Geostationary Lightning Mapper and Earth Networks Lightning Detection Over the Contiguous United States and Dependence on Flash Characteristics

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Abstract This study compared the detection capabilities of the Geostationary Lightning Mapper (GLM) and ground-based Earth Networks Total Lightning Network (ENL) over the contiguous United States (CONUS) from 25 April 2017 to 5 May 2018. GLM detection efficiency (DE) relative to ENL varied spatially with greater DE in the southeastern United States and lower DE in the Northern Plains. Regions with greater DE were often regions where most intracloud flashes had normal positive polarity, while lower DE regions frequently had inverted negative intracloud. According to the tripolar noninductive charging model, inverted intracloud flashes are lower altitude than normal intracloud flashes. This lower altitude flash may result in greater cloud scattering of the optical lightning signal, which at cloud top is less than the GLM radiant energy. DE was generally also greater for greater absolute peak current, which serves as a proxy for optical energy. Additionally, GLM observed flashes to be generally greater in area and duration in the eastern relative to the western CONUS, which may result in the greater DE. GLM DE was also varied with the solar zenith angle as greatest DE occurred at night. ENL DE relative to GLM was varied spatially over CONUS with greater DE over eastern CONUS. ENL DE was greater for flashes of greater GLM flash radiant energy, area, and duration.

1. Introduction

The launch of the Geostationary Lightning Mapper (GLM) presents new capabilities for lightning detection (Goodman et al., 2013). Lightning not only represents a hazard for life and property but also indicates storm intensity related to updraft strength and graupel flux (Barthe et al., 2010). Lightning also generates nitrous oxides, which are important precursors to tropospheric ozone production (Pickering et al., 1998). Evaluating and comparing the capabilities of GLM relative to ground-based lightning location systems (LLSs), such as Earth Networks Total Lightning Network (ENL), are important for the effective utilization of GLM and identifying its potential strengths or weaknesses.

1.1. Lightning and Electrical Charging

Proper evaluation of GLM and its detection necessitates understanding the cause of lightning and lightning characteristics. Noninductive charging (NIC), resulting from collisions of ice hydrometeors in the presence of supercooled water, likely represents the primary mechanism for electrical charging and the production of lightning in storms (Saunders et al., 2006). Charging of hydrometeors can be either positive or negative, with differences in charge partially neutralized by lightning discharges after sedimentation of charged hydrometeors. Stronger updrafts in the mixed-phase region (0°C to approximately −40°C) generally produce more charging and more frequent lightning flashes that are smaller and weaker (Bruning & MacGorman, 2013; Mecikalski et al., 2015). At warmer temperatures (e.g., 0°C to −10°C), graupel hydrometeors are positively charged during riming collisions, while ice particles are negatively charged. At cooler temperatures (e.g., −20°C to −40°C), graupel charges negatively, while ice hydrometeors charge positively. Since graupel is heavier relative to ice, a lowest positive-charged layer will generally form, while negatively charged ice particles are lofted to near negatively charged graupel, forming a negatively charged layer above the lowest positively charged layer. The positively charged ice is lifted upward to form an upper layer of positive charge. This forms the typical tripolar model of charging and lightning formation (see Figure 1 of Williams (1989) for further illustration). Examination of electric field data from balloons released into 33 thunderstorms indicates that the tripolar structure is generally observed in the updraft core (Stolzenburg et al., 1998).
Although less lightning flashes initiate outside the updraft core, the charge structure outside of the updraft core is more complicated and variable with often several layers.

Negative cloud-to-ground (−CG) flashes follow the tripolar structure by transferring negative charge in the middle layer through the lower positively charged layer and down to the surface. Positive cloud-to-ground (+CG) flashes, which are rarer than −CG, are not supported by this tripolar NIC model since +CG necessitates a positively charged layer above a lower most negatively charged layer. This structure could only be produced through shearing or advection of layers and/or sedimentation, lightning, or other charging mechanisms (Bruning et al., 2014). The tripolar model is supportive of intracloud (IC) flashes that transfers positive charge in the upper layer to the large middle negatively charged layer, termed normal polarity IC (i.e., positive polarity IC) flashes (Bruning et al., 2014).

Inverted-polarity IC (i.e., negative-polarity IC) flashes between the bottom two layers of the tripolar model are also possible if the lower positively charged layer is large enough. Laboratory studies (Saunders et al., 2006) suggest that the transition temperature (ranging from approximately −10°C to −30°C) determining the charge of graupel is dependent on supercooled cloud water content. Greater supercooled water amounts generally allow positive charging of graupel at cooler temperatures closer to −30°C, which can result in a larger lowest positively charged layer and a smaller middle negatively charged layer, supportive of inverted-polarity storms producing mostly inverted-IC flashes (Williams, 1989; Bruning et al., 2014). Strong updrafts with less warm rain residence time will generally allow greater cloud water in the mixed-phase region (0°C to −40°C). This is more common in drier environments with high cloud bases and shallow warm cloud depths (Fuchs et al., 2015). Greater concentrations of aerosols acting as cloud condensation nuclei (CCN) can also be more supportive of cloud water in the mixed-phase region and, hence, inverted-IC flashes. Idealized simulations using an electrification parameterization found no lowest positively charged layer for a simulation with few CCN (50 cm³), while increasing CCN (up to 5,000 cm³) allowed for a lowest positive layer that increasingly dominated the higher negatively charged layer and a weakening uppermost positively charged layer (Mansell & Ziegler, 2013).

This study offers an early assessment of the LLSs, GLM and ENL. Section 2 explains data for this assessment, while section 3 explains methods. Using the preceding knowledge about lightning and the LLSs, section 4 explores GLM and ENL detection capabilities. Lastly, conclusions are summarized in section 5.

