Research Applications for the Geostationary Lightning Mapper Operational Lightning Flash Data Product

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Abstract The Lightning Cluster Filter Algorithm in the Geostationary Lightning Mapper (GLM) ground system identifies lightning flashes from the stream of event detections. It excels at clustering simple flashes but experiences anomalies with complex flashes that last longer than 3 s or contain more than 100 groups, leading to flashes being artificially split. We develop a technique that corrects these anomalies and apply it to the 2018 GLM data to document all lightning across the Americas. We produce statistics describing the characteristics and frequencies of reclustered GLM flashes and thunderstorm area features. The average GLM Americas flash rate in 2018 was 11.7 flashes per second with the greatest flash rate densities occurring over Lake Maracaibo (157 flashes per km²/year). Lloró, Chocó, Colombia had the most thunderstorm activity with 256 thunder days. The longest GLM flash spanned 673 km, the largest flash covered 114,997 km², and the longest-lasting flash had a 13.496-s duration. The first case occurred over Rio Grande do Sul in Brazil, while the other two cases occurred in the central United States. All three extreme flashes are located in the stratiform regions of Mesoscale Convective Systems. The highest flash rate for a thunderstorm area feature was 17.6 flashes per second, while the largest thunderstorm was 216,865 km² in size. Both storms occurred in South America. These initial results demonstrate the value that the development of a reprocessed GLM science product would offer and how such a product might be created at a reduced computational cost.

Plain Language Summary NOAA’s newest geostationary weather satellites (GOES-16 and GOES-17) are the first to feature lightning detectors. These sensors are known as Geostationary Lightning Mappers (GLMs) and use the flash of light illuminating the cloud during a lightning discharge to detect it and determine where it occurred. GLM uses specialized algorithms to identify individual lightning flashes. These algorithms only have 5 s to find all of the flashes that occurred across North and South America and can easily get bogged down by the tremendous amount of GLM data coming down from the satellite. To overcome this, the algorithms quit when flashes become too complex, and this results in single natural lightning flashes being artificially split into multiple degraded flashes. We develop a technique for fixing this splitting problem and apply it to all of the 2018 GLM data. This new data set allows us to examine all types of lightning, not just simple flashes. We use this corrected data to show how often lightning and thunderstorms occur, to document what flashes look like, and to identify extreme examples of lightning across the Americas.

1. Introduction

Between 2016 and 2017 the National Oceanic Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA) launched, calibrated and validated, and operationalized the first of the current R-series of NOAA Geostationary Operational Environmental Satellites (GOES) as GOES-16 in the GOES-east position (75.2°W). GOES-16 is the first geostationary satellite and the first NOAA operational satellite to feature an optical lightning detector (Rudlosky et al., 2018). The Geostationary Lightning Mapper (GLM; Goodman et al., 2013) on GOES-16 builds on the quarter-century NASA heritage of space-based lightning detection and physical research to improve environmental awareness across the Americas.

Like the previous Optical Transient Detector (OTD; Boccippio et al., 2000) and Lightning Imaging Sensors (LIS; Christian et al., 2000; Blakeslee et al., 2014; Albrecht et al., 2016) operated by NASA, GLM detects lightning by looking for transient optical pulses at the 777.4-nm neutral oxygen emission line triplet that are characteristic of lightning (Boccippio et al., 2002; NOAA-NASA, 2019). Optical pulses from across GLM’s western...
hemisphere field of view (FOV) are recorded on its 1,372 × 1,300 pixel Charge-Coupled Device (CCD) array at 500 frames per second. The GLM CCD array has a unique pixel geometry that permits a consistent resolution of ~8 km across most of its FOV that only increases to 14 km by its edge (Goodman et al., 2013). Whenever the incident GLM pixel radiance exceeds the dynamic background average radiance by a configured threshold, the pixel is registered as an event. Events are the elementary data product of GLM and represent a cloud top pixel illuminated by lightning during a single 2-ms frame.

GLM transmits coherent events—or events that do not occur in isolation—to ground for further processing by the GLM Lightning Cluster Filter Algorithm (LCFA; Goodman et al., 2010; NOAA, 2018). The purpose of the LCFA is to analyze the event data stream and determine which events comprise the same optical pulse (termed group) and which groups are likely to describe the evolution of an individual lightning flash. Events are clustered into groups and groups into flashes according to their distributions in space and time. The reported group and flash locations are weighted by optical radiance. Flash clustering is important because events are not physical features representing complete lightning processes. Instead, events are sensor-defined features that depend on the alignment of the GLM fixed grid, the footprint size of the triggered pixel, and the configured threshold settings of the instrument. For example, when GLM (8 × 8-km pixels at nadir) and the LIS (5 × 5-km pixels at nadir) on the International Space Station (Blakeslee et al., 2014) simultaneously trigger during the same flash, GLM often detects more events describing a larger illuminated cloud top area because it has a higher sensitivity than LIS to low-energy cloud pulses.

The key value of the flash cluster data from OTD, LIS, or GLM is that it describes distinct and complete lightning phenomena that are necessary for evaluating the lightning hazard (Peterson et al., 2017), identifying the optical signatures of underlying physical processes and documenting the meteorological origins (Peterson et al., 2017b; Peterson & Liu, 2011) and Earth system consequences of lightning. Flash cluster data have been used to compute the total amount of lightning over specific geographical locations (Albrecht et al., 2016), within active thunderstorm areas (Zipser et al., 2006), and across the globe (Cecil et al., 2014; Christian et al., 2003). Flash cluster data provide a framework for characterizing lightning (Peterson & Liu, 2013) and comparing the evolutions (Peterson & Rudlosky, 2019), energetics, and structures (Peterson et al., 2018) of different flashes. The parent-child relationships built into the flash cluster data are also useful for identifying flashes with complex branching or signatures of interesting processes such as strokes (Koshak, 2010), continuing currents (Bitzer, 2017), K-process waves (Winn et al., 2011), and gigantic jets (Boggs et al., 2019).

Lightning has recently been recognized as an essential climate variable (Aich et al., 2018) because it is a convective indicator that can be remotely measured (Deierling et al., 2008; Williams, 2005). One of the ways that lightning is related to climate is through the Global Electric Circuit (GEC; Williams, 2009; Peterson et al., 2017c) wherein electrified weather around the world drives a series of electrical connections in the Earth-atmosphere system. The GEC enables global changes in electrified weather to be monitored through electric field measurements taken at single ground stations on fair weather days (Burns et al., 2017), airborne measurements of the ionospheric potential (Markson, 2007), or total lightning activity (Mach et al., 2011; Whipple, 1929; Williams, 1992). Single-instrument measurements only describe the load on the GEC, not where the sources are located. Such measurements must be related to the convective state of electrified weather through global satellite measurements (Peterson et al., 2015; Peterson et al., 2018b, 2018c). However, total lightning flash rate measurements made by lightning mapping systems like GLM can directly quantify relative GEC contributions from individual storms within their FOVs.

Even GLM products that are designed to rely only on the event data can benefit from the flash cluster data. GLM detects optical transients that resemble lightning, regardless of their origin. Solar intrusion into the sensor optics, reflections off of clouds and bodies of water, and fireballs from bolides burning up in the Earth’s atmosphere (Rumpf et al., 2019) can all be detected by GLM. These nonlightning artifacts often produce hundreds to thousands of events when they occur, but they usually describe sustained periods of optical emission on typical lightning time scales that would be clustered into single flashes. If artifact signatures can be reliably identified, then these flashes can be removed along with their constituent groups and events to improve the operational GLM products.

However, the high event rates during these nonlightning artifact flashes also expose a key caveat with the GLM flash cluster data: The minimal latency requirement imposed on the GLM LCFA. The LCFA has
only 5 s to process 5 s of real-time data. Between GLM’s hemispheric coverage and relatively high sensitivity, the data volume that the LCFA must process in this 5-s window vastly exceeds the legacy NASA lightning imagers in Low Earth Orbit. The LCFA is designed to scale back processing and terminate flashes early to prevent excessive latency (Goodman et al., 2010). This results in degraded flash cluster data that no longer represents the distinct and complete lightning phenomena that the LCFA was intended to capture. Clustering issues then propagate downstream where degraded flash clusters cause GLM applications to not work as expected or to produce misleading results.

The purpose of this study is to demonstrate GLM’s capabilities as a lightning mapper and evaluate GLM flash cluster data for scientific applications using the first full calendar year of public data (2018). To do this, we must evaluate the performance of the operational GLM LCFA, identify ground system processing anomalies, and then mitigate flash cluster degradation to recover the flash clusters that would have been produced nominally by the LCFA. Rather than rebuilding the cluster data from the event stream, we assess each GLM LCFA flash to identify features that should belong in the same flash cluster and then combine the groups from artificially split flashes into a single composite flash. The resulting reclustered flash data is a postprocessed data set that emphasizes cluster integrity over data latency and computational expense. This new data set differs from the operational GLM LCFA data set in three key areas:

1. We add two additional cluster feature types—the missing area features from LIS and OTD that approximate thunderstorm snapshots and series features that describe periods of sustained optical emission within the same flash.
2. We do not impose any hard limits on flash cluster composition, not even the 2,000 maximum groups per flash from LIS (Mach 2019, personal communication).
3. We do not terminate flash cluster processing early to reduce processing time. Instead, we take advantage of parallelized computing to limit the overall time required.

