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Key Points:

- Lightning/thunderstorm activity over Sao Paulo is analyzed with 11 years of data
- The onset of thunderstorms and lightning activity seems to have a close relation with the UHI
- Surrounding terrain, country breeze, sea breeze, and SACZ seem to amplify the UHI effects

Supporting Information:

- Supporting Information S1
- Movie S1

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The effects of Sao Paulo urban heat island on lightning activity: Decadal analysis (1999–2009)

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Abstract Eleven years of lightning data from the Brazilian Integrated National Lightning Detection Network were used to analyze the effects of the urban heat island (UHI) of Sao Paulo on lightning activity, extending the investigation of previous works. Cloud-to-ground lightning data were analyzed in both spatial and temporal perspectives, using different approaches: flash density, flash rate, thunderstorm hours (TH), and the cell initiation technique (CIT), which aims to identify the onset of thunderstorms. Land surface temperature (LST) from MODIS (Moderate Resolution Imaging Spectroradiometer) was used to analyze the UHI evolution over the years. MODIS data were validated using ground stations, distributed within the urban area. Different time intervals (seasonal and intraday) were used in an attempt to separate local convective systems from synoptic-scale events. The results indicate significant effects of the UHI (using LST) on THs and CIT. The CIT showed a nearly ring pattern, especially during the afternoon (14:00–18:00 LT) of summer months, reinforcing temperature contrast as a condition for storm initiation. The results also suggest an amplification of the UHI effects on thunderstorm activity by local factors (sea and country breeze, synoptic events, and terrain). Higher flash rates were also observed throughout the urban region, which influences the lightning density. Temporal analysis indicates that minimum temperature and lightning activity increase in wintertime. In summary, the results agree with previous studies about the UHI and indicate its importance on lightning occurrence, especially by increasing the temperature contrast and the instability in these regions.

1. Introduction

The development of lightning climatologies using data from Lightning Location Systems aims to identify patterns/trends in the lightning activity over long periods as well as to identify the possible physical aspects associated with these patterns. Among the most common physical aspects associated with lightning distribution are the urban effects, referring generally to the temperature and aerosol hypothesis [*Naccarato et al.,* 2003; *Steiger et al.,* 2002; *Westcott*, 1995]. The aerosol hypothesis relates to the effects of pollution over and around urban areas. The temperature hypothesis, on the other hand, relies on the surface temperature contrast caused by the differential heating, which generates instability over those regions. This heating is produced primarily by the alteration of surface thermal properties (heat capacity and thermal conductivity, as well as albedo and emissivity) and evapotranspiration ability and surface roughness (canyon geometry), which is directly related to the way that radiation interacts with the surface (increased surface area, multiple reflection by buildings, etc.). A secondary contribution may come from anthropogenic sources, like the production of heat by engines, industries, and air conditioners [*Landsberg*, 1981; *Oke*, 1982].

The effects of urban heat islands (UHIs) on the lightning distribution have been investigated by several authors and usually indicate an increase in the activity over and downwind of urban areas, with variations related to the size of those areas, surrounding topography, etc.[*Orville et al.,* 2001; *Soriano and de Pablo*, 2002; *Stallins et al.,* 2006]. Many researchers have also focused on the UHI effects on rainfall, as well as on different characteristics depending on the spatial scale of thunderstorms, i.e., small scale (local convection) or synoptic scale (frontal systems) [*Bornstein and Lin*, 2000; *Haberlie et al.,* 2015; *Shepherd et al.,* 2002]. The paper by *Stallins and Rose* [2008] presents an interesting review of many of these and other related studies. Besides the effects on the rainfall, thunderstorm occurrence, and lightning distribution, the understanding of the effect of UHIs on the onset of convective systems has become a recent concern for researchers [*Haberlie et al.,* 2015].

In the Brazilian case, different studies indicate relations of the urban areas with the lightning activity, showing in general an increase over these areas [*Farias et al.,* 2009; *Naccarato et al.,* 2003; *Pinto et al.*, 2013, 2004]. With regard to temperature, *Naccarato et al.* [2003] have found a close spatial relation between lightning activity