2. Data

2.1. GLM

The GLM is an Optical Transient Detector (OTD) using a charge-coupled device imager operating in the near infrared at 777.4 nm, which is chosen to better optimize the lightning signal relative to reflected sunlight (Goodman et al., 2013). The pixel field of view (FOV) is 8 km at nadir and increases to only 14 km at the edge of full-disk view through a special design to preserve resolution. The GLM instrument utilizes a 1,372-by-1,300 charge-coupled device array that images the Earth every 2 ms. A pixel that exhibits a sudden brightness increase from the pixel background level that exceeds a detection threshold is designated an event. Based on the magnitude of the brightness increase and the background value, a radiant energy value is assigned to the event.

Adjacent simultaneous events are clustered into groups by the Lightning Cluster-Filter Algorithm (GOES-R Algorithm Working Group and GOES-R Series Program, 2018; Goodman et al., 2012) with an area, cumulative energy, centroid latitude, and centroid longitude. Events occurring within 16.5 km and 330 ms of each other are clustered together to form flashes with an area, energy, start and end time, centroid latitude, and centroid longitude. Groups generally represent pulses (i.e., strokes or IC discharges), while events represent segments of these pulses. However, pulses may have durations extending two or more 2-ms frames (Bitzer, 2017). Consequently, multiple groups may represent the same pulse.

Similar near-infrared optically based instruments have previously flown in low-Earth orbit, including the OTD and Lightning Imaging Sensor (LIS). Pixel FOV was 8 km at nadir for OTD (Christian et al., 2003) and 4 km for LIS (Boccippio et al., 2002). Boccippio et al. (2002) estimated the LIS detection efficiency (DE) to range between 93% at night to 73% at local noon based on instrument specifications and observed background radiances. GLM DE would be expected to have similar dependencies on the sun angle. The
777.4-nm band utilized by GLM, LIS, and OTD has very little cloud absorption and acts as a conservative scatterer at this wavelength. However, the cloud at this wavelength will scatter the emission signal preferentially to the closest cloud boundary and potentially reduce radiance at cloud top below detectable levels (e.g., Light et al., 2001; Thomas et al., 2000; Yoshida et al., 2009). Yoshida et al. (2009) found generally less detected radiance for LIS flashes coinciding with greater cold (i.e., <0°C) cloud depth derived utilizing Tropical Rainfall Measuring Mission precipitation radar. Additionally, a small flash that occupies only a portion of a GLM pixel, or a portion of multiple pixels, will have a weaker signal than that occupying the entire pixel. Flash area in an intense storm commonly range between 1 and 100 km² (e.g., Bruning & MacGorman, 2013), relative to the common GLM pixel area of 64–100 km².

2.2. ENL

The ENL is a lightning locating system with sensors worldwide. Sensors detect very low frequency and low-frequency sferics in the 1-Hz to 12-MHz range from both CG and IC flashes. ENL metrics for each flash include estimated time, latitude, longitude, type (i.e., CG or IC), peak current, polarity, and multiplicity (i.e., the number of detected pulses/strokes that compose the flash). Time, flash type, peak current, and polarity are that of the strongest pulse (in terms of absolute peak current) of the flash. Earth Networks clusters pulses into flashes using 10-km and 0.7-s thresholds, consistent throughout the period of study (April 2017 to May 2018). Only flash data were readily available and used for this study.

While GLM detects optical signals, ENL detects very low frequency and low-frequency sferics. Both sferics and optical signals are typically generated during a pulse (Bitzer et al., 2016). ENL generally will not determine the full spatial extent of pulses in contrast to GLM events or Lightning Mapping Array (LMA) sources comprising a group/pulse. However, ETL may determine the location of compact pulses more precisely than GLM locates events.

Zhu et al. (2017) evaluated the quality of ENL through the examination of 36 rocket-triggered negative CG flashes at Camp Blanding and 219 natural CG flashes at the Lightning Observatory in Gainesville (LOG) during 2014–2015. LOG used optical high-speed cameras and electric field measurements to characterize CG lightning. Although rocket-triggered lightning is more characteristic of subsequent return strokes rather than the initial (typically strongest) return stroke of a CG flash, rocket-triggered lightning allowed the direct measurement of peak current. Median absolute current estimate error was 15% with location error of 215 m and 100% flash DE. Flash type classification was correct (i.e., correctly identified as CG) for 97% of the flashes at Camp Blanding and LOG. These errors were somewhat better than a study of 57 flashes during 2009–2012 using an earlier ENL processor (Mallick et al., 2015). Errors were greater for strokes with less absolute peak current. Consequently, DE and all flash characteristic estimates are generally worse for IC than for CG. The absence of truth data sets for IC flashes prevents accurate error estimates for IC flashes. However, positive and negative IC are expected to have similar DE, given similar distributions of peak current (Jeff Lapierre, personal communication). Also note, different error statistics are likely in other regions of the country due to different flash characteristics and density of sensors. However, ENL sensor density in northern Florida is similar to that across eastern and central United States (Zhu et al., 2017). No changes were made to ENL during our period of study in terms of their data-processing algorithm and sensor density that would appreciably affect DE over the contiguous United States (CONUS; Michael Stock, personal communication).

3. Methods

This study compares GLM and ENL observations from 0000 UTC 25 April 2017 to 1200 UTC 5 May 2018, excluding periods of missing data (e.g., 11–13 August 2017 and 1–17 December 2017). Observations were organized into 20-s periods, and any 20-s period without either a GLM or an ENL flash was excluded from analysis. Excluding additional 20-s periods before and after the periods of missing data had little effect on results.

