Where Are the Most Extraordinary Lightning Megaflashes in the Americas?

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ABSTRACT: The Geostationary Lightning Mappers (GLMs) on NOAA's current Geostationary Operational Environmental Satellites (GOES) map the lateral development of lightning flashes across the Western Hemisphere up to 54° latitude. As staring instruments that continuously observe the Americas (*GOES-16*) and the Pacific Ocean (*GOES-17*), the GLMs resolve the spatial extent of even the rarest and most exceptional lightning flashes. *GOES-16* GLM observations that include the Americas' hotspots for the largest and longest-lasting lightning "megaflashes" are used to document where and when mesoscale lightning occurs that exceeds the largest (321 km) and longest-lasting (7.74 s) flashes that have been measured by ground-based instruments. The most exceptional GLM megaflashes in terms of extent (709 km) and duration (16.730 s) were recently recognized as global lightning extremes by the World Meteorological Organization (WMO). These world record cases beat the next-largest flash by 36 km and the next-longest-lasting flash by 1.5 s. The top GLM megaflashes between 1 January 2018 and 15 January 2020 that exceed the previous LMA records are concentrated in the central United States (most frequently along the Oklahoma–Arkansas border) and southern Brazil (Rio Grande do Sul) and Uruguay. The top North American megaflashes are most common from April through June and occur on between 4 and 14 nights per month. The top South American megaflashes are most frequent between October and January and likewise have a nocturnal preference following the diurnal cycle of mesoscale convective systems (MCSs). Potential future field programs that aim to observe extreme megaflashes should focus on these regions and seasons.

KEYWORDS: Lightning; Mesoscale systems; Satellite observations

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While the common perception of a lightning flash evokes the image of a vertical bolt striking the ground beneath a towering convective cloud, some flashes develop horizontally over greater distances than they do vertically. The altitude of lightning discharges are limited by the tropopause height (<20 km), but the lateral extent of horizontal flash development depends on the size of the charge reservoir that the flash can access. Electrified stratiform clouds adjacent to the convective cores of mesoscale convective systems (MCSs) (Carey et al. 2005; Ely et al. 2008; Krehbiel 1986; Lang et al. 2004; Marshall and Rust 1993; Marshall et al. 2009; Stolzenburg et al. 1994) provide ideal conditions for lightning flashes to develop horizontally over tens or even hundreds of kilometers (Coleman et al. 2008; Lang et al. 2017; Lyons et al. 2020; Peterson et al. 2017a,b). This behavior is sufficiently unique and recognizable that lateral flash propagation can even be used to differentiate between convective and nonconvective clouds (Peterson et al. 2020a).

These long horizontal lightning flashes have been described as “megaflashes” (Lyons et al. 2020). After considerable discussion by the AMS Scientific and Technological Activities Commission (STAC), this term was recently accepted and subsequently added to the Glossary of Meteorology (American Meteorological Society 2020). A megaflash is now defined as “a continuous mesoscale lightning flash with a horizontal path length of approximately 100 km or greater. The tremendous distances covered by megaflashes necessitate long flash durations as well—typically 5 s or greater.” While megaflashes are uncommon at 100 km, the combination of rarity and size of the top cases that extend over multiple hundreds of kilometers or last many seconds make them difficult to capture. Identifying the largest megaflashes and documenting their extent and evolution requires an instrument with continuous staring coverage over a broad geospatial domain (on the order of megameters). Lightning Mapping Arrays (LMAs; Rison et al. 1999) that use radio-frequency observations to provide precise three-dimensional maps of flash structure are not well suited to this task because they only exist in certain regions around the world and have limited line-of-sight domains. Megaflashes would have to be positioned directly over the center of the array to have their structure resolved entirely—and even with this geometry, the top megaflashes would not be mapped in full.

