On the sensitivity of cloud-to-ground lightning activity to surface air temperature changes at different timescales in São Paulo, Brazil

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Received 19 January 2008; revised 18 June 2008; accepted 7 July 2008; published 31 October 2008.

[1] This paper presents a study about the sensitivity of cloud-to-ground (CG) lightning activity to changes in surface air temperature at daily, monthly, yearly, and decadal timescales in the city of São Paulo (Brazil). Lightning data collected in the city by the Brazilian Lightning Detection Network (BrasilDat) from 1999 to 2006 and thunderstorm day data obtained from 1951 to 2006 were analyzed and compared with surface air temperature data. The lightning activity increases significantly with increasing temperature, with a sensitivity of approximately 40% per 1°C for daily and monthly timescales and approximately 30% per 1°C for decadal timescale. For the yearly timescale, the increase is not statistically significant. The lower sensitivity for the decadal timescale suggests that the lightning sensitivity to changes in surface air temperature decreases for larger timescales, in agreement with what is expected on the basis of convective adjustment. The decadal lightning sensitivity found in this study is in reasonable agreement with the increase in the global lightning activity estimated by most climate models. The study is the first to investigate in detail this relationship in a large urban area inside the tropics and should contribute to the effort to understand the impact of the global warming on lightning activity.

Citation: Pinto, O., Jr., and I. R. C. A. Pinto (2008), On the sensitivity of cloud-to-ground lightning activity to surface air temperature changes at different timescales in São Paulo, Brazil, *J. Geophys. Res.*, *113*, D20123, doi:10.1029/2008JD009841.

1. Introduction

[2] Even though lightning activity is a result of nonlinear microphysical and thermodynamical processes acting through the entire troposphere and affected by many meteorological variables, it is well established that it is sensitive to variations in the surface air temperature at many temporal scales [*Williams*, 1992, 1994, 1999, 2005; *Price*, 1993; *Markson and Price*, 1999; *Reeve and Toumi*, 1999; *Price and Asfur*, 2006b; *Sekiguchi et al.*, 2006; *Markson*, 2007].

[3] In terms of temporal scales, lightning is generally more prevalent on average in the afternoon than at night and in the summer than in the winter, in direct response to variation in the solar insolation. It is also generally expected that global lightning activity tends to increase at the climate scale in response to global warming [*Williams*, 1992]. However, at present there do not appear to be any long-term trends in the lightning activity [*Price and Asfur*, 2006b; *Markson*, 2007], although many recent studies indicate a high positive correlation between surface air temperature and lightning activity [*Williams*, 2005; *Price and Asfur*, 2006a; *Sekiguchi et al.*, 2006]. The lack of known long-term trends in the lightning activity may explain why there is no specific reference to future changes in lightning activity in the last *Intergovernmental Panel on Climate Change* [2007] report. The reasons for not finding long-term trends in the global lightning activity, if it exists, may be the nonuniformity of the data sets available and/or a low sensitivity of the global lightning activity to global warming. The low sensitivity could be attributed to the difference between the spatial distribution of the global lightning activity, which indicates that lightning is on average considerably more frequent in the tropics than in the temperate and polar regions, and of the global warming, which is more pronounced at high latitudes [*Intergovernmental Panel on Climate Change*, 2007]. If on the one hand no trends are observed in experimental data, on the other hand most climate models predict an increase in the lightning activity [*Price and Rind*, 1994; *Schumann and Huntrieser*, 2007].

[4] In a global perspective, the lightning sensitivity to changes in global surface air temperature has been estimated from the analysis of lightning data obtained by satellites [*Reeve and Toumi*, 1999; *Ma et al.*, 2005], lightning-related thunderstorm day records [e.g., *Changnon*, 1988; *Changnon*, 2001], lightning-related upper-tropospheric water vapor [*Price and Asfur*, 2006a], lightning-related global atmospheric circuit ionospheric potential [*Markson*, 2007; *Williams*, 2007] and lightning-dominated Schumann resonance intensity changes [*Williams*, 1992; *Sekiguchi et al.*, 2006]. However, the observational analyses are limited by

