA-2000 system, which includes IMPACT (Improved accuracy from combined technology) sensors. At present, the network is being integrated with two other networks forming a large network. This large network will be formed by more than 20 sensors and will cover about one fourth of Brazil.

The southeastern region of Brazil is known to have a high lightning activity level associated with local and large-scale meteorological conditions. Among the large-scale conditions, lightning in the southeastern Brazil has been found to be related to the occurrence of fronts, the South Atlantic Convergence Zone (SACZ) and the Bolivian High (Solorzano et al., 1999). Also, it has been suggested that the convection in this region of Brazil, and in consequence the lightning activity, may be related to the El Niño Southern Oscillation (ENSO) (Cavalcanti, 1996), the Atlantic Ocean sea-surface temperature (Diaz and Studzinski, 1994) and the Madden and Julian Oscillation (MJO) (Kousky and Kayano, 1994). At the same time, the number of flashes increases with local conditions associated with deep convection, as expressed by the wet-bulb temperature, the equivalent potential temperature, and the convective available potential energy (CAPE) (e.g. Williams, 1992; Williams and Renno, 1993; Watson et al., 1994).

In this paper, the results of the analysis of about 10 million negative CG lightning flashes recorded by a lightning detection network in southeastern Brazil from November 1988 to December 1995 are presented. The analysis was done in terms of the annual, monthly, and local time distributions of the number, intensity and multiplicity of the flashes. The data for the period from July to December 1995 were processed without the events from the extra two sensors installed in July 1995. Data after December 1995, in turn, were not used in this study due to the major changes in the network configuration at this time. The results are compared to similar data obtained in other parts of the world.

2. The lightning network in Southeastern Brazil

Fig. 1 shows the region of interest (geographic coordinates 16°–22°S, 42°–48°W) and the location of the lightning sensors. From November 1988 to July 1995, the network consisted of 4 LPATS-III sensors, located approximately 350 km from each other and synchronized by a satellite signal. After July 1995, the number of sensors increased to 6. Taking into account that several studies (see Pinto et al. (1999a, b) and references therein) have shown that this type of network is subject to contamination by intra-cloud flashes, here we have only considered negative CG flashes with first stroke peak current larger than 15 kA. Using a lower peak current threshold, however, does not change the results of this paper. This value was adopted based on the local time distribution of CG flashes for different peak currents (Pinto et al., 1999b) and agrees with the results obtained by Zaima et al., (1997).

To obtain the number of flashes, we assume that strokes in the same flash have locations within 10 km of the first stroke, and that the time interval between consecutive strokes is less than 500 ms. We also assume that strokes with different polarities belong to different flashes, even though this assumption has no significant influence on the results of this paper. Similar procedure has been used by other authors (e.g. Casper and Bent, 1992).

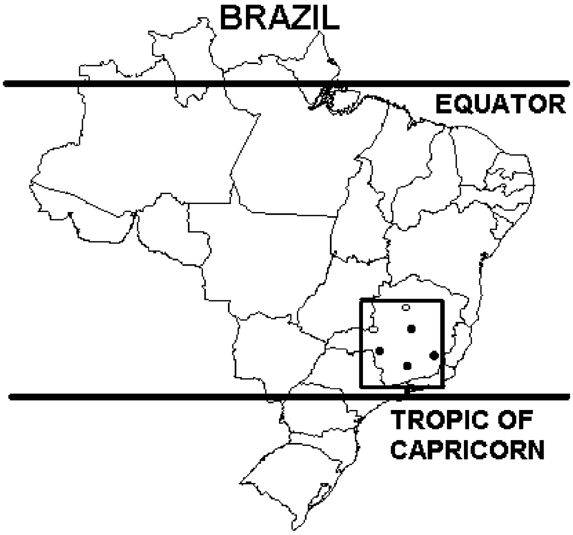


Fig. 1. Map of Brazil indicating the region of interest and the location of the lightning sensors. The two sensors included after July 1995 are indicated by white circles.

