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# Preliminary observation of Lightning Activity in the Peruvian high mountain conditions

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***Abstract*— Few studies about lightning activity in regions whose elevations are higher than 4000 MSL are available. This paper describes preliminary results of the cloud-to-ground – CG lightning activity based on a short initial observation period of a VLF/LF lightning detection network installed in Peru along the Andean Mountains. The orography in Peru varies between 0 and 6.700 MSL and cloud-to-ground lightning activity is analyzed over the terrain elevation. The influence of altitude is studied by analyzing peak current distributions for CG strokes at different altitude intervals.**

***Keywords—Thunderstorm, Ground Flash Density, VLF/LF ligthning detection system, High mountain***

## I. INTRODUCTION

Many studies have reported high lightning activity over the tropical zone, with highest Ground Flash Density – GFD and Keraunic Level – KL values [1 – 3]. This region located between latitudes +/-23º is characterized by solar radiation throughout the year and high temperatures. The climatic conditions of this region lead to the generation of precipitations and numerous associated thunderstorms during almost the whole year.

Particularly, on the Peruvian Andes, a high lightning activity on mountains with elevations higher than 4000 MSL is registered. Such atmospheric and orthographic characteristics are not common worldwide.

Peru has a monomodal thunderstorm regime that starts in October and ends in March, and where severe thunderstorm events have been registered with flash rate values greater than 300 strokes per minute.

Several papers such as [4 – 7] have studied the influence of mountain regions and topography on the lightning activity around the world. Other authors have analyzed the relationship between GFD and the elevations (higher than 3000 MSL) in South Africa [8] and Alps in Europe [9].

This paper focuses to the lightning activity on high mountain regions of Peru with altitudes greater than 4000 MSL and the performance of LLS installed in Peru.

## II. LIGHTNING DETECTION SYSTEM

The Total Lightning Detection System used in this paper was installed in Peru in 2018. It is composed by 15 VLF/LF magnetic field antennae based on the LINET technology previously presented by Betz et al [10, 11]. Sensors were deployed along the diverse orography of Peru at altitudes between 116 and 4376 MSL and with baselines varying from 100 to 250 km.

Fig 1 shows the location of the 15 sensors in which the majority are installed over the Peruvian mountain ranges. The analysis area (497.000 km$^2$) depicted as a red rectangle is shown. This area was selected because it is located in the center of network, where the best performance can be assumed.

TABLE I. ALTITUDES AND LOCATIONS OF THE TOTAL LIGHTNING DETECTION SENSOR SITES.

| Sensor site | Elevation [MSL] | Sensor site | Elevation [MSL] |
|---|---|---|---|
| Cerro de Pasco | 4376 | Arequipa | 2353 |
| Juliaca | 3832 | Tingo María | 653 |
| Orcopampa | 3790 | Satipo | 629 |
| Huancayo | 3292 | Tocache | 501 |
| Cusco | 3287 | Tarapoto | 272 |
| Coracora | 3178 | Pucallpa | 161 |
| Ayacucho | 2767 | B95 | 116 |
| Cajamarca | 2729 | - | - |

Fig 2 shows the elevation profiles between some of the 15 sensors installed in Peru. Sensors located in Cajamarca and Tarapoto present an elevation difference of 2457 m. It is important to notice that there are several altitude changes 120 km far from the Cajamarca sensor. Even though Tarapoto and Pucallpa sensors are located in altitudes lower than 1000 m, there are mountains between them with altitudes over 2000 m. Cerro de Pasco sensor is installed in an altitude of 4376 m, almost no references were found in which there were reported LLS sensors installed at higher elevations around the world. The elevation difference between Cerro de Pasco and Tingo María sensors is 3682 m, thus evidencing extreme conditions to detect and measure lightning activity. On the other hand, Cerro de Pasco and Huancayo sensors are located at altitudes over 3000 MSL; however, the difference between their elevations is close to 1043 m, and evidencing softer changes along the terrain. The elevation difference between Ayacucho and Cusco sensors is 520 m, however, several altitude variations, along 170 km, are presented, which can reach differences close to 3000 m. Arequipa sensor was installed at an elevation of 2353 m, it is located near to a mountain with altitudes higher than 5000 m.