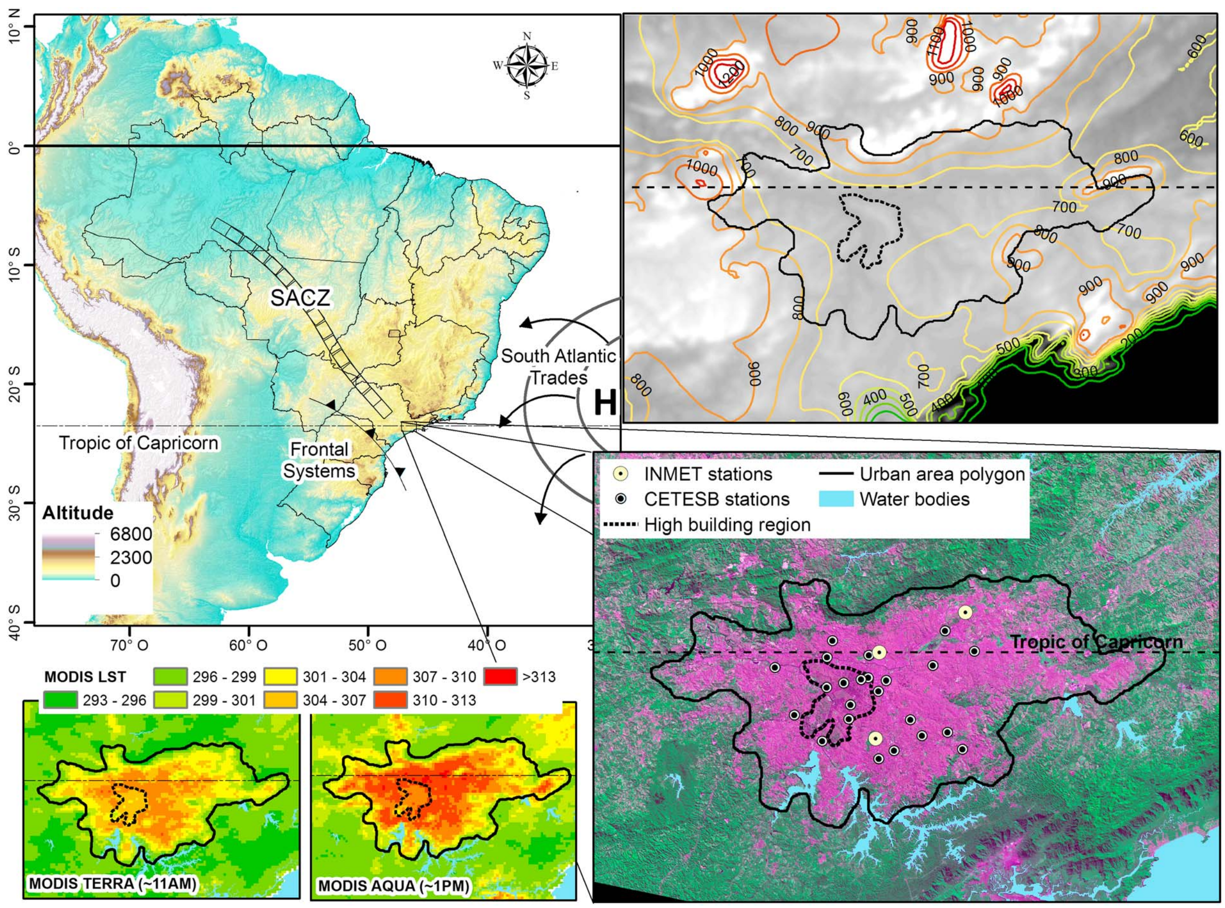

Figure 1. The study region. The black polygon was used to delimit the continuous urban area of the Sao Paulo Metropolitan Region. The inner black dashed polygon indicates the area with the tallest buildings (urban canyons), and yellow and white/black dots are the ground stations. The upper right image shows the altitude variations in gray scale; the contour lines are based on a smoothed version of the elevation model. Lower left figures show the surface temperature based on MODIS LST (Aqua and Terra), which indicates variations in the LST pattern due to the different pass time of the satellites. Some main trades and synoptic events affecting the region of Sao Paulo are also highlighted in the large map.

and the UHI of Sao Paulo using data over three years (2000–2002). On the temporal perspective, studies in the same region have also shown relations between lightning activity (considering thunderstorm days—i.e., days in which thunderstorms were noted—gathered from ground stations through five decades) and temperature, suggesting an increase in the trend over the years [*Pinto and Pinto*, 2008].

The weather in the Sao Paulo region is also known to be influenced by the sea breeze, especially in the early afternoon (14:00–16:00 LT), when the main wind flow changes direction, moving from northeasterly/northwesterly to southeasterly, making the sea breeze front flow over the mountain range along the coastline (see Figure 1) and accelerate toward the urban area, facilitating the development of thunderstorms [*Freitas et al.,* 2007; *Oliveira et al.,* 2003; *Rodriguez et al.,* 2010; *Vemado and Pereira Filho,* 2016]. *Rodriguez et al.* [2010] suggested that the interaction between the sea breeze and the South Atlantic Convergence Zone (SACZ) could regulate the (non) thunderstorm days in the urban area. Furthermore, the recent study by *Vemado and Pereira Filho* [2016] indicates that the convergence of the northwest winds related to the SACZ and prefrontal conditions with the sea breeze front over the urban area of Sao Paulo could be responsible for the increased number of severe events at this region.

In this paper, different approaches are used to produce a detailed analysis of the relation between lightning activity and the UHI of Sao Paulo, extending the previous studies on both spatial and temporal perspectives. These approaches include flash rate, thunderstorm hours (THs), and the so-called cell initiation technique (CIT). These methods are described in the following section. Additionally, we examine data from meteorological stations to understand the atmospheric dynamics in this region. With this analysis, we expect to produce a more comprehensive understanding about the UHI impact on the lightning activity and thunderstorm occurrences in the region of Sao Paulo.

2. Methodology

2.1. The Study Region

The Sao Paulo urban area is shown in Figure 1. With an average altitude of 770 m above sea level (asl), it is about 60 km from the coastline and separated by a mountain range [*Oliveira et al.,* 2003]. Additionally, the main urban region is confined by the mountains to the southeast and two other main mountain ranges in the western sector and to the north, which affect the main wind pattern observed through the region. This is shown by the top right gray scale image based on SRTM (Shuttle Radar Topography Mission) elevation model and the smoothed contour lines. Besides the influence of the sea breeze mentioned previously, the weather is governed by three major synoptic conditions: the northwesterly winds related to the SACZ; the quasi-stationary South Atlantic Anticyclone, defining the trade winds from east; and the frontal systems that move southeasterly, reinforcing the southeastward flow over the urban area during prefrontal conditions. Those configurations are also highlighted in Figure 1. A more complete analysis of the synoptic conditions and the sea breeze effects the readers may find is in the recent paper by *Vemado and Pereira Filho* [2016].

With regard to the urbanized surface, there is an almost continuous area with some branches of expansion. Based on the continuous surfaces, the authors manually defined the polygon used to analyze all of the data (black polygon in Figure 1), using Landsat 5 images as background. Due to the latitude of the city (almost at the Tropic of Capricorn), there are regular shade effects on the satellite images and lower surface temperatures (as observed in the lower left maps) in the region close to the urban core. These surface temperature maps were produced by averaging Moderate Resolution Imaging Spectroradiometer (MODIS) LST (Aqua and Terra) over five years (2005–2010). Each platform has a different average pass time, resulting in images for the period around 11:00 LT and 13:00 LT, respectively. The shade from the Landsat image and the lower surface temperatures from MODIS indicate the areas with higher buildings (defined by the black dashed polygon), which are expected to act as a barrier and change the natural flow over the area.

2.2. Data and Methods

Eleven years of data (1999–2009) from the Brazilian National Integrated Lightning Detection Network (RINDAT) were used to develop the lightning climatology based on different approaches: flash count inside the urban mask; flash rate, gathered in 10 min intervals; thunderstorm hours (THs); and the cell initiation technique (CIT), which attempts to identify new thunderstorm cells. All climatologies were produced over the region defined by the rectangle and the black polygon shown in Figure 1, which also shows the topography/elevation in the study region.

THs were accumulated over a grid with spatial resolution of 5 km (to ensure a good sample size) using a binary rule (if there was any discharge inside a grid cell during an hourly interval, there is an increment in the THs for that same cell). The results were then resampled to coincide with the grid cell size of the CIT analysis (1.5 km). THs are used along with the flash count because this approach is believed to be less dependent on the Lightning Location System performance variations over the years, as discussed in *Bourscheidt et al.* [2012a]. In the paper, the authors demonstrate that as one moves from the flash count to THs and thunder days, the impacts of the system performance on the resulting temporal analysis are reduced by factors of around 2 and 2.5, respectively. In the spatial perspective, the reductions are similar.

The CIT values are obtained based on the spatial and temporal analysis of the discharges: if an event does not precede another in a given time interval and search radius, this event will count as a CIT, indicating that a new thunderstorm cell is starting. Additionally to these criteria, more conditions were applied to improve the following results:

1. Only negative discharges are considered to avoid discharges from stratiform regions (mainly positive discharges) of being counted as a CIT.
2. A forward-time criterion (3 min) is used to avoid unexpected isolated events. Thus, if an event passes the previous criteria, but is not followed by other discharge after 3 min, the event is discarded.
3. Events with significant location errors, i.e., ellipse’s semimajor axis larger than 5 km, are also rejected.

