Assessment of the total lightning flash rate density (FRD) in northeast Brazil (NEB) based on TRMM orbital data from 1998 to 2013

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ABSTRACT

The Northeast region of Brazil (NEB) concentrates on average 18 % of the total deaths associated with lightning strikes in Brazil. When considering population, the state of Piauí had the highest mortality rate in the region (1.8 deaths million−1), much higher than the national rate (0.8) and the NEB rate (0.5). This work aimed to evaluate the space-time distribution of total lightning (intracloud, cloud-to-cloud and cloud-to-ground) in NEB, covering the period from 1998 to 2013. For this purpose, we used data from the Lightning Imaging Sensor (LIS) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite, which provided information on the occurrence of total lightning, and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor aboard on TERRA satellite, which provided the terrain elevation data to verify the influence of topography on the flash rate density (FRD). The full distribution was used to identify the hotspots (cities with the highest FRD), while the monthly distribution helped in the cluster analysis. NEB has great spatial and temporal variability of the recorded lightning rates, with average of 0–44.5 flash km−2 year−1. The regions with high total lightning rates are located in the states of Piauí, Maranhão and west of Bahia. The topography of the region seems to act as a facilitator of the convective process, leading to the formation of intense upward currents, essential for the generation of electric charges inside thunderstorms. CAPE values showed good relationship with lightning occurrence in the region. The cluster with the highest occurrence of lightning and hotspots is in the region of influence of the Intertropical Convergence Zone (ITCZ) and Mesoscale Convective Systems, suggesting an important relationship with large organized cloud systems.

1. Introduction

Lightning can generate major problems for society due to its high destructive capacity, which can lead to abnormalities or outage of the electricity distribution network, forest fires, accidents related to transportation such as airplanes and ships, damage to telecommunications systems, and fatalities of humans and animals (Cardoso et al., 2014; Santos et al., 2016). Due to the aggressive characteristics of the phenomenon, lightning in human history has been a central point of observation by scientists and laypeople around the world. Brazil is one of the countries with the highest lightning activity (Albrecht et al., 2016b; Pinto et al., 2009), a factor that deserves special attention, since the destructive potential associated with the phenomenon is significant. There are an estimated 60–75 million lightning strikes annually, responsible for the death of an average of 132 people every year in the country (Boccippio et al., 2000; Cardoso et al., 2014; Santos et al., 2017).

From 2000 to 2009 in Brazil, most lightning fatalities (19 %) happened in circumstances related to rural activities. However if only NEB is considered, this rate was 23 % (Cardoso et al., 2014). The highest occurrence of fatalities in rural activities was also observed in other countries, such as China (Zhang et al., 2011), Bangladesh (Holle et al., 2019) and India (Holle, 2016). With 18 % of the total, NEB was classified as the region with the third highest number of fatalities involving lightning, behind the Southeast (29 %) and Midwest regions (19 %), occupying the same position as the North region (Cardoso et al., 2014). When considering the annual rate of deaths caused by lightning (proportion between the number of registered cases and the total population), the Northeast and Southeast regions had the same value, 0.5 deaths per million. Regarding thunderstorm activity in NEB, Zipser
et al. (2006) indicated places where several categories of intense convection occur, including the highest flash rates. These places are near the boundary between Piauí and Maranhão, and in western Bahia.

In general, the spatial distribution of lightning activity is monitored by ground-based lightning sensor networks (Albrecht et al., 2014). For example, in Brazil several studies have used lightning data from the Brazilian Network for the Detection of Atmospheric Discharges (BrasiDAT) (Bourscheidt et al., 2016; Farias et al., 2014; Pinto et al., 2013; Santos et al., 2017, 2018). BrasiDAT detects and monitors cloud-to-ground and intracloud lightning and was implemented in 2011 by the Atmospheric Electricity Group (ELAT) of the National Institute for Space Research (INPE). BrasiDAT uses the time-of-arrival (TOA) method to detect intracloud pulses and cloud-to-ground strokes and operates in the frequency range between 1 Hz and 12 MHz (Mattos, 2015; Pinto and Pinto, 2008). This method employs three or more sensors to determine the moment the electromagnetic radiation emitted by lightning reaches the sensor, and with the relative temporal difference in the time of arrival at the sensors, hyperbolic curves are defined for each pair of sensors that detected lightning (Cummins et al., 2009).

These hyperbolas indicate the possible lightning locations according to the measured time differences, so the point of intersection indicates the possible lightning location. BrasiDAT has 56 sensors in operation throughout Brazil, but does cover most of NEB (only three of its nine states), and has very low detection efficiency (approximately 20%) (Naccarato et al., 2014; Paiva, 2015).

