ORIGINAL PAPER

Lightning climatology in Colombia

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Abstract

Colombia's lightning climatology was studied using 16 years of high-resolution data from the Tropical Rainfall Measuring Mission Lightning Imaging Sensor (TRMM LIS). The findings present the climatology of the country organized in two ways: where lightning occurs and when lightning occurs. The authors sorted data using Colombia's six natural regions and conditional mean values for day, month, quarter, and year for frequency occurrence. The findings show a high mean flash rate density (FRD) around 70 fl km^{-2} year^{-1} in 15% of the territory. Most of this activity concentrates in the northern part of the country between latitude 7° N and 11° N. Regarding time patterns, lightning reaches its maximum in most of the territory two times a year with a transition period marked by a steep fall. But, the areas with higher activity seem to have a single lightning season, with a maximum around August. These findings confirm the need to consider lightning activity based on regional contexts. During the day, activity is more probable from afternoon to evening in the southern part of the country; meanwhile, it tends to go from afternoon to early morning in northern regions.

1 Introduction

Satellite-based data is well suited to study spatial distribution and frequency occurrence of lightning activity in broad areas, especially in remote areas where the deployment of ground-based lightning observation instruments is complex. For example, Colombia has some well-established Lightning Location Systems (LLS); however, they are clustered around some areas and certainly do not cover the entire Colombian territory (Herrera et al. 2018; Aranguren et al. 2013). Therefore, data quality is insufficient or lacks better accuracy in those areas. This context motivated the authors of this study to establish the Colombian lightning climatology using observations that cover the entire territory.

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1.1 Methodology

This work establishes the frequency occurrence and spatial distribution of lightning activity in Colombia. To achieve those objectives, it selected lightning data from a satellite platform due to its coverage of the entire territory. Datasets used in this study are derived products from the Lightning Imaging Sensor (LIS) that were on board of Tropical Rainfall Measuring Mission (TRMM). This space-based instrument recorded total lightning activity (cloud to cloud flashes (CC), intracloud flashes (IC), and cloud to ground flashes (CG)) for 16 years. In Cecil et al.'s (2014) publication, there is a detailed description of the LIS instrument, the recorded raw data, and its derived data products.

Raw data from the observations recorded by LIS are available from January 1, 1998, to April 8, 2015, for the latitude band between 38° N and 38° S. But thanks to the work of re-processing raw data, there are available datasets in different resolutions (i.e., 0.5° × 0.5° and 0.1° × 0.1°). The last one is named TRMM LIS 0.1 Degree Very High-Resolution Gridded Climatology and was processed by Albrecht et al.

LIS VHR dataset used individual LIS orbit data files to compute the view time at 0.1° resolution. After that, flash counts were scaled according to LIS detection efficiency. Then, gridded climatology does not implement any smoothing to the full climatology data to have a higher gridding resolution. More details about data processing are available

in the supplement article of Albrecht et al. (2016) publication. Dataset produced includes gridded climatologies estimating total flash rate density (number of flashes per square kilometer per year) based on the flashes observed by LIS and the amount of time it is viewed in a given area. The data collection consists of five lightning climatologies: full climatological mean (LIS_VHRFC), annual cycle mean (LIS_VHRAC), seasonal mean (LIS_VHRSC), monthly mean (LIS_VHRMC), and diurnal mean (LIS_VHRDC). The high resolution of this dataset provides more information than LIS 0.5° resolution dataset. For Colombia, this means twentyfold more lightning data.

For the aim of this study, the data was limited in all products by the coordinates 13° N and 4.3° S; and 79.1° W and 66.3° W. That area encompasses the whole continental area of Colombia, parts of neighboring countries (Panama, Ecuador, Venezuela, Peru, Brazil), and some portions of open waters (the Caribbean Sea and the Pacific Ocean). Thus, the authors developed a spatial filter to remove the data from unwanted areas. In this way, the accuracy of the findings increases because the information is exclusively related to Colombian territory. Six different filters were developed to filter wanted data with the exact shape of the country and its natural regions. The required filters are arrays of 0's and 1's used for an element-wise multiplication between the lightning data and the mask filters. Figure 1 illustrates the idea behind this process.

This study found the spatial distribution and the frequency occurrence of total lightning activity in Colombia utilizing filtered datasets using available information. The analysis was performed for the entire country and its five natural regions. The spatial distribution analysis used two datasets to establish spatial distribution of lightning activity: LIS_VHRFC and LIS_VHRSC. In this way, it produces a general view of the lightning activity in the country, and at the same time, it reveals its relationship with the topography of the territory. The temporal variation analysis is similar to the previous one but uses LIS_VHRMC and LIS_VHRDC datasets to evidence the development of the lightning activity in monthly and daily time frames. Again the temporal analysis performed shows general and specific features of the whole territory and its


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Fig. 1 The figure depicts masking lightning data to filter only data related to Colombian territory. The left image represents an array of 0's and 1's, and the right image, an excerpt of lightning data to filter. The masking process consists of an element-wise multiplication between matrices

natural regions in those time frames. All data processing in this study used MATLAB®.

The spatial coverage is the primary advantage of TRMM LIS datasets, although it is also essential to recognize some data limitations related to features of the lightning sensor (LIS). The main disadvantages are its limited observation time of a point on Earth (around 90 s per orbit), the impossibility of discerning among CG and IC, or the detection efficiency of the sensor that varies from 69% near noon to 88% at night.

Consequently, some limitations are overcome through enhanced processing algorithms, but for others, there is little to do. While these limitations are real, the TRMM LIS data is enough to estimate reliable flash rates, and it has shown to be of great value to understand many aspects of lightning activity like its temporal development or its geographical distribution. There are many examples of studies developed using TRMM LIS products to estimate global lightning climatology (Cecil et al. 2014, 2015; Albrecht et al. 2016) and regional lightning climatology (Sonnadara et al. 2018; Muñoz et al. 2016; Sen Roy and Balling 2014; Bürgesser et al. 2013; Kuleshov 2012; Soula et al. 2016; Ongee et al.

2017). In the Colombian context, there are several works on lightning climatology mainly based on ground-based measurements of LLS batched in certain areas, and as a consequence with limited coverage of the Colombian territory (Aranguren et al. 2018; Herrera et al. 2018; Aranguren et al. 2017; López et al. 2016; Torres et al. 2015; Aranguren et al. 2014; Montaña et al. 2013; Santamaria 2006; Escobar et al. 2013). A previous work using TRMM LIS datasets of the first years of the mission is available in the Younes (2002) publication.

