JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES, VOL. 118, 5231–5246, doi:10.1002/jgrd.50282, 2013

A study of the long-term variability of thunderstorm days in southeast Brazil

O. Pinto Jr.,[1] I. R. C. A. Pinto,[1] and M. A. S. Ferro[2]

Received 30 August 2012; revised 23 January 2013; accepted 18 February 2013; published 10 June 2013.

[1] In this report thunderstorm day monthly records obtained in three cities of southeast Brazil (São Paulo, Campinas, and Rio de Janeiro) since the 19th century are analyzed. The analysis is complemented by the spatial distribution of lightning in the last decade. For São Paulo and Campinas, data indicate a significant increase in thunderstorm activity during the period from the end of the 19th century to the present, simultaneously to an increase in the surface temperature well correlated to the population growth of the cities. This result did not match anything expected from natural climate cycles and gives strong observational evidence for the anthropogenic influence on the thunderstorm activity. For Rio de Janeiro, data did not show a significant positive trend from the middle of the 19th century to the present in spite of the increase in the surface temperature, suggesting that variations are most probably a result of a complex combination of local and large-scale features. In addition, a statistical analysis of the data after 1951 shows that a significant increase (by a factor of 3.7) in the thunderstorm activity in Rio de Janeiro occurs for the simultaneous occurrence of a positive anomaly of the South Atlantic sea surface temperature and La Niña, compared to the simultaneous occurrence of a negative anomaly and El Niño, even though no significant variation was found when each large-scale phenomena occurs isolated. The same occurs for São Paulo and Campinas, although with a lower amplitude.

Citation: Pinto, O., Jr., I. R. C. A. Pinto, and M. A. S. Ferro (2013), A study of the long-term variability of thunderstorm days in southeast Brazil, *J. Geophys. Res. Atmos.*, *118*, 5231–5246, doi:10.1002/jgrd.50282.

1. Introduction

[2] Thunderstorms are part of a complex weather system that varies on all time scales, from years to decades to millennia to millions of years [*Jones and Mann*, 2004]. Thunderstorm climate variability can arise from a number of factors. In consequence, our ability to predict future climate changes in the thunderstorm activity depends on a better understanding of the climate system as a whole and the external factors that could be involved such as volcanic eruptions and solar variations, and human-induced changes in atmospheric composition. Such an understanding can only be achieved through a greater ability to document and explain observed past variations. The study of thunderstorm occurrence changes offered the opportunity to gain a better understanding of atmospheric electricity. Also, the possibility that, as global warming continues to evolve, increasing evidence of thunderstorm changes are found, will help the understanding of the climate system, because thunderstorms as ice factories play a key role in the vertical redistributors of the most important greenhouse substance—water vapor [*Price*, 2009; *Williams and Sátori*, 2004].

[3] At the present time, no direct or even indirect evidences of a global increase in the thunderstorm activity exist in response to the mean global temperature increase, although positive trends are observed in specific areas where larger temperature increases than the global increase are observed [*Pinto and Pinto*, 2008; *Williams*, 2009; *Pinto*, 2009]. In the tropics the current trend in global warming is less by a factor of four (0.1°C per decade) than at higher latitudes (0.4°C per decade), particularly in the Northern Hemisphere [*Trenberth et al.*, 2007]. This aspect tends to minimize any kind of response of global thunderstorm activity to global warming, because most thunderstorms on Earth occur in the tropical region [*Christian et al.*, 2003; *Pinto*, 2009].

[4] The goal of this article is to present and discuss the past observations of thunderstorms or thunder days (TD) at three different large cities in the southeast region of Brazil: São Paulo, Campinas and Rio de Janeiro. Data for more than 100 years for these three cities were considered to better identify long (decadal) climate changes in opposition to short annual changes. The data are complemented by network-based lightning observations in the last decade in terms of the spatial distribution of thunderstorms in this region.

---

[1] Atmospheric Electricity Group (ELAT), National Institute of Space Research, S. J. Campos, São Paulo, Brazil.

[2] Aeronautic and Space Institute (IAE/CTA), S. J. Campos, São Paulo, Brazil.

Corresponding author: O. Pinto Jr., Atmospheric Electricity Group (ELAT), National Institute of Space Research, S. J. Campos, São Paulo, 12227–010, Brazil. (osmar@dge.inpe.br, iara@dge.inpe.br)

2169-897X/13/10.1002/jgrd.50282

2. Basic Considerations

[5] Changes in the thunderstorm activity at decadal time scales can only be identified in thunderstorm day records, because other type of observations by satellite (infrared/visible images or optical lightning sensors) and lightning location systems [*Pinto*, 2009] are restricted to a few decades, making the decadal variability unresolved in these observations. Even most thunderstorm day records, mainly in the tropics, are limited to less than 50 years [e.g., *Nechet*, 1994; *Nathou and Hicks*, 2006], restricting their capability to conclusively identify long decadal climate changes. A thunderstorm day is defined as a day during which thunder is heard at least once at a given location. The practical range of audibility of thunder is about 15 km, the maximum range of audibility being typically about 25 km [*Rakov and Uman*, 2003]. The possible causes of decadal changes in thunderstorms include: (a) natural (non–man-induced) variations, (b) anthropogenic (man-induced) variations in the atmosphere, and (c) observational limitations.

[6] Natural decadal variations in thunderstorm activity are in general related to changes in the general circulation of the atmosphere that it is ultimately responsible for temporal variations in synoptic weather conditions that produce thunderstorms. In the southeastern part of Brazil, the prevailing synoptic condition associated with thunderstorm activity is the occurrence of cold fronts [*Cavalcanti and Kousky*, 2003]. Their frequency of occurrence is modulated by many mechanisms, among them the so-called South Atlantic Convergence Zone, a prominent band of cloudiness extending from the Amazon region to the subtropical Atlantic Ocean, passing over the southeastern region [*Carvalho et al.*, 2002], and by blocking anticyclones [*Wiedenmann et al.*, 2002], which in turn are influenced by large-scale phenomena such as the El Niño Southern Oscillation (ENSO) [*Barros et al.*, 2002; *Wiedenmann et al.*, 2002]. The circulation of the atmosphere is a result of dynamical processes controlled by many different aspects, in particular the coupled ocean-atmosphere processes. Among them, the most relevant to the atmospheric circulation and convection in the southeast region of Brazil are ENSO, related to the sea surface temperature (SST) of the equatorial Pacific Ocean, and the SST of the tropical South Atlantic Ocean that can be represented by the Tropical South Atlantic Index (TSA) [*Enfield et al.*, 1999]. The influence of ENSO on the precipitation/convection in southeastern Brazil has been discussed by many authors [*Grimm et al.*, 1998, 2000; *Coelho et al.*, 2002; *Liebmann et al.*, 2001; *Grimm*, 2003, 2004; *Vicente*, 2005; *Grimm and Natori*, 2006; *Sátori et al.*, 2009]. In turn, the influence of the SST of the South Atlantic Ocean on the precipitation/convection in southeastern Brazil has been studied only recently [*Liebmann et al.*, 2001; *Berri and Bertossa*, 2004; *Kayano et al.*, 2009]. These processes, in turn, may be modulated by the Pacific Decadal Oscillation (PDO) of the SST of the North Pacific Ocean [*Mantua and Hare*, 2002], the Atlantic Multidecadal Oscillation (AMO) of the SST of the North Atlantic Ocean [*Kerr*, 2000; *Schlesinger and Ramankutty*, 1994; *Chang et al.*, 1997; *Delworth and Mann*, 2000; *Andreoli and Kayano*, 2003; *Knight et al.*, 2005; *Rayner et al.*, 2006; *Chylek et al.*, 2011] and the tropical Atlantic dipole [*Servain*, 1991; *Enfield et al.*, 1999] and their interactions with the Hadley and Walker circulations. At this time, the physical reasons responsible for these decadal variation processes are incomplete [*Wang and Picaut*, 2004; *Seager et al.*, 2004]. The possible physical origin of PDO and AMO has been discussed by many authors [*Trenberth and Hurrell*, 1994; *Gershunov andBarnett*, 1998; *McPhaden and Zhang*, 2002; *Deser et al.*, 2004; *Goldenberg et al.*, 2001; *Sutton and Hodson*, 2005; *Trenberth and Shea*, 2006]. Also, the interaction among these processes is a relatively recent topic [*Saravanan and Chang*, 2000; *Kucharski et al.*, 2011] and there is no consensus if their variabilities are dynamically independent or result from ocean-atmosphere feedback mechanisms. Other relevant external natural aspects are volcanic eruptions and solar variations that may change the radiation balance of the Earth [*Trenberth et al.*, 2007] and, in consequence, the global circulation, although no published evidences of direct impact on the thunderstorm activity exist so far.

[7] Anthropogenic decadal variations in thunderstorm activity has been observed [*Kai-Hing*, 2003; *Pinto and Pinto*, 2008] and are supported by changes in precipitation [*Huff and Changnon*, 1973; *Changnon*, 1980] and lightning [*Westcott*, 1995; *Orville et al.*, 2001; *Steiger et al.*, 2002; *Naccarato et al.*, 2003; *Pinto et al.*, 2004; *Kar et al.*, 2009] over large urban areas. Most of these observations suggested that the urban heat island effect, associated with many physical differences between urban and rural areas, including absorption of sunlight, increased heat storage of artificial surfaces, obstruction of reradiation by buildings, absence of plant transpiration, differences in air circulation, and other phenomena [*Oke*, 1982; *Arnfield*, 2003], and the pollution (as condensation nuclei) affects the thunderstorm formation and its electrification processes. Their existence is also supported by large spatial-scale variations of the atmosphere conductivity [*Cobb and Wells*, 1970], precipitation [*Bell et al.*, 2008], lightning activity [*Bell et al.*, 2009; *Farias et al.*, 2011], and thunderstorm activity at regions subjected to large local warming [*Williams*, 2009], although other thunderstorm time series at high northern latitudes do not show the same behavior [*Gorbatenko and Dulzon*, 2001].

[8] Limitations in long time series of observations of any variable are subject to changes in the methods and/or changes in the boundary conditions related to the observations. In the case of thunderstorm day records, because they are man-made observations the main limitations are related to the method of definition of a thunder day, changes in the operational procedure adopted to make the observations and, finally, changes in the ambient conditions around the observational site that can influence the process or even the site location. Regarding the method of definition, almost all observations after 1897 consider a thunder day when observers hear, at any time of the day, thunder. Even before this year, such method was used, at least after the middle of the 19th century. In Brazil, this definition was adopted since the first continuous observations were made in the middle of the 19th century in the city of Rio de Janeiro. Earlier, short period observations made in this city in the end of the 18th century used another definition that considered a thunder day when observers see, at any time of the day, lightning, independently of heard thunder. For this reason, such observations are not considered anymore in this article. Changes in the operational procedure adopted to make the observations include a limited period of day in

which observations are made. In general, this limitation results in no observations during the period from midnight to about 0500. This brings to a false lowering of thunder day frequency. The influence of this aspect is strongly dependent on the daily distribution of thunderstorms in a given region, which is related to the predominant type of thunderstorm in this region. In the case of the southeast region of Brazil, these systems are: isolated and frontal system-related storms. In such type of systems thunderstorms beginning during this period of the day are very rare, what can be inferred from lightning occurrence in this period (9%) with respect to the complete day in the last decade [*Naccarato*, 2006]. For the last 20 years, satellite observations in South America (see http://www.cptec.inpe.br) did not show any evidence of change in these types of systems in the southeast region Brazil. Also, climatological data in the last century suggest that this pattern did not change [*Neto*, 2005]. Therefore, based on our present knowledge there is no reason to expect that the number of flashes in the morning hours have significantly changed along the time. In turn, the main aspect related to changes in the ambient conditions around the observational site that can influence the process is the increase in the noise level in observational site related to anthropogenic activity. This is more pronounced in sites located inside cities that have a large increase through the years. For the study reported in this research, the three cities considered have grown considerably during the period of the analysis. In consequence, this influence cannot be disregarded, mainly for the cities of São Paulo and Campinas. For Rio de Janeiro, this aspect is minimized by the fact that the observational site is located near the ocean. The increase in the noise level tends to reduce the maximum distance in which the observer heard thunder, reducing in consequence the number of thunder days recorded. Therefore, although it is difficult to estimate this effect quantitatively, it would tend to produce a negative trend in the thunder days records if no other effects were considered. This negative trend would be more evident mainly after 1950 in Sao Paulo and Campinas. Finally, changes in the site location even by a few kilometers may affect the observations, because the noise level may in a worst case be considerably different or the elevation of the site may be different. For the cities considered in this study, this aspect only applies to the city of São Paulo, where during the period of study small changes occurred in the location of the observation site. However, the comparison of data for two different sites after 1950 indicated very well correlated changes.