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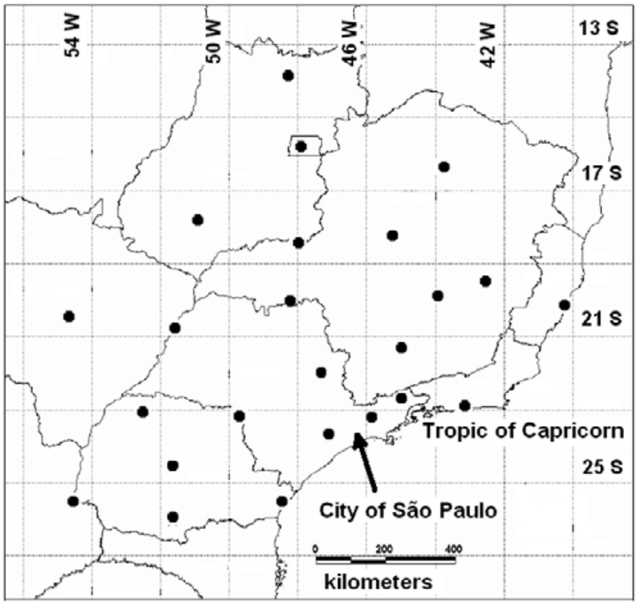

Figure 1. Map of Brazil indicating the configuration of BrasilDat network for the period of the study and the approximate location of the city of São Paulo.

the still short periods of the order of one decade (satellite lightning data and Schumann resonance data), the low accuracy of data over an extended period (thunderstorm days and upper tropospheric water vapor data) and to the weaker sensitivity of the data to lightning changes (ionospheric potential data). The lightning sensitivity to changes in global surface air temperature can also be estimated from global general circulation models of the atmosphere [e.g., *Price and Rind*, 1994], assuming an empirical relationship between lightning activity and a model parameter. However, the models still have many limitations. For instance, the models should be capable of considering high spatial resolution to resolve convective activity and to include atmosphere-ocean and photochemical-related processes. In addition, they also need to include detailed surface emissions and height-dependent meteorological fields. At the present time, however, many of these aspects are not well established. For instance, there is a lack of more complete information about the NOx production by different sources and tropospheric meteorological data, mainly in the tropical region [*Intergovernmental Panel on Climate Change*, 2007]. Such limitations cause a considerable variation in the predictions of such models, so that no definitive conclusions concerning the future impact of global temperature changes on the lightning activity can be reached. Finally, the lightning sensitivity to changes in global surface air temperature can also be estimated on the basis of physical arguments [*Williams*, 2005]. They suggest that a weaker sensitivity of global lightning at longer timescales in response to a convective adjustment, based on the assumption that for larger timescales the increase in the surface air temperature can be communicated to the temperature aloft, causing a lesser change in the convective available potential energy (CAPE). But the global response is an integration of local responses, and so it is important to thoroughly understand the local response.

[5] In a local perspective, in turn, the temporal variations of the lightning activity can be as complex, since local aspects may be as important as global aspects. Many local aspects could be important, among them changes in the local circulation of air masses in response to teleconnections, such as El Niño-related processes, and changes related to urban effects, such as heat island directly related to the nature of the surface and its response to solar radiation and pollution [*Steiger et al.*, 2002; *Naccarato et al.*, 2003]. These aspects may affect differently the lightning activity mainly at short timescales (less than one decade), though convective adjustment is taking place.

[6] In this paper cloud-to-ground (CG) lightning data collected by the Brazilian Lightning Detection Network (BrasilDat) from 1999 to 2006 and thunderstorm day data from 1951 to 2006 were analyzed to investigate the lightning sensitivity to changes in surface air temperature in the city of São Paulo, Brazil. This region was chosen for two reasons: first, the very high lightning activity in the city (a large area with flash densities above 11 flashes km^{-2} a^{-1} and a peak flash density of 17 flashes km^{-2} a^{-1}); and second, the observed and documented increase in the surface air temperature in the last decades [*Cabral and Funari*, 1997]. Both aspects are apparently related to the existence and growth of the large urban area of São Paulo in recent decades and the heat island effect associated with it [*Naccarato et al.*, 2003], although they may also be partially related to global temperature changes. Similar aspects have been observed in Hong Kong (Hong Kong Observatory, Global warming: The Hong Kong connection (1 August 2003), press release, available at http://www.weather.gov.hk/wxinfo/news/2003/pre0801e.htm).

