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Analyzing lightning characteristics in central and southern South America

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ABSTRACT

Lightning data has become an integral part of weather observation and has been shown to be an effective tool for alerting and nowcasting. The Earth Networks Total Lightning Network (ENTLN) is a global lightning detection network established in 2009. ENTLN consists of roughly 1800 broadband electric field sensors globally that detect intra-cloud (IC) and cloud-to-ground (CG) lightning, with over 140 sensors in South America. In this study, we analyze the geographical variation of lightning characteristics such as density, peak current, and polarity, with the goal of better understanding the meteorological processes that produce these thunderstorms. Results indicate significant variation in average peak current per flash, with a maximum occurring throughout Northern Argentina, and a localized strong minimum North of São Paulo, Brazil. This minimum is coincident with a region dominated by negative IC flashes. In Central and Northern Argentina, 40%–50% of CG flashes were observed to be positive. Conventional thunderstorms typically have around 10% positive CG flashes. The large-scale patterns observed in this study support the findings of previous case studies regarding inverted polarity storms, mesoscale convective systems, and transient luminous event production, most of which had more limited scopes.

1. Introduction

Lightning data has become an integral part of weather observation, especially when it comes to public safety and nowcasting. The importance of lightning data has spurred strong and varied efforts into improving lightning location/observing systems, both ground-based and space-based. Lightning occurs in convective weather systems which are sufficiently strong to have a significant quantity of mixed phase hydrometeors. These same storms are frequently the source of severe weather, including tornadoes, hail, high winds, and flash floods. Indeed, past studies have shown that lightning is a good predictor of severe weather [1–3]. Furthermore, lightning polarity can provide insight on the charge structure of a thunderstorm [4], ultimately leading to a better understanding of the storm microphysics and dynamics [e.g.,5–8]. Thus, lightning locations systems can be utilized to provide advance warning to people of the threats of severe weather, even in the absence of meteorological observations that provide spatial information about convection (such as precipitation radar). This study focuses on various lightning characteristics and analyzes their geographical variation throughout central and southern South America, as well as the surrounding ocean.

2. Data and methods

2.1. Earth networks total lightning network

The Earth Networks Total Lightning Network (ENTLN) continuously measures lightning stroke occurrence time, location, type (IC and CG), polarity, and peak current, around the world. ENTLN combines observations from over 1800 wideband electric field sensors with data from the World Wide Lightning Location Network [WWLLN,9,10] to detect both IC and CG flash signals efficiently. Individual strokes, or pulses, are clustered into flashes if the pulses are within 0.7 s and 10 km of one another. ENTLN has a detection efficiency for IC flashes of up to 95% [3,11,12] and CG flashes of up to 97% [13]. These peak detection efficiencies are for a region in the central and eastern U.S., where the sensor density is the highest; in general, detection efficiency varies depending on network coverage. WWLLN is a network of lightning location sensors operating at very low frequencies (3–30 kHz), which allows it to detect lightning from relatively large distances but with higher location error.

In this study, we analyze lightning data between Jan. 1 2019-Dec. 31 2021. These dates were chosen because the ENTLN expanded

