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New WMO Certified Megaflash Lightning Extremes for Flash Distance (709 km) and Duration (16.73 seconds) recorded from Space

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Key Points:

1. **Analysis using new satellite technology identifies far-larger lightning flashes (termed "megaflashes;" flashes >100 km) than previously detected.**

2. **Two megaflash events are identified from space that exceed global lightning extremes (horizontal length, duration) by a factor of two.**

3. **The new megaflash extremes: horizontal distance is 709 km on 31 October 2018 (Brazil); duration is 16.730 seconds on 4 March 2019 (Argentina).**

Plain Language Summary

Analysis of new satellite data has identified lightning extremes for horizontal distance (709 km) and greatest duration (16.730 s).

Abstract

Identification and validation of atmospheric extremes is essential to monitoring climate change, to addressing engineering and safety concerns, and to promoting technological advancement. An international World Meteorological Organization evaluation committee has critically adjudicated and recommended acceptance of two lightning megaflash events (horizontal mesoscale lightning discharges of 100s km in length) as new global extremes using analysis of Geostationary Lightning Mapper (GLM) data. The world's greatest extent for an individual lightning flash is a single flash that covered a horizontal distance of 709 ± 8 km (441 ± 5 mi) across parts of southern Brazil on 31 October 2018. The greatest duration for a single lightning flash is 16.730 ± 0.002 seconds from a flash that developed continuously over northern Argentina on 4 March 2019.

1 Introduction

Initial global extremes in lightning duration and horizontal distance were established in 2017 (Lang et al. 2017) by an international panel of atmospheric lightning scientists and engineers assembled by the WMO. This assessment used data collected by ground-based LMAs (Rison et al., 1999) to measure flash distance and duration. LMAs geolocate sources of radio-frequency emissions from lightning by comparing the precise arrival times of lightning signals at multiple stations in the network. Accurate GPS-based timing allows incremental lightning breakdowns to accurately mapped as flashes develop over time. Using this technology, the previous evaluation committee certified one flash that had a 321 km maximum great circle distance between LMA sources over the United States as the global lightning distance extreme, and a second flash that developed continuously for 7.74 s over France as the global lightning duration extreme (Lang et al. 2017). Many lightning scientists acknowledged (Lyons et al. 2020) that these official records approached the upper limit for the scale of lightning that could be observed by any existing LMA. Identifying megaflashes beyond these extremes would require a lightning mapping technology with a larger observation domain.

Space-based lightning mapping offers the ability to measure flash extent and duration over broad geospatial domains. The objective of this study is to identify and evaluate cases of extreme lightning measured from orbit that eclipse the former lightning extremes measured by the ground-based LMAs. While previous NASA instruments in low-Earth orbit only provided 90 second snapshots of lightning activity from a given thunderstorm that were insufficient for detecting megaflashes (Peterson et al., 2017), NOAA's new GLM on the next-generation Geostationary Operational Environmental Satellites (GOES-16/17) satellites continuously maps all lightning activity across North and South America (up to 54 degrees latitude) from their geosynchronous orbit. This dramatic augmentation of our space-based remote sensing capabilities has allowed the detection of previously unobserved extremes in lightning occurrence (Peterson 2019, Lyons et al. 2020) that far exceed the lightning records established with LMA measurements in Lang et al. (2017). Such events have been termed "megaflashes" and are defined as horizontal mesoscale lightning discharges that reach 100s of kilometers in length. Additional lightning imagers have been developed for current and future geosynchronous missions including China's FY-4 Lightning Mapping Imager (LMI: Yang et al., 2017) and EUMETSAT's Meteosat Third Generation (MTG) Lightning Imager (LI: Grandell et al. 2010). Together, these instruments will provide near-global coverage of total lightning (both intracloud flashes and cloud-to-ground flashes). However, the GOES-16 GLM is the only instrument that provides complete coverage of the Americas hotspots for Mesoscale Convective System (MCS) thunderstorms whose dynamics permit extraordinary megaflashes to occur – namely, the Great Plains in North America, and the La Plata basin in South America (Velasco and Fritsch, 1987). This makes the GOES-16 GLM an excellent platform for documenting extreme lightning.

