The intracloud/cloud-to-ground lightning ratio in Southeastern Brazil

P.E. de Souza[a] , O.Pinto Jr[a] , I.R.C.A. Pinto[a] , N.J. Ferreira[b] , A.F. dos Santos[b]

[a] National Institute of Space Research, São José dos Campos, Brazil

[b] Center for Weather Forecast and Climate Studies, Cachoeira Paulista, Brazil

* Corresponding Author:

Patricia Eugenio de Souza
National Institute for Space Research
Av dos Astronautas, 1.758 - Jd. Granja
São José dos Campos - SP
Brazil 12227-010

Email: patriciaeugenio@dge.inpe.br

Telephone: +55 (12) 3945 6828

FAX: +55 (12) 3945 6810

Abstract

The intracloud to cloud-to-ground lightning flash ratio (Z) has been estimated for the first time in Southeastern Brazil and in the tropical region using Lightning Imaging Sensor (LIS) and Brazilian lightning detection network (BrasilDat) lightning data obtained from 1999 to 2005. Geographical variations of Z and their relation to elevation, latitude, precipitation, total lightning density and percentage of positive CG lightning will be discussed. Daily variations of Z will also be presented. The results suggest that Z values are similar to studies outside the tropics and that are influenced by orographic features.

Key words

Lightning; Z ratio; Intracloud flash; Cloud-to-ground flash

1. Introduction

Total lightning observations by satellites sensors in recent years (Christian et al., 1992; Boccippio et al., 2001) has made possible the estimation of the intracloud (IC) to cloud-to-ground (CG) lightning flash ratio (Z) over large regions and for long time periods. The Z ratio gives information about the electrical activity in thunderstorms and can be a clue about how the centers of charge are disposed in the clouds. Moreover, the knowledge of Z is important for many others studies like the relationship between the lightning rate and the storm severity (MacGorman et al., 1989; Williams et al. , 1999; Buechler et al. , 2000), the production of atmospheric components like NOx (Chameides et al., 1977; Pickering et al., 1998; Rakov and Uman , 2003) and the contribution of lightning to the global electric circuit (Rycroft et al., 2000; Markson , 2007; Williams, 2007).

A comprehensive study of Z was recently made in the continental United States by Boccippio et al. (2001). Four years of observations from the NASA Optical Transient Detector (OTD) and National Lightning Detection Network (NLDN) were combined to determine the geographic distribution of the climatological lightning flash ratio Z, over the continental United States. They investigated the dependence of Z on latitude, longitude, orographic effects and other electrical parameters. Instead of comparing total lightning and CG lightning rates for the same time periods corresponding to the satellite overpass or, in other words, for individual thunderstorms, they assume that the average climatological data during the whole time period for a 0.5º x 0.5 º grid are representative of the respective rates for the region. They did not find a clear dependence of Z on the geographic location. Low values of Z were found in mountain regions, but this relation seems not to be unique and it was hard to predict when this behavior is connected with orographic effects or meteorological effects. The larger values of Z were found in regions with a high percentage of positive CG flashes and a high occurrence of severe storms. The suggestion of this study was that the intensity, morphology and/or level of organization of thunderstorms have more significant impacts on Z values than the environmental factors such as the freezing-level height, troposphere depth or surface elevation.

In another study, Kuleshov et al. (2006) using lightning data obtained by lightning flash counters (CIGRE-500 and CGR3) over a period of up to 23 years at 39 localities around Australia, as well as lightning data gathered by the NASA satellite based instruments (OTD and LIS – Lightning Imaging Sensor) over a period of eight years and the same methodology of Boccippio et al. (2001) estimate the Z ratio over Australia. They found values of Z in a range of values from 0.75 to 7.7. They concluded that for the range of latitude over Australia the most representative value of Z is about 2 ± 30%, and it is relatively independent of latitude.

Finally, Soriano and Pablo (2007) used five years of data from the Spanish lightning detection network and the NASA OTD sensor to make a spatial and temporal analysis of total lightning flash density and Z ratio over the Iberian Peninsula, also adopting the same methodology of Boccippio et al. (2001) and found a correlation between Z ratio and latitude. In addition, they observed a relation between Z and total flash density and a tendency of high values of Z to occur where the percentage of positive CG flashes is high, in agreement with the result of Boccippio et al. (2001).

The goal of this paper is to present the first study of the lightning flash ratio in Southeastern Brazil, using on-board LIS satellite and Brazilian Lightning Detection Network (BrasilDat) lightning data obtained over a period of seven years from 1999 to 2005. The study adopts the same methodology used in all the works cited above and includes the calculation of the geographical variation of Z, its daily variation and its dependence on total flash rate and percentage of positive CG flashes. The geographical variability is discussed and related to orography and features of the air circulation.

2. Methodology

The area of the study is situated in Southeastern Brazil, between 14ºS and 25ºS of latitude and between 40ºW and 54ºW of longitude. It is crossed by the Tropic of Capricorn, what indicates that this region is predominantly tropical in the climatic aspect, but the elevation can dominate over the thermal conditions related with its geographic localization.

The period of the study is from 1999 to 2005, in order to consider both the CG flash data obtained from Brazilian Lightning Detection Network (BrasilDat) data and the total lightning data obtained from the LIS (Lightning Imaging Sensor) sensor on-board the TRMM (Tropical Rainfall Measuring Mission) satellite that covers the whole tropical region. In this study we use the gridded satellite lightning data produced by the NASA LIS/OTD Science Team (Principal Investigator, Dr. Hugh J. Christian, NASA / MSFC - Marshall Space Flight Center) [available from the Global Hydrology Resource Center].

The region of the study was chosen because it is the only region in Brazil where CG lightning data are available for a long time period with good reliability. Other regions in the country were only reached by the BrasilDat network in later times, and some of them are not totally covered yet. BrasilDat is a lightning detection network consisting of LPATS and IMPACT ground sensors. The network is intended to detect only CG lightning, not including intracloud flashes. However, due to its limitation in discriminating low peak current positive CG flashes from intracloud flashes, positive flashes with peak currents less than 10 kA were not considered in the analysis (Cummins et al., 1998). The system has a spatial limitation related to the number and distribution of the sensors. For this reason, the CG data were corrected with a detection efficiency model (Naccarato and Pinto, 2008). The correction is more important in the borders of the network. Figure 1 shows a map of the detection efficiency used to correct the CG data in this study. More details about BrasilDat can be found elsewhere (Pinto et al., 2006, 2007).

