Severe Thunderstorms as observed from TRMM PR and LIS in South America

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ABSTRACT: Thunderstorms might be associated with severe weather conditions and lightning flash rates could be used as indicative of storms severity. Although the high lightning flashes rates are associated with huge thunderstorms, these storms might not be very convective intense, i.e., large rain volumes and intense vertical precipitation profiles. To explore those storms, this work identifies the severe thunderstorm based on 14 years of Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor and Precipitation Radar (PR) observation over South America. The thunderstorms were defined as clouds that had LIS flashes observed in a cluster delineated by the 10.8 μm of TRMM Visible and Infrared Scanner (VIRS) brightness temperature (Tb) threshold of 258 K. Over this time frame a total of 96281 thunderstorms were identified with at least one valid PR vertical profile. To cluster the thunderstorms according to its severity it was necessary to normalize the flash rate by the LIS view time (FT) and the cloud area (FTA – km^2). At the 90% level, it was found that the most severe thunderstorm had flash rates above 15 flashes sec^{-1} were associated with thunderstorm that had an area of 10^5 km^2 (radius $\sim$178 km), while the highest flashes rates per area had a maximum of 0.036 flashes km^{-2}sec^{-1} and were associated with clusters of 10^2 km^2 (radius – 12.6 km^2). By analyzing the radar reflectivity (Z) profiles it was found that highest FTA had the highest convective fraction and Z values at each level and development above 10 km height. For the FT though, it was found that the highest values had higher stratiform fraction and the lightning activity extension increased with cluster size. The FTA thunderstorm have stronger accretion process than FT, mainly in the southern region of South America. When we compare northern and souther thunderstorms, we see that the northern ones have a enhanced aggregation process and weaker accretion process when compared to the southern. To depict the thunderstorms it was found that the FTA index is more efficient to identify the regions with more severity.

INTRODUCTION

Nesbitt et al. [2000] introduced a methodology that clustered Precipitation Features (PF) by using TRMM Microwave Imager (TMI) and PR. In this w ork, they analyzed the PF with and without ice scattering signatures at the 85 GHz channel and found that African thunderstorms have more ligh tning and ice scattering than the South American ones. On the diurnal cycle analysis, they found that PFs with ice signature have well defined cycle, i.e., a maximum during the afternoon and over the continent. Over the ocean no time dependency was found during the diurnal cycle.

Later, *Cecil et al.* [2005] explores the PF dataset (*Nesbitt et al.* [2000]) and ordered by the flash rate. In this work they have found that only 10%(1%) of PFs over continent (ocean) had lightning. Moreover, higher flash rates were associated with large PFs. Finally, in South America (SA) the systems with more intense convection and more lightning production were located at southern SA,i.e., Argentina, Paraguay, Uruguay and southern Brazil.

Zipser et al. [2006] explored the PF database based on different methods (vertical reflectivi y profiles, 85 GHz and 37 GHz ice signatures and flash rates) to search for the severe thunderstorm along the globe in order to make a census. They found that all the methodologies appointed the south of SA is the region

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where it is found the most intense convection. Furthermore, the time of more frequent intense convection over land was between 15-16h local time.

In order to depict the main characteristics of the severe thunderstorms in South America, this study uses 14 years of TRMM PR, VIRS and LIS measurements. The thunderstorm severity is analyzed individually by the flash rate and flash rate normalized by area. Later, the severe thunderstorms observed by these 2 categories are analyzed in terms of the vertical PR profiles to seek a better understanding of the precipitation process and further effects on cloud electrification.

THUNDERSTORM DATABASE

The thunderstorms, clouds that have at least one lightning flash during its lifetime duration, have been identified by contiguous pixels that have a brightness temperature below 258 K in 10.8 μm VIRS channel and a least one LIS flashes [*Morales and Anagnostou*, 2003].

For this study, we have downloaded 14 years (1998-2011) of TRMM 1B01 and 2A25 version 7 and LIS (flash, group, events and view time) data from NASA ftp server (ftp://disc2.nascom.nasa.gov/-ftp/data/s4pa/). The data extraction was limited to an area of 40S-10N and 90W-30W that would represent South America.

As each instrument on board TRMM has different footprint resolutions, we decided to establish a common grid of 0,05$^\circ \times$ 0,05° to represent the thunderclouds as observed by VIRS, PR and LIS.

Therefore it is possible to identify the regions with coincident measurements and extract the thunderclouds. In this study, each thunderstorm is stored in a HDF file that has the following information:

- VIRS – 1B01 – latitude, longitude, Radiance – channel 4 (10,8 μm)
- PR – 2A25 – latitude, longitude, Corrected Z-factor, Rain Type
- LIS – latitude and longitude of, flashes, groups, events and View Time

Over these 14 years of measurements it was possible to identify 154,141 thunderstorms over South America, and due to the small swath of PR compared to VIRS, only 96,281 thunderstorm had a least one valid PR profile.

