Evidence of thermal and aerosol effects on the cloud-to-ground lightning density and polarity over large urban areas of Southeastern Brazil

K. P. Naccarato, O. Pinto Jr., and I. R. C. A. Pinto
Instituto Nacional de Pesquisas Espaciais, São Jose dos Campos, SP, Brazil

Received 7 April 2003; revised 16 May 2003; accepted 22 May 2003; published 2 July 2003.

[1] The Brazilian lightning detection network detected about 310,000 cloud-to-ground flashes over three large metropolitan areas in Southeastern Brazil during three summer seasons (from 2000 to 2002). It was observed an enhancement of 60–100% in the flash density over the urban areas compared to their surroundings. Conversely, a decrease of 7–8% in the percentage of positive flashes was also observed. The spatial distribution of the flashes follows closely the shape of the São Paulo city heat island, thereby supporting the thermal hypothesis. The PM_{10} concentration showed a positive linear correlation with the number of cloud-to-ground flashes and a negative correlation with the percentage of positive flashes, supporting the aerosol hypothesis. These results indicate that both hypotheses should be considered to explain the CG lightning enhancements over the urban areas. However, only the aerosol hypothesis could better support the decrease of the percentage of positive flashes. *INDEX TERMS:* 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3324 Meteorology and Atmospheric Dynamics: Lightning. **Citation:** Naccarato, K. P., O. Pinto Jr., and I. R. C. A. Pinto, Evidence of thermal and aerosol effects on the cloud-to-ground lightning density and polarity over large urban areas of Southeastern Brazil, *Geophys. Res. Lett.*, *30*(13), 1674, doi:10.1029/2003GL017496, 2003.

1. Introduction

[2] At present, many studies on lightning characteristics over cities in USA, Europe, and Brazil have provided enough evidence that the high-urbanized areas affect the cloud-to-ground (CG) flash density. *Westcott* [1995] was the first to show an enhancement of the CG flash density over 16 large cities in the USA based on the NLDN data. She speculated a combination of two factors to explain her findings: the increase of cloud condensation nuclei (CCN) concentrations due to anthropogenic emissions of particulate matter (PM_{10}) and SO_2, and the enhancement of the convergence due to the heat island effect. *Orville et al.* [2001], also using NLDN data, found an enhancement of the CG flash density over Houston (Texas, USA). A land-see breeze simulation revealed an enhancement of the convergence over Houston, probably due to the urban heat island. The high concentrations of PM_{10} and SO_2 from anthropogenic sources were also speculated to be a reasonable explanation to their findings. *Soriano and Pablo* [2002] showed that small urban areas in Spain could also contribute to the enhancement of local CG lightning activity. They suggested a link between the SO_2 concentration and the number of CG flashes. However, no correlation was found with the PM_{10} concentration. *Steiger et al.* [2002] showed that the urban area of Houston not only affects the CG flash density but also the percentage of positive flashes (+CG), which decreases as the total number of flashes increases. In Southeastern Brazil, *Gomes* [2002] found similar results over Belo Horizonte metropolitan area (state of Minas Gerais) using lightning detection network data from an 8-year period (1988–1996). *Steiger et al.* [2002] discussed several hypotheses to explain the CG lightning enhancement and the reduction of the percentage of +CG, but no link between the aerosol concentration and the number of flashes was presented. Apparently, neither the urban island effect (thermal hypothesis) nor the anthropogenic aerosol (aerosol hypothesis) can separately explain the changes in the CG flashes characteristics observed over urban areas.

[3] Using lightning detection network data, thermal band satellite data, and PM_{10} measurements over three large urban areas of Brazil, this work presents evidence that both the aerosol and the thermal hypotheses should be considered to explain the enhancement of CG flash density. However, the decrease of the percentage of +CG could only be related to the air-pollution, since currently the thermal hypothesis did not support this effect.

2. Data Description and Methods

[4] The CG lightning data were obtained by a 14-sensor hybrid network composed by both LPATS series III and IV, and IMPACT sensors (Figure 1). This data set comprises the summer seasons of 2000, 2001, and 2002, which correspond to the months of December, January, and February from Dec/1999 to Feb/2002. The CG flash data were reprocessed using a configuration that requires at least 4 time measurements and does not allow any LPATS III data which were identified as intracloud discharges (IC) to be used (to avoid misclassification). As a result, only 0.5% of the data set were +CG with peak currents lower than 10 kA, leading to a low IC contamination [*Wacker and Orville*, 1999; *Naccarato et al.*, 2001].