Optical lightning sensors on spacecraft in geosynchronous orbits have adequate spatial and temporal coverage for identifying even the largest and longest-lasting megaflashes. While lightning imager instruments have been flown by NASA in low Earth orbit since the 1990s (Mach et al. 2007), the first of these instruments placed in a geosynchronous orbit was the Geostationary Lightning Mapper (GLM; NASA 2019) on NOAA’s R-series Geostationary Operational Environmental Satellites (GOES). GOES-R (now *GOES-16*) is operational in the GOES-East position (75.2°W) while GOES-S (now *GOES-17*) was later launched to the GOES-West position (137.2°W). Between the two satellites, GLM observations extend from New Zealand in the west to the west coast of Africa in the east (Goodman et al. 2013) (see Fig. 2 in Goodman et al. 2013 for a coverage map). International partners either have (Zhang et al. 2019) or plan to (Grandell et al. 2009) launch similar instruments and, once all platforms are operational, these combined measurements will cover most regions of the world with notable thunderstorm activity.

Lightning imagers like GLM record narrowband optical lightning emissions at the 777.4-nm oxygen emission line triplet on a pixelated charge-coupled device (CCD) imaging array at a nominal frame rate of 500 frames per second (Goodman et al. 2013; Mach et al. 2007; Rudlosky et al. 2019). The instrument triggers when lightning illuminates the surrounding thundercloud, causing the radiant energy in one of its pixels (8 km at nadir, 14 km at the edge of its FOV) to suddenly increase during a 2-ms integration frame. Recording how the spatial distribution of energy from a lightning flash changes over time allows us to map the lateral development of the flash (Peterson et al. 2017a, 2018). Maps of lightning activity constructed

using optical lightning imager measurements resemble coarse two-dimensional composites of the detailed three-dimensional maps provided by an LMA. GLM maps may also be missing activity corresponding to LMA sources that occur below thick cloud layers that attenuate optical emissions (Carey et al. 2019; Clayton et al. 2019; Peterson, 2019b; Thomas et al. 2000).

Despite these limitations, GLM has recorded exceptional cases of lightning from across the Americas that are beyond the scale of any flash mapped by an LMA. Lang et al. (2017) described two LMA flashes that were previously certified by the World Meteorological Organization (WMO) as global lightning extremes. The LMA flash with the largest extent was 321 km across while the LMA flash with the longest duration lasted for 7.74 s. The *GOES-16* GLM routinely observes flashes on the same scale as these LMA records. Lyons et al. (2020) examined one case of a GLM flash that was over 500 km across, while Peterson (2019a) identified flashes that reached 673 km in extent and 13.4 s in duration. The overall top GLM megaflashes reach 709 km in horizontal extent and 16.7 s in duration. These two GLM flashes have recently been certified by the WMO as new lightning extremes (Peterson et al. 2020b). The new GLM records more than double the previous LMA-based records, and the flashes between the two sets of records represent a population of lightning flashes that has not previously been resolved. Given the interest in these large megaflashes for both public safety and physical lightning research, we aim to answer the question of where and when these largest and longest-lasting flashes in the Americas can be found.

Data and methodology

A total of 1,770 unique GLM megaflashes are identified in the *GOES-16* dataset between 1 January 2018 and 15 January 2020 that exceeded the Lang et al. (2017) LMA records. These exceptional cases represent the top 0.9% of the 194,880 megaflashes in this dataset. These GLM all megaflash and GLM top megaflash datasets have been published at Peterson (2020a). In total, 1,208 GLM flashes exceed the 321-km LMA distance record, 913 GLM flashes exceed the 7.74-s LMA duration record, and 368 GLM flashes exceed both LMA records. While oceanic lightning is more prone to lateral development than land-based lightning (Peterson et al. 2017a), only a few single megaflash cases reach this exceptional scale. We thus limit our analysis to observations from the *GOES-16* GLM, whose domain features complete coverage of the two hotspots for megaflash activity: the Great Plains in North America and the La Plata basin in South America.

The following sections detail how the GLM software delineates individual flashes, how postprocessing corrections are applied to prevent artificial megaflash splitting, how flash extent and duration are measured, and how nonlightning artifacts are removed from the sample.

Constructing GLM lightning flashes. The basic unit of GLM measurement consists of a single illuminated pixel on the CCD imaging array during one 2-ms integration frame. These “events” are not, individually, useful for describing lightning activity because they do not represent a complete and distinct physical lightning process. A single return stroke, for example, is bright enough to illuminate the entire cloud top at once—producing many events in the same frame. A flash, meanwhile, consists of multiple optical pulses over time from in-cloud processes as well as cloud-to-ground strokes (thus, producing events in many frames spread out over the flash duration).