To characterize the severity of the thunderstorms we have computed the following parameters:

– Time flash rate (FT) defined as the ratio of number of flashes (N_{fl}) by the mean view time (VT_m) in the thunderstorm area extracted, which is similar to the precipitation features defined by *Nesbitt et al.* [2000].

$$FT = \frac{N_{fl}}{VT_m} 86400 \; [fl \; day^{-1}] \tag{1}$$

– Time flash rate normalized by the thunderstorm area (A_t) defined as FTA

$$FTA = \frac{N_{fl}}{VT_m A_t} 86400 \; [fl \; day^{-1} \; km^{-2}] \tag{2}$$

In order to pull the severe thunderstorms, we will only analyze the thunderstorms that are above the 90th percentile. In that way, we have 2 severe thunderstorms groups: one for FT and one FTA.

To analyze the radar reflectivity (Z_{ef}) profiles associated with these 2 groups, we have computed the contoured frequency by altitude diagram (CFAD) [*Yuter and Houze Jr.*, 1995] by assuming bins of 1 dBZ every 250 m altitude resolution. In each CFAD we present the fraction of convective, stratiform and other Z_{ef} profiles, the respective number of profiles in each CFAD (P), then number of profiles at the level of

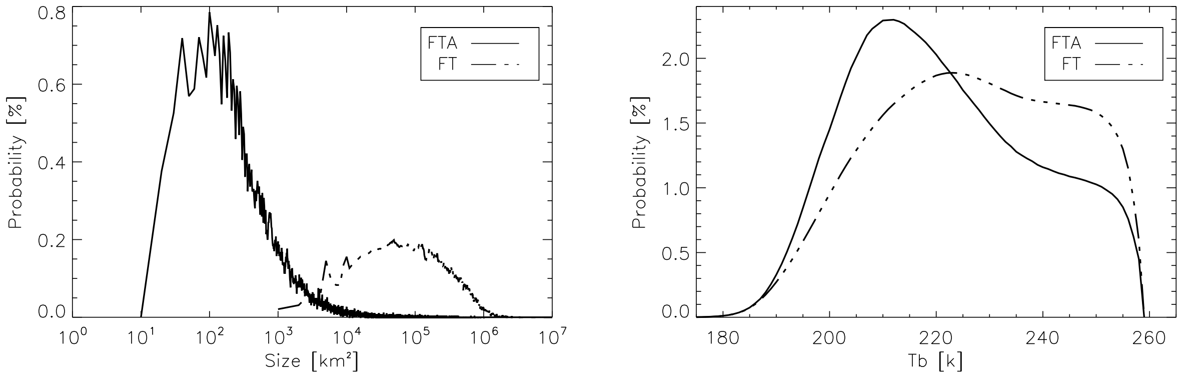


Figure 1: Probability density function of occurrence of sizes and VIRS brightness temperature for thunderstorms order by FTA and FT index.

maximum (Z_{ef}) (L) and the respective altitude of maximum Z_{ef} (H). Finally, only altitude levels with more than 10% of L were considered in the CFADs, guaranteeing a statistical representativeness.

To understand how the vertical Z_{ef} profiles are associated with the hydrometeor growth and electrification processes, the altitude level of each PR profile was converted in to temperature. For this conversion, we have used the NCEP RII reanalysis. So for each thunderstorm, we have extracted the temperature and geopotencial height profile to make the conversion and have created the contoured frequency by temperature diagram (CFTD) in addition to the cumulative CFTD (CCFTD).

SEVERE THUNDERSTORMS

General characteristics

Figure 1 presents the probability density functions of the severe thunderstorms defined by the 90th FT and FTA percentile. The PDFs are normalized by the thunderstorm size and cloud top temperature and it is possible to observe two distinct groups of thunderstorms.

The thunderstorms that have the highest FTA are 3 orders of magnitude smaller than the highest FT thunderstorms and are 10K colder, i.e, they are deeper.

The FT thunderstorms have large extension because as the cloud area increases the probability of having more lightning increases. So a thunderstorm with an area of 10^5 km^2, is more likely to have more lightning flash than with a 10^2 km^2. By normalizing by A_t, FTA represents a thunderstorm efficiency indexes.

By looking at the temperature distribution on Figure 1 it is noted that FTA is more liked to have cloud tops below 215 K, while the FT between 215 and 230 K. Since FTA represents small systems we would expect localized deep convection, while for FT we would expect large convective systems that show huge stratiform areas with few deep cloud tops [*Houze Jr et al.*, 2007; *Rasmussen and Houze*, 2011]. In terms of rain type classification (TRMM PR classification), Figure not show, the FTA thunderstorms have 70% of convective area, while FTA only 20% which is consistent with the Tb and area pdfs of Figure 1.