The other lightning data set was obtained from the LIS sensor and corresponds to total lightning information. The data were provided by the MSFC group and the flash definition adopted was the same that has been used in other publications (Boccippio et al., 2001). The sensor detects all types of flashes that occur in the tropical region and provides their geographic location (among other parameters not used in this study). The main problem of this system is the temporal limitation at a given location. The satellite sensor views an area of

600 x 600 km with a spatial resolution of 3-6 km. Since the TRMM satellite travels with a speed of 7 km/s, the sensor can detect flashes in any one region for only 90 seconds in each pass, which means a total of about 180 seconds per day in a give location. This limitation is minimized in this study, however, since a long time period is considered. Figure 2 shows a map of the total lightning in the region of study obtained from LIS.

The Southeastern region of Brazil is the most irregular region of the country. The combined effect of latitude, shape and distribution of the relief and distance from the ocean creates quite different situations with respect to temperature variation and rain distribution. The local atmospheric circulation marked by the action of the Tropical Atlantic and the Polar Atlantic air masses enhances these differences. Besides that, preliminary studies have already identified large differences in the distribution of CG lightning and the total lightning in this region (Naccarato, 2005).

In this study average flash rate for both data sets in a 0.5 x 0.5 degree grid were computed for the whole time period. Since LIS data contain total lightning information, while BrasilDat data contain only CG lightning information, the IC flash rate was calculated from the difference between LIS and BrasilDat flash rates. Then, the Z ratio was calculated by dividing the IC flash rate by the CG flash (BrasilDat) rate. The values of Z in each cell in the 0.5 x 0.5 degree grid were also plotted as a function of total lightning flash rate and percentage of positive CG flashes. Finally, the daily variation of the hourly average values of Z was calculated for a 2.5 x 2.5 degree grid and compared with the respective hourly average values of total lightning flash rate, CG flash rate and percentage of positive CG flashes.

3. Results and discussion

In this section we present the geographic distribution of Z in Southeastern Brazil, discussing it in the context of hypothesized relationships with elevation, CG flash density, precipitation, positive CG flash density, latitude, percentage of positive CG flashes and total flash density. Also, the daily variations of Z are compared to hourly average values of total lightning flash rate, the CG flash rate and the positive CG flash rate.

3.1. Geographic distributions

Figure 3 shows a map of the geographical distribution of the average values of Z for the period of study. The values are in the same general range of values registered in the United States (Boccippio et al., 2001), in Spain (Soriano and Pablo, 2007) and Australia (Kuleshov et al. (2006). The smallest values of Z are around 2 and the largest around 12, while in the United States they are around 1.1 and 9, respectively. The range of Z values indicates that the geographical distribution of total lightning is very similar to the geographical distribution of IC lightning, as it can be observed comparing Figures 2 and 4. The most relevant features in Figure 3 are: first, a negative anomaly (blue color) just before and partially over the region with higher elevations, as it can be observed comparing Figure 3 and Figure 5, which shows an orographic map with the same resolution as the Z map shown in Figure 3; second, a positive anomaly in the Southern part of the region. These features were found to be permanent features through the years and for different seasons, even though in the winter, the low number of flashes avoids a clear identification of them.

In turn, the maps of CG lightning density (Figure 6), annual mean precipitation (Figure 7) and positive CG density (Figure 8) indicate maximum values just before and over the mountains. This scenario seems to reveal an important role of the mountains on the formation of the storms and lightning distribution.

A recent work on lightning activity the Southeastern region of Brazil observed a tendency of most lightning to originate in frontal systems (Zepka, 2005). This fact suggests an hypothesis that when frontal systems moving from South to North reach the mountains, the convection is intensified, causing an increase in the total and CG lightning activities (Figures 2 and 6, respectively). The increases are such that a decrease in the Z values occurs. With the increase in the CG lightning activity over the mountains, the storms would be discharged, what would explain the subsequent increase in the Z ratio (Figure 3). This scenario is also in agreement with the precipitation data, with indicate that most precipitation related to the convective region occur before and over the mountains, decreasing after the mountains (Figure 7).

3.2. Dependence of Z on latitude, percentage of positive CG flashes and total flash density

Figure 3 shows that Z has no clear relation with latitude, at least for this region of Brazil. However, the range of latitudes covered in this study is not so large to investigate this relation.

Figure 9 shows the variation of Z as a function of the percentage of positive CG flashes. Each point corresponds to a cell in the 0.5 x 0.5 degree grid in the region of study. Differently of it was suggested by Boccippio et al. (2001) and Soriano and Pablo (2007), there is no relation among Z and the percentage of positive flashes. A possible explanation for this difference may be different levels of contamination by intracloud flashes in the different CG flash data sets, even though the same threshold for low peak current positive flashes was considered in all studies.

Contrary to the results obtained by Soriano and Pablo (2007) on the Iberian Peninsula and in agreement with the results of Boccippio et al. (2001), the graph of Z versus total lightning density (Figure 10) shows no correlation between these parameters. Our study suggest that if there is some dependence of Z on total lightning density, it is non-unique or less relevant than the dependence on others factors.

3.3. Hourly Variation of Z

The hourly variation of mean Z was calculated for a 2.5 x 2.5 degree grid (Figure 11). Before 14:00 LT the values show large variations probably related to the low statistical significance of the data due to the absence of morning storms. After this time the values are 20-30% higher and almost constant. The hourly variation of the normalized mean values of total lightning and CG lightning were also calculated and shown in Figures 12 to 13. They show a typical daily variation with a maximum at 17:00 LT. The similarity of the curves in Figures 12 and 13 explains why Z values are almost constant after 14:00 LT in Figure 11. The daily variation of Z in Figure 11 is in partially agreement with the results obtained by Soriano and Pablo (2007), who found a slow increase of Z along the day with maximum values around 22:00 LT.

4. Conclusions

This article presents the first study of the IC to CG ratio (Z) for a 7-yr data set in Southeastern Brazil. An influence of the orographic features on the geographical distribution of Z is suggested by the observations, in response to the occurrence with frontal systems. There is no clear correlation between Z and total lightning density, percentage of positive CG flashes and latitude. The hourly variation of Z, total lightning flash density, CG lightning flash density and positive CG lightning flash rate are presented. While all others parameters presented a strong correlation with the diurnal cycle of heating, the Z parameter shows a small dependence on the diurnal cycle. Clearly, further studies of the Z ratio are needed to better understand its relationship with other factors.

References

Boccippio, D.J., Cummins, K.L., Chiristian, H.J., Goodman, S.J. 2001. Combined Satellite and Surface Based Estimation of the Intracloud-Cloud-to-Ground Lightning Ratio over the Continental United States, Mon. Weather Rev., 129, 108– 122.