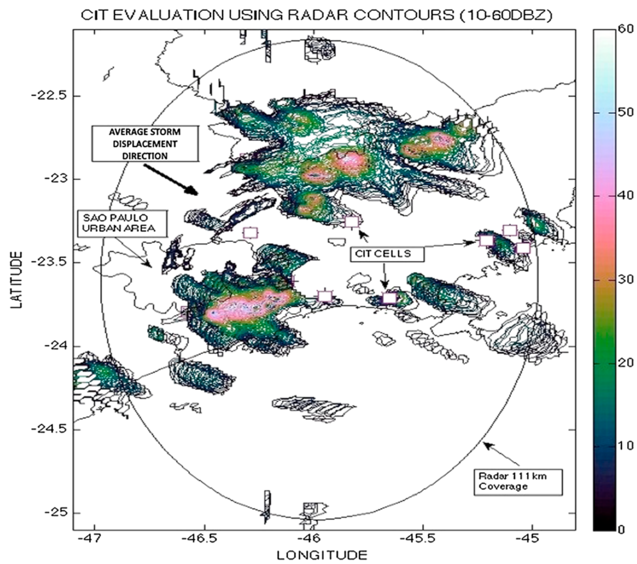

Figure 2. Example of CIT validation using radar: radar contours starting at 16:37:01 on 17 February 2008 and accumulated over time (5 min interval) indicate the storm propagation (thicker black arrow indicates the main direction), and the black white squares specify the CIT.

Radar data were used to validate the proposed method. Figure 2 illustrates the radar contours (10–60 dB*Z*), starting at 16:37:01 on 17 February 2008 and accumulated over time. The large arrow indicates the thunderstorms displacement direction observed in radar data, which is supported by other studies [*Held and Escobedo*, 2010]. The small rectangles specify the location of the onset obtained with the CIT method. A general good agreement between the cells onset and the radar information was observed. This methodology was previously used by the authors to analyze the relation of lightning activity with terrain features [*Bourscheidt et al.,* 2012b]. CIT events were interpolated using the Gaussian kernel, which gives a smoothed surface that is independent of the grid cell size, allowing to create a final map with a grid cell size of 1.5 km.

To go further in the analysis of lightning activity, flash rate maps were produced considering the average value and the 90th percentile based on data accumulated in 10 min intervals (and then converted to flashes per minute). Flash rate might give better information on the storm cell characteristics than the flash density. A spatial resolution of 5 km was used to avoid having flash rates from (moving) storms sprawled over many different cells, which may increase the bias in the results. *Held and Escobedo* [2010] found that the displacement speed for most of the storm systems (85%) is around 35 km/h in the central area of Sao Paulo State, which means about 6 km in 10 min. These maps were also resampled to 1.5 km resolution.

Surface temperature was obtained from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor through the land surface temperature (LST) product (MOD11, for reference). With a Sun-synchronous orbit, MODIS joins two platforms (Terra and Aqua) and is able to provide images for four distinct times each day (around 10:00, 14:00, 23:00, and 01:00 in the studied region). Data availability dates back to 2000 and 2002 for Terra and Aqua, respectively. Average values were obtained within a 5 km grid and then resampled to 1.5 km as well. Further information about MODIS LST products may be found in *Wan and Dozier* [1996].

To check for trends in the surface temperature over the years in the urban area, MODIS LST average values for summer months (December–March) were collected until 2010 within the urban polygon (according to Figure 1), as an attempt to identify the recent expansion of the UHI (with the sprawl of the urban area, more pixels with higher temperature are expected within the urban polygon, increasing the average temperature).

The LST products were validated against ground stations from Company of Environmental Sanitation Technology of Sao Paulo (CETESB) (http://www.cetesb.sp.gov.br). Figure 3 summarizes the validation, including the diurnal cycle (average temperature) obtained with ground stations, along with the r^2 value for the linear relation between ground stations and the four daily MODIS LST products. The agreement of MODIS data and ground stations is generally good. Since MODIS LST is estimated from surface emissivity, and ground stations measurements result from the air temperature near to the ground, a better agreement of the data sets is expected at nighttime, when the turbulent flux is minimum and temperature depends mainly on the longwave radiation from the surface. Figure 3 also indicates that MODIS tends to overestimate temperature during day and underestimates the temperature during night, which might be related to the heat exchange between surface and air (the heat transfer from the surface to the air is slower) and/or to the special way that fluxes occur over the urban area (thermal inversion, for example). Furthermore, the brightness temperature

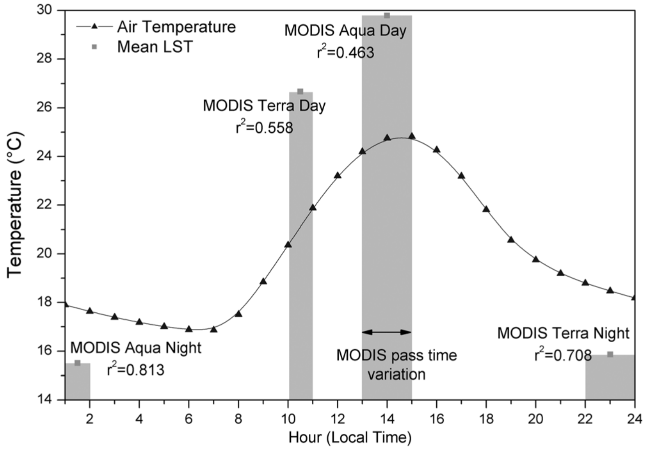

Figure 3. Summary of temperature data validation indicating a general good agreement. The black solid line (with triangle) shows the diurnal cycle based on the average temperature for all the CETESB stations. Columns indicate the average LST and the mean r^2 value for the four MODIS products. The r^2 value for the ground stations related to the daytime LST is quite lower (around 0.5) than that for the nighttime product (around 0.75). Column widths indicate the variation on the view time of the satellites for each product.

results of a mixture of ground and roof thermal values are expected to increase the deviations during daytime.

Along with air temperature, relative humidity (RH) and wind direction data from CETESB stations inside the urban area (as shown in Figure 1) were used to analyze the main synoptic conditions related with the thunderstorm formation. The data are available from 1999 to 2009, although there is an absence of data (temperature and relative humidity) for the year 2004 and few other gaps for single sensors along the specified period, which is not expected to affect the analysis. Wind direction data were organized in polar graphs using the same seasons as for the previous analysis and using hourly intervals based on the normalized frequency. RH and temperature were used to calculate the dew point temperature (T_d) based on the approximation of *Bolton* [1980] for the saturated water vapor pressure and, subsequently, to obtain the dew point depression ($DD = T_{air} - T_d$). The results were then organized in terms of anomaly by hour (h) such that dew point depression anomaly (DDA) = DD(h) − average(DD(h)). This approach was used to identify the days with lower DD, which indicate more moisture in the atmosphere, and how they relate with the main wind flow. To compare the DDA against the wind direction, 2-D histograms were produced. Even though CETESB data are suitable for the wind and DD comparison, the gaps in the data set would affect the creation of temporal trends. Thus, data two stations from the Brazilian National Institute of Meteorology (INMET) and one station from the Institute of Astronomy, Geophysics and Atmospheric Sciences/University of Sao Paulo (IAG/USP) station, from which are also within the delimited urban area in Figure 1, were used to create the temporal analysis.

The results accomplished by the described methods are summarized in the next section, followed by the discussion.