2. Lightning and Temperature Data

[7] Data from the Brazilian Lightning Detection Network (BrasilDat) from 1999 to 2006 in the city of São Paulo were used in this analysis to investigate the temporal sensitivity of lightning activity to changes in surface air temperature at the daily, monthly and yearly timescales. Data were corrected with a model for detection efficiency to account for changes in the network configuration during the period of analysis, even though for the region of the city of São Paulo such changes produced very small variations in the detection efficiency. The network consists basically of several sensors, which determine the angle to the lightning stroke at the sensor location and/or the time of the lightning event, and a processing unit, which calculates stroke characteristics like the strike point location, time, polarity, and estimates of the peak current. For a comprehensive description of lightning location techniques, see for example, *Cummins et al.* [1998a, 1998b] and *Rakov and Uman* [2003].

[8] Figure 1 shows the configuration of the BrasilDat network for the period of this analysis and the approximate location of the city of São Paulo, where the present analysis

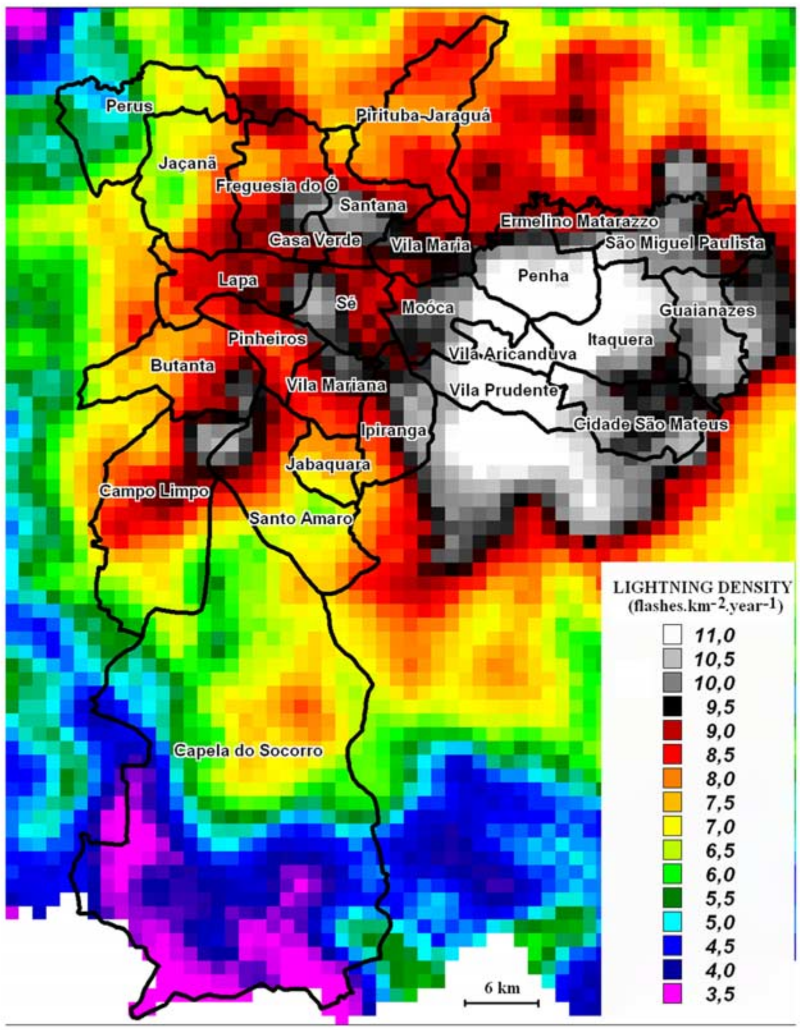

Figure 2. Map of the yearly mean values of lightning density (in flashes km^{-2} a^{-1}) in the city of São Paulo for a spatial resolution of 1 km × 1 km for the period of the study. The regions in white represent values of flash density larger than 11 flashes km^{-2} a^{-1}, while regions in purple represents values of flash density lower than 3.5 flashes km^{-2} a^{-1}. Also indicated (by blue symbols) are the locations of the meteorological stations, from which temperature data used in the study were obtained.