These observations were analyzed with three primary methods: (1) GLM DE relative to ENL flash observations and ENL characteristics, (2) ENL DE relative to GLM flash observations and GLM flash characteristics, and (3) GLM and ENL flash comparison to derive spatial location error statistics and how GLM and ENL flash characteristics relate to each other. Computation of GLM flash DE relative to ENL (method 1) entailed iterating through each ENL flash and determining if a GLM event occurred within 330 ms and 35 km of the...
ENL flash. If a GLM event occurred, then GLM events matched that ENL flash. These spatial and temporal criteria are similar to that used by Rudlosky and Shea (2013) and Rudlosky (2015) to evaluate LLS DE relative to LIS event observations, except our spatial criteria are 10 km greater due to greater GLM location uncertainty associated with parallax issues.

Rudlosky (2015) noted that relative DE are not sensitive to spatial and temporal matching criteria (generally less than 5%), unless applying very restrictive criteria such as 1 km and 50 ms, in which case DE can be reduced 50%. This is also confirmed by comparing Rudlosky (2015) and Bitzer et al. (2016), who both examined ENL DE relative to LIS events and/or flashes in 2013, except Bitzer et al. used 10-ms and 20-km criteria that better resemble a pulse DE than a flash DE. Despite these large matching criteria differences, the spatial patterns of the ENL DE relative to LIS over Central America and southern United States are similar between the two methods, but the restrictive methodology of Bitzer et al. uniformly yields DE of approximately 50% less (i.e., a DE of 80% decreases to approximately 40%). Additionally, restrictive matching criteria will greatly diminish relative DE values only when matching with elements such as events, groups, and pulses that have a single-associated time. If matching flashes that are clustered with time thresholds greater than 100 ms instead, then a more restrictive time criteria will not greatly diminish DE values.

Note that ENL pulses comprising an ENL flash may extend outside the ±330-ms window of our temporal matching criteria. Consequently, our estimates of GLM DE relative to ENL may more generally represent an underestimate since GLM may detect a weaker ENL pulse greater than 330 ms from the strongest pulse that represents the ENL flash time. However, 61% (87%) of GLM flashes over CONUS have a flash duration less than 350 (650) ms during the 18 December 2017 to 5 May 2018 period (as discussed later in section 4.8). Rudlosky et al. (2019) also noted similar values of flash duration. Additionally, the ENL flash time and location represents the pulse with the strongest peak current, which is the pulse that GLM would most likely detect. Further clustering the ENL flashes (which Earth Networks already cluster using a 700-ms and 10-km criteria) to more approximately match the criteria of GLM (i.e., cluster all ENL flashes within 330 and 16.5 km so that, for example, an undetected ENL flash that is combined with a detected flash is now a combined detected flash) had only minors effects (<5%) on values of relative GLM DE with spatial extremes tending to diminish slightly.

GLM experienced issues causing location error during postlaunch testing. These location errors were mostly systematic biases, and consequently, location offsets were applied to the GLM flash and event data to reduce these location errors. The derivation of these location corrections is described later. Another temporal offset is related to the time photons from lightning takes to travel from the Earth’s atmosphere to the GLM instrument in geostationary orbit, which is approximately 125 ms. Consequently, this study uniformly subtracted 125 ms from all GLM time information. This subtraction increases the number of matches and DE, while using the actual travel time (ranging 119–130 ms) has little marginal effect. This study computed ENL DE relative to GLM (method 2) by determining if any ENL flash matched the GLM flash within 330 ms before, during, or after temporally and within 35 km spatially of the location-corrected flash centroid latitude and longitude. It would be possible to determine whether or not each GLM event matched an ENL flash and then use GLM event-parent links to broadly determine if any ENL flashes matched the GLM flash. However, that is considerably more computationally intensive, and some events were orphans (i.e., had no associated parent flash) during postlaunch testing (Koshak et al., 2018). It is unlikely to greatly affect the DE values and should have less effect on the spatial patterns of DE. Utilizing the time and location of only the strongest ENL pulse will limit the number of matches and reduce the ENL DE as it also will for GLM DE (i.e., method 1). GLM flashes with quality control flags, related primarily to flashes of excessively long duration or number of events, were excluded from this analysis due to greater likelihood of being false alarms. However, their exclusion has little effect on results.

A third analysis (method 3) sought to match each ENL flash to a single, closest GLM flash for direct comparison. For this analysis, ENL flashes were clustered to better match GLM flash criteria by combining ENL flashes that were within 330 ms and 16.5 km of each other. A 35-km and 330-ms criterion was again used for matching between ENL and GLM flashes. However, some ENL flashes may match multiple GLM flashes. To choose the most representative GLM flash, a 100-ms difference between the ENL flash and GLM central flash time was equated to a 2-km error in distance when determining which GLM flash was closest in time and space to the ENL flash. A location difference between the ENL and GLM matched flashes could then be
calculated from each ENL flash that had a GLM flash match. These differences were averaged for the latitudinal and longitudinal directions on a 1°-by-1° grid for four separate periods corresponding to GLM processing updates: 25 April to 2000 UTC 28 June 2017, 2000 UTC 28 June to 1841 UTC 7 September 2017 (Revision G), 1841 UTC 7 September to 1 December 2017 (Revision H), and 18 December 2017 to 5 May 2018 (GOES-East position). These average latitudinal and longitudinal offsets were then used to fix some portion of the error in the GLM event and flash latitudes and longitudes. Consequently, the ENL to GLM flash matching (method 3) was rerun (i.e., reiterated) with the improved GLM flash latitudes and longitudes for the GLM-ENL flash comparison shown later. These improved GLM latitudes and longitudes were also used for the GLM and ENL DE computation (methods 1 and 2) described above. Note, however, the location corrections are small (i.e., <5 km for CONUS) for GLM data during the postdrift GOES-East position and primarily related to assumed light emission heights for parallax error correction.

