The 13 years of TRMM Lightning Imaging Sensor: From individual flash characteristics to decadal tendencies

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ABSTRACT: How often lightning strikes the Earth has been the object of interest and research for decades. Several authors estimated different global flash rates using ground-based instruments, but it has been the satellite era that enabled us to monitor lightning thunderstorm activity on the time and place that lightning exactly occurs. Launched into space as a component of NASA's Tropical Rainfall Measuring Mission (TRMM) satellite, in November 1997, the Lighting Imaging Sensor (LIS) is still operating. LIS detects total lightning (i.e., intracloud and cloud-to-ground) from space in a low-earth orbit (35^o orbit). LIS has collected lightning measurements for 13 years (1998-2010) and here we present a fully revised and current total lightning climatology over the tropics. Our analysis includes the individual flash characteristics (number of events and groups, total radiance, area footprint, etc.), composite climatological maps, and trends for the observed total lightning during these 13 years. We have identified differences in the energetics of the flashes and/or the optical scattering properties of the storms cells due to cell-relative variations in microphysics and kinematics (i.e., convective or stratiform rainfall). On the climatological total lightning maps we found a dependency on the scale of analysis (resolution) in identifying the lightning maximums in the tropics. The analysis of total lightning trends observed by LIS from 1998 to 2010 in different temporal (annual and seasonal) and spatial (large and regional) scales, showed no systematic trends in the median to lower-end of the distributions, but most places in the tropics presented a decrease in the highest total lightning flash rates (higher-end of the distributions).

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ABSTRACT: The frequency of lightning over the Earth has been the object of interest and research for decades. Several authors estimated different global flash rates using ground-based instruments, but it has been the satellite era that enabled us to monitor lightning occurrence on a global scale in time and location. Launched into space as a component of NASA's Tropical Rainfall Measuring Mission (TRMM) satellite, in November 1997, the Lightning Imaging Sensor (LIS) is still operating. LIS detects total lightning (i.e., intracloud and cloud-to-ground) from space in a low-earth orbit (35° inclination) and has now collected lightning measurements for 13 years (1998-2010). In this paper we present a fully revised and current total lightning climatology over the tropics. Our analysis embraces characterizing individual flash (e.g., number of events and groups, total radiance, area footprint, etc.), generating composite climatological maps (in 0.25 and 0.10 degree resolutions), and finally computing trends for the observed total lightning during these 13 years of LIS mission. We have identified differences in the energetics of the flashes and/or the optical scattering properties of the storms cells due to cell-relative variations in microphysics and kinematics (i.e., convective or stratiform rainfall). On the climatological total lightning maps we found a dependency on the scale of analysis (resolution) in identifying the lightning maximums in the tropics. The analysis of total lightning trends observed by LIS from 1998 to 2010 in different temporal (annual and seasonal) and spatial (large and regional) scales, showed no systematic trends in the median to lower-end of the distributions, but most locations in the tropics did show a decrease in the highest total lightning flash rates (higher-end of the distributions).

1. INTRODUCTION

The Tropical Rainfall Measuring Mission (TRMM) satellite was launch in November 1997 at 350 km of altitude and a 35° inclination, and then boosted 402.5 km in August 2001 to prolong the mission lifetime. During the pre-boost, TRMM's Lightning Imaging Sensor (LIS) field-of-view was 580 x 580 km at the cloud top using a 128 x 128 charge coupled device (CCD) array, which implied a 3.7 km spatial and 80 s temporal pixel resolutions at nadir. With the boost, the field-of-view increased to 668 km, with 4.3 km spatial and 92 s temporal pixel resolutions at the nadir. This short sampling time during the satellite overpass limits the data usage for forecast and requires several years to compute high resolution climatology. Nowadays, LIS has collected

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lightning measurements for over 13 years making possible the compilation of a total lightning climatology maps in high resolution such as 0.25° and 0.10° of horizontal resolution.

TRMM is a polar orbit satellite which implies that LIS observes the Earth's surface differently at each overpass. Moreover, the instrument lenses design decreases its view time rapidly from the nadir to its borders decreasing also flash counts at the borders, and during very high flash incidence the sensor saturates and both flash counts and view time are decreased. Due to these facts, *LIS flash counts alone have no meaning*, and it is necessary to account for the instrument view time when computing the number of flashes, resulting in the variable flash rate density (FRD – flashes per kilometer square per year, fl km^{-2} yr^{-1}).