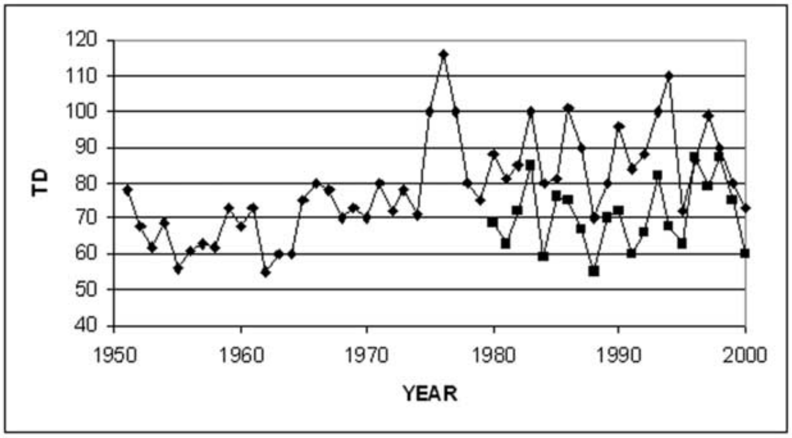

Figure 3. Comparison of thunderstorm days (TD) time series from two stations in the city of São Paulo.

was performed. Additional details about BrasilDat are given by *Pinto* [2003, 2005], *Pinto and Pinto* [2003], *I.R.C.A. Pinto et al.* [1999], and *O. Pinto et al.* [1999, 2003, 2006a, 2006b, 2007].

[9] Figure 2 shows a map of the mean lightning density in the city of São Paulo for a spatial resolution of 1 km × 1 km during the period of the study. The regions in white in Figure 2 represent values of flash density larger than 11 flashes km^{-2} a^{-1}, while regions in purple represents values of flash density lower than 3.5 flashes km^{-2} a^{-1}.

[10] For the decadal timescale, since no lightning data from BrasilDat are available, observations of lightning-related thunderstorm days (TD) were used to investigate the temporal sensitivity of lightning activity to surface air temperature changes. Although this type of data is known to have lower reliability than lightning data from lightning location networks [*Changnon*, 2001], it is available for a longer time period. Also, since they are obtained by a simple and well-defined procedure, no appreciable changes over time are expected. TD data were obtained from two different stations: the Guarulhos aerodrome surface meteorological station in the city of São Paulo from 1980 to 2000 [*Nogueira Filho et al.*, 2002], and the University of São Paulo station from 1951 to 2006 [*Morales et al.*, 2008]. The two time series are shown in Figure 3. The comparison of both TD time series for the period from 1981 to 2000 shows consistent features. The data from the University of São Paulo for five decades were used in the direct comparison with the temperature data.

[11] The temperature data used in the analysis were obtained from two different surface meteorological stations in the city of São Paulo, located at Água Funda and Mirante de Santana [*Cabral and Funari*, 1997]. The locations of the stations are included in Figure 2. From 1951 to 2000 annual means for both stations, shown in Figure 4, were used. From 1999 to 2006 daily means for both stations were used. The agreement between the two data sets is very good and both show a slow increase with time. Because the data from Mirante de Santana station are limited to 1951 to 1995, however, only data from Água Funda station were considered in the analysis. The temperature data for the Água Funda station after 1995 were also validated comparing them with data from other

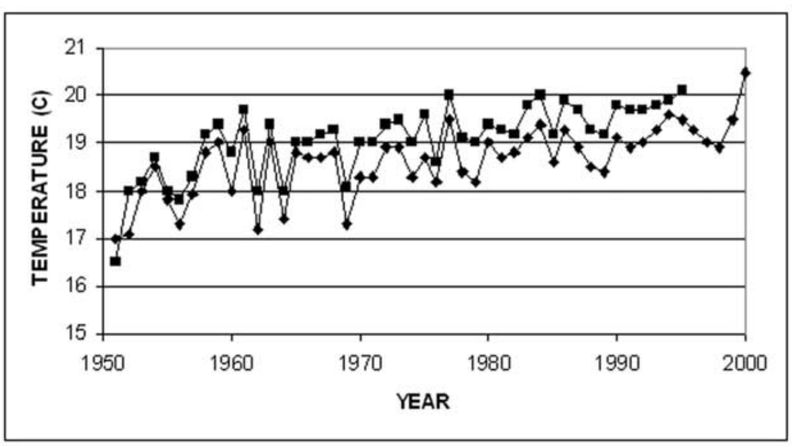

Figure 4. Comparison of temperature data for two meteorological stations in the city of São Paulo.

