Thunderstorm analysis for a TGF/lightning coincidence case in Colombia

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ABSTRACT: In this paper we present a study about a TGF detected by RHESSI on August 2013 in the north of Colombia. The TGF occurred ~235ms after the third cloud-to-ground stroke of a multiple stroke-flash and ~120 km away from the sub-satellite point. The long lived thunderstorm producing the TGF is analyzed. Satellite data of cloud tops and lightning evolution show that the TGF occurred during the mature phase of the thunderstorm when cloud-to-ground lightning rates and coldest cloud covered area were high. Surface CAPE of the thunderstorm at TGF time presented a relatively low value. The analysis showed that cloud tops of the thunderstorm reached the tropopause, located at ~15 km. These results are discussed and compared with previous analysis of thunderstorms producing TGFs.

INTRODUCTION

Since the discovery of Terrestrial Gamma ray Flashes (TGFs) 20 years ago by BATSE [Fishman et al. 1994] and thanks to different satellite missions designed to detect these energetic emissions like RHESSI [Smith et al. 2005], AGILE [Marisaldi et al. 2010] and FERMI [Briggs et al. 2010] many of the features of TGFs are nowadays very well-known. Many studies have revealed that TGFs occurs mainly over thunderstorms in tropical regions over land [Smith et al. 2005]. Moreover, in some cases TGF are correlated within few milliseconds between lightning [Shao et al. 2010, Lu et al. 2011]. The link between TFG and lightning has been confirmed by simulations of TGF source altitude [Dwyer and Smith 2005, Østgaard et al. 2008]. Although no TGF production mechanism has been proven yet, the most accepted theories are the relativistic feedback mechanism and lightning emission models [Dwyer 2008].

In this paper we present a TGF detected by RHESSI TGF occurring ~230 ms after lightning stroke detected by STARNET lightning detection network. We discuss the occurrence of the event in relation with the annual distribution of TGF over America. Then satellite images, lightning data and

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meteorological models are used to describe the occurrence.

DATA AND INSTRUMENTATION

On the 8th of August of 2013 at 12:05:40.666 h (Universal Time, UT) RHESSI detected a TGF when it was flying over Colombia at 8.57º N latitude -76.9º longitude. The lightning detection network STARNET [Morales et al., 2002] detected a stroke ~235 ms before the TGF that was located at ~125 km away from the sub-satellite point. GOES-EAST infrared images and World Wide Lightning Location Network, WWLLN, [Lay et al., 2004] data has been used to analyze the thunderstorm phase when TGF occurred. NCEP-NCAR reanalysis data is used in order to analyze other thunderstorm features like CAPE, mixed phase altitude, thunderstorm altitude and tropopause altitude. Additionally, RHESSI and WWLN data from 2009 to 2012 in -120º to -40º longitude and -44º to 44º latitude has been analyzed to study the monthly latitudinal TGF and lightning occurrences.

RESULTS AND DISCUSSION

Monthly latitudinal distribution

Boxplot in figure 1 shows the monthly latitudinal TGF (red) and lightning occurrence (black) over America. Both distributions follows the displacement of the Intertropical Convergence Zone (ITCZ), where tropopause altitude reaches its highest north latitude maximum in the months of June to August whereas in the months of December to February its lower latitude to the south, that agrees very well with results in Splitt et al. [2010]. The TGF analyzed in this paper occurs in concordance with this graphic, in the north, around 10ºN, when TGF latitudinal occurrence and ITCZ reaches these latitudes.