[9] Thunderstorms are extreme events very localized in space and associated with a complex chain of physical and even chemical processes occurring in the atmosphere at different time and space scales, so that the thunderstorm day records in a given location may not necessarily reflect the variations in a large region around this location or even the globe. In consequence, observations at multiple locations are in general required to obtain more significant results.

[10] The most comprehensive study about long-term historical data on thunderstorm-day frequencies was done by *Changnon and Hsu* [1984] using data obtained from 1901 to 1980 collected from 90 weather stations throughout North America, and 131 other stations scattered around the world. The goal of the study was to describe the statistical properties and the climatological rationale of their seasonal and annual fluctuations, with emphasis given to data in North America. The results of the study indicated that in North America the number of thunderstorm days increased by 15% from 1901 to 1930s and then decrease by 10% from 1940 to 1980, with a sharp increase in the 1970s. All stations above 50°N (including those outside North America) showed a positive trend in the period after 1970. In the study, the only stations in the tropics were located in Australia and Zambia and have data restricted to short periods (less than four decades in Australia and less than two decades in Zambia). No stations in Brazil were considered in the study.

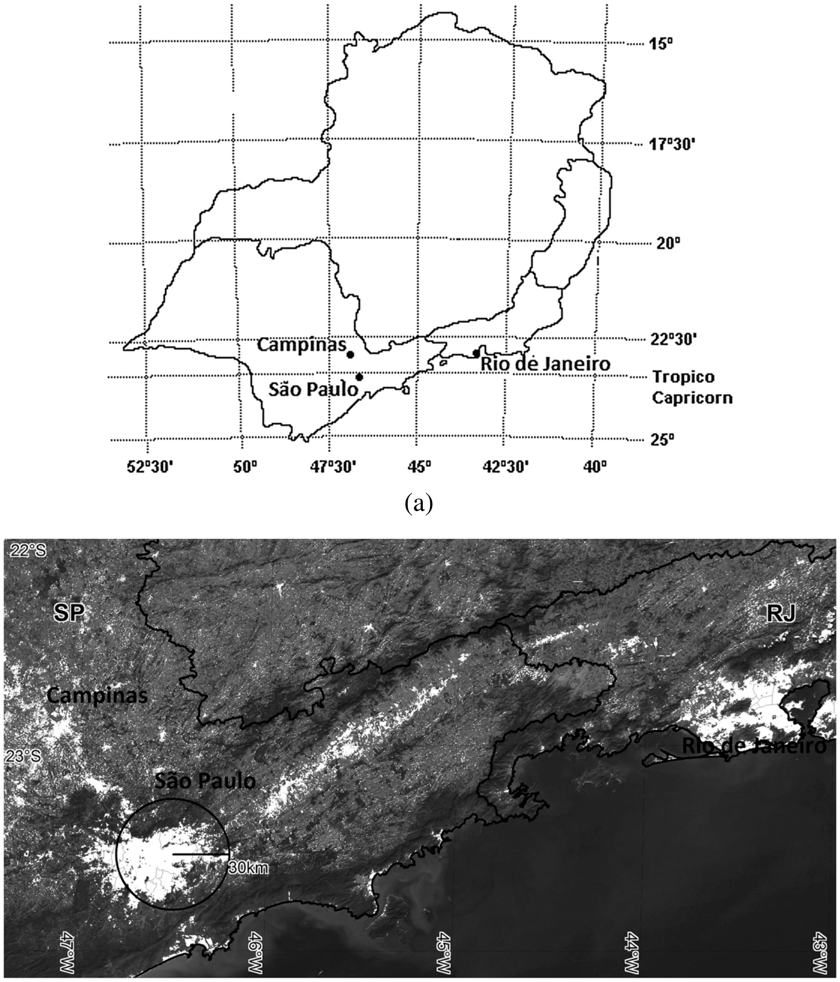
3. Thunderstorm Day Observations in Southeast Brazil

3.1. Background Data

[11] From the careful analysis of thunderstorm day data obtained from several cities in southeastern Brazil, we found that only the three cities have reliable data before 1951, the year when TD started to be collected by the airports. Figure 1 shows the location of the three cities that have the following approximate geographic coordinates: Sao Paulo (23°34’S, 46°39’W), Campinas (22°50’S, 47°00’W), and Rio de Janeiro (22°57’S, 43º11’W) with respect to the tropic of Capricorn, the boundary for the tropical region or tropics, and the urban spot associated with them. Also shown in Figure 1 is the time evolution of the urban area of the city of São Paulo along the last century. The city started to grow at the end of the 19th century and the increase in the urban area is more pronounced at the middle of the 20th century. The increase in the urban areas of Campinas is discussed by *Bernardo* [2002]. The increase of the urban area of Campinas also started at the end of the 19th century and is more pronounced at the middle of the 20th century. For instance, the urban area of Campinas increased from 12.3 km^2 in 1940 to 197.1 km^2 in 1990. In contrast, the city of Rio de Janeiro started to grow in the middle of the 19th century and the increase of urban area is more pronounced in the beginning of the 20th century, being less significant after the middle of the 20th century [*Marenga*, 2009; *Lucena et al.*, 2011]. This difference can be seen by the population of cities in the beginning of the 20th century, because the urban area of a given city is linked to the size of its population, as suggested by *Oke* [1982]. For instance, the population of Rio de Janeiro in 1900 was already 820,000 inhabitants, while the population of São Paulo and Campinas were only 300,000 and 70,000 inhabitants, respectively.

[12] The urban area of a given city is directly related the intensity of the heat island and in consequence on the thunderstorm activity. However, this relationship in tropical countries could be different from temperate climates [*Marques Filho et al.*, 2009]. *Lucena et al.* [2012] have also emphasized that metropolitan areas of tropical cities of the Southern Hemisphere may have distinct particularities and singularities when compared to other regions of the globe.

[13] Figure 2 shows the lightning activity (in flashes$\cdot$$km^{-2}\cdot yr^{-1}$) observed from 1999 to 2009 in the southeast region of Brazil for a spatial resolution of 10 km × 10 km, as observed by the Brazilian lightning detection network (RINDAT) [*Pinto et al.*, 2003, 2006, 2009; *Pinto*, 2009].



(a)

(b)

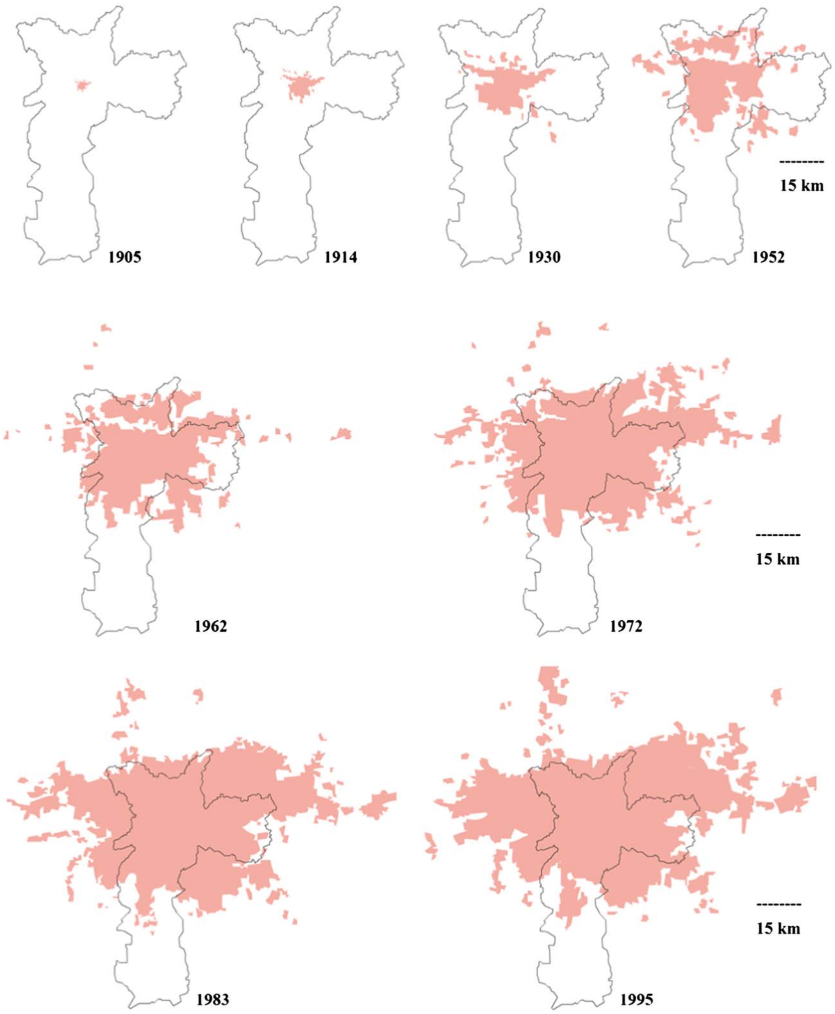
Figure 1. (a) Location of the three cities (São Paulo, Campinas, and Rio de Janeiro) of southeast Brazil with respect to the Tropic of Capricorn, the boundary for the tropical region or tropics, for which thunderstorm day records were studied; (b) location of the urban spots (in white color) associated with the cities. For São Paulo, a circle with radius of 30 km is also indicated; and (c) the time evolution of the urban area of the city of São Paulo along the last century.

A comprehensive review on the physical principles of operation of lightning location systems can be found in *Cummins et al.* [1998] and *Rakov and Uman* [2003]. It can be seen that in most of the region the lightning activity is very high. Average values for São Paulo, Campinas, and Rio de Janeiro for this spatial resolution are 8 flashes·km^{-2}·yr^{-1}, 7 flashes·km^{-2}·yr^{-1}, and 3 flashes·km^{-2}·yr^{-1}, respectively. Peaks in the lightning activity are seen over São Paulo, Campinas, and in the southern part of the state of Rio de Janeiro. While the first two peaks are coincident with urban areas, suggesting that the peaks may be related to urban heat island effect [*Lombardo*, 1984] and have been discussed previously [*Naccarato et al.*, 2003; *Pinto and Pinto*, 2008], the last peak (in the southern part of the state of Rio de Janeiro) has probably an orographic origin related to the local elevated topography [*Campos et al.*, 2011]. No significant peak is evident over the city of Rio de Janeiro.

[14] Figure 3 shows for the city of São Paulo a comparison of thunderstorm days observed routinely from thunder and estimated from RINDAT lightning data, assuming a practical range of audibility of thunder of 7.5 and 10 km (these values are lower than the typical value of 15 km, but reasonable for a large urban area like São Paulo) from 1999 to 2006. The correlation of the data in Figure 3 is very good, indicating that the methodology of recording thunderstorm days is accurate.

