Thunderstorm incidence in Southeastern Brazil estimated 1 from different data sources 2 3 4 O. Pinto Jr.*, K. P. Naccarato, I. R. C. A. Pinto 5 6 {Instituto Nacional de Pesquisas Espaciais, São Jose dos Campos, Brazil} 7 8 *Correspondence to: O. Pinto Jr. (osmar@dge.inpe.br) 9 10 11 Abstract 12 This paper describes a comparative analysis of the thunderstorm incidence in Southeastern 13

Brazil obtained from thunderstorm days observed at two different epochs (from 1910 to 1951 14 and from 1971 to 1984) and from lightning data provided by the Brazilian lightning location 15 16 system RINDAT (from 1999 to 2006) and the Lightning Imaging Sensor (LIS) on board the TRMM satellite (from 1998 to 2010). The results are interpreted in terms of the main synoptic 17 patterns associated with thunderstorm activity in this region, indicating that the prevailing 18 synoptic pattern associated with thunderstorm activity is the occurrence of frontal systems and 19 20 their modulation by the South Atlantic Convergence Zone (SACZ) and topography. Evidence of urban effects is also found. The results are also discussed in the context of practical 21 applications involving their use in the Brazilian lightning protection standards, suggesting that 22 the present version of the Brazilian standards should be revised incorporating RINDAT and 23 24 LIS data. Finally, the results are important to improve our knowledge about the limitations of the different techniques used to record the thunderstorm activity and support future climatic 25 26 studies.

28 1 Introduction

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30 The thunderstorm incidence in a given place can be recorded by different techniques. The first technique used to record thunderstorm activity was to record the number of days per year in 31 32 which an observer heard at any time of the day, thunder. This technique was called thunderstorm days - TD (WMO, 1953; Rakov and Uman, 2003). This technique has been 33 34 used since the end of the nineteenth century for different applications (e.g. Changnon and Hsu, 1984; Pinto, 2009; Bielec-Bakowska and Lapikasza, 2009; Wei et al., 2011). One of the 35 36 main applications of TD is provide information to lightning protection standards through the so-called isoceraunic maps (Rakov and Uman, 2003). Such maps have been extensively used 37 in many national lightning protection standards. More recently, these maps have been 38 replaced by lightning density maps obtained by lightning location systems (LLS) or optical 39 40 satellite instruments (Diendorfer et al., 2009). Another important application of TD data is 41 study climatic changes in the thunderstorm activity (Pinto and Pinto, 2008).

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In the second half of the twenty century other technique to monitor the thunderstorm activity 43 44 became available, the lightning location systems (LLS). More recently optical lightning sensitive sensors on board satellites have been used to monitor thunderstorm activity on large 45 scale. However, all techniques have limitations. For instance, TD values are subject to 46 limitations related to changes in the operational man-made procedure adopted to make the 47 48 observations. Also changes in the environment or the local orography around the observational site may influence the maximum distance from the site that thunder is heard. 49 More details about the other limitations are described elsewhere (Changnon and Hsu, 1984). 50 In turn, observations by LLS and optical sensors are subject to changes in the sensor detection 51 52 efficiency due to variations in ground conductivity, satellite orbit, among others.

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This paper describes a comparative analysis of the lightning incidence in Southeastern Brazil obtained from thunderstorm days observed at two different epochs (from 1910 to 1951 and from 1971 to 1984) and from lightning data provided by the Brazilian lightning location system - RINDAT (from 1999 to 2006) and by the Lightning Imaging Sensor (LIS) on board the TRMM satellite (from 1998 to 2010). Previous comparative analyses in Brazil (Pinto and Pinto, 2003) were limited to a smaller number of data sources and data sample. The analysis here is restricted to this region of Brazil due to fact that it is the unique region of the country where thunderstorm day data for two different epochs and RINDAT data are available.

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In the Southeastern region of Brazil, the main synoptic patterns associated with thunderstorm 63 64 activity are believed to be the occurrence of frontal systems (Cavalcanti and Kousky, 2003) and local convection related to topography (Campos et al., 2011), although no detailed study 65 66 exists. Frontal systems are frequent throughout the whole year, come from Argentina and sometimes are preceded by deep convection, called pre-frontal (Andrade, 2007). Their 67 frequency of occurrence is modulated by many mechanisms, among them the so-called South 68 Atlantic Convergence Zone (SACZ), a prominent band of cloudiness extending from the 69 70 Amazon region to the subtropical Atlantic Ocean, passing over the Southeastern region 71 (Carvalho et al., 2002), and by blocking anticyclones (Wiedenmann et al., 2002), which in turn are influenced by large scale phenomena such as Southern Oscillation - ENSO (Barros et 72 al., 2002; Wiedenmann et al., 2002). The SACZ is developed when the convection from a 73 74 cold front is coupled with the Amazonian convection, forming a zone of heavy precipitation oriented northwest-southeast all along Brazil that lasts for several days to weeks. 75

