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Anomalous lightning activity over the Metropolitan Region of São Paulo due to urban effects

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ABSTRACT

A significant enhancement in the number of negative cloud-to-ground (CG) lightning and a decrease in the percentage of positive CG flashes are observed over the city of São Paulo, similar to observations in other large urban areas. Strong evidence indicates that this anomalous behavior results from several mechanisms related to the urban effect. In this paper, we investigated the importance of the air pollution using CG lightning data provided by the Brazilian lightning detection network (BrasilDAT) for a 6-year period (1999–2004). Due to the large variations in the CG lightning activity in response to different meteorological processes, it is not an easy task to infer the contribution of air pollution to the enhancement in the lightning activity. In order to overcome such difficulty, two approaches were considered: (1) the weekly variation of the number of days with lightning in comparison to the mean concentration of particulate matter (PM_{10}), as well as other thermodynamical parameters; (2) the variation of the number of CG flashes and the maximum storm flash rate per individual thunderstorm for different levels of pollution. The results of both analyses suggest that: first, the enhancement in the CG lightning activity during the week days over São Paulo metropolitan region is related to the PM_{10} concentration (pollution); second, the PM_{10} concentration tends to increase the lifetime of the storms and, in consequence, the number of flashes per storm, and not the flash rate of the thunderstorm; and third, the effect of the pollution in the enhancement of the CG lightning activity is probably less significant compared to the effect of the urban heat island.

1. Introduction

The influence of the urban effect on the CG lightning activity is the subject of several studies (e.g., Orville et al., 2001; Steiger et al., 2002; Naccarato et al., 2003; Pinto et al., 2004). The urban effect is apparently a combination of a thermodynamic effect due to the differential heating of the surface over the city and an increase of the pollution concentration in the local atmosphere caused mainly by human activities. However, at the present time the physical mechanisms responsible for these effects are still not well established due to the complex correlations.

In particular, the urban effect on the CG lightning activity over the city of São Paulo was studied by Naccarato et al. (2003). They observed that the region of large CG activity is coincident with the location of the main urban area in the city and the region with larger surface temperature as obtained from the thermal band of the LandSat-7 satellite. They also observed a decrease in the percentage of positive CG flashes over the city area.

Many studies show a temperature gradient from the surroundings to the center of the urban area causing a local circulation and an increase of precipitation, which support the existence of a local microclimate over these areas (Hobbs et al., 1974; Landsberg, 1981; Changnon, 1980; Changnon et al., 1981; Oke, 1982; Lombardo, 1985; Westcott, 1995; Bornstein and Lin, 2000).

In recent years, the influence of aerosols on cloud microphysics, precipitation and also cloud electrification have been extensively studied and the effect of aerosol concentration on cloud electrification has been discussed by several authors.

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Bréon et al. (2002) discuss that the increase in the aerosol concentration reduces the droplet size, decreasing the warm rain coalescence process and enhancing the cloud water that reaches the mixed phase region. This fact tends to increase the amount of liquid water in the cloud, leading to variations of the distribution of droplets and thus modifying the microphysical processes of icing and cloud electrification. Andreae et al. (2004) studied different source mechanisms and compositions of the aerosol particles in smoky and clean regions, and their concentration variations, and suggest that aerosols can invigorate the convection in the polluted transition season in Brazil.

Williams et al. (2002) compared measurements of electrification of thunderclouds for polluted and clear conditions in the lightning-active pre-monsoon period and pointed out that the effect of the aerosol on the lightning activity is not clear. In turn, Orville et al. (2001), Steiger et al. (2002) and Naccarato et al. (2003) reported evidence of enhancement of CG lightning activity over Houston and São Paulo cities, suggesting that it can also be related to the urban aerosols. Clearly, there is no consensus about the effect of pollution on the enhancement of CG flashes in urban areas due to its intrinsic complexity.