Other regional lightning localization systems (LLS) operating in Brazil are the Integrated Network for the Detection of Atmospheric Discharges (RINDAT) in the Southeast/South regions, and the Lightning Network (LINET) in São Paulo State (Fornenten et al., 2013; Santos et al., 2017; Williams et al., 2016). In addition, the Sferics Timing and Ranging Network (STARNET) is a long-range LLS that operates at very low frequency (VLF), between 7 and 15 kHz (Morales et al., 2011; Morales Rodríguez, 2019). STARNET is based on the propagation of electromagnetic waves emitted by lightning strokes in the VLF band (Sferics) that travel thousands of kilometers. This network continuously measures the vertical electric field, which is temporally synchronized by a global positioning system (GPS), and uses the TOA method to locate lightning strokes (Morales et al., 2014). Currently, the STARNET network has a total of nine sensors installed in Brazil, two of them in NEB, with detection efficiency of 35% and location error between 2 and 5 km (Morales, 2018; Morales Rodríguez, 2019). Additionally, long-range LLS in Brazil are the Global Lightning Dataset (GLD360) (Said et al., 2013) and Worldwide Lightning Location Network (WWLLN) (Hutchins et al., 2012).

Although several studies have used ground-based LLS, monitoring total lightning over extensive areas requires a dense lightning sensor network, not yet available. In addition, inaccessible regions, such as oceanic and rainforest regions, generally do not have this type of monitoring networks. In these cases, the use of satellite orbital sensors is a good alternative (Cecil et al., 2014; Christian et al., 2003; Dewan et al., 2018b; Tazarek et al., 2019). Over the past few decades, lightning detection from space has become feasible with the launch of the Tropical Rainfall Measuring Mission (TRMM) satellite with the Lightning Imaging Sensor (LIS) aboard, able to monitor the entire tropical region (Albrecht et al., 2016b; Christian et al., 2003; Dewan et al., 2018b; Rasmussen and Houze, 2011; Sonnadara et al., 2019). For example, Christian et al. (2003) documented that approximately 78% of all lightning strikes occur in the tropical region of the globe. This remarkable result is probably associated with the larger energy potential attributable to convection and availability of aerosol particles to act as cloud condensation nuclei (CCN) in these regions (Williams and Stanfill, 2002).

The use of orbital sensors has become an important alternative tool for the study of lightning, especially where there is no coverage of ground-based networks or where there is coverage, but the detection efficiency is low, as in NEB. For this reason, there are no studies in the literature regarding lightning occurrence, distribution and variability in NEB. With determination of factors that influence lightning distribution in this region, the population can be better warned of probable lightning occurrences and safety procedures, which in turn can decrease the number of lightning fatalities.

Several factors influence the occurrence of lightning strikes over a given region. Naccarato et al. (2003) and Farias et al. (2014) highlighted that apparently the effect of cities on lightning activity is the result of a combination of the thermodynamic effect due to the differential heating of the surface of cities, called the urban heat island phenomenon, and the increase of pollutant concentrations (aerosols acting as CCN) in the local atmosphere, caused mainly by the human activity. However, due to the complexity of the relationships between the variables involved, the physical mechanisms responsible for these effects have not been completely elucidated. Another factor identified as important in the occurrence of lightning is the topography, as reported in the Brazilian states of Rio Grande do Sul (Bourscheidt et al., 2009) and São Paulo (Mattos and Machado, 2009) and the United States (Barros and Kuligowski, 1998; Kastman et al., 2017; López et al., 1997), India (Kandalaonkar et al., 2005), and several other places in the tropics, including the Earth’s lightning hotspots (Albrecht et al., 2016b).

NEB is a region of predominantly semi-arid climate, subject to periodic droughts with severe impact on society (Cabral Júnior et al., 2019). These factors led Trewartha (1961) to highlight it as a region of “problematic climate”, an claim later supported by Hastenrath (2012) and Xavier et al. (2019). As respect to climate, a few studies have evaluated the climate projection of lightning. Finney et al. (2018) indicated there is a tendency for reduction in lightning strikes due to increased global mean temperature. The authors identified this tendency based on the cloud-top height and upward cloud ice flux approaches in global climate models. The opposite, i.e., a prediction of increased global lightning activity with climate change over the coming century, was also reported (Krause et al., 2014; Price and Rind, 1994).

Similar results can be found for the United States, based on convective available potential energy (CAPE) and precipitation rate (Rompé et al., 2014; Tippett et al., 2019; Tippett and Koshak, 2018), as well as over the Indian subcontinent (Saha et al., 2017). For Brazil, Santos et al. (2017), using global climate models from the Climate Model Intercomparison Project Phase 5 (CMIP5), showed that the future climate projections indicate the occurrence of above average anomalies of most lightning events, both in the low pollution emission scenario and in the high pollution emission scenario. These studies reinforce the importance of long-term spatial-temporal analysis of lightning around the globe, and especially in regions with scarcity of observations like NEB.

Therefore, the primary goal of this study is to evaluate the occurrence of the total lightning flash rate density (FRD) over NEB, in order to determine the behavior of the spatial and temporal distributions of lightning. As described above, the most adequate datasets for this region, because of the scarcity of ground-network lightning detection coverage, are satellite-based. Here we use TRMM LIS observations, from 1998 to 2013, to assess the spatio-temporal variability of lightning based on annual distribution and seasonality, the relationship among lightning occurrence, precipitation, CAPE and topography, as well as to identify the lightning hotspot municipalities (defined as the regions with highest FRD) in the study area.