1.2 Geography and climate of Colombia

Colombia locates in the northwest of South America with an approximate extension of 1,142,000 km² (Fig. 2). It is the only country in South America with coastlines on both the Pacific and the Atlantic Oceans. Its geographical diversity is due to three parallel mountain ranges extending south-north through the territory that belongs to the Andes mountain range, locally known as Western, Central, and Eastern Cordilleras. In those mountains, there are altitudes above 3,000 m.a.s.l, and between the cordilleras, there are
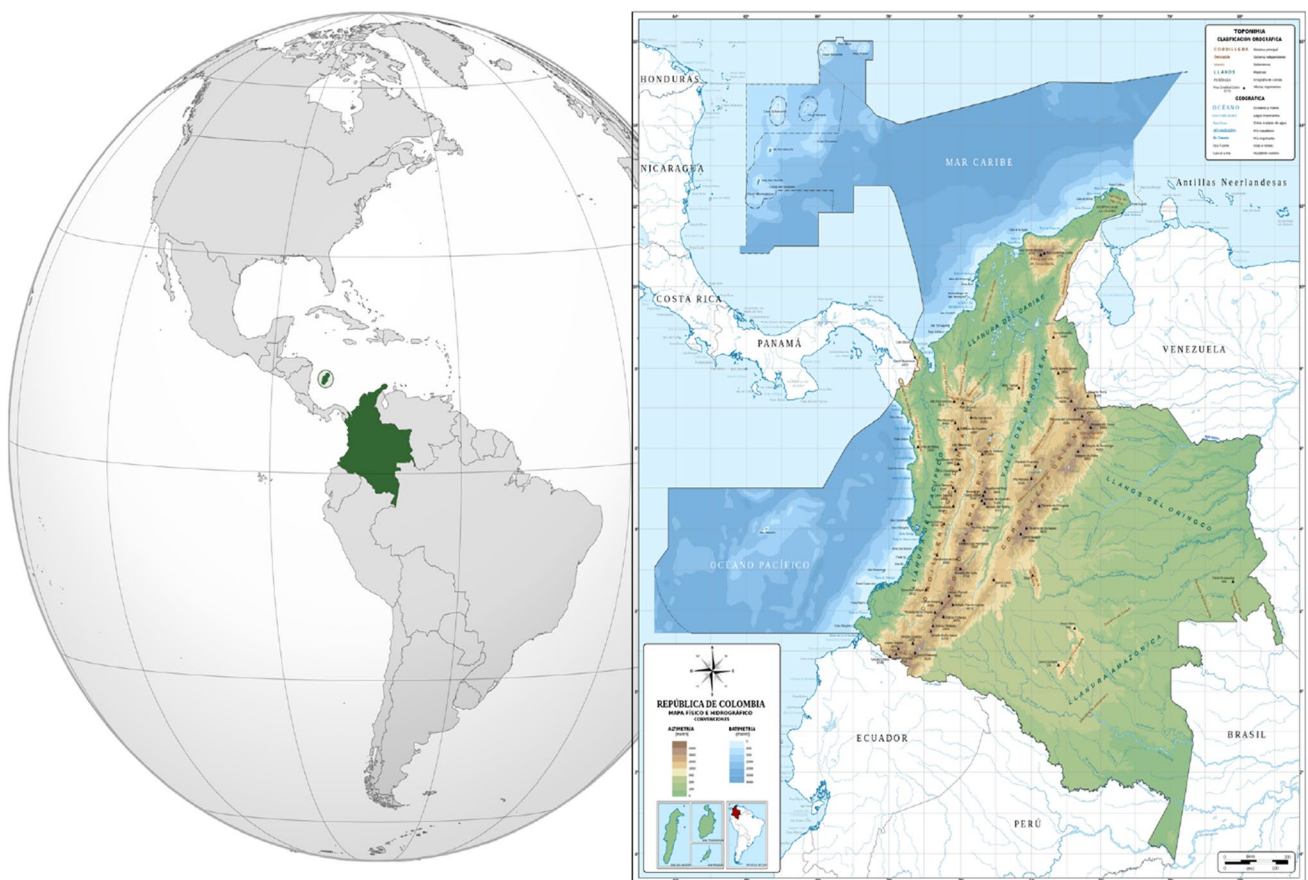

Fig. 2 The figure depicts the location of Colombia in the north of South America. The inset in the figure shows the relief map of Colombia where the Andes mountain range runs along south-north direction through the country (source: adapted from wikimedia commons)

elongated valleys and Andean plateaus. The Cauca River Valley divides the Western and Central Cordilleras, and the Magdalena River Valley the Central and Eastern Cordilleras. There are also smaller river valleys (e.g., Atrató River, Sinú River, San Jorge River, among others) located between the mountain ranges and other smaller mountain chains (i.e., Sierras and Serranías). The referred geography creates five natural regions: the Andean Region, the Pacific Region, the Caribbean Region, the Amazon Region, and the Orinoquia Region, each with well-differentiated geographical and climatic features. Some general characteristics of these natural regions are:

Amazon Region comprises almost 40% of the Colombian territory. It belongs to the jungle of the Amazon rainforest; thus, it is mostly flat land with a few low-altitude mountain chains, a lot of rivers, and dense vegetation. Despite its territorial size, less than 1 % of the Colombian population inhabited the region.

Andean Region covers 24% of the Colombian territory. The presence of branches of the Colombian Andes, plus the Cauca and Magdalena River Valleys running south-north, defines its biodiversity and natural characteristics. Topography is mountainous and rugged in the Andean region. Most of the big Colombian cities are in this region; thus, it is the more densely populated region of the country. The Metropolitan area of Bogotá, the capital city, has around 8 million inhabitants. Medellin and Cali are two other major metropolitan areas with over 2 million inhabitants.

Caribbean Region covers an area of 12% of Colombian territory. It is a region where lowlands prevail, and major rivers encounter creating enormous flooding plains, surrounded by the foothills of mountain ranges. It is the second most populated region in the country.

Orinoquia Region covers 17% of the territory. Most of the region is lowlands (savannah), locally known as Llanos that belongs to the Orinoco River basin. It is the second region with fewer inhabitants.

Pacific Region covers an area of roughly 7% of the territory. The region is flanked west by the Pacific Ocean and east by Western Cordillera. Two small mountain ranges lie in the northern part of the region: Serranía del Baudó and Serranía del Darién. The area is primarily flat and covered by dense rainforests, rivers, swamps, and mangroves.

Insular Region covers an area of 0.3% of Colombian territory. The region includes hundreds of small continental islands and a few oceanic islands. Gorgona is the main oceanic island in the Pacific Ocean (26 km^2). In the Caribbean Sea, the archipelago of San Andres, Santa Catalina, and Providence are the main islands (26 km^2). These two become the focus regarding lightning activity for Insular Region.

Wind regimes in Colombia are affected by several global and local patterns. Some of them worth mentioning are:

- Seasonal migration of the Inter-Tropical Convergence Zone (ITCZ) (Pulwarty et al. 1998).
- Interaction with northeast and southeast trade winds (Andrade-Amaya 2000).
- Presence of offshore and inland Mesoscale Convective Systems (MCSs) (Jaramillo et al. 2017; Velasco and Fritsch 1987).
- El Niño-Southern Oscillation (ENSO) (Hoyos et al. 2013).
- The Atlantic Multidecadal Oscillation (AMO).
- The Pacific Decadal Oscillation (PDO).
- Low-level jets (CHOCO and Caribbean) (Guzman et al. 2014).
- Caribbean cold fronts (Otero et al. 2013).