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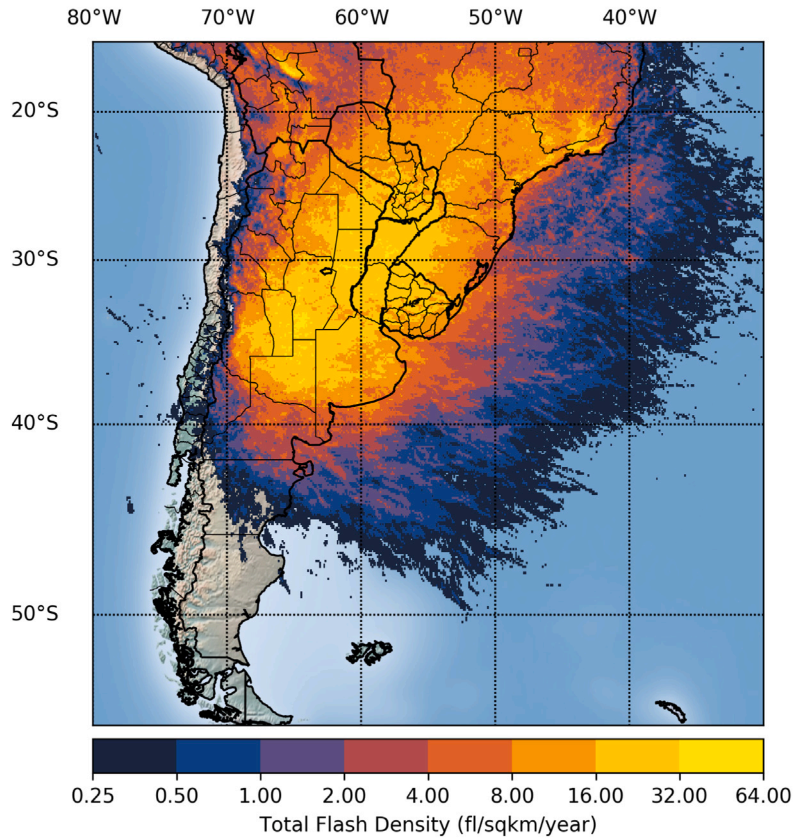

Fig. 1. Total flash density.

network coverage in Argentina in 2018. The geographical distribution of the flash density over this 3-year period is shown in Fig. 1.

2.2. Methodology

This study looks at the geographical variation of lightning characteristics. To do this, we aggregated 3 years of lightning flash data from ENTLN and binned various characteristics of those data into a 0.1×0.1 degree grid (0.2×0.2 degree for the polarity maps). These characteristics include: total flash density per grid cell (fl/km^2/year); the spatial distribution of the average peak currents of all CG and IC flashes in a given grid cell (kA/fl); total IC flash percentage; and the percentages of positive CG and IC flashes. The peak current and polarity of a given flash are determined from the largest amplitude pulse within that flash. If a given grid cell contained fewer than 50 total flashes over the 3 year aggregation period, it was omitted from the analysis. This masking criteria served to eliminate spurious results in IC percentage and positive flash percentage calculations, particularly over the distant ocean regions.

3. Results and discussion

The goal of this study is to analyze the geographical distribution of several lightning characteristics across parts of South America. The flash density distribution shown in Fig. 1 clearly shows that Argentina and Uruguay experience the largest amounts of lightning in this region. Specifically, the provinces of Entre Ríos, Santa Fe, and Córdoba had high activity during the analysis period. There is also a very localized maximum observed over Chimoré, Bolivia, which was corroborated by data from the space-based lightning detection system OTD/LIS [14] and an ENTLN thunder hours climatology [15], demonstrating that this local lightning maximum is also a local thunderstorm frequency maximum.

Next, we present the average peak current per flash. The geographical distributions of average peak current for CG and IC flashes are shown in Figs. 2 and 3, respectively. One notable feature in both maps is the region in Northern Argentina that experiences high average peak current for all flashes. This is an area that often experiences cold fronts moving north that stall out, and the convection along those fronts produces copious lightning [16]. This is also the region where monsoonal flow out of Brazil in the summer enhances convective activity [17]. There is steady upslope flow that occurs with North-eastern monsoon flow that enhances thunderstorms along the foothills of the Andes. As a result, organized single-celled convection often initiates in this region and grows upscale into multicellular storms, which can further develop into mesoscale convective systems (MCSs). Long lived MCSs moving from west to east are common in this region [18].