A true direct comparison between ENL and GLM is not possible since ENL detects the electromagnetic sferics from lightning pulses typically lower in the cloud while GLM detects optical signals of events appearing at cloud top. Consequently, differences will always exist between the ENL and GLM flash definitions as well as matching criteria for determining the GLM DE relative to ENL (method 1) and ENL DE relative to GLM (method 2). As a result, the flash densities and relative DE values between the two LLS cannot be directly compared, but differences in general spatial patterns can be elucidated. The matching criteria for both methods 1 and 2 are similar enough to allow some general comparison, but the drawbacks of the methods and both LLS must be considered with these metrics.

4. GLM and ENL Comparison

This study considers GLM and ENL observations accumulated over three periods: 25 April to 1 December 2017 (predrift period with GOES-16 at 89.5°W), 18 December 2017 to 5 May 2018 (postdrift period with GOES-16 at 75.2°W), and the entire period 25 April 2017 to 5 May 2018. The largest reduction in GLM false alarms came with an update on 28 November 2017, based on subjective examination of daily GLM flash density plots. Other updates to GLM occurred between 18 December 2017 and when GLM reached provisional maturity on 18 January 2018 but had no similar noticeable effect. An update on 31 October 2017 modified GLM flash area so that the approximate minimum flash area changed from 3 to 1 GLM pixels. However, ENL flashes during 31 October to 1 December 2018 represent less than 1% of the flashes over CONUS during 25 April to 1 December 2017. Consequently, the inclusion or exclusion of these periods has little effect on the statistics. Instead, we chose to evaluate the predrift and postdrift periods due to the effect on satellite angles and distance from the subpoint for CONUS.

4.1. Flash Density Comparisons

The spatial patterns of GLM (Figure 1a) and ENL (Figure 1b) flash density are similar during the predrift period (25 April to 1 December 2017). Local maxima and minima generally coincide in both panels. Note that a 15-km Gaussian spatial smoothing filter was applied to the GLM and ENL flash densities (as also used for all other lightning-related spatial plots). ENL has generally greater flash densities than GLM, which occurs because of differences in flash clustering algorithms as well as varying DE (discussed later). ENL flashes could be grouped to better match the GLM clustering algorithm. However, ENL detects the electromagnetic sferics from lightning pulses lower in the cloud, while GLM detects optical signals of events at cloud top, and consequently, differences will always exist between the ENL and GLM flash definitions. The general greatest densities over CONUS are in western Kansas, eastern Oklahoma, and the Florida peninsula for both GLM and ENL. However, the absolute maximum is in western Kansas for ENL and eastern Oklahoma for GLM.

Relatively little lightning is observed near the CONUS west coast with GLM and ENL flash densities generally less than 0.5 fl/km² (blue regions in Figure 1). A disparity between GLM and ENL flash densities exists over the Pacific Ocean, where ENL DE is expected to be less due to absence of sensors. However, this disparity is primarily due to infrequent lightning over the Pacific and GLM false alarms contributing to a significant portion of the total GLM lightning. During the postdrift period (18 December 2017 to 5 May 2018), both GLM (Figure 1c) and ENL (Figure 1d) flash densities are mostly less than 0.01 fl/km² over the Pacific. Flash densities over CONUS are notably lower during this period indicative of flash totals that are 90% less than the previous period. However, local maxima and minima in the GLM and ENL flash densities are still generally coincident. The greatest values during this period (Figures 1c and 1d) are over eastern
Kansas and eastern Texas into Louisiana. GLM flash densities are greater than ENL in an approximately latitudinal band east of the Bahamas, which are mostly GLM false alarms that coincide with a real-time event processor boundary. This issue is expected to be addressed in a later GLM update (Koshak et al., 2018).

### 4.2. Spatial Variations in GLM Detection

GLM and ENL observations can be compared more closely through the calculation of a DE. The GLM DE relative to ENL is the percent of ENL flashes that are approximately coincident (within 330 ms and 35 km) with a GLM event, as described in section 3 as method 1. Figure 2a indicates GLM DE relative to ENL during the predrift period. Areas with less than 0.5 ENL fl/km² are masked out due to the inability to compute representative statistics. Results should also be interpreted cautiously away from CONUS where there are fewer ENL sensors and mislocated ENL flashes are more likely. The greatest GLM DE over CONUS is near the Texas/Louisiana and Oklahoma/Arkansas borders (~90%). DE exceeds 80% across much of the southeastern United States, with lower values in the western United States, Northern Plains, and parts of the Mid-Atlantic. Much of CONUS has flash densities less than 0.5 fl/km² during the postdrift period. However, the same general spatial pattern of GLM DE relative to ENL (Figure 2b) is persistent with greater DE in the southeastern United States and lesser DE in the plains. This spatial difference is consistent with Fuchs et al. (2016) that found larger discrepancies between LMA flash densities and LIS/OTD climatology in northeastern Colorado compared to northern Alabama and the Washington, D.C. area, although OTD (the sole optical information source north of 38°N) had bandwidth limitations unlike GLM.