Regarding climate in Colombia, it goes from warm temperatures along coastlines, lowlands and eastern plains where mean temperature is higher than 24 °C to colder temperatures in highlands and moorlands (i.e., páramos) where mean temperature is around 10 °C or lower. Depending on the methodology, experts can identify up to seventeen climates throughout the country (Guzman et al. 2014; Cruz-Bernal et al. 2018).

Another relevant factor affecting the climate in Colombia is the presence of moisture over the country which mainly depends on interactions between four primary sources: the Atlantic Ocean, the Pacific Ocean, the Orinoco River basin, and the Amazon River basin (Hoyos et al. 2018; Sakamoto et al. 2012).

Mentioned factors, among others, configure a great diversity of climates and vegetation. Therefore, depending on the region, one or two major rainy seasons occur, particularly at medium altitudes around the foothills of mountain ranges (Oster 1979).

2 Spatial distribution of total lightning activity in Colombia

2.1 Annual spatial distribution of total lightning activity

The data products used in this study provide information about the mean lightning activity. There is no lightning data per year; thus, they lack information to establish lightning trends for the observation period. Therefore the authors turn to the TRMM LIS datasets, which provide yearly data with similar information but coarser resolution. From that dataset was possible to establish an annual trend for the observation period. The result shows a behavior mark for two characteristics: (i) it seems to exist an increasing trend of lightning activity in Colombia, (ii) there is a quasi-periodical variation of lightning activity.

Later matches variations in El Niño Oceanic Index for Region 3.4. This index is widely used for climatological studies on the influence of El Niño in different countries because it measures anomalies in mean sea surface temperature in the equatorial Pacific Ocean. Some studies establish a correlation between El Niño and rain anomalies in Colombia. Lightning data obtained also seems to confirm some relation between variations of lightning activity and abnormalities of the phenomenon. Although El Niño could explain the variations in lightning activity, it cannot explain the increasing trend. Some studies suggest that the increase could be due to the increment of greenhouse gases in the atmosphere; others say it could be a consequence of global warming, but that hypothesis demands further research. Figure 4 depicts the lightning activity in Colombia and the corresponding variations of the El Niño Oceanic Index for the 16 years of observations of this study.
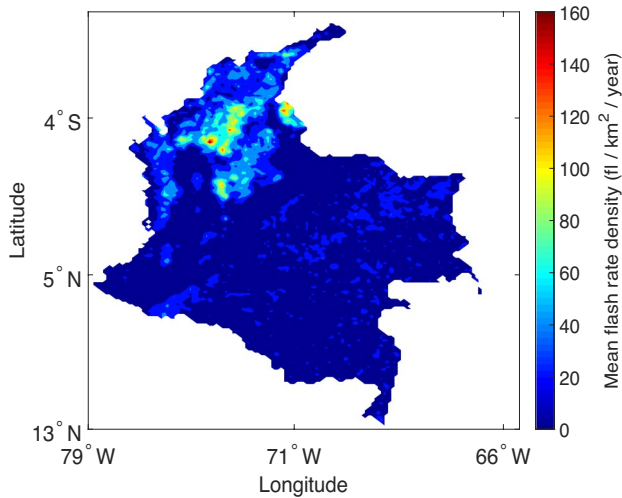
Dataset LIS_VHRFC has the full climatological mean of total flash rate density per year. According to this dataset, Colombia has an FRD greater than 40 fl km^{-2} $year^{-1}$, in 100,000 km^2, roughly 10 % of its territory. Detailing analyzed data by natural regions their mean values are as follows: Caribbean Region 32 fl km^{-2} $year^{-1}$, Pacific Region 17 fl km^{-2} $year^{-1}$, Andean Region 11 fl km^{-2} $year^{-1}$, Orinoquia Region 14 fl km^{-2} $year^{-1}$ and, Amazon Region 12 fl km^{-2} $year^{-1}$. For the Archipelago of San Andres, Providence, and Santa Catalina (most of the Insular Region), the mean value is 4 fl km^{-2} $year^{-1}$.

Figure 3 shows referred values depicting the mean FRD per year of total lightning activity in Colombia. Figure 5 shows box plot detailing results for every natural region. The outliers in this graph correspond to lightning hotspots present in that natural region. The hotspots are areas with lightning activity well above the average.
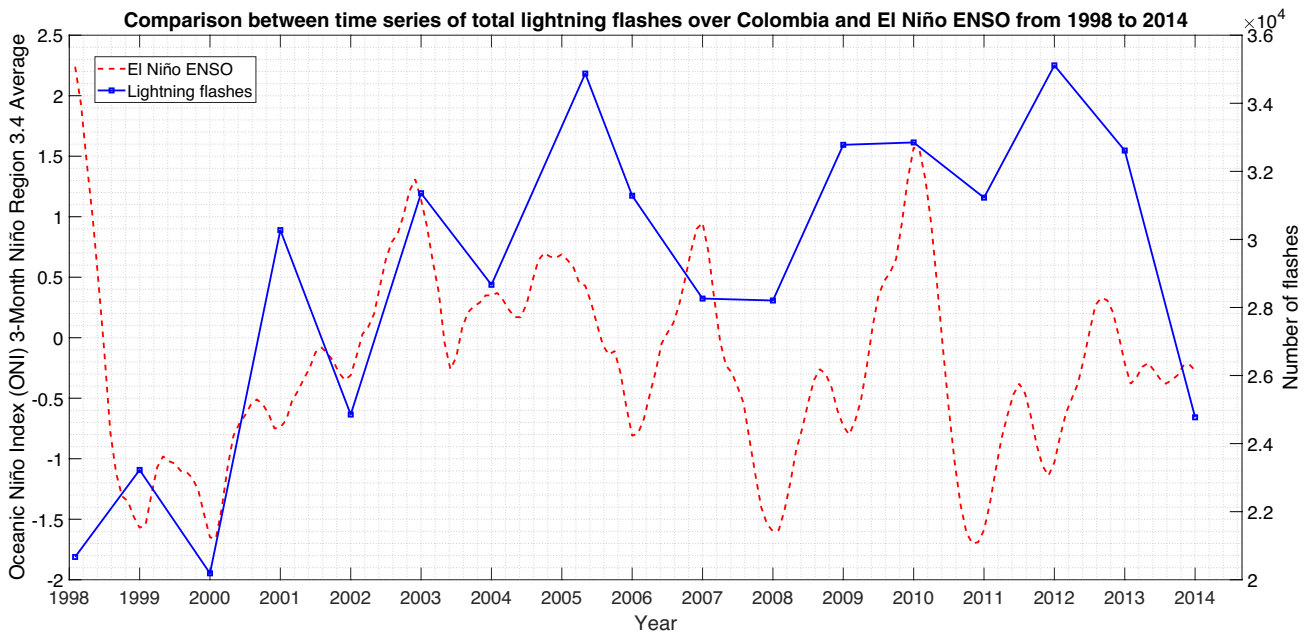

Fig. 3 Conditional mean flash rate density over Colombia obtained from 16 years (1998–2013) of observations of lightning activity with TRMM/LIS. According to this data, roughly 65 % of the Colombian soil has a flash rate density over 10 fl km^{-2} $year^{-1}$, but around 15 % of the territory has a flash rate density over 70 fl km^{-2} $year^{-1}$