This region is also characterized by storms that have relatively high percentages of +CG flashes, which is shown in Fig. 5. Typically, the CG flashes in a given storm are only around 10% positive [19, ch. 5]. Therefore, to have such a large region where around 50% of CG flashes are positive is remarkable. Studies examining storms which produce a large fraction of +CGs have determined that they have a charge structure which is distinct from most other storms. The standard model of thunderstorm charge distribution is the tripole model [20], which states that a thundercloud has three layers of charge: one in the low levels, one in the mid levels, and one in the upper levels. A "normal" polarity thunderstorm, which is the more common type, is characterized by substantial mid-level negative charge in the cloud, and then layers of positive charge above and below it. Conversely, an "inverted" polarity thunderstorm is characterized by substantial mid-level positive charge, and upper and lower negative charge [4,21,22]. The CGs produced by a normal polarity storm are predominantly negative, and those produced by an inverted polarity storm are predominantly positive. A storm's overall polarity is controlled by its thermodynamic and microphysical

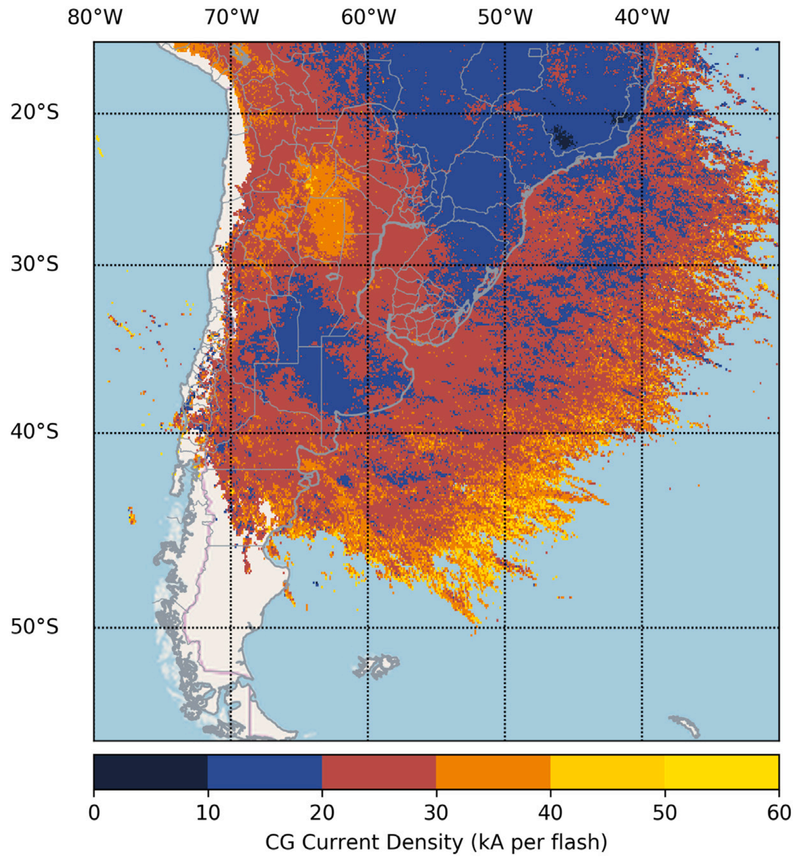

Fig. 2. Average peak current per CG flash.