3. Results

Based on MODIS data, there were no trends for the average LST along the years over the urban area of Sao Paulo (using the polygon defined in the methodology). This might be associated with the short period used in the analysis: the urban growth area is estimated to be around 1.5% in the analyzed period [*Young*, 2013] and probably not enough to discriminate new "hot" urban pixels for the available spatial resolution (1 km). In the same way, average air temperature from INMET and IAG/USP ground stations did not show clear tendencies in general. This information is shown in Figure 4 along with the minimum temperature, as a filled area graph for three distinct periods: summer, from December to March; winter, from April to November; and the month of November alone. This month was used as an attempt to define the beginning of the thunderstorm season, when the atmospheric thermodynamic changes could result in more instability and more noticeable thunderstorm formation. Additionally, there are indications that the changes in temperature over the years in Sao Paulo are larger in the intermediary seasons and for wintertime [*dos Santos et al.,* 2006], which is a well-noticed effect of the UHI. This single month analysis, unfortunately, could only be performed in the temporal perspective because the amount of data is not sufficient for a spatial analysis. Figure 4 also indicates the variation in the number of THs and thunderstorm initiation (CIT) inside the urban mask. THs were used due them having less dependence on the network performance, as stated in section 2.

Despite the general scenario, there are some indications of trends, especially in the minimum temperature during wintertime and for the isolated analysis of November (as indicated by the linear fits), which is

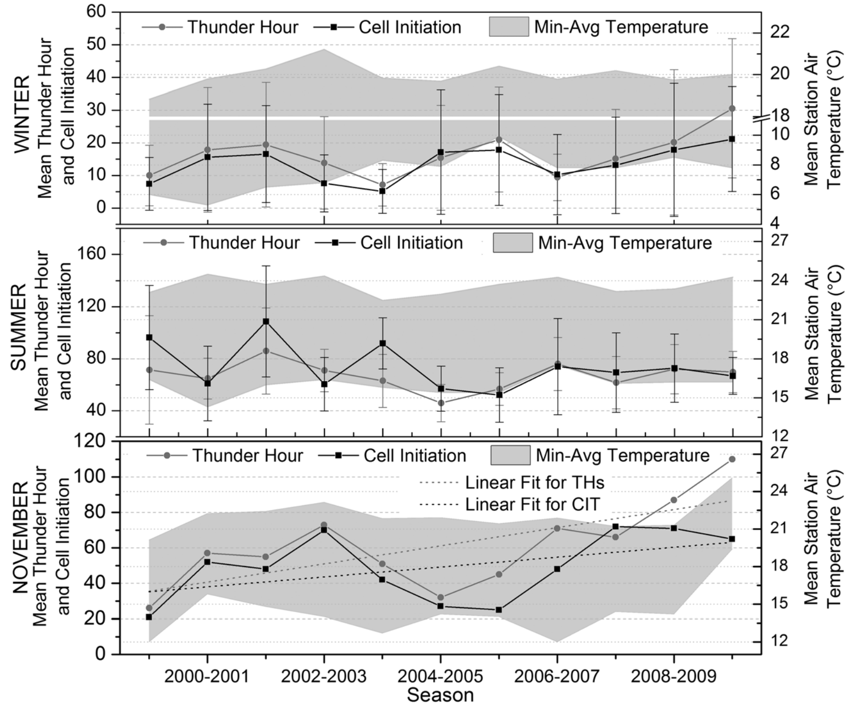

Figure 4. Annual variation of THs, CIT, and air temperature (filled area in gray from minimum to average) for (top) winter months (April–November), (middle) summer months (December–March), and (bottom) for November solely considering data inside the urban polygon and from INMET/USP stations. Dashed lines indicate the linear fit for cell initiation (in black) and thunder hours (in gray). Evidence of positive trends was observed only for the last case.

followed by an increase in the lightning activity. From the average values of the minimum temperature for the three first and the three last years in the winter, for example, it is possible to observe an increase of about 2°C. At the same period, considering the equivalent approach, there is an increase of around 30% and 25% in the number of THs and CIT, respectively. For summertime, on the other hand, there are no observed trends.

Nevertheless, some oscillations seem to occur that might be related to other phenomena (El Niño, La Niña, etc.). Figure 5, which shows a spectral analysis of the daily flash count from 1999 to 2009, indicating three basic cycles (annual, interannual, and longer period cycles), supports this assumption. The previously stated phenomena usually have a period of 3–5 years.

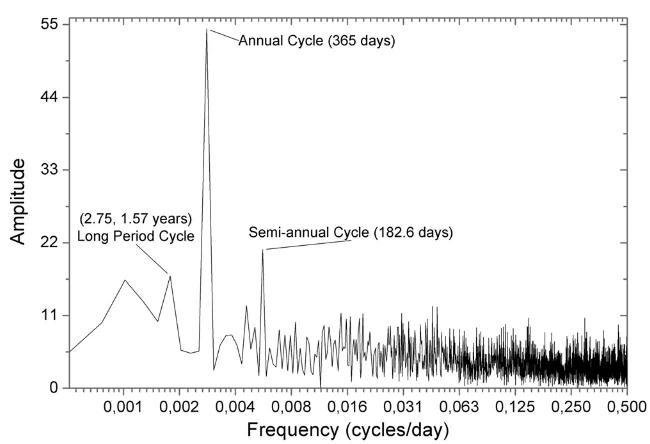

Figure 5. Spectral analysis of daily FC from 1999 to 2009. Three basic cycles are highlighted: annual, semiannual, and long period cycles. The last may be associated with El Niño/La Niña.

Concluding the temporal analysis, Figure 6 summarizes the diurnal variation of the lightning activity, taking into account only data inside the urban polygon and using a half hour scale. Values were normalized as percentages. For the lightning flash activity, the diurnal peak seems to occur at 15:00 h (local time, LT). In the case of CIT, despite the peak at the same time, there seems to be a slight shift among the two distributions, with the CIT being more widespread over time than flash activity,

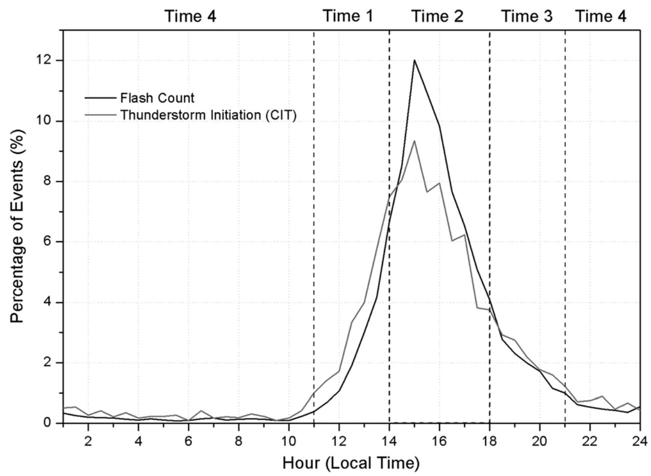

Figure 6. Daily cycle of the lightning activity within the urban mask: flash count (black line) and thunderstorm initiation (gray line). Despite the peak at the same time (15:00 LT), CIT is more widespread over time and seems to anticipate the lightning activity at around midday. Dashed lines define the time intervals used in the spatial analysis.

anticipating the lightning (flash) activity at around midday, which is an expected behavior (storms initiating prior to the maximum lightning activity). The peak time is in agreement with previous studies in lower latitudes [e.g., *Lima and Wilson*, 2008].