3.2. Thunderstorm Data and Local Features

[15] Monthly observations of thunderstorm days in three cities in the southeast region of Brazil were studied: São Paulo, Campinas, and Rio de Janeiro. For São Paulo, data are available since 1887, for Campinas since 1889, and for Rio de Janeiro since 1851, although there are some gaps in the data and, for some periods, only averages for a group of years are available without standard deviations. These facts put some limitations on the statistical analysis. For this reason, the analysis will be divided in two parts. In the first part, only the period from 1951 to 2009 is considered, for which data are available with a few and short gaps. In the second part, the analysis is extended to the beginning of



(c)

Figure 1. (Continued)

the records at the end of the 19th century. In this case, however, it was necessary to consider the large gaps in the data and the other limitations mentioned previously.

3.2.1. São Paulo

3.2.1.1. Period From 1951 to 2009

[16] Monthly thunderstorm days for the city of São Paulo after 1951 are available with a few gaps between 1965 and 1979 and are shown in Figure 4. The data were collected in the Guarulhos International Airport. The figure shows that TD values have (as expected) a strong intra-annual variation and a positive trend through the period. The positive trend is more evident and statistically significant ($p < 0.01$) in the summer season (in the South Hemisphere from 22 December to 21 March) as shown in Figure 5, which shows annual thunderstorm days for the period. It is worth mentioning that despite the increased urban noisiness in São Paulo, the TD annual summer values shows a positive trend, that is, they are not suppressed but still increase, suggesting that the real trend could be even stronger.

[17] To investigate the cause of the positive trend in Figure 5, we need to look for how the city changes during this period. At present, São Paulo is the largest city of the state of São Paulo and of Brazil with a population of about 10 million people. In contrast, at the end of the 19th century it was a very small city with a population of lower than 100,000 people (Geographic and Cartographic Institute of São Paulo (IGC); http://smdu.prefeitura.sp.gov.br/historico_demografico/1900.php). The city began to grow very rapidly at the beginning of the 20th century. The growth of the city gave rise to a strong urban heat island effect [*Lombardo*, 1984], with an increase of approximately 2°C degrees in the surface temperature. Figure 6 shows that the linear regression between average annual surface temperature versus the average population (only for the years when the population is available) and average annual number of thunderstorm days versus average annual surface temperature. Annual surface temperature data corresponds to average of hourly values along all days of the year from the same station where thunderstorm day data were recorded. The linear correlation in both cases is significant at the 1% significance level, confirming the close relation between the variations of these parameters and suggesting that the increase in urban activity in São Paulo in terms of the increase of the area affecting sensible heat flux is related to the increase in the thunderstorm activity. A contribution of the increase of pollution in the city of São Paulo cannot be disregarded as well.

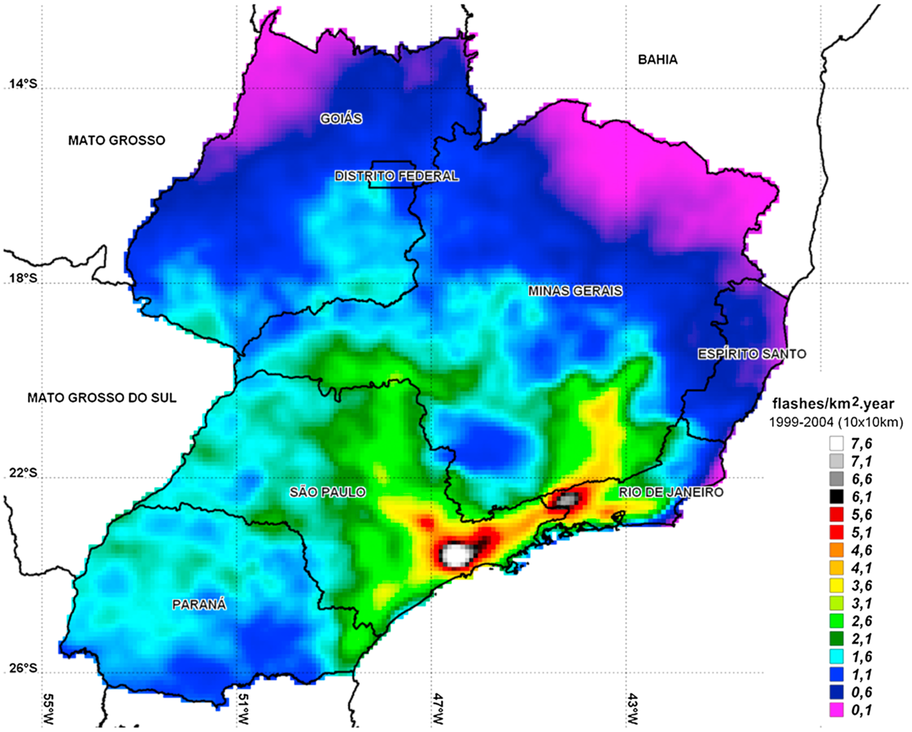


Figure 2. Annual average lightning flash density for 10 km spatial resolution observed by the RINDAT network in the southeast region of Brazil from 1999 to 2009.

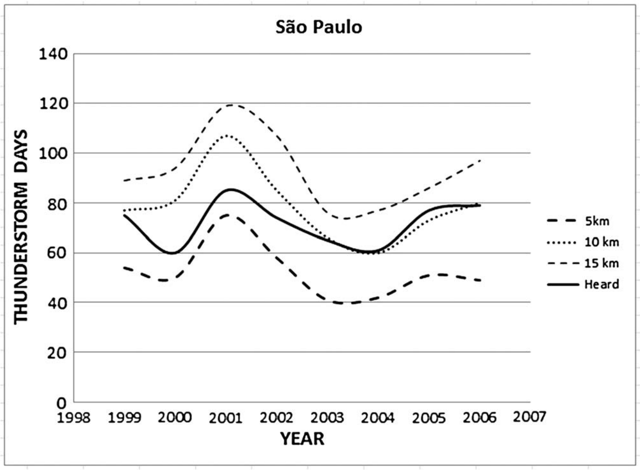


Figure 3. Thunderstorm days in the city of São Paulo observed and estimated by RINDAT from 1999 to 2006 for three different distances around the observation site: 5, 10, and 15 km.

[18] Figure 7 shows the correlation between the monthly values of thunderstorm days for two different stations in São Paulo (Congonhas and Guarulhos) 15 km apart for the period from 1951 to 2009. The linear correlation is significant at the 1% significance level, indicating the representativeness of this variable for the region.

3.2.1.2. The Entire Period Since the 19th Century

[19] Monthly thunderstorm days for the city of São Paulo are available since 1887 with a gap in 1922 to 1950 from a station located in the "Patio do Colégio" station in

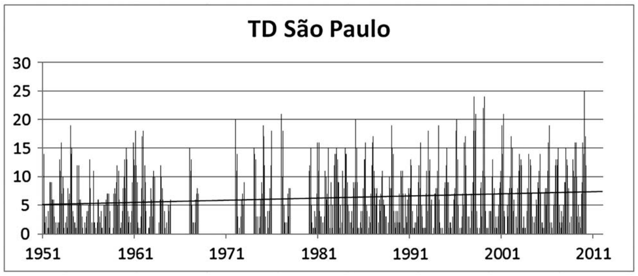


Figure 4. Time series of monthly thunderstorm day for São Paulo after 1951.

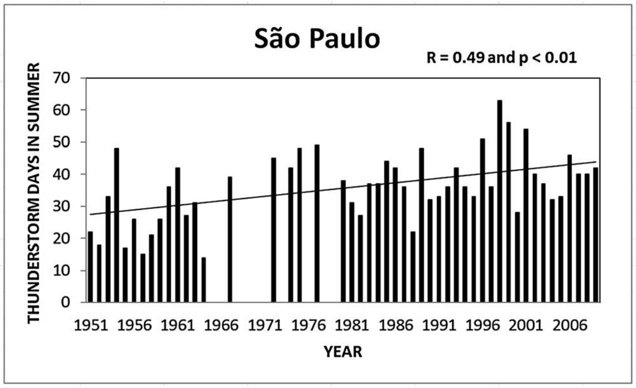
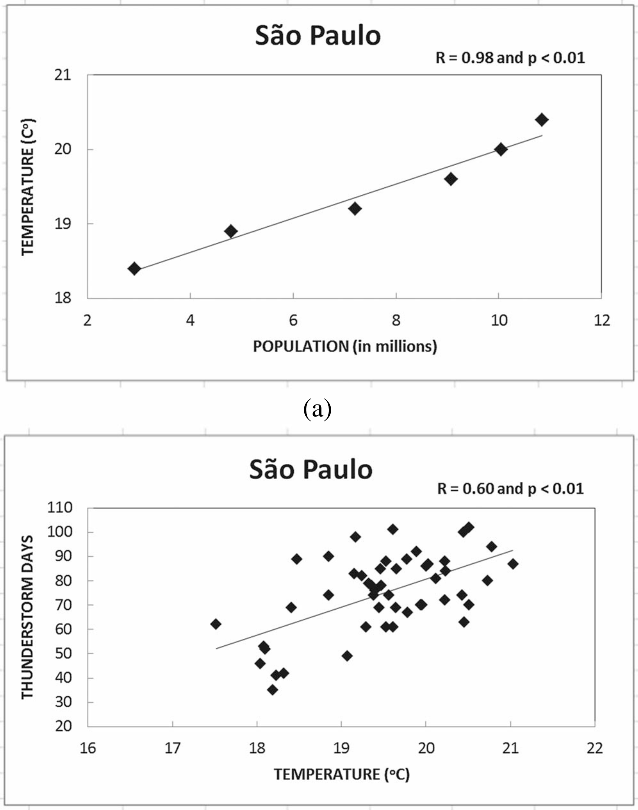


Figure 5. Time series of annual thunderstorm days in the summer for São Paulo after 1951, indicating a significant positive trend.



(a)

(b)

Figure 6. Linear regression between (a) the average annual surface temperature versus annual population for some specific years (see text for details) and (b) average annual number of thunderstorm days versus average annual surface temperature for São Paulo after 1951.

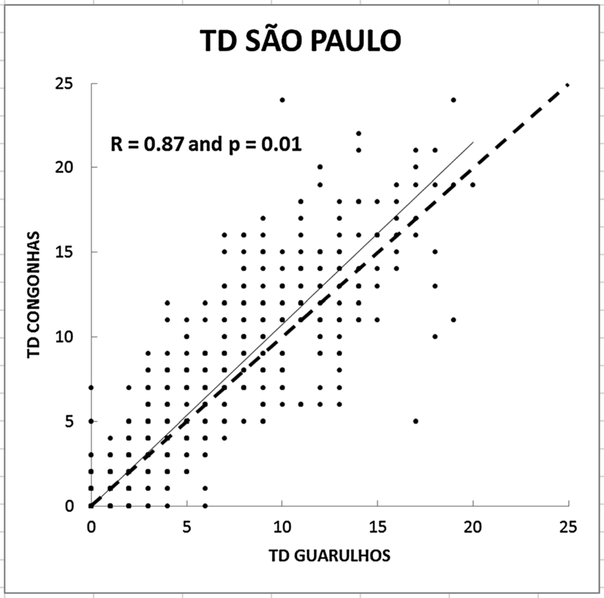


Figure 7. Correlation between the monthly values of thunderstorm days in two different stations in São Paulo (Congonhas and Guarulhos airports) for the period from 1951 to 2009 showing a very significant linear correlation. The dashed line indicates the line with slope equal to 1.

downtown São Paulo. However, from 1887 to 1921 data are available only as monthly averages for a group of years, without standard deviations. To compare these data with more recent data, recent data were grouped in periods to reduce random variations and keep similar significance for each data point in a time series. The series is shown in Figure 8, where average monthly thunderstorm day data are shown for four specific periods. The monthly average number of thunderstorm days shows a significant positive trend in the summer (January to March), with a maximum variation from the second to the third periods, which coincide with the maximum growth of the city as evident in the variation of the area of the city in Figure 1c and the variation of the population in Table 1. The difference in the thunderstorm days in the summer between the second and the third periods is significant at the 5% significance level and between the second and fourth periods at the 1% significance level. No statistically significant variations at the 5% significance level were found in other seasons, although an increase has been observed in the spring (from 22 September to 21 December) in the last period compared to the previous periods. It is difficult to say if this fact has a physical interpretation or it is a result of a statistical limitation related to the lower occurrence of thunderstorms in other seasons than summer.