The flash detection efficiency of the network, that is, the fraction of the actual flashes that are detected and reported by the network, was considered to be about 80% in the center of the network, decreasing to about 40% in the edges of the region of study. These values were computed using an empirically derived source distribution, assuming that the range-normalized peak field is proportional to the peak current and using a simple model for field propagation (Cummins et al., 1998b). They correspond to average detection efficiency in the region of study of about 70%. During the period of study, no information was available to verify these values. The use of this simple calculation to estimate the flash detection efficiency, however, has no significant influence on most of the results presented in this paper, since they are based on relative time variations of the flash characteristics.

The estimates of first stroke peak current and multiplicity of a negative CG flash obtained by LPATS networks are based on several assumptions (Bent and Lyons, 1984; Casper and Bent, 1992; Holle and López, 1993; Cummins et al., 1998a, b; Orville, 1999). To estimate the peak current of a flash based upon the peak radiation field it is necessary to assume a lightning current model involving the knowledge of the return stroke velocity, which for large peak current negative flashes is poorly known. Also, it is necessary to describe the attenuation of the radiation field over the conducting ground (Cummins et al., 1998b). However, this attenuation may vary from one region to another and, in some cases, it may be difficult to be established (Cooray et al., 2000). The most comprehensive evaluation of the peak current obtained by a lightning network was done by Orville (1991) for an LLP network. He limited his evaluation to negative triggered flashes below 60 kA, being probably more accurate for subsequent than first-stroke flashes. In small networks with few sensors, like the one described in this paper, there are two additional limitations that can seriously affect the accuracy of peak current estimates. The first is related to a small number of sensors detecting a stroke. This causes a large uncertainty in the estimated range-normalized signal strength (RNSS) at the source. The second limitation arises when different sensors measure fields that propagate over variable terrain with different propagation losses. In small networks, the uncertainty in the values of peak current can be as large as 50% (Cummins et al., 1998a). In this paper, only peak current results for first strokes are reported.

To estimate the multiplicity of a flash, it is necessary to consider a method for grouping individual strokes into a flash that assumes an arbitrary maximum spatial (in our case, 10 km) and temporal separation of subsequent strokes (in our case, 500 ms). This method tends to underestimate the true multiplicity, because the LPATS data used in this work does not take into account the uncertainty in the location of a stroke. This uncertainty may be large for the LPATS network used in this work, due to the small number of sensors detecting a stroke. In more recent networks, this uncertainty is expressed by the location confidence region (location error ellipse), so that if a stroke is more than 10 km from the first stroke (and less than an arbitrary clustering radius), it is still included in the flash if its location confidence region has a point less than 10 km from the first stroke (Cummins et al., 1998a). Also, the multiplicity is dependent on the stroke detection efficiency, which in general is lower than the flash detection efficiency because the fields radiated by first strokes tend to be larger than for subsequent strokes. This limited stroke detection efficiency of the network may cause some bias toward lower multiplicity values (Diendorfer et al., 1998). In addition, average values of peak current and multiplicity are affected by the sensor spacing, gain, threshold, and the overall flash rate. Due to uncertainties discussed above, the variations are the focus of this paper and not the absolute magnitude of the average peak current and multiplicity.

3. Results and discussion

Fig. 2a shows the geographical distribution of the average annual total flash density in the region of study obtained by the LPATS network, referenced to grid blocks that are approximately 55 × 55 km. Fig. 2b shows the same distribution obtained by a network of 43 CIGRE 10 kHz flash counters from 1985 to 1995. The CIGRE counters record pulses by a trigger circuit with a bandpass filter centered at 10 kHz. Its effective range is about 10–30 km for ground flashes, with about 5% of the total registration being due to cloud flashes (Anderson et al., 1973, 1979; Anderson, 1980; CIGRE, 1977). Fig. 2c shows the distribution of the average annual precipitation in the same region since 1960. The geographical distributions in Fig. 2 are very similar. Fig. 3 shows that a reasonable correlation between the LPATS and the flash counter data exists, even though there are intrinsic differences associated with each technique, such as the low number of counters, corresponding to an average spacing of 60 km. The correlation coefficient is 0.6.