Fig. 4 Comparison between total lightning activity in Colombia and Oceanic Niño Index for region 3.4 from 1998 to 2013

Fig. 5 Box plot of total lightning activity in Colombia. Depicted data corresponds to the observation period from 1998 to 2013 sorted by natural regions of the country. The outliers correspond to lightning hotspots, most of them located north of the country. Dispersion of data for the Andean Region is due to its physical extension covering from north to south of the Colombian territory
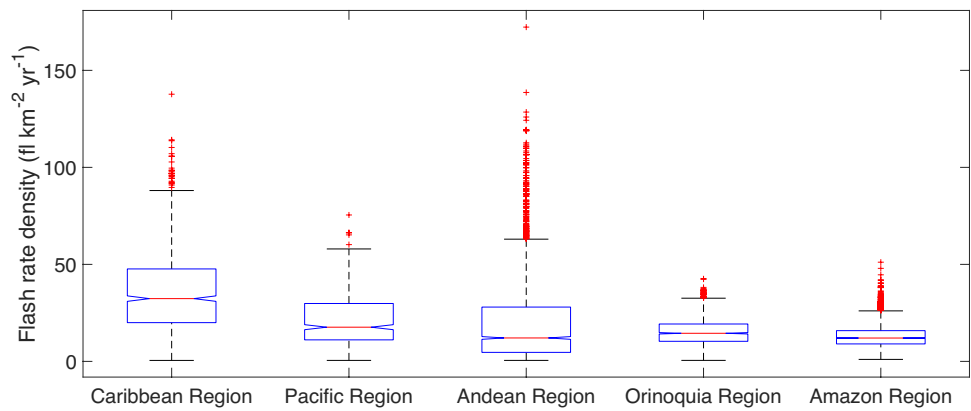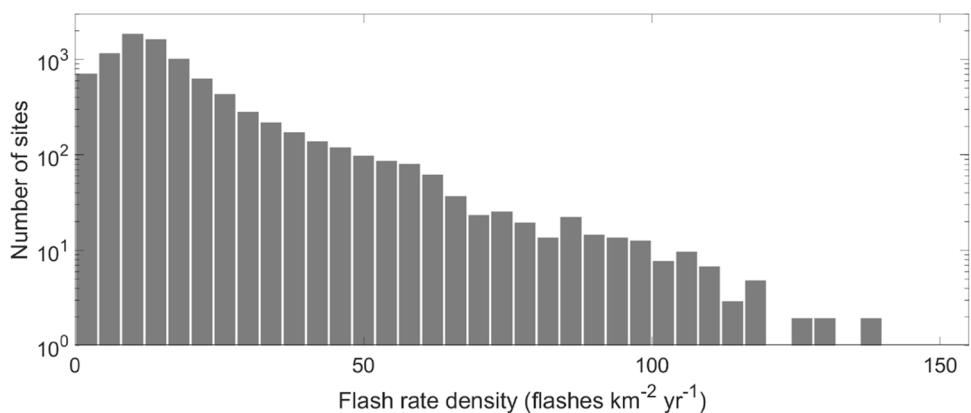
Findings for each natural region allowed to identify areas with the highest values of FRD inside that region.

– The highest values in the Caribbean Region corresponds to the subregion named Momposina Depression, geological depression in the upper Magdalena River basin where many major rivers confluence. This result is in agreement with findings presented in Montaña et al. (2013).
– The highest values in the Pacific Region are in the Atrató River basin.
– The Andean Region has its highest values in the subregion called Catatumbo. The latter belongs to Lake Maracaibo basin, where is located the highest lightning activity in the world (Catatumbo lightning, FRD of 232 fl km^{-2} year^{-1}) (Albrecht et al. 2016; Muñoz et al. 2016).
– Orinoquia Region, the highest values are in the Meta River basin.
– Amazon Region has its highest values in Sibundoy valley (southeastern flank of Western Cordillera).

Additional areas with values of FRD over 20 fl km^{-2} year^{-1} are Piedemonte Llanero (foothills on the eastern flank of the Eastern Cordillera) and the high plains in the Orinoquia Region; Pubenza Valley, Aburrá Valley, and middle Magdalena River valley in the Andean Region.

Histogram for the annual mean value of FRD (Fig. 6) provides some additional insights about the annual spatial distribution of total lightning activity. It reveals that 65% of the territory (around 760,000 km^2) has an FRD over 10 fl km^{-2} year^{-1}. But, there is an area similar in size to Norway that has an FRD over 50 fl km^{-2} year^{-1}. Fitting a log-logistic distribution to the data, the mean value estimated for the whole country is around 18 fl km^{-2} year^{-1}.

Ground flash density (GFD) is a term used to refer to the effective number of CG touching earth. Its estimation regularly uses ground-based instruments, but this study has no ground-based data. TRMM LIS does not discern between IC and CG. Thus, it is not possible to estimate values of GFD directly. Fortunately, in the absence of reliable or scarce observations of GFD, the IEEE guide, Std 1410-2010, recommends assuming that CG represents one-third of total lightning activity.

Using referred recommendation, it is estimated a total lightning activity of 20 million flashes per year in Colombia, which would mean around 6.8 million CG per year in all the country or a GFD of 6 fl km−2 year^{-1}. Performing the analysis by natural regions, values of GFD are:

– Caribbean Region, 1.4 millions of CG per year (GFD 12 fl km−2 yr^{-1}).

Fig. 6 Histogram of the annual mean of total lightning activity in Colombia. Depicted data corresponds to the observation period from 1998 to 2013. The whole histogram fits a log-logistic probability distribution with a mean value of 18 fl km^{-2} year^{-1}

- Andean Region 2.2 millions of CG per year (GFD 6.5 fl km−2 yr−1).
- Pacific Region 0.4 million of CG per year (GFD 6.9 fl km−2 yr−1).
- Orinoquia Region 1 million of CG per year (GFD 5.1 fl km−2 yr−1).
- Amazon Region 1.8 millions of CG per year (GFD 4.3 fl km−2 yr−1).

These values are directly in line with previous studies on this matter (Torres et al. 2015; Aranguren et al. 2017; Herrera et al. 2018; Pareja 2018).

Generally speaking, topography strongly influences the GFD factor in Colombia; thus, its value tends to be inversely proportional to the altitude (high values of GFD in lower altitudes, low values of GFD in higher altitudes) (Aranguren et al. 2017). This result also matches the image shown in Fig. 3 where intense lightning activity locates around foothills of the mountain ranges.

San Andres, Providence, and Santa Catalina islands are in the Caribbean Sea, about 750 km from the Colombian mainland; meanwhile, Gorgona island is 35 km from the Pacific coast. In these islands, total lightning activity has an FRD of 4 and 2 fl km−2 year−1 respectively. However, this estimation is quite uncertain because the resolution of the datasets overpasses several times the dimensions of the islands. Therefore this information is only a raw estimation of lightning activity that considers both land and ocean that surround the islands.