The intervals defined by the dashed lines in Figure 6 were used in the spatial analysis summarized in the panel of Figure 7. It shows the results for THs, CIT, and MODIS LST divided into two seasons (summer, from December to March, and winter, from April to November) and four intervals during the day, according to Figure 7: 11:00–14:00 LT (T1), 14:00–18:00 LT (T2), 18:00–21:00 LT (T3), and 21:00–11:00 LT (T4). Those intervals stand as an attempt to separate the effects of different meteorological conditions acting over the region at each time of the day and along the different seasons, separating local convective systems from synoptic-scale events (e.g., frontal systems), as well as other effects expected to depend on season and daytime (e.g., topographic effect and sea breeze). Thus, by applying those intervals over the 11 years of data, we expect to isolate some seasonal and geographic effects keeping the spatial distribution on these conditions. MODIS LST images depend on the satellite pass time, and each product was associated with a specific time interval based on the average value: MODIS Terra day to T1, MODIS Aqua Day to T2, and MODIS Aqua Night associated to T4. As MODIS images for T3 were not available, a weighting factor was applied to estimate the LST for this time interval ($MODIS_{T3} = [MODIS_{T2} \times 1.2 + MODIS_{T4}] / 2$).

From Figure 7, there is a clear concentration of the THs and CIT counts over the urban area predominantly in the summer months during the time interval between 14 h and 18 h LT (rows 1 and 3; column 2 in Figure 7—R1C2 and R3C2). The comparison of these results with the UHI (using the LST from MODIS images, rows 7 and 8), for the same interval, indicates a close relation of the lightning activity with the period of higher surface temperature contrast. This observation may indicate the importance of the heat island, associated with other factors (e.g., moisture and flow direction), in the thunderstorm formation and lightning occurrence, which is discussed in the next section. Temperature may be important in the context of sea surface thermal capacity as well, as being observed in R1C4. The southeast portion of the image (over the ocean) indicates the formation of storms during the night/morning, i.e., an “inverse contrast” in the lightning occurrence related to the land-ocean relation, following the ideas of *Williams and Stanfill* [2002].

When analyzing the thunderstorm initiation from R3C4 in detail (Figure 8a), it seems that a reduction in the number of CIT, i.e., starting storms, occurs around the middle of the urban area, which is not observed in the THs data. Additionally, the separation of the CIT in two more time intervals (Figures 8b and 8c) shows that the ring pattern is more evident between 16:00 and 18:00 LT.

Flash rate maps for the second time interval and during summer period are shown in Figure 9. As stated earlier, flash rate maps result from accumulation of data in 10 min intervals and then converted to flash per minute. Both average values and 90th percentile show a concentration of higher flash rates over the urban area and indicate that storms occur more often over the urban area and have greater flash rates.

Figure 10 explores in more detail the main wind pattern and the (expected) sea breezes effects on the lightning activity and storm initiation, based on the wind data, averaged into daily and seasonal scales for the entire data set. Each wind polar plot refers to a group of months, and the lines with different colors indicate the wind direction at each hour. Along with the polar plots, 2-D histograms show the relation between the dew point depression anomaly (DDA) and the wind direction. There is a general change in the wind direction

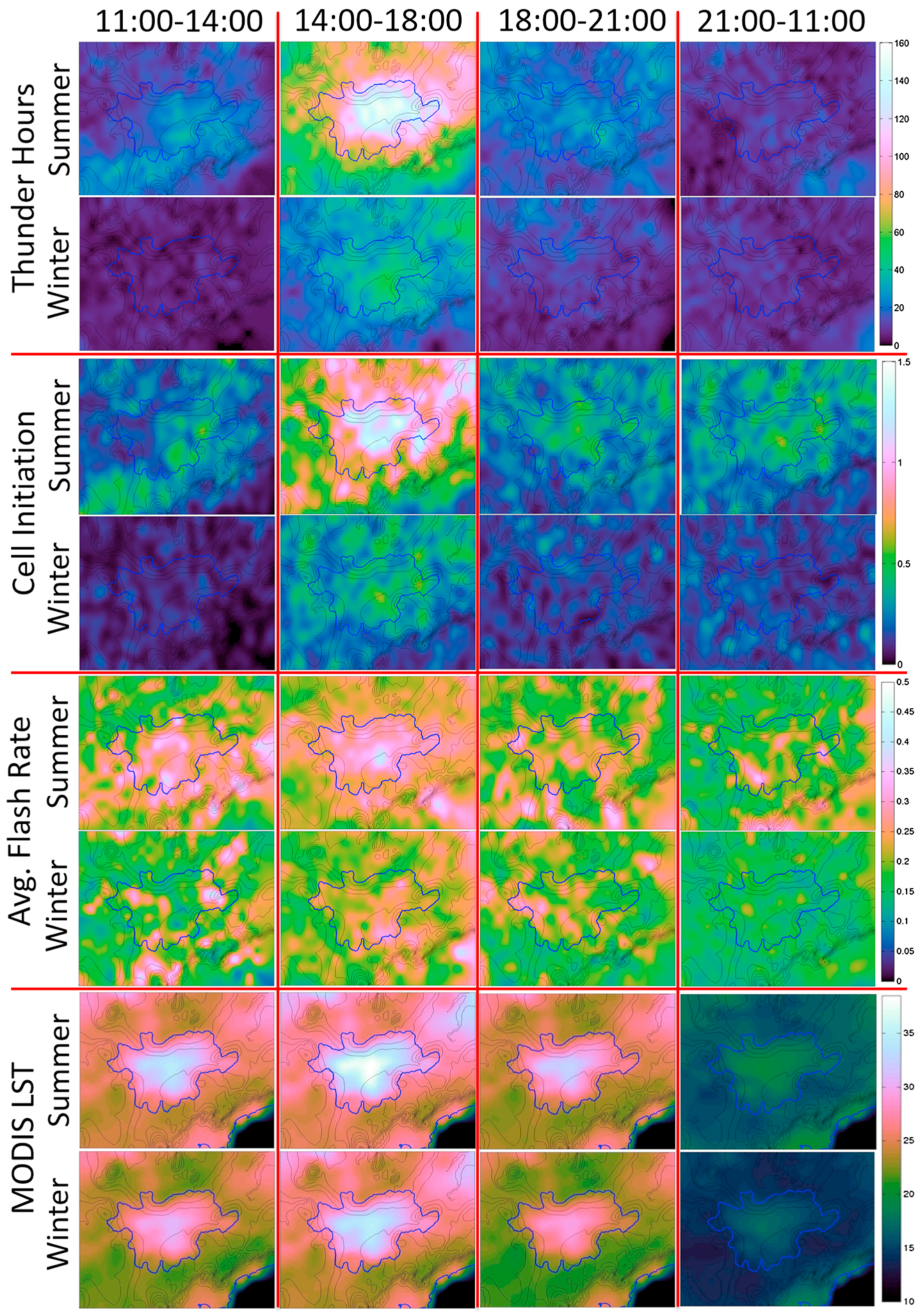

Figure 7. Summarized panel including (rows 1 and 2) THs, (rows 3 and 4) CIT, (rows 5 and 6) flash rate, and (rows 7 and 8) MODIS LST over the urban region of Sao Paulo (thick polyline) for four daytime intervals and two main seasons. Thin black polylines indicate the elevation contours. The dark region from MODIS LST indicates the ocean. Most of the thunderstorm and lightning activity are concentrated in the summer and the time interval between 14:00 and 18:00 LT (R1C2 and R3C2), when the temperature of the urban area is also higher (row 7, column 2—R7C2). Ocean land contrast may be observed in the THs during nighttime (21:00–11:00) (R1C4 and R2C4).