2. Material and methods

2.1. Study region

Northeast Brazil is located between the geographic coordinates 01°S and 18°S; 34°W and 49°W (Fig. 1). NEB includes nine Brazilian states: Maranhão (MA), Piauí (PI), Ceará (CE), Rio Grande do Norte (RN), Paraíba (PB), Pernambuco (PE), Sergipe (SE), Alagoas (AL) and Bahia (BA). A total of 1794 municipalities are located in these nine
states, with the capital of each state being the largest urban center. According to the Brazilian Institute of Geography and Statistics (IBGE, 2010), the region has more than 53 million inhabitants, occupying an area of 1,554,291 km². The region has the largest number of states and the third-largest land area in the country.

NEB has very diverse characteristics in terms of topography, vegetation and climate. Alvares et al. (2013) explained that NEB can be divided into three sub-regions (coastal, semiarid and Amazon), where annual rainfall is less than 500 mm in semiarid and more than 1500 mm along the coast and northwest of NEB. Another subdivision of NEB was presented by Oliveira et al. (2017) based on the monthly precipitation, composing five sub-regions: northern coast (50–200 mm), northern semiarid (0–150 mm), southern semiarid (0–150 mm), northwest (0–300 mm) and southern coast (50–150 mm).

2.2. Data

2.2.1. LIS data

The Lightning Imaging Sensor (LIS) is an instrument that detects total (intracloud and cloud-to-ground) lightning by measuring radiant energy emitted during lightning development throughout day and night. Two LIS instruments were built in the 1990s, one for the TRMM and a spare. The first operated successfully for over 17 years (November 1997 to April 2015), while the spare LIS was launched to the International Space Station (ISS) in February 2017 for a two to four year mission (Bitzer, 2017; Blakeslee et al., 2020; NASA, 2017).

The LIS is a lightning detector that groups multiple lightning events in space and time. A charge coupled device (CCD) detects lightning emissions in the 777.4 nm channel (neutral oxygen line) that exceed a threshold at the top of the cloud at a rate of 2 milliseconds (Boccippio et al., 2002; Christian et al., 2003, 1999; Goodman et al., 1988). Pixels that exceed the radiance threshold are called events, while contiguous events in a single frame are called groups. The coherent groups in time and space are aggregated and called flashes (Bitzer, 2017; Christian et al., 2000). The temporal and spatial thresholds used to compose flashes are 330 ms and 5.5 km, respectively.

The data used in this study were processed by Albrecht et al. (2016a), and organized in the form of very high resolution (0.1°) climatologies (full, annual, seasonal and monthly), composing observations from 01 January 1998 to 31 December 2013 (Albrecht et al., 2016a). Data after this period were not included in the climatologies because TRMM began its downward path to decommissioning in 2014, with several instrument outages, possibly introducing errors. The entire dataset is available for download from the NASA Earth Observing System Data and Information System (EOSDIS) Global Hydrology Resource Center (GHRC): https://doi.org/10.5067/LIS/LIS/DATA306.

This work differs from that carried out by Albrecht et al. (2016b), since our aim is to characterize the regional spatial and seasonal lightning distribution in the study area, looking in depth for intrinsic factors that may be related to the lightning occurrence, as well as to analyze hotspots, clusters, topography, precipitation and CAPE in the NEB region.

2.2.2. Additional data: topography, CAPE and precipitation

The topography data used in this study are from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) onboard the TERRA satellite. The ASTER sensor operates in high spatial resolution in 14 bands from visible to thermal infrared, and provides stereoscopic viewing capability for the creation of digital elevation models (Abrams et al., 2002). More specifically, we use ASTER Global Digital Elevation Model (GDEM) Version 3 (ASTGTM), which provides elevation at its best resolution of 1 arc second (~ 30 m) (NASA/METI/
The Euclidean distance is defined as
\[ d_{ij} = \sqrt{\sum (x_{ik} - x_{jk})^2} \] (1)

The procedure continued with application of the agglomerative hierarchical technique developed by Ward (1963), and also used by Lyra et al. (2014) and Mutti et al. (2020). Ward’s method is based on the principle that at each stage of the algorithm, the sum of squares within each existing cluster is calculated. This sum can be understood as the square of the Euclidean distance of each element of the cluster in relation to the average of the group in question. At each step of the algorithm, Ward’s method combines two clusters that result in the smallest total sum of squares between them. The structure of the cluster dendrogram was used to determine the appropriate number of clusters (Lyra et al., 2014; Wilks et al., 2006), and the decision related to the cut in the dendrogram (determination of the number of clusters) was based on the lightning activity of the region, elucidated in previous studies (Houze, 2018; Houze et al., 2015; Liu and Zipser, 2015; Machado and Rossov, 1993; Rasmussen et al., 2014; Yuan and Houze, 2010; Zipser et al., 2006). It was possible to establish clusters that present homogeneous occurrence of lightning, providing a better understanding of this geophysical variable’s spatial variability across NEB.

The precipitation database described in Section 2.2.2 was used to verify the relationship between lightning and rainfall in each of the groups found in the cluster analysis. We considered all the points within each of the clusters to generate a monthly average, which was later illustrated along with the quantitative lightning variable to observe its behavior.

2.3.2. Hotspots

Once the distribution of the lightning occurrence in the NEB was determined for the period 1998–2013, these data were organized in descending order to obtain the lightning hotspots in NEB. The pixels that registered the highest values (hotspots) were superimposed on the municipality map, thus making it possible to determine the nearest city. This comparison was also performed by Albrecht et al. (2016b); Cecil et al. (2014) and Christian et al. (2003). The most frequent occurrences were analyzed individually to describe their characteristics and discuss the high occurrence of lightning.

