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Characterization of the lightning activity of "Relámpago del Catatumbo"

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ABSTRACT

The "Relámpago del Catatumbo" (Catatumbo Lightning) is a phenomenon known for more than 500 years that occurs in Venezuela. This phenomenon occurs almost all along the year in a very small region of the southwest region of Maracaibo Lake and, according to the Lightning Imaging Sensor (LIS) data, this region presents the highest lightning activity of the world. The region presents a complex topography with particular climatic conditions. The lightning activity of the region was examined using the World Wide Lightning Location Network (WWLLN) data. The results show two very localized high-lightning activity centers: one of them is confined around [9.5°N; 71.5°W] over the southwest region of the Maracaibo Lake, and the other is around [9°N; 73°W] near the Colombia–Venezuela border. The lightning activity has a semiannual behavior with two maxima, one around May and another one around October. The diurnal cycle shows substantial lightning activity during local nights.

1. Introduction

Southwest of the Maracaibo Lake in Zulia State, Venezuela, is a region with frequent thunderstorms and significant lightning activity. The phenomenon that takes place in this inhospitable location is known as the "Lighthouse of Catatumbo" or "Catatumbo Lightning" (Relámpago del Catatumbo, in Spanish), the most persistent thunderstorm of the world. It is visible throughout almost the whole year in a confined region, lasts up to nine hours every night and has become a part of indigenous people's tales. The Spanish poet Lope de Vega mentioned this unusual phenomenon in his classic poem "La Dragoneta" in 1597; it tells the story of how the lightning lights prevented the attack of English pirate Sir Francis Drake on Maracaibo. This phenomenon was observed by the famous German naturalist Alexander von Humboldt as well.

The Meteorological Office of Venezuela presents an isokeraunic map built with data gathered between 1950 and 1971, which shows more than 100 thunder days in the Maracaibo regions (Ramírez and Martínez, 1997). Martínez et al. (2003), using the data detected by the Lightning Imaging Sensor (LIS) between 1998 and 2002, reported the lightning activity of different regions of Venezuela. They found a maximum in the lightning event detected by LIS in the State of Zulia, where the Maracaibo Lake is located, and found a maximum activity between the months of September and October. These authors also made an isokeraunic map of Venezuela, which shows more than 70 thunder days on Maracaibo Lake. Tarazona et al. (2006) presented the data obtained by a monitoring system of lightning activity over Venezuela between the years 2000 and 2004. These authors reported more than 200 thunder days over the Maracaibo Lake. It is possible to observe that the number of days with thunderstorms reported in this region is significant. Possibly, the different results obtained are due to the different techniques used in the determination of this parameter. On the other hand, Pinto et al. (2007) compared the lightning observation of local detection system with the lightning detection by LIS. They show a flash density of 181 fl $km^{-2}\,yr^{-1}$ over Venezuela with an estimated IC/CG ratio of 12.6. Albrecht et al. (2011) used 13 years of lightning data from LIS and found that the Maracaibo Lake has the highest flash rate of the world with 250 fl $km^{-2}\,yr^{-1}$, followed by 232 fl $km^{-2}\,yr^{-1}$ over the Congo Basin.

Falcón et al. (2000) reported several expeditions to the Maracaibo Lake region and located two small regions where the phenomenon seems to occur, both around [9°N; 72°W]. The authors reported that the phenomenon occurs during the whole night but it is better observed between 19:00 and 04:00 (local time) and has a mean frequency of 28 fl min^{-1}. The authors proposed a microphysical model based on the crystalline symmetry of the methane molecule in order to explain the observed lightning activity. The pyroelectrical model (Falcón and Quintero, 2010) uses the self-polarization property of methane to predict an increase in the electric field inside thunderstorms, due to the presence of small fractions of methane, which could facilitate the lightning generation. Falcón et al. (2000) suggested that the methane accumulation is major in night hours when the methane is not photodissociated and under cumulonimbus clouds because the clouds act as a filter to solar radiation and, according to the model, this explains the occurrence of the phenomenon during night time. These authors also argue that during the wet season (June–November) the decrease of the phenomenon is explained by the wash-out of the methane due to precipitations.