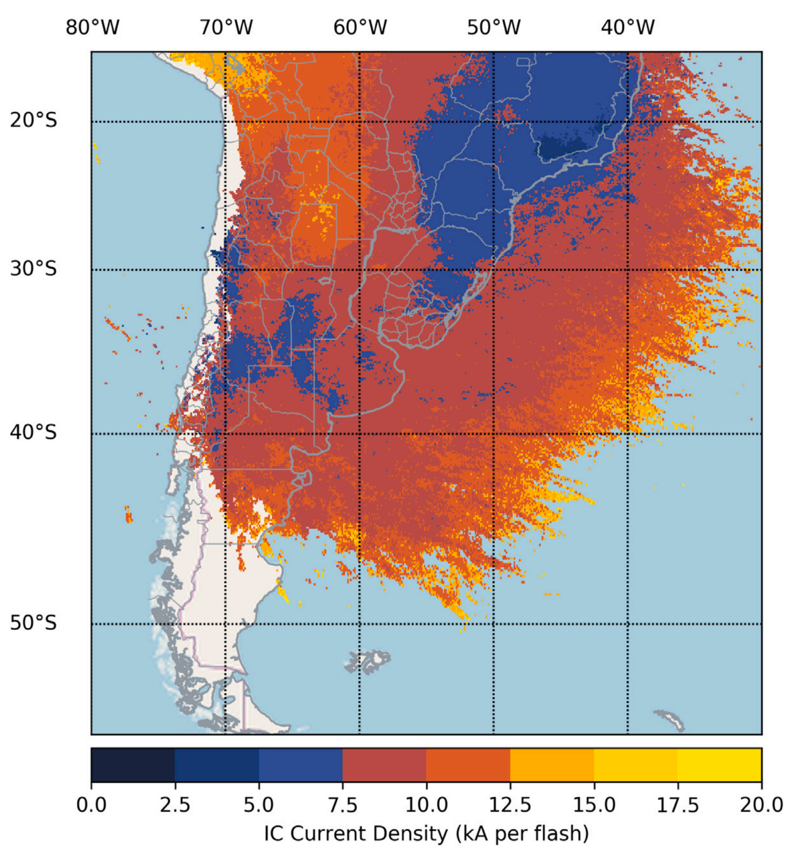

Fig. 3. Average peak current per IC flash.

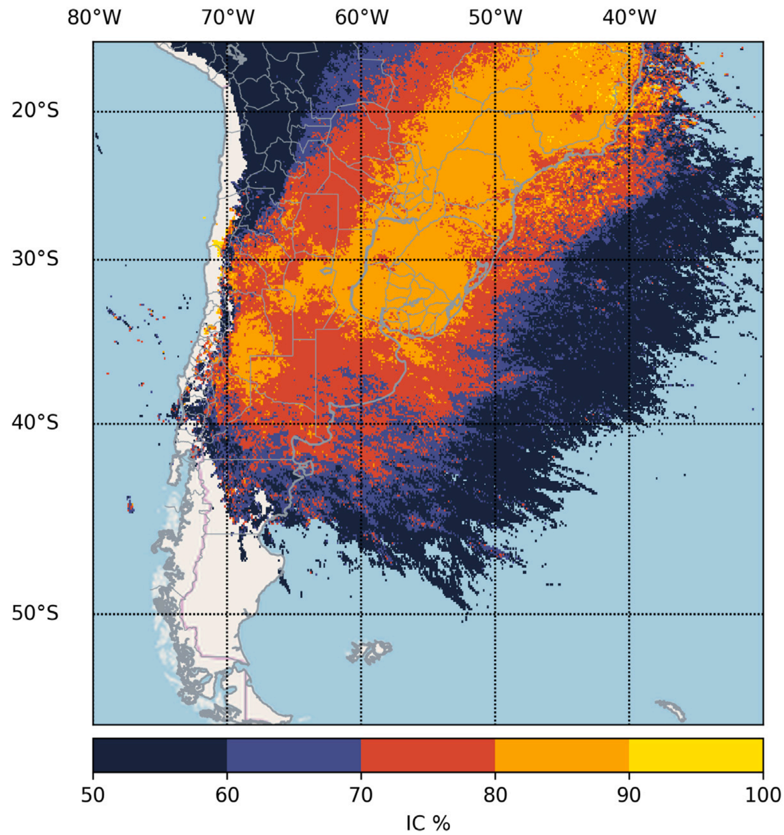

Fig. 4. IC flash percentage.

characteristics, which, in turn, are controlled by environmental parameters. Specific environmental parameters are thought to facilitate the development of inverted polarity storms, such as cloud base height, humidity, and aerosol concentration [23–25]. [26] observed that most +CG flashes occur in moderately sized single- and multi-cell storm systems, and [25] noted that the high plains of the US, just east of the Rockies, are where +CG-dominated storms occur the most frequently. The high plains of the US also happens to be where most upscale growth of storms into MCSs takes place, which suggests that environments which favor clusters of storms organizing into MCSs also favor +CG occurrence. Although many studies regarding inverted polarity storms are focused on cases in the central and southern United States, some recent studies [e.g.,27–29] have demonstrated that the La Plata Basin in South America frequently experiences inverted polarity storms, including many storms that initiate just east of the Andes and then grow upscale into eastward-propagating MCSs. The high fraction of +CGs in this region identified by the ENTLN corroborates the findings of past literature.