[5] About 310,000 flashes were detected in the region that includes only three large metropolitan areas (shaded in Figure 1): the Campinas metropolitan area (RMC), the São Paulo metropolitan area (RMSP) and the São José dos Campos metropolitan area (RMSJC). These three highly populated areas stand for about 12% of the total population of Brazil. With about 46,800 km^2 of area, the region is

0094-8276/03/2003GL017496$05.00

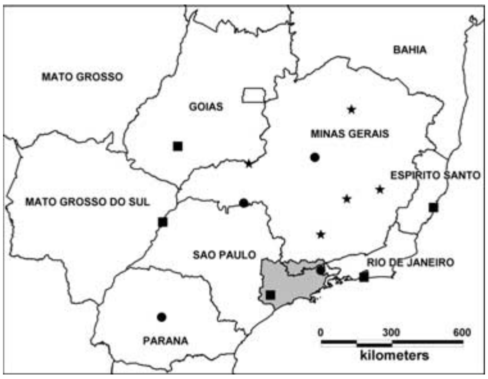

Figure 1. The 14-sensor hybrid network used in this work. The coordinates of the lower left corner are 26.72°S; 58.17°W and the upper right corner, 12.40°S; 39.67°W. The stars (★) represent LPATS III sensors, the squares (■), LPATS IV and the circles (●), IMPACT 141-T sensors. The shaded area (with about 46,800 km^2) indicates the region that contains the three metropolitan areas.

located between latitude 22.19°S and 24.25°S, and longitude 44.62°W and 47.62°W. The estimated network detection efficiency for this region is 90% (lightning data were not corrected for the network DE) and the location accuracy is less than 1 km. A medium urban area (Sorocaba) was also included in the analysis, since PM_{10} measurements are available there for comparison to the three main urban areas.

[6] CETESB (the governmental agency for natural environment protection of State of São Paulo) maintains, at present, 29 automatic stations distributed over the cities of São Paulo, Campinas, Sorocaba and São José dos Campos that continuously measure the concentration of PM_{10} (in $\mu g/m^3$) and compute an average value every full hour [*CETESB*, 2001]. Since the SO_2 concentrations were not available for all the considered urban areas, they were not included in this work. It was selected seven circular areas with 10 km radius over the RMSP, RMC, RMSJC, and the city of Sorocaba, where the PM_{10} concentrations and the CG flash data were compared only for thunderstorms days. The objective was to identify a possible correlation between the urban aerosol and the lightning activity over the these metropolitan areas.

3. Results

[7] Figure 2a presents the CG flash density for the region shown in Figure 1. It shows clearly an enhancement of the CG flash density over the three metropolitan areas. The increase of the CG lightning activity for the RMC and RMSJC related to their surroundings was about 50–60%. In the RMSP, a higher variation of 150–200% was observed.

[8] Figure 2b shows that the percentage of +CG flashes decreases over the urban areas where the flash density reaches its higher values. Over the RMC and RMSJC areas, the decreasing related to their surroundings was about 5–7%. The lowest percentages were found over the RMSP, where a reduction of about 10–12% was observed.

[9] No effect was observed in the average peak current and multiplicity of the CG flashes over the three metropolitan areas. This is in agreement with *Steiger et al.* [2002] for

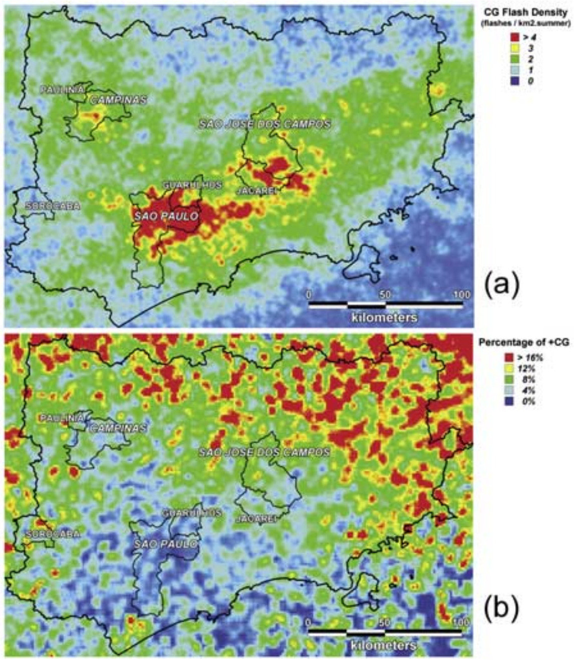

Figure 2. (a) CG lightning density in flashes.km^{-2}. summer^{-1} for the region shown in Figure 1 with 1 km resolution. (b) Percentage of +CG flashes with 2 km resolution. The outlined area in both figures is located between latitude 22.19°S and 24.25°S, and longitude 44.62°W and 47.62°W. In the legend, intermediate values are represented by the variation of the primary colors.