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Analogously, during the dry season (December–May) the phenomenon should be enhanced since the methane concentration increases because of the increase in the mean temperature and evaporation rate.

In this work, the World Wide Lightning Location Network (WWLLN) Stroke B data (Rodger et al., 2009) are used to examine the lightning activity of the Maracaibo region. By covering the region with a $0.1^\circ \times 0.1^\circ$ grid cell, the high lightning activity centers in the region were recognized and analyzed in terms of time scale ranging from hours to years.

2. Topography and climatology

The northwest of Venezuela includes the Maracaibo basin, the east–west orientated Cordillera de la Costa ($\sim$1500 m high) and the prominent southwest–northeast oriented Cordillera de Merida (up to 5000 m high). Fig. 1 shows the topography of the region where the Maracaibo basin is located. The gray scale shows the ground elevation of the region in meters with the national border of Venezuela and Colombia and the main cities of the region. The two branches of the Andes Mountains (Cordillera de la Costa and Cordillera de Merida), which surround the Maracaibo Lake, can also be observed. The ground elevation data used in Fig. 1 were obtained from the Global Land One-kilometer Base Elevation (GLOBE, http://www.ngdc.noaa.gov/mgg/topo/globe.html).

This topography creates a rather complex precipitation regime. The north–south trending system and the presence of a major moisture source (Caribbean Sea) to the north of the landmass produce very particular climatic conditions (Pulwarty et al., 1992). Stensrud (1996) has shown that there is a nocturnal Low-Level Jet (NLLJ) in the Maracaibo Lake, which is part of the larger-scale Caribbean Low-Level Jet (LLJ). The NLLJ is a LLJ that maximizes at night. These LLJs transport moisture and heat, which produce a favorable thermodynamic condition for deep convection (Beebe and Bates, 1955) and may be a mechanism for prolonging the lifetimes of convective activity (Bonner, 1966).

Velásquez (2000), based on the precipitation regimes between 1961 and 1999, found a bimodal distribution of the precipitation in the northwest region of Venezuela. Negri et al. (2000) found a mean rain rate of over 200 mm per month over Maracaibo Lake with a dry season between December and May. Mapes et al. (2003) reported that Maracaibo Lake presents an annual mean rainfall rate larger than 0.6 mm h^{-1}, with a peak ($\sim$1.5 mm h^{-1}) between 02:00 and 04:00 local time. They also found nocturnal convection over Maracaibo Lake and suggest that the convective cloud systems have similar scales to those of the topography.

3. Methodology

The lightning data used in this study came from two independent lightning detection systems: the World Wide Lightning Location Network (WWLLN) and the Lightning Imaging Sensor (LIS).

The WWLLN (http://wwlln.net) is a real-time, world-wide and ground network that detects preferentially strong lightning strokes. The WWLLN receivers detect the very low frequency (VLF) radiation (3–30 kHz) from a lightning stroke and use the time of group arrival (TOGA) to locate the position of the lightning. The propagation and low attenuation of VLF waves in the Earth–Ionosphere waveguide allow, with fewer antennas compared with other ground detection systems, a global and real-time detection of lightning activity (Dowden et al., 2002, 2008; Lay et al., 2004; Rodger et al., 2005; Jacobson et al., 2006).

The WWLLN had 20 stations at the beginning in 2004 and reached 40 stations during 2010. The stations consist of a 1.5 m whip antenna, a Global Positioning System (GPS) receiver, a VLF receiver and a processing computer with Internet connection. Residual minimization methods are used in the TOGA data at the processing stations to create high quality data of lightning locations. The WWLLN data processing ensures that the time residual is less than 30 μs and that the data delivered by the network correspond to lightning strokes detected by at least five stations (Rodger et al., 2009). The lightning location accuracy of the network is $\sim$5 km (Abreu et al., 2010).