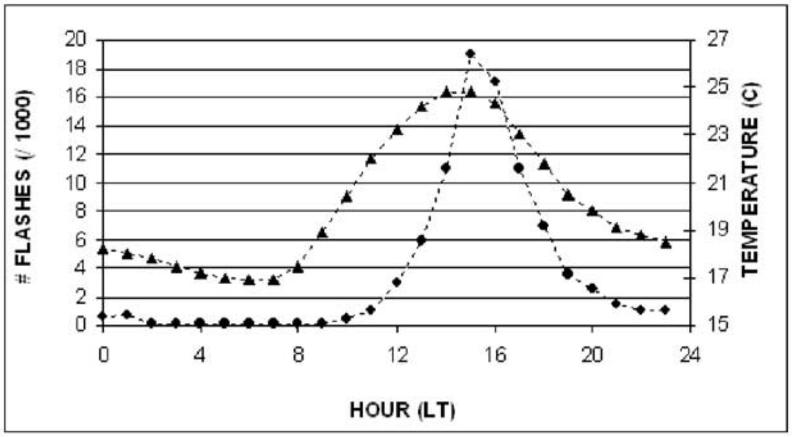

Figure 5. Hourly mean numbers of flashes observed by BrasilDat (circles) and hourly mean surface air temperatures (triangles) from 1999 to 2006 in the city of São Paulo.

stations [*Companhia de Tecnologia de Saneamento Básico* (*CETESB*), 2005]. Throughout the analysis the standard deviations in the temperature data were neglected since they are much lower than those associated with lightning and lightning-related data.

3. Results

3.1. Daily Variation of Lightning Activity

[12] Figure 5 shows the hourly mean numbers of flashes observed by BrasilDat and the hourly mean surface air temperatures from 1999 to 2006 in the city of São Paulo. Both variables show the typical daily variation with higher values during afternoon and lower values during the morning.

[13] Figure 6 shows the relationship between the hourly mean numbers of flashes detected by BrasilDat and the hourly mean surface air temperatures in the city of São Paulo from 1999 to 2006. A linear fit and its squared correlation coefficient are indicated in Figure 6, as well as the standard deviations associated with the hourly mean numbers of flashes. The correlation is significant as tested by the nonparametric Spearman test ($\rho < 0.001$). From the derivative of equation obtained from linear fit and the mean flash rate, the mean increase in the number of flashes with temperature is found to be 42% per 1°C of temperature.

3.2. Monthly Variation of Lightning Activity

[14] Figure 7 shows the monthly mean numbers of flashes observed by BrasilDat (divided by 1000) and the monthly mean surface air temperatures from 1999 to 2006 in the city of São Paulo. The monthly mean numbers of flashes were obtained by averaging the monthly numbers of flashes for each year. Both variables in Figure 7 show the typical seasonal variation with

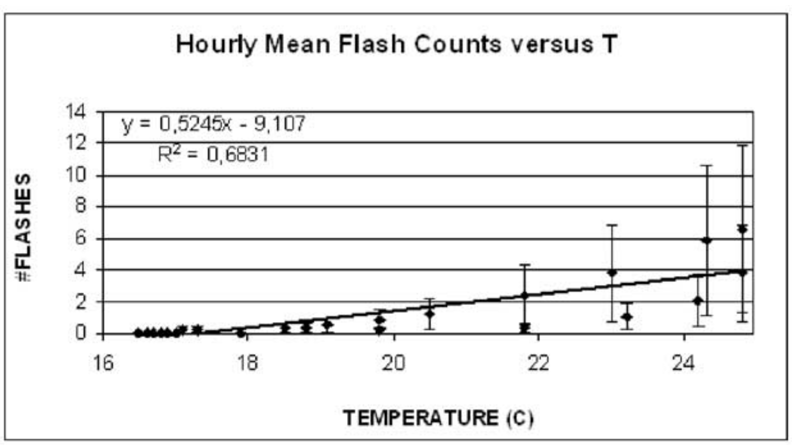

Figure 6. Relationship between hourly mean numbers of flashes observed by BrasilDat and the hourly mean surface air temperatures from 1999 to 2006 in the city of São Paulo. A linear fit and its squared correlation coefficient are indicated, as well as the standard deviations associated with the hourly mean numbers of flashes.