[20] Table 1 shows the time evolution of the average surface temperature measured in the same station where thunderstorm day data were collected, average population during the period computed fitting the available data to a polynomial curve and average annual number of thunderstorm days, for the same periods indicated in Figure 8. The periods were chosen takning into account the limitations in the data before 1951 and dividing the period after 1951 in a min-

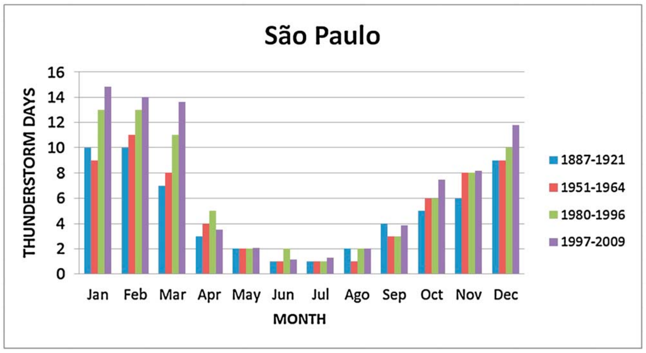


Figure 8. Average monthly thunderstorm day data for four specific periods for the city of São Paulo.

Table 1. Time Evolution of the Average Surface Temperature, Average Population, and Average Annual Number of Thunderstorm Days for the City of São Paulo, for the Same Periods Indicated in Figure 4

Period	Temperature (C)	Population (in Million)	Annual TD
1887–1921	17.8	0.3	60
1951–1964	18.5	2.5	63
1980–1996	19.7	8.6	76
1997–2009	20.3	10	84

imum number of periods to fit the data to a linear regression, as shown in Figure 9. While during the whole period the temperature increased by approximately 2.5 degrees, the average annual number of thunderstorm days increased by approximately 40%.

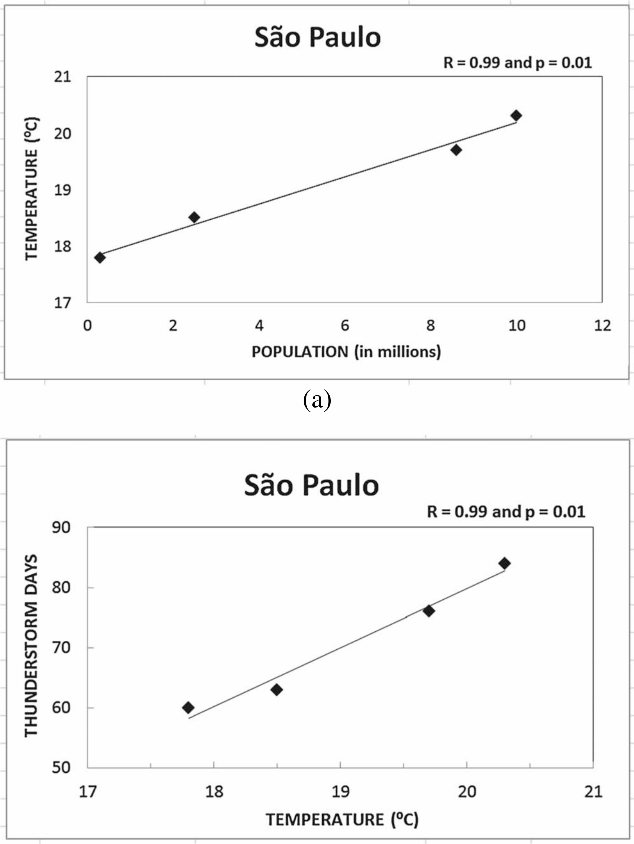
[21] In Table 1, it is evident that all variables show a positive trend, with a maximum variation from the second to the third period. This fact gives strong support to a close relationship among them. Figure 9 shows the linear regression between average temperature versus the average population and average annual number of thunderstorm days versus average temperature using values in Table 1. In spite of the low number of data points, the linear correlation in both cases is very high ($r = 0.99$ and $p = 0.01$), confirming the results obtained after 1951 shown in the previous section. As a whole, the results give strong support to the conclusion that the increase in the thunderstorm activity in the city of São Paulo is due to the increase in urban activity in the city.

3.2.2. Campinas

3.2.2.1. Period From 1951 to 2009

[22] Monthly thunderstorm days for the city of Campinas after 1951 are available without any gap and are shown in Figure 10. Data were collected in the Campinas International Airport near downtown Campinas. The figure shows that TD values have also a strong intra-annual variation. Figure 11 shows the time series of annual thunderstorm days in Campinas for the summer season. A positive trend is also evident. The linear correlation, however, is lower than in São Paulo, but still statistically significant at the 1% significance level.

[23] Campinas is the second largest city in the state of São Paulo. The city grew very rapidly at the beginning of the 20th century like São Paulo and at the present time the population is around 1 million people. Figure 12 shows the linear regression between average annual surface temperature (obtained in the same station were thunderstorm day data were collected) versus the average population (only for the years when the population is available), and average annual number of thunderstorm days versus average annual surface



(a)

(b)

Figure 9. Linear regression between (a) the average temperature versus average annual population and (b) the average annual number of thunderstorm days versus average temperature for the values in Table 1.

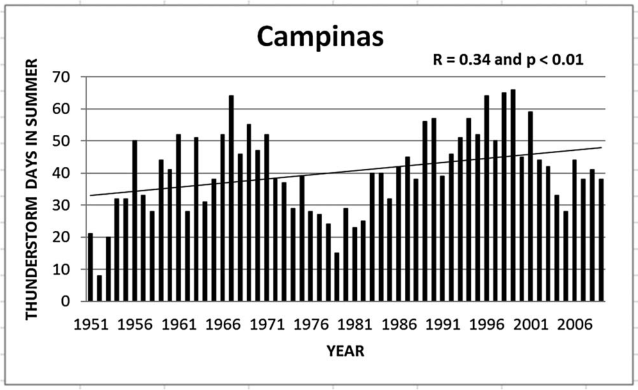


Figure 11. Time series of thunderstorm days in the summer for Campinas after 1951, indicating a significant positive trend.

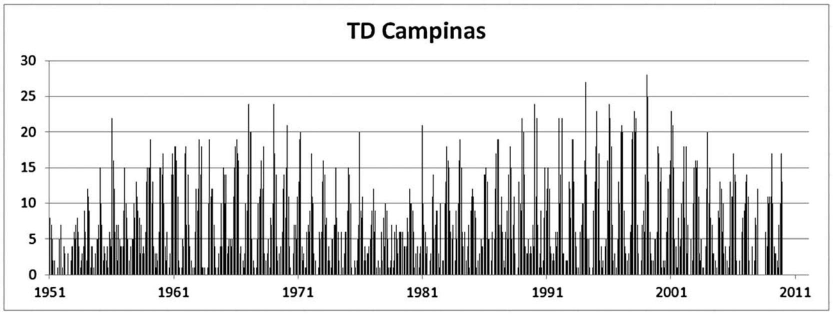
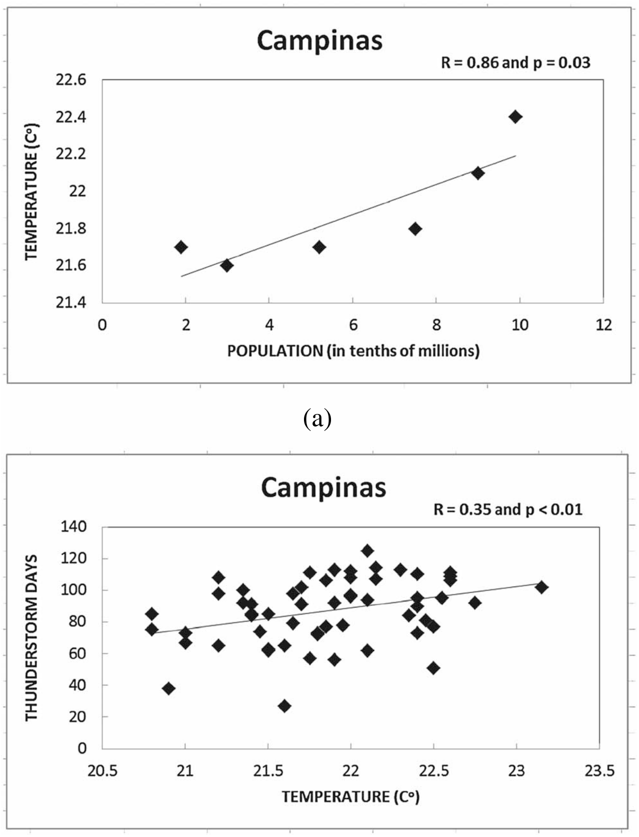


Figure 10. Time series of monthly thunderstorm day for Campinas after 1951.



(a)

(b)

Figure 12. Linear regression between (a) the average annual surface temperature versus annual population for some specific years (see text for details) and (b) average annual number of thunderstorm days versus average annual surface temperature for Campinas.

temperature. The linear correlation is lower than in São Paulo, but still significant at the 3% and the 1% significance level, respectively, as would be expected considering that the urban heat island effect in Campinas [*Tarifa and Armani*, 2001] is also lower than in São Paulo. The increase in the surface temperature during the period is approximately 0.8°C instead of the approximately 2°C degrees observed in São Paulo during the same period. The results support again a close relation between the variations of these parameters and suggest that the increase in urban activity in Campinas is also responsible for the increase in the thunderstorm activity. However, the low correlation in Figure 12b seems also to suggest the influence of another(s) factor(s) than the urban activity. This fact can also be seen in Figure 11 that shows a decrease in the thunderstorm activity in the period from 1976 to 1981 and a small decrease in the period 2003–2005. The reason for these decreases is presently unknown and further analysis is necessary in the future.

3.2.2.2. The Entire Period Since the 19th Century

[24] Monthly thunderstorm days for the city of Campinas are available since 1889 with a gap from 1922 to 1950 from a station located very close to the present location of the Campinas International Airport. However, from 1889 to 1921 data are available only as monthly averages for a group of years, without standard deviations. Figure 13 shows the average monthly data for almost the same four specific periods in Figure 8. The monthly average number of thunderstorm days shows the same significant positive trend for the summer months (in this case including December) identified in the data for São Paulo in Figure 8. The difference in the thunderstorm days in the summer and spring between the first and the third (or fourth) periods is significant at the 1% significance level. No statistically significant variations at the 5% significance level were found in other seasons.

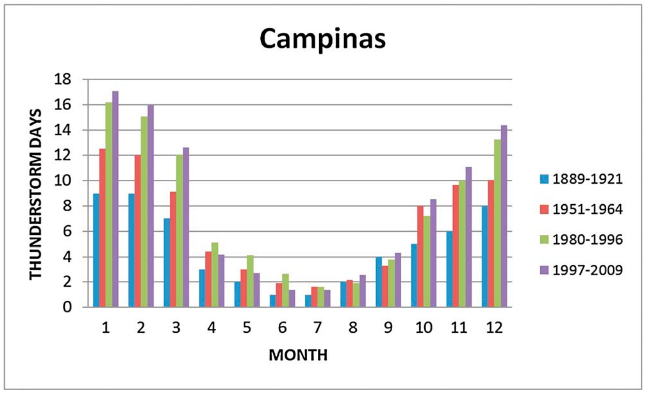


Figure 13. Average monthly thunderstorm day data for four specific periods for Campinas.