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77 2 Data sets and Methodology

78 Three different data sources related to the thunderstorm activity were used in this study. The 79 first set of data comes from man-made TD observations in two different epochs. One corresponds to observations made in the first half of the twentieth century between 1910 and 80 81 1951 from a small (53) number of observation sites and the period of observations at different sites varies from 5 to 42 years. These observations were part of a global effort of the World 82 83 Meteorological Organization (WMO, 1953) to obtain a global map of the thunderstorm activity. In Brazil they were done in all regions of the country. Figure 1 shows the location of 84 the sites for this period in Southeastern region. The other corresponds to observations made 85

between 1971 and 1984, considering a larger number (500) of observation sites. Again, the
period covered by the observations changes considerably in different states, varying from 5 to
14 years. Figure 2 shows the location of the sites for this period in the Southeastern region.
Most of the observational sites mentioned above are not operational anymore. Only airports
still keep recording thunderstorm days at the present time.

91 The two other datasets used in this study are thunderstorm-related lightning data recorded by 92 two different techniques. One set comes from cloud-to-ground lightning data obtained by the RINDAT network, a LF network that partly covers the Brazilian territory, from 1999 to 2006 93 (Pinto et al., 2007). This information is believed to be the most accurate available information 94 95 to describe the thunderstorm activity in a given region and in this study is considered as a 96 ground true. Figure 3 shows the location of the lightning sensors in the Southeastern region. The sensors are LPATS and IMPACT sensors and the baseline is typically 350 km. The 97 98 performance of RINDAT network was evaluated extensively in the past (for a review see 99 Pinto, 2009). For the Southeastern Brazil, the average RINDAT flash detection efficiency is 100 thought to be approximately 85%.

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The third dataset is total lightning data observed by the Lightning Imaging Sensor (LIS), an 102 103 optical sensor on board the Tropical Rainfall Measuring Mission (TRMM) satellite, obtained 104 from 1998 to 2010 (Christian et al., 1999). Due to the orbital characteristics of the TRMM satellite, LIS data needs a long period of integration to provide a reliable pattern. In this study, 105 13 years of data were used, although a definitive pattern was obtained after 10 years of data. 106 107 LIS data are corrected by local time detection efficiency and view time dependence on latitude (Naccarato et al., 2008) and converted to cloud-to-ground data assuming an intracloud 108 109 to cloud-to-ground ratio of 4, which is obtained by comparing RINDAT and LIS flash data (Pinto et al., 2003). This value, however, can change at different places due to the 110 predominance of different types of thunderstorms at different locations; in consequence, the assumption 111 of a constant ratio should be seen as a first approximation. In particular, in the Southern region of Brazil 112 113 where a larger number of mesoscale convective systems occurs compared to the other regions makes, this 114 ratio is probably higher.

116 3 Results and Discussion

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Figures 4 and 5 show maps of the average annual number of thunderstorm days for a 118 resolution of approximately 50 km (0.5° x 0.5° grid cell). Here, we have used a 0.5° x 0.5° 119 grid cell for plot thunder records, to avoid a high interpolation error due to the limited number 120 of stations. Figure 4 corresponds to the observations made between 1910 and 1951 and Figure 121 5 to observations made between 1971 and 1984. We assume here that the interannual 122 variability is negligible, because for some cells the relative differences in Figures 4 and 5 are 123 higher than 100%. Those differences are too high to be associated only to interannual 124 125 variations.

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Figure 6 shows data obtained from RINDAT from 1999 to 2006 presented in two different 127 128 ways. Figure 6a shows cloud-to-ground lightning flash density in flashes/km², year for a 10 km resolution, the best resolution that can be obtained considering the time period. Data are not 129 corrected for the detection efficiency of the system. Figure 6b shows RINDAT data converted 130 131 to thunderstorm days in the same resolution of Figures 4 and 5 (50 km), assuming that if lightning is recorded in a circle of radius of 15 km (the typically range of thunder audibility -132 133 Rakov and Uman, 2003) centered in a given cell in a given day, this day is classified as a thunderstorm day in that cell. Figure 6c shows a comparison of thunderstorm days computed 134 by thunder observations and estimated from RINDAT data for three different ranges: 5, 10 and 135 15 km in the Guarulhos International Airport in São Paulo, supporting that 15 km range of 136 thunder audibility as a reasonable value. The same analysis was done for the other 8 airports 137 in the Southeast Brazil where thunderstorm observations are still done routinely obtaining 138 139 values between 10 and 15 km.

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Finally, Figure 7 shows the cloud-to-ground flash density obtained from LIS data in the Southeastern Brazil for a resolution of approximately 50 km (0.5° x 0.5° grid cell), after correcting the data for detection efficiency and view time and converting total to cloud-to-ground flash as explained previously. The resolution of LIS data is limited by the

145 view time of the satellite and the time period of the data.