Vertical Structure

To explore how the Z_{ef} vertical profile varies according to the severity of the thunderstorms, we computed the CFADs based on the profiles that had or not lightning for the FT and FTA groups, Figure 2. But instead of showing all the CFAD over the entire SA, we selected only 2 regions that were defined as the most electrically active, i.e., highest lightning flash rate (40-30S and 70-60W) and highest thunderstorm frequency of occurrence (0-10N and 70-60W) [*Anselmo and Morales*, 2014].

It is possible to observe on Figure 2 that the precipitating areas that did not have lightning are more stratiform and have lower Z_{ef} (frequency of 2-10% in all altitude levels).

For the electric active areas, it is found a higher percentage of convective profiles and higher Z_{ef} values in all heights. For example, if we use only the levels with probability between 3-5% (green), the non-lightning profiles do not reach 38 dBZ (Figures 2a e 2c) while with lightning, Figures 2b e 2d, it reaches 50 dBZ.

Near the surface, the FT thunderstorms show moderate precipitation while the FTA thunderstorms show broader distributions but with higher Z_{ef} values. At high altitudes, the FTA groups are in general 1-1,75 km taller than the FT thunderstorms, which concurs with the temperature distribution (Figure 1). Around 5km, the FTA (figure 2b) thunderstorms are in general 1-3 dBZ stronger than the FT (figure 2d).

Precipitation and Electrification Processes

The previous sub-section showed how the vertical profiles vary with height, but to understand why some portions of the thunderstorm has lightning or not, we would need to explore the charge centers. As this information is not available, we could investigate instead which precipitation processed are involved since the charge transfer depends on temperature, liquid water content, hydrometeor size and concentration, terminal velocity and updraft (*Takahashi* [1978]; *Saunders et al.* [1999]) In that way, we computed CFTD for FTA and FT and the correspondent CCFTD. Then we evaluated the rate of change of Z_{ef} with temperature (dBZ/°C) for the quintiles of 30%, 50%, 70% e 95% observed on the CFTD distributions (not shown), figure 3a.

At 0°C Z_{ef}, figure 3a, it is possible to note that FT thunderstorms present at least 0.2 dBZ/°C more than the FTA. As FT have large stratiform area (3.7% higher, figure 2), it is possible to state that more snowflakes are melting, thus increasing Z_{ef}. Between -5°C e -18°C though, the rate of Z_{ef} change for FTA is more pronounced than FT which can be attributed to a more efficient accretion process. If we consider *Takahashi* [1978] and *Saunders et al.* [1999] work, we would expect more charge transfer on this region, thus more lightning.

As the profiles are more severe (higher quintiles), the rate of change gets colder for both thunderstorm distributions. At 95% the maximum rate is at -12°C for FTA and -8°C for FT, while at 50% is at 7 and 8 km respectively. This result might indicate that FTA thunderstorms have large mixed regions when compared to FT thunderstorms, thus promoting more hail and graupel.

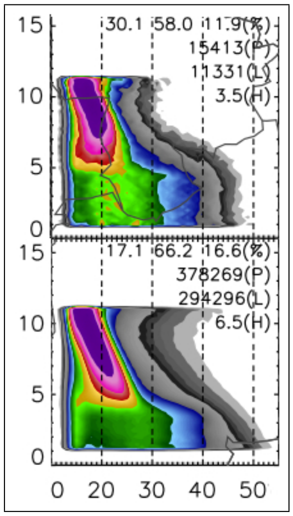
Now when we compare the two regions, i.e., the highest lightning rate [*Cecil et al.*, 2005; *Albrecht et al.*, 2010], 40-30S and 70-60W (figure 3a with the 0-10N and 70-60W (figure 3b) we do see significant differences on the rate of change of de Z_{ef} with temperature.

First, by comparing both areas it is possible to observe that in between -25°C and -40°C the northern (Figure 3b) area presents higher dBZ/°C rates than the southern one, Figure 3a, while at southern storms the rate of change is more pronounced between the levels of 0 and -15ºC.. These results indicate that in the south, the accretion is the main mechanism while in the north the aggregation.

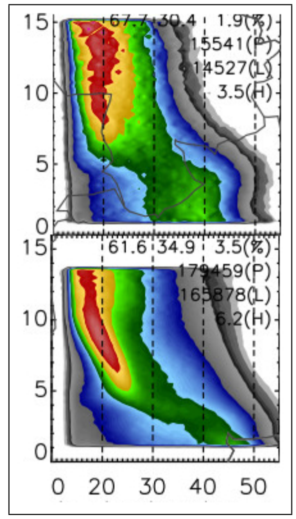
In the northern thunderstorms the FT systems presented higher rates of change between -5°C and -12°C than the FTA, which could be an indication that more super-cooler liquid water droplets could be presented in this layer, and consequently producing more graupel and hail.