+CG flashes are also relatively common in MCS stratiform regions, and the region of high +CG fraction identified in this study is associated with frequent MCS occurrence [14,30,31]. The electrical structure of MCSs has also been heavily studied in the US, typically via balloonborne electric field meters [e.g.,32–35]. The current conceptual model of charge distribution for the trailing stratiform regions of MCSs comprises 4–5 horizontally extensive charge layers, including possible positive charge layers at the cloud base and around the 0°C isotherm, and a more dominant positive charge layer higher in the cloud, with negative charge layers sandwiched in between [33]. This electrical structure is conducive to preferential +CG production compared with -CG production in stratiform regions of MCSs, as documented by observational studies of MCSs in the US [e.g.,36,37]. The frequency of +CGs reported in a part of South America characterized by frequent trailing stratiform region MCSs is thus consistent with MCS lightning studies documented in the US [30].

Past studies have found that South America is a favorable region for observing storms that produce transient luminous events (TLEs), especially sprites [38,39]. Sprites are known to be caused by lightning with large charge moment change [40,41], which most often occurs during the continuing current of +CG flashes. Sprites have often been observed above MCS stratiform regions, which is consistent with the observation that +CGs frequently occur within MCS stratiform regions [e.g.,42].

Past studies have also shown that there is a large peak current difference between oceanic and land flashes with negative peak current [43–46]. A study performed by [47] looked at the global distribution of average peak current (Fig. 4 of that paper) and found that, for regions such as the Eastern United States (US) coast, West African coast, many tropical Asian island countries, etc., there is a distinct increase in peak current when transitioning from land to ocean. Oceanic convection in some of those regions initiates and develops over the ocean thanks to local convergence over warm ocean waters, which is often enhanced by the sea/land breeze circulation and/or the presence of warm ocean currents [e.g.,48]. That ocean/land contrast in the peak current data of this study is not as sharp as that of the other aforementioned coastal regions, which was also noted by Said et al. This is likely because this region's oceanic convection is dominated by long lasting MCSs or convection associated with synoptic scale cyclones from this region that form over the land and travel Eastward out into the ocean, rather than locally initiated oceanic storms, which results in smoother transition in the lightning traits shown here [49,50].

The Southern part of the Minas Gerais state of Brazil is a region which exhibits very low average CG peak current (Fig. 2). The same minimum is visible in the IC average peak current (Fig. 3), but over a larger area. This feature is located within a region of elevated terrain and may indicate that the geography plays a role in flash amplitudes here. There is no indication of exceptionally high or low flash densities (Fig. 1) in this same region, which suggests that this feature is not an artifact of some sort. This region is of further interest considering