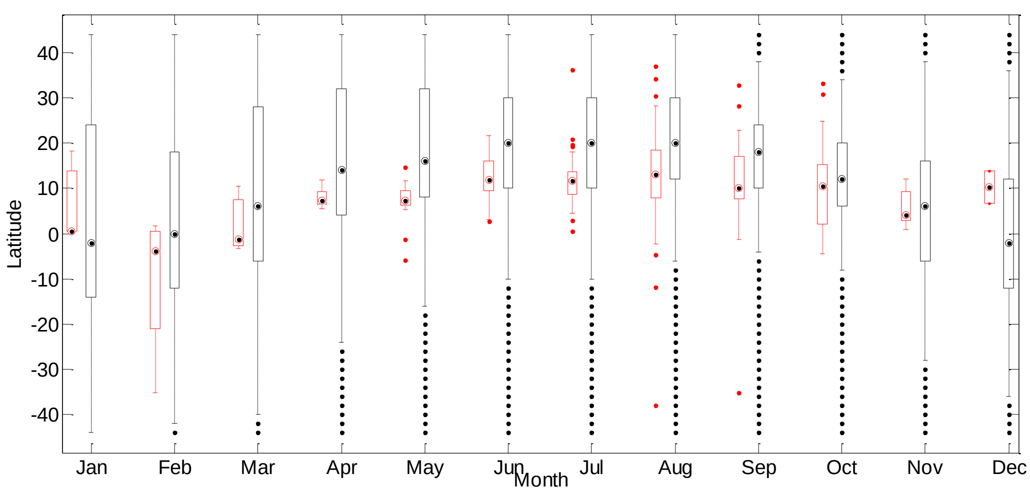


Figure 1. Boxplot of the montly latitudinal distribution of RHESSI TGFs (red) and WWLLN detected strokes (black) in the period 2009-2012 over America, in -120º to -40º longitude and -44º to 44º latitude

TGF and Stroke coincidence

Figure 2a plots the RHESSI sub-satellite point on the 8th of August of 2013 at 12:05:40.666 h (UT) when the TGF was detected. Satellite at this time was at *h*~529.6 km over Earth surface. The TGF occurred at 12 UT that is 7 LST. Such local time corresponds to a minimum activity in the TGF occurrence reported by Splitt et al. [2010]. The satellite was over a thunderstorm where a stroke detected by STARNET occurred at 12:05:40.432746 UT located at 9.05ºN latitude -77.93ºS longitude. The distance of the stroke to the subsatellite point in the moment that detects the TGF is *d*~124.4km (calculated using the Haversine method to calculate distance over Earth). Knowing that RHESSI clock lags 1.8 ms UTC [Grefenstette et al., 2009] and calculating the time of a TGF travelling from the stroke location to the satellite spacecraft, assuming that is produced at 15 km over Earth surface [Dwyer and Smith, 2005], the time difference Δt between TGF and stroke is calculated using equation 1(*c* is the speed of light). TGF occurs 235 ms after stroke.

$$\Delta t = t_{TGF} + 1.8ms - \frac{\sqrt{(h-15)^2 + d^2}}{c} - t_{str} = -235ms \quad (1)$$

The stroke is the last one of a flash composed by three (or probably four strokes). Table 1 shows occurrence, location and location error (major ellipse error) of the 4 strokes that are detected at least by five sensors. As it will be discussed in the next section, the TGF occurred during the thunderstorm mature phase where CG lightning activity is maximum. In addition, since the even occurred in the periphery if the STARNET network and it has long baselines, it is assumed that is the last stroke of a CG flash.

Table 1. Strokes of the flash related to TGF

Time	Latitude	Longitude	Error (m)
12:05:40.001851	9.369	-77.519	7121
12:05:40.176578	9.064	-77.882	7089
12:05:40.284903	9.069	-77.914	6936
12:05:40.432746	9.052	-77.932	6385

Dwyer [2012], in an extensive review of High-Energy Atmospheric Physics and after collecting models, theories and all TGF/lightning coincidences up to date, ensures that TGF occurs in the initial stages of Intra Cloud (IC) lightning flashes or directly to IC lightning leaders. Due to long time difference between the TGF and the stroke presented here, it seems quite clear that the TGF is not directly produced by the stroke but may be related to the lightning flash. Two suggestions have been made. First, it is proposed that, after the last stroke, a lightning leader continued to travel through the cloud and finally produced the TGF on upward direction. Lightning Mapping Array (LMA) analysis of CG flashes makes this hypothesis plausible [ ]. The second one is based on the possibility that last stroke had long continuing current (LCC) component. Measurements of such events show that a LCC duration of ~235 ms is possible [Kitagawa et al, 1962]. Then, the TGF may be produced by some IC activity related with this continuing current like K-changes. Montanyà et al., [2014] reports emissions of X-rays by long laboratory sparks simultaneously with RF at microwaves. Stepped leaders and k-changes are efficient emitting in V-UHF. Moreover, the low ratio of coincidences TGF-CG makes improbable of being independent events (probabilistic analysis of TGF-CG coincidences is in process).