Fig. 4 shows the annual variation of the number of negative flashes from 1989 to 1995. During this period, the distribution shows variations as large as 80%. This large variance should be taken into account in any short-term study of flash density in this region. To investigate the possible origin of the variations in Fig. 4, we have computed separately the annual number of frontal systems and SACZ events affecting the southeastern region of Brazil during the period of interest, even though these variables are not independent. The SACZ is typically seen as a cloud band enduring for at least 4-days in satellite imagery; its role in the number of flashes in the southeastern Brazil has previously been investigated (Solorzano et al., 1999). It was found that the number of flashes tends to increase during SACZ events. The number of fronts and SACZ events are shown in Fig. 5 together the southern oscillation index (SOI). The SOI is based on the mean sea level pressure difference between Tahiti (French Polynesia) and Darwin (Australia) and is a

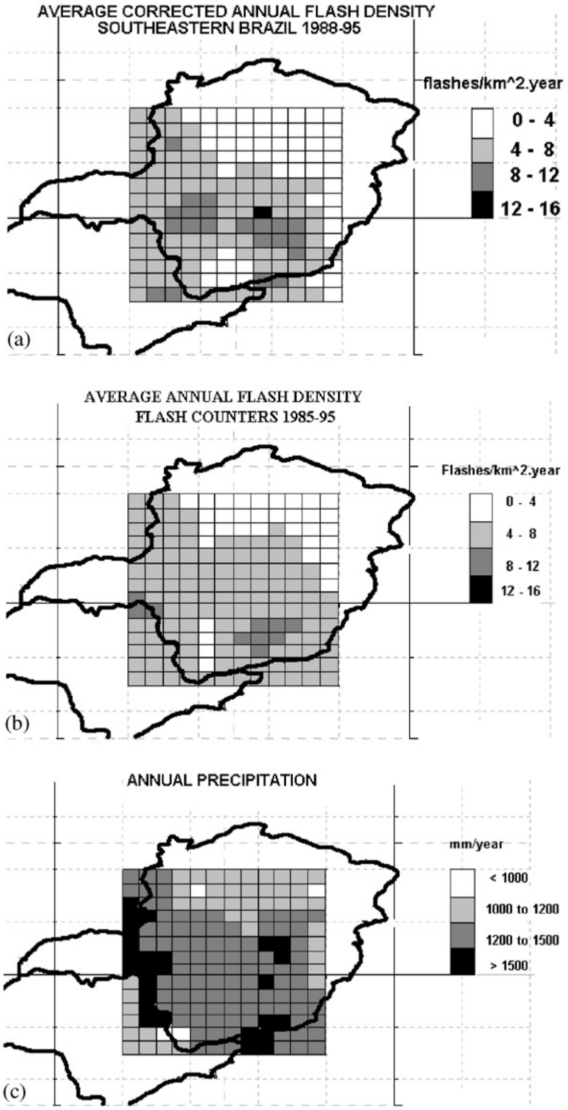


Fig. 2. (a) Average annual flash density in the region of interest, obtained by 4 LPATS sensors from 1998 to 1995. (b) Average annual flash density in the region of interest as recorded by a network of 43 CIGRE 10 kHz flash counters from 1985 to 1995. (c) Historic data (since 1960) of the annual precipitation in the region of interest.