2.2 Quarterly spatial distribution of total lightning activity

LIS_VHRSC has FRD data sorted by seasons. The information available divides the year into four quarters, namely, December, January, February (DJF) for the first quarter; March, April, May (MAM)for the second quarter; June, July, August (JJA) for the third quarter and September, October, November (SON) for the fourth quarter. For each quarter, data correspond to the conditional FRD per day.

FRD per day for the first quarter (December, January, February) is shown in Fig. 8a. The image evidences a generalized low FRD (mean value of 0.02 fl km−2 day−1) in the whole territory that coincides with the annual dry season in Colombia (Guzman et al. 2014). During this quarter, the ICTZ is in its further south localization, and the wind velocity of the CHOCO low-level jet is in its lowest values of the year (Poveda et al 2014).

Despite generalized low FRD, lightning hotspots during this quarter located in the middle part of the Magdalena River and the Catatumbo in the Andean Region, and the Sibundoy valley in the Amazon Region.

For second quarter (March, April, May), Fig. 8b shows the FRD per day. The ITCZ starts to move north of the equator during this period, shifting across the Colombian mainland. This displacement causes an intensification of rain, reaching a peak around April (Guzman et al. 2014). Lightning activity has a twofold increase (mean value of 0.04 fl km−2 day−1). However, some areas in the north of the country experience a major increase reaching 0.3 fl km−2 day−1. These areas correspond to the far north of the Andean, Pacific, and most Caribbean regions.

Momposina Depression, and Catatumbo subregions, have the highest values of FRD. Other areas with high values of FRD are the Meta and Arauca rivers basins as well as the high plains in the Orinoquia Region; both Pubenza and Sibundoy valley in the Andean and Amazon Regions, respectively.

Figure 8c shows flash rate density per day for the third quarter (June, July, August). During this quarter, there is a general reduction of lightning activity except in the north part of the country where it keeps high and even increased in some subregions (mean value from 0.02 fl km−2 day−1 to 0.6 fl km−2 day−1). There is a marked decrease in most of the Andean Region, the Amazon Region, and the southern part of the Pacific Region.

In addition to the mentioned areas, the lightning activity stays moderate in the confluence of the rivers Meta and Orinoco in the Orinoquia region. It is interesting to note that the only exception to the almost continuous intense lightning activity in the Caribbean Region is the subregion named Alta Guajira which is a desertic area. Nevertheless, during this quarter, the lightning activity in this subregion reaches its peak of activity.

Finally, fourth quarter (September, October, November), FRD per day is shown in Fig. 8d. This quarter comprises the second rainy season in most of Colombia. Regarding lightning activity, there is also a generalized second peak of activity (mean value of 0.06 fl km−2 day−1). Lightning activity in the Caribbean slightly reduces but stills high (mean value of 0.04 fl km−2 day−1).

During this quarter, lightning hotspots are in Catatumbo and foothills of the Sierra Nevada de Santa Marta, Momposina Depression, and middle Magdalena River valley.

For the Archipelago of San Andres, Providence, and Santa Catalina (most of the Insular region of Colombia), the lightning activity presents a single peak of activity throughout the year, reaching its maximum around mid-year. In this case, the height of lightning activity matches the peak of rain in the islands (IDEAM and Cormagdalena 2001).

Box plot in Fig. 7 shows values of lightning activity for every season. The number of outliers matches the trend of lightning activity in the country's north. This finding shows that lightning activity in this area is way more intense and follows a different temporal development that in the rest of the country.

Fig. 7 Box plot of seasonal total lightning activity in Colombia. Depicted data corresponds to the observation period from 1998 to 2013. The trend in the number of outliers matches the pattern of lightning activity in the Caribbean Region. DJF stands for December, January, February; MAM stands for March, April, May; JJA stands for June, July, August; SON stands for September, October, November
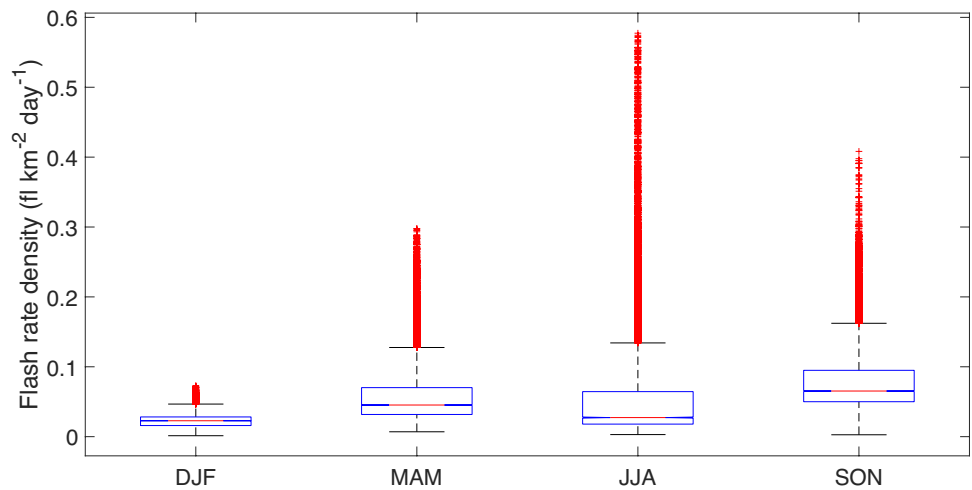
Fig. 8 Quarterly variation of total lightning activity in Colombia obtained from 16 years (1998–2013) of satellite-based observations of lightning activity with TRMM LIS. Each map depicts the total lightning activity for a quarter. DJF stands for December, January, February; MAM stands for March, April, May; JJA stands for June, July, August; SON stands for September, October, November. Flash rate density has units of fl km^{-2} day^{-1}
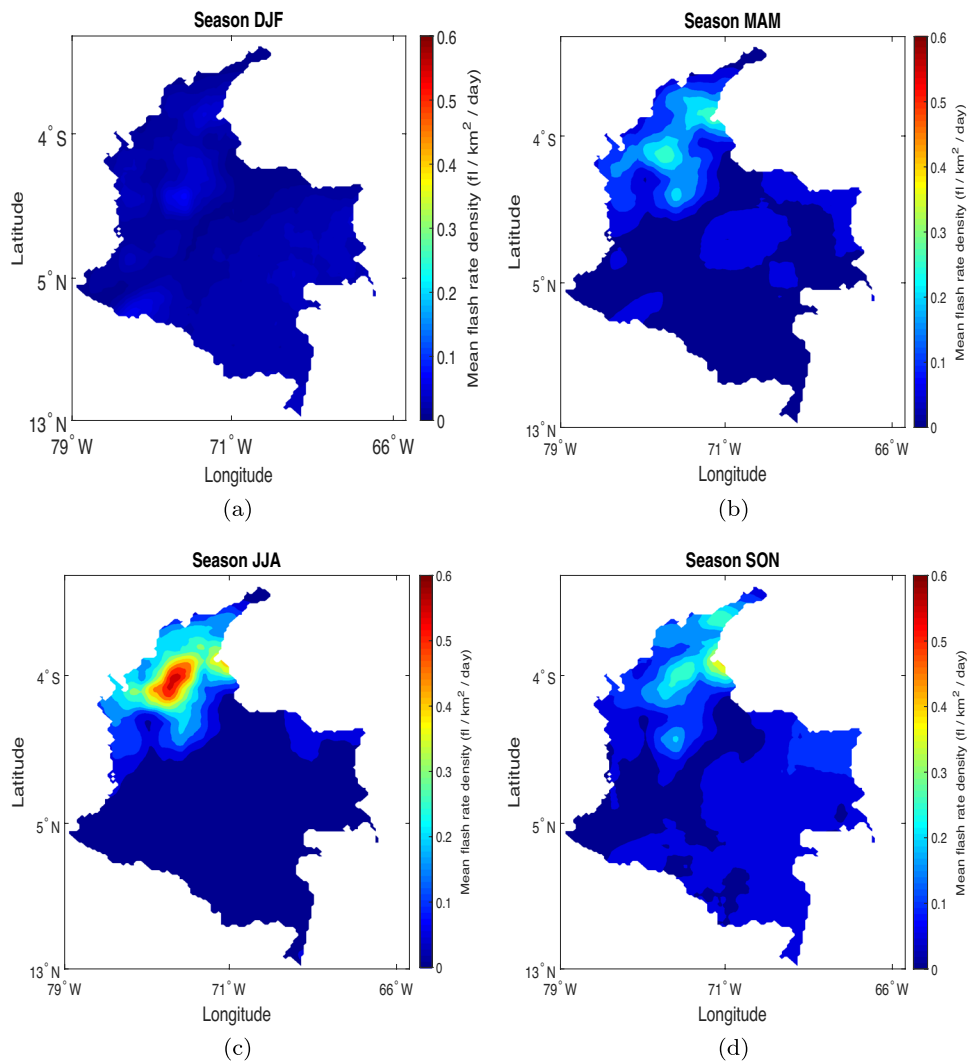
3 Frequency occurrence of total lightning activity in Colombia