We use this new flash cluster data set to present cases and statistics that demonstrate GLM’s capabilities for documenting the lightning hazard and evaluating the evolution and structure of complex lightning flashes—including the most extreme lightning in the Americas.

2. Data and Methodology

2.1. Lightning Cluster Feature Definitions

The flash clustering technique employed by the GLM LCFA as described in its Algorithm Theoretical Basis Document (ATBD; Goodman et al., 2010) is largely identical to the LIS flash clustering algorithm (Christian et al., 2000), but with spatial thresholds adopted from the OTD flash clustering algorithm (Mach et al., 2007) to account for the larger footprint sizes of GLM pixels (8–14 km compared to 5 km for LIS). The consistency between the GLM LCFA and the clustering algorithms from the legacy NASA lightning imagers allows GLM to directly benefit from NASA’s heritage of space-based lightning detection, as these algorithms are well documented (Christian et al., 2000; Mach et al., 2007) and their on-orbit performance has been extensively studied (Boccippio et al., 2002; Buechler et al., 2012; Mach et al., 2007; Zhang et al., 2019).

The GLM LCFA and NASA legacy flash clustering algorithms take georeferenced event data in sensor units (referred to henceforth as GLM Level-1b or L1b data) and construct multiple types of features that describe lightning activity over a range of time and spatial scales (designated GLM level-2 or L2 data). Between the NASA/NOAA clustering algorithms and community efforts, four types of optical lightning features have been defined above the event level that will be considered in this study: groups, series, flashes, and areas. These feature types are related to one another through simple parent-child relationships. This cluster hierarchy fills out a top-down tree data structure where a single parent may have multiple children but a child cannot have multiple parents. The definitions of each feature and where it falls on the tree are discussed below and also summarized for quick reference in Table 1.

The basic cluster feature produced by the LCFA is the group. Groups are defined as collections of events in the same 2-ms frame that fill a contiguous region on the CCD array. Events in the same group light up pixels that share either a side or a corner with one another. While events are considered the basic unit of GLM data (Goodman et al., 2013), groups are the basic unit of GLM data that is relevant to lightning science. Groups are the parents of events and capture the optical signals from one or more physical lightning processes—for
example, strokes or cloud pulses—within a single 2-ms frame. The optical signals generated during these processes are modified by the cloud layer between the source and the satellite through scattering and absorption (Koshak et al., 1994; Light et al., 2001; Thomas et al., 2000; Thomson & Krider, 1982). Scattering permits point emissions sources with sufficient optical energy to illuminate entire cloud tops and produce dozens of events in the same frame that would still be described as a single group. The largest group recorded by LIS covered more than 10,000 km$^2$ of illuminated cloud top area (Figure 1 in Peterson & Liu, 2013) due to reflections off lower cloud decks surrounding the convective cell that produced the flash. However, because the horizontal distribution of radiant energy falls off quickly with distance from the emitter (Light et al., 2001) and the group location is defined as the radiance-weighted centroid of all constituent events, the irregular footprint of this particularly radiant group had no effect on the horizontal separation of groups in the flash (Peterson & Liu, 2013).

As groups are limited to a single 2-ms frame, they are insufficient for describing lightning phenomena that radiate optical energy over a sustained period. This was recognized by Bitzer (2017) who identified groups in at least five consecutive LIS frames as possible continuing currents. Peterson, Rudlosky, and Deierling (2017) introduced a new formal LIS cluster feature to describe sustained periods of optical emission that we termed series. For both LIS and GLM, series features are injected into the clustering hierarchy as the parents of groups and the children of series. Every parameter describing flashes in the LIS science data set is also computed for the new series features. Series statistics for the LIS on the Tropical Rainfall Measuring Mission satellite are presented in Peterson and Rudlosky (2019). In addition to the continuing current cases suggested by Bitzer (2017), series have proven valuable for capturing leader activity and recoil processes, as well as gigantic jets (Boggs et al., 2019). Optical signatures of these processes are difficult to identify in the flash-level GLM data because there are other radiant processes that contribute to the flash. The GLM flashes presented in Boggs et al. (2019), for example, contain normal temporally isolated cloud pulses preceding the gigantic jets. Series features capture the light curves (plots of received radiance over time) from distinct periods of sustained emission, and their characteristics may be used to infer the originating process.

However, some optical signals—for example, from leader and recoil processes—are sufficiently weak that they are typically recorded by LIS near its threshold for detection. This results in series being split by single empty frames where the radiance momentarily falls below this threshold. An example of such series splitting can be found in Figure 1 of Peterson, Rudlosky, and Deierling (2017). To mitigate this effect, we generally define series as periods of near-continuous optical emission within the same flash feature where groups are separated in time by no more than one empty frame.

Events, groups, and series all describe the evolution and structure of individual lightning flashes. There has been some variation on the definition of a lightning flash in space-based lightning imager data sets since the early days of OTD. However, all variants consider groups that fall within 330 ms and 5.5 km—16.5 km of

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### Table 1

**Summary of GLM Lightning Cluster Feature Definitions**

| Feature definition | In GLM L2-LCFA? |
|--------------------|-----------------|
| Area               | NO              |
| $\downarrow$ Flash | YES             |
| $\downarrow$ Series| NO              |
| $\downarrow$ Group | YES             |
| $\downarrow$ Event | YES             |

*To satisfy the Weighted Euclidian Distance (WED) model and be clustered into the same feature, candidate cluster features must fall within the surface defined as

$$WED^2 = \left( \frac{X}{dX} \right)^2 + \left( \frac{Y}{dY} \right)^2 + \left( \frac{T}{dT} \right)^2$$
each other to be a single flash. Differences in the flash definition between LIS and OTD are discussed in Mach et al. (2007), while the particularities of the GLM flash clustering algorithm are described in the LCFA ATBD (Goodman et al., 2010). A first-order simplification of how LIS and GLM cluster groups into flashes is that a Weighted Euclidian Distance (WED) model determines whether nearby groups in geolocated space (longitude and latitude) and time conform to the specified thresholds and then assigns groups that meet the thresholds to the same flash. The key differences between the GLM and LIS clustering algorithms are the distance thresholds used (4.5 km for LIS and 16.5 km for GLM) and how they handle cases where a new group could belong to multiple existing flash clusters. LIS would nominally assign any new groups that could belong to either flash to the first flash observed in time (first fit), while GLM merges the flashes together into a single new flash cluster (full fit; Mach 2019, personal communication).

The final lightning cluster feature describes lightning-producing areas of interest that approximate thunderstorms in a given 15-min window. These features are known as areas and are created by applying the same clustering technique used for flashes to the georeferenced flash data—but with relaxed space and time thresholds. LIS and OTD define areas as clusters of flashes whose centroids fall within 16.5 km from one another during the same orbit (Mach et al., 2007). Because both sensors were on Low Earth Orbit satellites, area features effectively have a maximum duration between 1 and 3 min. We define areas using a 15-min time threshold for consistency with the full disk update cycle of the Advanced Baseline Imager (ABI; Schmit et al., 2005) on GOES-16 during the 2018 period examined in this study.

2.2. The Operational GLM Level 2 LCFA Data Set

The first public GOES-16 GLM data have been released from December 2017 (Rudlosky et al., 2018) and are continuously transmitted over NOAA’s GOES Ground Rebroadcast feed and archived at NOAA’s Comprehensive Large Array-data Stewardship System. We choose to focus on the first full calendar year of public GLM data that includes all observations made during 2018. This year-long record spans three versions of the GLM ground system software (DO 06.02 released 11/28/2017, DO 06.03 released 6/19/2018, and DO 07.00 released 10/15/2018) and four patches (PR 06.02.05 released 1/10/2018, PR 07.01.00 released 10/29/2018, PR 07.02.00 released 11/05/18, and PR 07.03.00 released 11/15/1028). These updates adjusted the GLM Level 1b filters, removed so-called radiation dots that manifest as single-group flashes, fixed metadata issues and ground system software crashes, and resolved the issue of orphaned events and childless groups. The DO 07.00 update released on 10/15 and the subsequent patch PR 07.01.00 released on 10/29 were the most substantial software changes in 2018 for end user applications. The DO 07.00 update changed how event times are reported in the Level 2 product, migrating from 2 ms frames to precise floating-point time stamps. The PR 07.01.00 patch, meanwhile, changed the ellipse used in GLM event navigation to reduce parallax near the edge of the instrument FOV (Rudlosky & Armstrong, 2019).