The GLM ground system software (Goodman et al. 2010) clusters events into complex features that are intended to describe physical lightning phenomena, and are linked together through parent–child relationships. The “parents” of events are “group” features. Groups approximate individual optical pulses from a lightning flash and are defined as the set of all events during a single integration frame that fill a contiguous region on the CCD array. This approximation is not perfect, however, as it is possible that multiple optical

pulses might occur during a single 2-ms frame or that a single pulse could be split across multiple frames.

The latter case is handled by a supplemental feature level above the group called a “series” (Peterson and Rudlosky 2019). Series features stitch together groups that are part of the same lightning flash and describe a period of sustained optical emission. Series features require flash cluster data in their formulation and are not constructed as part of NOAA’s operational data product. Series features are added during the reclustering process described in the next section.

Finally, GLM “flash” features are defined as collections of groups whose child events occur in a tight space and time coincidence window. The GLM ground system uses a weighted Euclidean distance (WED) model to assess whether two groups belong to the same flash. This model is described in Goodman et al. (2010) and assessed in Mach (2020). The GLM thresholds for group-to-flash assignment are 16.5 km and 330 ms. Groups whose child events meet these thresholds are assigned to the same flash.

Repairing the operational GLM flash clusters. While GLM nominally constructs lightning flashes using the algorithm described in the previous section, the strict latency requirements imposed on GLM data processing have resulted in hard thresholds on flash complexity being coded into the operational algorithm to ensure performance. Flashes that exceed 101 groups or that reach a 3-s duration will be terminated and any further events/groups will define an entirely new and independent flash feature. These limits are purely computationally based and are not informed by lightning physics, as cases that exceed these values exist in the former NASA Lightning Imaging Sensor (LIS) flash cluster data that the GLM processing software is based on Peterson et al. (2017b).

Megaflashes are artificially split by these hard thresholds into multiple “flash” features in NOAA’s operational GLM product. Fortunately, this operational product preserves the groups and events that comprise the flashes, making it possible to repair the degraded flash clusters reported by the GLM ground system. Peterson (2019a) describes an algorithm that assesses the quality of the flash clusters in the operational GLM product and then modifies only the flashes in need of repair. This targeted approach significantly reduces the computational expense of generating complete and distinct GLM flash cluster data compared to reapplying the full GLM flash clustering algorithm in postprocessing.

However, the Peterson (2019a) algorithm was subject to one key caveat: in order to maximize parallelization, it was not designed to repair flash clusters that were split across file boundaries. This caveat became problematic when identifying candidate flash cases for the WMO lightning extreme evaluation, as GLM data packets span 20 s of observations and the top flash candidates reached durations up to 16 s. To resolve this issue, a new version of reclustering code was developed that could repair flashes that were originally stored in different data files. This algorithm has now been applied to all *GOES-16* GLM data from 1 January 2018 to 15 January 2020.

Measuring lightning flash extent and duration with GLM. The reclustered GLM lightning flash data preserve the parent–child links between feature levels. For every flash, we can identify which groups and events participated in the flash, where there they were located, and when they occurred. The extent and duration of the flash can thus be measured based on the coordinates of its constituent features. Flash duration, for example, is simply measured as the time difference between the first group in the flash and the last group in the flash.

Measuring flash size is more complicated, however, as multiple methods for doing so exist in the literature. GLM reports a “flash area” parameter that describes the total cloud-top area that is illuminated by lightning. The issue with this parameter is that radiative transfer through

the cloud scene artificially increases flash sizes. Bright optical pulses from processes such as strokes cause large areas of cloud to be illuminated at the same time. These clouds may not contribute to the discharge or even be electrified. They simply capture optical emissions from the flash and their hydrometeors scatter the photons to space where they are detected by GLM. Thus, the illuminated cloud area often exceeds the physical dimensions of the flash that would be measured by an LMA by a considerable margin. The largest illuminated areas from a single radiant process exceed 10,000 km² and most of the events are located in the lower clouds surrounding the thunderstorm core (Peterson et al. 2017b).