Houston, but in contrast to *Lyons et al.* [1998] for the 1998 smoke event in the central USA. This could be an evidence that the smoke aerosol should affect the CG lightning activity in a different way related to the urban aerosol.

4. Discussion

4.1. Enhancement of CG Flash Density

[10] Figure 3 compares the CG flash density in the RMSP with the geographic position of São Paulo city and its

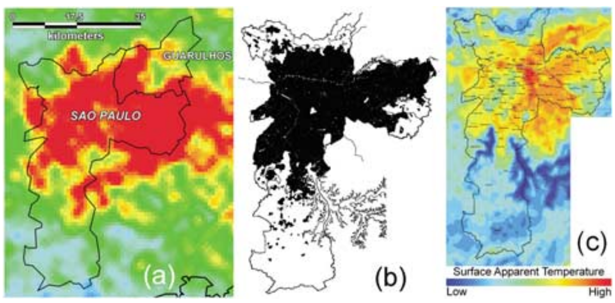

Figure 3. Spatial comparison of the CG lightning density with the RMSP urban heat island and the geographic position of the São Paulo city. (a) Same as Figure 2a, but showing only the RMSP. (b) Location of the São Paulo city (the black areas indicates where the urbanization occurs within the geopolitical contour of the city). (c) Apparent surface temperature of RMSP computed using the LandSat-7 thermal data.

apparent surface temperature. Figure 3b presents the region where the São Paulo city is located (represented by the black area) within its geopolitical limit and Figure 3c, computed from the thermal band of the Land-Sat 7 satellite, indicates the heat island effect. Both figures (3b and 3c) were obtained from SMMA (the environment secretary of São Paulo city) and SEMPLA (the urban planning secretary of São Paulo city) in http://www.prodam.sp.gov.br/svma/atlas_amb/. There is a clear agreement between the three maps, showing that the CG flashes tend to roughly concentrate over the urbanized area, which also correspond to the warmer region.

[11] The strong relationship between Figures 3a and 3b indicates that the CG lightning activity tends to concentrate where the human activities are more intense. This anthropogenic influence results in both an increase of the local temperature (due to the man-made structures and the lack of vegetation) and an increase of the aerosol emissions (due to the traffic and industrial activity).

[12] The good spatial correlation between the regions of higher number of CG flashes and higher apparent surface temperature (Figures 3a and 3c) might support the thermal effect, as proposed by *Williams and Stanfill* [2002]. They considered islands to discuss the influence of a portion of land on the cloud electrification and lightning. A critical area was computed to assess how large an island should be to guarantee continental behavior. According to the thermal hypothesis, the minimum area required was 110 km^2 against about 20,000–30,000 km^2 achieved by the aerosol hypothesis. The former calculation was supported by thunder days counts over 55 islands all over the world. Furthermore, they discussed the suppression of coalescence over the continent considering the traditional thermal hypothesis, which states that the larger updrafts over land would allow less time for droplets to interact for coalescence, thus preventing the warm rain. They proposed, as a conclusion, that the thermal hypothesis (rather than the aerosol theory) could better explain the appreciable difference in the lightning activity between land and sea. Considering now the urban heat islands in land, the thermal hypothesis could also explain increases in the number of flashes over these warmer regions (similar to islands in sea), particularly for the RMSP, where the heat island has about 1,600 km^2 of area (much larger then the critical area). A further support to the thermal hypothesis was present by *Orville et al.* [2001], who showed that the land-sea breeze convergence over Houston combined with the urban island effect might intensify the thunderstorm development over the city.

[13] Figure 4a presents a positive linear correlation between the number of CG flashes and PM_{10} average concentrations in the seven circular areas over the cities shown in Figure 2a. Although more studies are required to establish the effect of the anthropogenic emissions on the lightning activity, this result gives an addition support to the Rosenfeld-Lensky theory [*Rosenfeld and Lensky*, 1998] as a possible explanation for this effect. *Steiger et al.* [2002] pointed out this theory as an important factor to explain the urban increase of the number of CG flashes (the aerosol hypothesis). They also mentioned an evidence that the cities might be thermodynamically less favorable for thunderstorm development. Still according to Steiger et al., the large number of CCN could greatly reduce the coalescence process in urban thunderclouds due to the increase in the