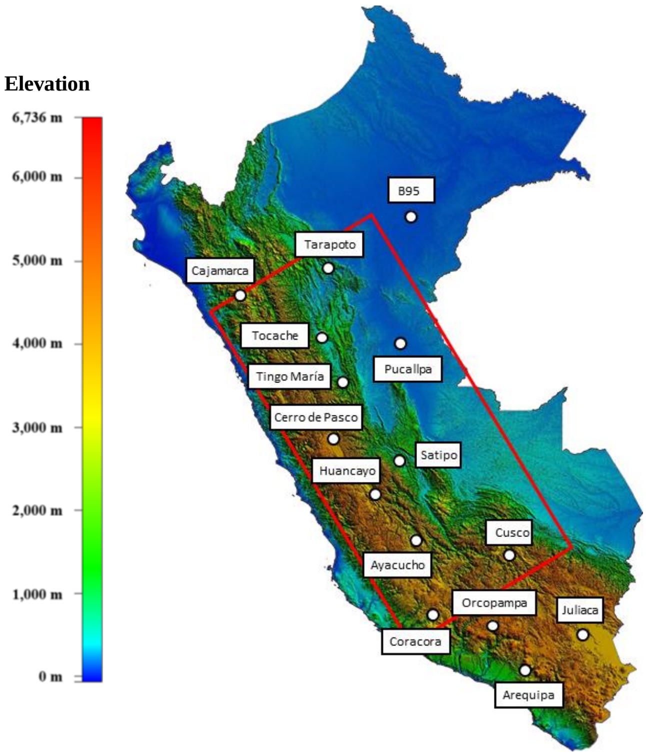


Fig. 1. Total Lightning Detection Network in Peru (LINET), sensor locations and terrain elevation.

Extreme topographical conditions in Peru, altitude differences between sensors, high terrains and sensors installed over 4000 MSL presented challenges at the time to measure lighting activity around the country and characterize the phenomenon.

LINET technology uses a 3D Time-Of-Arrival (TOA) method, thus providing altitude, longitude and latitude information of each stroke measured. The methodology provides information of both Intra-Cloud (IC) and Cloud-to-Ground (GC) strokes, as long as the baselines between sensors are shorter than 250 km. The configuration of the LLS (baselines and internal detection thresholds) has allowed measuring currents as low as 3 kA [10, 11].