[25] Table 2 shows the time evolution of the average surface temperature measured in the same station where thunderstorm day data were collected, average population (calculated following the same procedure described in the description of Table 1) and average annual number of thunderstorm days, for the same periods indicated in Figure 13. While during the whole period the temperature increased by 2°, the average annual number of thunderstorm days increased by approximately 68%, a value larger than that for São Paulo. However, it is worth noting that although the periods in Tables 1 and 2 are almost the same, they correspond to different periods in terms of the growth of the cities.

[26] Figure 14 shows the linear regression between average temperature versus average population and average annual number of thunderstorm days versus average temperature using values in Table 2. The linear correlation in both cases is high, although lower than in São Paulo, confirming the close relation between the variations of these parameters evident in the analysis in the previous section and suggesting again that the increase in urban activity in Campinas is responsible for the increase in the thunderstorm activity.

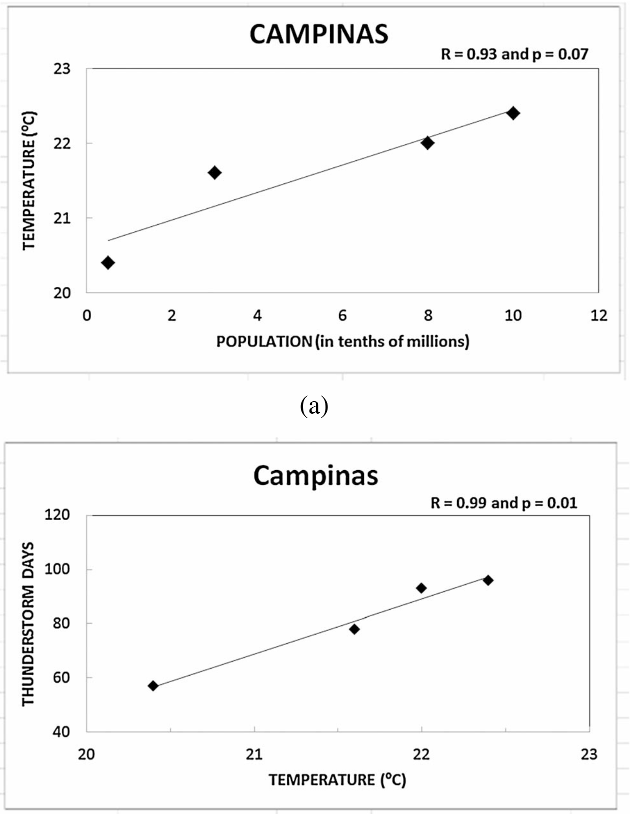
3.2.3. Rio de Janeiro

3.2.3.1. Period From 1951 to Present

[27] Monthly thunderstorm days for the city of Rio de Janeiro after 1951 are available with a gap only in 2007 and 2008 from a station located in the Santos Dumont

Table 2. Time Evolution of the Average Annual Values of Surface Temperature, Population, and Annual Number of Thunderstorm Days for the City of Campinas, for the Same Periods Indicated in Figure 6

Period	Temperature (C)	Population (in Million)	Annual TD
1889–1921	20.4	0.05	57
1951–1964	21.6	0.3	78
1980–1996	22	0.8	93
1997–2009	22.4	1	96



(a)

(b)

Figure 14. Linear regression between the average temperature versus (a) average annual population and (b) average annual number of thunderstorm days for the values in Table 2.

Airport and are shown in Figure 15. The figure shows that TD values also have a strong intra-annual variation, and no clear positive trend. Figure 16 shows the time series of annual thunderstorm days in Rio de Janeiro for the summer season, indicating no positive trend.

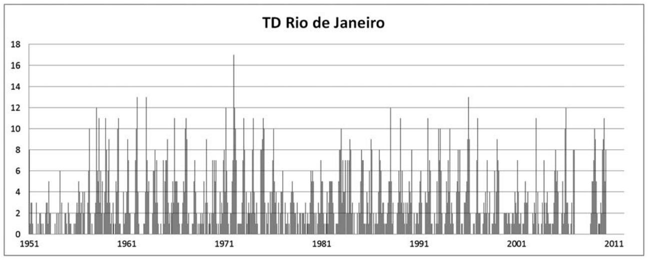


Figure 15. Time series of monthly thunderstorm day data in Rio de Janeiro after 1951.

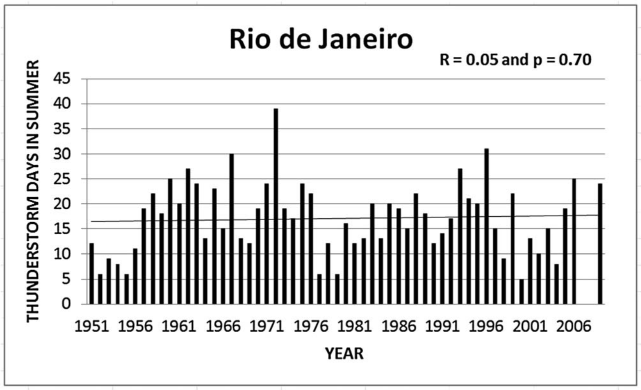
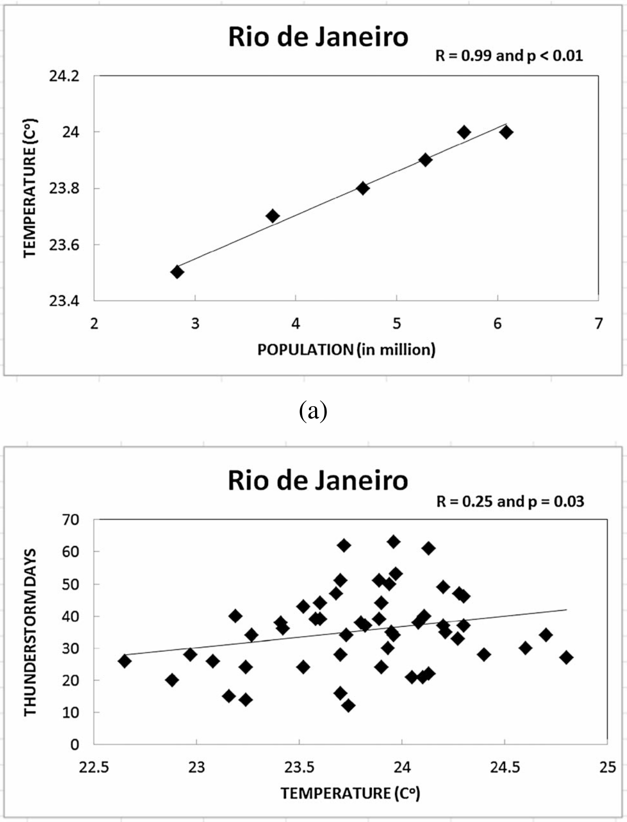


Figure 16. Time series of thunderstorm days in the summer for Rio de Janeiro after 1951, indicating no positive trend.



(a)

(b)

Figure 17. Linear regression between (a) the average annual surface temperature versus annual population for some specific years (see text for details) and (b) average annual number of thunderstorm days versus average annual surface temperature for Rio de Janeiro.

[28] Figure 17 shows the linear regression between average annual surface temperature (obtained in the same station were thunderstorm day data were collected) versus the average population (only for the years when the population is available) and average annual number of thunderstorm days versus average annual surface temperature. Although there is a significant linear correlation between surface temperature and population, at the 1% significance level, there is a low correlation between average annual number of thunderstorm days and average temperature ($p = 0.03$), in contrast with São Paulo and Campinas (in both cases $p < 0.01$).

[29] Rio de Janeiro is the second largest city of Brazil. Differently of São Paulo and Campinas, the city started to grow very rapidly at the middle of the 19th century and at the beginning of the 20th century it was already a large city with 800,000 inhabitants. At the present time the population is around 6 million people. In consequence, an urban heat

island effect is also observed [*Tarifa and Armani*, 2001] and it is confirmed by the significant correlation at 1% significance level between the surface temperature and population as shown in Figure 17. The increase in the surface temperature during the period is of approximately 0.6°C, a value lower than the observed in São Paulo and Campinas for the same period, reflecting probably the lower increase in the urban area in the 20th century as discussed previously. In addition, the correlation between the thunderstorm days and the surface temperature is lower than in São Paulo and Campinas, as can be seen comparing Figure 17 with Figures 6 and 12. These facts are in general agreement with the idea that in Rio de Janeiro the lower increase in the urban area (and, in consequence, in the area of enhanced sensible heat flux to facilitate the occurrence of thunderstorms) in the second part of the 20th century, as compared to São Paulo and Campinas, made the influence of the urban effect on the thunderstorm activity in this period less significant.

3.2.3.2. The Entire Period Since the 19th Century

[30] Monthly thunderstorm days for the city of Rio de Janeiro are available since 1850 with a gap from 1922 to 1950 from a station located in the same place where now is located the Santos Dumont Airport. However, from 1889 to 1921 data are available only as monthly averages for a group of years, without standard deviations. Figure 18 shows the average monthly data for five specific periods after 1850.

[31] Table 3 shows the time evolution of the average surface temperature measured in the same station where thunderstorm day data were collected, average population (calculated following the same procedure described in the description of Table 1), and average annual number of thunderstorm days, for the same periods indicated in Figure 18.

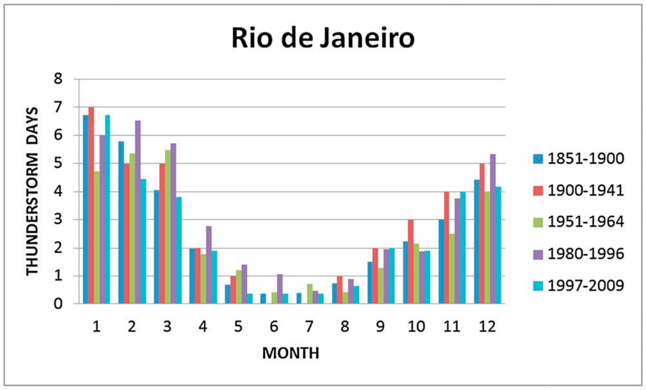


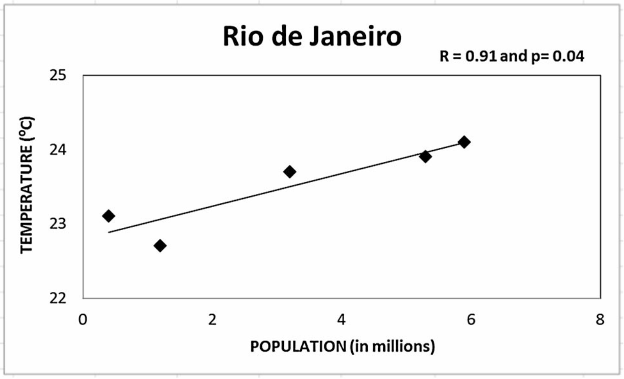
Figure 18. Average monthly thunderstorm day data for five specific periods for the city of Rio de Janeiro.