We have been screening for radiation dots and orphaned/childless cluster features before these features were implemented in the ground system software. Since there have been no other reported changes affecting how events are clustered into groups and groups into flashes, we do not expect these software updates to directly affect our reclustered data. However, changes to the Level 1b event filtering will have an impact on what is clustered originally by the ground system. We can only repair flashes whose groups and events make it to Level 2. If the operational clustering algorithm is unaware of detected events, then we have no way of...
restoring the data. A key example is the GLM coherency filter. Because single-event detections are often noise or particle impacts on the CCD array, the first event in a GLM flash is registered but not preserved. If no further events occur, then no further action is required by the GLM software. If a second event triggers, then this second event and all subsequent events are pushed to Level 2 processing. There is no putback filter with GLM like there was with LIS, so the first event detection from every GLM flash cannot be recovered.

Operational Level 2 GLM data are distributed in packets that represent 20 s of observations. All 2018 data packets include six parameters describing GLM events, six parameters describing GLM groups, and six parameters describing GLM flashes. These parameters specify the space/time coordinates of the clusters, report cluster characteristics, document the clustering parent-child relationships, and alert flash or group cluster quality issues. Newer data files after the October GLM software update (DO 07.00.00) contain additional parameters that we do not consider because they are unavailable over the full year. Copious metadata is also provided in the GLM data packets that describe the state of the instrument, the GOES-16 platform, and the operational real-time data processing.

GLM data packets are constructed to minimize file size and thus enable broad transmission of GLM observations. This is accomplished by converting floating point numbers into short integers with scale factors and offsets that adhere to the NetCDF Climate and Forecast (CF) convention. As a result, floating point parameters that are subject to this conversion—such as flash total energy and the footprint area of the cloud top illuminated by the flash—are quantized with only a fixed number of possible values. The implementation of this conversion on the 2018 GLM data also has an unexpected behavior where integers declared as unsigned can still take on negative values in certain versions of the NetCDF software. This results in an underflow condition that must be detected and corrected by the end user.

In total, the GLM ground system produced 1,567,322 LCFA Level 2 packets with lightning data in 2018 accounting for 362.8 days of observations or 99.4% of the total duration of the year. Figure 1 counts the number of GLM Level 2 data packets each day that are missing, devoid of lightning data, or nominal otherwise. Nominal data accounts for all but a few minutes of most days in 2018. Missing or degraded data accounts for less than 1 hr on all but 12 days. The worst outage was on 6 January, when 6 hr of GLM data are missing.

2.3. Degraded Flash Cluster Data in the L2-LCFA Data Set

The operational LCFA Level 2 product assigns quality flags (QF) to groups and flashes that alert of clustering anomalies. These anomalous states describe scenarios where the flash cluster data produced by the ground system can be considered degraded and not representing the physically isolated and complete flash clusters intended by the clustering algorithm described in the LCFA ATBD.

Conditions that trigger the various group and flash QFs are summarized in Table 2. The flash and group QFs can take on one of four possible values that are largely consistent for both types of features. A flag set to 0 indicates nominal cluster data. The flash or group in question is sufficiently simple that the ground system can process it normally following the clustering algorithm in the ATBD. The 99.7% of all groups and 96.3% of all flashes have nominal QFs. A QF of 1 alerts that the event data stream is not in the correct time order and may be invalid. The group QF also uses a value of 1 to alert that the parent flash has a nonzero QF set. Since 0.2% of groups have a QF of 1 compared to $6 \times 10^{-5}%$ of all flashes, the flash QF component of the group QF does the heavy lifting for this anomalous state.

QFs set to 3 or 5 indicate that the constituent event data violate hard thresholds in the ground system software for the maximum number of events per feature or the maximum feature duration. These thresholds prevent latency and ensure stable LCFA performance. They are typically invoked only in the cases of complex flashes and high flash rate thunderstorms that we are interested in here. A flag of 3 alerts that the flash or group is degraded because it contains too many child features, while a flag of 5 alerts that the feature is degraded for having a duration that is too long. Though the metadata in the GLM data packets clearly state that a QF value of 3 is triggered by an event count, analysis of the operational LCFA data from 2018 indicates that the group count is actually what triggers flash degradation. For example, Table 3 shows the maximum durations and child feature counts of nominal flashes and groups on the first and last days of 2018. These dates were chosen to account for any changes to the ground processing throughout the year. Examining every nominal flash on these 2 days reveals hard cutoffs at 2,998 ms and 101 groups. No flash...
with a longer duration or that contains more groups is clustered nominally. However, the maximum number of events per flash does not appear to be bounded by a similar threshold. If such a threshold exists, it exceeds 20,000 events per flash and given the LCFA group count threshold is not likely to be reached by natural lightning. The maximum number of events per group threshold also does not appear to be enforced as described in the product metadata. While nominal groups can contain upward of 500 events, groups with as few as 135 constituent events can be flagged as degraded for containing too many events.

We will focus on the flash duration and child count thresholds because they will affect the apparent evolution and structure of the resulting flash cluster. The GLM thresholds at 100 groups per flash and 3 s are both considerably smaller than the legacy LIS thresholds due to its larger CCD array (1,372 × 1,300 pixels instead of 128 × 128 pixels). LIS could cluster up to 2,000 groups into a single flash lasting up to 30 s. That is a tenfold decrease in maximum resolvable flash complexity from the LIS instrument to GLM. Clustering anomalies that result from these lower LCFA thresholds will cause complex GLM L2-LCFA flashes to appear fundamentally different than LIS flashes.

We demonstrate the impact that GLM clustering anomalies have on the extent of the lightning hazard and the parent thunderstorm flash rate by examining the case of a horizontally expansive GLM spider flash with nonnominal flash QFs set. The evolution of the flash as it propagates deep into the trailing stratiform region of a South American Mesoscale Convective System (MCS) is plotted in Figure 2. The central panel depicts the plan view of the flash and shows the overall illuminated cloud footprint brightening the background ABI 11.2-μm infrared cloud top imagery. The lateral development of the flash is traced by drawing line segments between each group centroid and the centroid of the nearest preceding group in the flash. The latitude and longitude extents of each group are plotted in the top and right panels, while a time series of group area and energy is plotted along the bottom of the figure. All group plots share the same gray scale color scheme that is indexed by group number with older groups shaded darker and later groups shaded lighter.

A strict implementation of the flash clustering algorithm described in the LCFA ATBD to the 2,916 groups and 21,307 events during the 8.8 s window shown in Figure 2 produces a single flash cluster that begins at the rear of the MCS convective core (top of figure) and then propagates 262 km southward into the stratiform region. At no point during this 8.8-s window are the groups separated by a sufficient distance or time to spawn a new flash according to the WED model described in the ATBD.

The group count and duration for this case far exceed the LCFA thresholds. This results in the ground system dividing the single flash into 33 distinct operational L2-LCFA flash clusters. These 33 flashes are counted in the plan view of Figure 2 with the indices of the split flash clusters plotted at their centroid locations. Colored numbers correspond to flashes with degraded QFs, while black numbers designate flashes with nominal QFs set. The LCFA processes the stream of the event data until the sheer

### Table 2

**Explanation of GLM L2-LCFA Quality Flags (QFs)**

| QF code | QF definition                                                                 | QF frequency |
|---------|-----------------------------------------------------------------------------|--------------|
| Group   |                                                                            |              |
| 0       | Nominal group cluster                                                       | 99.775%      |
| 1       | Degraded due to events out of time order OR degraded flash quality          | 0.215%       |
| 3       | Degraded due to event count exceeding threshold                             | 0.009%       |
| 5       | Degraded due to group duration exceeding threshold                          | 0%           |
| Flash   |                                                                            |              |
| 0       | Nominal flash cluster                                                       | 96.356%      |
| 1       | Degraded due to flash constituent events out of time order                  | 0.000006%    |
| 3       | Degraded due to flash cluster count exceeding threshold                     | 3.544%       |
| 5       | Degraded due to flash duration exceeding threshold                          | 0.099%       |

Note. 99.7% of groups and 96% of flashes were clustered nominally during 2018.

### Table 3

**Operational Assessment of GLM L2-LCFA QF Thresholds on First and Final Days of 2018**

|                         | 1 January 2018 | 31 December 2018 |
|-------------------------|----------------|------------------|
| Nominal flashes (QC = 0) | 2,998          | 2,998            |
| Max. duration (ms)      | 100            | 101              |
| Max. groupsflash        | 20,358         | 19,726           |
| Nominal groups (QC = 0) | 461            | 550              |
| Max. events/group       | 142            | 135              |

Note. The LCFA degrades flashes when they exceed 100 groups or 3 s in duration.
number of groups pushes it into an anomalous clustering state. At this point, a new flash is defined that is entirely separate from the constituent groups and events in the previous flashes. Because of this, flashes that begin with a clustering anomaly can still terminate nominally if their final group counts and durations fall within the LCFA thresholds. We note five nominal flashes in this case that all coincide with the final development of distinct branches in the group-level flash structure.

The designation of L2-LCFA flash clusters as either nominal or degraded obscures this behavior to the end user of GLM data and may lead them to draw incorrect conclusions about the lightning hazard. The L2-LCFA QFs are typically used as a means for identifying and mitigating artifacts. It is a common practice to ignore all nonnominal GLM flashes. This approach eliminates most glint and solar intrusion artifacts because they radiate over broad regions of the GLM CCD array for multiple seconds and would either be caught by the maximum group threshold or the maximum duration threshold. It also limits the effect of cluster splitting on the thunderstorm flash rate. In Figure 2, the total flash count would be reduced from 33 to 5, which is closer to the true value of 1.