2 Megaflash Lightning Events

Two flashes have been recently identified in the GOES-16 GLM record that even exceed the megaflashes reported by Lyons et al. (2020) and Peterson (2019). As part of the ongoing work of the WMO in detection and documentation of global weather extremes (e.g., El Fadli et al. 2013; Merlone et al. 2010), an international WMO evaluation committee was created to critically adjudicate these two GLM megaflash cases as new records for extreme lightning. The GLM candidate flash for the extreme lightning distance record developed over a 709 km distance across parts of Brazil on 31 October 2018 (Fig. 1). The GLM candidate flash for the duration record, meanwhile, occurred over Argentina (Fig. 1) and lasted 16.730 s.

Figure 1. Linear representations (with endpoint plotted) of the Brazil flash on 4 March 2019 with the greatest horizontal distance (709 km) and of the Argentina flash on 31 October 2018 with the longest duration (16.73 seconds) using the maximum group separation method described in the text. The starred “LMA” refers to the centroid

location of the Lightning Mapping Array near Cordoba Argentina (Lang et al., 2020); see Figure 4.

Most lightning is located in the convective cores of thunderstorms where strong updrafts are found. However, the size of lightning is limited by the scale of the thunderstorm. Even in cases of clear air bolts from the blue, the lightning channel only propagates 10s of kilometers out from the convective cell that initiated the flash. Normal convective thunderstorms are not conducive for producing megaflashes because they have limited sizes and because there is a natural opposition between flash size and flash frequency (Bruning and MacGorman, 2013). Megaflashes are generally not observed in compact active convective storm regions that are constantly flashing and depleting their charge reservoirs.

The ideal conditions for megaflash occurrence involve large electrified clouds with low flash rates that are attached to more active thunderstorm cells. The overhanging anvils and raining stratiform regions in MCSs meet both criteria. Either cloud type each only generates 6% of all lightning – the other 88% coming from convection - (Peterson and Liu, 2013), while extensive horizontal charge layers in these regions may promote lateral development (Stolzenburg et al., 1998; Coleman et al., 2003).

Both previous WMO lightning extremes from Lang et al. (2017) were cases of extensive stratiform lightning in MCSs over Oklahoma and southern France. It follows that global lightning extremes should reflect the global hotspots for MCS activity. The Oklahoma LMA flash represents one hotspot (the Great Plains region of North America), but the other key regions for the world's largest MCSs (most notably the La Plata basin in South America; Zipser et al. 2006; Avila et al, 2015; Albrecht et al. 2016, Morales 2019) lacked LMA coverage at that time – while even the current LMA coverage in these regions is incomplete.

As with all WMO evaluations of extremes (e.g., temperature, pressure, wind, etc.), the proposed lightning extremes are identified based on only those events with available quality data that are brought to the WMO's attention by the meteorological community. Environmental extremes are living measurements of what nature is capable, as well as scientific progress in being able to make such assessments. It is likely that greater extremes still exist, and that we will be able to observe them as lightning detection technology improves.

3 Analysis

The new GLM candidates are more than double the previous records from Lang et al. (2017), and the magnitude of this change was due to the availability of new space-based observations. LMAs are limited by their line-of-sight field of view. Distant sources may not be detectd by enough sensors to provide an accurate geolocation, or might not be detected at all. The typical size of LMA domains (~400 km) is on the same scale as the lightning extremes in Lang et al. (2017). For a megaflash of this scale to be resolved completely by an LMA network, it must be located directory over the center of the array. These measurement constraints significantly limit the capabilities of current LMA systems for documenting the largest lightning flashes found in nature.

Space-based instruments in geosynchronous orbit like GLM are better suited to this task than LMAs because they provide comparable lightning mapping capabilities continuously over a hemispheric-scale domain. The extents and durations of the rarest and most exceptional megaflashes can be measured, regardless of where the flash occurred on the continent. GLM is the first lightning sensor to be placed in geosynchronous orbit, but lightning detection from space has long existed (e.g., Turman 1977; Orville and Spencer 1979; Vonnegut et al. 1985; Lyons and Williams 1994; Christian et al. 2003; Mach et al. 2007; Cecil et al. 2014). GLM builds on NASA's heritage of optical lightning detectors that also includes the Optical Transient Detector (OTD: Christian et al., 2003) and Lightning Imaging Sensor (LIS: Christian et al., 2000) that were placed in Low Earth Orbit in the 1990s (and a second LIS was launched to the International Space Station in 2017: Blakeslee et al., 2014, 2020). These instruments consist of Charge-Coupled Device (CCD) high-speed (500 frames per second) pixelated imaging arrays that detect rapid changes in cloud illumination caused by lightning in a narrow spectral band around the 777.4 neutral oxygen line triplet. Individual pixels that light up in a single frame are termed detection "events." Events that fill a contiguous region on the CCD array are clustered into features called "groups" that approximate the cloud region illuminated by a single lightning pulse. Groups that occur in close proximity in both space and time are then clustered into flashes.