Table 3. Time Evolution of the Average Annual Values of Surface Temperature, Population, and Annual Number of Thunderstorm Days for the City of Rio de Janeiro, for the Same Periods Indicated in Figure 18

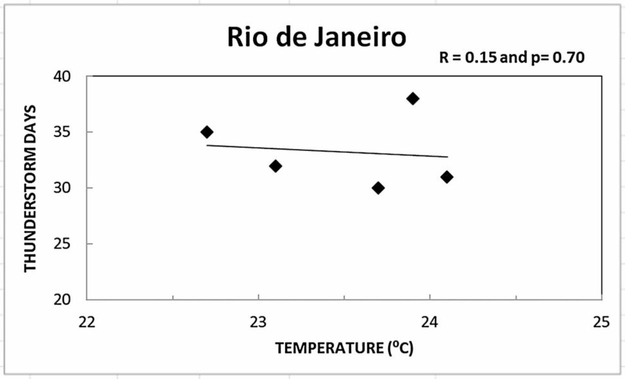
Period	Temperature (C)	Population (in Million)	Annual TD
1851–1900	23.1	0.4	32
1900–1941	22.7	1.2	35
1951–1964	23.7	3.2	30
1980–1996	23.9	5.3	38
1997–2009	24.1	5.9	31

[32] Figure 19 shows the linear regression between average surface temperature versus average population and average annual number of thunderstorm days versus average surface temperature using values in Table 3. The same results obtained in the previous section are found. Although there is a linear correlation between average temperature and average population (the statistical significance, however, is lower than in São Paulo and similar to that in Campinas), there is no correlation between average thunderstorm days and average temperature for the different periods. Considering that the urban heat island effect is also evident in Rio de Janeiro, the lack of correlation between thunderstorm days and surface temperature suggests that other aspects should be more relevant. Differently of São Paulo and Campinas, Rio de Janeiro is a coastal city adjacent to the Atlantic Ocean and, in consequence, its climate is strongly influenced by the changes in the sea surface temperature of the Atlantic Ocean; second, again in contrast with the situation for São Paulo and Campinas, Rio de Janeiro is located in a mountain terrain.

[33] In addition to the expected lower effect of the urban activity on the thunderstorm occurrence in the 20th century, as discussed previously, other aspects (the proximity of the ocean and topography) could be relevant to explain the anomalous thunderstorm behavior of Rio de Janeiro compared with



(a)



(b)

Figure 19. Linear regression between (a) the average temperature versus average annual population and (b) average annual number of thunderstorm days versus average temperature for the values in Table 3.

São Paulo and Campinas. The larger proximity of the ocean of Rio de Janeiro compared to São Paulo and Campinas (see Figure 1) change the influence of the "continentality", that is, the set of physical processes that makes the convection larger over the continents than over the oceans. This can be seen comparing Figures 5, 11, and 16, which show that TD in Rio is lower than São Paulo and Campinas. In addition, the larger proximity of Rio de Janeiro of the ocean makes the influence of changes in SST in TD larger in Rio compared to the other cities. The possible role of topography is supported by physical basis, in the sense that mountains act as forcing mechanism to convection. The topography is shown in Figure 20, which shows an altitude map in meters with 2 km spatial resolution in the region of the study. For this spatial resolution, it can be seen that altitude changes around the cities of São Paulo and Campinas are lower than 150 m, while around the city of Rio de Janeiro they reach values above 400 m. Also shown in Figure 20 is a more detailed altitude map for the region of the city of Rio de Janeiro.

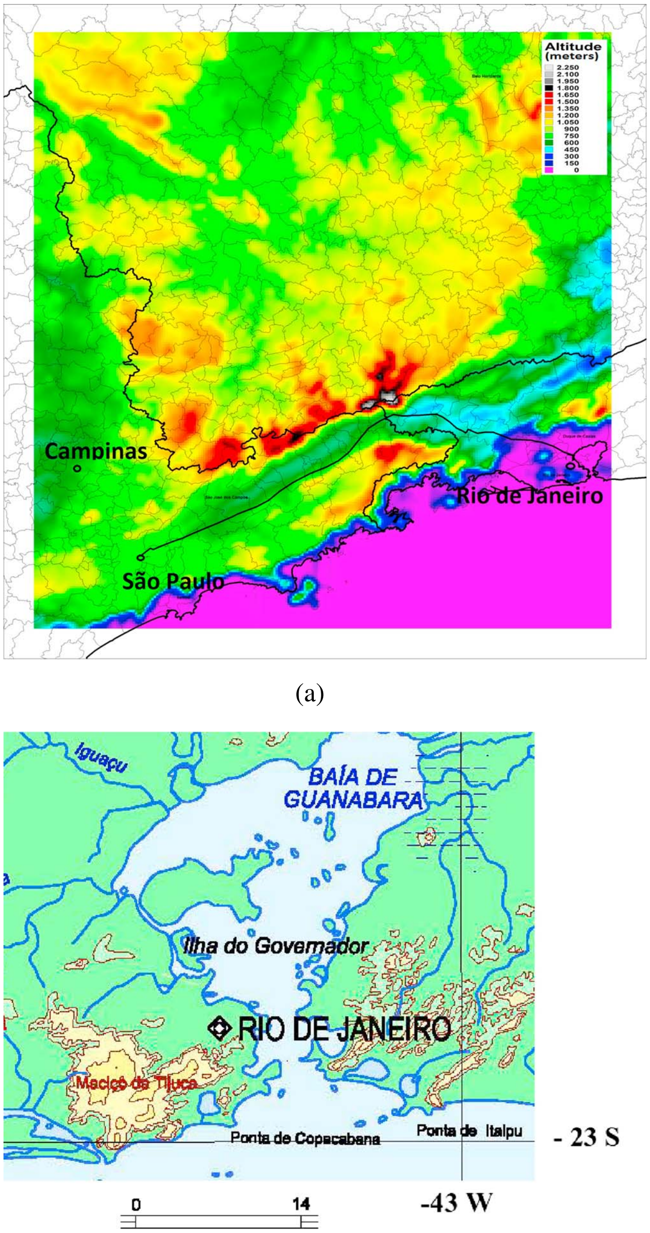
[34] Regarding the other aspect, differently of São Paulo and Campinas, Rio de Janeiro is a coastal city. The proximity of the Atlantic Ocean tends to minimize the urban island effect, as well as to intensify the influence of the ocean in the deep convection development and thunderstorm activity. This aspect will be discussed in the next section.

3.3. Monthly Thunderstorm Data and Large Scale Phenomena

[35] Some recent studies [*Liebmann et al*., 2001; *Vicente*, 2005] have suggested that the climatology and interannual variability of heavy precipitation events related to deep convection in southeastern Brazil, defined at each station when daily rainfall exceeds a certain percent of its seasonal or annual mean, are correlated with SST anomalies in the equatorial Pacific Ocean and tropical South Atlantic Ocean.

[36] In turn, the correlation of thunderstorm days and large-scale phenomena has been addressed only by a few authors, in general with respect to the solar activity [*Kleymenova*, 1967] and using annual data for short time periods. This aspect puts clear limitations in the results obtained, both in physical terms because it does not take into account the marked seasonal variation in the thunderstorm activity as in statistical terms, due to the limited data sample to address decadal or multidecadal variations.

[37] In this section, we will investigate if variations of the thunderstorm days in São Paulo, Campinas, and Rio de Janeiro in the three cities studied are correlated with SST of the equatorial Pacific Ocean and tropical Atlantic Ocean, because as described earlier these phenomena area are believed to be the most significant large-scale phenomena to influence thunderstorm activity in South America. The analysis considered approximately 60 years of data, with monthly time resolution (see text below). No previous analysis of this type has been published in the literature. The ENSO was characterized by the Southern Oscillation Index (SOI) and the sea surface temperature of South Atlantic Ocean was characterized by the TSA index. In the context of this article, besides to investigate a possible correlation between thunderstorm activity and ENSO or TSA, this analysis is useful to verify if the positive trends observed in the cities of São Paulo and Campinas and well correlated with the anthropogenic urban activity (urban heat island effect) could be alternatively explained by a correlation with these large-scale phenomena.



(a)

(b)

Figure 20. (a) Altitude map (in meters) in the region of the interest. Black curves represent the limit among the different states, the border with respect to the Atlantic Ocean (purple color) and the Dutra interstate highway that connects São Paulo and Rio de Janeiro. (b) Altitude map (in meters) for the region of the city of Rio de Janeiro.

[38] Due to the limitations in TD values before 1951 described earlier and considering that TSA values are available only after 1951, the analysis in this section is limited to this period. Figure 21 shows the time series of monthly values of SOI and TSA (both provided by the Earth System Research Laboratory, NOAA: http://www.esrl.noaa.gov/psd/data/climateindices/list/) since 1951.

[39] To verify a possible relation of thunderstorm days with SOI and TSA, a linear regression analysis was done

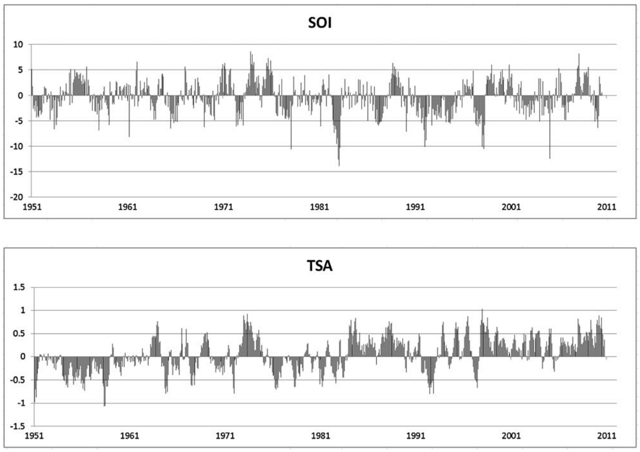


Figure 21. Times series of (a) SOI and (b) TSA monthly values for the period from 1951 to 2009.

between these indices and thunderstorm days for the period after 1951. The results of this analysis indicate that there is no significant correlation between SOI and TSA and thunderstorm days. On the other hand, while ENSO phenomena exhibit alternately periods of El Niño and La Niña almost randomly, TSA has presented a significant positive trend of 0.6° comparing the average values for the 1997–2009 and 1951–1964 periods, as indicated in Figure 22. The trend is coincident with the positive trend in thunderstorm days in São Paulo and Campinas. However, the absence of a positive trend in the thunderstorm days in Rio de Janeiro after 1950 make this coincidence probably fortuitous or, at least, indicate that the influence of TSA on the thunderstorm days in the three cities is less relevant than the influence of other aspects, at least if it is considered independently of other aspects.

[40] To investigate a possible relation of SOI and TSA with the thunderstorm days in São Paulo, Campinas, and Rio de Janeiro, and considering that TD has a strong interannual variation with very low values outside the summer periods, the average of monthly values of thunderstorm days were calculated during the summer season corresponding to two combinations of monthly values of SOI and TSA: months with SOI > 2 and TSA > 0.4, which corresponds to intense La Niña–like months with a significant positive TSA anomaly; and months with SOI < -2 and TSA -0.4, which corresponds to intense El Niño–like months with a significant negative TSA anomaly. The choice of these two combinations follows the assumption that we might expect an intensification of the thunderstorm activity in the southeast region of Brazil for the first and a decrease for the second combination. Such an assumption is based on the following physical arguments, which take into account the response of the Hadley and Walker circulation cells to SOI as discussed by *Wang and Picaut* [2004]. In the first combination of indices (SOI > 2 and TSA > 0.4), a large SOI corresponds to a weakening of the Hadley cell (with a consequent increase of the cold fronts reaching the southeast region), while a large TSA corresponds to an intensification of local humidity convection facilitating the local convection. Both situations tend to increase the thunderstorm activity in the tropical region. The opposite combination (SOI < -2 and TSA < -0.4) tends to produce the contrary effect, that is, a decrease in the local convection. For other combinations of large values of SOI and TSA, the effects of SOI and TSA act in the opposite direction. Table 4 shows the average of monthly thunderstorm days for summer months (from 1 December—instead of 22 December—to 21 March to improve statistics) corresponding to the two combinations mentioned above for the three cities studied. There is a significant difference at the 1% confidence level in the values for the two combinations for all cities.