After determination of the hotspots, their time series was analyzed to evaluate the temporal behavior and the tendency of location. Here the nonparametric Mann-Kendall statistical test was used. Its use is linked to the absence of a need for normal distribution of the variable. According to Santos et al. (2016a), this test compares each value of the data series with the subsequent values, calculating the number of times the remaining terms are greater than the value analyzed. The test is used to analyze the existence of a rising or falling trend. It is the most appropriate way to analyze climate change in climatological data series. The last step of this study was to evaluate the relationship between the degree of stability of the atmosphere, from CAPE values, precipitation and FRD in each hotspot. Monthly analyses were performed according to Dewan et al. (2018a).

3. Results and discussion

3.1. Annual distribution

The map of lightning occurrence in NEB (Fig. 2) represents the average FRD (flash km$^{-2}$ yr$^{-1}$) from TRMM LIS over 16 years (1998–2013) with a horizontal spatial resolution of 0.1°. As described in Section 2.2.1, this dataset was prepared by Albrecht et al. (2016b) aiming to analyze lightning occurrence throughout the Intertropical Zone. There was a marked difference between regions closer to the east coast and the interior of the continent, whereby electrical activity increased when analyzing more central regions of the continent. The lower occurrence of lightning along NEB’s east coast (values close to 0 flash km$^{-2}$ yr$^{-1}$) may be linked to lower convective activity in the region. According to Palharini and Vila (2017), there is predominance of warm cloud occurrence along NEB’s east coast.

However, some coastal regions had moderate flash rate densities (up to 20 flash km$^{-2}$ yr$^{-1}$), as also found for the southern coast of Bahia, which can be associated with large-scale convergence zones, such as the South Atlantic Convergence Zone (SACZ), according to Christian et al.
The northern part of the study region is notable for its high flash rate (> 30 flash km\(^{-2}\) yr\(^{-1}\)), associated with the penetration of onshore breeze during the afternoon, enhanced by the easterly trade winds, as well as the positioning of the Intertropical Convergence Zone (ITCZ), a system described as one of the most important to the sustained formation of intense convective updrafts, generation of electric charges and lightning occurrence (Albrecht et al., 2016b; Buechler et al., 2014; Christian et al., 2003; Collier and Hughes, 2011; Machado et al., 2014).

The states of Piauí, Maranhão and Bahia usually had the greatest flash rates in NEB, a result similar to that found by Oda (2019).

Moderate flash activity (20–30 flash km\(^{-2}\) yr\(^{-1}\)) was also observed in the states of Rio Grande do Norte and Pernambuco, a fact that can be explained by the topography of those states. The Borborema Plateau (central region of Pernambuco, Paraíba and Rio Grande do Norte) is a topographic barrier, with altitude up to 1200 m (Fig. 1). When the east/southeast trade winds hit the elevated terrain, this airflow ascends, causing the development of thunderstorms and favoring orographic precipitation on the east side of the barrier, as well as lightning activity, since the topography increases convective updrafts and favors cloud electrification. The orography also seems to influence the central region of Bahia, which also presents moderate electrical activity (20-30 flash
and an orographic barrier called Chapada Diamantina (center-west of Bahia), with altitudes over 2000 m. This orography and lightning enhancement hypothesis discussed here has been observed in the states of Paraná (Beneti et al., 2002), Rio Grande do Sul (Bourscheidt et al., 2009) and São Paulo (Mattos, 2009) in Brazil, as well as in India (Kandalgaonkar et al., 2005), central regions of the United States (Kastman et al., 2017) and Pennsylvania (Barros and Kuligowski, 1998) and Arizona (López et al., 1997).

3.2. Hotspots

The regions with higher FRD (more than 34 flash km$^{-2}$ yr$^{-1}$) are distributed between western Bahia, southern Piauí and Maranhão, and the northern region of both states (see Fig. 3 and Table 1). The NEB has hotspots with significantly lower values of FRD than those identified globally by Albrecht et al. (2016b). The top ranked hotspot globally, Lake Maracaibo, presents FRD over 5 times greater (233 flash km$^{-2}$ yr$^{-1}$) (Albrecht et al., 2016b) than our first ranked hotspot: Batlha, PI, with 44.57 flash km$^{-2}$ yr$^{-1}$.

The hotspots located in northern portion of Piauí and Maranhão (Ranks 1, 4, 7, 9, 14, 16 and 18), due to their geographical location, are influenced by the ITCZ (Molion and Bernardo, 2002; Uvo, 1989). The remaining hotspots (southwest of NEB) should be more influenced by Mesoscale Convective Systems (MCS). As pointed out by Rasmussen et al. (2014), this region has large amounts of lightning associated with convective cores, both deep and wide, especially during the austral summer. Previous studies, such as Machado and Rossow (1993), already pointed to the occurrence of convective systems in this region.

The southern Piauí, western Bahia and southern Maranhão, hotspots are located in regions with very well marked orography (Chapada das Mangabeiras, Serra Geral do Goiás and Serra do Penitente, respectively), indicating that the occurrence of the convection can be influenced by local topography.