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147 From the analysis of Figures 4 to 7 several aspects related to physical processes responsible for the thunderstorm activity are evident. First, all figures show a systematic decrease from 148 149 the lower left corner to the upper right corner. This variation is consistent with the location of the SACZ, which develops oriented northwest-southeast along the Southeastern region and 150 151 lasts for several days in the summer causing deep convection. Second, from the high resolution data in Figures 6a it can be seen that the thunderstorm activity is also modulated by 152 153 the orography, which is shown in Figure 8. The influence of orography has been discussed also by Bourscheidt et al. (2008). Third, also from Figure 6a it can be seen a large spot (the 154 region in white in the state of São Paulo) of high flash density coincident with the location of 155 the city of São Paulo, the largest city of the country with population larger than 10 million 156 157 people, suggesting that the urban activity is affecting the thunderstorm activity (Naccarato et 158 al., 2003; Pinto et al., 2004; Farias et al.; 2008; Bourscheidt et al., 2012). The effect of orography and urban area are not evident in the low resolution data in Figures 4, 5, 6b and 7. 159 In general, these results suggest that the prevailing synoptic pattern associated with 160 161 thunderstorm activity in the Southeastern Brazil is the occurrence of frontal systems and their modulation by the SACZ and the orography, and in the particular case of the city of São Paulo 162 by the urban activity. 163

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165 From the analysis of Figures 4 to 7 also a practical relevant result is evident. At present time, the observations of thunderstorm days shown in Figures 4 and 5 are used to produce the 166 isoceraunic maps presented in the Brazilian Standard for protection of structures against 167 lightning (ABNT NBR-5419). The isoceraunic values in the maps are converted to flash 168 density and used in the standards to define the level of protection. In order to test if these 169 170 maps represent accurately the thunderstorm spatial distribution in this region, a linear correlation analysis between these maps and RINDAT and LIS data was performed. Figure 9 171 172 shows the correlation of the RINDAT data converted as described above with the data Figures 4, 5 and 7. The highest correlation is found between thunderstorm days computed from 173

174 RINDAT and LIS flash counts. This result suggests that LIS data can replace thunderstorm175 days in the Brazilian standards.

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177 4 Conclusions

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179 The results of this study of the thunderstorm activity in the Southeastern Brazil indicate that:

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the prevailing synoptic pattern associated with thunderstorm activity in the
 Southeastern Brazil is the occurrence of frontal systems and their modulation by the
 SACZ and the orography, and in the particular case of the city of São Paulo by the
 urban activity;

the thunderstorm day values obtained from 1971 to 1984 with a large number of
 observational sites represent quite well the thunderstorm spatial distribution in the
 Southeastern Brazil as observed by lightning data obtained by the Brazilian lightning
 location system - RINDAT from 1999 to 2006. In contrast, the thunderstorm day
 values obtained from 1910 to 1951 with a lower number of observational sites fail to
 represent this spatial distribution. This result suggests that the Brazilian Standard for
 protection of structures against lightning (ABNT NBR-5419) should be revised;

the better correlation of RINDAT data with LIS data than with thunderstorm day data
 suggest that LIS data could be used to replace the past thunderstorm days in the
 Brazilian standards for lightning protection.

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Finally, the results are important to improve our knowledge about the limitations of the different techniques used to record the thunderstorm activity and support future climatological studies.

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Figure 1. Location of the 53 observation sites in the Southeastern Brazil used to record thunderstorm

277 days from 1910 to 1951. The names of the states are also indicated.

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280 Figure 2. Location of the 500 observation sites in the Southeastern Brazil used to record thunderstorm

281 days from 1971 to 1984.





Figure 3. Location of the lightning sensors of RINDAT for the period of study in the Southeastern

287 Brazil.





based on observations between 1910 and 1951.



Figure 5. Map of the average annual number of thunderstorm days in the Southeast region of Brazil

- based on observations between 1971 and 1984.





Figure 6. Map of the (a) average annual flash density in flashes/km².year and (b) average annual number of thunderstorm days in the Southeast region of Brazil based on RINDAT lightning data obtained from 1999 to 2006; (c) Thunderstorm days in the Guarulhos International Airport in São Paulo based on man-made observations (heard) and estimated from RINDAT for three different ranges: 5, 10 and 15 km.



- 313 Figure 7. Map of the cloud-to-ground flash density in the Southeast region of Brazil based on lightning
- 314 LIS data obtained from 1998 to 2010.











Figure 9. Scatter plot of the correlation between RINDAT data converted to thunderstorm days with: (a)
thunderstorm days from 1910 to 1951 (Figure 4); (b) thunderstorm days from 1971 to 1984 (Figure 5);
(c) flash density from LIS (Figure 7). In all plots the value of the correlation coefficient (r) is indicated.
All data have a resolution of approximately 50 km (0.5° x 0.5° grid cell).