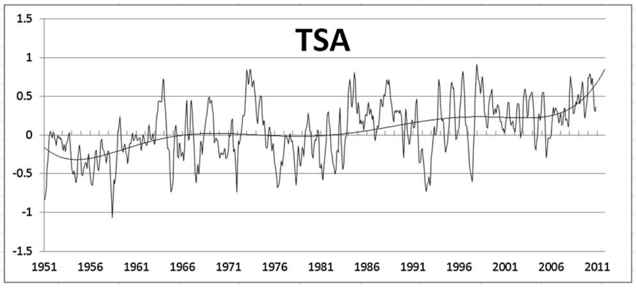


Figure 22. Time series of TSA after 1951 indicating a positive trend as suggested by the 5-running average best fit curve.

[41] On the other hand, if the average of the monthly values of thunderstorm days during the summer were calculated for the same different intervals of positive and negative values of SOI and TSA in Table 4, but if they are considered separately, that is, months with SOI >2 against months with SOI < -2 and months with TSA > 0.4 against months with TSA < -0.4, the differences are not significant even at the 5% significance level. The above results suggest that values of SOI and TSA have a combined influence on the thunderstorm days in the southeast region of Brazil. The same significant variation occurs for São Paulo and Campinas, although with a lower amplitude. Considering that the ENSO phenomena has alternated periods of El Niño and La Niña almost randomly, while the TSA has presented a significant positive trend of 0.6° in temperature, the findings above indicate that the thunderstorm activity in southeast Brazil tends to increase in the incoming years.

[42] Finally, an investigation was carried out to identify any correlation between TD values and other large-scale

Table 4. Averages and Error Bars (for 1% Significance Level) of Monthly Values of Thunderstorm Days for Summer (From 01 December to 21 March to Improve Statistics) Months Corresponding to Two Different Combinations of SOI and TSA Values From 1951 to 2009 for São Paulo, Campinas and Rio de Janeiro, and the Ratio (Factor of Increase) Between the Values for the Two Different Conditions

Summer Months With	São Paulo	Campinas	Rio de Janeiro
SOI > 2 and TSA > 0.4(28 cases)	15.1 +/− 2.1	15.1 +/− 4.5	6.3 +/− 2.9
SOI < -2 and TSA < -0.4(20 cases)	7.4 +/− 3.1	6.3 +/− 3.3	1.7 +/− 1.4
Factor of Increase	2.0	2.3	3.7

phenomena. The investigation is limited by the availability of data: while AMO data are available since 1860, POD data are restricted to the period after 1951. The positive trend in the TD values in São Paulo and Campinas cannot be explained by decadal variations of AMO or POD. Also, changes in the TD values in Rio de Janeiro are not correlated with these phenomena. These results put additional support that the positive trends observed in São Paulo and Campinas and discussed previously are due to local effects related to urban aspects, in particular the urban heat island effect.

4. Conclusions

[43] Monthly thunderstorm days for three cities (São Paulo, Campinas, and Rio de Janeiro) in southeastern Brazil since the 19th century were investigated in terms of the main phenomena related to their changes. The analysis was complemented by the spatial distribution of lightning in the last decade in the southeast region.

[44] In southeast Brazil, the variability of the thunderstorm activity may be related to many processes that can be divided in two types: changes associated with enhanced urban activity at a local or small scale and changes associated with variations in the atmospheric circulation that modulate the convective activity at a large scale. The urban activity is believed to influence the thunderstorm formation and evolution by two different mechanisms: pollution and heat island. Such influence is expected to be more significant in regions where small cities have grown to become large urban areas. Large-scale variations in the convective activity in southeast Brazil are driven mainly by variations in the ENSO and the surface temperature of the tropical South Atlantic Ocean (which can be represented by the TSA Index). Such influence may be related to decadal variations of these phenomena that result from natural cycles such as the POD and the AMO or, more recently, from global warming.

[45] For São Paulo and Campinas, the TD data indicate that the thunderstorm activity showed a significant increase during the period of study simultaneously with an increase of approximately two degrees in the surface temperature well correlated with the population growth of the cities in terms of population, while the lightning data indicate that the two cities can be considered as thunderstorm spots with respect to their surrounding areas. Both results did not match anything expected from natural climate cycles and give strong observational evidence for the anthropogenic influence related to the urban activity on thunderstorm activity. The increase occurs mainly in the summer, with smaller amplitude in the spring. This fact seems to suggest that the impact of the urban activity on thunderstorm activity is dependent on the prevailing meteorological conditions.

[46] For Rio de Janeiro, TD data did not show a positive trend in spite of the increase in the surface temperature, suggesting that variations are most probably a result of a complex combination of different features. Besides the lower increase in the urban area of Rio de Janeiro along the second part of the 20th century, two other aspects may be relevant to the occurrence of thunderstorms in Rio de Janeiro and not in the other two cities: the presence of large mountains and the proximity of the Atlantic Ocean.

[47] In addition, the statistical analysis of TD data after 1951 in the three cities studied regarding large-scale phenomena shows a novel result. A significant variation of thunderstorm activity in Rio de Janeiro (by a factor of 3.7) occurs when comparing TD values for summer months characterized for the simultaneous occurrence of a positive anomaly of TSA and La Niña with TD values for summer months characterized for the simultaneous occurrence of a negative anomaly of TSA and El Niño, even though no significant variation was found when each large-scale phenomena occurs isolated. The same significant variation occurs for São Paulo and Campinas, although with lower amplitude (by a factor of 2 and 2.3, respectively), suggesting that the proximity of Rio de Janeiro to the Atlantic Ocean tends to intensify the influence of these two large-scale phenomena. Although the significant change in the thunderstorm activity in response to the different combinations of TSA and SOI is in general agreement with basic physical ideas, at the present time no complete physical interpretation for this change is available, because the influence of the behavior of the SST of the oceans and their interactions on the convection activity over Brazil are poorly known. In addition, considering that the ENSO phenomena has alternating periods of El Niño and La Niña almost randomly, while the TSA has presented a significant positive trend of 0.6° in temperature, the findings above suggest that the number of periods satisfying the condition “positive anomaly of TSA and La Niña” tends to become gradually higher than the condition “negative anomaly of TSA and El Niño”, which implies that the thunderstorm activity in southeast Brazil tends to increase in the coming years. This conclusion suggests that the ocean behavior tends to drive the land thunderstorm behavior in the future, at least in this region of Brazil.

[48] Following the same rationale above, considering that at the present time there is no consensus about the tropical Pacific’s response to global warming in the sense that it is not clear if the structure of changes in the ocean surface temperature will more closely resemble an El Niño or a La Niña [*Vecchi et al.*, 2008; *McPhaden et al.*, 2011], and if the El Niño or La Niña will be more intense [*Watanabe et al.*, 2012], while it is believed that TSA will maintain a positive trend that it is partially related to global warming [*Trenbert and Shea*, 2006], the results also suggest that the thunderstorm activity in southeast Brazil tends to increase in response to global warming.

References

Arnfield, A. J. (2003), Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island, *Int. J. Clim.*, *23*(1), 1–26, doi:10.1002/joc.859.

Andreoli, R. V., and M. T. Kayano (2003), Evolution of the equatorial and dipole modes of the sea surface temperature in the Tropical Atlantic at decadal scale, *Meteor. Atmos. Phys.*, *83*, 277–285, doi:10.1007/s00703-002-0568-4.

Barros, V., A. M. Grimm, and M. E. Doyle (2002), Relationship between temperature and circulation in southeastern South America and its influence from El Niño and La Niña events, *J. Meteor. Soc. Japan*, *80*, 21–32.

Bell, T. L., D. Rosenfeld, K.-M. Kim, J.-M. Yoo, M.-I. Lee, and M. Hahnenberger (2008), Midweek increase in U.S. summer rain and storm heights suggests air pollution invigorates rainstorms, *J. Geophys. Res.*, *113*, D02209, doi:10.1029/2007JD008623.

Bell, T. L., D. Rosenfeld, and K.-M. Kim (2009), Weekly cycle of lightning: Evidence of storm invigoration by pollution, *Geophys. Res. Lett.*, *36*, L23805, doi:10.1029/2009GL040915.

Bernardo, R. G. (2002), The history of the land occupation in the city of Campinas. Master Thesis, University of São Paulo, São Paulo (in Portuguese).

Berri, G. J., and G. I. Bertossa (2004), The influence of the tropical and subtropical Atlantic and Pacific Oceans on precipitation variability over

Southern Central South America on seasonal time scales, *Int. J. Clim.*, *24*(4), 415–435, doi:10.1002/joc.1000.

Campos, D. R., O. Pinto Jr., I. R. C. A. Pinto, and W. R. G. Farias (2011), An 11-year study about the spatial and temporal variations of the lightning flash density in the southeastern Brazil, Proceedings of the XIV International Conference on Atmospheric Electricity, August 08–12, 2011, Rio de Janeiro, Brazil.

Carvalho, L. M. V., C. Jones, and B. Liebmann (2002), Extreme precipitation events in southeastern South America and large-scale convective patterns in the South Atlantic Convergence Zone, *J. Climate*, *15*, 2377–2394.

Cavalcanti, I. F. A., and V. E. Kousky (2003), Climatology of South American cold fronts. Proceedings of the International Conference on Southern Hemisphere Meteorology and Oceanography, Wellington, New Zealand.

Chang, P., L. Ji, and H. A. Li (1997), A decadal climate variation in the Tropical Atlantic Ocean from thermodynamic air-sea interactions, *Nature*, *385*, 516–518.

Changnon, S. A. (1980), Evidence of urban and lake influences on precipitation in the Chicago area, *J. Appl. Meteor.*, *19*(10), 1137–1159.

Changnon Jr., S. A., and C. F. Hsu (1984), Temporal distributions of global thunder days, Final Report NSF ATM-81-14724, Illinois State Water Survey Champaign, Illinois, 79p.

Chylek, P., C. K. Folland, H. A. Dijkstra, G. Lesins, and M. K. Dubey (2011), Ice-core data evidence for a prominent near 20 year time-scale of the Atlantic Multidecadal Oscillation, *Geophys. Res. Lett.*, *38*, L13704, doi:10.1029/2011GL047501.

Cobb, W., and H. J. Wells (1970), The electrical conductivity of oceanic air and its correlation to global atmospheric pollution, *J. Atmos. Sci.*, *27*, 814–819.

Coelho, C. A. S., C. B. Uvo, and T. Ambrizzi (2002), Exploring the impacts of the tropical Pacific SST on the precipitation patterns over South America during ENSO periods. *Theor. Appl. Clim.*, *71*(11), 11–17.

Christian, H. J., et al. (2003), Global frequency and distribution of lightning as observed from space by the Optical Transient Detector, *J. Geophys. Res.*, *108*(D1), 4005, doi:10.1029/2002JD002347.

Cummins, K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer (1998), A combined TOA/MDF technology upgrade of the U.S. national lightning detection network, *J. Geophys. Res.*, *103*(D8), 9035–9044.

Delworth, T. L., and M. Mann (2000), Observed and simulated multidecadal variability in the Northern Hemisphere, *Clim. Dyn.*, *16*, 661–676, doi:10.1007/s003820000075.

Deser, C., A. S. Phillips, and J. W. Hurrell (2004), Pacific interdecadal climate variability: Linkages between the tropics and the north Pacific during boreal winter since 1900. *J. Clim.*, *17*, 3109–3124, doi:10.1175/1520-0442.

Enfield, D. B., A. M. Mestas, D. A. Mayer, and L. Cid-Serrano (1999), How ubiquitous is the dipole relationship in tropical Atlantic sea surface temperatures? *J. Geophys. Res.*, *104*(C4), 7841–7848.

Farias, W. R. G., O. Pinto Jr., I. R. C. A. Pinto, and K. P. Naccarato (2011), The influence of urban effect on lightning activity: Evidence of weekly cycle, Proceedings of the XIV ICAE, Rio de Janeiro.