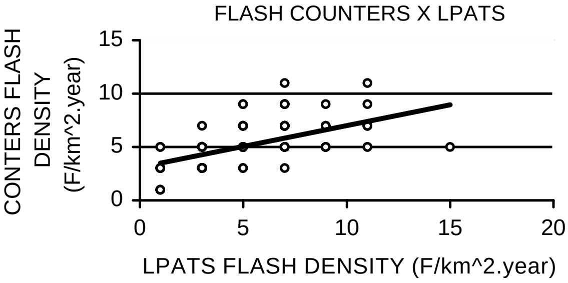


Fig. 3. Linear regression between the flash density obtained by a network of flash counters and by the LPATS network. The correlation coefficient is 0.6.

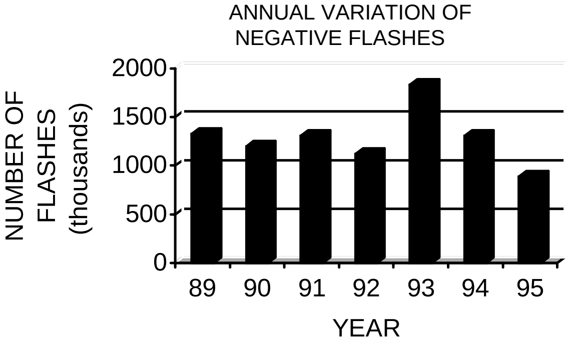


Fig. 4. Annual variation of the number of negative flashes in the region of interest from 1989 to 1995.

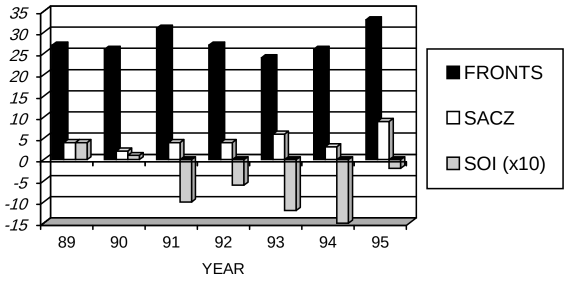


Fig. 5. Annual number of frontal systems and SACZ events in the southeastern Brazil and the SOI from 1989 to 1995.

measure of the strength of the trade (tropospheric) winds. The SOI is related to the El Niño/La Niña phenomena (Deser and Wallace, 1987). Based on climate data, the impact of El Niño (La Niña) on the weather in the southeastern Brazil has been predicted as an increase (decrease) in the average temperature. Fig. 5 shows that the annual distribution of the number of fronts has two peaks in 1991 and 1995, whereas the annual number of SACZ events shows a quasi-biennial oscillation. The SOI, in turn, shows that the period of study begins with stronger than normal trade winds and La Niña conditions, followed by an unusual long event (from 1991 to 1994) of weaker than normal trade winds and El Niño conditions. A comparison of the distribution of the number of negative flashes in Fig. 4 with the parameters in Fig. 5, however, does not show any clear relationship of the annual variations of the number of flashes with any these parameters, possibly indicating the complex interactions of different processes responsible for the lightning activity (e.g. Liebmann et al., 1999). Clearly, a more in depth analysis is necessary to identify the reasons for this annual variability.

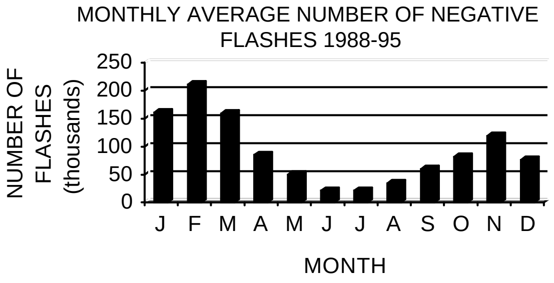


Fig. 6. Monthly variation of the average number of negative flashes in the region of interest for the 1988–1995 period.