It is important to comment that the majority of hotspots are located in the western portion of NEB. The FRD occurrence in this area is also probably linked to summer circulation at high atmospheric levels. In the austral summer, the Bolivian High is frequently observed over the Bolivian Plateau, which by conservation of potential vorticity generates a trough over the east of NEB (Kousky and Gan, 1981). Kousky and Gan (1981) and Lenters and Cook (1997) showed there is an area of large scale flow influence between the Bolivian High and the trough in NEB. This influence is responsible for the intense convection observed in the region, and is associated with topography and CAPE (to be discussed next), explaining the greater occurrence of lightning.

3.3. Seasonality

The seasonal analysis of lightning activity (Fig. 4) pointed to an increase during the months of December, January and February (average of about 0.04 flash km$^{-2}$ day$^{-1}$), corresponding to the austral summer. The season with the second highest FRD was autumn (average 0.02 flash km$^{-2}$ day$^{-1}$), followed by spring and winter (0.016 lightning flash km$^{-2}$ day$^{-1}$ and 0.002 flash km$^{-2}$ day$^{-1}$, respectively). It should be noted that although the metric expressed the value in relation to the daily quantity, the average was calculated in relation to each season of the year, aiming to better express the quantities of each season.
During the summer, the occurrence of lightning flashes varied with the lowest values recorded near the coastal regions (mainly eastern NEB) and the largest in the south of Piauí and Maranhão (near to 015 flash km⁻² day⁻¹). The season which presented the lowest lightning activity was the winter, when almost all NEB did not present records of lightning, except in the north of Piauí and Maranhão, along the north coast. Interestingly, this region exhibits lightning activity throughout the year, marking the region where afternoon onshore breeze is most intense, with convection penetrating inland about 100 km. It is noticeable that this line of convection does not penetrate farther inland during winter as in other months. This is probably a reflection of less intense trade winds in this season.

More specifically, Palharini and Vila (2017) examined the behavior of clouds in NEB and reported that the highest occurrence was associated with precipitation during the period from December to April, when there were also higher rates of deep convection in NEB, except for the east coast, where the highest accumulations of precipitation occurred during the winter, with predominance of warm clouds, agreeing with the results described here. The deep convection indexes are related to the occurrence of storms and higher records of lightning (Zipser et al., 2006; Lal and Pawar, 2011; Liu et al., 2011; Rasmussen and Houze, 2011; Cecil et al., 2015).

### 3.4. Cluster analysis

The cluster analysis, based on the Euclidian distance described in section 2.3.1, used all the 12,794 grid points (0.1° × 0.1°) of LIS climatology representing NEB to determine 4 distinct FRD clusters: cluster 1 (5982 points), cluster 2 (2862 points), cluster 3 (1749 points) and cluster 4 (2201 points), as seen in Fig. 5.

Cluster 1 (in blue) corresponds to contiguous low FRD (< 0.014 flash km⁻² day⁻¹), with the majority of its area in the eastern NEB region, a large range from Bahia to Ceará states. Cluster 2 (in green) presented mean values between 0.014 and 0.021 flash km⁻² day⁻¹, covering areas such as the Borborema Plateau (states of RN, PB, PE), Serra Grande (PI and CE) and Chapada Diamantina in the midwestern part of Bahia. Cluster 3 (in yellow) presented higher values of lightning occurrences in relation to clusters 1 and 2, reaching 0.042 lightning flash km⁻² day⁻¹. The highest values were observed in cluster 4 (in red), which comprises almost all of the hotspots previously cited in this study, with the maximum flash rate of 0.07 flash km⁻² day⁻¹.

Interestingly again, this cluster analysis delineated precisely the northern region influenced by onshore breeze and trade winds in northern NEB.

The metropolitan regions of state capitals of NEB are in the first cluster, the ones with the lowest lightning indices, with the exception of Teresina-PI and São Luís-MA, inserted in clusters 3 and 2, respectively. These results differ from those presented by Santos et al. (2016b), who applied cluster analysis for the incidence of cloud-to-ground lightning in the state of São Paulo, using data from the RINDAT and BrasilDAT networks. They found six distinct areas in the state, with the highest concentration of flashes occurring in the region containing large urban centers such as São Paulo, Guarulhos and Santo André (among others), with elevation around 1000 m. The lowest concentration of discharges occurred in the most distant region of the São Paulo Metropolitan Region (SPMR), composed by a forested and flatter area (altitude of approximately 200 m).

The SPMR has more than 19 million inhabitants, distributed in almost 8 thousand km², while the largest metropolitan region of NEB is Recife, with a little over 3.5 million inhabitants spread over 3.2 thousand km² (IBGE, 2010). This can explain the differences between our results and those found by Santos et al. (2016b). In this sense, the SPMR appears to exert a more intense effect on the environmental conditions of its region due to its large size, as proposed by Farias et al. (2009), associated with the effect of urban heat islands and the concentration of particulate matter.

In order to analyze the seasonal variation of lightning occurrence in each cluster, a monthly normalized FRD (flash km⁻² month⁻¹) was calculated for each month (Fig. 6). The data were normalized due to the different observation times of each region of the Earth. As previously demonstrated, cluster 4 presented the highest lightning occurrence indices, followed by clusters 3, 2 and 1, in that order. The distribution of the monthly averages of the four clusters is similar, with the lowest values between May and September and the highest values from October to March. The difference between clusters is exactly the amount of lightning observed, not the seasonality.