throughout the day, moving from the northeasterly direction in early morning to the northwesterly around 11:00 LT and rapidly changing to southeasterly at around 15:00 LT. It indicates a general agreement with the work of *Rodriguez et al.* [2010] and *Oliveira et al.* [2003], with the inversion of the wind in the afternoon, changing from the mainly northwesterly/northeasterly direction to a southeasterly flow. Further, there are a clear larger number of days with lower DD (negative DDA) for southeasterly winds, which indicates the penetration of the sea breeze. The increase in frequency of northwesterly wind around midday in the austral

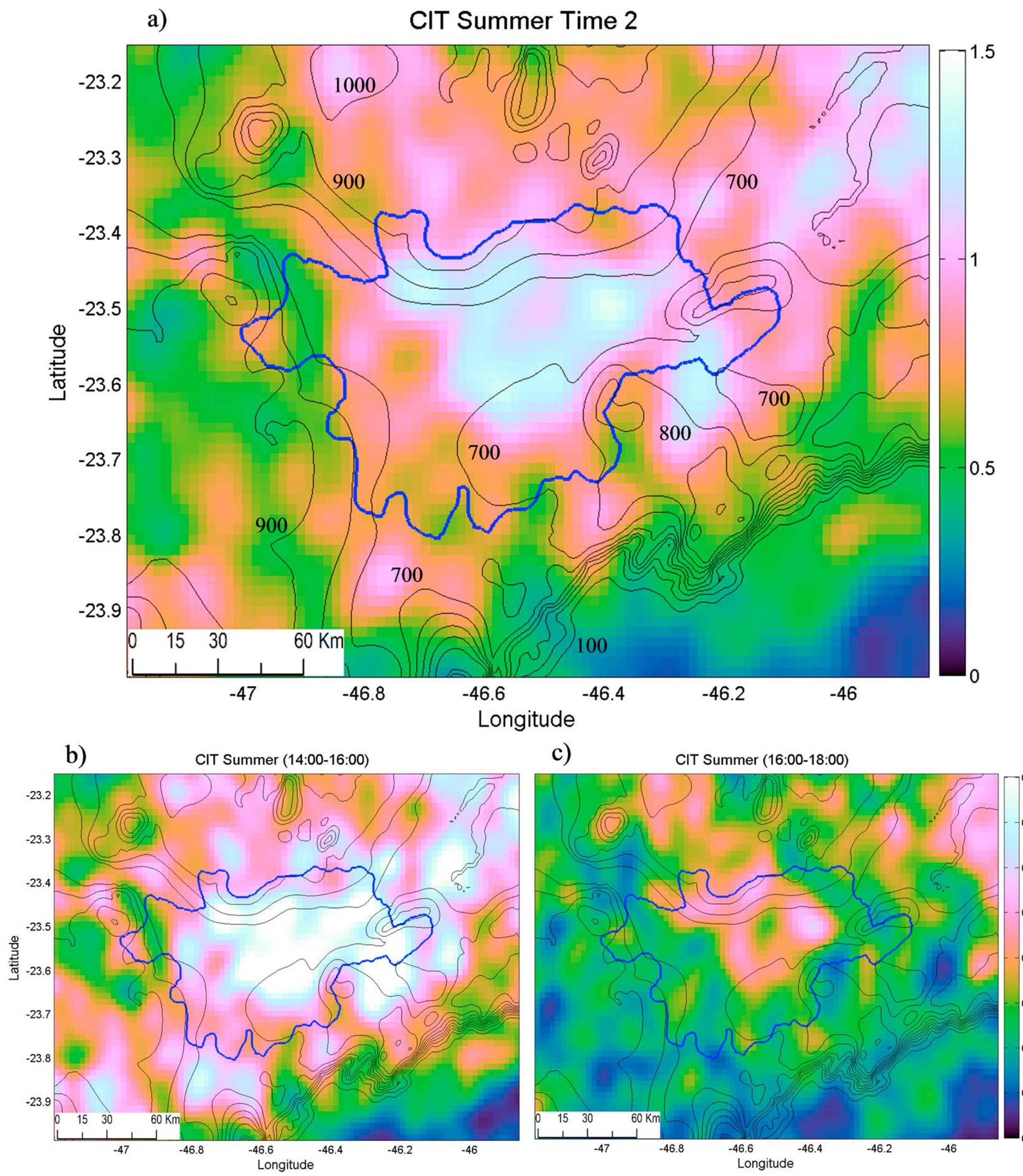

Figure 8. Cell initiation for the summer period and time interval between (a) 14:00 and 18:00 LT shows a nearly ring pattern over the urban area. The slight shift to east might be associated with the high buildings barrier effect in the west portion of the urban area. The separation of this interval in (b) 14:00–16:00 LT and (c) 16:00–18:00 LT indicates that late storms are more related to the ring pattern. Polylines in the plot indicate the elevation contours (thinner, with some labels) and the urban polygon (strong line).

summer (December–March) is possibly related with the propagation of frontal systems and the development of the SACZ [*Carvalho et al.*, 2004; *Dias et al.*, 2013].

4. Discussion

Pinto and Pinto [2008] did already found a close relation between increasing temperatures and the number of thunderstorms over Sao Paulo. What is interesting from this new study is that even for the short analyzed period (2000 to 2009), considering the wintertime (or even the month of November solely), as the minimum temperature increases over the years (which is a noticed effect of the UHI), an increase in the lightning activity is observed. For summer months, no trends were observed for THs, CIT, or