Buechler, D. E., Driscoll, K. T., Goodman, S. J., Christian, H. J. 2000. Lightning activity within a tornadic thunderstorm observed by the Optical Transient Detector (OTD), Geophys. Res. Lett., 27, 2253–2256.

Cummins, K.L., Murphy, M. J., Bardo, E. A., Hiscox, W. L., Pyle, R. B., Pifer, A. E. 1998. A combined TOA/MDF technology upgrade of the U.S. national lightning detection network, J. Geophys. Res., 103, 9035-9044.

Chameides, W., Stedman, D., Dickerson, R., Rusch, D., Cicerone, R. 1977. NOx Production in Lightning. J. Atmos. Sci., 34, 143–149.

Christian, H. J., Blakeslee, R. J., Goodman, S. J. 1992.,Lightning imaging sensor for the Earth Observing System, Tech. Rep. NASA TM-4350, NASA, Washington, D. C.

Kuleshov, Y., Mackerras, D., Darveniza, M., Spatial distribution and frequency of lightning activity and lightning flash density maps for Australia, J. Geophys. Res., 111, D19105, doi:10.1029/2005JD006982, 2006.

MacGorman, D. R., Burgess, D. W., Mazur, V., Rust, W. D., Taylor, W. L., Johnson, B. C. 1989. Lightning rates relative to tornadic storm evolution on 22 May 1981, J. Atmos. Sci., 46, 221–250.

Markson, R., 2007. The global circuit intensity: its measurement and variation over the last 50 years, Bull. Amer. Meteorol. Soc., 88, 223–241.

Naccarato, K. P., 2005. Análise das características dos relâmpagos na região sudeste do Brasil. 2005-07-25. 362 p. (INPE-14083-TDI/1069). PhD Thesis, Instituto Nacional de Pesquisas Espaciais, São José dos Campos (in Portuguese).

Naccarato, K. P., Pinto Jr., O., Damata, G. 2008. Improvements to the detection efficiency model for the Brazilian lightning detection network, Atmos. Res., submitted.

Pickering, K.E., Wang, Y., Tao, W.-K., Price, C., Müller, J.-F. 1998. Vertical distributions of lightning NOx for use in regional and global chemical transport models, J. Geophys. Res, 103, 31203-31216.

Pinto Jr, O., Naccarato, K. P., Pinto, I. R. C. A., Fernandes, W. A., Neto, O. P. 2006. Monthly distribution of cloud-to-ground lightning flashes as observed by lightning location systems, Geophys. Res. Lett., 33, L09811,doi:10.1029/2006GL026081.

Pinto Jr., O., Pinto, I.R.C.A., Naccarato, K.P. 2007. Maximum cloud-to-ground lightning flash densities observed by lightning location systems in the tropical region: A review, Atmos. Res., 84, 189-200.

Rakov, V. A., Uman, M. A. 2003. Lightning: Physics and Effects,Cambridge Univ. Press, New York.

Rutledge, S. A., Williams, E. R., Keenan, T. D. 1992. The Down Under Doppler and Electricity Experiment (DUNDEE): Overview and preliminary results, Bull. Amer. Meteor. Soc., 73, 3-16.

Rycroft M.J., Israelsson, S., Price, C. 2000. The global atmospheric electric circuit, solar activity and climate change, J. Atmos. Solar-Terr. Phys., 62, 1563-1576.

Soriano, L. R., Pablo, F. de 2007. Total flash density and the intracloud/cloud-to-ground lightning ratio over the Iberian Peninsula, J. Geophys. Res., 112, doi:10.1029/2006JD007624.

Williams, E., Boldi, R., Martlin, A., Webwer, M., Goodman, S., Buechler, D., Hodanish, S., Sharp, D. 1999. The behavior of total lightning in severe Florida thunderstorms, Atmos. Res.,51, 245-265.

Williams, E., 2007. The global electrical circuit: a review, Proceedings of the 13th International Conference on Atmospheric Electricity (ICAE), 1-4, Beijing, China.
Zepka, G. S., 2005. Estudo para o Desenvolvimento de um Previsor de Descargas Elétricas Atmosféricas Aplicado à Região Costeira do Estado do Rio de Janeiro, Msc Thesis, FURG, (in Portuguese).

Figure Captions

1. Map of the detection efficiency of BrasilDat used to correct the CG lightning data in this study. The red stars represent the capitals of the different states.

2. Map of total lightning density (in flashes.km^{-2}.year^{-1}) for the region of study obtained from the LIS sensor.

3. Regional distribution of average Z (=IC/CG) values in Southeastern Brazil for a 0.5 x 0.5 degree grid.

4. Map of intracloud (IC) lightning density (in flashes.km^{-2}.year^{-1}) for the region of study.

5. Orographic map with altitude values in meters in Southeastern Brazil for a 0.5 x 0.5 degree grid. The names of the states are indicated.

6. Map of the cloud-to-ground (CG) lightning density (in flashes.km^{-2}.year^{-1}) in Southeastern Brazil for a 0.5 x 0.5 degree grid.

7. Mean annual precipitation from 1998 to 2005 (in mm) in Southeastern Brazil.

8. Regional distribution of the positive CG lightning density (in flashes.km^{-2}.year^{-1}) in Southeastern Brazil in a 0.5 x 0.5 degree grid.

9. Variation of Z (=IC/CG) versus the percentage of positive CG flashes. Each point corresponds to a cell in the 0.5 x 0.5 degree grid in the region of study.

10 Variation of Z (=IC/CG) versus total lightning flash rate. Each point corresponds to a cell in the 0.5 x 0.5 degree grid in the region of study.