However, ignoring nonnominal flashes does not address the underlying problems with the flash clusters produced by the LCFA during cases of complex lightning. It arrives at reasonable flash rates by throwing away a substantial amount of valid observations (28 of 33 flashes containing 2,817 of 2,916 groups and 20,998 of 21,307 events) that were only artificially split by the ground system. With the anomalous flashes ignored, the case in Figure 2 would no longer propagate from the convective core into the stratiform region. The extent of the lightning hazard would be reduced to only a few isolated locations deep in the trailing stratiform region of the MCS, which would give the appearance of stratiform lightning generated by in situ processes rather than from a convective origin.

### 2.4. The Postprocessed GLM Level 2 LCFA Reclustered Data Set

The clustering anomalies described in section 2.3 impact the completeness but not the validity of the operational L2-LCFA flash cluster data. The key difference between the real-time operational L2-LCFA data and our strict application of the clustering algorithm described in the LCFA ATBD for the case in Figure 2 lies in how many flash clusters exist and how the groups and events are distributed between them. We computed the cluster separations for the original L2-LCFA data to determine whether the LCFA was constructing flashes according to the clustering approach and the space and time thresholds described in the ATBD.
This analysis yielded no evidence that the LCFA is clustering groups into the same flash that should be separate according to the WED model in the ATBD.

Making the assumption that LCFA clustering anomalies split flashes but do not otherwise compromise their integrity enables us to recover the flash cluster features that were intended by the clustering algorithm in its ATBD without reclustering all flashes from the Level 1b event data. We simply must evaluate the flashes in the operational Level 2 product and assess whether each flash is truly isolated according to the WED model. Flashes whose groups are sufficiently close in space and time to be considered part of the same flash are then merged together to form a new composite flash cluster.

This reclustering approach considerably reduces the computational expense and processing time required to produce valid and complete flash clusters, but high event rates during eclipse season still pose a major roadblock to producing Level 2 LCFA Cluster Assurance (L2-LCFA-R) data in real time. While most 20-s L2-LCFA data packets require on the order of 0.1 s to process, packets with the highest data rates from solar artifacts still require days to process. Using parallelized computing across six nodes, however, we were able to produce a complete 2018 record of postprocessed L2-LCFA-R data in just 2 months of wall clock time.

The instrument vendor has developed a blooming filter for GLM (Tillier, 2019, personal communication) that went live recently at the time of writing and will reduce the number of artifact events from solar contamination. Blooming is a common issue for CCD-based instruments where saturation in one pixel (i.e., from the Sun) can cause nearby pixels to trigger as excess charge is spilled over into neighboring pixels on the array. The forthcoming blooming filter and some frequency domain methods we are developing for screening solar artifacts may make real-time L2-LCFA-R processing feasible in the future.

We collect 20-s L2-LCFA-R data packets into 15-min periods aligned to the UTC hour and construct databases that summarize the lightning activity therein. Here we identify series cluster features that document periods of sustained optical emission within individual flashes and area cluster features that approximate the overall extent of the lightning hazard in individual thunderstorms during this 15-min window. Because we only use a subset of the database parameters in the present study, the full list is provided in supporting information S1 for reference. Parameters that are not derived from the operational L2-LCFA data files are adapted from the LIS metrics defined in Peterson, et al. (2018).

Comparing our 2018 reclustered data with the original L2-LCFA data highlights the consequences of the implementation of LCFA thresholds on the operational GLM Level 2 data product. Distributions for the durations and constituent feature counts of L2-LCFA-R flashes are shown in Figure 3. The black lines depict the total number of L2-LCFA-R flashes at a given duration or feature count, while the blue lines total the number of flashes that exceed that duration or event/group count. Flash frequency falls off quickly as the number of events per flash (Figure 3a) and the number of groups per flash (Figure 3b) increase. The frequency of flashes at the LCFA threshold maximum groups per flash (dashed line in Figure 3b) is only around 1% of the number of single-group flashes. However, GLM’s staring hemispheric coverage means that large numbers of flashes are still degraded and split by the algorithm. More than 100,000 flashes contain exactly 100 groups, and 5 million flashes contain 100 groups or more. Even the higher LIS threshold does not capture all of the GLM L2-LCFA-R flashes, as there are 100,000 flashes with more than 2,000 groups.

The most complex GLM flashes tend to be either expansive spider flashes like the case in Figure 2 (with 2,916 groups) or solar artifacts. Solar artifacts generally radiate persistently and on longer time scales than lightning whose definition has traditionally included the phrase less than 1 s (Lang et al., 2017). Solar artifacts are usually flagged as degraded for exceeding the maximum duration threshold if they are not first split by a clustering anomaly after exceeding the maximum group count threshold. As we saw with the case in Figure 2, LCFA splitting does not guarantee that the resulting flash clusters will be flagged as degraded. A single solar artifact may be split into 100 flashes with a handful near the end of the event terminating as nominal flashes. As a result, analyses that ignore flashes with degraded QFs will still be contaminated by glint and solar intrusion cases. These artifacts become glaringly obvious in their hemispheric lightning distributions because glint occurs in regions of the GLM domain with little lightning.

Since our approach recombines the degraded L2-LCFA flashes into distinct and complete flash features, finding cases of sustained optical emission on the scale of solar artifacts is as simple as assessing the new flash durations or flash maximum series durations. The distribution of L2-LCFA-R flash duration is
shown in Figure 3c along with the LCFA maximum duration threshold at 3 s (dashed line). The frequency of flashes at this threshold is an order of magnitude less than the maximum group count threshold in Figure 3b. Flash frequency does not fall off quickly beyond this threshold and instead increases between 17 s and the GLM data packet length of 20 s due to long-lasting solar artifacts.

We take two different approaches to mitigate solar artifacts in our analyses. In the first approach, every L2-LCFA-R flash that lasts longer than 10 s is flagged as a possible artifact. All of the following statistical analyses do not include these flashes. They are considered in our assessments of flash extremes, however.

Instead, we remove solar contamination by converting the temporal evolution of group radiances (i.e., light curves) into the frequency domain from 1 to 500 Hz using a backward fast Fourier transform. Flashes that have a peak near 1 Hz are thrown out. Unfortunately, this approach only works well for extreme lightning and its performance degrades for short-duration flashes. For this reason, we only apply it to candidate flashes for the hemispheric extremes that are also flagged as possible glint by the flash duration filter.

3. Results

In the following sections, we examine the operational L2-LCFA and reprocessed L2-LCFA-R GLM data to document the frequency and characteristics of lightning across the hemisphere. In section 3.1 we determine the total 2018 flash rate for GLM’s Americas field of view and assess how severely LCFA clustering anomalies impact cluster rates. In section 3.2 we compute statistics for the characteristics of GLM L2-LCFA-R flashes and compare them with published LCFA statistics that document the extent, evolution, and energetics of GLM flashes. We also identify and examine extreme cases of GLM lightning and compare them with LIS and ground-based Lightning Mapping Array (LMA) extremes. Finally, in section 3.3 we use the new GLM area features to compute statistics for thunderstorm frequency, thunderstorm flash rate, and thunderstorm extent across the hemisphere.

3.1. Americas Total Lightning Rates Recorded by GLM During 2018

North and South America comprise the Americas chimney region that supplies the GEC. In our previous analyses of sources for the Direct Current (DC) branch of the GEC, we described the tropical chimneys in terms of equal-area longitude quadrants centered on the boundaries of continental landmasses (Peterson, Deierling, et al., 2017b; Peterson, Deierling, et al., 2018c). These broader chimneys include contributions from both land and ocean electrified storms, and our Americas longitude quadrant (124.5°W–34.5°W) roughly corresponds to the GOES-16 GLM field of view. Thus, keeping with this convention will enable us to make comparisons between the AC source (lightning) and DC source (Wilson Current) for the GEC.
Table 4. Diurnal and annual comparisons between the GLM operational L2-LCFA (left) and postprocessed L2-LCFA-R (right) flash rates during 2018. Contour plots (center) show the flash rate in 15-min bins for each day of the year. Average diurnal cycles (top) and 15-day average flash rates (outer) are also shown. The reduction of solar artifacts and complex lightning into single flashes is responsible for flash rate reductions between 03:00 and 09:00 UTC and between 15:00 and 18:00 UTC in the L2-LCFA-R data.