CONCLUSIONS

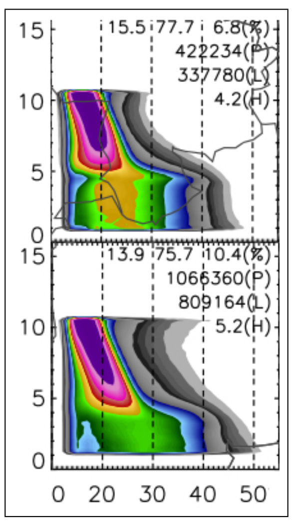
A group of thunderstorms sorted by the flash rate per km^2 show that in the 90th percentile the largest FTA have less lightning flashes and are smaller than the FT systems with the highest flash rates. When



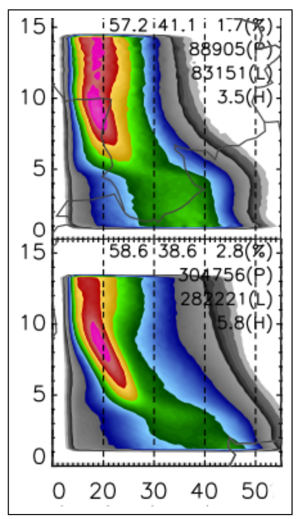
(a) 90th percentile of FTA without lightning



(b) 90th percentile of FTA with lightning

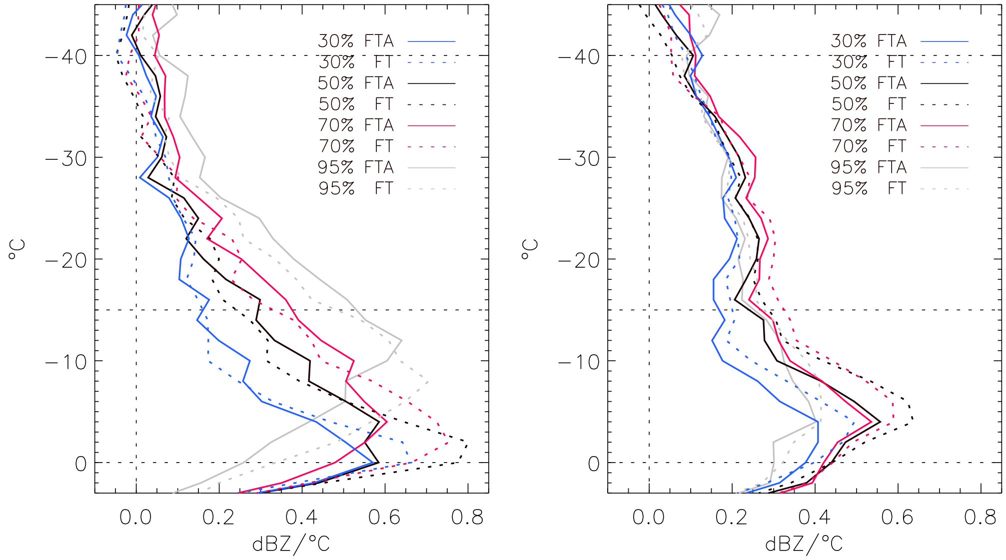


(c) 90th percentile of FT without lightning



(d) 90th percentile of FT with lightning

Figure 2: Contour frequency by altitude diagram for thunderstorms order by 90th of percentile of FTA and FT for the South America in each $10^{\circ} \times 10^{\circ}$. The precipitation profiles from PR-TRMM (1998-2011) were separated by with and without lightning. In each box we can check the percentage of convective, stratiform and others profiles respectively marked by (%), (P) the numbers of profiles computed, (L) the number of occurrence of reflectivity on level of maximum occurrence and (H) the level of maximum occurrence.



(a) 30S-40S e 60W-70W

(b) 0N-10N e 60W-70W

Figure 3: Derivatives contour line of frequency by temperature (CFTD) diagram for quintiles of 30%, 50%, 70% and 95%.

looking at the convective fraction, FTA have 50% more area than FT.

Although the FT thunderstorm have highest number of lightning flashes, the PR vertical profiles showed that in those systems the aggregation process dominate while in the FTA systems the accretion.

When normalizing by the temperature, it was possible to find that FTA thunderstorm have stronger accretion process than FT. When we compare northern and souther thunderstorms, we see that the northern ones have a enhanced aggregation process and weaker accretion process when compared to the southern.

Those results could explain why we do observed the highest flash rates over the southern part of South America, i.e., because they have a efficient accretion mechanism when compared to the region we found the most thunderstorm that does not produce so much lightning because it has a better aggregation process.

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