The Lightning Imaging Sensor (LIS) is a space-based instrument, on board the TRMM satellite (http://thunder.msfc.nasa.gov), specifically designed to continuously detect the total lightning activity, both intra-cloud (IC) and cloud to ground (CG; Christian et al., 1999), of any given storm that passes through the field of view (600×600 km^2) of its sensor. The observation time of the storm is 80 s. Since the TRMM satellite orbit has an inclination of 35°, the LIS instrument can detect lightning activity only between 35° north latitude and 35° south latitude. The LIS data used in this study belong to the period between 1998 and 2010 and included the spatial location of each flash (latitude, longitude) detected. Also, the data contain a grid, with

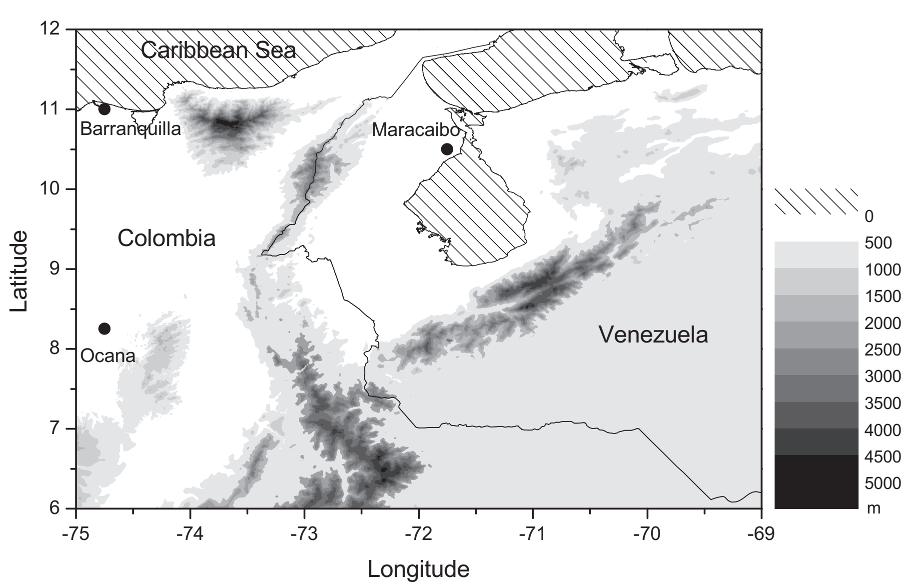

Fig. 1. Topography of the region (gray scale) with national border (solid line) and main cities (black circles). The gray scale is in meters over sea level (GLOBE).

spatial resolution of $0.5^{\circ} \times 0.5^{\circ}$, with the effective observation time of each grid cell.

4. Results and discussions

In this study, the lightning activity in the spatial window [6–12°]N of latitude and [75–69°]W of longitude was examined as shown in Fig. 1.

The total flashes per year ($F_w[i,j]$) detected by the WWLLN in each grid point centered at $[i,j]$ of latitude and longitude, respectively, were computed for each year between 2005 and 2010. It is important to point out that the recent upgrade of the WWLLN detection algorithm and the installation of additional detection stations in the network have resulted in a consistent increase in lightning detection efficiency throughout the years. In order to take into account this variation, the values of $Fw[i,j]$ were normalized to the total flashes in the spatial window for the whole year ($\Sigma_i \Sigma_j F_w[i,j]$). Thus the variable

$$F_{w,n}\ (\text{year})\ [i,j] = \frac{F_w[i,j]}{\sum_i \sum_j F_w[i,j]}$$

is used as an indicator of the lightning activity on each grid point. Fig. 2 shows the spatial distribution of $F_{w,n}$ between 2005 and 2010.