Average feature rates recorded by GLM in 2018 are summarized in Table 4. These rates do not consider the detection efficiency of GLM or whether they necessarily come from lightning and thus only represent the rate at which such features are recorded by the instrument. GLM detected an average of 589 events clustered into 232 groups for every second of observation time. Land-based lightning produced 63% of all events and 64% of all groups, while oceanic lightning accounted for the remaining ~36%.
The average flash rate in the operational L2-LCFA data set was 12.1 per second during 2018. Our reclustering reduces the average flash rate to 11.7 per second, removing approximately the same number of flashes as are marked with QF flags in the LFCA data (0.4 per second). Clustering anomalies occur in the L2-LCFA data at an average rate of one degraded flash or group for every 2 s of observation, or 10 in the average 20-s GLM data packet. GLM flashes are more concentrated over land than groups or events with a 75% land fraction compared to the previous 63%. This may be attributed to an increased ability for GLM to resolve details in oceanic lightning that tend to occur in nocturnal thunderstorms and favor long horizontal channels (Peterson, Deierling, et al., 2017b). It may be a coincidence that the DC branch of the GEC likewise produces a similar 60:40 split between land and ocean sources (and between thunderstorm and ESC currents), but connections between the AC and DC branches of the GEC are certainly worth exploring in the future.

Diurnal and annual cycles for the GLM flash rate are shown in Figure 4 for both the operational L2-LCFA data (left) and our postprocessed L2-LCFA-R data (right). Total Americas flash rates for each hour of each day are shown in the two-dimensional contour plots at the bottom center of the figure (d and e). The average hourly flash rates for all days in 2018 are shown above the contour plot (a and b), while the average 15-day flash rates are shown in (c) for the L2-LCFA data and (f) for our L2-LCFA-R data. Differences between the L2-LCFA flash rate and L2-LCFA-R flash rate are plotted as dashed lines in the average annual and diurnal plots.

In most days and hours, the L2-LCFA and L2-LCFA-R flash rates are nearly identical. The Americas flash rate peaks at around 20:00 UTC, while the average 15-day flash rate peaks in the last week of September and first week of October. The average flash rate difference between the operational data and our postprocessed data is less than 1 flash per second on most days, but differences exceeding this value can be noted in Figures 4a and 4b between 06:00 and 09:00 UTC and between 15:00 and 18:00 UTC. This is due to large and complex flashes being reclustered into single flashes (and then removed in the case of solar artifacts).

Hemispheric distributions of the average event, group, and flash rates are presented in Figure 5. We scale the feature rates computed for each pixel by the areal extent of the pixel to report features per year per square kilometer for consistency with the LIS/OTD flash rate climatology in Cecil et al. (2014). While the broad strokes of the event rate (Figure 5a), group rate (Figure 5b) and L2-LCFA-R flash rate (Figure 5c) density distributions largely agree, moving upscale from events to groups to flashes reduces the oceanic contributions and mutes the influence of solar artifacts. Much of this artifact reduction is done at the flash level through our reclustering technique. Figure 5d computes the fraction of L2-LCFA flashes removed during our postprocessing at each point across the GLM field of view. Our L2-LCFA-R data only differ by 1–5% compared to the original L2-LCFA data in most land-based regions, but oceanic regions that are home to frequent glint artifacts have between 25% and 100% of their flashes removed during reclustering. The La Plata basin in Argentina and the Great Plains in the United States are both home to local maxima in the removed flash fraction due to frequent MCS activity that produces large and complex flashes (i.e., Figure 2). Anomalously high removal fractions can also be found southeast of Lake Maracaibo in Venezuela and in northern Brazil due to some combination of solar artifacts and the splitting of natural flashes.

Comparing the regions with high flash removal fractions in Figure 5d with the remaining flash rate densities in Figure 5c shows that not all solar contamination is removed by reclustering. Furthermore, reclustering does not address CCD anomaled that occur along RTEP boundaries and result in horizontal lines along rows of pixels in the hemispheric distributions. Additional work is required to address these issues.

The high-resolution flash rate density map (Figure 5c) highlights regions where orography and land-sea interactions drive convection that influences the flash rate. Key regions for lightning production (in no particular order) include northwestern Colombia, Lake Maracaibo, central America into western Mexico, Cuba, Florida, and the Gulf Coast of the United States, the Dominican Republic, Puerto Rico, the La Plata basin in Argentina, and Amazonian Brazil. An offshore maximum in lightning production can be noted along the Gulf Stream, while a single pixel-wide lightning minimum starts along the southern shore of Lake Maracaibo and then follows the path of the Andes from Colombia through Ecuador, Peru, and Bolivia, finally terminating at the Paraguayan border.

Americas lightning hot spots are identified as the nearest reverse-geocoded place name to the 0.1° bins that have the highest average L2-LCFA-R flash rate densities in Figure 5c. This is a similar technique to the one used in Albrecht et al. (2016) to identify global lightning hot spots in the LIS science data, though we allow...
repeated place names so as not to bias against undeveloped or offshore locations that lack geocoded names down to the finest level. The top 25 flash rate density hot spots across the Americas as recorded by GLM are summarized in Table 5 and color coded by country. The top three flash rate density pixels in Figure 5c are located in Lake Maracaibo, which had an average detected flash rate density as high as 157 flashes per day.
In 2018, Rounding out the top five unique places are Nordeste, Colombia, with 135 flashes per year/km², Distrito Colón, Zulia, Venezuela, with 132 flashes per year/km², and Municipio Catatumbo, Venezuela, with 129 flashes per year/km². The top 25 lightning hot spots are divided between nine Colombian locations, eight Venezuelan locations (including the three Lake Maracaibo pixels), and right Guatemalan locations.

Our GLM-detected flash rate densities in Table 5 may be lower than the LIS values in Albrecht et al. (2016) because we are looking only at 1 year of data rather than a 15-year average, but much of this difference certainly comes from the fact that we do not adjust the flash rate densities to account for the detection efficiency (DE) of GLM. Albrecht et al. (2016) scale their detected LIS flash rate densities by the DE's listed in a simple look-up table based on local hour to produce their published values. A better approach would be to leverage the vast quantity of GLM flashes across the hemisphere to construct location-specific DE tables that account for local differences in thunderstorm precipitation structure (and thus scattering effects). However, since that is beyond the scope of this study, we apply the LIS-based DE look-up table from Albrecht et al. (2016) to our hot spot GLM-detected flash rate densities to examine how much the flash rates might change if a diurnal variation in DE is considered. Flash rate densities adjusted for DE are listed in the final column of Table 5. The highest value over Lake Maracaibo increases from 157 flashes per year/km² to 181 flashes per year/km². This is closer to the 232 flashes per year/km² flash rate density listed for the lake in...
Albrecht et al. (2016) but is still 51 fl ashes per year/km² lower. In fact, DE-adjusted fl ash rate densities over all hot spots in Table 5 have less lightning than Albrecht et al. (2016).

### 3.2. Characteristics of the Flashes Observed by GLM During 2018 and Lightning Extremes

Our hypothesis that the operational L2-LCFA data does not properly represent complex lightning fl ashes is based on the hard thresholds set by the LCFA. Extensive stratiform fl ashes like the world record cases in Lang et al. (2017) would be split into tens to hundreds of fl ashes with the majority of the fl ash features marked as degraded like our GLM fl ash case in Figure 2. Complex fl ashes are clustered nominally in our L2-LCFA data, and this allows us to examine every type of lightning that occurs across the Americas.

Statistics for the characteristics of L2-LCFA-R fl ashes presented in Table 6 reveal that GLM is capable of observing the exceptional lightning seen by LIS and beyond. Typical GLM L2-LCFA-R fl ashes have footprints between 328 (median) to 627 km² (oceanic mean), while 90th percentile fl ashes illuminate 1,088 km² of cloud top area. Oceanic lightning is larger, more energetic, and has a longer duration than continental lightning in both the operational L2-LCFA data and the L2-LCFA-R data. However, the average L2-LCFA-R fl ash is 12% larger than the average operational L2-LCFA fl ash from Rudlosky et al. (2018). The median L2-LCFA-R fl ash is ~2x the size of the median LIS fl ash from Peterson and Liu (2013), while the 90th percentile GLM fl ash is between 1.3x (night) and 1.7x (day) larger. This is primarily due to the sensitivity and pixel size differences between the two instruments. Flash duration is less influenced by instrument sensitivity than fl ash footprint area, and here we see that the median GLM fl ash duration (244 ms) and 90th percentile fl ash duration (656 ms) compare better with the LIS medians (200 ms for day and 220 ms for night) and 90th percentiles (650 ms for day and 750 ms for night).

The average GLM L2-LCFA-R fl ash contains 50 events clustered into 20 groups that are divided between 10 series. Each fl ash has an average of 1.8 series with a 1-sigma (bright) group and a total of 2.5 bright groups at the 1-sigma level. The number of standard deviations above the mean for these bright groups is calculated relative to all groups in the fl ash. The average peak group energy recorded by GLM is 62 fJ, while the average total fl ash energy is 309 fJ. In other words, the single brightest group in each fl ash contributes an average 20% of the total recorded optical energy. Moreover, all groups in the same fl ash are typically within one pixel of one another based on the average 8.8-km maximum group separation, while the total length of all horizontal development (i.e., the total length of all lines in Figure 2) is 16.3 km (~2 GLM pixels) in the average fl ash.