Thunderstorm Phase

Using all GOES-EAST channel 4 images between 8h UT and 16h UT every 30 minutes, the areas covered by cloud tops with temperature between -30º and -80º have been computed. The analysis shows that the TGF occurred in a mature phase of the thunderstorm where the coverage area by clouds between -80ºC and -70ºC is higher (figure 2b). Moreover, time evolution of all WWLN strokes in the thunderstorm (mostly CG) in the same time interval that GOES images analysis is plotted on figure 3a. This graphic shows two different peaks of stroke occurrence. The first may be due to a first active phase of the thunderstorm coinciding with the first presence of a cloud tops over -80º (figure 2b). After this peak, instead of decrease, the thunderstorm is reactivated reaching a new mature phase at 12 UT when TGF occurs. It is assumed that WWLLN has higher efficiency for CG lightning strokes rather than IC lightning, so that, we assume that most of the strokes in figure 3b are CG. That means that TGF is occurring during a peak of CG occurrence, what agrees with Smith et al. [2010]. Smith et al. [2010] showed that most of TGFs occurs in periods with high CG activity. But TGFs are thought to be produced by IC lightning [Williams 2006].

Furthermore, the TGF occurred not long after the moment that the updraft stopped growing, that is very similar to the timing of sprites reported in Soula et al. [2009, 2012], although those are not tropical cases.

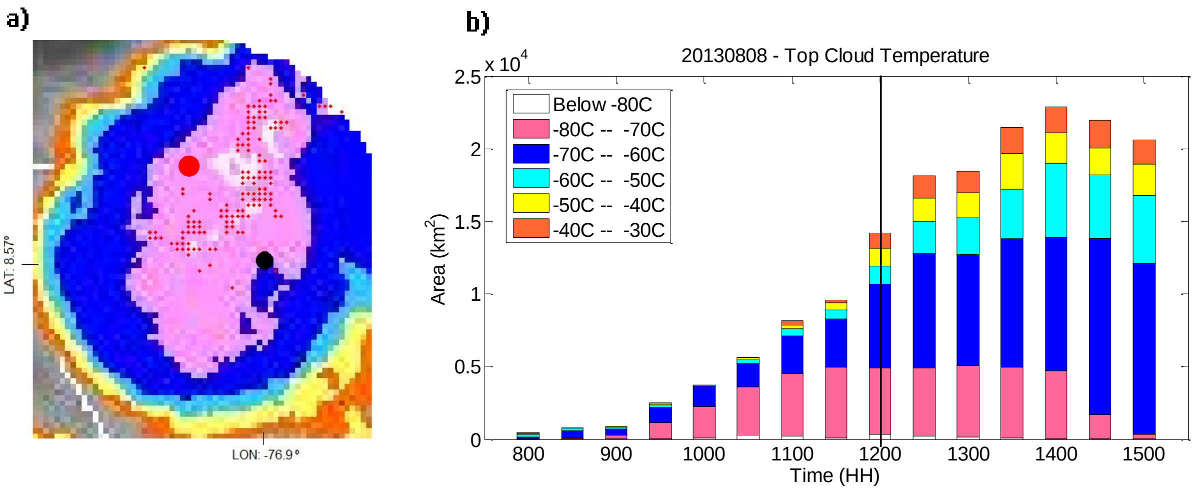


Figure 2. a) Thunderstorm cell producing TGF at 12 UT (Coloured Goes-East image), stroke related (Red point) and TGF (Black point). b) Cloud Top temperature evolution between 8UT and 16UT of the cell in figure 2a.