11. Variation of average hourly values of Z (=IC/CG) for a 2.5 x 2.5 degree grid.

12. Variation of average normalized hourly values of total lightning rate for a 2.5 x 2.5 degree grid.

13. Variation of average normalized hourly values of CG lightning rate for a 2.5 x 2.5 degree grid.

Fig. 1

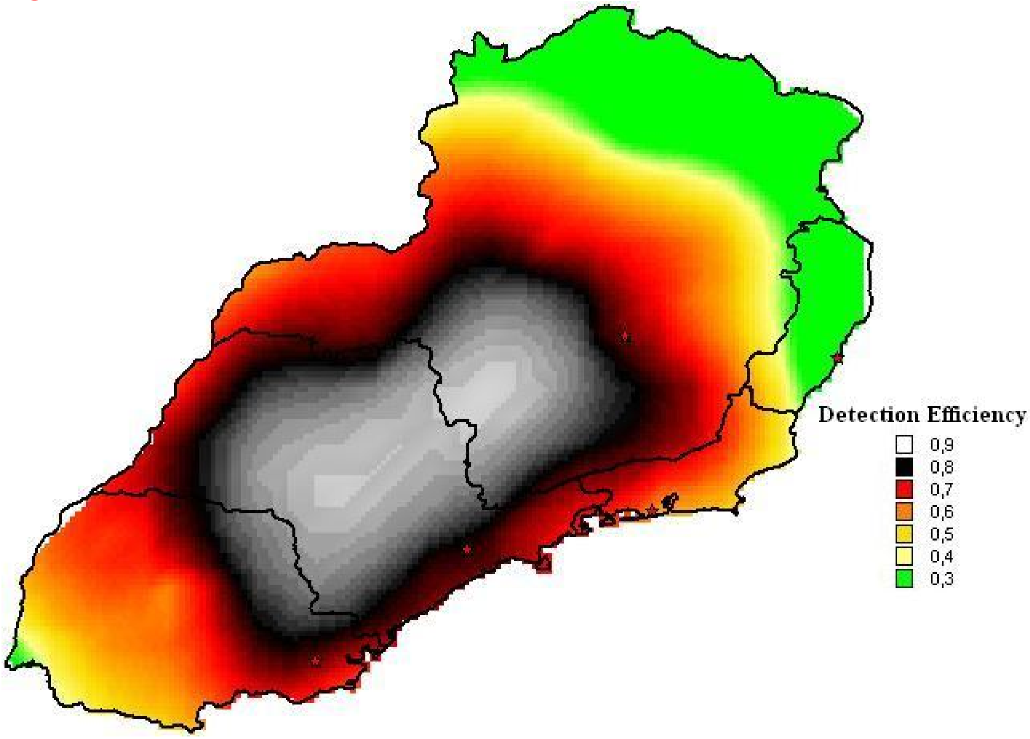

Detection Efficiency
0,9
0,8
0,7
0,6
0,5
0,4
0,3

Fig. 2

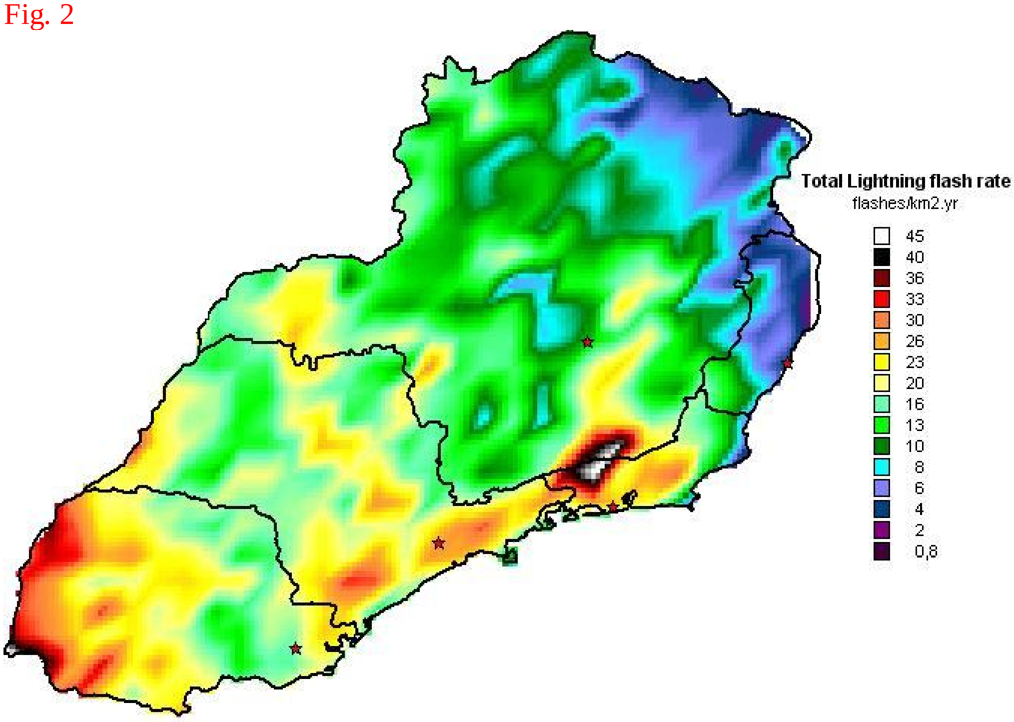

Total Lightning flash rate
flashes/km2.yr
45
40
36
33
30
26
23
20
16
13
10
8
6
4
2
0,8