Another approach is to use flash extent to measure flash size. Flash extent is defined as the maximum great circle distance between the constituent features that comprise a flash. It can be computed using either the event locations or radiance-weighted group centroid positions. Measuring flash extent with group centroids is an attractive choice because group centroids are not sensitive to radiative transfer effects to the same degree as the event data. The energetic pulses illuminating complex cloud scenes may drastically increase the flash illuminated area and the maximum event separation, but the maximum group separation generally does not increase by a significant distance in these scenarios.

The primary caveat with using flash extent to approximate flash size is that megaflashes do not progress from the first group to the last in a straight line, and the meandering and branching structure of the flash is not taken into account with this approach. Flash length can be estimated from the GLM data by totaling the incremental distances measured between subsequent groups in the flash. The total incremental group separation for the 709-km top extent flash was 11,124 km while the total group separation for the 16.7-s top duration flash was 12,511 km. The total group separations are 16 and 25 times larger than the extents reported for each flash. These numbers overestimate flash length because subsequent reillumination of the lightning channel will add to the flash length estimate. Thus, flashes with longer durations and more groups (like the top duration flash with 9,593 groups) will have longer total group separation distances than flashes with fewer groups (such as the top extent flash with 7,293 groups).

More powerful processing techniques can mitigate this reillumination bias and produce more reasonable flash length estimates, but they come at a high computational cost. Peterson et al. (2018) developed one such technique that constructed a skeleton image of the group-level structure of each flash and then estimated the flash length by totaling the lengths of the unique line segments in the skeleton. This approach yielded total flash lengths that were ~3 times greater than the reported flash extent (Fig. 4a in Peterson et al. 2018). The total length for the record GLM flashes would be ~2,400 km for the top-extent flash and ~1,500 km for the top-duration flash. However, the processing time required to apply this technique to the comparably small LIS flashes demonstrated that it would not be a feasible approach for assessing GLM megaflash sizes.

In the end, we decided to use flash extent defined as the maximum great circle distance between group centroids to measure flash size in Peterson et al. (2020b). While this approach has the benefits of being computationally inexpensive and not as sensitive to radiative transfer effects as other options, the primary reason for this choice was because it most closely matches the methodology used in the Lang et al. (2017) assessment of lightning extremes. They defined flash extent as the maximum great circle distance between LMA sources—which we substitute for group centroids here. Even if the Peterson et al. (2018) flash length algorithm could be simplified to work efficiently with GLM data, the reported flash sizes would be universally larger—obscuring the difference in scale between the top flashes measured from space and from the ground.

Identifying and filtering nonlightning artifacts. Solar artifacts are a common source of false detections for GLM megaflash cases. Glint off of bodies of water as well as solar intrusion

directly into the instrument optics can cause large numbers of false events that become clustered into large-extent or long-duration flashes. To identify extraordinary megaflash cases, a collection of filters was developed to specifically differentiate between extreme lightning and episodes of solar contamination.

The first filter is a pixel-level version of the series filter described in Peterson (2020b). Whenever a GLM pixel is continuously illuminated for more than 0.5 s, any flash that produces an event in that pixel is excluded from the sample. When this occurs, then the filter is reapplied with the condition that any pixel that is part of an excluded flash is also considered to be contaminated with glint. Any flashes that occur near the contaminated pixels (i.e., within a 0.4° box) are then flagged and excluded. This process continues until the number of flashes flagged as contamination remains constant between iterations. This iterative sustained illumination filter removes all spurious detections near the peak region for solar contamination that do not quite reach the threshold level for glint.

The second filter is the frequency-domain filter described in Peterson (2020b). This filter transforms the flash optical energy time series into the frequency domain and then looks for a low-frequency peak in measured energy that is consistent with solar illumination. Natural lightning lacks such a peak, and this filter allows lightning megaflashes to be differentiated from large-scale solar illumination that makes it through the first filter.

These two automated filters reduce the number of possible GLM megaflash cases that exceed the Lang et al. (2017) records to a reasonable number for manual evaluation. The remaining cases are plotted on top of Advanced Baseline Imager (ABI; Schmit et al. 2017) infrared cloud imagery, and flashes that occur over clear-air regions or whose group-level structure is not consistent with the lateral development of natural lightning (i.e., random group positions or paths that are too linear) are discarded. Applying all of these filters yields the 1,770 GLM flashes noted previously that exceed the former LMA records.