The present work analyzes the effect of pollution on the enhancement of CG lightning activity in the city of São Paulo using CG lightning data provided by the Brazilian lightning detection network (BrasilDAT) for a 6-year period (1999–2004). Since the CG lightning activity, when considering the individual thunderstorms, presents variations of many orders of magnitude (from one flash to several hundreds of flashes) in response to different meteorological conditions, it is hard to infer the contribution of the air pollution to the enhancement of overall lightning activity. For this reason, two approaches were considered: (1) the weekly variations of the number of days with lightning were compared to the variations of the mean particulate matter concentration (PM_{10}), which decreases during the weekend, mainly on Sundays. The analysis was extended to include the weekly variation of others parameters: the cloud base height (CBH), relative humidity (RH), air temperature, wet bulb potential temperature (WBPT), dew point temperature (DPT), equivalent potential temperature (EPT) and the SO_2 concentration; (2) thunderstorms were grouped for different levels of PM_{10} concentrations and the number of flashes and the maximum storm flash rate were calculated for each level. After that, the results were averaged for three different ranges of PM_{10} concentrations: 0–30, 30–60 and 60–90 μg m^{-3}.

2. Methodology

The CG lightning data used in this study were provided by BrasilDAT network (Pinto et al., 2006a,b, 2007) over a 50 km diameter area that includes the main urban area of São Paulo city for a 6-year period (1999–2004). In this period, only days with CG flashes during the spring and summer seasons (from October to March) were considered and, for these days, only lightning data from 14 h to 20 h LT, which corresponds to the time of the day with maximum lightning activity. The region was considered representative of the urban heat island and presented the highest concentration of pollutants (PM_{10}). First of all, the number of CG flashes per individual storm was calculated and compared to the average PM_{10} concentration related to that particular storm. Although an increase in the number of flashes per individual storm was found with increase in the PM_{10} concentration, the high variability in the data prevented any statistically significant result. Another approach was then evaluated, considering the average number of CG flashes per individual storms in the 6-year period for the 30 more polluted days (21.4±31.9) and the 30 less polluted days (5.2±28.1). Again, the mean values were quite different, but the difference was not statistically significant due to the high standard deviation values. The large variability in the results is a consequence of the high variability of the CG lightning activity based on individual thunderstorms, which presents variations of several orders of magnitude depending on different meteorological conditions. In order to overcome this limitation, two new approaches were considered: (1) the CG lightning data were converted to the number of days with lightning (NDL). The mean NDL and its standard deviation were calculated for each week day considering each year separately. Then, the values were compared to the average concentration of particulate matter (PM_{10}) for each week day calculated for each year separately.

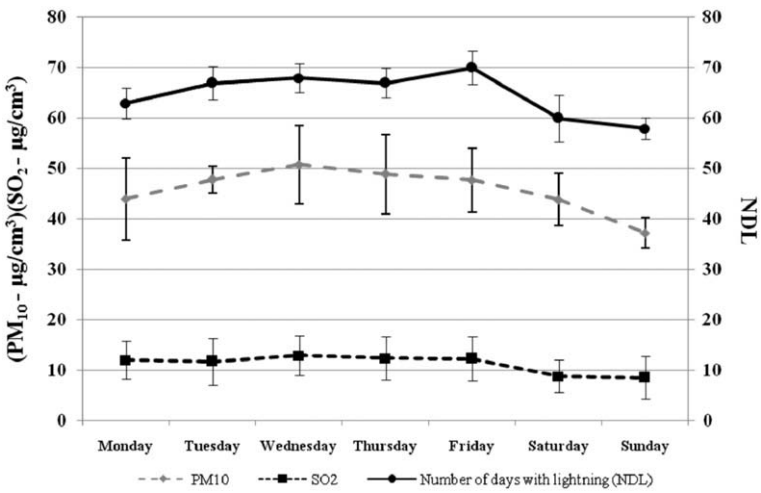

Fig. 1. Weekly distribution of NDL, PM_{10} and SO_2.

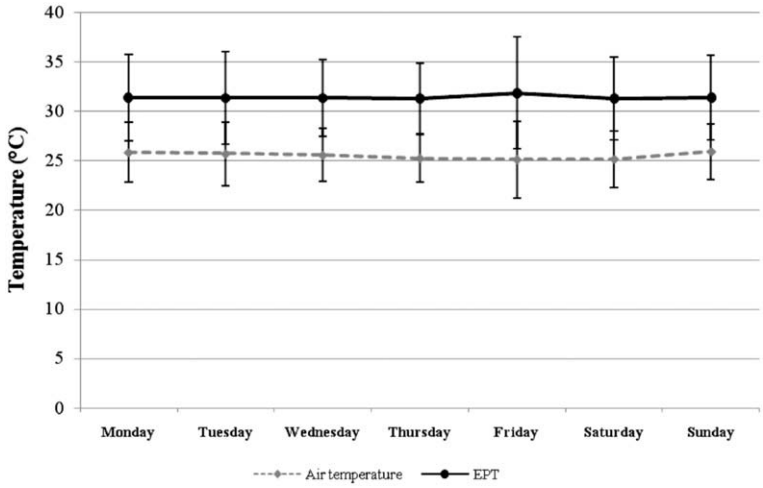

Fig. 2. Weekly distribution of air temperature and EPT.