The Mann-Kendall test was performed to verify the trend of the time series data for each of the clusters described in this study. It indicated absence of a trend for these data during the study period (Cluster 1 p-value = 0.62335; Cluster 2 p-value = 0.86442; Cluster 3 p-value = 1; Cluster 4 p-value = 0.6588).

### 3.5. Relationship of lightning occurrence, precipitation, CAPE and topography

Several authors have documented the influence of topography on storm occurrence and lightning production in many areas of the world (Albrecht et al., 2011, 2016b; Bourscheid et al., 2009; Naccarato and Pinto, 2012; Rasmussen and Houze, 2011). Here, we observed lightning
clusters associated with orographic barriers. The most evident is the cluster 2 region, located in RN, PB and PE (Fig. 5), due to proximity to the Borborema Plateau (Fig. 3). This is true for cluster 4, which in addition to including all hotspots, also has higher terrain, such as the Diamantina Plateau.

To better depict the influence of topography on lightning activity, we divided NEB into four altitude classes, according to the quartiles of the NEB topography distribution: 0 to 175 m, 176–356 m, 357–516 m, and 517 to 1655 m. Fig. 7 shows the monthly mean occurrence of flashes for each quartile. In general, mean flash rate densities were higher (annual mean 0.6 flash km$^{-2}$ month$^{-1}$) in regions with higher elevations (between 357 and 1655 m) from October to February. This period coincides with the rainy season in most of the study region (Oliveira et al., 2017; Mutti et al., 2019). The exception was observed for the quartile with lowest elevations (0–175 m), which presented higher flash rates from March (1.13 flash km$^{-2}$ month$^{-1}$) to August (0.13 flash km$^{-2}$ month$^{-1}$), featuring the seasonality of rain systems that occur mainly in the extreme east and south of the study region.

Fig. 4. Seasonality of FRD (flash km$^{-2}$ day$^{-1}$) in NEB between 1998 and 2013. (A) summer, (B) autumn, (C) winter and (D) spring.
behavior that will be detailed later in this paper. Typically, the effects of topography on the occurrence of intense convection are better verified when analyzed in the region’s dry season, as reported by Gonçalves et al. (2015). They observed higher precipitation intensities in elevated Amazonian areas only during the dry
period, while during the rainy season precipitation was homogeneous throughout the area. This is due to the fact that during the dry period, no large-scale meteorological systems are observed and the convection is only local, strongly influenced by topography (Gonçalves et al., 2015). Similar results were found by Albrecht et al. (2011) for thunderstorm development in the southwestern Amazon.

As previously mentioned, the occurrence of lightning in NEB did not follow the pattern of the Amazon. The main reason for this is probably related to the nature of the precipitation systems that occur in the region. In the Amazon, isolated convective systems occur in the dry season, generating significant rainfall accumulations and lightning activity due to the nature of the local convection, which is generated by diurnal heating and the high humidity (Albrecht et al., 2011; Gonçalves et al., 2015). In NEB, the precipitation seasonality is well-marked, with a significant decrease in the dry period, which occurs mainly during the austral winter, except in the eastern part of the region. Also, during the dry season, no deep convection is observed in most of NEB (Palharini and Vila, 2017), explaining the behavior of the monthly mean occurrence of FRD for each topography quartile in Fig. 7.

As already mentioned, from March to August the highest FRD (> 0.13 flash km⁻² month⁻¹) occurred at the lowest altitudes (0–175 m). Probably this is due to the Easterly Wave Disturbances (EWD) that act in the eastern part of NEB, which mainly has lower altitudes. This result is in agreement with that presented by Yamazaki and Rao (1977), who stated that the austral winter precipitation along the east coast of NEB seems to be associated with this system.

In order to verify if each of the four FRD clusters (Fig. 5) also are subject to topographical effects, Table 2 shows the number of FRD grid points in each cluster and topography quartiles. Clusters with lower FRD (clusters 1 and 2) have significantly lower elevations (25.86 % and 38.78 % for the first two topography quartiles). On the other hand, the cluster with the highest FRD value (cluster 4) also concentrates the highest percentages of elevated terrain (33 % ranging from 517 to 1655 m), indicating a possible relationship between FRD and topography. High FRD values at low altitudes are also observed in cluster 4 (25 % ranging from 0–175 m, and 16 % ranging from 176–356 m), a fact that could reflect the probability of nocturnal lightning occurrence in valleys or lower regions adjacent to mountains and foothills, as described by Albrecht et al. (2016b).

Fig. 8 shows the mean monthly lightning activity for each cluster subdivided into the topography quartiles of NEB. In general, the behavior was similar to the seasonality of the FRD over NEB as a whole (Fig. 7), with greater lightning activity (> 0.2 flash km⁻² month⁻¹) during the austral summer and smaller lightning activity in the austral winter. Accumulated precipitation (Fig. 5) tendencies followed those of FRD, i.e., during months of higher rainfall accumulation, higher lightning rates were also observed in regions with higher elevation. However, for all clusters, in the winter period the highest lightning activity occurred at lower elevations. This might be due to the diurnal heating pattern along the coast and the consequent onshore breezes, which are diminished during the winter, but are active throughout the year.