Results

Distributions of the top GLM megaflashes across the Americas are shown in Fig. 1. Figure 1a plots the 2-yr megaflash count over the hemisphere as a flash extent density (FED; Lojou and Cummins, 2005; Bruning et al. 2019). FED accounts for the spatial extent of lightning by incrementing the flash count by one for every unique pixel that is illuminated by each GLM flash. In this way, it provides a measure of how many exceptional megaflashes an observer is expected to see at a given point on the map. There are four local maxima in the plot: one on the Oklahoma–Arkansas border, one near Omaha, Nebraska, one along the Uruguay–Brazil border, and one centered in the southern Brazilian state of the Rio Grande do Sul. However, because 2 years of data are not sufficient to mitigate the influence of individual storms with frequent megaflash activity on the localized behavior of these distortions, we focus on the large-scale hotspot regions in each continent rather than the local maxima. The central United States is referred to as the North America hotspot while the region encompassing the Uruguayan and Brazilian peaks is referred to as the South America hotspot. These top megaflash hotspot regions are also known to have some of the strongest thunderstorms on Earth (i.e., Fig. 6a in Zipser et al. 2006) and are close to hotspots for sprite-class lightning with large charge moment changes (Cummer et al. 2013; Beavis et al. 2014). The relationships between megaflashes, the dynamics of their parent thunderstorms, and related physical phenomena is an ongoing area of research that is enabled by continuous hemispheric-scale GLM observations.

All other regions within the GLM Field of View produced few, if any, exceptional megaflashes over the 2-yr period. Exceptional megaflashes over the Gulf of Mexico, off the west coast of Central America, in the Amazon, or in the Atlantic Ocean occur sporadically at a rate of $<1 \text{ yr}^{-1}$. These flashes outside of the continental hotspot regions are also at the low end of the extent and duration distributions (closer to 321 km or 7.74 s). Thus, the previous

Fig. 1. (a) Hemispheric flash extent density (FED) distribution, and histograms by (b) flash extent and (c) flash duration for the top GLM flashes that exceeded 321 km or 7.74 s.

LMA records represent the tip of the megaflash distribution outside of the North America and South America hotspots.

Histograms of top megaflash extent and duration are shown in Figs. 1b and 1c. These distributions group the megaflash cases into 10-km or 0.1-s bins and then draw one point on the vertical axis for every flash in a given bin. The precise extents and durations are additionally listed above or below their corresponding points in Figs. 1b and 1c for the top 10 flashes in each category. The top megaflashes certified by the WMO included one flash case whose extent reached 709 km between groups, and another flash that lasted for 16.73 s. The GLM flash with the second-largest extent (673 km across) was discussed in Peterson (2019a). The 36-km difference in flash extent between these two contenders is notable because the next five candidates were 667, 660, 659, and 657 km across. The difference in extent between these flashes and their next-smallest contender was smaller than a GLM pixel (nominally 8 km), which would have added uncertainty to the assessment of which flash was truly larger.

The top GLM flashes in terms of duration, meanwhile, are separated by margins that are considerably longer than the 2-ms frame integration time of GLM. The top 5 megaflash cases lasted for 16.730, 15.205, 14.708, 14.398, and 14.194 s. The GLM megaflash case certified by the WMO as the lightning duration extreme lasted for 1.5 s longer than the next contender. The previous top GLM case described in Peterson (2019a) was ranked fourth, overall, after improving the reclustering code to fix flashes that were split across file boundaries.

To better resolve the megaflash hotspots, Fig. 2 maps the FED distribution from Fig. 1a over only the North America hotspot (Fig. 2a) and South America hotspot (Fig. 2c) regions. The right side of Fig. 2 computes the number of top megaflash days accumulated over the 2-yr period in these regions. Megaflash days are defined as simply the number of unique calendar days where an exceptional megaflash was observed over a given point on the map. This definition is adapted from the concept of thunder days. The FED maps in Figs. 2a and 2c contain 638 individual megaflashes over North America from 83 megaflash days (41 in 2018, 40 in 2019, and 2 in 2020) and 1,095 megaflashes over South America from 97 megaflash days (51 in 2018,

44 in 2019, and 2 in 2020), which, together, account for 98% of all exceptional GLM megaflashes in the *GOES-16* dataset.