The values in Table 6 are all higher than the values listed in Rudlosky et al. (2018) due to fl ash splitting in the L2-LCFA data. The splitting effect is most noticeable by comparing their 99th percentile entries with ours. Our 99th percentile group count per fl ash, for example, is 117 (above the LCFA threshold), while theirs is...
83 (below the threshold). Since they use only the operational L2-LCFA flash data files, if they reported the 99.9th percentiles, then their group count would be exactly 101 groups per flash (the highest group count in nominal flashes) compared to 509 for the L2-LCFA-R data, while their 99.9th percentile flash duration would be 3,000 ms compared to our 3,764 ms.

Lightning flashes in the top tenth of a percentile illuminate nearly 6,000 km² of cloud top area and are composed of 1,391 events clustered into 509 groups divided between 193 series. We find that 54 total groups are considered bright at the 1-sigma level, and 24 series contain such groups. The longest series (or period of sustained optical emission in the flash) lasts for a full 120 ms, while the maximum group separation is 81.6 km and the total group separation is 287 km. The largest propagating LIS flash recorded to date was 89 km across and GLM is recording flashes on this scale routinely.

The most extreme lightning observed by GLM is truly exceptional by LIS standards. We use our L2-LCFA-R data to identify the top GLM flashes by length (measured by maximum group separation), size (measured by flash footprint area), and duration. Solar artifacts are removed using an experimental frequency domain filter. All flashes that pass this filter are analyzed, and any remaining solar artifacts are removed manually. The lightning cases below describe flashes that have logical incremental group progressions that resemble stepped leader activity extending individual lightning channels. They do not have the randomly positioned groups associated with the overgrouped cases observed by LIS (Peterson, Rudlosky, & Deierling, 2017) nor do they begin as separate flashes that merge later on. They are thus presented as candidates for the top lightning cases measured by GLM during 2018.

The lightning flash with the greatest length was observed by GLM over southern Brazil on 10/31/2018 at 08:40:23 UTC (05:40:23 local time) and spanned a horizontal distance of 673 km between its most distant groups. The evolution of this flash is plotted in Figure 6 and animated in S2. It was an extensive spider flash like the current records in Lang et al. (2017) that propagated first to the northwest and then branched out to the west and the east, continuing to develop in both directions over the next 4 s. The total duration of the flash was 7.4 s, and it contained 322 series, 6242 groups, and 42,772 events. It was almost continuously producing light as its branches developed laterally through the electrified cloud—each group incrementally extending the flash toward its final 673-km length and 101,000-km² footprint area.

The lightning flash with the greatest footprint area was observed by GLM over east Texas, northern Louisiana, and southern Arkansas on 3/29/2018 at 09:29:39 UTC (04:29:39 local time) and illuminated a cloud top area of 114,997 km². The evolution plot for this flash is shown in Figure 7, and an animation is shown in S3. It is another expansive spider flash that propagated westward from the convective core of the MCS before branching out into the stratiform region in all directions. Its length rivals the case in
Figure 6 at 634 km across, but it had a longer duration (10.48 s) with more series (337), groups (8,027), and events (52,643). It is important to note that the diameters of these flashes are limited by the extent of the electrified stratiform region. In this case, the major axis of the flash footprint is aligned parallel to the convective line, which exceeds the diameter of the storm along its front-to-rear axis. The largest recorded LIS flash (Peterson, Rudlosky, & Deierling, 2017) could fit within the footprint of this flash 10 times over. That LIS flash was only large due to its high energy and favorable viewing conditions (i.e., near the edge of the storm with nearby lower clouds to reflect optical radiance), not because it had lateral structure like the top GLM flashes.

The longest-lasting flash observed by GLM is shown in Figure 8 and animated in S4. It occurred in a mesoscale thunderstorm near Sioux City, Iowa, on 6/2/2018 at 06:55:17 UTC (01:55:17 local time). It is another case of a horizontally expansive lightning flash that is 326 km across with an illuminated cloud top area of 57,195 km². Only five of the largest recorded LIS flash would fit in its footprint. However, it lasted for 13.492 s during which time it propagated from the south to the north before branching out westward and...
eastward. LIS flashes with similar durations actually represented thunderstorms that had such high flash rates that they did not pause long enough to spawn a new flash, while Tropical Rainfall Measuring Mission was overhead (Peterson, Rudlosky, & Deierling, 2017). Such cases are easily identifiable because their groups are distributed randomly throughout the flash footprint and do not follow an organized trajectory. We are confident that this flash is not one of these overgrouped cases because the groups trace a clear path from one to the next that can be easily noted in the group extent by latitude and longitude plots in Figure 8.

The top five GLM flashes by length, size, and duration are summarized in Table 7. Flashes that appear in multiple top 5 lists are shaded. The top GLM flashes are incredibly rare, only representing the top $1 \times 10^{-8}$% of Americas lightning. This is a major reason why LIS did not resolve any lightning at these scales. With its low Earth orbit, LIS would have to be in the right place at exactly the right time to see it. Ground-based LMAs are also unlikely to detect such flashes because they are range-limited to domains with ~300-km radii. A 600-km flash would have to be exactly centered on this domain to be fully resolved by an LMA. GLM, meanwhile, continuously records lightning across the entire hemisphere and thus readily detects extreme flashes when they occur.

Four of the top five GLM flashes in terms of length contain groups that are separated by at least 600 km. All flashes in the top five list are examples of expansive propagating stratiform flashes like the case in Figure 6. There are both physical and instrument-based reasons that extreme GLM flashes would favor stratiform lightning. Our previous LIS analyses showed that the top propagating cases are almost exclusively found in the stratiform regions of large MCSs because their horizontally large and layered charge structures are conducive to lateral flash development (i.e., Krehbiel, 1986; Peterson, Rudlosky, & Deierling, 2017; Stolzenburg et al., 1994). The MCS diurnal cycle is also delayed relative to typical convection (Nesbitt & Zipser, 2003), as it takes additional time for the system to grow upscale and mature to develop the large electrified stratiform regions required for this type of lightning. Thus, large stratiform flashes favor occurring at night when the GLM sensitivity is greatest, enabling the imager to resolve more of the flash structure.

### Table 7

**Characteristics of the Top Five GLM Flashes of 2018 in Three Categories: Maximum Group Separation (Length), Illuminated Cloud Footprint Area (Size), and Flash Duration**

| Date/time (UTC) | Location | Duration (ms) | Footprint (km$^2$) | Series Group Count | Max duration (ms) | Group Count | Max separation (km) |
|-----------------|----------|---------------|-------------------|-------------------|-----------------|-------------|-------------------|
| **Top flash features sorted by maximum group separation** | 10/31/18 08:40:23 | 52.9°W, 29.5°S | 7,470 | 101,367 | 322 | 246 | 6,242 | 673 |
| | 4/14/18 07:50:59 | 92.7°W, 34.2°N | 5,934 | 67,838 | 214 | 358 | 4,907 | 666 |
| | 9/23/18 04:47:39 | 52.7°W, 33.6°S | 8,922 | 113,104 | 298 | 884 | 9,404 | 659 |
| | 3/29/18 09:29:39 | 93.6°W, 31.8°N | 10,484 | 114,997 | 337 | 438 | 8,027 | 623 |
| | 9/30/18 05:03:38 | 55.5°W, 30.7°S | 4,732 | 79,357 | 112 | 696 | 5,826 | 582 |
| **Top flash features sorted by footprint area** | 3/29/18 09:29:39 | 93.6°W, 31.8°N | 10,484 | 114,997 | 337 | 438 | 8,027 | 623 |
| | 9/23/18 04:47:39 | 52.7°W, 33.6°S | 8,922 | 113,104 | 298 | 884 | 9,404 | 659 |
| | 3/29/18 10:33:59 | 92.8°W, 32.2°N | 4,664 | 107,870 | 98 | 206 | 5,156 | 432 |
| | 12/14/18 08:12:03 | 57.9°W, 34.5°S | 12,170 | 106,667 | 539 | 296 | 665 | 450 |
| | 12/27/18 08:28:24 | 94.6°W, 33.9°N | 6,260 | 106,613 | 190 | 654 | 7,213 | 433 |
| **Top flash features sorted by duration** | 6/2/18 06:55:17 | 96.8°W, 42.4°N | 13,496 | 57,195 | 718 | 280 | 5,351 | 318 |
| | 9/23/18 06:00:18 | 52.0°W, 33.1°S | 12,376 | 104,531 | 590 | 316 | 8,123 | 516 |
| | 9/29/18 23:01:38 | 54.0°W, 32.6°S | 12,320 | 50,477 | 636 | 232 | 4,261 | 365 |
| | 12/14/18 08:12:03 | 57.9°W, 34.5°S | 12,170 | 106,667 | 539 | 296 | 665 | 450 |
| | 9/23/18 05:19:39 | 51.5°W, 33.3°S | 11,990 | 29,033 | 667 | 302 | 2,900 | 271 |

*Note.* Flashes that appear in multiple lists are shaded.