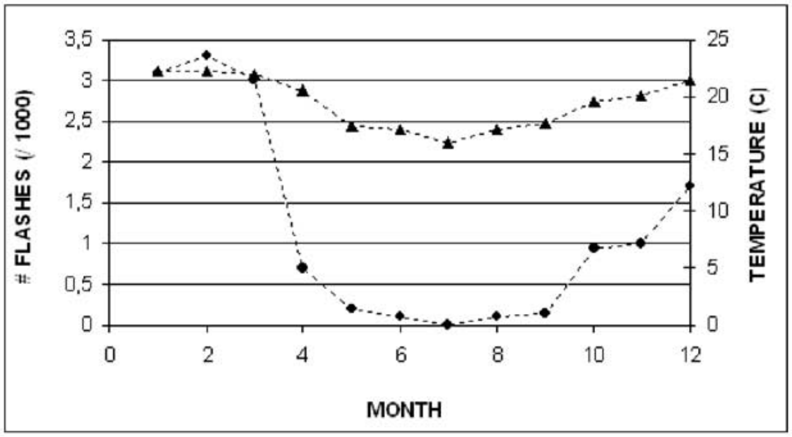

Figure 7. Monthly mean numbers of flashes observed by BrasilDat (divided by 1000) (circles) and monthly mean surface air temperatures (triangles) from 1999 to 2006 in the city of São Paulo.

higher values during the summer and lower values during the winter, with intermediate values at the other seasons.

[15] Figure 8 shows the relationship between the monthly mean numbers of flashes (divided by 1000) detected by BrasilDat and the monthly mean surface air temperatures in the city of São Paulo from 1999 to 2006. A linear fit and its squared correlation coefficient are indicated in Figure 8, as well as the standard deviations associated with the monthly mean numbers of flashes. The correlation is significant as tested by a nonparametric Spearman test ($\rho < 0.001$). From the linear fit, the mean increase in the number of flashes with temperature is 42% per 1°C of temperature, the same value obtained for the daily variation.

3.3. Yearly Variation of Lightning Activity

[16] Figure 9 shows the yearly numbers of flashes observed by BrasilDat (divided by 1000) and the yearly mean surface air temperatures from 1999 to 2006 in the city of São Paulo. A reasonable agreement can be observed between the two variables.

[17] Figure 10 shows the relationship between the yearly mean numbers of flashes (divided by 1000) detected by BrasilDat and the yearly mean surface air temperatures in the city of São Paulo from 1999 to 2006. A linear fit and its square correlation coefficient are indicated, as well as the standard deviations associated with the yearly mean numbers of flashes. In contrast with the hourly and monthly analyses, the correlation in this case is not statistically significant as tested by the nonparametric Spearman test ($\rho = 0.68$). An attempt was also done to address the yearly analysis considering only the month with peak activity or the months when the lightning activity is substantial (October to April). Although such approaches are physically attractive, the

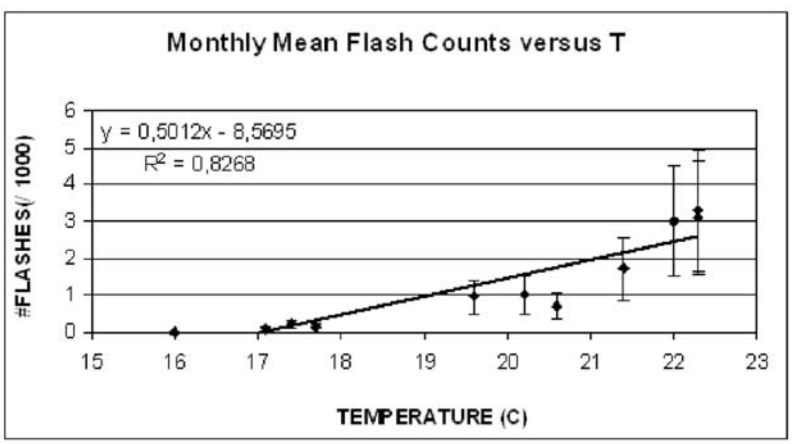

Figure 8. Relationship between the monthly mean numbers of flashes (divided by 1000) detected by BrasilDat and the monthly mean surface air temperatures in the city of São Paulo from 1999 to 2006. A linear fit with and its squared correlation coefficient are indicated, as well as the standard deviations associated with the monthly mean numbers of flashes.