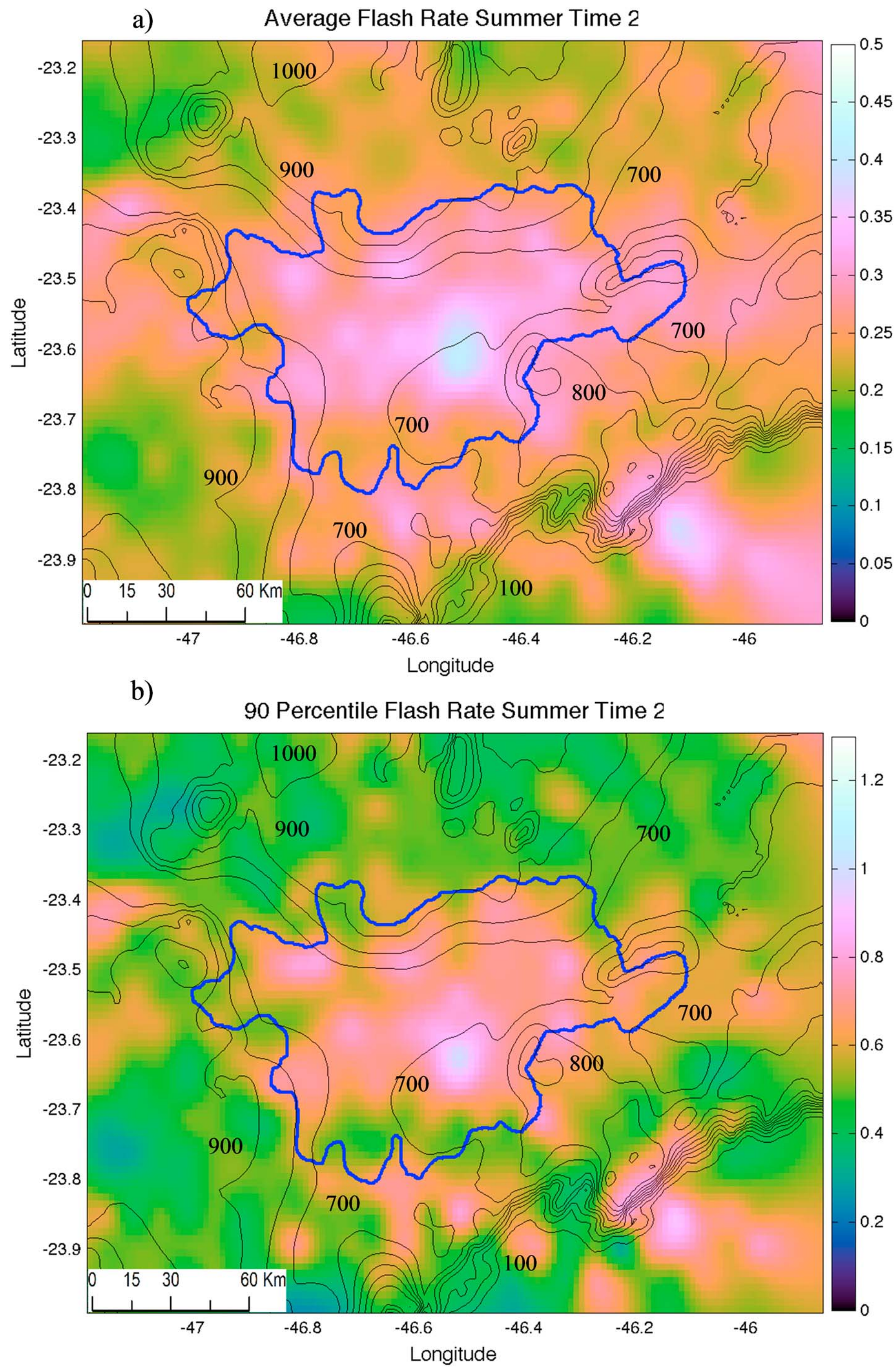

Figure 9. Flash rate for summer period and time interval between 14:00 and 18:00 LT, including the (a) average and (b) the 90th percentile value. Lines in the plot indicate the elevation contours (thinner, with some labels) and the urban polygon (strong line). As for the other variables, these time and season show the highest values right over the urban area.

temperature. It is worth to mention that while in summer the heating conditions for triggering thunderstorm are frequently reached, during the winter, a small change in the temperature is more likely to increase instability and, thus, the formation of thunderstorms. From these observations, it might be possible that an important part of the increasing trends in the thunderstorm occurrence observed over the urban area of Sao Paulo in the last decades could be related with the changes in the minimum temperature caused by the UHI.

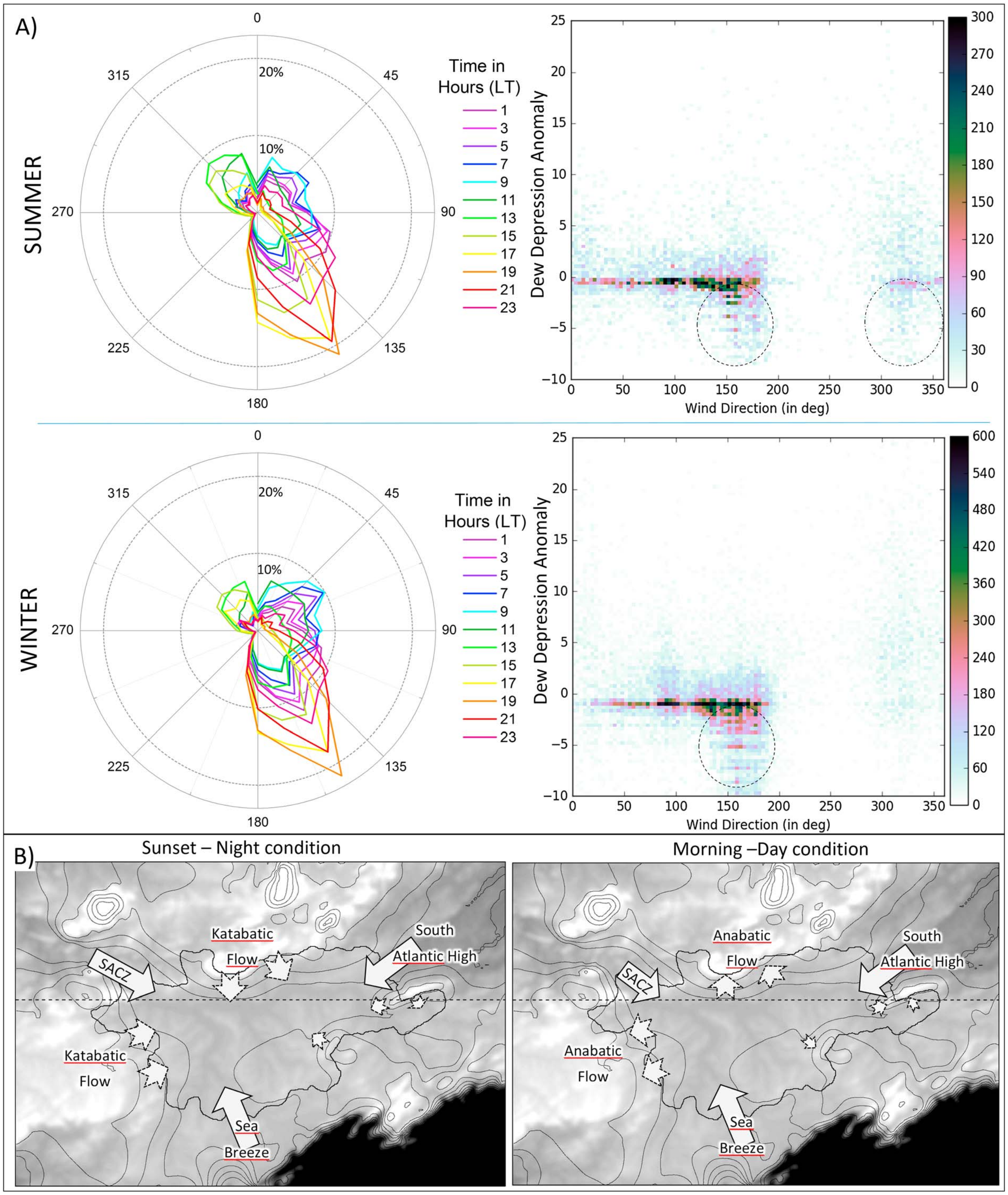

Figure 10. Wind flow and sea breeze effects analysis based on wind and dew point depression for (a) summer and winter: polar wind polygons separated by hour representing the frequency on the left; 2-D histograms of the dew depression anomaly related to the wind direction (azimuth) on the right. Dashed line highlighted areas indicate the sea breeze influence at the urban area. Dash-dotted area indicates the additional effect of the SACZ and prefrontal conditions. From the observed pattern, (b) two schematic models of the main wind flow directions and its origin for summer time and two periods of the day (late afternoon/nighttime, on the left, and morning/daytime, on the right) were produced.