Spatial distributions give information of where total lightning activity occurs, while frequency occurrence provides when of that lightning activity. Accordingly, using different time references, it is possible to analyze the whole activity as a continuous process that changes over time. To this aim, Colombia's total lightning activity was described monthly, daily, and hourly. Again the analysis was made over the whole territory and for each natural region. The results show different time patterns among the natural regions, probably due to their distinct geographical and climatic features.

3.1 Annual variation of total lightning activity

LIS_VHRMC has data of monthly FRD of 16 years. Calculation of monthly patterns for each area helps find a year-round trend for the country and its natural regions. Figure 9 shows results of these calculations. According to the results, at first glance, Colombia seems to have two lightning seasons, with one peak in April, followed by a greater peak in September. Also, there is a smooth transition between the two seasons without a great reduction in lightning activity. The behavior described is shown in Fig. 9a. This graph

details that most of Colombia's lightning activity occurs in two nonconsecutive quarters, the first quarter: March, April, May, and the second quarter: September, October, and November. Even though this finding is in line with previous studies, more detailed findings go beyond previous reports, showing that the "country behavior" does not properly describe the temporal variations in every region.

For example, Caribbean Region (Fig. 9b) has a clear uni-modal pattern, which means there is a single peak of total lightning activity per year. Lightning activity in this region starts with low values of FRD in January and, from that point, increases to reach its maximum values around August. Then the lightning activity starts to decrease to its lowest values by the end of the year. These findings are in line with a previous study (Inampués et al. 2017).

Pacific Region (Fig. 9d) also has a uni-modal pattern, but unlike the Caribbean Region, the trend shows an almost constant high value of FRD from April to September. The latter seems to match the presence of a high number of MCSs in the region (Sakamoto et al. 2012).

The Andean Region (Fig. 9c) has a bimodal pattern, with two peaks centered in April and September, respectively. The transition between these two seasons is smooth, slightly reducing lighting activity around mid-year.

The Orinoquia Region has two lightning seasons, with a well-marked transition between periods. The first season

Fig. 9 Annual variation of total lightning activity in Colombia. Despite the differences among natural regions, most of the lightning activity in the country occurs in two quarters (March, April, May, and September, October, November). Data is presented as flash rate density versus months
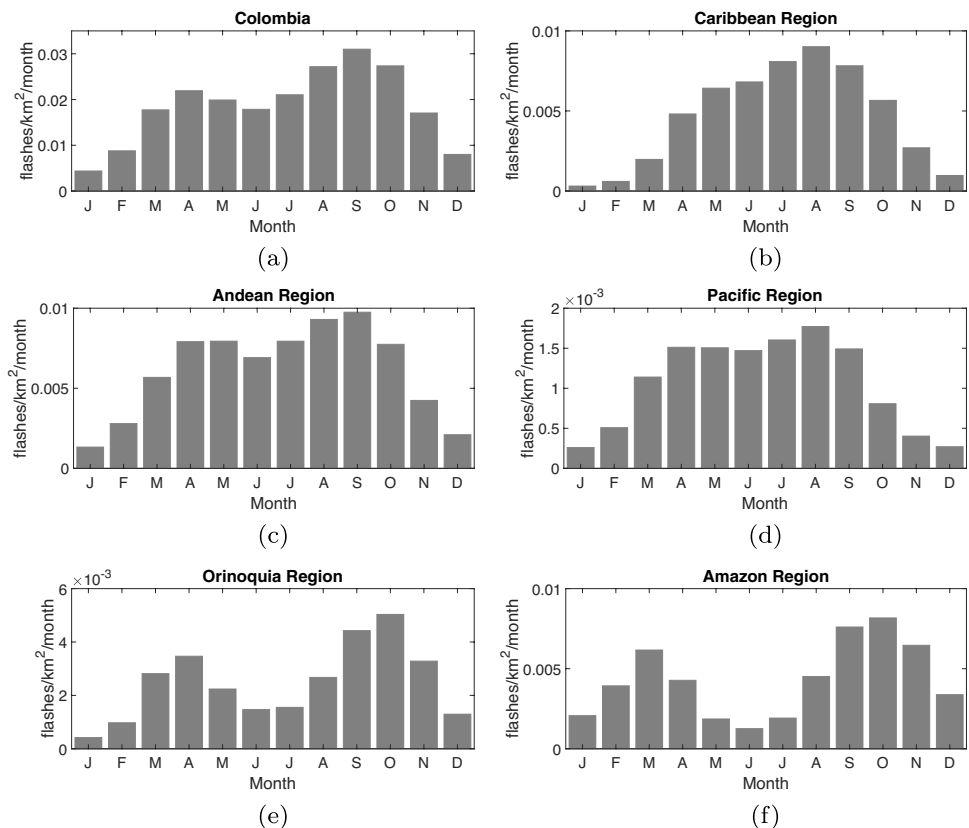
peaks around April and the second season around October. The latter is the more intense season of the year in this region.