Peak megaflash activity is split evenly between the northern (FED maximum of 89 flashes) and southern (FED maximum of 90 flashes) hemispheres. However, the localized behavior of the FED and megaflash day distributions within the larger hotspot regions can be influenced by individual MCSs that produce frequent megaflash activity at these exceptional scales. For example, the local maximum over Omaha (Fig. 2a) comes from just 1–2 megaflash days (Fig. 2b). This pronounced peak results from the passage of just a single MCS. Observers located along the southern Oklahoma–Arkansas border have the best chance to observe an

extreme megaflash, not only because the peak in the FED distribution is located here, but also because these 89 megaflashes are spread throughout the 1 January 2018–15 January 2020 period over 8 total megaflash days. It should be noted that the thunder days at a given pixel may or may not correspond to the same thunder days at neighboring pixels. Of the two peaks in the South America megaflash distribution, the Uruguay peak is the better choice for recording exceptional megaflash cases because its 90 cases of exceptional megaflash occurred over 17 total megaflash days in the 2-yr period. The southern Brazil peak, like the Omaha peak in the Northern Hemisphere, is the result of a small number of exceptional MCSs that occurred in 2018.

Figures 1 and 2 show where the top megaflashes in the Americas occur, but when they occur is equally important. Figure 3 counts the number of top megaflash days (top row) per month, the total number of top megaflashes (middle row) per month, and the total number of top megaflashes per local hour (grouped in 2-h bins in the bottom row) during each year and in total for the North America (left column) and South America (right column) megaflash hotspots. The megaflash days depicted here correspond to the hotspot region as a whole, and thus peak at higher yearly totals than the per-pixel megaflash days shown in Fig. 2.

Exceptional megaflash activity is most common during the spring and early summer in both hotspot regions. Between the two full years in our GLM sample, top megaflashes were detected over the central United States (Fig. 3a) on 4–7 different days in April, 6–14 days in May, and 7–12 days in June. The Southern Hemisphere hotspot (Fig. 3b) similarly had around a week of megaflash days during each month from October through December. Total megaflash counts

Fig. 2. GLM top megaflash frequency in the (a),(b) North American and (c),(d) South American hotspots. The top megaflash FED from Fig. 1 is plotted in (a) and (c), while the number of unique thunder days with exceptional megaflash activity (megaflash days) is plotted in (b) and (d).

(Figs. 3c,d) were highest in May in the Northern Hemisphere and November in the Southern Hemisphere. These single months accounted for 21%–23% of all exceptional megaflashes observed throughout the year over these hotspot regions, while the March–June period contained 62% of all top megaflashes in the central U.S. hotspot and the September–December period contained 77% of all top megaflashes in the South America hotspot.

However, these fractions are subject to considerable year-to-year variability from individual MCSs that produce large numbers of exceptional megaflashes. The March peak in Fig. 3c and the November peak in Fig. 3d are both caused by exceptional MCSs in one of the two full years in the dataset (2019 for the Northern Hemisphere, and 2018 for the Southern Hemisphere). In both cases, the other year had little megaflash activity compared to even neighboring months in the same year. The Southern Hemisphere hotspot had similar numbers of megaflash days in November during 2018 (9) and 2019 (7), but the 2018 storms produced a total of 212 exceptional megaflashes compared to 19 in 2019. Different populations of MCSs can produce an average of 2 exceptional megaflashes per day (as in November 2019) or 23 exceptional megaflashes per day (as in November 2018). These particularly favorable MCSs for exceptional megaflash activity can also occur in the cold season. The December–January peaks in Fig. 3c are the result of individual MCSs in January 2020 and December 2018. More work is needed to understand how certain MCSs are able to produce these exceptional megaflashes in large numbers, while others produce few or none at all.