PM_{10} is a measurement of the mass concentration of particulate matter smaller than 10 μm in suspension in the atmosphere. The comparison was extended also to the weekly variation of CBH, RH, air temperature, WBPT, DPT, EPT and the SO_2 concentration; (2) the thunderstorms were classified according to different levels of pollution (from 0 to 90 μg m^{-3} with bins of 10 μg m^{-3}) and the number of CG flashes and the maximum storm flash rates (in flashes per minute) were calculated for each storm, then averaged for three different ranges (0–30, 30–60 and 60–90 μg m^{-3}). Both methods rely on average values in order to reduce the large variability in the number of CG lightning counts.

2.1. Thermodynamic data

The following parameters were considered in the weekly analysis: CBH, RH, AT, WBPT, DPT and EPT. According to Williams et al. (2003), the CBH plays an important role in controlling the CAPE transformation into upward kinetic energy. In a simplified way, CBH can be represented by the following equation: $CBH = 122(T - Td)$, where T is the surface air temperature and Td is the dew point temperature (Williams, private communication). All data were provided by the São Paulo environment agency (CETESB) and were obtained by several automatic stations existing in the area (CETESB, 2005).

2.2. PM_{10} and SO_2 data

The PM_{10} and SO_2 data used in this work were also provided by CETESB. According to its annual report (CETESB, 2005), for the São Paulo metropolitan region, the automotive vehicles are the main sources of carbon monoxide (CO), total hydrocarbons (HC) and oxides of nitrogen (NO_X). The industrial processes are responsible for most of sulfur oxides (SO_X). Both vehicles and industrial activity are the main sources of inhalable particles or particulate matter (PM_{10}). In this work only the spring and summer seasons were analysed. In autumn and winter the pollution concentration tends to increase, mainly due to the

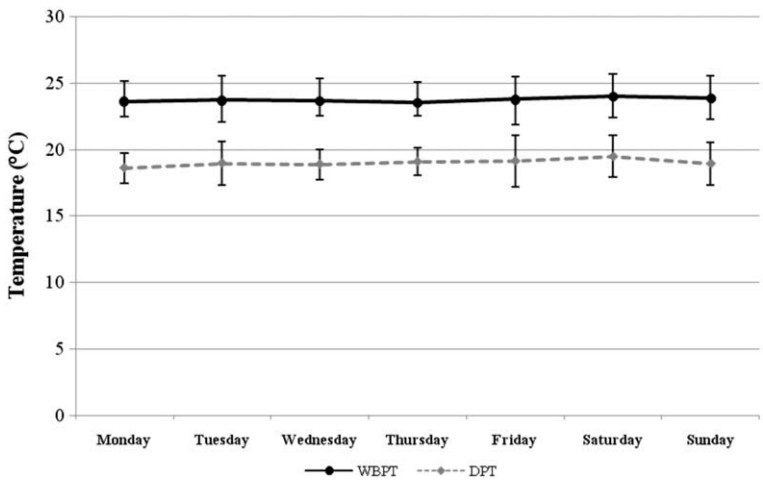

Fig. 3. Weekly distribution of WBPT and DP.

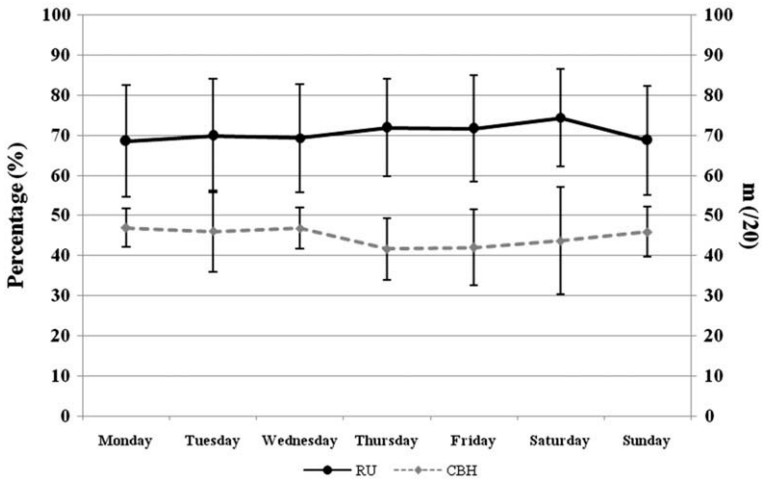

Fig. 4. Weekly distribution of RM and CBH.

increase of thermal inversions and the decrease of dispersion of pollutants by wet deposition compared to the spring and summer seasons.