There are some key tradeoffs for using GLM to examine megaflashes instead of LMAs. The optical emissions that GLM measures interact with the clouds, causing the detection efficiency of the sensor to decrease for sources below thick cloud layers. In particular, GLM may miss lightning sources near the cloud base. While instruments like GLM have DEs that range from 90% at night to 70% during the day (Boccippio et al., 2002) and GLM meets its required 70% DE specification (Bateman and Mach, 2020), these statistics are dominated by flashes in ordinary thunderstorm cells. Given the extensive size and large number of bright groups observed in all megaflashes to date, we estimate megaflash detection efficiency is ~100%, though group detection efficiency is somewhat less than 100% for the reasons mentioned above. A notable feature of GLM measurements is that the flash can "go dark" during some periods – where the optical emissions appear to cease for tens of milliseconds. This does not mean that the lightning flash has stopped, however. Usually, after a dark period occurs, the flash resumes its development along the same path through the cloud. Continued activity during "dark" periods in observations from GLM-like sensors is supported by recent work with a similar pixelated lightning imager that demonstrated flashes still emit both RF signals and optical signals during such periods (Peterson and Light, 2019). The implication of the pixelated lightning imager "going dark" while the large-FOV wideband photodiode and the RF sensors both continue to record activity is that the optical signals coming from the flash are just too attenuated or spatially diluted to transmit through the cloud layer and trigger the pixelated instrument.

A second tradeoff is that the spatial and temporal accuracy of geolocated lightning sources is significantly reduced – on the order of kilometers and milliseconds for GLM compared to meters and microseconds for LMAs. GLM uses variable-pitch CCD pixels to maintain a consistent size of ~8 km over most of its field of view, only increasing to 14 km at the limb (Rudlosky et al. 2019). Like all geostationary imagers, these pixels lie on a fixed grid that is projected onto the Earth. An assumption must then be made for the height of the illuminated cloud tops that GLM is measuring. GLM currently uses a climatological tropopause height as the basis for where the optical emissions originate. Storms that are shorter or taller than this single height value will be subject to parallax that prevents spatial coincidence with other lightning observations. However, since all GLM pixels belonging to a single flash are subject to the same parallax, and both GLM flash cases are far from the edge of its FOV (where the sensitivity to parallax is greatest), the GLM parallax issue will not affect the flash size assessment. Based on the design limitations of GLM, we estimate that the spatial error in our assessment of flash size is ±8.25 km (half the group-to-flash separation threshold and approximately the size of a nominal pixel), while the uncertainty in the duration measurement is ±2 ms (the frame integration time for the instrument). We do not attempt to account for processes that might be detected by other instruments but go undetected by GLM, making our estimate a conservative one.

A third tradeoff is that the GLM instrument is subject to a considerable amount of solar contamination from both direct solar intrusion into the instrument optics and glint reflections off bodies of water or clouds on the Earth's surface. This contamination often illuminates large portions of GLM's CCD array, causing solar artifacts to masquerade as exceptional lightning flashes. Identifying extreme GLM flashes that are lightning and not glint cases requires carefully assessing each extreme flash to determine whether it is physical.

In addition to these unavoidable instrument limitations, there is also a data quality issue that prevents the identification of megaflashes in the GLM data distributed by NOAA. Because GLM is an operational instrument, stringent latency requirements are placed on the GLM ground system. To prevent latency, the ground system vendor incorporated arbitrary hard thresholds for the maximum number of events in a group, the maximum number of groups in a flash, and the maximum flash duration. Flashes that exceed these considerably low thresholds (101 events per group or groups per flash, 3 s duration) will be artificially split into multiple flashes in NOAA's GLM data product. A single distinct megaflash may consist of tens of thousands of groups that could be divided into hundreds of degraded "flash" features in the operational GLM data.