Fig.3

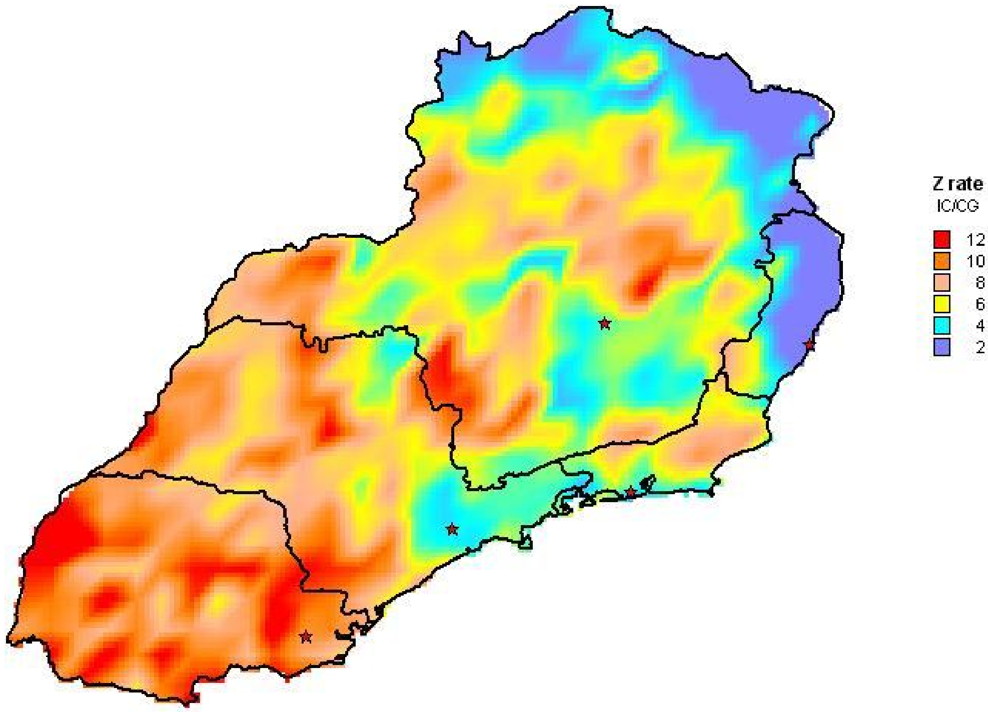

Z rate
IC/CG
12
10
8
6
4
2

Fig. 4

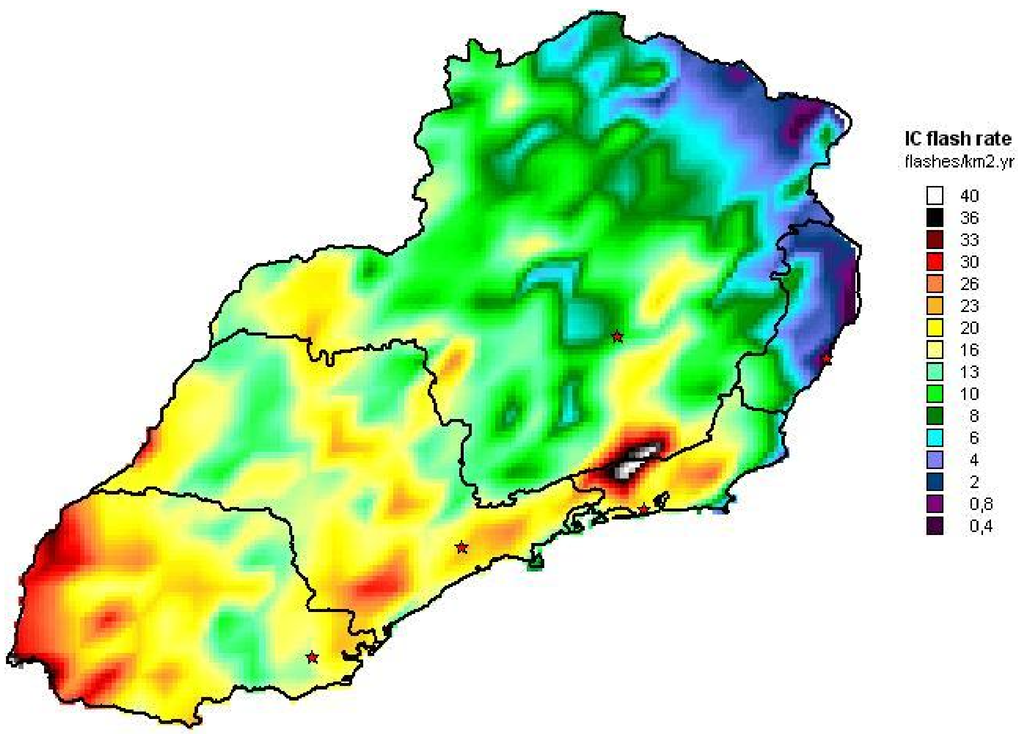

IC flash rate
flashes/km2.yr
40
36
33
30
26
23
20
16
13
10
8
6
4
2
0,8
0,4

Fig.5

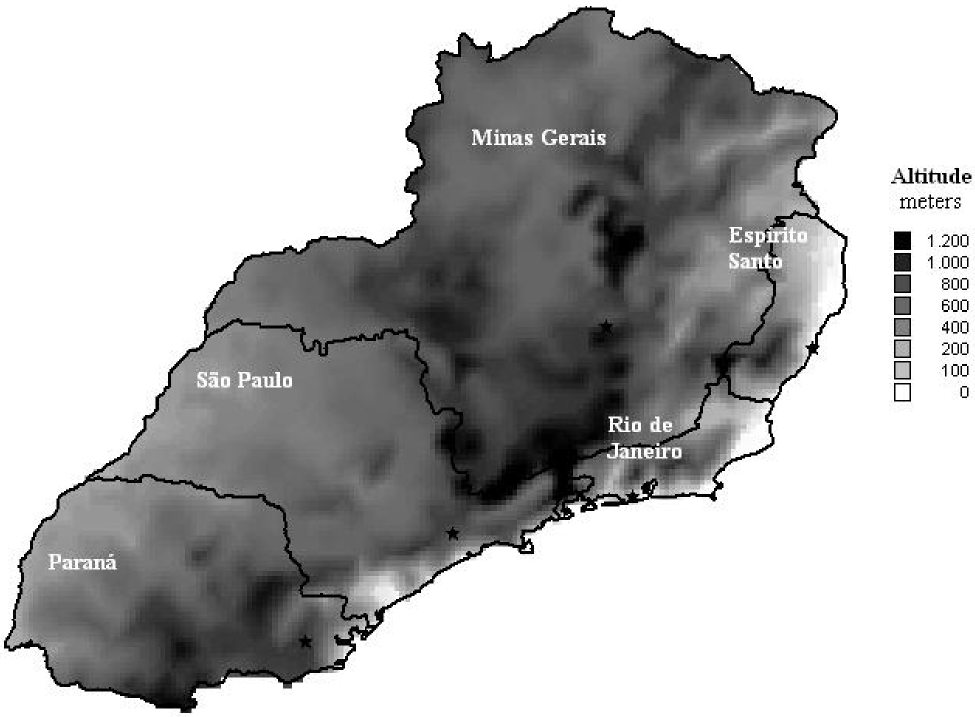

Minas Gerais
Espírito
Santo
São Paulo
Rio de
Janeiro
Paraná
Altitude
meters
1.200
1.000
800
600
400
200
100
0