Therefore in this study each LIS orbit were tracked over the surface of the Tropics (±35° of latitude) in 0.25° and 0.10° grids, computing the view time and the number of flashes that the instrument starred at each pixel during each orbit passage. The flash count at each pixel was corrected by the instrument flash detection efficiency according to the pixel's local standard time (LST). LIS detection efficiency is ~93% at night and ~73% at noon [Boccippio et al., 2002]. Finally, the FRD was computed by weighting the flash counts (corrected by detection efficiency) to their respectively view time, in a cumulative method.

2. CLIMATOLOGICAL TOTAL LIGHTNING MAP AND ITS MAXIMUM

Boccippio et. al. (2000) and Christian et al. (2003) presented the first detailed lighting climatology maps, which described the frequency and distribution of lightning over the tropics and the globe, respectively. These authors found that the highest flash rates occur in coastal areas, mountainous regions (Himalayas, Sierra Madre, Andes, Italian Alps), regions with frequent extra-tropical synoptic scale cyclones, and large-scale convergence zones (South Atlantic, South Pacific and Intertropical Convergence Zones). They also pointed the equatorial Congo Basin as the "hot spot" of the planet. However, due to the nature of low-orbit satellites, the total time of observations was limited and these total lightning climatology studies were done with a horizontal grid resolution of ½ degree (with a spatial moving average of 2 ½) [Christian et al., 2003] or individual cloud area [Boccipio et al., 2000].

Here we present the 13-year climatological total lightning map over the tropics, derived from LIS overpasses during 01 January 1998 to 31 December 2010, in 0.25° resolution. An even higher resolution was generated (0.10°, not shown), but the details revealed using both resolutions were in general the same. The basic characteristics of total lightning distribution found by Christian et al. [2003] and Boccippio et al. [2000] are reinforced here: i) The difference between land and ocean can be clearly observed by deep convection (associated to high lightning production, >20 fl km^{-2} yr^{-1}) occurring more frequently over continental than oceanic environments [Nesbitt et al., 2000]; ii) However, some coast-oceanic regions presented moderate FRD (1 to 10 fl km^{-2} yr^{-1}) associated to frequent synoptic scale extratropical cyclones and cold fronts (such as south-southeast coasts of Brazil, South Africa, Australia and United States), and large-scale convergence zones (such as the South Atlantic, South Pacific, and the Intertropical Convergence Zones).

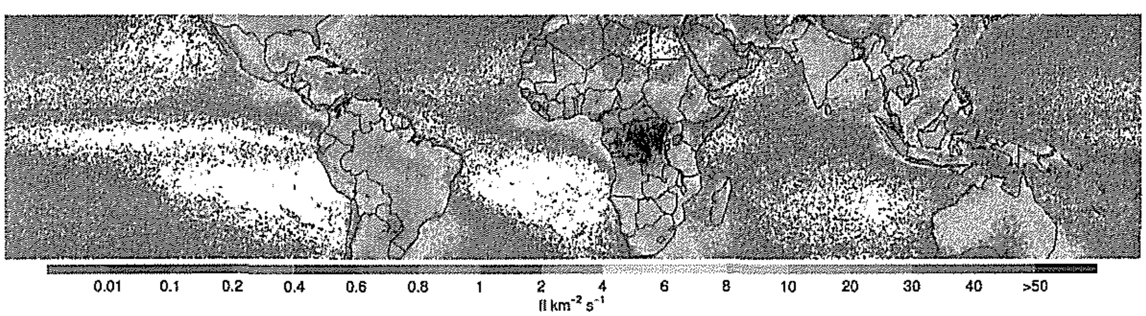

Figure 1 – Total lighting flash rate density (fl km^{-2} yr^{-1}) derived from 13 years (1998-2010) of TRMM LIS observations.

As we compiled a higher resolution climatology map, the total lighting "hot spot" has moved from Congo Basin [Christian et al., 2003] to at Lake Maracaibo in Venezuela, with 250 fl km^{-2} yr^{-1}., leaving Congo Basin in second place with 232 fl km^{-2} yr^{-1}. Both Venezuela's and Congo' s maximums are related to the complex topography of the region. The Maracaibo Lake is located inside Andes mountain ranges, at their most north chain, where the Andes form a fork of elevated terrain, up to ~3650 m of height. The fork mountain configuration associated to the proximity to the ocean shore and the fact that Lake Maracaibo water is warm all year long (28 to 31°C) make this region perfect for development of thunderstorms. During the night, the mountain-valley breeze of both ridges of the mountain fork converges over the lake, a land-lake breeze is also developed converging over the lake as well, and the land-ocean breeze likewise blows toward the lake. All this convergence over a hot and humid environment over the lake makes it the perfect spot for thunderstorm development and high flash rate occurrence (>100 flashes per day) over 240 days of the year (from April to early December) during nighttime. These thunderstorms are not large in extent, but they are formed and developed at the same spot almost all year long. As they are quite small in extent explains why they were not reported by Christian et al. [2003] at their 0.50° resolution total lightning climatology. A maximum of mean annual rainfall over the tropics was reported by Mapes et al. [2003] at Lake Maracaibo, with a nocturnal peak.