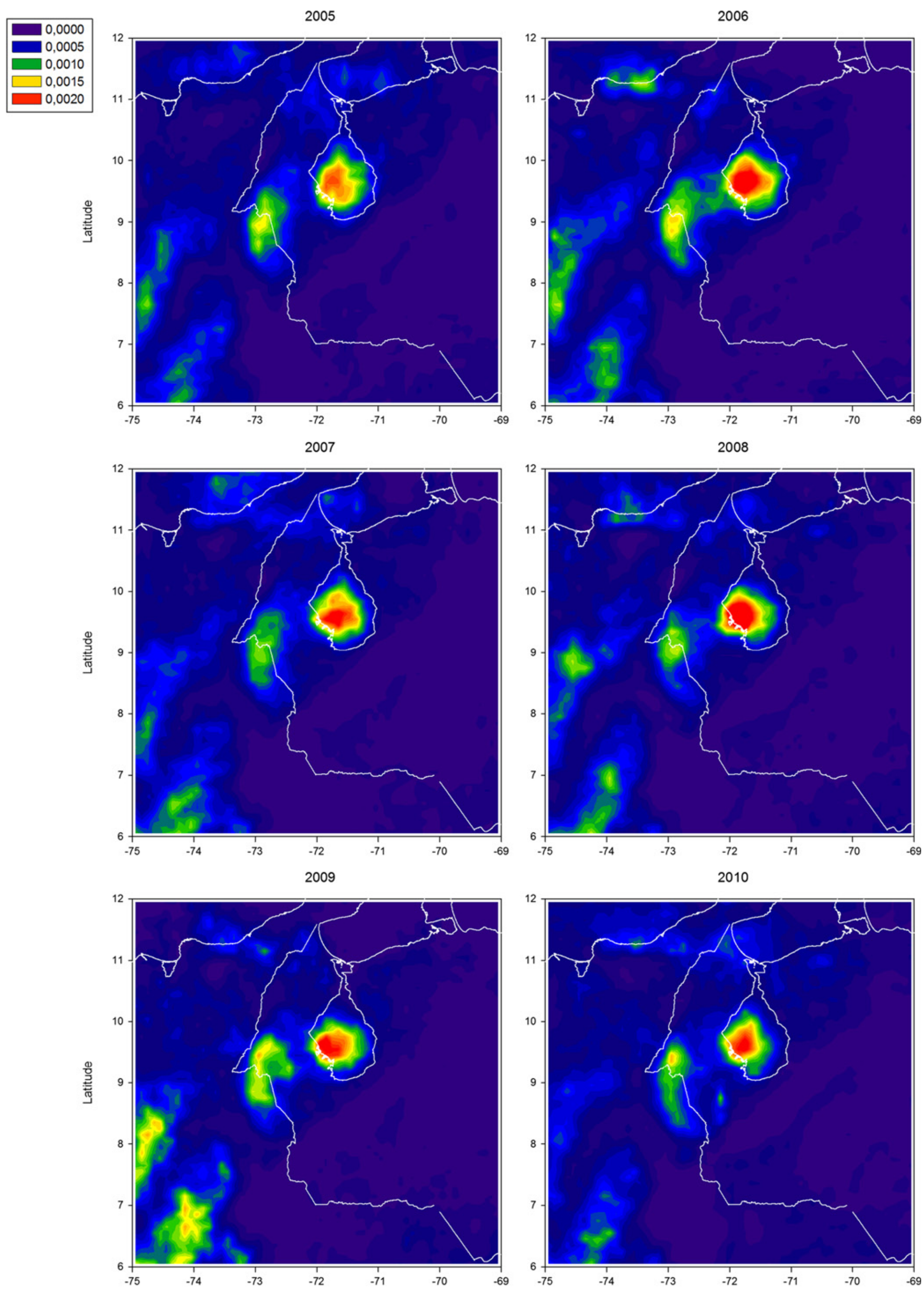

Fig. 2. Spatial distribution of $F_{w,n}$ values for the years between 2005 and 2010.