As stated in section 3, the GLM DE relative to ENL presented in this study may represent an underestimate due to ENL flash duration ambiguity (i.e., flash start and end time being unknown). This ambiguity does not appear to greatly alter results as DE still increases as the number of pulses in a flash (i.e., multiplicity) increases for ENL flashes over CONUS during the entire 25 April 2017 to 5 May 2018 period (solid line using right axis in Figure 3a). The CONUS region is defined by the grey contour in Figure 4. The lowest DE is for the ENL flashes with a single pulse, which have no time ambiguity.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** (a, c) GLM and (b, d) ENL flash density (fl/km²) during the predrift period (a and b; 25 April to 1 December 2017) and postdrift period (c and d; 18 December 2017 to 5 May 2018) with a 15-km Gaussian smoothing filter applied. ENL = Earth Networks Total Lightning Network; GLM = Geostationary Lightning Mapper.
Note that the markers in Figure 3 indicate DE for that bin is significantly greater (blue upward pointing triangles) or less than (red downward pointing triangles) the DE for all flashes. Statistical significance is within the 95% interval and uses a bootstrapping method (10,000 random samples) that assumes each of the 376 days (using 1200 UTC to begin/end a day) are independent. The significance test helps to indicate uncertainty or sensitivity, which is low for Figure 3.

Single pulse flashes represent over 40% of total ENL flashes for CONUS (histogram bars using left axis in Figure 3a). However, one may expect the increase in DE from 1 pulse to 2 pulses (1.5%) to be similar to that from 2 pulses to 3 pulses (5.5%). Since the increase is smaller, the time ambiguity likely affects the DE for 2 pulse flashes. This difference is smaller for the Northern Plains (3.9% and 4.8% DE increases, respectively; region defined in Figure 4), which suggests that the time ambiguity affects this region less and is not the reason for its lower DE. Consequently, this time ambiguity affects the DE values, but it is not expected to appreciably affect the spatial pattern of values or the relationship of DE with other flash characteristics.

4.3. GLM Detection and IC Polarity

Evaluation of how GLM DE relative to ENL varies with flash characteristics may help explain the spatial variations in GLM DE relative to ENL. Most lightning over CONUS (defined in Figure 4) during the entire 25 April 2017 to 5 May 2018 period has peak current (estimated by ENL) in the $-10$ to $12$ kA range (histogram bars using left axis in Figure 3b). These are mostly IC flashes, and somewhat more positive polarity (>0 kA) flashes are observed than negative polarity (<0 kA). The GLM DE relative to ENL (solid line using right axis) as a function of ENL peak current indicates lowest DE values for smaller absolute peak current values (e.g., $-6$ to 4 kA), and generally greater DE values for positive values relative to negative values. This latter result is consistent with positive polarity flashes (whether IC or CG) being generally higher in altitude (e.g., Brook et al., 1982; Fuchs & Rutledge, 2018) and less likely to have its optical signal greatly attenuated/diffused by an optically thick portion of cloud from the cloud-top GLM perspective.

Regions with IC flashes of predominantly normal (i.e., positive) polarity are also generally regions of greater GLM DE. Figure 4a shows the percent of ENL IC flashes with normal polarity during the predrift period. During this period, normal IC dominates across the southeast and parts of the Mountain West, such as the Colorado Plateau. Inverted IC dominates across much of the Northern Plains and is also more frequent than normal IC in the Snake River Valley of Idaho, southwest of Phoenix in Arizona, as well as other small regions in the east of the Appalachians. If filtering out weak CG flashes (e.g., absolute peak current <15 kA), these will also generally be regions of +CG (not shown) as documented previously (e.g., Zajac & Rutledge, 2001). These local minima in Figure 4a also tend to be regions of lower GLM DE (Figure 2a). Caution is advised in interpreting the polarity information away from CONUS as IC flashes and flash polarity are difficult for ENL to correctly identify due to, for example, reduced sensitivity as well as ionospheric reflections where sensor density is lacking.
During the postdrift period (Figure 4b), normal IC is again more dominant over the southeast, and inverted IC is more dominant over the plains, coinciding with general regions of greater and lesser GLM DE (Figure 2b), respectively. Across the southeast, there is evidence of predominantly inverted-IC storms, such as north of Dallas in Texas and near the Everglades in Florida (Figure 4b), which were dominated by normal IC during the predrift period. This suggests that inverted IC may be more common across the southeast in
the winter and early spring, as opposed to late spring and summer represented in the predrift period. Again, these regions of inverted IC near Dallas and the Everglades are also regions of lower GLM DE. GLM DE as a function of ENL peak current differs in the Northern Plains region (Figure 3c) relative to the southeast (Figure 3d; regions defined in Figure 4). For all bins of peak current, GLM DE is less for the Northern Plains than the southeast region. Consequently, even a normal IC flash will have lesser DE in the Northern Plains than the southeast, and likewise an inverted IC will have greater DE in the southeast than the Northern Plains. These inverted-IC flashes in the southeast may be more likely to occur outside a strong updraft core where IC polarity may have less correspondence to flash altitude (Stolzenburg et al., 1998). Inaccurate estimates of polarity or the grouping of a dominant inverted-IC pulse with weaker normal-IC pulses may also affect the regional differences in inverted-IC DE. However, other factors likely also contribute to the lower DE in the Northern Plains relative to southeast. These factors may relate to greater GLM pixel FOV and zenith angles in Northern Plains, other flash characteristics, or optical storm characteristics that cause more scattering and loss of detectable signal.