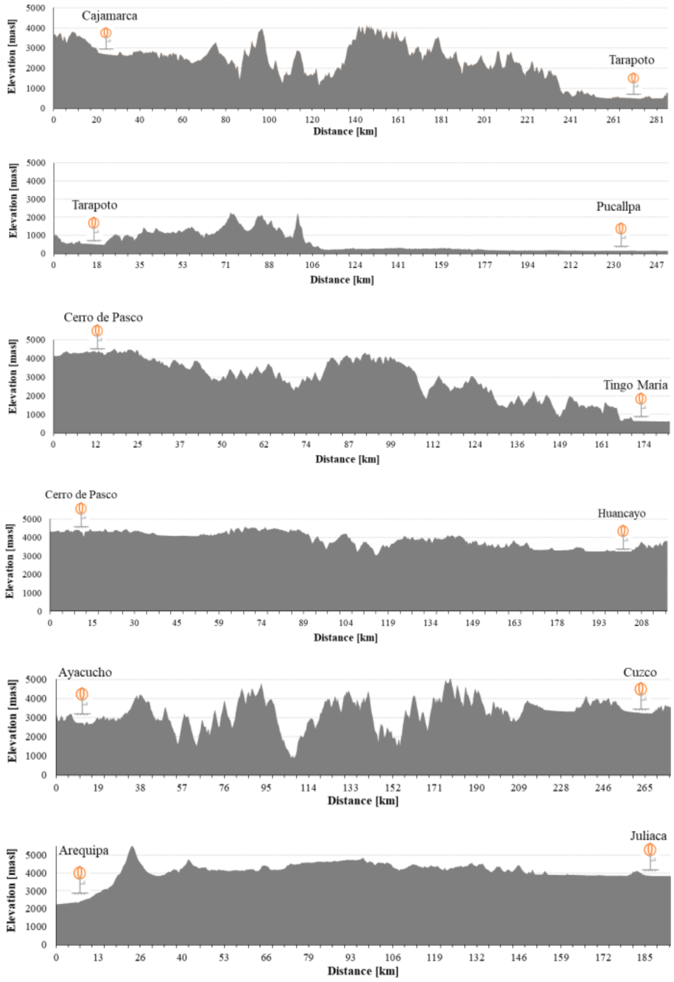


Fig. 2. Altitude profiles along different baselines of the Peruvian Total Lightning Detection System.

Fig 3 presents the Detection Efficiency (DE) map, by means of the minimum detectable peak current. It was calculated using the methods to compute relative detection efficiency given by CIGRE Task Force C4.404A [9], where reference peak current distributions are used (e.g reference peak current distribution by lightning data obtained in the central part of United States using the National Lightning Detection Network [19]). A median value of 12.8 kA and a standard deviation of 0.6 kA were used to compute the efficiency.

As can be observed in the majority area of the country, it is possible to measure peak currents lower than 6 kA. By considering the expected typical cloud-to-ground peak current distributions, the minimum detectable peak current of 6 kA could be related to a Detection Efficiency – DE equal or higher than 90%; however, the mountain effects on the LLS DE and the CG/IC lightning discrimination have not yet been deeply studied under high mountain conditions. Lightning-sensitive systems, as the Peruvian Power System are located mostly in the center and the west part of the country where the locations system shows high detection efficiency levels.

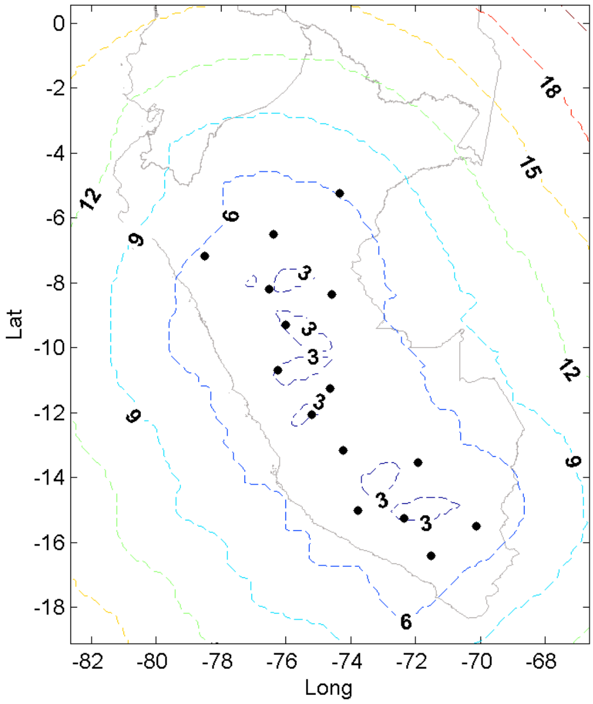


Fig. 3. Minimum detectable peak current map, for CG strokes, of the Total Lightning Detection System in Peru. Minimum detectabe peak current is an indicator of Detection Eficiency.

The Location Accuracy is given by the standard error ellipse at each solution as discussed by Betz et al [6, 19]. The average and median values of the location accuracy of the data given by the Peruvian Total Lightning Detetion System are 0.319 km and 0.280 km, respectively, thus supporting the reliability of the data used in this analysis.

## III. LIGHTNING ACTIVITY IN PERU

Based on the installation of the Total Lightning Detection System in 2018, 6 million strokes have been detected all around the country. The dataset was used to perform some spatial and temporal analysis presented in this section.

Fig 4 shows the variation of the lightning activity in Peru since October 2018 to April 2019 in the highest DE zone. During 28 January 2019, the severest thunderstorm was measured with around 92.372 strokes, followed by 06 April 2019 with 80.184 strokes registered. In 28 days, the thunderstorm flash rate was higher than 100 flashes/min. Fig 5 shows the variation of the lightning activity along the hours. The variations is unimodal, presenting peak values at 14:00 and 15:00 local hour. The minimum values were found since 08:00 to 10:00 am.