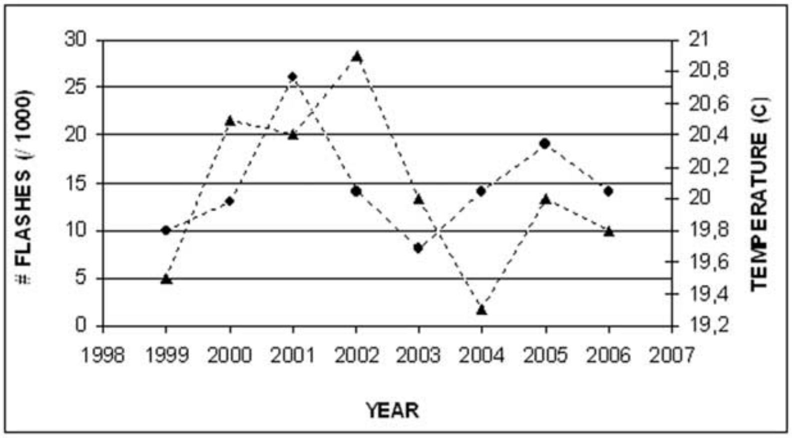

Figure 9. Yearly mean numbers of flashes observed by BrasilDat (divided by 1000) (circles) and yearly mean surface air temperatures (triangles) from 1999 to 2006 in the city of São Paulo.

correlation between the yearly mean numbers of flashes and yearly mean surface air temperatures remained not statistically significant.

[18] The lack of correlation in this case may be due to the small data sample and/or to the action of many other factors related to the general circulation of the atmosphere driving the yearly lightning activity.

3.4. Decadal Variation of Lightning Activity

[19] In contrast with the other timescales, the decadal variation of lightning activity can be assessed only from TD data. Figure 11 shows the decadal TD values and the decadal mean surface air temperatures from 1950 to 1990 decades in the city of São Paulo. Again, it can be observed a reasonable agreement between both variables.

[20] In order to estimate the decadal increase in the number of flashes per 1°C of temperature, it is necessary to convert the TD values to number of flashes. In general, these variables are related by a power law equation of the type [e.g., *Rakov and Uman*, 2003; *Schulz et al.*, 2005]:

$$N = \mathrm{a\ TD}^{\mathrm{b}},$$

where N is the number of flashes or flash density and "a" and "b" represents constants.

[21] In the calculation of "b," values of TD and of the number of flashes from 1999 to 2006 (the only period in which data for both variables are available) were fitted to the equation above. Then, the TD values were converted to number of flashes. Figure 12 shows the relationship between the decadal mean numbers of flashes (divided by 10,000) and the decadal mean surface air temperatures in the city of São Paulo from the 1950 to 1990 decades. A linear fit and its squared correlation coefficient are indicated, as well as the standard deviations associated

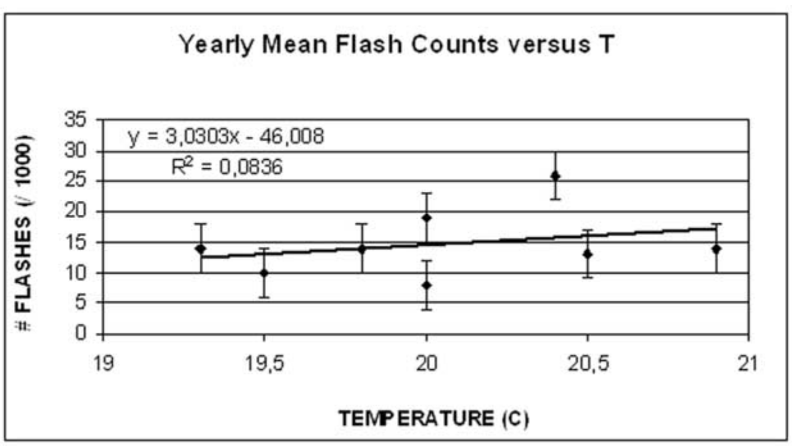

Figure 10. Relationship between yearly mean numbers of flashes (divided by 1000) and yearly mean surface air temperatures from 1999 to 2006 in the city of São Paulo. A linear fit and its squared correlation coefficient are indicated, as well as the standard deviations associated with the yearly mean numbers of flashes.