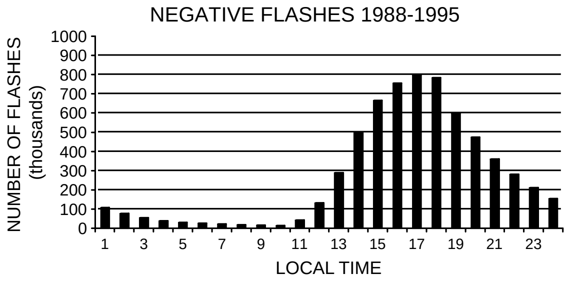


Fig. 8. Local time variation of the number of negative flashes in the region of interest for the 1988–1995 period.

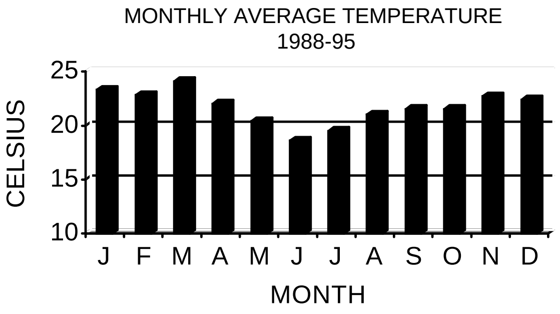


Fig. 7. Monthly variation of the average temperature from 1989 to 1995 for the region of study.

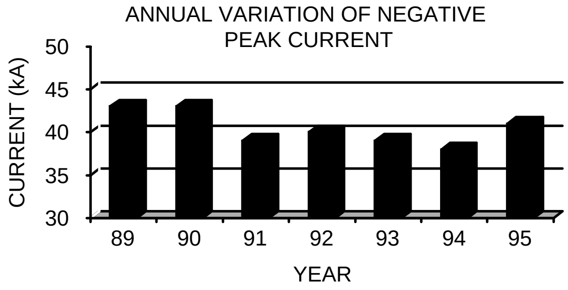
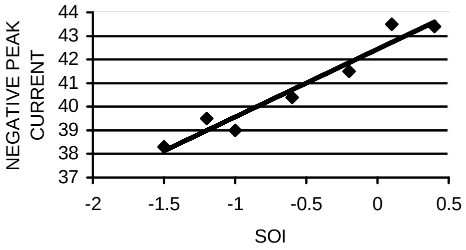


Fig. 9. Annual variation of average peak current of negative flashes from 1989 to 1995.

Fig. 6 shows the monthly distribution of the average number of negative flashes from 1988 to 1995. It has two peaks in the months of February and November. Fig. 7 shows the monthly variation in the air temperature in the region of study in the same period. The variation is very similar to that in Fig. 6, confirming the tendency verified by Pinto et al. (1999b) of the monthly variation of the number of flashes to follow the variation of the air temperature in the tropics. Orville et al. (1997) and Blakeslee et al. (1999) have found similar variations in Papua New Guinea and in the northern part of Brazil, respectively. This distribution seems to be responsible for the seasonal distribution of the fair weather electric field (Bering et al., 1998), indicating that lightning and other thunderstorm-related process in the tropics control the global atmospheric electrical circuit. This monthly distribution is different from that observed in middle latitudes, where only one peak occurs in the summer (Orville and Silver, 1997; Orville and Huffines, 1999b).

The local time distribution of the negative flashes from 1988 to 1995 is shown in Fig. 8. The distribution has a typical variation found in other regions of the world, with a maximum around 1600–1800 LT associated with the maximum air temperature and convective activity during this period, in response to the diurnal cycle of insolation. This distribution indicates that most flashes in this region originate from diurnally forced thunderstorms. A similar distribution was found by Blakeslee et al. (1999) in the northern region of Brazil. In this study, no evidence was found of a secondary peak around 0500 LT, as observed by Orville et al. (1997) in their observations in Papua New Guinea.