*a* Analysis limited to only propagating flashes (>100-km maximum group separation) to remove solar and high flash rate compact thunderstorm clustering artifacts.
The stratiform preference is also fortunate because stratiform lightning is not likely to be overclustered like the longest-lasting LIS flashes we noted previously. LIS flashes with extreme durations were entirely convective and captured the highest flash rate thunderstorms. These storms did not stop flashing long enough to generate a new flash. Lightning is infrequent in the stratiform region compared to convection (Peterson & Liu, 2011). With low stratiform flash rate densities, stratiform flashes are not likely to sufficiently concentrated in space and time to be overgrouped into a single amalgamated flash cluster. Regardless, none of the flashes in Table 7 show evidence of random group propagation, which we discussed was a marker for overgrouped flashes in our discussion of Figure 8 (see Figure 6 in Peterson, Rudlosky, & Deierling, 2017, for an example of an overgrouped flash). All top flash cases follow a logical progression from one group to the next that we would expect to see with a single stratiform lightning flash developing laterally over multiple seconds.

As we can be reasonably confident that the flashes in Table 7 represent physically complete and distinct lightning flashes, these cases represent the lightning extremes measured by GLM during 2018: 673 km in length, 114,997 km² in footprint area, and 13.496 s in duration. We assert that these values describe minimum estimates for extreme lightning in the Americas because GLM has difficulty resolving flash structure below a thick cloud layer (i.e., the portion of the flash developing in the convective core). Obscured portions of the lightning tree could add hundreds of kilometers to the lengths shown in Table 7. The evolutions of these extreme GLM flashes and their meteorological contexts will be examined in an upcoming study.

### 3.3. Americas Thunderstorm Area Rates and Characteristics Recorded by GLM During 2018

The lightning flash rate densities in Figure 5c serve as a proxy for the total integrated convective intensity across the hemisphere but do not provide information on the frequency or scale of convection or the intensity of individual convective systems. To quantify this, we must define a lightning cluster feature that encapsulates thunderstorms. We use the area features from the legacy NASA lightning imagers to fill this role. Areas are defined as clusters of flashes that occur within 16.5 km of each other during the same 15-min sampling period aligned with the UTC hour. GLM areas are thus updated at the same frequency as ABI full disk imagery during 2018 (4x per hour).

The frequency of thunderstorm activity during 2018 is quantified across the GLM field of view in Figure 9 in terms of traditional thunder days (Figure 9a) and the total integrated thunderstorm duration over the year (Figure 9b). Thunder days are calculated as the number of calendar days where lightning occurs in each
The total integrated thunderstorm duration is essentially equivalent to a duty cycle for thunderstorm activity but expressed as a time rather than a percentage. In each 15-min time period over the year, 15 min are added to each bin that falls within an area feature footprint. The resulting annual total represents the accumulated time that thunderstorms spend over that pixel.

Northern Colombia, Panama, Costa Rica, Guatemala, northeastern Brazil, and parts of the Amazon all had more days with thunderstorms in 2018 than days without (i.e., greater than 182 thunder days in Figure 9a). Tropical regions up to 25° latitude frequently see at least 120 thunder days with regional maxima along the Andes, throughout the broader Amazon region, and up through central America, as well as in Cuba, the Dominican Republic, and Jamaica. Florida was the clear 2018 thunder day capitol of the United States with nearly the entire state reporting at least 100 thunder days.

North of the Gulf Coast, the central United States recorded around 50 thunder days over the year, which was comparable to the number of thunder days in the La Plata basin in Argentina. Low thunder day counts in these regions suggests that more lightning occurred over fewer days here than the tropics. The total integrated thunderstorm duration (Figure 9b) confirms that thunderstorm activity is less frequent in these regions despite high flash rate densities in Figure 5c. The total flash rate densities in tropical regions of Figure 5c are spread over the equivalent of 10–20 days of continuous thunderstorm activity (Figure 10b), but all lightning in 2018 across much of the Midwest or the La Plata basin could be condensed into 48 consecutive hours.

Terrain influences on thunderstorm activity can be noted in Figure 9, particularly in South America. Figure 10a shows the total thunderstorm duration over this region in greater detail, while Figure 10b contours the terrain elevation and overlays the locations of river systems. Elevations are also contoured at a lower 1° resolution in Figure 10a with isolines drawn for each kilometer above sea level. Convective initiation in the southwestern Amazon in particular has been extensively studied (Albrecht et al., 2011). This region is unique due to its interactions between large-scale circulation (i.e., the South Atlantic Convergence Zone), orographic lifting, aerosol production, and differing heat fluxes from a vast array of terrain classifications due to the natural geography of the region and deforestation. These factors have a pronounced impact on thunderstorm type and lightning frequency (Albrecht et al., 2011; Albrecht et al., 2016).

Figure 10. South America (a) total thunderstorm durations with elevation as isocontours and (b) terrain elevations with river systems overlaid. The dashed box shows the region where the course of the Amazon River system is most evident in the GLM data as a local lightning minimum.
The two key features that stand out in Figure 10a are the local enhancement along the eastern slopes of the Andes and local minima in the Amazon basin that follow a branching pattern. Enhanced lightning activity in the southwest Amazon was attributed to orographic lifting in Albrecht et al. (2016). The Andes is a tall
mountain range that exceeds 4-km altitude over much of their extent (Figure 10b). The regions of enhanced thunderstorm activity in the southwestern Amazon and Andes (Figure 10a) are aligned with the peaks along the eastern and western ranges of the Andes, while the thin lightning minimum between them traces out the valley between the ranges.

The branching local lightning minima in Figure 10a that run through the heart of the Amazon region, meanwhile, are caused by the Amazon River, and for this reason they trace out its precise path shown in Figure 10b for reference. The mechanism behind this apparent lull in thunderstorm activity over the river likely results from differential solar heating of land and river water that can set up a circulation system similar to a sea breeze (de Oliveira & Fitzjarrald, 1993, 1994). Preferential heating of the land surrounding the river would favor onshore thunderstorm initiation rather than over the river, thus explaining the local minimum following its course.

The disparity in storminess between the tropical and midlatitude lightning hot spots is caused by the fact that the subtropics experience all four seasons, while the tropics remain warm and moist year round. This is enhanced by subtropical area features favoring large and organized convection, while the tropical area features favor widespread convection that is small and disorganized. Figure 11 shows hemispheric distributions for the GLM average area rate density (Figure 11a), area feature mean flash rate (Figure 11b), area feature size (Figure 11c), and area feature flash rate density (Figure 11d). The Great Plains and La Plata basin have low area feature rates despite high flash rates because the areas that occur in these subtropical regions encompass large MCSs that span thousands to tens of thousands of square kilometers, on average. The average area flash rate density (feature flash rate scaled by feature area) does not vary as much as the feature flash rate between land-based locations across the hemisphere.

### Table 8

| Lat  | Lon  | Place name                                         | Total flash count | Thunder days (days) |
|------|------|----------------------------------------------------|-------------------|---------------------|
| 5.5°N| 76.5°W| Lloró, Chocó, Colombia                             | 9,441             | 256                 |
| 5.5°N| 76.7°W| Paimadó, Chocó, Colombia                           | 8,317             | 253                 |
| 5.3°N| 76.7°W| Managro, El Cantón del San Pablo, Chocó, Colombia  | 10,921            | 252                 |
| 5.8°N| 76.7°W| Las Mercedes, Quibdó, Chocó, Colombia              | 7,917             | 251                 |
| 6.1°N| 73.3°W| Suaía, Santander, Colombia                         | 8,115             | 250                 |
| 5.6°N| 76.5°W| Lloró, Chocó, Colombia                             | 9,679             | 248                 |
| 5.5°N| 76.4°W| Lloró, Chocó, Colombia                             | 7,386             | 248                 |
| 5.3°N| 76.5°W| Tapón, Tadó, Chocó, Colombia                       | 7,881             | 248                 |
| 5.3°N| 76.6°W| Animás, Las Ñímas, Chocó, Colombia                 | 7,776             | 247                 |
| 5.6°N| 76.7°W| Atrato (Yuto), Chocó, Colombia                     | 8,217             | 246                 |
| 5.4°N| 76.5°W| Cértegui, Chocó, Colombia                          | 8,301             | 246                 |
| 5.2°N| 76.7°W| Istmina, Chocó, Colombia                           | 7,798             | 246                 |
| 6.1°N| 73.4°W| Tolota, Suáita, Santander, Colombia                | 5,634             | 245                 |
| 5.1°N| 76.7°W| Andagoya, Medio San Juan, Chocó, Colombia          | 6,857             | 245                 |
| 5.5°N| 76.6°W| Atrato (Yuto), Chocó, Colombia                     | 9,571             | 244                 |
| 5.6°N| 76.6°W| Atrato (Yuto), Chocó, Colombia                     | 9,422             | 243                 |
| 5.5°N| 76.8°W| Paimadó, Chocó, Colombia                           | 7,035             | 243                 |
| 5.4°N| 76.7°W| Puerto Nuevo, El Cantón del San Pablo, Chocó, Colombia| 10,522           | 243                 |
| 8.0°N| 74.4°W| Montecristo, Bolívar, Colombia                     | 7,798             | 242                 |
| 5.6°N| 76.4°W| Lloró, Chocó, Colombia                             | 8,205             | 242                 |
| 5.3°N| 76.8°W| El Cantón del San Pablo, Chocó, Colombia           | 7,198             | 242                 |
| 8.0°N| 74.5°W| Montecristo, Bolívar, Colombia                     | 12,321            | 240                 |
| 5.4°N| 76.4°W| Bagadó, Chocó, Colombia                            | 7,016             | 239                 |
| 5.7°N| 76.5°W| Quibdó, Chocó, Colombia                            | 14,107            | 238                 |
| 5.4°N| 76.6°W| Cértegui, Chocó, Colombia                          | 11,884            | 238                 |

*Note. All entries are located in northwestern Colombia with all but four located in the Chocó department.*

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Another important aspect of Figure 11a to note is that while glint artifacts are suppressed in larger-scale features, the differing performance characteristics of the subarrays on the GLM CCD imager become more pronounced. The locations of certain Real Time Event Processors (RTEPs) are apparent as boxes and linear streaks in Figure 11a. Two of these particularly sensitive RTEPs are located along the west coast of South America, while a third is located northeast of Cuba. Differences in performance among the RTEPs become clear in large-scale features like areas because they have no minimum constituent feature threshold. An area may consist of two events in a single group in a single flash or an entire MCS with 10,000 flashes. Both of these cases would be given an equal weight in the area rate density distribution in Figure 11a.