3. INDIVIDUAL FLASH CHARACTERISTICS

LIS sensor is an event detector and a lighting flash is the grouping of multiple events in space and time. When a lightning flash happens, LIS charge coupled device (CCD) detects lightning emissions at 777.4 nm (neutral oxygen line) that exceeded a background threshold at the top of the cloud at a 2 ms rate. Each CCD pixel that exceed the threshold is a lightning event, and these events are grouped in space and time to compose a lightning flash. Therefore, each LIS lightning flash has a certain number of events and groups. In his section we show some characteristics of lightning groups detected over convective and stratiform precipitation as defined by TRMM Precipitation Radar (PR) 2A25 product[1], from 1998 to 2009.

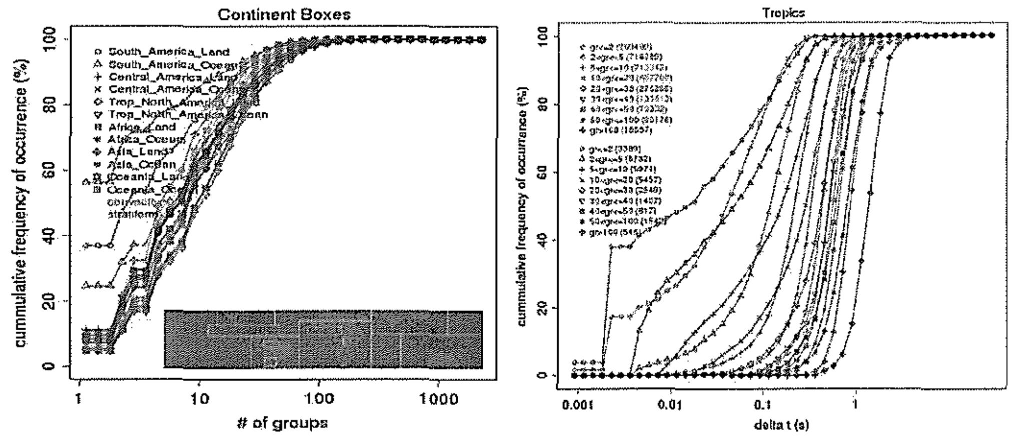

Figure 2 – (left) Cumulative frequency of occurrence of the number of groups in specific continental boxes, and (right) cumulative frequency of occurrence of the flash duration (delta t) segregated by intervals of number of groups, for each individual flash detected by LIS from 1998 to 2009. Red and blue lines represent flashes that occured over, respectively, convective and stratiform precipitation.

Figure 2 shows the cumulative frequency of occurrence of the number of groups for each individual flash detected by LIS from 1998 to 2009. The flashes were divided in some specific continental regions shown in the figure by yellow boxes. It can be noticed that flashes over stratiform and convective precipitation have a quite similar distribution in terms of the number of groups, except for flashes that occurred over South America. Convective and stratiform flashes over ocean at South America have, respectively, 24% and 56% of flashes with only up to 3 groups. These occurrences are higher than those over the remaining boxes for both land and ocean, which have 3 to 10% of flashes with up to 3 groups. This could be the artifact of the South Atlantic Anomaly, but the frequency of occurrence of groups from flashes of convective precipitation over South America land were similar to the rest of the boxes. Figure 2 also shows the time duration of flashes for convective and stratiform precipitation, segregated by intervals of groups. It can be seen that over 75% of stratiform flashes with up to 10 groups have shorter duration than the convective ones. The opposite is observed for flashes with more than 50 groups: stratiform flashes present a longer duration than the convective ones. One possible explanation is that those stratiform flashes with fewer groups would be happening within the thunderstorm's anvil where the travel distance between the charge centers is shorter. In the same line of thought, the stratiform flashes with more than 50 groups could be those that travel the whole anvil toward the convective cores of the cloud, therefore lasting longer. However, this is merely an assumption and it has to be verified in further analysis.