The GLM event and group data from megaflashes still exists in the operational data files though, and this means that the megaflash cases can be recovered. Peterson (2019) developed a post-processing software to repair GLM flashes and thus describe lightning at any scale and complexity. This reclustering software assesses the output of the GLM ground system software, identifies cases where the groups in multiple flashes satisfy the model used by the ground system construct flashes (Goodman et al., 2013), and then merges the split flashes back together. Applying this technique to all 2018 GLM data allowed Peterson (2019) to identify cases of GLM flashes that reached 673 km in length and 13.496 s in duration. However, this software was not equipped to repair flashes that were split between different GLM data files. Since data files are 20-s in length and megaflashes can exceed 10 s in duration, splitting between files was a key limitation for the previous study.

The GLM extreme lightning candidate flashes submitted to the current WMO evaluation committee were identified using an improved version of Peterson's (2019) reclustering software that was able to repair flashes across file boundaries and automatically remove most solar contamination (Peterson, 2020). All GOES-16 GLM data from 1/1/2018 until 1/15/2020 were reprocessed and the top flashes in terms of the maximum great circle distance between groups and the maximum time difference between groups were recorded.

The top GLM flash in terms of distance ended at 11:05:57 UTC on 10/31/2018 over southern Brazil, and is depicted in Figure 2. The central panel maps the incremental development of the flash over time (line segments) on top of a pixelated total optical energy grid (color scale). The overall extent of the flash (dashed line connecting the most distant groups) was measured to be 709±8 km across. A convex hull (solid line) is also drawn around the groups that comprise the flash. The top and right panels depict the longitude (top) and latitude (right) extent of each group, and show how the flash began in the center of the map (51 W, 28 S) and then developed simultaneously in two directions over time: one branch propagating to the northwest, and another to the southeast. The time series across the bottom of the figure shows variations in group energy (above) and group area (below) over the 11.360±0.002 s flash duration. Most groups resulted from dim (< 100 fJ) pulses that illuminated a few hundred square kilometers at a time. Though there were times during the flash when no groups were recorded, the flash continued to develop in an orderly sequence from one group to the next over its entire duration.