Finally, the Amazon Region also has two lightning seasons, but the height of the first season is around March, and the height of the second season is around October. Lightning activity in this region seems to be influenced by the transitions between dry and wet seasons (Saraiva et al. 2016).

Another finding was that bordering sites between natural regions have a transitional pattern. For example, sites located in the far north of the Andean Region have a similar pattern to the Caribbean Region; this means a uni-modal instead of a bimodal pattern. The same is true for the Pacific Region where the far north shows a trend similar to the Caribbean Region; meanwhile, areas in the far south are more like the Andean Region.

3.2 Hourly variation of total lightning activity

In this case, the product employed was LIS_VHRHC, which has data FRD per hour of 16 years of observations. The estimated trends show infrequent lightning activity during the morning. The activity starts in the afternoon, followed by an upward trend that peaks around the evening and then a downward trend that continues decreasing up to early morning. Inampués et al. (2017) reached a similar conclusion. This hourly pattern is shown in Fig. 10a where the height of total lightning activity takes place around 18:00 LST (Local Standard Time). All findings in these sections are in the local standard time of Colombia (UTC -05:00).

Hourly variations show differentiating features among regions, especially lightning activity between midnight and early morning. The Caribbean Region regularly experiences lightning activity since afternoon with a maximum of around 19:00 LST. Then lightning activity reduces and keeps moderate up to midnight, finally drops during the early morning (Fig. 10b).

Andean Region also has an upward trend since noon, reaching a substantial intensification around 18:00–19:00 LST, and then has a maximum around 23:00 LST; finally, the activity tends to decrease during the first hours of the day (Fig. 10c).

Pacific Region reaches a well-differentiated peak of lightning activity around 19:00 LST; after that, the activity decreases during the night and the early morning (Fig. 10d).

Fig. 10 Total lightning activity analysis in Colombia and its natural regions in an hourly time frame. The hours with more lightning activity are from noon to well into the evening. In some regions, lightning activity even extends to the early morning. The period with less lightning activity is mid-morning

(a)

(b)

(c)

(d)

(e)

(f)
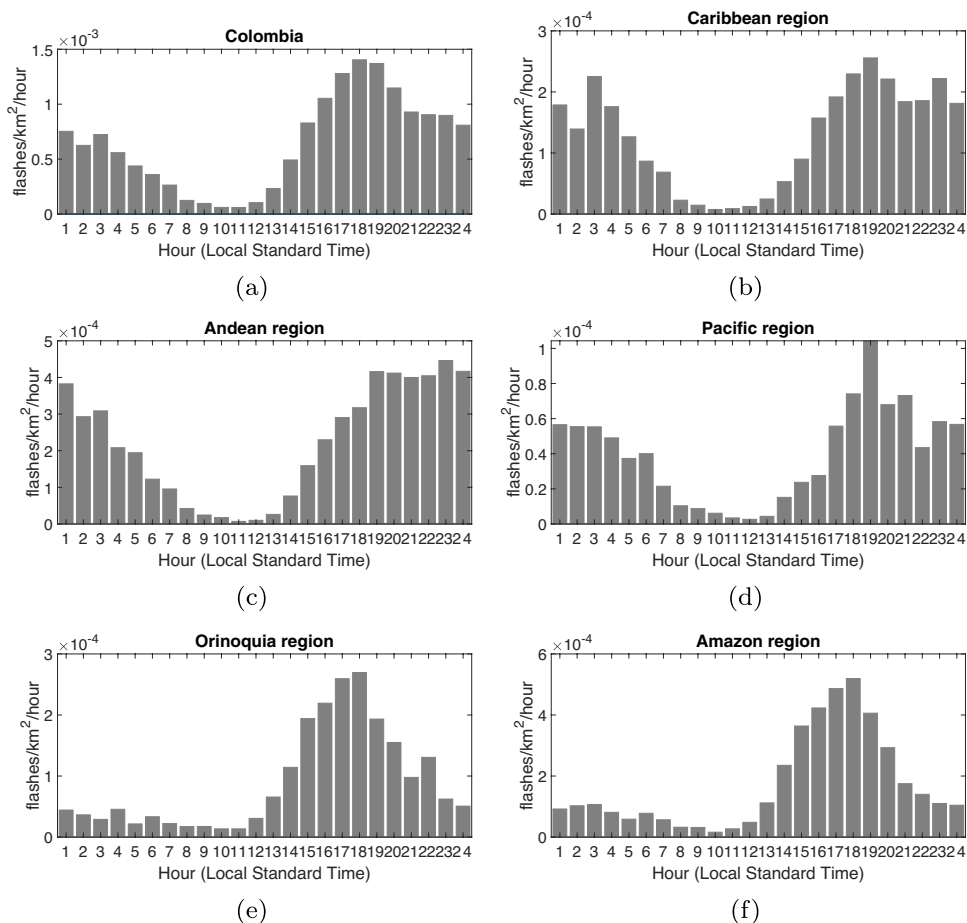
In the Orinoquia Region, lightning activity occurs during the afternoon, reaching a maximum around 18:00 LST, immediately there is a downward trend with almost no lightning activity after midnight (Fig. 10e). Similarly, the Amazon Region has a matched pattern with the Orinoquia Region, meaning scarce lightning activity after midnight (Fig. 10f).

4 Additional insights about lightning hotspots in Colombia

According to Albrecht et al. (2016), Colombia holds twenty positions in the 500 lightning hotspots on Earth ranking. Consequently, Colombia is the third country with more positions in this list, only preceded by the nations of the Congo Basin (Democratic Republic of Congo and the Central African Republic). Following the methodology of the mentioned study, these lightning hotspots must be interpreted as areas and not as single points. Consequently, the area of influence of these lightning hotspots in Colombia covers an approximated area of 160,000 km^2 (around 14% of the Colombian soil). Table 1 summarizes the location of these Colombian lightning hotspots.

Colombian lightning hotspots have a mean value of FRD of 83 fl km^{-2} year^{-1}. Most of those lightning hotspots are located in the Caribbean Region and north of the Andean Region, except for two Pacific region sites. The geographical coordinates of those sites reveal their occurrence between latitudes 7° N and 11° N roughly matching the north part of the country. Concerning longitude, these sites tend to align around the basins of Atrató, Cauca, and Magdalena Rivers.

From Table 1, it is evident that most lightning hotspots take place in inter-Andean valleys and foothills of mountain ranges. Their altitudes are around 500 m.a.s.l. and lower, meaning those areas have average temperatures higher than 24 °C. Considering mentioned information plus Koppen climate classification, the referred areas correspond to rainforest, monsoon, and savanna climates.

It is worth mentioning that some lightning hotspots take place close to densely populated centers, especially those located in some areas of the Caribbean Region, the Magdalena River Valley, and the Pubenza Valley. This finding is important because roughly one-fourth of the Colombian population inhabit these areas (DANE Departamento Administrativo Nacional de Estadistica 2019; Cruz et al. 2013).