Fig. 9 shows the annual variation of the average negative peak current from 1989 to 1995. The average peak current value for the whole period is 40.4 kA. Fig. 9 also shows that the average peak current has a significant (at a 1% significance level in the F test) decrease during the period from 1991 to 1994, recovering to about the value prior to 1991 in 1995. It is interesting to note that this decrease is also evident in the SOI, but does not appear in the other variables in Fig. 5. A correlation between El Niño and lightning activity has been recently reported (Goodman et al., 2000). The authors, however, do not show any information about peak current. Fig. 10 shows the linear regression between the average peak current of negative flashes and the SOI, indicating that these variables are well correlated with a high correlation coefficient of 0.97. The decrease seems to be related to the variation in the ratio of the cold season to the warm season number of flashes, as it can be seen from a comparative analysis of the monthly distributions of the number of flashes (Fig. 6) and average peak current (see Fig. 11). We found that during the 1991–1994 period this ratio, ~ 0.45, is lower than in the other years, ~ 0.40 (see table in Fig. 10). Considering that in the warm season the peak current is larger than in the cold season, the annual average peak current during the 1991–1994 period is lower. This



YEAR	PEAK CURRENT(kA)	Ratio
1989	43.4	0.43
1990	43.5	0.36
1991	39.0	0.46
1992	40.4	0.42
1993	39.5	0.48
1994	38.3	0.44
1995	41.5	0.39

Fig. 10. The linear regression between the annual average peak current of negative flashes and the smoothed SOI. The correlation coefficient is 0.97. The ratio of the cold season to warm season number of flashes for each year is also indicated.

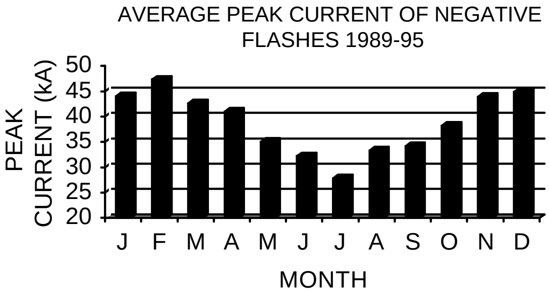


Fig. 11. Monthly variation of the average peak current of negative flashes from 1988 to 1995.

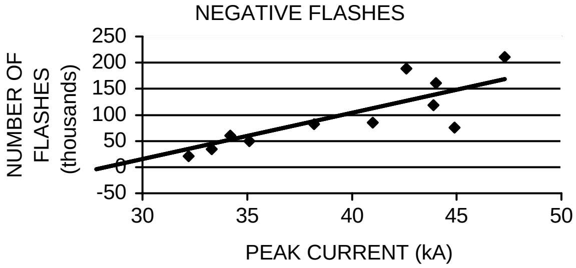


Fig. 12. The linear regression between the monthly average negative peak current and the monthly average number of negative flashes. The correlation coefficient is 0.84.

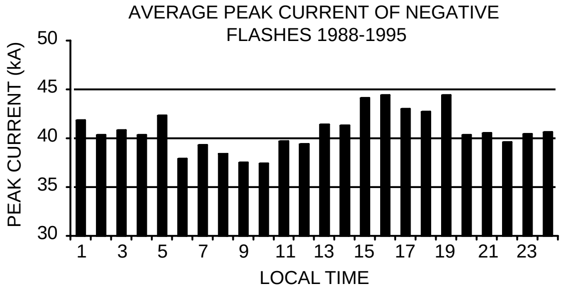


Fig. 13. Local time variation of the average peak current of negative flashes from 1988 to 1995.

result suggests that the different ratios may be related to temperature changes caused by El Niño. El Niño events are known to produce higher temperatures in the cold season than La Niña events in the southeastern Brazil (Cavalcanti, 1996; Pezza and Ambrizzi, 2002).

Fig. 11 shows the monthly distribution of the average negative peak current from 1989 to 1995. It indicates that the negative flashes are less intense in the winter than in the summer. This distribution is different from that obtained by Orville and Huffines (1999b) for the contiguous United States from 1995 to 1997, who found an unexpected peak in December. It also differs from the distribution obtained by Orville and Huffines (2001) for the contiguous United States from 1989 to 1998, who found negative flashes more intense in the winter. Orville and Huffines (2001) have argued that the variation from a high in the winter to a low in the summer may be explained by the observations of Brook (1992) in Albany, New York, which suggest that electric fields initiating lightning in winter appear to be greater than in the summer. This explanation, however, cannot explain the monthly distribution found in this study.