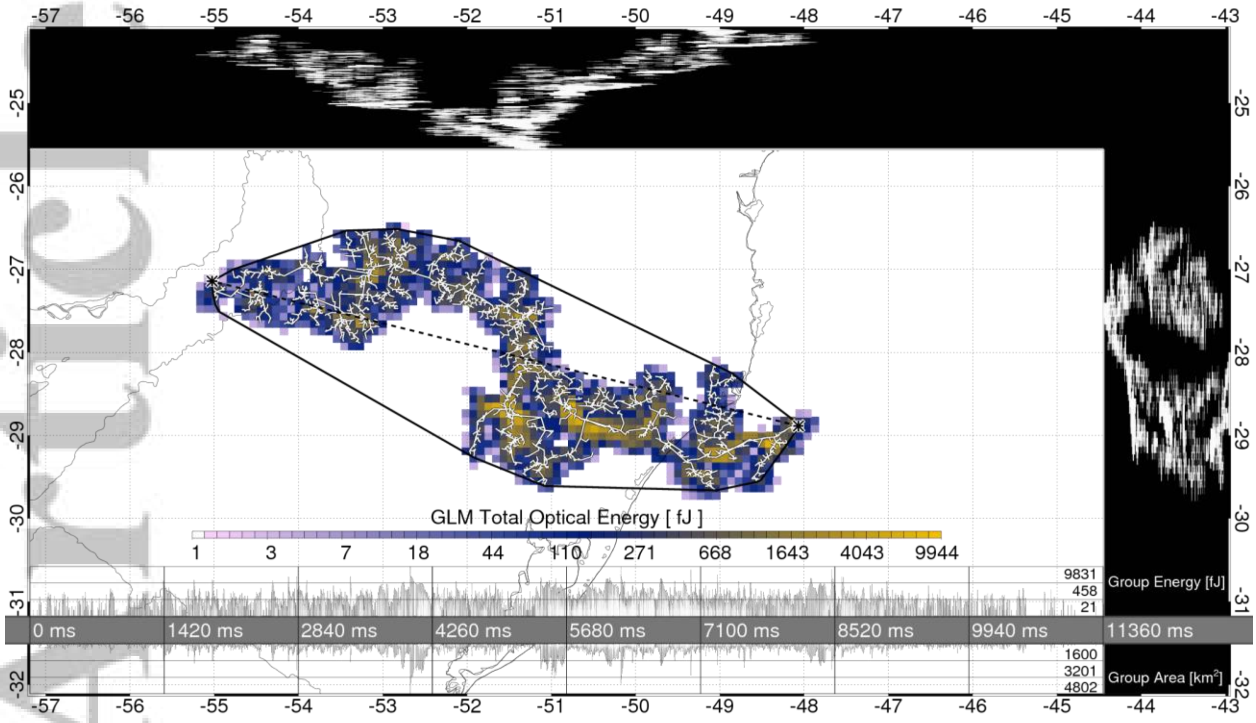

Figure 2. The evolution of the 709±8 km megaflash over southern Brazil. Incremental flash development is plotted over a total optical energy grid in the central panel. Group extents in longitude (top) and latitude (right) are shown in the outer panels as a function of time-ordered group index starting at the edge of the plan-view plot. Negative longitudes indicate degrees west while negative latitudes indicate degrees south. Timeseries of group energy (above) and group area (below) are shown aligning the bottom of the figure. The dashed line connects the most distant groups (marked with asterisks) while the solid line draws a convex hull around the groups in the flash.

The top GLM flash in terms of duration ended at 08:09:54 UTC on 3/4/2019 over northern Argentina, and is shown in Figure 3. This 16.728±0.002 s flash began along its eastern flank and then meandered westward through the stratiform region of its parent MCS, turning back towards the convective line to the north. GLM measured this flash at 473±8 km across (dashed line).

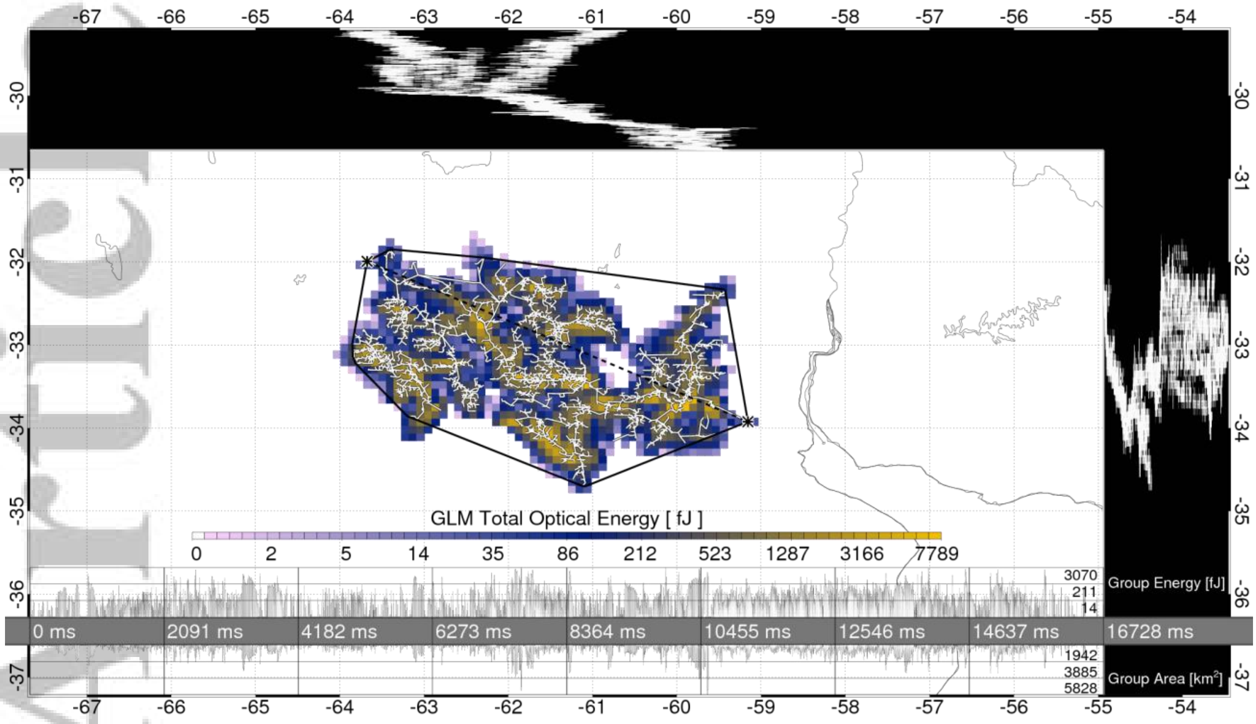

Figure 3. The evolution of the 16.728±0.002s duration megaflash over northern Argentina. Panels are identical to those shown in Figure 2.

