Mitigation of Geostationary Lightning Mapper Geolocation Errors

KATRINA S. VIRTS^a AND WILLIAM J. KOSHAK

NASA Marshall Space Flight Center, Huntsville, Alabama

(Manuscript received 13 June 2019, in final form 13 July 2020)

ABSTRACT

The geolocation of lightning flashes observed by spaceborne optical sensors depends upon a priori assumptions of the cloud-top height (or, more generally, the height of the radiant emitter) as observed by the satellite. Lightning observations from the Geostationary Lightning Mappers (GLMs) on *Geostationary Operational Environmental Satellite 16 (GOES-16)* and *GOES-17* were originally geolocated by assuming that the global cloud-top height can be modeled as an ellipsoidal surface with an altitude of 16 km at the equator and sloping down to 6 km at the poles. This method produced parallax errors of 20–30 km or more near the limb, where GLM can detect side-cloud illumination or below-cloud lightning channels at lower altitudes than assumed by the ellipsoid. Based on analysis of GLM location accuracy using a suite of alternate lightning ellipsoids, a lower ellipsoid (14 km at the equator, 6 km at the poles) was implemented in October and December 2018 for GLM-16 and GLM-17, respectively. While the lower ellipsoid slightly improves overall GLM location accuracy, parallax-related errors remain, particularly near the limb. This study describes the identification of optimized assumed emitter heights, defined as those that produce the closest agreement with the ground-based reference networks. Derived using the first year of observations from GOES-East position, the optimal emitter height varies geographically and seasonally in a manner consistent with known meteorological regimes. Application of the optimal emitter height approximately doubles the fraction of area near the limb for which peak location errors are less than half a GLM pixel.

1. Introduction

The Geostationary Operational Environmental Satellite (GOES)-R series spacecraft each include for the first time a Geostationary Lightning Mapper (GLM; Rudlosky et al. 2019). With the advent of GLM, total lightning [cloud to ground (CG) and intracloud (IC)] is observed continuously over the full disk, permitting real-time tracking of the evolution of Western Hemisphere thunderstorms as well as the continuation of the satellite lightning observational record for climatological studies (Goodman et al. 2013).

GOES-16 became operational as GOES-East (75.2°W) on 18 December 2017, and *GOES-17* became GOES-West (137.2°W) on 12 February 2019. Together, GLM-16 and GLM-17 continuously monitor lightning occurrence from the extreme western African coast, across the Americas, to as far west as the Aleutian Islands and New Zealand.

A key unknown in the geolocation of lightning flashes observed in the optical range from orbit is the height at which the illumination was detected by the sensor, which must be assumed a priori. The application of various assumptions of illumination detection height produces a family of geolocation solutions that are aligned along a great circle route originating at the satellite subpoint. At the satellite subpoint, the family of geolocation solutions is identical (i.e., any assumed emitter height will yield the same result). The potential for parallax errors increases with increasing sensor boresight angle (i.e., increasing zenith angle from the perspective of cloud top) and is largest at the edge of the satellite's field of view. If the assumed height is higher than the actual height of the radiant emitter, the geolocated lightning will be displaced too far toward nadir, and vice versa.

Denotes content that is immediately available upon publication as open access.

Supplemental information related to this paper is available at the Journals Online website: <https://doi.org/10.1175/JTECH-D-19-0100.s1>.

^a Current affiliation: University of Alabama in Huntsville, Huntsville, Alabama.

Corresponding author: Katrina S. Virts, katrina.virts@uah.edu

DOI: 10.1175/JTECH-D-19-0100.1

© 2020 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the [AMS Copyright Policy](#) (www.ametsoc.org/PUBSReuseLicenses).

FIG. 1. For the original lightning ellipsoid ($e_1 = 16$ km and $p_1 = 6$ km), (a) the assumed lightning emitter height (km) and (b) the magnitude (km) of the geolocation error produced by a 5-km error in the estimated emitter height of a hypothetical GLM-16 group. The color bar in this and subsequent related figures have been chosen to emphasize the areas with large parallax-related geolocation errors that are the focus on this study.

The longest record of satellite-based lightning observation to date was by the Lightning Imaging Sensor (LIS; Christian et al. 1999; Albrecht et al. 2016), which operated aboard the Tropical Rainfall Measuring Mission (TRMM; Kummerow et al. 1998) satellite from 1997 to 2015. TRMM operated in low-Earth orbit over the tropics, and a constant emitter height of 12.5 km was assumed in the geolocation of LIS data (D. M. Mach 2019, personal communication). Due to its full-disk field of view from geostationary orbit, GLM observes thunderstorms at both larger boresight angles and higher latitudes than LIS. Thus, it was decided during GLM development that rather than applying a constant height throughout its field of view, the assumed emitter height would approximate the climatological annual-mean tropopause height. Specifically, an oblate spheroid defined by the World Geodetic System of 1984 (WGS84) model was employed, but with the semimajor (equatorial) axis increased by a height of $e_1 = 16$ km, and the semiminor (polar) axis increased by a height of $p_1 = 6$ km (Fig. 1a). This approach mimics a tropopause height that gradually slopes downward from equator to poles.