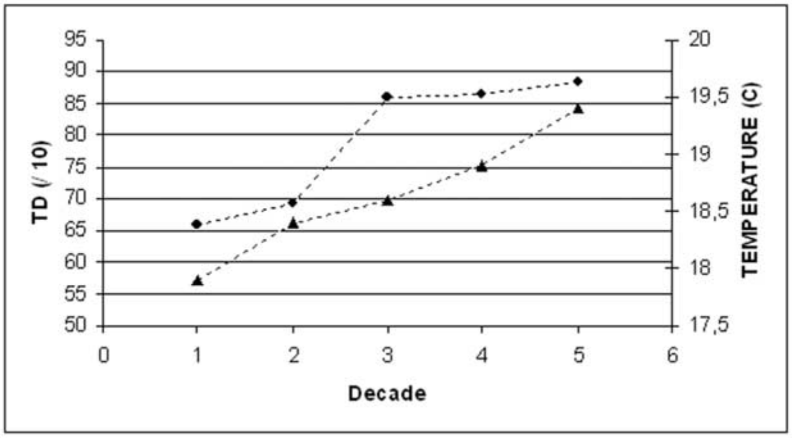

Figure 11. Relationship between the decadal thunderstorm days (TD) values (circles) and decadal mean surface air temperatures (triangles) for the decades of 1950 to 1990 in the city of São Paulo.

with the decadal mean numbers of flashes. The correlation is significant as tested by the nonparametric Spearman test (ρ < 0.001). From the linear fit, the mean increase in the number of flashes with temperature is 30% per 1°C of temperature.

4. Discussion and Conclusion

[22] Recently, *Williams* [1999] has made a comprehensive review on the sensitivity of the global lightning activity to variations in the global surface air temperature at many temporal scales. After reviewing the scarce information available on this topic he suggested that the lightning sensitivity to temperature appears to diminish at longer timescales. The suggestion was based mainly on lightning-related information and not on quantitative lightning data, mainly for longer timescales. *Williams* [1999, 2005] claimed that this behavior might be explained by convective adjustment, although it is worth noting that when the surface air temperature increases, the upper air temperature also increases, so that the simultaneous change may result in no increase in instability (if CAPE is invariant), or even in a decrease in instability (if CAPE should decrease).

[23] This study is the first to investigate in detail the sensitivity of CG lightning activity on surface air temperature changes at different timescales in a large urban area (the city of São Paulo). The results show that the lightning activity increases significantly with increases in the temperature, with sensitivity of approximately 40% per 1°C for the daily and monthly timescales and of approximately 30% per 1°C for the decadal timescale. For the yearly timescale, the results are not statistically significant, probably due to the small data sample and/or the action of many other factors related to the general circulation of the atmosphere affecting the yearly lightning activity. The lower sensitivity for the decadal timescale suggests that the lightning sensitivity to surface air temperature decreases for longer timescales in the city of São Paulo,

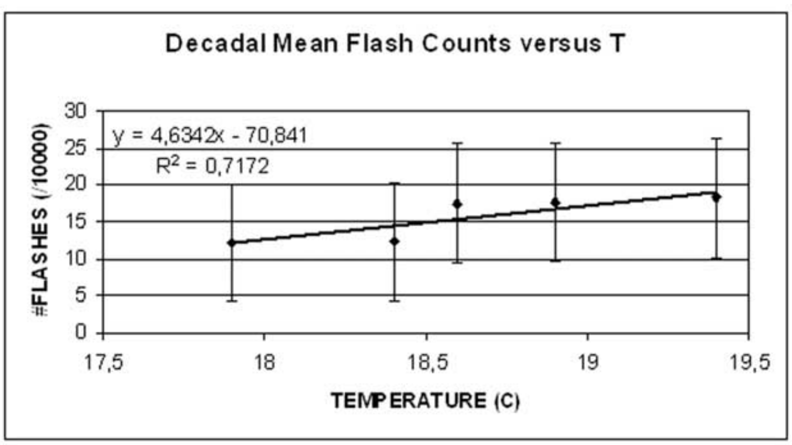

Figure 12. Relationship between the decadal mean numbers of flashes (divided by 10,000) and the decadal mean surface air temperatures in the city of São Paulo for the decades 1950 to 1990. A linear fit and its squared correlation coefficient are indicated, as well as the standard deviations associated with the decadal mean numbers of flashes.

in agreement with what is expected on the basis of convective adjustment [*Williams*, 2005].

[24] It is worth mentioning that the decadal lightning sensitivity of 30% per 1°C found in this study is in reasonable agreement with the increase in the global lightning activity estimated by most climate models (for a review, see *Schumann and Huntrieser* [2007]).

[25] **Acknowledgments.** The authors would like to thank FAPESP (grant 03/08655-4) and CNPq for supporting this research and Earle Williams from MIT for many useful discussions.

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