Fig.6

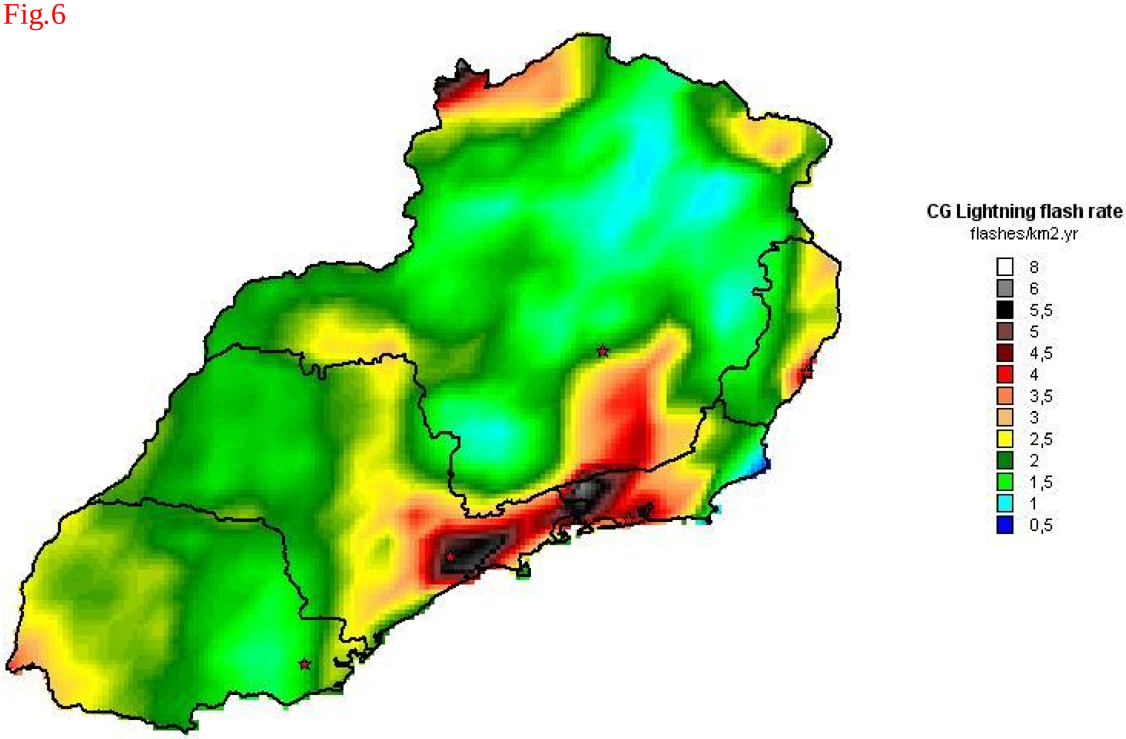

CG Lightning flash rate
flashes/km2.yr
8
6
5,5
5
4,5
4
3,5
3
2,5
2
1,5
1
0,5

Fig.7

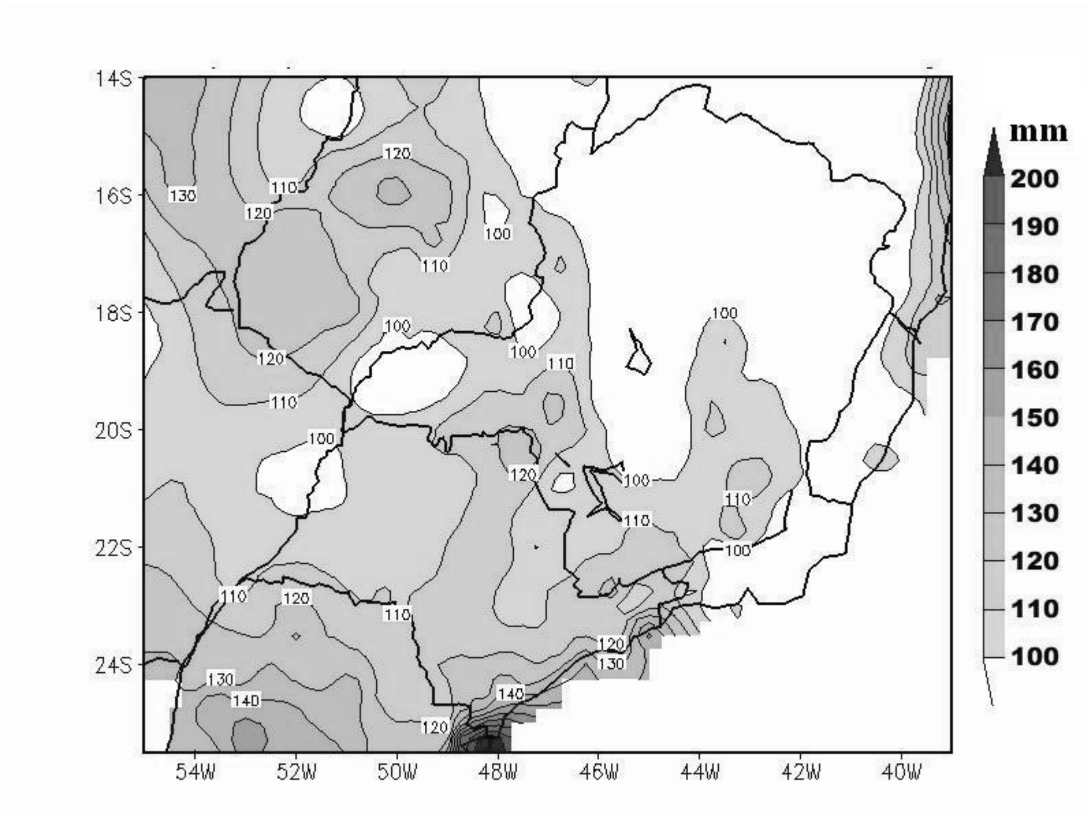

mm
200
190
180
170
160
150
140
130
120
110
100
14S
16S
18S
20S
22S
24S
54W
52W
50W
48W
46W
44W
42W
40W

Fig.8

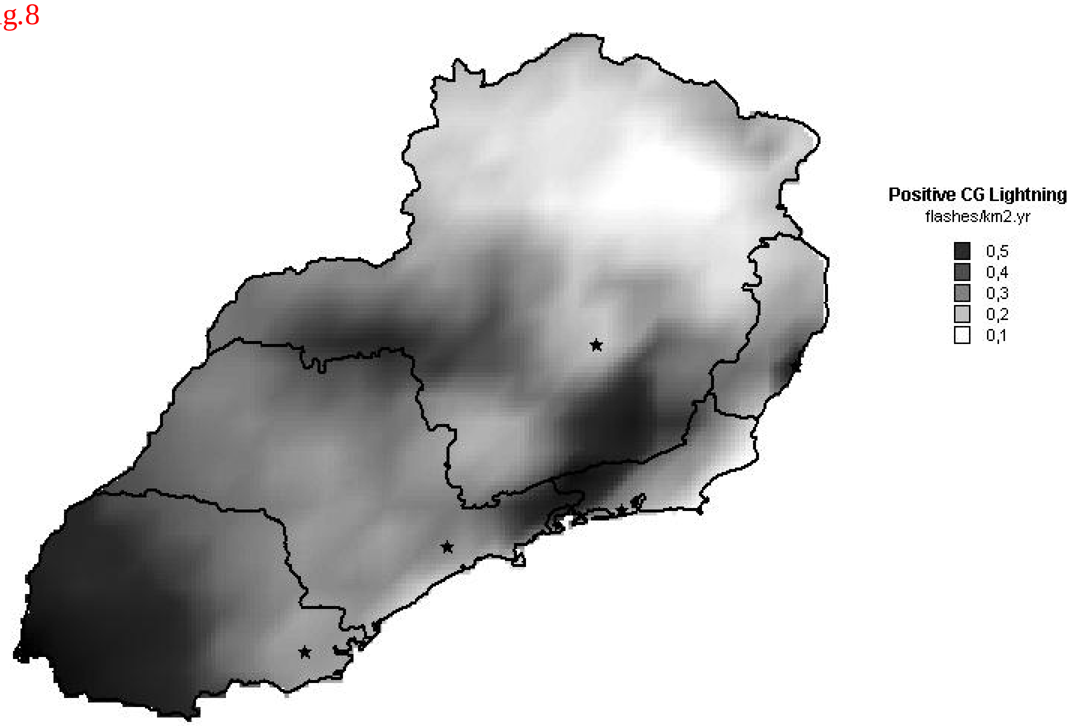