This flash partially fell within the coverage domain of an LMA located in the viscinity of Cordoba, Argentina (Lang et al. 2020). While most of the flash occurred > 200 km from the center of the array, and thus was not mapped, the ground-based network did detect the rapid northwest propagation of the flash starting after 08:09:48 (Fig. 4). This result clearly demonstrates the value of GLM over LMAs in mapping the complete horizontal extent (and duration) of lightning flashes. GLM measurements can provide additional detail to LMA flashes that extend to the edge of the range-limited LMA domain (Peterson and Rudlosky, 2018). However, the benefit of complementary measurements is not one-directional, and this case also demonstrates how GLM can miss flash development that is resolved by the LMA. A northward extension of the LMA-mapped flash, near -63° longitude and -32° latitude, did not produce any GLM events (Fig. 4d). This occurred despite the unmapped leader processes being located near 10-km altitude, indicating that the lack of detection was not likely caused by excessive cloud optical depth (e.g., Fuchs and Rutledge 2018). Because this appendage occurred entirely within the 16.728-s duration of the GLM flash, it had no impact on this particular record. However, the knowledge that GLM may not detect every dendritic extension of a flash does pose a key limitation to using this type of space-based instrumentation to establish length and duration records. Certain flashes may have their horizontal extents and temporal durations underestimated due to this detection issue.