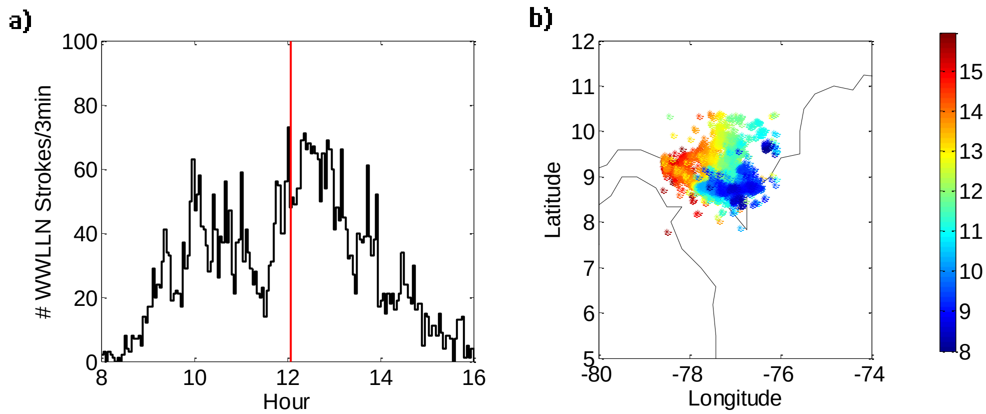
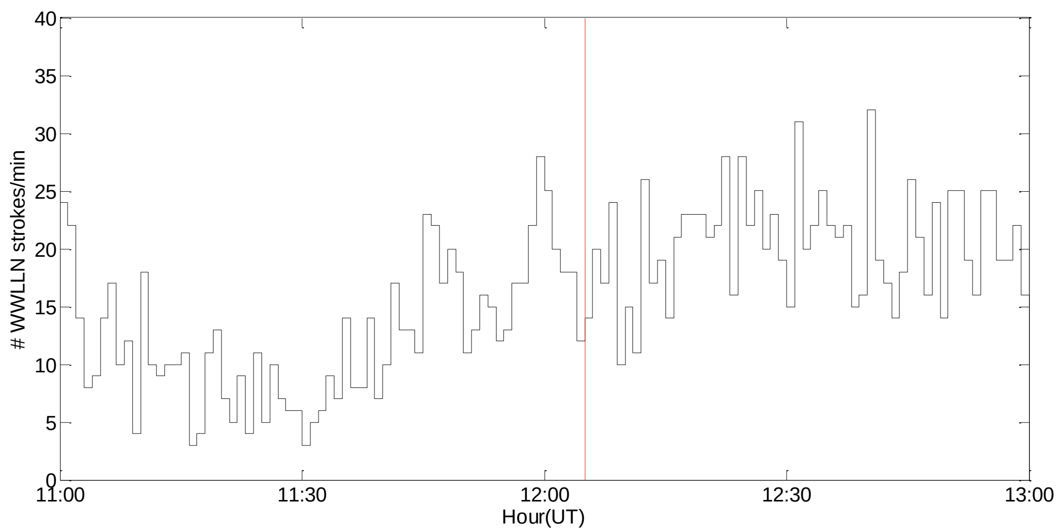


Figure 3. a) Time evolution of WWLLN strokes (#strokes/3min) in the same time period and cell that figure 2 (black stairs) and TGF time occurrence (red line). b) Time evolution of geographical distribution of WWLN strokes in figure 3b

Figure 4 top, presents a plot of WWLLN strokes in the period of 2 hours around TGF (11UT – 13 UT) for the thunderstorm cell. The figure shows that the TGF occurred between two peaks of ~25 strokes/minute just in a minimum of ~12 strokes/minute but where the general trend is quite constant as seen in the accumulated plot.