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A horizontal grid of [0.1° × 0.1°] spatial resolution was used. Two very well localized centers with high-lightning activity can be observed for each one of the years analyzed, one center is confined in [9–10°]N of latitude and [72–71°]W of longitude over the south-west region of Maracaibo Lake, and the other one is around [9°N; 73°W] near the Colombia–Venezuela border. The first center is coincident with the observations made by Falcón et al. (2000).

Many studies (Lay et al., 2004; Rodger et al., 2005, 2006; Jacobson et al., 2006; Abarca et al., 2010; Abreu et al., 2010) have evaluated the WWLLN performance using a local detection system as ground truth for different time windows. These studies have shown that the detection efficiency of the WWLLN is about 10% and is strongly dependent on the lightning peak current. Abarca et al. (2010) used the USA National Lightning Detection Network as ground truth to evaluate the WWLLN performance between April 2006 and May 2008. They found an improvement in the overall detection efficiency of cloud-to-ground flashes of the WWLLN year-to-year from 3.88% in 2006/2007 to 10.30% in 2008/2009 as a consequence of the addition of new detection stations. Also, they found the detection efficiency to be dependent on lightning peak current, which is less than 2% for lightning with peak current values lower than 10 kA and reached 35% for stronger currents (130 kA). Abreu et al. (2010) compared the events detected by WWLLN with the events detected by the Canadian Lightning Detection Network in a region centered in Toronto, Canada, which has occurred between May and August of 2008. The WWLLN detection efficiency found in that study was 2.8% with a current peak threshold of ~20 kA, and the detection efficiency increases from 11.3% for peak currents > 20 kA to 75.8% for peak currents > 120 kA. Besides the low detection efficiency of the WWLLN and its strong dependence with peak current, these studies show that the lightning location accuracy of the network is ~5 km and that the detection efficiency depends on the geographical location. Therefore, in order to validate the results found with WWLLN data, a spatial analysis of the lightning activity was performed using LIS data.

The lightning flash rate in the spatial windows [6–12°]N of latitude and [75–69°]W of longitude was calculated using data from WWLLN and LIS with a spatial resolution of [0.5° × 0.5°]. Fig. 3 shows the lightning flash rate calculated using the WWLLN data (*FRw*, Left Panel) for the year 2010 and shows the results obtained using LIS data (*FRLis*, Right Panel) between the years 1998 and 2010. The LIS data results also show two regions with high lightning activity coincident with those observed using WWLLN data. Both maps show a very good spatial correlation with a Pearson coefficient of 0.86 ($p < 10^{-4}$), and also show a maximum value of the lightning flash rate in the grid cell centered at [9.75°N; 71.75°W] with 161 fl km^{-2} yr^{-1} detected by LIS and 42 fl km^{-2} yr^{-1} detected by WWLLN. Assuming that LIS has a detection efficiency of 0.85 (Boccippio et al., 2002), we estimate that the detection efficiency of WWLLN in the region of interest is around 20%. Albrecht et al. (2011), using a spatial resolution of 0.25° × 0.25°, found in this region a maximum flash rate of 250 fl km^{-2} yr^{-1}. Using the same spatial resolution used by Albrecht et al. (2011), we found a maximum flash rate value of 50 fl km^{-2} yr^{-1} with the WWLLN data for the year 2010; therefore, the corresponding detection efficiency is ~20% for this subset of the WWLLN data. This estimated detection efficiency value is consistent with the values found by Abarca et al. (2010) and Abreu et al. (2010).