Fig 6 shows the variation of the lightning activity in Peru during last six months (Nov. 2018 – Apr. 2019), by means of the Ground flash Density. It can be observed the influence of the orography in the lightning activity around the country.

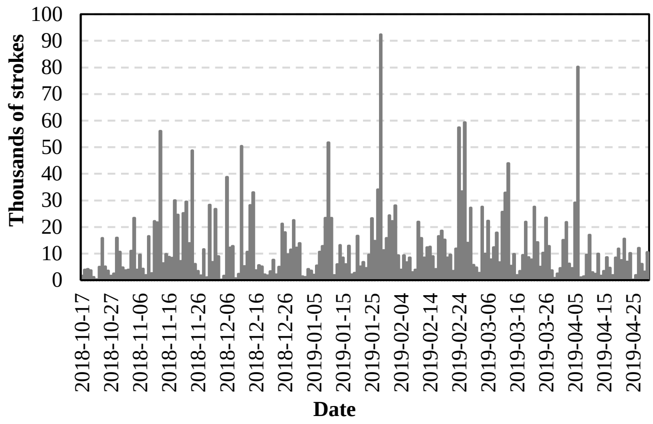


Fig. 4. Daily variation of the lightning activity in Perú since october 2018.

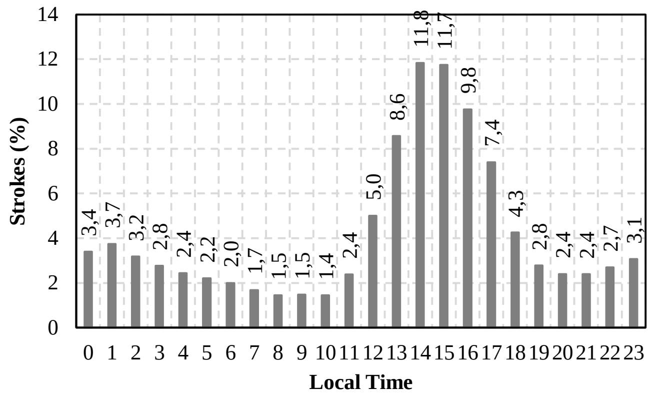


Fig. 5. Hourly variation of the lightning activity in Perú.

Thunderstorms usually arrive from east (Amazon region), in the lowland rainforest (Omagua), thus interacting with the high jungle (Rupa Rupa - with altitudes from 400 msl to 2000 msl) and increasing the lightning activity levels, especially in the high jungle and inter-Andian valleys where the highest values of Ground Stroke Density - GSD were found.

On the other hand, the lowest lightning activity is found all along the Peruvian coast. The topography in this region change from 0 MSL up to 4800 MSL in very short distances between the coast and the tip of the mountains, near to 40 km to 130 km approximately.

Greatest values of GSD are found along the common area of Pasco, Huánuco and Ucayali regions, where the high jungle valley and the inter-Andean valley are located. GSD found in these regions reach values higher than 40 flashes/km$^2$ during six months of analysis. As expected, the lowest values are found near the coast with values lower than 0.1 flashes/km$^2$ or even lower. The known coastal desert climate along the Peruvian pacific littoral is caused, in part, by the proximity of the very high mountains of the Andean Mountain Range, which also produce abrupt lightning activity changes in very short distances, varying from 0 in the coast to very high GSD (e.g. 20 flashes/km$^2$) in a few tens of kilometers.