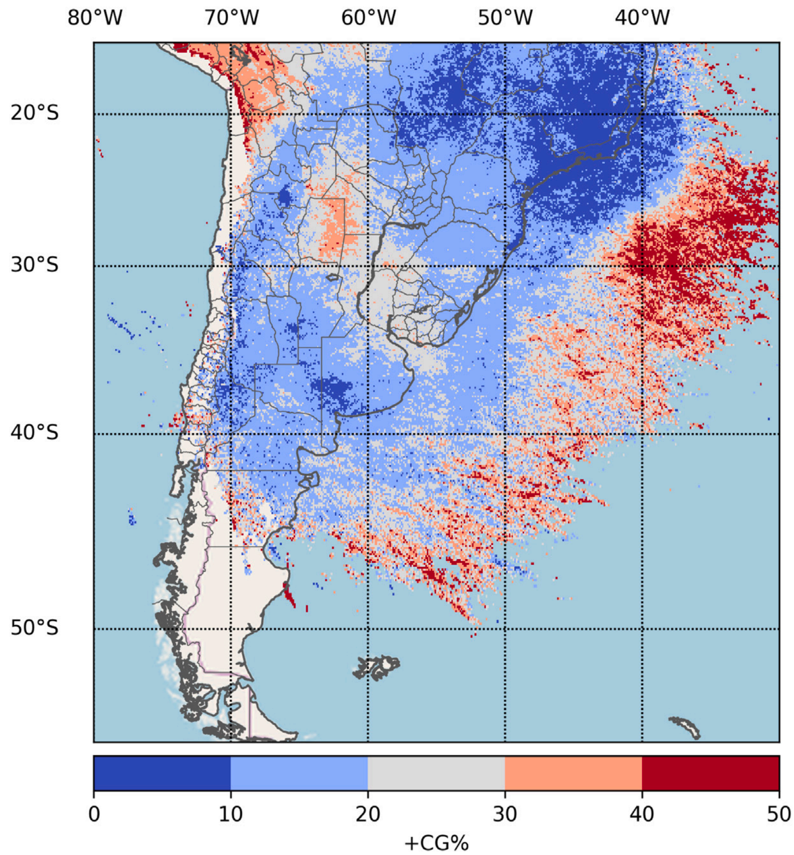

Fig. 5. CG flash percentage which are positive.

it also experiences very high IC percentage (Fig. 4), which is consistent with past studies [e.g.,51], as well as being dominated by -IC flashes (Fig. 6). The latter fact (-IC dominated) has been shown to be associated with regions which experience frequent inverted polarity thunderstorms [12]. [30] observed that the vicinity of Juiz de Fora, which is directly east of the peak current minimum noted herein, had a relatively high number of +CG flashes. They also came to the conclusion that this was due to storms there having inverted charge structures. Furthermore, this general region has been reported to have a high incidence of hailstorms [27]. The consistency of these results with the results of inverted polarity storm case studies suggest that storms in this region often have elevated cloud base height and, consequently, shallower warm cloud depth (WCD) [e.g.,28]. The combination of high elevation and probable inverted polarity structures in storms in this area suggest that the storms have relatively shallow updrafts overall before propagating to lower elevations in the vicinity of Juiz de Fora, which would also lead to shallow WCD. Shallow WCD contributes to most supercooled water residing in the 0-10^{o} range of the mixed phase region of storms, which leads to predominantly positive charging of graupel/hail [52,53] and thus inverted polarity storms.

Fig. 7 shows the minimum peak current, represented at the 5th percentile reported per grid over the entire 3-year analysis period. Over most of the continental domain, the minimum peak current is between 2–4 kA, with few regions being less than 2 kA. As expected, over the oceans the minimum peak currents increase with distance from the coast. This effect is primarily due to the network performance degrading as the distance from sensors increases, although it has been shown that -CG lightning over the ocean have higher peak currents on average than over continental regions, as discussed previously.

Notably, the region in Southern Minas Gerais reports very low minimum peak current. This indicates that the previously discussed observations of high -IC fraction there are not related to detection efficiency, since if that were the case the minimum peak currents would be higher in that region than elsewhere in the domain. This further indicates that the low average peak currents observed here are likely a real feature, and that there are some unique meteorological effects occurring in the region. In Northern Argentina and Western Paraguay, there is an increase in the minimum peak current compared with other parts of the domain, up to 4–6 kA from 2–4 kA. This coincides with elevated average CG peak current (Fig. 2) and IC peak current (Fig. 3), as well as a high +CG% (Fig. 5). There does not seem to be any indication of unusually low flash densities (Fig. 1) for this region. Therefore, this feature in the minimum peak current distribution could be related to the meteorology of northern Argentina. There appear to be some interesting features just off the southern coast of Argentina as well, where there are small pockets of very low minimum peak currents. The reason for these local minimums is currently unknown, and will be left for future investigation.