In addition to the EWD during the winter, another factor that explains the occurrence of lightning in this period is the frontal systems, mainly along the southern coast of NEB. Fedorova et al. (2016) reported that during the winter, frontal zones (FZs) are more intense and faster moving, and sometimes reach tropical and equatorial latitudes, which influence regions such as southern Bahia (an average of 15 times a year) or Aracaju-SE (mean of 5 times a year) and Maceió-AL (average of twice a year). Regarding the relationship of FZs with the incidence of lightning, Albrecht et al. (2016b) mentioned that some coastal regions have an incidence associated with extratropical cyclones and frontal systems that occur throughout the year and at any time of the day, not being associated with an annual or daytime cycle.

With respect to cluster 1, the occurrence of high values of FRD during the summer is due to lightning activity in the northern portion of this cluster area, where the ITCZ assumes its southernmost position, as well as by the occurrence of Upper Tropospheric Cyclonic Vortices (UTCV), as explained by several authors (Farias and Correia, 2008; Gan and Kousky, 1986; Petersen et al., 2006). Cluster 2 has similar behavior as cluster 1, where from April to May the highest FRDs are at located at lower altitudes, and from October to March at higher altitudes. Cluster 2, since it extends to the western portion of NEB, is also influenced by convective processes during the summer (local convection and sea breeze influence), which may explain the higher FRD values. For clusters 3 and 4, the processes are similar, with the formation of deep convective processes.

Many studies have analyzed the relation between atmospheric energy, i.e., CAPE values, and the intensity of convection over many parts of the world (Chakraborty et al., 2016; Gonçalves et al., 2015; James and Markowski, 2010; Linders and Saetra, 2010; Molinari et al., 2012; Williams and Renno, 1993), and others have specifically examined the relation between CAPE and lightning occurrence (Dewan et al., 2018a; Galanaki et al., 2015; Murugavel et al., 2014; Pawar et al., 2010; Romps et al., 2014; Siingh et al., 2014). Based on these studies, we analyzed the annual cycle (monthly mean values) of CAPE, precipitation and FRD for the 20 hotspots presented in Table 1. All of them showed a very similar and well-defined annual cycle for all three variables. For brevity, Fig. 9 shows the mean monthly values of FRD, CAPE and precipitation only for the first three hotspots. During the rainy season (November to March), the peaks occurred of FRD (> 0.02 flash km⁻² day⁻¹), precipitation (> 30 mm month⁻¹) and CAPE (> 100 J Kg⁻¹). On the other hand, during the dry season (from July to August), the three variables decreased abruptly.

The statistical significance of the monthly relationship between CAPE and FRD is 0.95 according to the Pearson correlation coefficient. This value is similar to that calculated by Dewan et al. (2018a), who studied the relation between CAPE and lightning in India, observing a value of 0.90 for their monthly analysis. The monthly Pearson correlation between FRD and precipitation is 0.88. The fact that the correlation between FRD and precipitation is smaller than the correlation between FRD and CAPE is explained by the nonlinear relationship between lightning and rainfall (Soula, 2009), especially in NEB, where rainfall tends to be heaviest in warmer periods (Liu and Zipser, 2009). It is also important to point out that CAPE values observed here for NEB are smaller than in other studies, such as in Dewan et al. (2018a); Galanaki et al. (2015); Murugavel et al. (2014) and Romps et al. (2014). However, our study domain is not a monsoon area, which potentially increases CAPE values. In addition, the most important result is that even the relatively smaller CAPE values presented good agreement with lightning in NEB, which should be explored through other scientific techniques, such as in numerical modeling, to properly simulate

| Cluster | Topography classes (mode/mean) | Number of points |
|---------|-------------------------------|-----------------|
| 1       | 0 – 175 m (0 / 77)            | 1546 (26 %)     |
|         | 176 – 356 m (334 / 259)      | 1344 (22 %)     |
|         | 357 – 516 m (385 / 432)      | 1539 (26 %)     |
|         | 517 – 1655 m (527 / 709)     | 1553 (26 %)     |
| 2       | 0 – 175 m (0 / 102)          | 534 (19 %)      |
|         | 176 – 356 m (207 / 257)      | 1110 (39 %)     |
|         | 357 – 516 m (385 / 443)      | 690 (24 %)      |
|         | 517 – 1655 m (525 / 712)     | 528 (18 %)      |
| 3       | 0 – 175 m (0 / 90)           | 563 (32 %)      |
|         | 176 – 356 m (249 / 261)      | 397 (23 %)      |
|         | 357 – 516 m (444 / 444)      | 408 (23 %)      |
|         | 517 – 1655 m (642 / 674)     | 381 (22 %)      |
| 4       | 0 – 175 m (0 / 68)           | 554 (25 %)      |
|         | 176 – 356 m (197 / 277)      | 343 (16 %)      |
|         | 357 – 516 m (469 / 442)      | 569 (26 %)      |
|         | 517 – 1655 m (517 / 734)     | 735 (33 %)      |
lightning in the area.