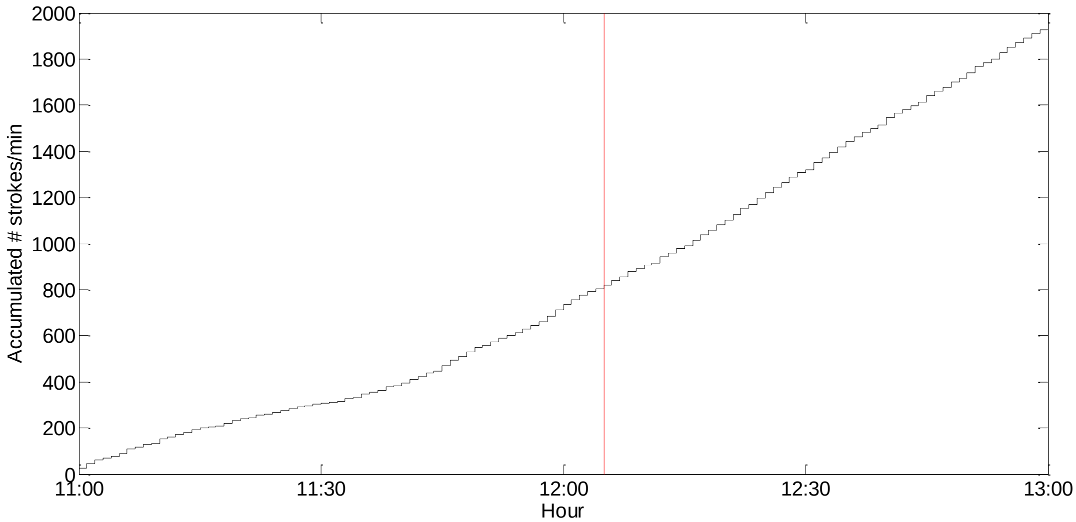


Figure 4. Top) Time evolution of WWLLN strokes (#strokes/min) cell that figure 2 for the period between 11 UT and 13 UT (black stairs) and TGF time occurrence (red line). Bottom) Accumulated stroke occurrence in time for the same period than top (black stairs) and TGF occurrence time (red line)

Thunderstorm and meteorological characterization

To characterize the thunderstorm producing the TGF it has been analyzed the Convective Available Potential Energy (CAPE), tropopause temperature, tropopause altitude, and temperature of the 400 hPa level what can give an approximation for the mixed phase altitude at 12 UT, assuming that it is the same at the TGF time.

Figure 4 shows the CAPE for the same region used to study thunderstorm phase. These CAPE values are not really high for the region where CAPE can reach values higher than 3000 J/kg. The values presented here are similar to those values in mid-latitudes where TGF occurrence is practically null. However, the CAPE presented here is at the time of the TGF where the storm was already active for more than 4 hours. The low CAPE values at that time could be due to the energy removal by storm. At 6 UT and 9 UT CAPE reaches values relatively high around 2500J/kg.