Gershunov, A., and T. P. Barnett (1998), Interdecadal modulation of ENSO teleconnections. *Bull. Am. Meteorol. Soc.*, *79*, 2715–2725.

Goldenberg, S. B., C. W. Landsea, A. M. Mestas-Nuñez, and W. M. Gray (2001), The recent increase in Atlantic hurricane activity: causes and implications, *Science*, *293*, 474–479.

Gorbatenko, V., and A. A. Dulzon (2001), Variations of thunderstorm, Biology and Ecology, Korus.

Grimm, A. M. (2003), The El Niño impact on the summer monsoon in Brazil: regional processes versus remote influences, *J. Climate*, *16*, 263–280, doi:10.1175/1520-0442.

Grimm, A. M. (2004), How do La Niña impact on the summer monsoon system in Brazil?, *Clim. Dyn.*, *22*(2–3), 123–138, doi:10.1007/s00382-003-0368-7.

Grimm, A. M., and A. Natori (2006), A. Climate change and interannual variability of precipitation in South America, *Geophys. Res. Lett.*, *33*, L19706, doi:10.1029/2006GL026821.

Grimm, A. M., S. E. Ferraz, and J. Gomes (1998), Precipitation anomalies in Southern Brazil associated with El Niño and La Niña events, *J. Climate*, *11*, 2863–2880.

Grimm, A. M., V. R. Barros, and M. E. Doyle (2000), Climate variability in Southern South America associated with El Niño and La Niña events, *J. Climate*, *13*, 35–58.

Huff, F. A., and S. A. Changnon (1973), Precipitation modification by major urban areas, *Bull. Am. Meteorol. Soc.*, *54*, 1220–1232.

Jones, P. D., and M. E. Mann (2004), Climate over past millennia, *Rev. Geophys.*, *42*, doi:10.1029/2003RG000143.

Kai-Hing, Y. (2003), Important Notes, Hong Kong Observatory Report.

Kar, S. K., Y.-A. Liou, and K.-J. Há (2009), Aerosol effects on the enhancement of cloud-to-ground lightning over major urban areas of South Korea, *Atmos. Res.*, *92*, 80–87, doi:10.1016/j.atmosres.2008.09.004.

Kayano, M. T., C. P. Oliveira, and R. V. Andreoli (2009), Interannual relations between South American rainfall and tropical sea surface temperature anomalies before and after 1976, *Int. J. Clim.*, *29*(10), 1439–1448, doi:10.1002/joc.1824.

Kerr, R. (2000), A North Atlantic climate pacemaker for the centuries, *Science*, *288*, 1984–1985.

Kleymenova, E. P. (1967), On the variation of the thunderstorm activity in the solar cycle, *Glav. Upirav. Gidromet. Scuzb., Met. Gidr. 8*, 64–68 (in Russian).

Knight, J. R., R. J. Allan, C. K. Folland, M. Vellinga, and M. E. Mann (2005), A signature of persistent natural thermohaline circulation cycles in observed climate, *Geophys. Res. Lett.*, *32*, L20708, doi:10.1029/2005GL024233.

Kucharski, F., I.-S. Kang, R. Farneti, and L. Feudale (2011), Tropical Pacific response to 20th century Atlantic warming, *Geophys. Res. Lett.*, *38*, L03702, doi:10.1029/2010GL046248.

Liebmann, B., C. Jones, and L. M. V. Carvalho (2001), Interannual variability of daily extreme precipitation events in the state of São Paulo, Brazil, *J. Climate*, *14*, 208–218.

Lombardo, M. A. (1984), The heat urban island in the metropolitan area of São Paulo. PhD Thesis, University of São Paulo (in Portuguese).

Lucena, A. J., E. B. Correa, O. C. Rotunno Filho, L. F. Peres, J. R. A. França, and M. G. A. da Silva Justi (2011), Heat island and precipitation events in the metropolitan area of Rio de Janeiro (RMRJ). Proceedings of the XIV World Water Congress (in Portuguese).

Lucena, A. J., O. C. Rotunno Filho, J. R. A. França, L. F. Peres, and L. N. R. Xavier (2012), Urban climate and clues of heat island events in the metropolitan area of Rio de Janeiro, *Theor. Appl. Climatol.*, doi 10.1007/s00704-012-0668-0.

Mantua, N. J., and S. R. Hare (2002), The Pacific Decadal Oscillation, *J. Oceanogr.*, *58*, 35–44.

Marenga, R. C. (2009), The influence of the military fortifications on the urban expansion of the city of Rio de Janeiro. Master Thesis, Institute of Military Engineering, Rio de Janeiro (in Portuguese).

Marques Filho, E. P., H. A. Karam, A. G. Miranda, and J. R. A. Franca (2009), Rio de Janeiro's urban climate. Urban Climate News, Quarterly Newsletter of the International Association of Urban Climate (IAUC), 32, June, 5–9.

McPhaden, M. J., and D. Zhang (2002), Slowdown of the meridional overturning circulation of the upper Pacific Ocean, *Nature*, *415*, 603–608.

McPhaden, M. J., T. Lee, and D. McClurg (2011), El Niño and its relationship to changing background conditions in the tropical Pacific Ocean, *Geophys. Res. Lett.*, *38*, L15709, doi:10.1029/2011GL048275.

Naccarato, K. P., O. Pinto Jr., and I. R. C. A. Pinto (2003), 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*, 1674–1677, doi:10.1029/2003GL017496.

Naccarato, K. P. (2006), Analysis of the lightning characteristics in the Southeast Brazil, PhD. Thesis, Brazilian Institute of Space Research (INPE) (in Portuguese).

Nathou, N., and E. Hicks (2006), Climatological analysis of deep convective days in Guadeloupe, Proceedings of the 15th Meeting of the Caribbean Academy of Sciences.

Nechet, D. (1994), Thunderstorm days in the Amazon, Proceedings of the 8th Brazilian congress of meteorology, *Belo Horizonte*, *1*, 180–183 (In Portuguese).

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

Oke, T. (1982), The energetic basis of the urban heat island, *Q. J. R. Meteorol. Soc.*, *108*(455), 1–24.

Neto, J. L. S. (2005), Decadal climatology of the Southeastern Brazil. *Brazil. J. Clim.*, *1*(1), 43–60, ISSN: 1980-055x.

Pinto, I. R. C. A., O. Pinto Jr., M. A. S. S. Gomes, and N. J. Ferreira (2004), Urban effect on the characteristics of cloud-to-ground lightning over Belo Horizonte-Brazil, *Ann. Geophys.*, *22*(2), 697–700, doi: angeo-22-697-20.

Pinto Jr., O., I. R. C. A. Pinto, and H. H. Faria (2003), A comparative analysis of lightning data from lightning networks and LIS sensor in the North and Southeast of Brazil. *Geophys. Res. Lett.*, *30*(2), 1073–1076 doi:10.1029/2002GL016009.

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

Pinto Jr., O. (2009), Lightning in the tropics: from a source of fire to a monitoring system of climate changes, pp. 109, Nova Science Publishers, New York.

Pinto Jr., O., I. R. C. A. Pinto, D. R. de Campos, and K. P. Naccarato (2009), Climatology of large peak current cloud-to-ground lightning flashes in southeastern Brazil, *J. Geophys. Res.*, *114*, D16105, doi:10.1029/2009JD012029.

Price, C. (2009), Will a drier climate result in more lightning? *Atmos. Res.*, *91*, 479–484, doi:10.1016/j.atmosres.2008.05.016.

Rakov, V. A., and M. A. Uman (2003), Lightning: Physics and Effects, Chapter 2, pp. 687, Cambridge University Press, Cambridge.

Rayner, N. A., P. Brohan, D. E. Parker, C. K. Folland, J. J. Kennedy, M. Vanicek, T. J. Ansell, and S. F. B. Tett (2006), Improved analyses of changes and uncertainties in sea surface temperature measured in situ since the mid-nineteenth century: the HadSST2 dataset, *J. Clim.*, *19*, 446–469, doi:10.1175/JCLI3637.1.

Saravanan, R., and P. Chang (2000), Interaction between Tropical Atlantic variability and El Niño-Southern Oscillation, *J. Clim.*, *13*(13), 2177–2194.

Sátori, G., E. Williams, and I. Lemperger (2009), Variability of global lightning activity on the ENSO time scale, *Atmos. Res.*, *91*, 500–507, doi:10.1016/j.atmosres.2008.06.014.

Schlesinger, M. E., and N. Ramankutty (1994), An oscillation in the global climate system of period 65–70 years. *Nature*, *367*, 723–726.

Seager, R., A. R. Karspeck, M. A. Cane, Y. Kushnir, A. Giannini, A. Kaplan, B. Kerman, and J. Velez (2004), Predicting Pacific decadal variability, in Earth's Climate: the ocean–atmosphere interaction, edited by C. Wang, S. Xie, and J. A. Carton, Geophysical Monograph Series, 147, pp. 105–120, American Geophysical Union, Washington DC.

Servain, J. (1991), Simple climatic indices for the tropical Atlantic ocean and some applications, *J. Geophys. Res.*, *96*(C8), 15137–15146.

Steiger, S., R. E. Orville, and G. Huffines (2002), Cloud-to-ground lightning characteristics over Houston, Texas: 1989–2000, *J. Geophys. Res.*, *107*, 4117–4129.

Sutton, R. T., and D. L. R. Hodson (2005), Atlantic Ocean forcing of North American and European summer climate. *Science*, *290*, 2133–2137, doi:10.1126/science.1109496.

Tarifa, J. R., and G. Armani (2001), The urban climate. University of São Paulo, 199 p., (in Portuguese).

Trenberth, K. E., and J. W. Hurrell (1994), Decadal atmosphere–ocean variations in the Pacific, *Clim. Dyn.*, *9*, 303–319.

Trenberth, K. E., and D. J. Shea (2006), Atlantic hurricanes and natural variability in 2005, *Geophys. Res. Lett.*, *33*, L12704, doi:10.1029/2006GL026894.

Trenberth, K. E., et al. (2007), Observations: Surface and Atmospheric Climate Change, in Climate Change 2007: The Physical Science, Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 11p.

Vecchi, G. A., A. Clement, and B. J. Soden (2008), Examining the tropical Pacific's response to global warming, *EOS Trans.*, *89*(9), 81–83, doi:10.1029/2008EO090002.

Vicente, A. K. (2005), Extreme precipitation events in the Metropolitan Area of Campinas, Master Thesis, University of Campinas.

Wang, C., and J. Picaut (2004), Understanding ENSO physics – a review, in Earth's Climate: the ocean–atmosphere interaction, edited by C. Wang, S. Xie, and J. A. Carton, Geophysical Monograph Series, 147pp. 21–48, American Geophysical Union, Washington DC.

Watanabe, M., J.-S. Kug, F.-F. Jin, M. Collins, M. Ohba, and A. T. Wittenberg (2012), Uncertainty in the ENSO amplitude change from the past to the future, *Geophys. Res. Lett.*, *39*, doi:10.1029/2012GL053305.

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

Wiedenmann, J. M., A. R. Lupo, I. Mokhov, and E. A. Tikhonova (2002), The climatology of blocking anticyclones for the Northern and Southern Hemispheres: block intensity as a diagnostic. *J. Climate*, *15*, 3459–3473.

Williams, E. R., and G. Sátori (2004), Lightning, thermodynamic and hydrological comparison of the two tropical continental chimneys, *J. Atmos. Solar Terr. Phys.*, *66*, 1213–1231, doi:10.1016/j.jastp.2004.05.015.

Williams, E. R. (2009), The global electrical circuit: A review, *Atmos. Res.*, *91*, 140–152, doi:10.1016/j.atmosres.2008.05.018.