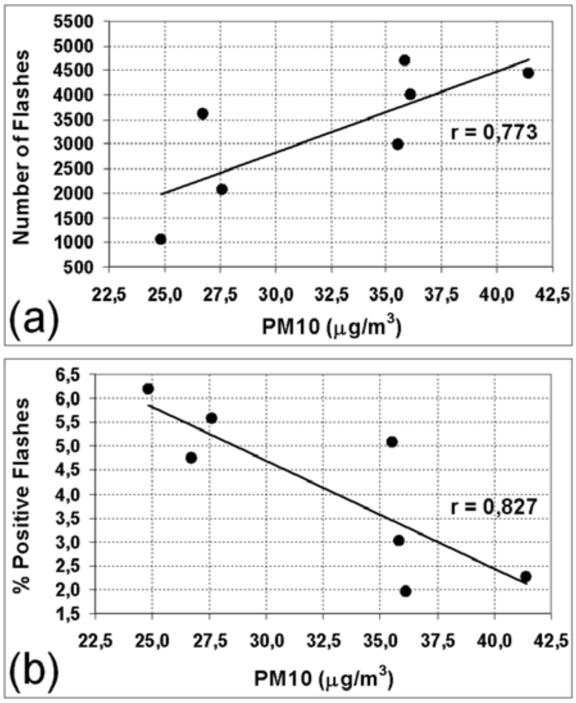

Figure 4. (a) Positive linear correlation (r = 0.773) between the number of CG flashes and PM_{10} concentrations in the seven circular areas with 10 km radius. (b) Negative linear correlation (r = −0.827) between the PM_{10} concentrations and the percentage of +CG flashes for the same circular areas.

number of droplets, thereby suppressing the mean droplet size. By itself, this reduction in coalescence could enhance the charge separation in the thundercloud by increasing the liquid water content (LWC) in its mixed-phase region, thus leading to the increase of lightning activity.

4.2. Decrease of the Percentage of Positive Flashes

[14] Figure 4b shows a negative linear correlation between the PM_{10} average concentrations and the percentage of the +CG flashes in the same seven circular areas. This finding differs from other results, which suggest that the percentage of +CG flashes tends to increase with the aerosol concentration (like in forest fires) [*Lyons et al.*, 1998; *Murray et al.*, 2000]. However, it could explain the behavior observed in Figure 2b. On the other hand, it is still not clear how the heat island effect could support the observed decrease in the percentage of +CG flashes.

[15] *Steiger et al.* [2002] were the first to observe a decrease in the percentage of +CG over urban areas. They speculated that impurities in cloud water (due to the emission of anthropogenic particulate) could appreciably affect the charge separation in the urban thundercloud, thereby increasing the negative lightning activity. According to their hypothesis, high concentrations of contaminants in supercooled cloud droplets led to negative charging of graupel at warmer cloud temperatures. Thus, the main negative charge region could extend itself towards the cloud base, suppressing the positive charge center below. This might produce more −CG flashes, thus decreasing the percentage of +CG flashes.

[16] On the other hand, [*Lyons et al.*, 1998; and *Murray et al.*, 2000] presented just an opposite effect for thunderstorms in the central USA, which had been contaminated by forest fires aerosol plumes from Mexico. Based on the NLDN data, they observed a significant increase in the percentage of +CG flashes. Furthermore, *Avila et al.* [1999] showed that a smaller-droplet spectrum leads to positively charged graupel between −10°C and −25°C. Considering that urban clouds might have smaller droplet sizes [*Rosenfeld and Woodley*, 2001; *Bréon et al.*, 2002], this finding suggests that the lower positive charge region of the cloud should extend to higher altitudes, thus producing more +CG flashes. Therefore, the percentage of +CG flashes should increase. This hypothesis can reasonably explain the enhance of the percentage of +CG flashes in thunderstorms forming in smoke-contaminated air masses (like the forest fires), but does not support the effect over the urban areas.

5. Conclusions

[17] Based on a CG flash data set for three summer seasons (1999–2002), it was found an average enhancement of 60–100% on the lightning activity over three large metropolitan areas in the Southeastern Brazil: São Paulo, Campinas and São José dos Campos. Conversely, the percentage of +CG presented an average decrease of 7–8% over the same areas. There is still no explanation for these effects, but two main hypotheses have been discussed: 1) the urban heat island (related to the thermal hypothesis), which enhances the convergence over the urban area leading to more thunderstorms; 2) the anthropogenic particulate emissions (related to the aerosol hypothesis), which affects the electrification processes in the thundercloud, thereby contributing to an enhance of the lightning activity. By the other hand, no effect was observed in the average peak current and multiplicity.