Lindsey et al. (2006) indicated that the most frequent occurrence of 3.9-μm reflectivity greater than 5% for ice clouds during the warm season over CONUS was near the Colorado/Kansas border ranging from the northern Texas panhandle to western Nebraska, which is similar in location to the area of mostly inverted-IC flashes in the Northern Plains. Greater 3.9-μm reflectivity generally indicates greater amounts of ice with smaller particle sizes typically associated with clouds with strong updrafts, high cloud bases, and/or greater concentrations of CCN (Heymsfield et al., 2005). These small ice particles not only cause scattering but also increase the optical depth somewhat at visible and 777-nm wavelengths (McFarquhar & Heymsfield, 1997) for a given ice water path, which may obscure the lightning signal that GLM detects. This area of more frequent inverted IC in the Northern Plains is also the area of generally greater number of annual hail days as estimated by radar (Cintineo et al., 2012). Greater ice path would also increase the optical depth and reduce lightning signal. Fuchs and Rutledge (2018) noted that a larger percent of lightning sources over northeastern Colorado coincided with reflectivity of 20 dBz or greater relative to other LMA regions, which would also indicate more ice path near the flash.

The regions dominated by inverted IC are also agricultural areas and/or valleys, suggesting a possible link between inverted-IC and air chemistry and/or steeper temperature lapse rates associated with mid-level orographic descent and capping inversions that localize convection or concentrate emissions (Davies, 2004). Most of these minima in normal-IC percent (Figure 4a) coincide with locations of greater ammonia emissions and/or concentrations. Kharol et al. (2018) illustrates ammonia concentrations for the 2013 warm season derived from the Cross-track Infrared Sounder (their Figure 1a) with maxima near western Kansas, Snake River Valley, and eastern North Carolina. The primary source of ammonia emissions is livestock waste, while agricultural fertilizer and biomass burning also contribute (Behera et al., 2013). Despite the occurrence of inverted-IC-dominated storms over southern Florida and the Everglades in spring of 2018 (Figure 4b), the Everglades is generally not a documented area of high ammonia emissions. However,
ammonia emissions likely occurred due to wildfires and/or from the onset of the rainy season after drought (Placella & Firestone, 2013). An increase in CCN from wildfires in southern Florida (Holle, 1971) may have also affected polarity. Previous studies have hypothesized a relationship between flash polarity and atmospheric/aerosol chemistry affected by the presence/absence of ammonia, nitrates, and sulfates (e.g., Chronis, 2016; Jungwirth et al., 2005). Ammonia concentrations may relate to aerosol concentrations as well as the pH of hydrometeors and subsequent charging. Properly addressing this subject is beyond the scope of this article.

4.4. GLM Detection and GLM Flash Characteristics

The spatial pattern of the mean GLM flash energy (Figure 5a) over CONUS during the predrift period has some similarities to that of GLM DE relative to ENL (Figure 2a) and to the normal-IC percent pattern (Figure 4a). Specifically, flash energy is generally lower in the Northern Plains where GLM DE and normal IC is lower, while flash energy, GLM DE, and normal-IC prevalence is greater in the southeast, excluding peninsular Florida. Flash energy is weaker in central and southern Florida where GLM DE was somewhat less compared to the southeastern United States as a whole despite the large dominance of normal IC over inverted IC. This suggests that although the flashes tend to be high altitude, they also tend to have a weaker signal that GLM is less likely to detect. The Colorado Plateau also has a similar occurrence of weaker mean flash energy and less GLM DE relative to the southeast, despite the predominance of normal-IC lightning. The mean GLM flash area (Figure 5b) also is smaller in the Mountain West, which may help explain the lower GLM DE relative to the southeast. Smaller flash areas will generally provide less signal that may only occupy a portion of the GLM pixel. That signal is then likelier to be less than background radiance levels. The mean GLM flash duration (Figure 5c) is similar in spatial pattern to the mean GLM flash area, with generally smaller values in the western United States.

During the postdrift period, lower GLM DE is also generally coincident with less the mean GLM flash energy, area, and duration but is not shown due to the small area with sufficient flash densities. Also, note that the spatial patterns of GLM flash energy, area, and flash duration are similar if only averaging for GLM flashes with an ENL match, albeit with generally greater values (not shown). Consequently, the patterns are not due to false alarm contributions. One may also question the effect that greater GLM pixel FOV in the western United States has on the mean GLM flash area, energy, and duration. However, the smaller flash area and duration may relate to the relatively drier environment with shallow warm cloud depths that may limit the expanse of charged particles and, consequently, the size and duration of lightning flashes.

Figure 5. Mean (a) GLM flash radiant energy (fJ), (b) flash area (km²), (c) flash duration (ms), and (d) solar zenith angle of ENL flashes (degrees) during predrift period. Only areas with GLM (a–c) or ENL (d) flash density greater than 0.5 fl/km² during period are shown. GLM = Geostationary Lightning Mapper.
Fuchs and Rutledge (2018) indicated that convective environments with shallow warm cloud depths have thunderstorms with more supercooled liquid water that lead to IC lightning mostly confined to the updraft cores that are broader but produce smaller volumes of reflectivity greater than 30 dBZ (values typically associated with lightning when in the mixed-phase region). Although all these dry environment thunderstorms were inverted-IC-dominated storms, they were also low-shear storms and, consequently, are likely representative of general environmental conditions for thunderstorms over the western United States, despite possible flash altitude differences.

4.5. GLM Detection and Dependence on Solar Angle

The GLM DE relative to ENL is a function of the solar zenith angle (Figure 3e) and has a range for CONUS similar to the DE estimated for LIS. GLM DE for CONUS ranges from 64% for 35°–40° bin to 81% during approximate nighttime (>90° bin in Figure 3e), compared to the 73–93% estimated range for LIS (Boccippio et al., 2002). This range is greater for the Northern Plains (43–72%) than Southeast (74–91%; not shown). The mean solar zenith angle for ENL flashes during 25 April to 1 December 2017 (Figure 5d) indicates flashes that are common overnight and for low sun angles over the Central Plains. This appears to be a result of mesoscale convective systems that commonly occur overnight (Houze et al., 1990). The nighttime thunderstorms likely boost the DE in this region. Mean solar zenith angles of ENL flashes are small over parts of the Mountain West and Florida, likely depressing GLM DE in these regions where midday thunderstorms are common. Note that plots of mean solar zenith angle for GLM flashes (not shown) are very similar. Regions of more midday flashes also tend to be regions of small GLM flash area (Figure 5b).