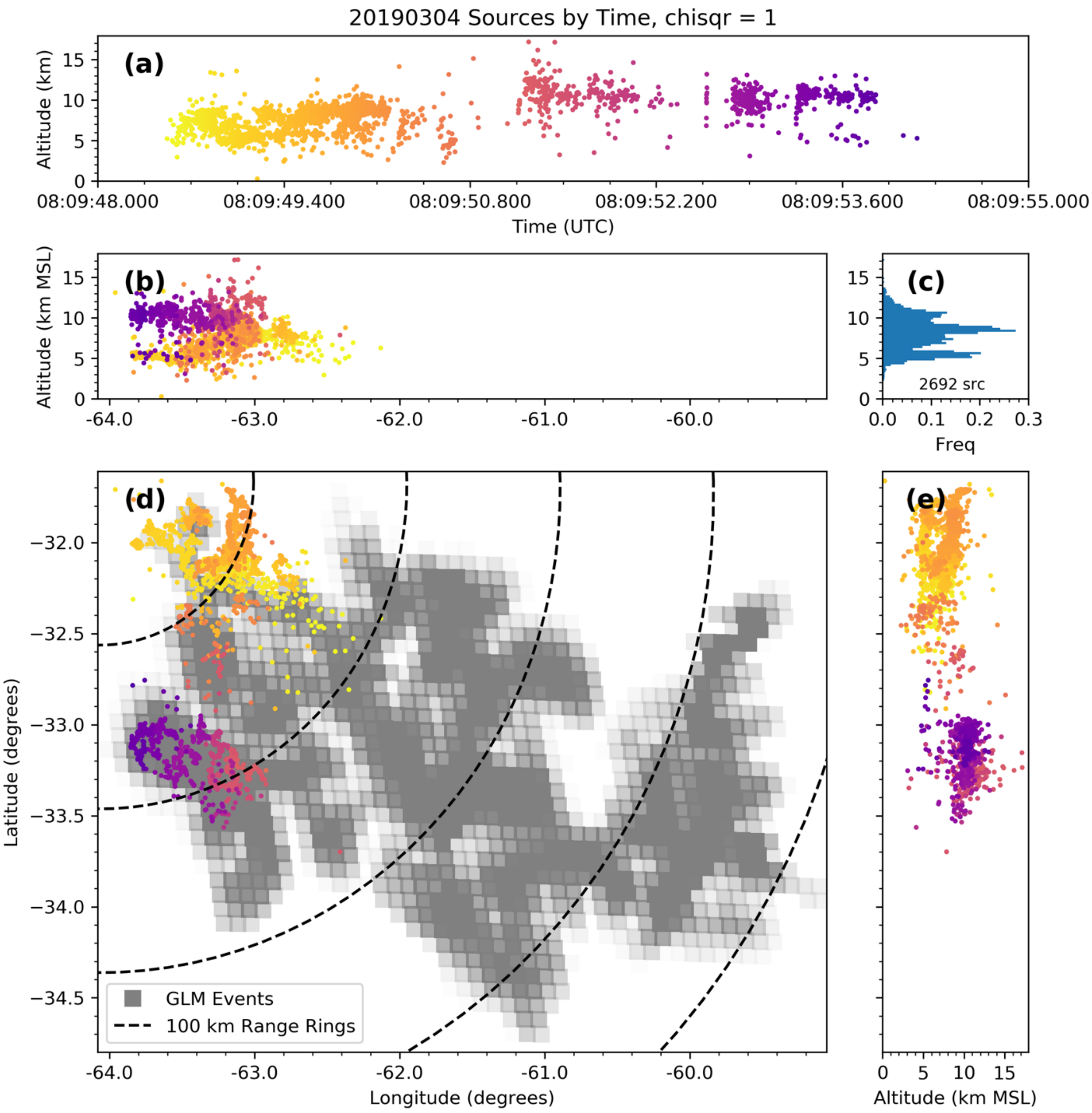

Figure 4. Argentina LMA *(16)* observations of the 4 March 2019 longest duration flash over northern Argentina. VHF sources are colored by time. (a) Time-height evolution. (b) Longitude-height. (c) Source distribution by altitude. (d) Plan view. Also shown are GLM events (gray boxes, with increasing opaqueness indicating higher event density in that pixel) for the flash and 100-km range rings from the LMA center (near 64.1° W longitude, 31.7° S). (e) Latitude-height evolution.

4 Conclusions

The evaluation of the GLM lightning extreme candidates in Figures 2 and 3 also reignited the critical discussions from the previous evaluation committee for the Lang et al. (2017) LMA flashes. Key among them were the fundamental definition of a lightning flash, and how lightning flash distance should be measured. Using LMA technology and analysis techniques, Lang et al. (2017) had modified the existing American Meteorological Society (AMS) definition of a lightning discharge as “the series of electrical processes by which charge is transferred along a discharge channel between electric charge centers of opposite sign within a thundercloud (intracloud flash), between a cloud charge center and the Earth's surface (cloud-to-ground flash or ground-to-cloud discharge), between two different clouds (intercloud or cloud-to-cloud discharge), or between a cloud charge and the air (air discharge)” thereby eliminating the portion of the old definition relating to duration (AMS, 2015: “taking place within 1 second.”)

Ideally, the committee (and the scientific community in general) would prefer a single physical definition of a lightning flash, such as (proposed by this committee) “a connected ionized channel along which currents of various magnitudes (spatial, temporal, energetic) can flow as part of a whole lightning discharge.” However, currently the data to obtain precisely such a measurement simply do not exist. GLM is only capable of resolving the horizontal development of lightning channels. The source could be located at any height within the cloud layer and when multiple channels occur at different altitudes, GLM will not be able to differentiate them. In this way, GLM provides an integrated two-dimensional view of the three-dimensional flash structure mapped by LMAs. While LMAs may be closest to accomplishing this goal of a physically-accurate lightning flash definition, LMA networks are not ubiquitous around the world, and have a finite detection range. Consequently, the evaluation committee was constrained practically to using a clearly defined metric tailored to one detection system's operation, in this case space-based GLM lightning detection.

After considering the capabilities and limitations of GLM for lightning mapping from geostationary orbit, and the evolutions and meteorological context of the cases submitted for evaluation, the committee unanimously recommended acceptance of these two GLM-identified extremes as new global records. Consequently, the longest WMO-recognized lightning flash is the single stratiform flash that covered a horizontal distance of 709 ± 8 km (440.6 ± 5 mi) across parts of southern Brazil on 31 October 2018. The greatest WMO-recognized duration for a single lightning flash is the 16.730 ± 0.002s the flash that developed continuously through the stratiform region of a storm over northern Argentina on 4 March 2019. These new records more than double the previous WMO-recognized extremes for horizontal lightning distance (from 321 km to 709 km) and duration (7.74s to 16.73s).

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The reprocessed GLM data used in this study correct the operational GLM data hosted by NOAA at their Comprehensive Large Array-data Stewardship System (CLASS), which can be accessed via the public portal at class.noaa.gov. These reprocessed data are identical to the operational GLM data, except hard limits on flash complexity employed to ensure minimal

latency have been mitigated. The process for correcting the GLM data is documented in Peterson, 2020 (DOI: 10.1029/2019JD031054) and the reprocessed data files are hosted at data.wxarch.com. . The LMA data are available at DOI http://dx.doi.org/10.5067/RELAMPAGO/LMA/DATA101.

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