[18] In this work, it was found that the enhancement of the CG lightning activity over São Paulo city (the largest urban area in Brazil) follows closely the increase of the apparent surface temperature (which indicates the heat island), thus supporting the thermal hypothesis. However, a positive linear correlation between the number of CG flashes and the PM_{10} average concentrations was also found, suggesting that also the aerosol hypothesis support the increase of the number of CG flashes. It seems that, at least for the CG lightning activity, both hypotheses act on the same way (probably with mutual interaction). Furthermore, it was also found a negative correlation between the percentage of +CG flashes and the PM_{10} average concentrations. This result, which cannot be fully supported by the thermal hypothesis, provides additional evidence that the aerosol also plays an important role on the lightning polarity over urban areas.

[19] **Acknowledgments.** The authors would like to thank Armando Cazetta Filho from CEMIG for the reprocessing facilities of the CG flash data and CETESB for the PM10 data. This research is supported by FAPESP (Grant No. 01/04026-7).

References

Avila, E. E., R. G. Pereyra, G. G. A. Varela, and G. M. Caranti, The effect of the cloud-droplet spectrum on electrical-charge transfer during individual ice-ice collisions, *Q. J. R. Meteorol. Soc.*, *125*(557), 1669–1679, Part A, 1999.

Bréon, F. M., D. Tanré, and S. Generoso, Aerosol effect on cloud droplet size monitored from satellite, *Science*, *295*(5556), 834–838, 2002.

CETESB, *Relatório de qualidade do ar no Estado de São Paulo - 2001*, edited by CETESB, São Paulo, 2002. (http://www.cetesb.sp.gov.br/Ar/relatorios/RelatorioAr2001.zip)

Gomes, M. A. S. S., *Estudo dos relâmpagos na Regiao Sudeste do Brasil em função das características geográficas*, PhD thesis, edited by INPE, São José dos Campos, 2002.

Lyons, W. A., T. E. Nelson, E. R. Williams, J. A. Cramer, and T. R. Turner, Enhanced positive cloud-to-ground lightning in thunderstorms ingesting smoke from fires, *Science*, *282*(5386), 77–80, 1998.

Murray, N. D., R. E. Orville, and G. R. Huffines, Effect of pollution from Central America fires on cloud-to-ground lightning in May 1998, *Geophys. Res. Lett*, *27*(15), 2249–2252, 2000.

Naccarato, K. P., O. Pinto Jr., I. R. C. A. Pinto, A. Cazetta, G. E. Amorim, Influence of the lightning location system configuration on the cloud-to-ground lightning flash characteristics, paper presented at VI International Symposium on Lightning Protection (SIPDA), Santos, Brazil, 2001.

Orville, R. E., G. R. Huffines, J. Nielsen-Gammon, R. Zhang, B. Ely, S. Steiger, S. Phillips, S. Allen, and W. Read, W, Enhancement of cloud-to-ground lightning over Houston, Texas, *Geophys. Res. Lett.*, *28*(13), 2597–2600, 2001.

Rosenfeld, D., and I. M. Lensky, Satellite-based insights into precipitation formation processes in continental and maritime convective clouds, *Bull. Am. Meteorol. Soc.*, *79*(11), 2457–2476, 1998.

Rosenfeld, D., and W. Woodley, Pollution and clouds, *Phys. World*, *14*(2), 33–37, 2001.

Soriano, L. R., and F. Pablo, Effect of small urban areas in central Spain on the enhancement of cloud-to-ground lightning activity, *Atmos. Env.*, *36*(17), 2809–2816, 2002.

Steiger, S. M., R. E. Orville, and G. R. Huffines, Cloud-to-ground lightning characteristics over Houston, Texas: 1989–2000, *J. Geophys. Res.*, *107*(D11), art. 4117, 2002.

Wacker, R. S., and R. E. Orville, Changes in measured lightning flashes count and return stroke peak current after the 1994 U.S. National Lightning Detection Network upgrade: 1. Observations, *J. Geophys. Res.*, *104*(D2), 2151–2157, 1999.

Westcott, N. E., Summertime cloud-to-ground lightning activity around major Midwestern urban areas, *J. Appl. Meteorol.*, *34*(7), 1633–1642, 1995.

Williams, E. R., and S. Stanfill, The physical origin of the land-ocean contrast in lightning activity, *Comp. Rendus Phys.*, *3*(10), 1277–1292, 2002.

K. P. Naccarato, O. Pinto Jr., and I. R. C. A. Pinto, Divisão de Geofísica Espacial, Coordenação de Ciências Espaciais e Atmosféricas, Instituto Nacional de Pesquisas Espaciais, P. Box 515, 12245-970, São José dos Campos/SP, Brazil.