We list the GLM hotspots for thunderstorm activity in Table 8 for thunder days and Table 9 for total integrated thunderstorm duration. Both lists of the top 25 locations for thunderstorms are dominated by the Chocó department in Colombia. In fact, all thunderstorm hot spots fall within northwestern Colombia over the Chocó, Santander, Bolivar, Antioquia, or Caldas departments. The town of Lloró in Chocó department, Colombia, tops both lists with 256 thunder days and the equivalent of 27.5 continuous days of thunderstorms throughout the year. The thunderstorm duty cycle for Lloró would be 6.8% for the observations period.

The top thunderstorm area features in 2018 are shown in Figure 12 in terms of feature flash rate (Figure 12a) and feature size (Figure 12b). The contour plots depict the Flash Extent Density (FED) across the feature. FED is an operational GLM gridded product that increments each bin on the grid by 1 for every unique flash that touches it (Stano, 2018). In this way it combines analyses of flash extent and flash rate to better visualize the overall lightning hazard. We also draw convex hulls as dashed lines around the...
centroids of the groups that comprise each top GLM area feature to show its overall extent. As seen in Figure 12b, the convex hulls may include clear air regions if the area features are curved squall lines. For this reason, we use the illuminated cloud footprint of the area feature to define the thunderstorm size rather than the convex hull.

Both top area features were South American MCSs. The top area feature by overall flash rate (Figure 12a) occurred on 12/14/2018 at 02:30 UTC (23:30 local time on 12/13) over Argentina and Uruguay. It produced an average of 17.6 flashes every second and covered a land area of 153,389 km$^2$ and was primarily composed of convection. The largest thunderstorm area feature, meanwhile, occurred primarily over Rio Grande do Sul in southern Brazil on 10/31/2018 at 08:45 UTC (05:45 local time). This thunderstorm was 216,865 km$^2$ in size and had an average flash rate of 9.1 flashes per second. Unlike the previous case, more than half of the thunderstorm footprint was contributed by stratiform lightning. Stratiform FEDs in Figure 12b were 0.39 flashes per minute, on average or 1 stratiform flash every 2.5 min. By comparison, the convective core was flashing at a rate of 5–18 flashes per minute.

The top five GLM thunderstorm area features by total flash rate and size are ranked in Table 10. Since area features are defined in each 15-min sampling period, the same thunderstorm appears multiple times in each

![Figure 12. GLM flash extent density for (a) the highest flash rate thunderstorm area feature, and (b) the largest thunderstorm area feature during 2018. Convex hulls are drawn around the group centroids included in the areas of interest. The largest and highest flash rate features are both expansive South American Mesoscale Convective Systems.](image)

| Date/Time [UTC] | Location | Lightning Rates | Thunderstorm Size [km$^2$] | Flash Rate Density [flashes hr$^{-1}$ 100 km$^{-2}$] |
|-----------------|----------|-----------------|-----------------------------|---------------------------------|
|                 |          | Flashes s$^{-1}$ | Series s$^{-1}$ | Groups s$^{-1}$ | Events s$^{-1}$ |                                   |                                   |
| Top area features sorted by total flash rate | 12/14/18 02:30 | 61°W, 33°S | 17.6 | 213 | 321 | 694 | 153,389 | 41.2 |
|                | 10/31/18 03:30 | 57°W, 29°S | 16.5 | 263 | 415 | 874 | 146,626 | 40.4 |
|                | 10/31/18 03:45 | 57°W, 29°S | 15.7 | 245 | 393 | 826 | 156,400 | 36.1 |
|                | 12/14/18 02:45 | 60°W, 33°S | 15.5 | 190 | 294 | 652 | 170,438 | 32.7 |
|                | 10/31/18 03:00 | 57°W, 29°S | 15.4 | 262 | 440 | 908 | 143,275 | 38.6 |
| Top area features sorted by thunderstorm size | 10/31/18 08:45 | 55°W, 27°S | 9.10 | 132 | 265 | 693 | 216,865 | 15.2 |
|                | 9/30/18 01:15 | 59°W, 29°S | 11.2 | 120 | 235 | 613 | 195,863 | 20.5 |
|                | 12/14/18 05:00 | 60°W, 33°S | 10.6 | 110 | 183 | 448 | 193,856 | 19.7 |
|                | 10/31/18 07:15 | 57°W, 28°S | 12.4 | 148 | 257 | 641 | 186,858 | 23.9 |
|                | 10/31/18 06:45 | 57°W, 28°S | 13.1 | 173 | 291 | 698 | 185,849 | 25.4 |

*Note. Storms that appear in multiple entries on either list are shaded.*
list. In fact, the 10 total slots contain only three unique South American MCSs between both lists: The two storms in Figure 10 and a third MCS on 9/30/2018 that took the number two spot for thunderstorm size.

4. Conclusion

We document the on-orbit performance of the GLM LCFA and the quality of its Level 2 flash cluster data product. We find that the hard limits on the maximum group count per flash and maximum flash duration imposed by the LCFA in its current configuration prevent nontrivial GLM flashes such as horizontally extensive stratiform flashes from being properly represented in the operational product. Such flashes are split into multiple flash clusters where most (but not all) split flash clusters are flagged as degraded. When end users choose to ignore flashes with degraded QFs (as is common practice), their assessments of the lightning hazard may not be correct.

We have developed an efficient reclustering technique that mitigates flash splitting by the LCFA and recovers the flash clusters that it would produce nominally without a latency requirement or hard thresholds. We apply this approach to the first full calendar year of public GLM LCFA data (2018) to generate a reclustered (LCFA-R) data set that properly represents all types of lightning across the Americas. We use the L2-LCFA-R data to document the characteristics of GLM flashes, produce statistics of lightning occurrence, and identify cases of extraordinary lightning flashes. We also create legacy LIS/OTD area of interest (or area) features representing thunderstorms to assess thunderstorm frequency across the hemisphere.

The average hemispheric flash rate recorded by GLM was 12 flashes per second in 2018, which varied from an average minimum of 4 flashes per second at 13:45 UTC to an average maximum of 25 flashes per second at 20:30 UTC. The annual peak in hemispheric lightning activity occurred in the last week of September and first week of October. While Lake Maracaibo was the primary lightning hot spot in terms of GLM flashes in 2018 with a peak flash rate density of 157 flashes per km²/year (181 flashes per km²/year when adjusted for the assumed instrument DE), the town of Lloró in Chocó department, Colombia, was the top location for thunder days (256 days) and total accumulated thunderstorm duration (25.7 days).

The characteristics and frequencies of GLM flash and area features vary considerably across the hemisphere due to influences from general circulation, diurnal heating, geography, and aerosol effects on the precipitation and electrical structures of thunderstorms. A few noteworthy trends in the GLM feature data include orographic enhancement in lightning activity along the Andes, an apparent Amazon breeze reduction in thunderstorm duty cycle that follows the precise course of the Amazon river, and increased thunderstorm organization in the midlatitudes expressed as low area rates and large area sizes coinciding with local flash rate density maxima (for example, in the La Plata basin in Argentina).

GLM flashes are identified whose lengths reached 673 km and whose durations reached 13.496 s. The overall largest GLM flash covered an area of 114,997 km². Meanwhile, the largest GLM thunderstorm area feature spanned 216,865 km² in horizontal extent and the most active thunderstorm area feature had a flash rate of 17.6 flashes per second.

The operational GLM L2-LCFA product was designed with the purpose of improving forecasts and environmental awareness. These initial results with our reclustered (L2-LCFA-R) product clearly demonstrate that once the operational data anomalies are corrected, GLM can be a powerful asset for addressing a broad range of environmental research applications. Our preprocessed L2-LCFA-R product is offered as an improvement to the operational GLM data set produced in real time.

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