Therefore, there is a clear lightning threat to the lives of human beans, but the risk also applies to the country's

Table 1 List of the Colombian lightning hotspots according to Albrecht et al. (2016)

Global Rank	FRD (fl km^{-2} yr^{-1})	Grid latitude	Grid longitude	Altitude hotspot (m.a.s.l)	Nearest populated place	Departament
4	172.29	7.55° N	75.35° W	107	Caceres	Antioquia
7	138.61	8.85° N	73.05° W	584	El Tarra	Norte de Santander
11	124.26	5.75° N	74.95° W	833	Norcasia	Caldas
18	114.19	8.45° N	74.55° W	23	Majagual	Sucre
25	105.73	8.15° N	76.85° W	2	Turbo	Antioquia
46	95.38	11.15° N	72.95° W	124	Barrancas	Guajira
136	77.02	10.45° N	75.35° W	106	Santa Rosa	Bolivar
137	76.88	6.85° N	74.25° W	119	Puerto Parra	Santander
140	75.46	5.35° N	76.75° W	57	El Canton de San Pablo	Choco
152	73.51	9.75° N	72.95° W	1,252	Becerril	Cesar
161	72.08	8.05° N	73.55° W	95	San Martin	Cesar
214	66.44	7.25° N	76.65° W	36	Mutata	Antioquia
217	66.25	6.25° N	76.75° W	29	Bellavista	Choco
271	62.27	9.35° N	74.95° W	93	San Pedro	Sucre
282	61.32	9.35° N	73.95° W	69	Astrea	Cesar
293	60.40	8.65° N	75.75° W	38	San Carlos	Cordoba
304	59.93	6.05° N	73.25° W	2,200	Suaita	Santander
343	57.75	10.55° N	74.35° W	26	El Reten	Magdalena
397	54.64	4.35° N	74.85° W	279	Nariño	Cundinamarca
422	53.49	2.65° N	76.65° W	1,685	Cajibio	Cauca

The number in the rank column refers to the position in the global ranking. The altitude listed corresponds to the hotspot coordinates and not the altitude of the nearest populated place

economic infrastructure. For instance, previous findings showed that part of rural electric power systems in Colombia have interruption rates above the global mean, due to lightning accidents (Aranguren et al. 2015). Other relevant studies focus on lightning accidents in Colombia can be found in Cruz-Bernal et al. (2018); Cristancho C. et al. (2017); Cristancho et al. (2017).

5 Discussion

The spatial distribution of lightning activity in Colombia shows that the country's north has the highest activity in the territory. Most lightning occurs in the foothills of mountain ranges and inter-Andean valleys. Undoubtedly, activity is higher in most Caribbean Region, except for the Alta Guajira because of its desert-like climate. In the Andean Region, the higher activity aligns with the Magdalena River basin. In the Orinoquia Region, the activity centers in the Meta River basin and the sub-regions Piedemonte Llanero and the high plains. The higher activity in the Pacific Region takes place in the Atrató River basin. Finally, lightning activity in the Amazon Region is high around the southeastern foothills of the Western Cordillera and the far south of the region.

The annual variation of lightning activity in Colombia can only be described accurately on a regional basis because of the country's well-differentiated features of each of the five natural regions. The Caribbean Region has a single lightning season throughout the year, with a maximum of activity around August. This pattern also applies to the Archipelago of San Andres, Providence, and Santa Catalina but with a peak of lightning activity around mid-year. The Andean and Pacific Regions have two lightning seasons with a smooth transition between seasons. For their part, Amazon and Orinoquia Regions also have two lightning seasons but with a steep reduction of lightning activity between seasons.

The hourly variation of lightning activity in Colombia shows that most of the lightning activity in the country takes place from the afternoon and extends to the early morning. This pattern applies to the Caribbean, Andean, and Pacific Regions. For Amazon and Orinoquia regions, the lightning activity is relatively infrequent after midnight.

The findings suggest that high values of FRD in Colombia are a consequence of an almost continuous lightning activity throughout most of the year. Indeed, results highlight the exceptional duration of moderate to high lightning activity, occurring between six and ten months per year.

Results justify due to the conjunction of factors, such as varied topographic conditions, wind patterns, and availability of humidity that favors conditions extending the duration of convective activity producing deep convection (Bürgesser et al. 2012). The heat necessary to warm air comes from the

constant sunlight, guaranteed because of the near-equator location of the country.

The mentioned conditions are especially relevant in lightning hotspots present in the Caribbean, Andean, and Pacific Regions. In contrast, Amazon and Orinoquia Regions are mainly flatlands, which would explain why these regions have less lightning activity than the other areas.

A final consideration is that lightning activity does not always match the peaks of rainy seasons but seems to occur during the transitions between wet and dry seasons.

Worth mentioning accuracy of results relies on the quality of datasets. Data from TRMM/LIS have some impairments due to the nature of the instrument. In all cases, view time over a specific area was short because the sensor boarded a low orbit satellite. Thus, total view time is not equal for all latitudes because it was the sum of all view times that the instrument accumulated for a specific area over the years. For Colombia, the mean observation time is around 57×10^4 s. Additionally, this value varies 10% between Colombia's northern and southern latitudes.

The other central element to consider is the efficiency of the sensor. LIS was an optical sensor; therefore, it depended on the detectable illuminations emanated from the top of the clouds. This detection is challenging during daylight or with simultaneous thunderstorms. Nonetheless, satellite-based data is successfully used to study lightning activity. Indeed, all findings in this work are consistent with previous studies that used satellite and ground-based data.

6 Conclusion

This study aimed to find patterns for frequency occurrence and spatial distribution of total lightning activity in Colombia using 16 years of data from TRMM/LIS.

Two relevant findings are the following: First, it presents the spatial distribution of lightning that correlates well with previous studies and demonstrates the almost continuous activity in the territory, especially in northern latitudes. The intense lightning activity also occurs around the foothills of mountain ranges and inter-Andean valleys. Second, it shows the inconvenience of describing the frequency occurrence of lightning activity based on mean values for the whole country because occurrence patterns differ based on particularities of each natural region.

Thus, lightning activity in Colombia has two peaks or a single peak of activity, depending on the region. The Caribbean and Insular Regions have a uni-modal pattern; Andean, Pacific, Amazon, and Orinoquia Regions have a bimodal pattern.

Lightning activity in Colombia occurs between noon and early morning in the Caribbean, Andean and Pacific

Regions. For Amazon and Orinoquia Regions, lightning happens between noon and evening.

Lightning hotspots in Colombia are areas with mean FRD values of 83 fl km^{-2} year^{-1} or more representing 14 % of the territory (i.e., 160,000 km^2). They are mainly located in the Caribean Region and lie along foothills of mountain ranges and rivers basins of main Colombian rivers.

Data availability TRMM LIS/OTD data and gridded climatologies are distributed by NASA EOSDIS Global Hydrology Resource Center Data Analysis and Archive Center (DAAC), Huntsville, Alabama (http://thunder.nsstc.nasa.gov). Other datasets generated during the current study are available from the corresponding author on reasonable request.

Code availability Any code used in this paper is available upon request.

Declarations

Ethics approval All authors accept all ethical approvals

Consent to participate All authors consent to participate.

Consent to publication The authors consented to publish the paper.

Conflicts of interest The authors declare no competing interests.

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