When comparing ENL peak current to the mean GLM flash area for ENL flashes matched to GLM flashes (described in section 3 as method 3) and distinguishing between approximate night and day flashes (i.e., using 90° solar zenith angle threshold), GLM flash area on average is greater during the night than day for a given bin of ENL peak current (2-kA frequency; Figure 6a). This may be an indication of better GLM DE (particularly, greater likelihood of low energy events passing background radiance thresholds; Goodman et al., 2013) during night instead of actual greater flash areas at night, or more likely indicates both effects. Solar forcing and the consequent differential heating, associated with shorelines, mountain slopes, and other surface or land-use differences, may have a tendency to produce thunderstorms that are more isolated than a storm at night that may be forced more broadly at the meso-beta to synoptic (greater than 20 km) scale. This broader forcing may initiate updrafts occupying a broad area or in close proximity to other updrafts that may help produce larger flash areas. These updrafts at night may also typically be weaker and, consequently, produce larger and less frequent flashes (Bruning & MacGorman, 2013).

Mean flash energy (Figure 6b) is also greater for night compared to day. As absolute ENL peak current increases, mean flash area and flash energy also generally increase. For a given magnitude of ENL peak current, the energy is generally less for the negative value/polarity (i.e., inverted polarity for IC) than the positive value (i.e., normal polarity for IC). The weaker energy and signal may result because of the tendency for negative-polarity flashes to be lower altitude than positive polarity flashes as previously discussed in section 4.3. Mean flash area does not appear to be a strong function of polarity in Figure 6a. Note that plots for the postdrift period are similar, although mean flash energy values are generally greater (not shown).

4.6. Spatial Variations in ENL Detection

Examination of ENL DE relative to GLM (described in section 3 as method 2) indicates small variations across the eastern United States (Figure 7). During the predrift period (Figure 7a), ENL DE is mostly near 80% east of the Mississippi River, except near the Canadian border and Maine. This high DE area coincides with the general region of greatest ENL sensor density (Bitzer et al., 2016). DE values are generally 70–80% across the southwest and Central Plains. Values are smaller in the mountains and into Montana, North Dakota, and Canada. Values are also small into Mexico and fall off into the Atlantic. Many of the peculiar latitudinal banding structures in the ENL DE (e.g., >85% DE band extending from near the satellite subplot longitude southwest of Chicago to southern Connecticut) are artifacts of GLM. During the postdrift period (Figure 7b), values of ENL DE relative to GLM are generally greater with typical values near 90% over CONUS where flash densities are sufficiently great (i.e., >0.5 fl/km³). Smaller values are seen over inland Mexico. The effect of false alarms is seen in the band east of the Bahamas (also in Figure 1c) with values less than 20%. False alarm effects are also seen during the predrift period near D.C., Monument Peak near the...
California/Mexico border and offshore near Pensacola, Florida and northeast Lake Erie, and Ontario (Figure 7a) but are not apparent in recent GLM data (not shown). False alarms near D.C. and Monument Peak were associated with laser beacon testing of GLM (Buechler et al., 2018).

**Figure 6.** Mean (a) GLM flash area (km^2) and (b) flash radiant energy (fJ) as a function of ENL peak current (data points every 2 kA on x-axis) over contiguous United States for night (dashed) and day (solid) flashes. ENL = Earth Networks Total Lightning Network; GLM = Geostationary Lightning Mapper.

Figure 7. As in Figure 2, but percent of ENL DE relative to GLM (a, b). DE = detection efficiency; ENL = Earth Networks Total Lightning Network; GLM = Geostationary Lightning Mapper.
4.7. Temporal Variations in ENL and GLM Detection

A 30-day running ENL DE relative to GLM (solid red line in Figure 8) over CONUS also indicates gradual changes in DE until GOES-16 drifted east, coinciding in an approximate 15% increase. Although the values of ENL DE relative to GLM and GLM DE relative to ENL should not be directly compared due to differences and limitations in methodology, variations in the 30-day running GLM DE (solid blue line in Figure 8) are generally greater than the ENL DE (solid red line) within the predrift and postdrift periods. GLM DE also correlates well to the 30-day running percent of IC flashes that are normal IC (solid black line in Figure 8).

30-day running ENL DE decreases after February, somewhat similar to GLM DE. This likely results from weaker storms during this winter and early spring period that generally produce flashes that are larger and more energetic (Bitzer, 2017) and, hence, are more easily detectable. The increase in ENL DE after the GLM updates near December likely is primarily due to the reduction in false alarms, which artificially reduces the ENL DE during the predrift period. However, some of the reduction in the GLM false alarms may be at the expense of missed detection of smaller and weaker flashes that ENL is less likely to detect. Although the postdrift period does not have enough data to conclude, the potentially less GLM detection is somewhat evidenced by the lower 30-day running GLM DE at the end of the period on 8 May 2018 compared to mid-May 2017, which are periods when storms should have similar intensity and optical property.