The inclusion of SO_2 in the analysis was due to the results of some studies which suggest that increase in cloud condensation nuclei (CCN) activity can be related to the oxidation of SO_2 into sulfate inside the cloud droplets (Hobbs, 1993). The dissolved SO_2 oxidizes into sulfate ions, and the additional sulfate deposited on the particles makes them activate at super saturation levels smaller than that required to activate the original CCN. In the troposphere as a whole, the conversion of SO_2 into sulfate by clouds corresponds to a mechanism that consumes SO_2 at a rate 10 to 15 times higher than homogeneous oxidation in the gaseous phase (Hobbs, 1993).

3. Results and discussion

3.1. Weekly analysis

As already discussed, in order to reduce the large variability in the average number of CG flashes, the lightning data were converted into the number of days with lightning (NDL). Fig. 1 shows the NDL weekly distribution together with the distribution of the mean values of PM_{10} and SO_2. The weekly variation of air temperature and EPT is presented in Fig. 2, WBPT and DPT in Fig. 3 and RM and CBH in Fig. 4.

An analysis of all studied variables shows a decrease of about 17% in NDL during the weekend that is accompanied by a decrease of 19% and 11% respectively in the mean values of PM_{10} and SO_2, while the other variables do not show any effect during the weekend (Figs. 2–4). In order to verify this result, a correlation analysis was done for all variables. It was found that the only significant correlations were found between the NDL×PM10 (r=0.89) and between NDL×SO_2 (r=0.89). So, this analysis suggests that the CG lightning activity decreases as the pollution concentration decreases.

It is interesting to note that a recent totally independent analysis of intense rain events in the city of São Paulo (Alves Filho and Ribeiro, 2007) for almost the same period of this study found a decrease in the number of events during the weekend in agreement with the results of this work.

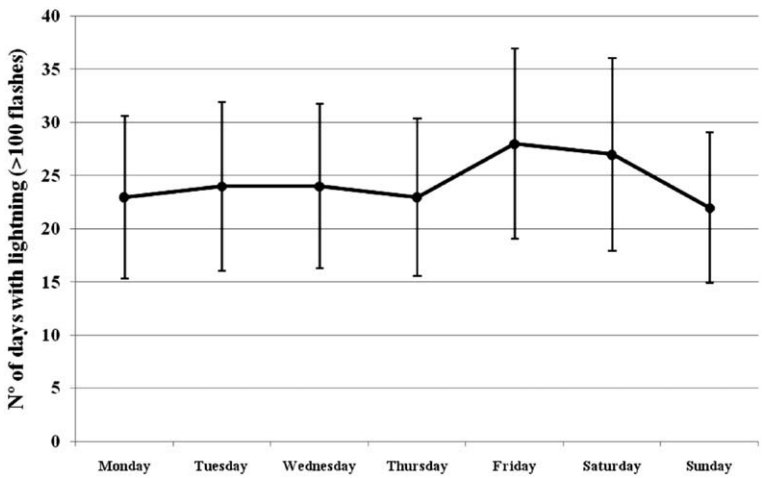

Fig. 5. Weekly distribution of the number of days with more than 100 flashes.

Then, it was verified whether the NDL with a large number of CG flashes (>100) also decreases during the weekend or not. Fig. 5 shows that it is not the case. This result agrees with the observations of Steiger et al. (2002), which showed that the enhancement in CG lightning activity over Houston is not associated with days with more than 100 flashes. This suggests that the urban effect on the CG lightning activity tends to be more evident for days with less than 100 flashes.