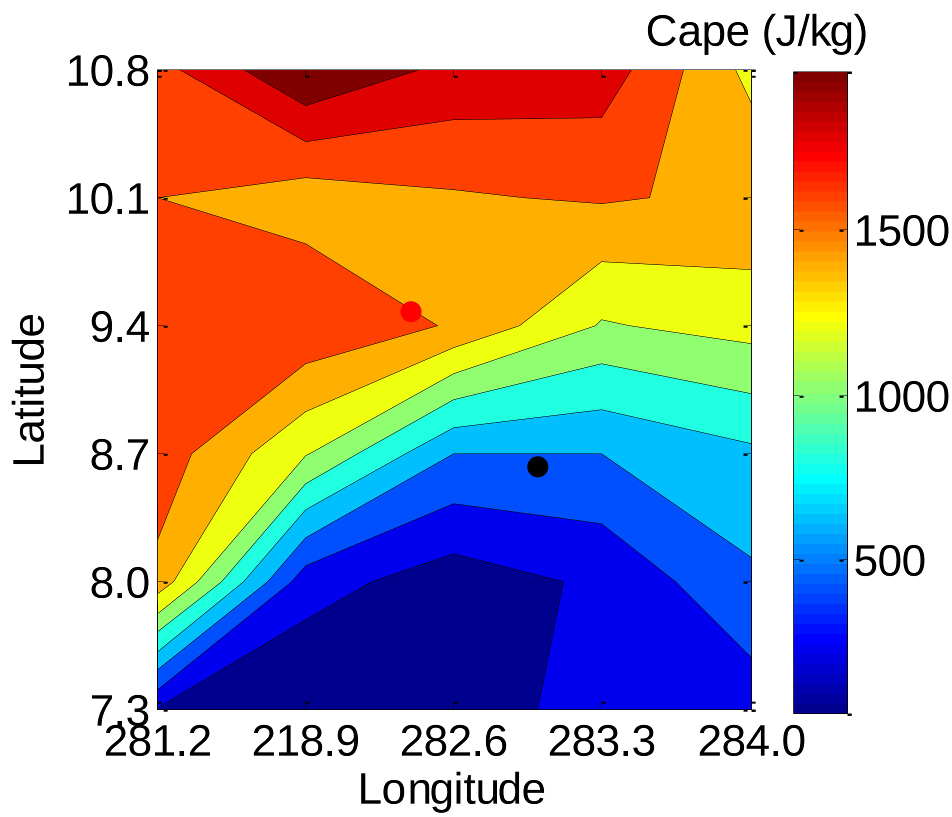


Figure 4. Geographical distribution of CAPE for the same cell than figure 2a at 12UT, stroke related (Red point) and TGF (Black point).

In table 2, pressure (P) and temperature (T) of tropopause are showed for the location of the stroke thought to be related to TGF. Tropopause was at ~15 km with a temperature of ~198K (-75ºC). Looking at temperatures of figure 2a it is possible to infer that cloud tops in the temperature range of -80ºC to -70ºC reached the tropopause. That agrees with Williams [2006] that proposes that IC in the tropics are produced higher in the atmosphere allowing TGFs to overcome easily the atmospheric attenuation and reaching satellite detectors. This would explain the higher TGF production in the tropics. Correlations of TGFs production with ITCZ movement shown in figure 1 reinforce this theory.

Table 2 summarizes pressures and temperatures at tropoapuse and 400 hPa (~7.2 km) levels for the assumed TGF location. Temperature of the 400 hPa is -20ºC, what means that mixed phase is at altitude not really high compared to midlatitudes that can achieve values between 5 km to 7 km. Although 7 km is a maximum value achieved in the months of maximum solar irradiance, what could explain the low ratio of TGF detection in midlatitudes due to production deeper in atmosphere what makes more difficult to escape due to atmospheric attenuation [Williams 2006].

Table 2. Tropopause temperature and pressure at stroke location. Temperature of 400 hPa level at stroke location.

Level	Variable	Values
Tropopause	Pressure	115 hPa
Tropopause	Temperature	-75^{o} C

400 hPa	Temperature	-20ºC

CONCLUSIONS

TGF studied on this paper occurred in in the north of Colombia in August 2013. In this region the probability to detect a TGF on this month is high due to the latitudinal movement of the ITCZ. At this time the TGF production is high, but it is not possible to say if it is due to increase of lightning occurrence or other specific meteorological features of the ITCZ region that affects to TGF production. Splitt et al. [2010] found that meteorological features like CAPE in situations conducing to TGFs reaches values higher than CAPE in random tropical locations for the same TGF analyzed. In the present study, CAPE value is not really high. On the other hand, Smith et al. [2010] found that TGF deficits in regions where lightning production is comparable to others with high TGF production suggesting that regional meteorological differences may play an important role in TGF production. Here results of tropopause and 400 hPa levels only suggest that, as Williams [2006] indicates, TGFs produced higher in atmosphere may overcome atmospheric attenuation, explaining higher TGF detection in tropics. Since the case presented here is compared to other TGF studies, it is not possible to say anything about meteorological preferences for TGF production. That is why an analysis of all satellite detecting TGFs passes over South America is being carried out in order to compare situations seen by satellite with and without detections of TGFs. Finally, the TGF was produced in a mature phase of the thunderstorm when CG lightning activity was high. That agrees with Smith et al. [2010] and seems very similar to the timing of sprites. Due to the TGF occurred ~235 ms after a CG stroke, we suggest that the TGFs may be produced by lightning leader after the last detected stroke or to some IC activity consequence of LCC, what do not disagrees with TGF production theories [Dwyer 2012]. This assumption opens the possibility to reanalyze TGF data to find CG lightning correlation in the range of hundred milliseconds.