4. Conclusion

This study evaluated total lightning spatial and temporal distribution in Northeastern Brazil. The use of remote sensing data has been an important alternative for research in regions with the absence of ground-based lightning detection networks. Due to great territorial extension, NEB has large spatial and temporal variability in flash rate densities, with average values varying from 0 to 44.5 flash km$^{-2}$ yr$^{-1}$. The regions with highest FRD (> 34 flash km$^{-2}$ yr$^{-1}$) are located in the states of Piauí, Maranhão and west of Bahia, comprising all 20 NEB lightning hotspots. The FRD maps confirmed the previous general observations of high lightning activity in continental areas, due to deep convection and low lightning activity over the coastal regions. The lowest values (near to 0 flash km$^{-2}$ yr$^{-1}$) were observed in eastern NEB

![Fig. 8. Mean monthly occurrence of FRD (bar chart, flash km$^{-2}$ month$^{-1}$) and monthly cumulative precipitation (line chart, mm) for each of the four FRD clusters, subdivided into topography quartiles of NEB.](image)

![Fig. 9. (left) Mean monthly values of FRD (flash km$^{-2}$ day$^{-1}$), Convective Available Potential Energy - CAPE (J kg$^{-1}$) and (right) precipitation for the first three hotspots: (a, b) Batalha-PI, (c, d) Barreiras do Piauí-PI, (e, f) São Desidério-BA.](image)
coastal regions.

Using the Mann-Kendall test, we verified that the FRD time series did not have a trend during the period studied (1998–2013) and presented a nearly half-yearly cycle, approaching the cycle of precipitation across NEB territory. In terms of seasonality, the months corresponding to summer and autumn (winter and spring) showed the highest (lowest) values of FRD, confirming that the high air temperature and consequent convection is related to the occurrence of this phenomenon, i.e., supporting the thermal hypothesis (Williams and Sátori, 2004; Williams and Stanfill, 2002).

Some regions with high FRD (20–30 flash km−2 yr−1) surrounded by places with low lightning activity coincided with areas of elevated terrain, strengthened by the division of the topography into classes. Topography seems to act as a facilitator of the convective process, producing stronger updrafts and ice particle formation, which are essential for the electrification process and lightning occurrence. These regions can be exemplified by the Borborema Plateau, Chapada das Mangabeiras, Chapada Diamantina and Serra Geral do Goiás.

The analysis of FRD clusters and of the hotspots allowed us to determine that the Intertropical Convergence Zone, Mesoscale Convective Systems, Upper Tropospheric Cyclonic Vortices, Frontal Zones and Easterly Wave Disturbances are the main large-scale systems associated with lightning occurrence in NEB, and the first two are associated with the points of highest FRD. We suggest that the strong convective characteristics associated with these large-scale atmospheric systems have a relevant role in the development of thunderstorms.

Regarding the influence of topography on lightning occurrence as a function of FRD clusters, a direct relationship was not observed. However, we noted that from November to March, the largest occurrences of lightning were concentrated in areas with high elevation (517 – 1655 m). This is recognized as the period of the year with greatest convective activity in the region, which was also directly influenced by topography. During the austral winter, this behavior is reversed. This result, in part, can be explained by the EWD occurrence in the eastern NEB, a region with low elevation, and FZs in the southern part of NEB.

Throughout the year, CAPE values showed good relationship with lightning occurrence in the region, ratifying previous research findings. Consequently, due to the close relation, CAPE can be an important indicator to predict thunderstorms-related lightning in NEB. Furthermore, Convective Inhibition Energy (CINE) over the entire NEB was very small (≤ 50 J kg−1) throughout the year (not shown). Therefore, the thermodynamic scenario of NEB, composed of small or nil CINE with moderate CAPE, is already capable of triggering convection, but two other factors play important roles in explaining the spatial distribution of lightning activity throughout the NEB region. The first one is diurnal differential heating along the coast and the development of onshore breeze. In the northern portion of NEB, this breeze is accelerated by the parallel trade winds. Second, the inland slopes of high terrain can further strengthen thunderstorm updrafts, invigorating storms’ mixed phase, where charge transfer occurs and lightning is formed (Cotton and Anthes, 1989; Ludlam, 1980). In this scenario, another possible role of topography is further acceleration of the onshore breeze due to differential heating of the elevated hillsides.

It should be emphasized that we used data from TRMM, a satellite with approximately two passages per day over NEB. This orbit pattern could cause uncertainties in the derived FRD in the study domain, but 16 years of observations should minimize this. However, there are no published studies of lightning activity in NEB, a predominantly semi-arid region that generally does not draw attention of researchers interested in atmospheric electricity, even with the high death rate from lightning strikes (Cardoso et al., 2014). To improve optical observations of lightning from satellites, further analysis of the spatial and temporal distribution of lightning in NEB can now be performed using the Geostationary Lightning Mapper (GLM) sensor on board the GOES-16 satellite, which provides continuous total lightning detection in near real time.

CRediT authorship contribution statement

Lizandro P. de Abreu: Conceptualization, Methodology, Software, Writing - original draft. Weber A. Gonçalves: Conceptualization, Methodology, Software, Writing - review & editing. Enrique V. Mattos: Conceptualization, Methodology, Resources, Writing - review & editing. Rachel I. Albrecht: Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jag.2020.102195.

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