Fig. 12 shows that the monthly distributions of the average negative peak current and the number of negative flashes are correlated, with a correlation coefficient of 0.84. Recently, Huffines and Orville (2000) have also found the same relationship between average values of peak currents and flash density for negative flashes. No explanation was found for this correlation.

Fig. 13 shows the local time distribution of the average negative peak current from 1988 to 1995. The distribution shows small variations, which follow approximately the local time variations of the number of flashes (see Fig. 8). This tendency is similar to that observed for the monthly variation of the average peak current discussed in the above paragraph (Fig. 12), although it is less apparent than in that case.

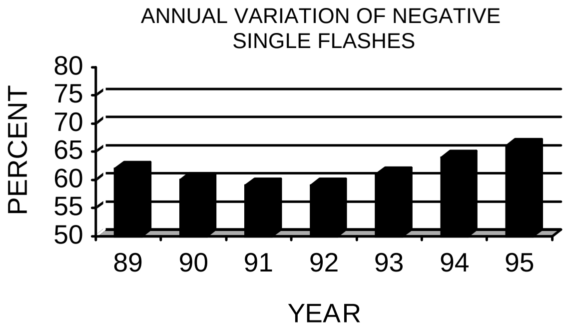


Fig. 14. Annual variation of the average percentage of negative single-stroke flashes in the region of interest from 1989 to 1995.

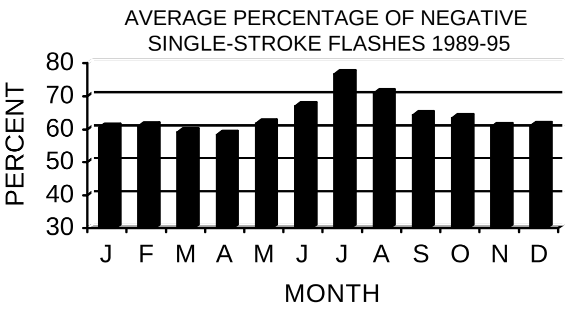


Fig. 15. Monthly variation of the average percentage of negative single-stroke flashes from 1988 to 1995.

Fig. 14 shows the annual distribution of the average percentage of negative single-stroke flashes from 1989 to 1995. This percentage is related to the average multiplicity of negative flashes. No apparent relationship was found between this percentage and the variables in Fig. 5. The average percentage of negative single-stroke flashes shows a systematic increase after 1992. The reason for this increase is, at present, unknown.

Fig. 15 shows the monthly distribution of the average percentage of negative single-stroke flashes from 1988 to 1995. An increase (decrease) in the average percentage of negative single-stroke flashes (multiplicity) in the winter is apparent. This variation is in agreement with those reported by Orville et al. (1987) and Orville and Huffines (2001) for the United States. It is possible that the decrease in the multiplicity of negative flashes in the winter can be a result of the small average height of the thunderstorms in this season, as suggested by Orville and Huffines (1999b). Evidence suggesting that the average height of thunderstorms varies with the seasons (highest in the summer and lowest in the winter) has been reported by several authors (e.g. Kessler, 1985). If this relationship can be confirmed, the multiplicity could be seen as a proxy variable to monitor the thunderstorm height distribution.

Finally, Fig. 16(a) shows the local time distribution of the average percentage of negative single-stroke flashes from 1988 to 1995, indicating a small increase during daytime. This tendency is a result of a decrease in the average percentage of negative multiple-stroke flashes with five or more strokes during this period, as shown in Fig. 16b. In this figure, it is evident that there is a sunrise/sunset variation. It is possible that it is of instrumental origin. At present, however, there is no explanation for such a variation.