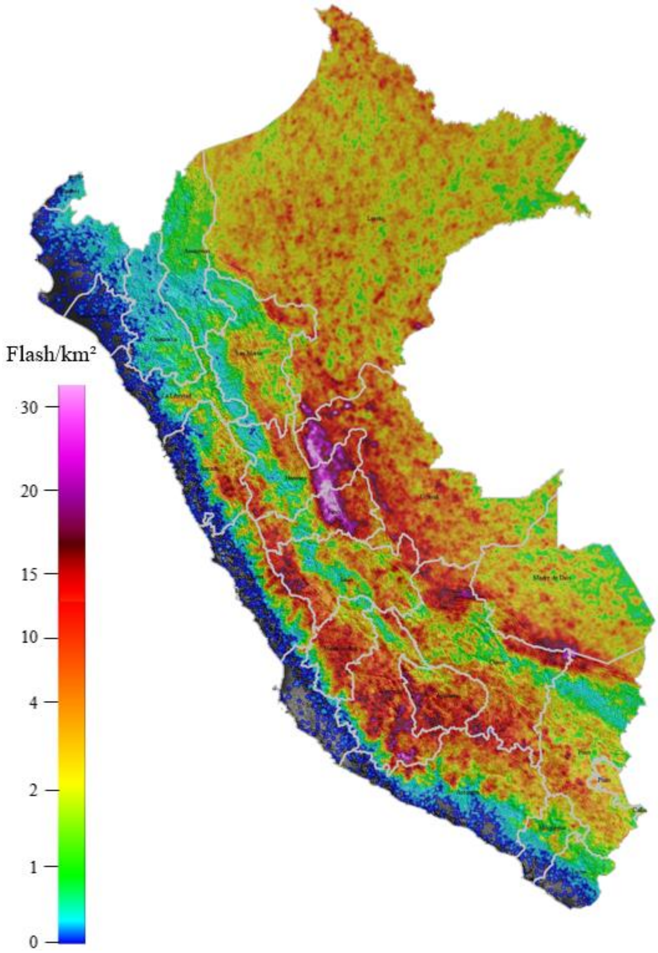


Fig. 6. Ground Stroke Density over Peru during the period from October 2018 to April 2019. It is not given as the standard unit of flash/km$^2$yr due to the short bservation period.

## IV. TERRAIN ELEVATION EFECTS ON LIGHTNING PATTERNS AND DETECTION

In this section, the relation between altitudes and lightning activity is presented. Table II shows the relation between the intervals of different altitudes. The total area of analysis is 492,840 square kilometers, the median value of the peak current is 9.7 kA and the mean value is 15 kA.

The area of places which elevations are higher than 3000 MSL represent 39% of the total area analyzed and represent 39% of the total strokes detected by the location network. Zones with altitudes higher than 4000 MSL represent 22% of the total study area and 27% of the total number of strokes.

Even though the area of places with altitudes lower than 500 MSL represents 32% of the total study area, its lightning activity is lower than the activity found in altitudes over 2000 MSL. In this sense, it is possible to relate the effects of altitudes in the lightning activity.

TABLE II. MAIN CLOUD-TO-GROUND LIGHTNING CHARACTERISTICS GIVEN FOR SEVERL ALTITUDE INTERVAL

| **Altitude Interval, H (MSL)** | **Área (km$^2$)** | **CG strokes** | **Mean Ip (kA)** | **Median Ip (kA)** | **Standard deviation ()** |
|---|---|---|---|---|---|
| **H < 500** | 156,168 | 949,723 | 14.20 | 8.8 | 0.312 |
| **500 ≤ H < 1000** | 43,893 | 268,447 | 15.87 | 10.3 | 0.320 |
| **1000 ≤ H < 2000** | 58,059 | 232,064 | 16.81 | 10.8 | 0.325 |
| **2000 ≤ H < 3000** | 43,767 | 86,395 | 16.63 | 11.1 | 0.298 |
| **3000 ≤ H < 4000** | 81,009 | 293,892 | 14.85 | 10.3 | 0.255 |
| **4000 ≤ H < 5000** | 106,362 | 666,337 | 14.96 | 10.0 | 0.286 |
| **5000 ≤ H** | 3,582 | 23,717 | 14.42 | 9.5 | 0.298 |
| **0 ≤ H (All)** | 492,840 | 2,519,735 | 14.98 | 9.7 | 0.310 |
| **CIGRE C4.404** | - | - | 12.8 | | 0.6 |

The mean and median peak current values vary for each altitude interval. Mean values vary from 14.2 kA to 16.8 kA, while the median values vary from 8.8 to 11.1 kA. In general, for higher altitudes, higher median peak current values. Lower values of mean peak current vales occurred for the biggest areas in Peru, H<500 MSL and H>3000 MSL. Some conclusions can be obtained analyzing the peak current $I_p$ from the distribution curves for each altitude interval.