4. DECADAL TRENDS

Monthly LIS lightning flashes and view time were computed from 1998 to 2008 constraining the instrument field-of-view (FOV) to the pre-boost FOV, to exclude the increased sampling area after the boost. A quantile trend of the monthly FRD was computed for several regions over the boxes. The quantile trend is an estimate coefficient from quantlie regression in units of flashes per year. An example of quantile trends (from quantile 0.05 to 0.95, by intervals of 0.05) is shown in Figure 3. The solid red line is the trend from least-squares regression of flash rate density as a function of year and the dashed lines delineate the 90% confidence band about this trend. The 90% confidence band is under the assumption that errors are independent and identically

[1] http://disc.sci.gsfc.nasa.gov/precipitation/documentation/TRMM_README/TRMM_2A25_readme.shtml

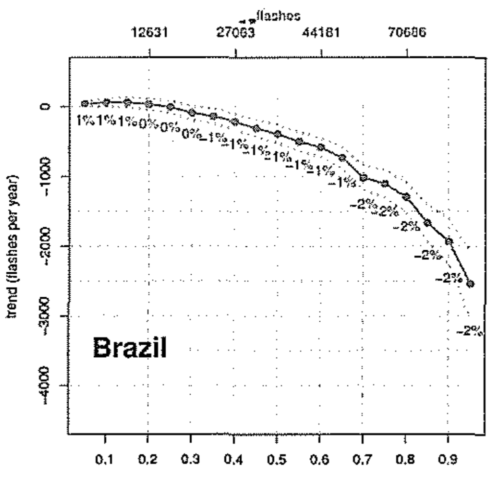

Figure 3 – Quantile trends (flashes per year) over Brazil.

distributed. It can be seen from Figure 3 that thunderstorms over Brazil have a stable trend (±1%) over the low (<0.5) and median (=0.5) quantiles. The trend increases to -2% for quantiles 0.7 to 0.95, meaning that the highest flash rates are diminishing more rapidly. No statistical significance of the results were performed by the time of this manuscript. The percent trend is calculated by the ratio of the trend and the actual quantile value.

Figure 4 shows the 0.95 quantile trends over land and over ocean for several regional boxes indicated. Most of the regional boxes show negative trends both over land and ocean. The exceptions are south of South Atlantic Ocean, west of Indian Ocean, and north-central Pacific Ocean, which present positive trends of up to 1%. The region with most pronounced negative trend is the southeast United States over lad with -3%. Quantile trends were also calculated for latitudinal bands and only negative trends (up to -2%) where found over land and ocean for quantiles over 0.80. Seasonal quantile trends were calculated as well, and the trend behavior is not uniform, but most of the seasons present negative trends for the upper quantiles. Again, no statistical significance of these results were performed by the time of this manuscript.

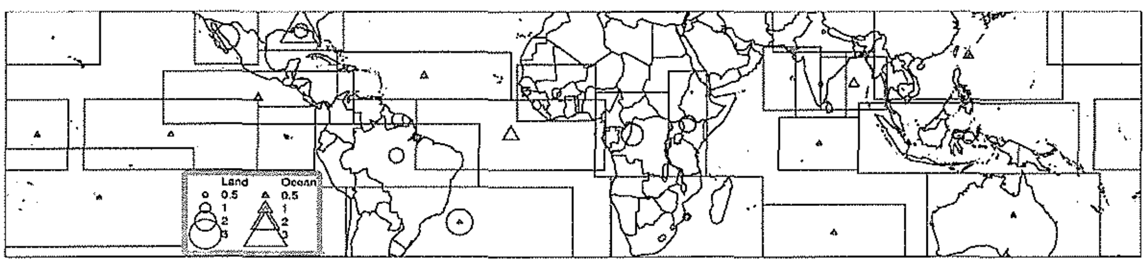

Figure 4 – Trend (%) of quantile 0.95 (upper 5% of the distribution) over the regional boxes shown. Circles indicate trends over land and triangles indicate trends over ocean, blue color indicate negative trends and red colors positive trends.

5. SUMMARY AND CONCLUSIONS

In this paper we present the most current total lightning climatology over the tropics. The climatological map in 0.25° and 0.10° based on 13 years (1998-2010) of LIS mission revealed interesting and unknown features of thunderstorm activity over the tropics. The lighting "hot spot" is actually the Lake Maracaibo in Venezuela. The analysis of individual LIS flashes showed interesting features in the number of groups and flash duration for flashes that happened over stratiform and convective precipitation. The analysis of total lightning trends in different temporal (annual and seasonal) and spatial (large and regional) scales, showed no systematic trends in the median to lower-end of the distributions, but most locations in the tropics did show a decrease in the highest total lightning flash rates (higher-end of the distributions).

These results showed that high resolution and long term monitoring of thunderstorms are very important for a fully understanding of cloud electrification. The upcoming Geostationary Lightning Mapper (GLM) onboard of the future GOES-R satellite will improve our knowledge of lightning activity and will be an important tool into future nowcasting algorithms of severe weather and quantitative precipitation estimation.

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