On the spatial perspective, there are some interesting observations. As mentioned in the earlier section, the results from Figures 7 and 8, regarding especially the CIT (and secondarily to THs), indicate that regions with the largest instability are along the urban perimeter and that the temperature variation when moving from rural to urban surfaces is an important factor in the thunderstorms' onset. Especially from Figure 8, storms are expected to start at regions with a large temperature contrast (near to the urban perimeter) and then propagate over the urban area, where actually most of the THs (and discharges) seem to occur. To give a better understanding of the suggested behavior of the thunderstorm formation over the urban area, the hypothesis raised by *Williams et al.* [2004] on the development of storms over isolated islands could be extended to this work. Similarly, the flow would converge over the urban area and trigger the thunderstorms.

This assumption, however, depends on the flow pattern around the urban area. In the particular case of Sao Paulo, different factors seem to act together to define the flow pattern. One of the more important might be the penetration of the sea breeze, characterized as a southeasterly airflow, which reaches the urban area in the early afternoon, as observed in Figure 10. The figure also indicates a northwest flow associated to frontal systems and to the SACZ (a persistent unstable area associated with stationary frontal systems) that may interact with sea breeze by bringing hot, moist air over the studied region, increasing instability and contributing to the amplified lightning activity observed over the urban area. This may explain the existence of a negative DDA in both the southeasterly and northwesterly flows during the summer (Figure 10a) and is in agreement with the observations of *Vemado and Pereira Filho* [2016]. Additionally, there is a main northeasterly flow related with the South Atlantic High trades that is also expected to influence the storm onset and the CIT pattern. Those are considered important factors to increase the thunderstorm occurrence at this region [*Freitas et al.*, 2007; *Oliveira et al.*, 2003; *Rodriguez et al.*, 2010], especially when observing that the CIT ring shape has three main portions that are well aligned with those main flow patterns observed from Figure 10.

Nonetheless, part of the ring pattern observed in Figure 8 is probably associated with terrain (thermal and mechanical) effects, particularly in the northern limit of the urban area in the figure (Figures 8a and 8c mainly), where the CIT events are concentrated along the elevation contour lines, as well as associated with the occurrence of the country breeze. Since the UHI of Sao Paulo is defined not only from the urban and nonurban boundaries but also by the surrounding terrain, it is expected to intensify the effects of the katabatic and anabatic flows, which could also intensify the formation of the country breeze in the late afternoon period under optimal weather conditions, with weak regional winds. This might be the case of some episodes during summer time at the region. All the flow interactions mentioned above are summarized in the schematic model of Figure 10b, which is an attempt to show the convergence caused by different factors and the expected enhancement of the thunderstorm formation and lightning activity related to the UHI. Lastly, the reduced number of CIT events and THs in the west portion of the urban area could result from the urban shape and its barrier effect at this region, as well as due to the existence of water bodies in the southwestern (refer to Figure 1).

Another consideration that is brought to the analysis relates to the high flash rates observed over the urban area, which possibly explains the high flash density observed in other studies at this region [*Bourscheidt et al.,* 2012a; *Naccarato et al.,* 2003]. The higher activity near to the center of the urban area is possibly related to the penetration of the sea breeze as well, which reaches the urban area in the early afternoon, resulting in deep convection [*Vemado and Pereira Filho,* 2016], as described earlier.

Finally, this paper concentrates on the analysis on the UHI thermodynamics and its effect on the lightning/thunderstorm activity. This does not implicate that other factors affecting cloud microphysics are not important for the lightning activity over the urban areas (aerosol hypothesis). In fact, those aspects have already been analyzed in detail and showed significant effects on electrical activity in the region of Sao Paulo [*Farias et al.*, 2009, 2014].

5. Conclusions

The urban heat island (UHI) of Sao Paulo was analyzed using 11 years of cloud-to-ground lightning data. The proposed CIT approach was used together with THs, flash rate, and MODIS surface temperature to evaluate the UHI effects. The results for the spatial analysis were organized into two seasons and four daily intervals and indicate that the lightning activity mainly occurs during the period between 1400 and 1800 (local time) and during the summer months and are closely related with the urban area.

The CIT showed a singular spatial pattern over the urban area, suggesting greater instability associated with the temperature contrast, although some spatial patterns of CIT are possibly related to terrain effects (mechanical forcing or by the mountain-valley breeze). Nevertheless, since the number of CIT events observed is relatively small, a large data set would be important to confirm these hypotheses. Sea breeze penetration seems to be important to the lightning activity and thunderstorm formation, partially defining the CIT-observed ring pattern, especially when interacting with the frontal systems and SACZ in the summer months, which is reinforced by the wind and dew point depression analysis. The ring pattern is also likely affected by the country breeze and by the katabatic/anabatic flows during late afternoon-nighttime and morning-daytime during periods with weak regional winds.

The results are consistent for the land-ocean contrast as well: lightning flashes are concentrated over the sea for the period between 2100 and 1100, indicating an inverse contrast. Flash rate was seen to be higher over the urban area and, along with the increased number of thunder hours and thunderstorm initiation events (CIT), it may be responsible for the higher flash density over this region.

The temporal analysis of the UHI indicates a possible increase in the minimum air temperature which is followed by an increase in the lightning activity for the winter months (and November exclusively) of the analyzed period. The same trend is not observed in the summer months. These results indicate that winter period might be an important part of the increase trends observed in previous studies at the region.

Notation

UHI	urban heat island.
SACZ	South Atlantic Convergence Zone.
CIT	cell initiation technique, specific methodology used in the paper.
TH	thunderstorm hour.
LST	land surface temperature.
asl	above sea level.
LT	local time.
Rs	rows.
Cs	columns.
DD(A)	dew point depression (anomaly).
MODIS	Moderate Resolution Imaging Spectroradiometer.
SRTM	Shuttle Radar Topography Mission, elevation data.
RINDAT	Brazilian National Integrated Lightning Detection Network.
INMET	Brazilian National Institute of Meteorology (joining the WMO).
CETESB	Company of Environmental Sanitation Technology of Sao Paulo.
IAG/USP	Institute of Astronomy, Geophysics and Atmospheric Sciences/University of Sao Paulo.

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