In order to study the daily evolution of the lightning activity of the "Catatumbo Lightning," the daily value of the amount of lightning flashes (f_w) detected by WWLLN was computed for each high lightning activity center observed. A 1° × 1° grid point centered at [9.5°N; 71.5°W] (first center) and at [9°N; 73°W] (second center) was used in the calculation. Again, in order to take into account the variation in the detection efficiency of the WWLLN, the *fw* values were normalized to the total number of flashes in the year. Thus the variable

$$f_{w,n} = \frac{f_w}{\sum_{\text{all year}} f_w}$$

is used as an indicator of the daily variation of the lightning activity on each grid point. Fig. 4 (Upper Panel) shows the moving average with 32 days of $f_{w,n}$ for both grid points. It can be seen that the lightning activities show a good time correlation with the Pearson coefficient of 0.85 ($p < 10^{-4}$). Both grid points have a semiannual behavior with two maxima, one around May and another one around October. It is observed that during the dry season period, January and February, the lightning activity is reduced. The daily variation of the lightning activity was compared to the daily evolution of the solar zenith angle (SZA) at midday, which was determined using the equations given by Paltridge and Platt (1976) and the Fourier coefficient from Spencer (1971). Fig. 4 (Lower Panel) shows the daily evolution (SZA) at midday. The SZA has two minima (SZA=0), one around April 15 and the other around the end of August. These two minimum values correspond to the maximum solar heating at the surface, which results in rising thermals and vertical mixing in the atmosphere. Several studies (Williams, 1994; Heckman et al., 1998; Price and Asfur, 2006) had found a positive relationship between temperature and lightning at different timescales. However, there is a time lag of ~30 days between the minimum values of the SZA and the maximum values on the lightning

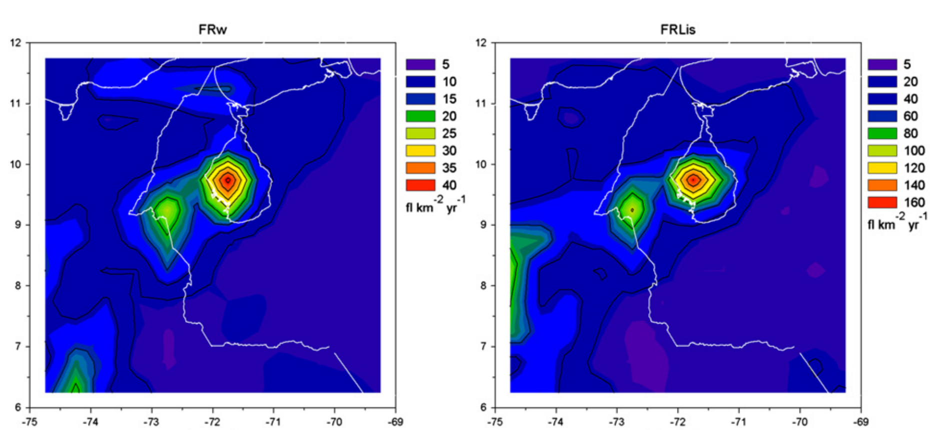

Fig. 3. Spatial distribution of the flash rate computed using WWLLN data (*FRw*, Left Panel) and LIS data (*FRLis*, Right panel).

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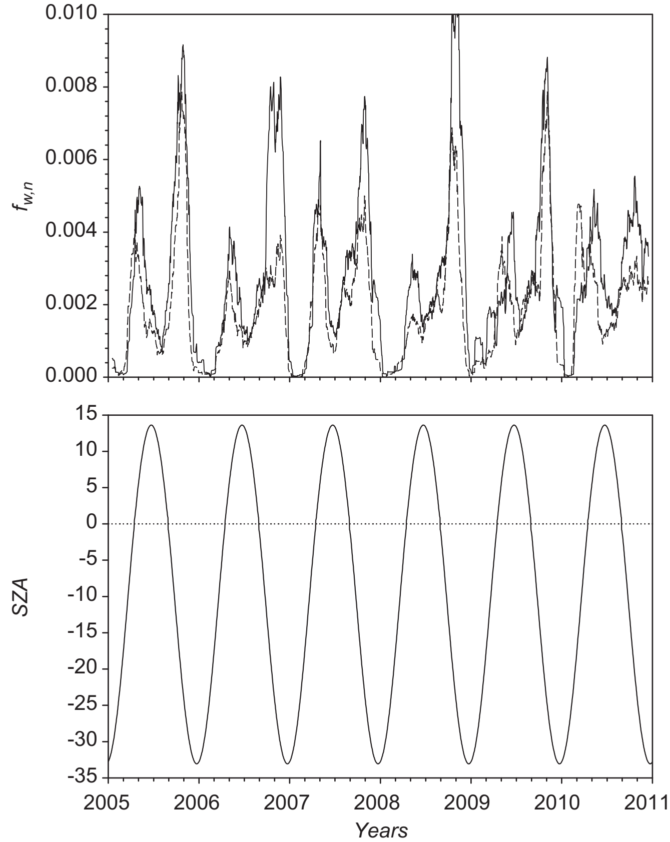