4. Summary and conclusions

In this study, we investigated the geographical distribution of three years of lightning data from the ENTLN over central and southern South America with the goal of better understanding the large scale meteorological and geographical features that produce lightning. We identified several unique features specific to these parts of South America, and corroborated those findings with past research, much of which had a more limited scope. First, we found that Argentina and Uruguay experienced the largest peaks in lightning frequency during this time, with another very localized peak occurring in Bolivia. We also observe that the land/ocean contrast in peak current evident in many regions of the world is not as sharp on the East coast of South America.

We noted higher-than-normal fractions of +CGs and -ICs in parts of southeastern Brazil and northern Argentina. These regions have

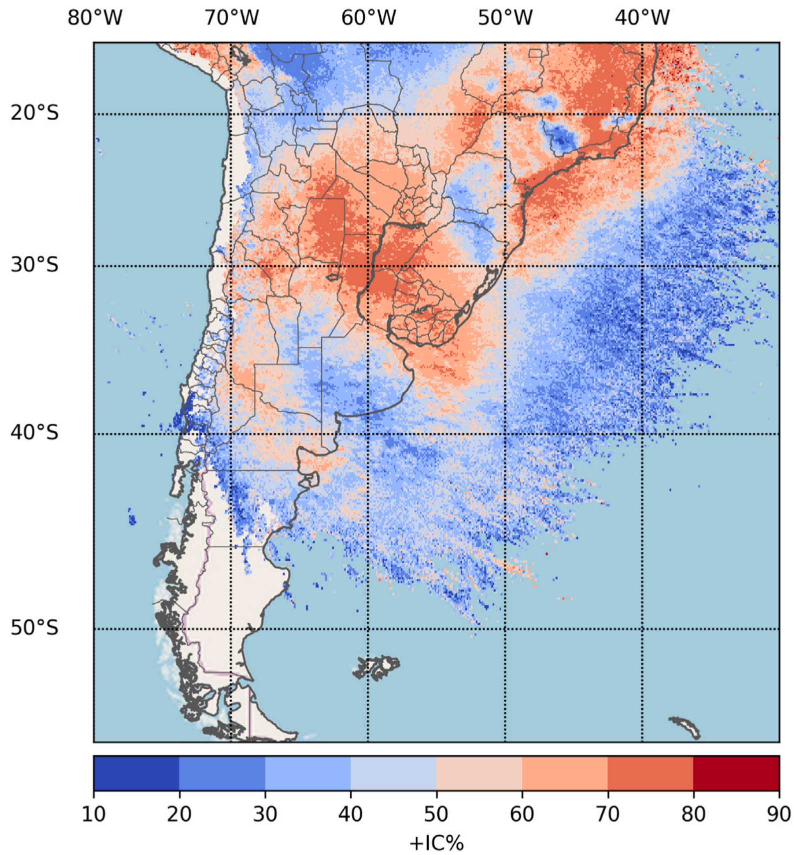

Fig. 6. IC flash percentage that are positive.

been the subject of previous studies examining MCS frequency and the frequency of inverted polarity thunderstorms: both of these types of storms produce copious +CGs, and inverted storms also tend to be characterized by predominantly -ICs. +CGs have also been noted by past studies to be correlated with sprite production, and sprites have been documented as forming above the stratiform regions of MCSs in northern Argentina. The large-scale trends in flash polarity seen in three years of ENTLN data thus support the findings of past literature, which is significant because much of that past literature is comprised of individual case studies.

One caveat to the discussion of +CG frequency that should be addressed relates to compact intracloud discharges (CIDs), also known as narrow bipolar events (NBEs). CIDs/NBEs are a highly energetic type of IC which have historically been misclassified as CGs by lightning location networks [e.g.54]. +NBEs being misclassified as +CGs could therefore be inflating the +CG frequency in this region. Although there is a wealth of existing literature emphasizing the frequent occurrences of inverted polarity storms in the La Plata Basin, future studies identifying CIDs/NBEs in this region would bring clarity to the actual +CG fraction observed here.