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REFERENCES

Briggs, M. S., et al., 2010, First results on terrestrial gamma ray flashes from the Fermi Gamma-ray Burst Monitor, *J. Geophys. Res.*, **115**, A07323

Dwyer, J. R., Smith, D.M. and Cummer, S.A, 2012, Hgh-Energy Atmospheric Physics: Terrestrial Gamma-Ray Flashes and Related Phenomena, *Space Sci. Rev*.

Dwyer, J. R., and D. M. Smith , 2005, A comparison between Monte Carlo simulations of runaway breakdown and terrestrial gamma-ray flash observations, *Geophys. Res. Lett.*, **32**, L22804

Fishman, G.J., et al., 1994, Discovery of intense Gamma-Ray flashes of atmospheric origin, *Science,* **264**, 1313-1316

Grefenstette, B. W., et al., (2009), First RHESSI terrestrial gamma ray flash catalog, *J. Geophys. Res.*, **114**, A02314

Kitagawa, N., M. Brook, and E. J. Workman (1962), Continuing currents in cloud-to-ground lightning discharges, *J. Geophys. Res.*, **67*(2),*** 637–647

Lay, E.H., et al., 2004, WWLL global lightning detection system: Regional validation study in Brazil, *Geophys. Res. Lett*, **31**, L03102

Lu, G., et al., 2011, Characteristics of broadband lightning emissions associated with terrestrial gamma ray flashes, *J. Geophys. Res*., **116**, A03316

Marisaldi, M., et al., 2010, Detection of terrestrial gamma ray flashes up to 40 MeV by the AGILE satellite, *J. Geophys. Res*., **115**, A00E13

Morales, C. et al., 2002, Continuous Long-Range Thunderstorm Monitoring by a VLF Receiver Network Part II: Cloud-to-Ground and Intra-Cloud Detection Efficiency, (http://www.zeus.iag.usp.br/publication.php?lan=en)

Motanyà, J., et al., 2014, X-rays and microwave RF power from high voltage laboratory sparks, *ICAE 2014,* Oklahoma

Østgaard, N., et al., 2008, Production altitude and time delays of the terrestrial gamma flashes: Revisiting the Burst and Transient Source Experiment spectra, *J. Geophys. Res*., **113**, A02307

Shao, X.-M., et al., 2010, A closer examination of terrestrial gamma-ray flash-related lightning processes, *J. Geophys. Res*., **115**, A00E30

Smith, D.M., et al., 2005, Terrestrial Gamma-Ray Flashes observed up to 20 MeV, *Science*, **307**, 1085

Smith, D. M., et al., 2010, Terrestrial gamma ray flashes correlated to storm phase and tropopause height, *J. Geophys. Res.*, **115**, A00E49.

S. Soula et al., 2009, Analysis of thunderstorm and lightning activity associated with sprites observed during the EuroSprite campaigns : Two case studies, *Atmos. Res.*, **91**, 514-528

S. Soula et al., 2012,Multi-instrumental analysis of large sprite events and their producing storm ins southern France, *Atmos. Res.*, **135-136**, 415-431

Splitt, M. E., et al., 2010, Thunderstorm characteristics associated with RHESSI identified terrestrial gamma ray flashes, *J. Geophys. Res.*, **115**, A00E38

Williams, E., et al., 2006, Lightning flashes conducive to the production and escape of gamma radiation to space, *J. Geophys. Res*., **111**, D16209.