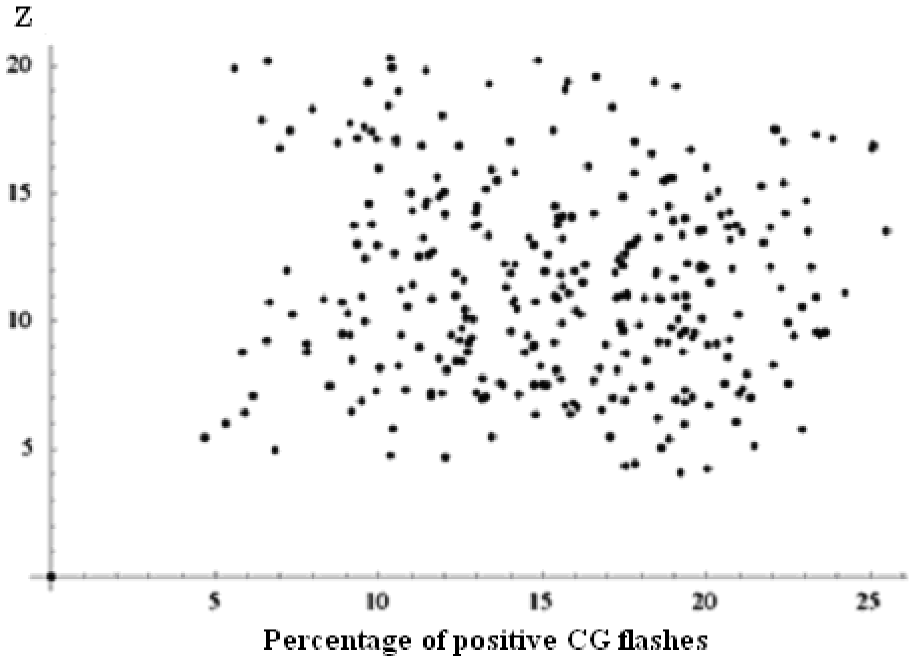
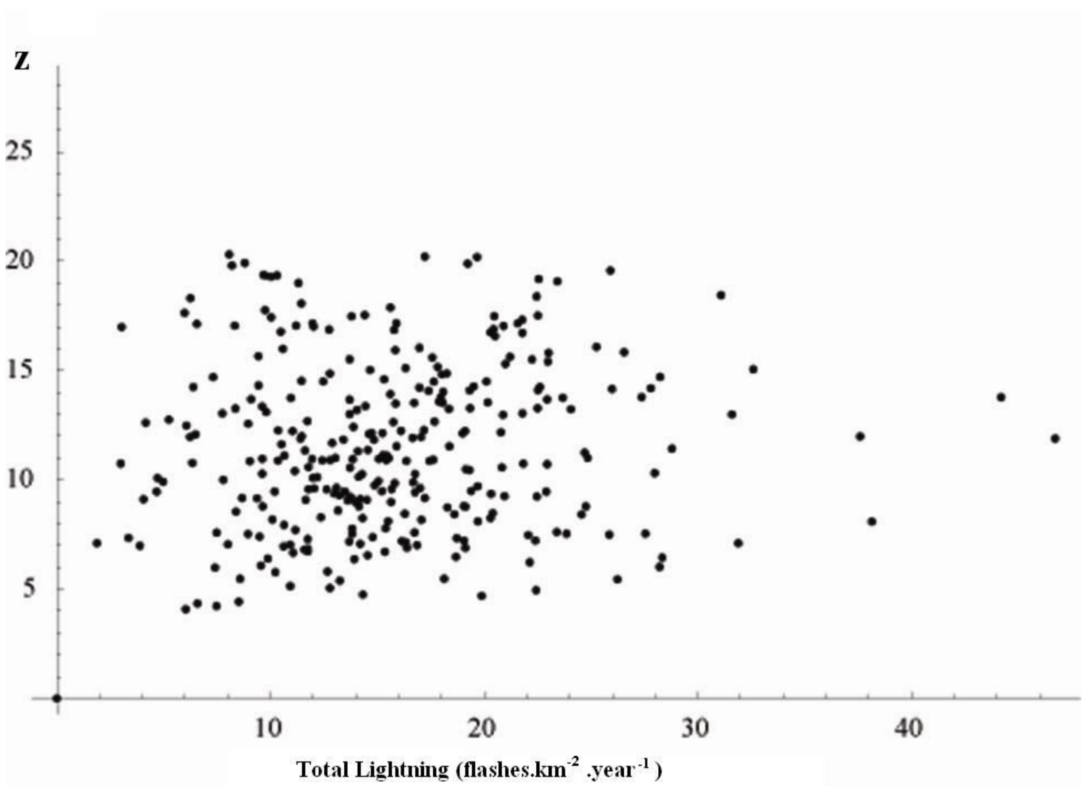

Positive CG Lightning
flashes/km2.yr
0,5
0,4
0,3
0,2
0,1

Fig. 9



Z
20
15
10
5
5
10
15
20
25
Percentage of positive CG flashes

Fig.10



Z
25
20
15
10
5
10
20
30
40
Total Lightning (flashes.km^{-2} .year^{-1})