3.2. PM_{10} analysis

Fig. 6 shows average values for three different levels of PM_{10} concentration of the number of flashes per storm and the maximum storm flash rate. More than 400 individual thunderstorms per year were analyzed. An increase in the mean number of flashes per storm from the 0–30 μg m^{-3} range to the 30–60 μg m^{-3} range can be observed, then it remains almost constant from the 30–60 μg m^{-3} to the 60–90 μg m^{-3} ranges. Conversely, the average maximum storm flash rate did not present the same behavior for the same PM_{10} ranges. These results suggest the PM_{10} concentration (pollution), tends to increase the lifetime of the storms in MRSP and, in consequence, the number of flashes per storm, and not the flash rate.

4. Conclusions

A decrease in the number of days with lightning (NDL) in the weekend over the São Paulo metropolitan area was verified, apparently associated with a decrease in the PM_{10} and SO_2 concentrations. This fact is supported by the almost constant behavior of the thermodynamic variables through the week. It was also verified that the NDL with a large number of CG flashes (>100) did not decrease during the weekend, in agreement with the results of Steiger et al. (2002) over Houston.

Also, it was observed that the average values of the number of CG flashes for three different ranges of PM_{10} concentrations (0–30, 30–60 and 60–90 μg m^{-3}) increase from the first to the second range considering more than 2500 thunderstorms. Conversely, the average maximum storm flash rate did not present the same behavior for the same PM_{10} ranges. These results suggest the PM_{10} concentration (pollution), tends to increase the lifetime of the storms in MRSP and, in consequence, the number of flashes per storm, and not the flash rate.

The above results are in agreement with the results found by Alves Filho and Ribeiro (2007), who suggested that the high pollutant concentration in the São Paulo metropolitan

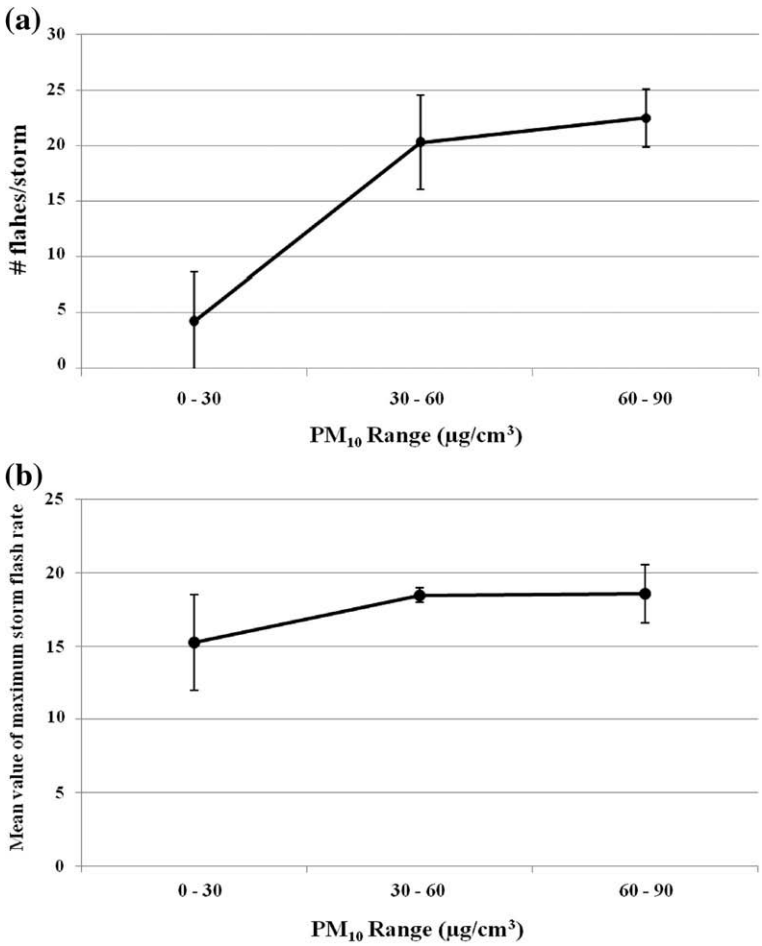

Fig. 6. Average values for three different levels of PM10 concentration of (a) the number of flashes per storm and (b) the maximum storm flash rate.

area intensifies the rain formation during the week in comparison to the weekend days.

Finally, considering that the enhancement in the CG lightning activity in São Paulo is larger than a factor of two with respect to the surroundings (Naccarato et al., 2003), the results also suggest that the role of the PM_{10} concentration in the enhancement in the overall CG lightning activity in São Paulo is less relevant than the urban heat island effect.

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