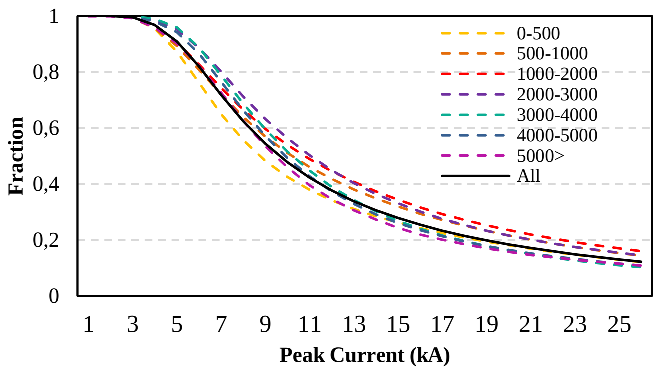


Fig. 7. Cumulative Peak Current distributions for "All" strokes, a theoretical reference [7] and strokes in the interval from H>0 to H≥5,000 MSL.

Differences in the measured peak current distributions at different heights are probably caused by changes in the LLS performance, such as the DE and the IC/CG misclassification rate, or real changes in the cloud-to-ground lightning stroke currents in those regions. The identification of those effects would require the use of additional precise and more sophisticated measurement systems (e. g. Lightning Mapping Array; video record systems), which could be used as reference, not yet available.

Ground Flash Density also exposes special patterns when analyzed as a function of elevation. Fig. 8 gives the mean, standard deviation and maximum values of Ground Flash Density for the entire elevation range from 0 to 6.000 MSL. Regions at altitudes around 500 MSL present the highest values of GFD with a maximum close to 45 flashes/km$^2$yr and an average of 5.3 flashes/km$^2$yr. The GFD magnitudes tend to decrease with altitude until reaching a level around 2.500 MSL where maximum GFD is close to 12 flashes/km$^2$yr and mean values are around 2.5 flashes/km$^2$yr; thereafter, the tendency changes and the GFD values increase with altitude. Very high GFD values are found in a wide altitude interval from 3.000 to 5.000 MSL with maximum GFD up to 36 flashes/km$^2$yr and a mean value of 4.5 flashes/km$^2$yr.

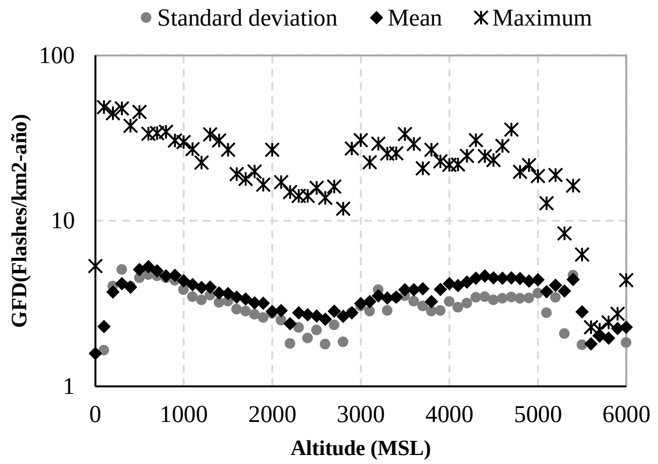


Fig. 8. Variation of mean, maximum and standard deviation values for the Ground Flash Density with altitude.

Some effects on the IC/CG discrimination performance of the LLS could explain high GFD magnitudes at high altitudes. Nonetheless, previous described high GFD values are located at high altitude Andean plateaus, as those described in Fig. 2 (Cerro de Pasco – Huancayo; Arequipa - Juliaca), where severe thunderstorm conditions, with long life cycle thunderstorms, were identified during several days of observation as described in Fig.4.