Fig. 3. Histograms of exceptional megaflash activity in the (a),(c),(e) North American and (b),(d),(f) South American hotspots. The number of (a),(b) top megaflash days and the top megaflash frequency by (c),(d) month and (e),(f) local hour are plotted for all years (light blue) and individually for each year.

Exceptional megaflashes are most frequent at night in both hotspot regions (Figs. 3e,f) and peak at 0300 local time in the Northern Hemisphere and 0400 local time in the Southern Hemisphere. Meanwhile, extreme megaflashes are least common at 1700 local time in North America and 1800 local time in South America. Though the minima and maxima of the top megaflash diurnal cycles agree to within an hour between hemispheres, the overall distributions differ substantially. The Northern Hemisphere hotspot has infrequent megaflash activity throughout the morning and afternoon, but there is a secondary noontime peak in the distribution. While a peak at noon might appear to suggest solar contamination, analyzing the 52 flashes that contribute to this peak (1100:00–1259:59 local time) indicated that these flashes were primarily land based (87%) and occurred in large MCSs like their nocturnal counterparts. Noontime megaflashes can even be noted in the multiday MCS event analyzed in Peterson et al. (2020c). Figure 7f in Peterson et al. (2020c) plots the group-level structure of GLM flashes at 1700 UTC (1200 CT), and a large flash can be seen extending behind the convective line in the stratiform region that developed over the previous day.

In contrast to the single-peak diurnal cycle of megaflashes in the North America hotspot, the South America diurnal cycle contains multiple peaks that are staggered in time. Since only tens of thunder days (Figs. 3a,b) are contributing to these diurnal statistics, individual MCSs could have a pronounced impact on the extreme megaflash diurnal cycles, as discussed previously. For example, 25 of the 52 noontime extreme megaflashes in the North America hotspot (48%) came from just three storms on 15 April 2018, 14 April 2019, and 19 May 2019. The staggered peaks in the South America diurnal cycle in Figs. 3e and 3f do not result from single storms, but common MCS storm tracks over the hotspot regions are expected to have a pronounced impact on the distributions.

These analyses demonstrate two important points about the top lightning megaflashes. First, while these megaflashes can occur in isolation (i.e., in the oceanic regions of Fig. 1a), most of the largest megaflashes occur in individual organized MCSs that are primed for megaflash activity and produce multiple megaflashes over time. These storms, while uncommon, are an enduring hazard for the general public with regard to stratiform cloud-to-ground strikes from megaflashes. The threat is not over after the first megaflash. Second, while megaflashes tend to occur at night, some of these MCS thunderstorms produce substantial numbers of megaflashes between 1000 and noon local time. On an instrument performance note, this shows that GLM can resolve lateral flash structure even at midday when the background scene is brightest. However, it also demonstrates that the megaflash hazard can intersect with the work day when lightning-sensitive operations are under way. Future research into MCS evolution and megaflash production will not only help to understand the physical origins of these exceptional lightning events, but it will also improve lightning safety.

Conclusions

Two years of *GOES-16* GLM measurements over the Americas from 2018 to 2020 are used to identify megaflashes that exceed the flash-extent and flash-duration records established by ground-based LMAs. In total, 1,770 exceptional GLM megaflashes were identified, including the top GLM flashes (709 km in extent and 16.73 s) that were recently certified as lightning extremes by the WMO. These top cases exceeded their next contender by 36 km and 1.5 s, respectively. This collection of extreme megaflashes is used to compile statistics that show where and when the top megaflash cases in the Americas occur.

While single isolated cases of exceptional megaflashes occur at various places across the continent, most of the top cases occur in one of two regions: the central United States, and Uruguay and the neighboring regions of Brazil and Argentina. Specific locations within these hotspots saw ~90 extreme megaflashes during the 2-yr period.

Exceptional megaflash activity occurs primarily in the spring and early summer in both hotspot regions (March–June in North America and September–December in South America), and these flashes are most frequent at night. On a regional scale, the two hotspots each produce the equivalent around a week of megaflash thunder days per month during the spring–summer period. Potential future field programs that aim to measure these exceptional flashes should focus on nocturnal operations during the spring and early summer in either eastern Oklahoma–western Arkansas or Uruguay–Rio Grande do Sul, Brazil.

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