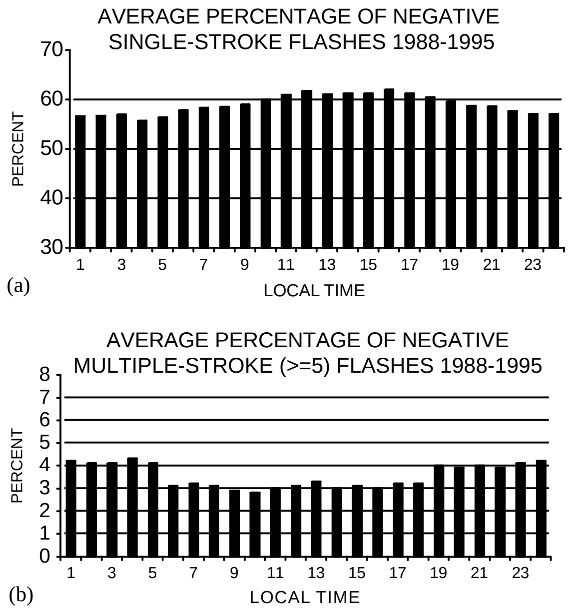


Fig. 16. (a) Local time variation of the average percentage of negative single-stroke flashes from 1988 to 1995. (b) Local time variation of the average percentage of negative multiple-stroke flashes with five or more strokes from 1989 to 1995.

4. Conclusions

In this paper, a 7-year study of the number, intensity and multiplicity of negative CG flashes with first stroke peak current larger than 15 kA was presented. The study is based on approximately 10 million CG flashes recorded in southeastern Brazil by a LPATS lightning detection network from November 1988 to December 1995. The results were compared to similar results obtained in other regions of the world. The main conclusions are:

- The annual distribution of the number of negative flashes shows variations as large as 80%. The variations does not show any clear relationship with any meteorological parameter, possibly indicating the complex interactions of different processes responsible for the lightning activity. Clearly, a more in depth analysis is necessary to identify the reasons for this annual variability.
- The monthly distribution of the average number of flashes shows a double peak feature typical of the tropics,

with peaks in February and November. The peaks follow closely the variation of the air temperature in the region.

- The local time distribution of the number of negative flashes has a peak in the afternoon around 1600–1700 LT, coincident with the period of maximum convective activity in response to the diurnal cycle of insolation.
- The annual distribution of the average negative peak current shows an average value of 40.4 kA, with a significant decrease from 1991 to 1994. The decrease is a direct consequence of the increase in the ratio of the warm season to the cold season number of flashes in this period compared to the other years, and is well correlated with the SOI. This correlation may indicate a different influence of the El Niño on the temperature and thunderstorm activity during the year.
- The monthly distribution of the average negative peak current shows a double peak feature, with peaks in February and November, well correlated with the number of negative flashes. The values are lower in the winter than in the summer, in contrast with the recent long-term results published for the contiguous United States (Orville and Huffines, 2001). The reason for this difference is, at present, unknown.
- The local time distribution of the average negative peak current shows small variations, which follow approximately the local time variation of the number of flashes. Although this tendency is less evident than that observed for the monthly distribution of the average peak current, and it may be caused by the same physical process. To our knowledge, no similar data have previously been reported.
- The annual distribution of the average percentage of negative single-stroke flashes shows a systematic increase after 1992. The increase is not related to any of the meteorological parameters investigated in this study.
- The monthly distribution of the average percentage of negative single-stroke flashes shows a significant increase during the winter, indicating a seasonal variation of the multiplicity. This result is in agreement with observations in the United States, and is consistent with the hypothesis that the multiplicity is related to average height of the thunderstorms.
- The local time distribution of the average percentage of negative single-stroke flashes shows a small increase during daytime. The increase is related to a decrease in the number of negative flashes with high multiplicity during sunrise and sunset, and it may be of instrumental origin.

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