Reported intra-cloud lightning emission heights are described in Fig. 8. Similar Total Lightning Detection Systems are available in Colombia [7] and Peru, these countries are located at similar latitudes but opposite with respect to the Ecuador, and those have relevant mountain conditions given by the Andean Mountains; much more extreme in Peru. Therefore, comparisons of IC emission heights expose interesting patterns. Geographical conditions of both countries are apparently very similar regarding the latitude and the tropical conditions influence, and no important differences would be expected about the IC lightning height distributions. As observed in Fig. 8 the median emission heights (and standard deviations) in Colombia and Peru are 10.2 km (3.09 km) and 10.9 km (3.18 km) respectively. Reported IC emission heights tends to be a little higher in Peru. It is not possible to state at this moment if altitude differences are due to performance effects. Once again, changes in the LLS IC/CG misclassification rate under this high mountain conditions could explain that IC emission height distribution tend to slightly higher altitudes in Peru when compared to a reference IC emission height distribution in a country with quite similar geographical conditions. However, as in all previous sections, not conclusive results are still possible and deeper studies are needed based on complementary measurement instruments about lightning activity at high mountains.

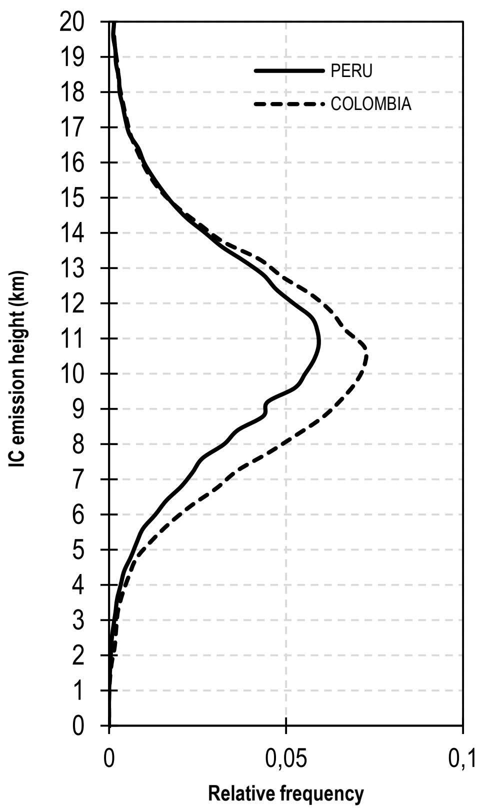


Fig. 9. Intracloud IC emission height in Peru and Colombia based on similar Total Ligthning Detection Systems.

## CONCLUSIONS

This paper described some initial results based on the first lightning data provided by a Total Lightning detection System recently deployed along the Peruvian geography. Sensor site altitudes are very atypical for all kind of lightning location technologies in the world and the performance characteristics are in fact a challenging research topic. In this paper, a robust LINET lightning location network is used and, despite the short observation period, important characteristics about the lightning activity are concluded.

The season of maximum lightning activity from 2018 to 2019 showed several days of severe conditions with long life thunderstorms, most of them located at the Amazon forest lowlands, mid-altitude valleys and at high Andean Plateaus.

Patterns of Ground Flash Density are clearly identified as a function of the orographic conditions. Transition regions from the lowland Amazon rainforest, high jungle valleys and high altitude plateaus, unique of Peru, depict large areas of very high activity, reaching GFD values up to 45 flashes/km$^2$yr; that contrast with the practically null activity in the pacific littoral.

Cloud-to-ground peak current distributions give some indications about the effects of the high mountain on the lightning activity and detection. Contrary to some results from previous studies, it is not possible to conclude clear increasing or decreasing tendencies with altitude of the average peak current. Reduction or increment of the average peak current with altitude, under conditions of an estimated DE quite homogeneous, usually indicates some effects of mountains on the LLS performance. However, no clear tendencies are obtained in this paper and indicate that lightning activity in the studied area responds to very different and complex thunderstorm regimes that change from one region to another. Very high lightning active areas are found at high terrain, along very large plateaus (3000 to 5000 MSL), which are practically unique to the Peruvian territory.

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