4.8. ENL Detection and GLM Flash Characteristics

ENL DE relative to GLM is a function of GLM flash energy, area, and duration (Figures 9a–9c). ENL DE increases monotonically for GLM flash energy, area, and duration during the postdrift period, except for some small decreases in the highest few bins with fewer flashes. Only this period is shown since the GLM flash area and energy distribution changed with a 31 October 2017 GLM update, although relationships with ENL DE are very similar for the predrift period. There also are no strong differences comparing CONUS with Northern Plains or southeast, except for generally higher or lower DE values seen in Figure 7. ENL DE is perhaps somewhat more strongly dependent on GLM flash energy (Figure 9a) than area (Figure 9b) and duration (Figure 9c), although the range of ENL DE will differ if choosing bins differently. Figure 9a uses the square root of energy so that the distribution is somewhat more normally distributed and 1.53 fJ represents the most basic unit of the GLM energy data. Likewise, 70 km² represents the typical area of a GLM pixel (Figure 9b). ENL DE is expected to be a strong function of GLM energy since the brightness of the flash relates to the peak current generated by the flash and estimated by ENL as exhibited in Figure 6 and discussed in section 4.5. A weaker, less bright flash generally has less amplitude for ENL sensors to detect (Figure 6b). Smaller flashes also typically have less energy and less ENL DE. A longer duration flash typically also has greater energy with more pulses that ENL has greater likelihood of detecting. ENL DE relative to GLM has little dependence on time of day as measured by the solar zenith angle (Figure 9d). DE is slightly lower at night (i.e., zenith angle greater than 90°) likely due to better GLM DE at night (Figure 3e).
5. Conclusions

This study compared GLM and ENL observations from 25 April 2017 to 5 May 2018 to gain insight into how detection capabilities differ regionally over the CONUS and as a function of flash characteristics for both systems. These capabilities among lightning locating systems not only had similarities but also had many differences. The goal of this study was not to determine which system is best but to provide a qualitative comparison of the detection capabilities in the early lifetime of the GLM instrument, subject to further improvements to its Lightning Cluster-Filter Algorithm.

GLM DE relative to ENL (i.e., the percent of ENL flashes that approximately coincide with a GLM event) differed regionally, with generally greater DE in the southeast and lower DE in the Northern Plains and other smaller regions in the western United States and east of the Appalachians. This region of greater DE in the southeast was also where most IC flashes were positive polarity (normal IC), whereas most IC flashes were inverted IC in the Northern Plains and many of the other locations of lower DE. Assuming a tripolar NIC model with a negatively charged layer between a higher and lower positively charged layer, these inverted IC would generally occur at lower altitudes than normal IC. Since GLM optically detects lightning emissions typically near cloud top, the lower IC flash will generally have weaker signal that is less likely to reach detectable levels above the background radiance levels. Inverted ICs were noted to be more common in areas of agricultural ammonia emissions, which may affect the charging of ice particles through molecular effects or the number of CCN and amount of supercooled water.

Figure 9. Probability density (bars in percent using left y-axis) and ENL DE relative to GLM (line in percent using right y-axis) as a function of the square root of (a) GLM flash energy, (b) GLM flash area, (c) GLM flash duration, and (d) solar zenith angle of GLM flashes over contiguous United States during postdrift period. DE = detection efficiency; ENL = Earth Networks Total Lightning Network; GLM = Geostationary Lightning Mapper; PDF = probability density function.
However, even normal IC have lower DE in the Northern Plains compared to the southeast. This likely indicates other contributing factors to lower DE in the Northern Plains. Bruning and MacGorman (2013) hypothesize that high frequency lightning storms with intense updrafts may have a complex lattice of small patches of negative and positive charge that small lightning flashes discharge between. Consequently, the polarity of IC flashes in these storms would not generally indicate flash altitude as in the tripolar model. Instead, other contributing factors to lower DE likely include smaller flash area and weaker flash energy, whether in terms of brightness (estimated by GLM) or peak current (estimated by ENL). A flash that occupies only a portion of a GLM pixel (which typically has 8- to 10-km FOV) will generally have a weaker signal than one that occupies the entire pixel. The mean GLM flash area was generally smaller in the western United States, which likely contributes to lower DE in this area, even in regions where normal IC were dominant. Reasons for this smaller flash area in the western United States need to be explored further, including any role longer distances from the satellite subpoint and consequent larger pixel size and larger satellite zenith angles may have. However, the smaller flash area may be related to more isolated updrafts, occurring predominantly during day. Drier environments with shallow warm cloud depths may also limit the expanse of charged particles capable of forming larger lightning discharges. GLM DE was noticeably improved at night relative to small solar zenith angles (~17% greater GLM DE over CONUS). This improvement is similar to the estimates for the optical, low-orbiting LIS instrument (Boccippio et al., 2002).

ENL DE relative to GLM was fairly uniform across the eastern United States, with lower DE near the borders with Canada and Mexico as well as in the northern Rockies. ENL DE was positively correlated to GLM flash energy, area, and duration with DE less for weaker, smaller, and shorter duration GLM flashes. ENL DE was not a strong function of solar angle or time of day.

GLM flash energy and area may also have important utilization for diagnosing storm strength or whether GLM DE may be low. A storm with the mean GLM energy and flash area near the lower detectable thresholds will have many flashes missed below the threshold. However, this needs to be studied at the storm scale beyond using a seasonal or annual statistical period. A storm scale study could also be used to further study the prevalence and cause of inverted-IC-dominant storms associated with lower GLM DE, which can occur even in regions with overwhelming normal-IC proportions at the annual scale, as seen near the Florida Everglades in spring 2018.

GLM greatly expands the lightning monitoring capabilities over the CONUS and much of the western hemisphere, while also providing new insights into lightning and its correspondence to storm intensity. GLM will enhance forecasting capabilities for many facets of storm impact with appropriate research. Improved forecasting of thunderstorm hazards save lives and prevents property damage.

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