Fig. 4. Evolution of $f_{w,n}$ at the grid points centered at [9.5°N; 71.5°W] (solid line) and at [9°N; 73°W] (dotted line) (Upper Panel). Daily evolution of the solar zenith angle (SZA) at midday (Lower Panel).

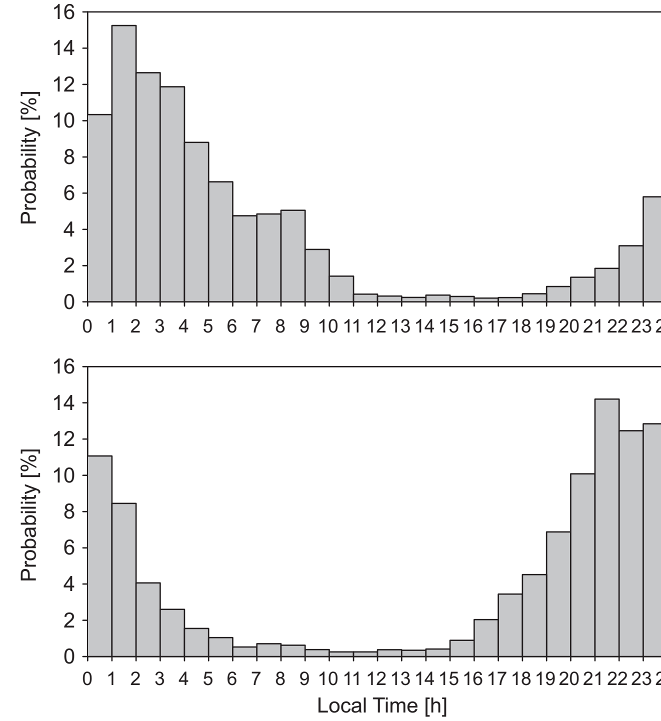

Fig. 5. Probability of the hourly distribution of *FRw* at the grid points centered at [9.5°N; 71.5°W] (Upper Panel) and at [9°N; 73°W] (Lower Panel).

activity, which could be due to the thermal inertia of the land/water mass.

The pyroelectrical model (Falcón and Quintero, 2010) is unable to explain the daily lightning activity observed since the model predicts high lightning activity during the dry season and low lightning activity during the wet season. These predictions are opposite to the daily variation of the lightning activity in both the high lightning-activity centers analyzed.

The climatology of the Maracaibo Lake region is affected by several factors such as the Inter Tropical Convergence Zone (ITCZ) migrations, the Caribbean Low-level Jet (CLLJ) and the Western Hemisphere Warm Pool (WHWP). The CLLJ dominates the Caribbean circulation and it is associated to convective activity and regional precipitation features (Amador, 2008). The CLLJ has an annual cycle with two wind maxima, one in July and the other one in January–February and has minima in May and October (Muñoz et al., 2008). During the maxima, the vertical wind shear over the Caribbean reached a maximum, which is unfavorable for convection. This semiannual behavior of CLLJ is consistent with the semiannual behavior of the daily lightning activity observed. The WHWP, a warm pool with water temperature warmer than 28.5 °C, has a minimum area during January and February and reaches its maximum area during September–October when it expands to reach the north coast of South America (Wang and Enfield, 2001, 2002). During September–October, the WHWP could act as a vapor supply and enhance convection. It seems plausible to assume that the lightning activity found in this region is a consequence of the local systems and weather patterns.