Finally, we examined a region in the Southern part of the Minas Gerais state of Brazil where we detect low peak current. This region is located in elevated terrain and also exhibits high IC percentage, as well as being dominated by -IC flashes compared with +IC flashes. We hypothesize that the storms with low average peak current occurring over the elevated terrain west of Juiz de Fora may have relatively shallow updrafts due to how elevated they are. Shallow updrafts separate less charge than deep updrafts, which could lead to weaker average flash peak current in shallower storms. If those storms move east over lower terrain, their updrafts have the chance to deepen, which would lead to a greater risk of severe hail and high-amplitude flashes. Shallow storms at elevation furthermore have very little WCD, which has been noted by past studies to contribute to the development of inverted polarity storm charge structures. Inverted polarity storms typically produce predominantly -ICs and +CGs. A +CG preference for this region was not observed, but the overall small CG fraction here may have muted that signal.

CRediT authorship contribution statement

Elizabeth DiGangi: Writing – original draft, Conceptualization, Investigation, Formal analysis, Supervision. **Jeff Lapierre:** Writing – review & editing, Conceptualization, Methodology, Investigation, Formal analysis, Visualization. **Michael Stock:** Writing – review & editing, Conceptualization. **Mark Hoekzema:** Writing – review & editing, Conceptualization. **Bruno Cunha:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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We would like to thank Dr. Rachel Albrecht for her helpful knowledge and insightful comments, which greatly improved the quality of this paper. Funding and data for this study were provided by Earth Networks.

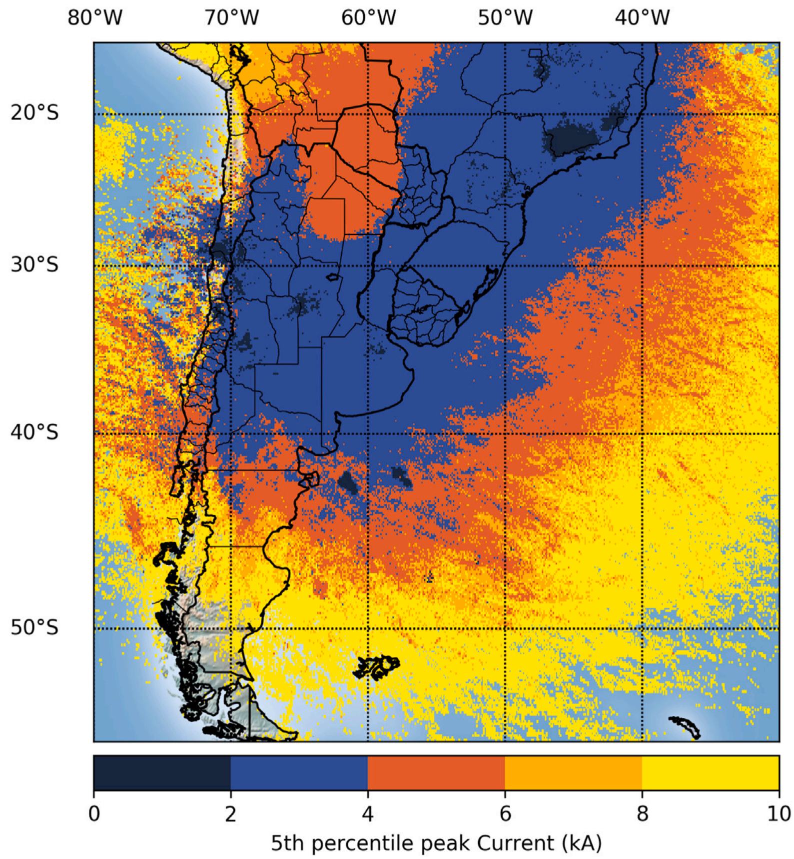

Fig. 7. Minimum detected peak current.

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