Fig.11

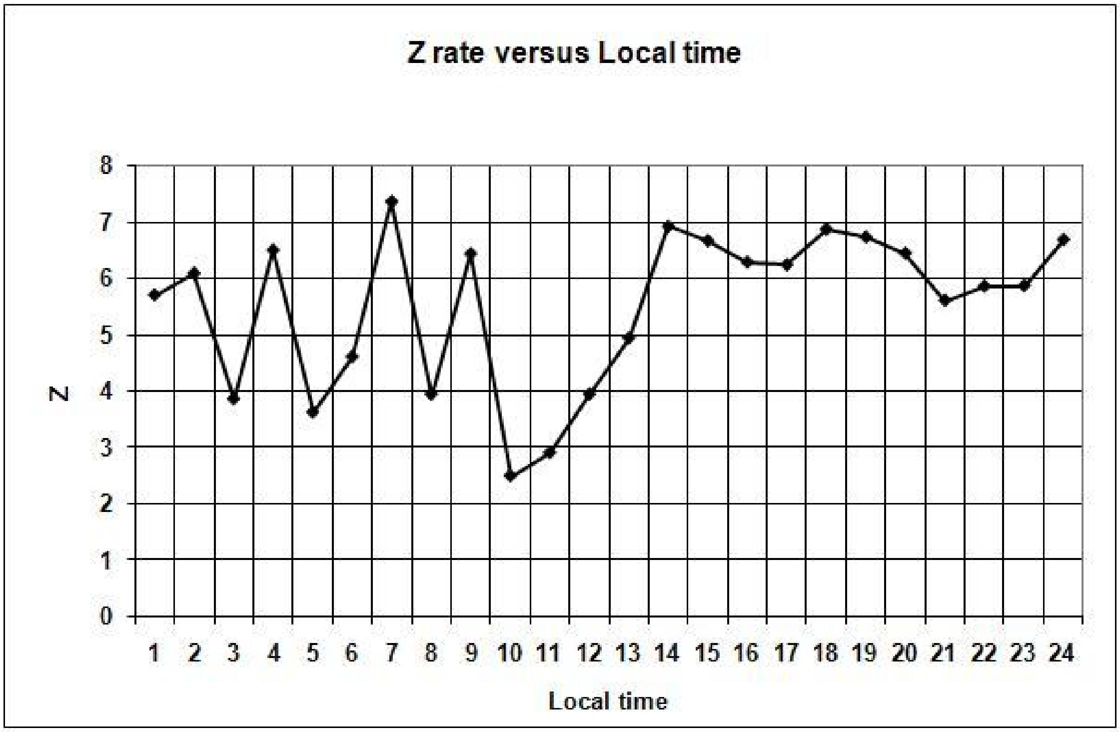

Z rate versus Local time
Z
0
1
2
3
4
5
6
7
8
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Local time

Fig.12

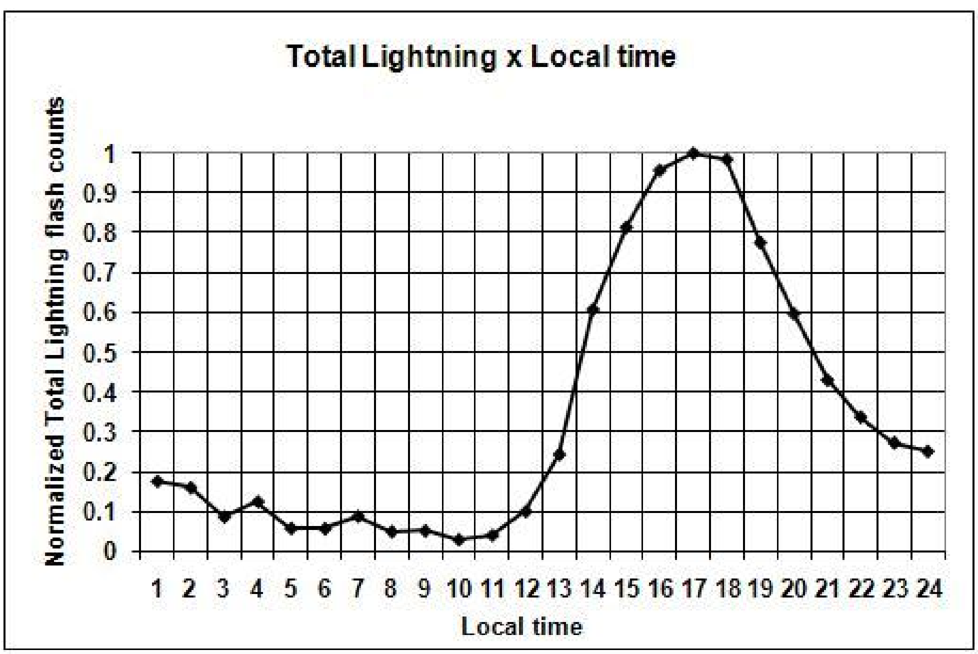
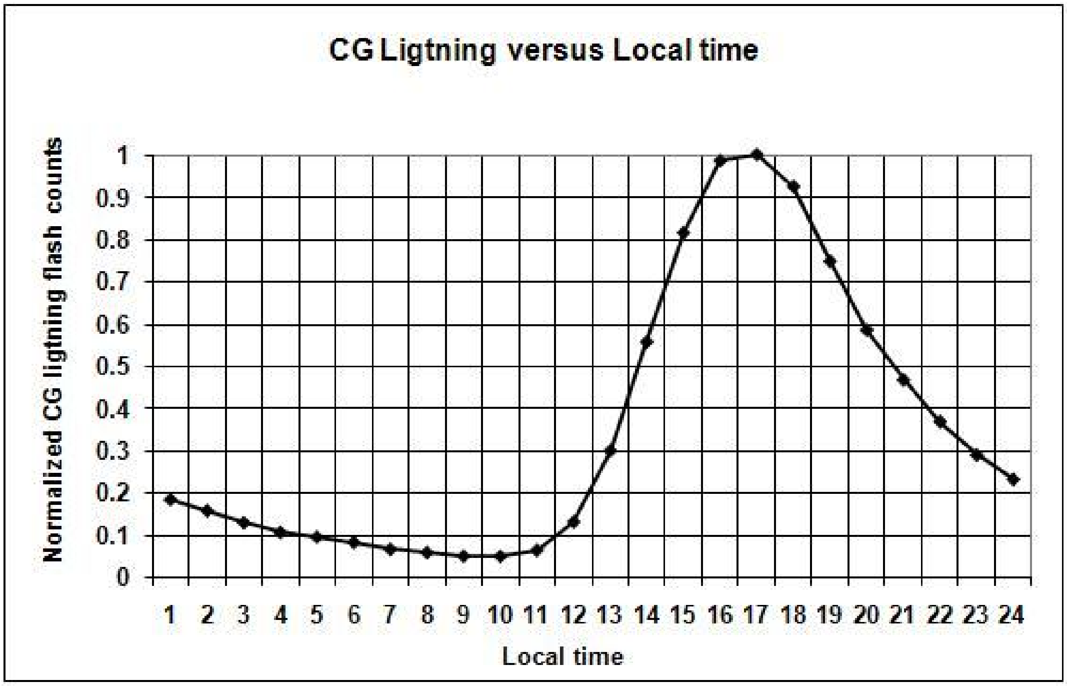

Total Lightning x Local time
Normalized Total Lightning flash counts
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Local time

Fig.13



CG Ligtning versus Local time
Normalized CG ligtning flash counts
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Local time