The diurnal variation of the lightning activity in the 1° × 1° grid points centered at [9.5°N; 71.5°W] and [9°N; 73°W] are shown in Fig. 5. The vertical bins represent the fraction of the total lightning during a whole year as a function of the local time; the counts are grouped into 1-h bins. The diurnal cycle of the first center (Fig. 5, Upper Panel) displays a scarce lightning activity between 12:00 and 19:00 (local time) with an average flash rate of 7 fl km^{-2} yr^{-1}. Also, the diurnal cycle shows substantial lightning activity between 23:00 and 9:00 and the peak occurs between 1:00 and 3:00, with a flash rate higher than 200 fl km^{-2} yr^{-1}. The second center (Fig. 5, Lower Panel) shows a similar diurnal cycle with a scarce lightning activity between 6:00 and 15:00 (local time) and high lightning activity between 21:00 and 1:00 (local time) with a flash rate higher than 200 fl km^{-2} yr^{-1} at 21:00 (local time).

The diurnal cycle observed is consistent with the in-situ observation made by Falcón et al. (2000) and with the nocturnal convection observed. Also, the maximum value in the flash rate occurs before the peak of the rainfall (2:00–4:00 local time) as obtained by Mapes et al. (2003). It is important to note that the diurnal variation of the lightning activity differs considerably from the typical diurnal cycle of flash rate over land. The global observations by LIS and the Optical Transient Detector (OTD) show that the tropical continental lightning has a clear diurnal peak in flash rate between 16:00 and 18:00 local time (Williams et al., 2000). Likely, the complex local topography and the particular dynamic and thermodynamic local conditions are responsible for the particular diurnal variation of the lightning activity observed in this region.

5. Conclusions

The lightning activity in the spatial windows [6–12°]N of latitude and [75–69°]W of longitude, belonging to the Maracaibo region, was examined using the WWLLN and LIS data. Two very well localized centers with high lightning activity were detected. One center is confined around [9.5°N; 71.5°W] over the southwest region of the Maracaibo Lake, and the other one is around [9°N; 73°W] near the Colombia–Venezuela border.

The two centers show an important lightning activity during the whole year except for the months of January and February. The lightning activity has a semiannual behavior with two maxima: one around May and another one around October. This behavior is consistent with the seasonal insolation variation over the region and it is opposite to the stated annual variation of the CLLJ cycle.

The diurnal cycle of lightning events shows a scarce lightning activity at local noon and it displays a significant lightning activity during the night hours. The diurnal variation is consistent with the nocturnal convection and the precipitation regimens observed in the region.

The key of this unique landmark most likely lies in the interaction between a unique local topography, wind and heat. High mountains surround the Maracaibo plain on three sides. Specific wind (low level jet) blows from the only side that is free of mountains—from the north-east. Hot tropical sun has heated the lake and swamps during the day—wind accumulates the produced heat and moistness. On the other hand some researchers consider that these peculiarities are caused by a specific chemistry. Expeditions by scientists resulted in one more hypothesis: the pyroelectrical mechanism. It proposes that winds above the Maracaibo plains collect methane, which is considered to be the main cause of the phenomenon. This hypothesis, however, does not seem very plausible, since the methane content in the atmosphere is not high enough to cause such a process. There are many areas in the world where methane concentration in the air is much higher but no such phenomenon is observed.

The "Catatumbo Lightning" was reported as the region with the highest flash rate of the globe with almost 250 fl km^{-2} yr^{-1} (Albrecht et al., 2011). This flash rate is higher than the activity observed in Africa, South America and the Maritime Continent, the three zones recognized as the major components of the global electrical circuit (Whipple, 1929).

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