The ellipsoid assumption contains obvious limitations in that it assumes that the emitter height varies in a predictable manner from equator to pole, with similar behavior over land and ocean at all times. In fact, a variety of factors might cause GLM to observe lightning illumination at altitudes other than the climatological tropopause at that location. Tropopause heights vary seasonally, particularly in midlatitudes (Fueglistaler et al. 2009; Gettelman et al. 2011), and in association with synoptic weather systems that frequently produce

thunderstorms (Dell'Aquila et al. 2007). Cloud-top altitude also varies during the convective life cycle. GLM sometimes detects lightning illumination both at the top of the parent thunderstorm as well as reflected off adjacent low-level cloud layers, a phenomenon previously reported in examination of TRMM-LIS data (Peterson et al. 2017). Furthermore, as horizontal distance from the satellite subpoint increases, so does the possibility that GLM will detect illumination from the side rather than the top of a convective cloud, or below-cloud lightning channels. GLM may also detect illumination that is reflected from Earth's surface. Thus, in radiative transfer terms, the radiant emitter observed by GLM is typically the cloud that produces the lightning flash but may instead be reflections off another cloud, reflections off Earth's surface, or even direct emissions from the lightning channel itself. This further implies a broad range of potential emitter heights, particularly near the GLM limb. Figure 1b shows the magnitude of the geolocation error produced by a hypothetical 5-km error in the assumed emitter height of a GLM-16 group as a function of location within the field of view. These sample geolocation errors range from 0 km at the satellite subpoint to ~ 20 km near the limb. Despite these known limitations, the lightning ellipsoid was chosen as the best available geolocation framework for GLM given the lack of information on the actual emitter height and its variability.

In this study, we describe methods to improve GLM location accuracy by adjusting the assumed emitter height, in anticipation that an alternate method will be implemented either in the GLM ground system or in the gridded quality-controlled GLM products (Bruning et al. 2019).

We first document the performance of the lightning ellipsoid, including its poor performance near the limb, and describe an adjustment that has already been implemented to improve its performance (section 3). We then present analysis of the actual emitter height based on comparison with ground-based lightning detection networks, and demonstrate that the application of a geographically and seasonally varying optimal emitter height significantly improves GLM location accuracy for areas near the limb (section 4). Section 4 also includes a preliminary comparison with cloud-top heights derived from the Advanced Baseline Imager (ABI; Schmit et al. 2005) also aboard *GOES-16*, which are not presently linked to the GLM geolocation processing chain.

2. Data and methods

a. Data sources

GLM monitors a narrow ~ 1 nm spectral band in the near-infrared (777.4 nm) in order to detect the radiation produced by lightning flashes. Each GLM instrument consists of a 1372×1300 pixel charge-coupled device (CCD) focal plane array with variable pitch such that pixel footprint sizes range from ~ 8 km at nadir to ~ 14 km near the limb. The instrument operates at 500 frames per second, and the basic observation unit is the frame-by-frame illumination of individual pixels above the dynamically varying background. These illuminated pixels are reported as *events*, and contiguous events within the same frame are termed *groups*. Groups are then clustered into *flashes* using spatiotemporal windows of 330 ms and 16.5 km (Mach 2020; Rudlosky et al. 2019).

For initial testing, *GOES-16* and *GOES-17* were positioned at 89.5°W for nearly a year after their respective launches before moving to their operational slots as *GOES-East* (75.2°W) on 18 December 2017 and *GOES-West* (137.2°W) on 12 February 2019. As we will demonstrate, the emitter height is influenced by a complex combination of geography, seasonal and diurnal variability, and viewing angle. For this reason, we do not analyze lightning observed while GLM-16 was in test position and instead focus on observations after the shift to the *GOES-East* position, and our analysis period is January–December 2018 unless otherwise indicated (GOES-R Algorithm Working Group and GOES-R Series Program Office 2018a). During this year GLM-16 reported about 365 million flashes and 5.9 billion groups, after the quality controls described in Rudlosky et al. (2019) are applied. GLM-16 level 2 data officially reached provisional validation status on 19 January 2018, or just 19 days after our analysis period begins. The Ground Segment software fix (revision DO.07.00.00) implemented

in the GLM ground system on 15 October 2018 adjusted the reported event, group, and flash times to account for the time of flight to the satellite. This revision was not applied retroactively by the ground system to earlier GLM data; however, we have manually applied this adjustment to groups observed prior to revision DO.07.00.00 so that the timing is consistent throughout the analysis period. The ground system revision during 2018 that significantly affected the geolocation of GLM groups was the adjustment to the ellipsoid used to estimate detection height (see section 3). GLM overall detection efficiency has been found to exceed 70% (Bateman and Mach 2020), although performance for the outmost portion of the field of view is reduced (Murphy and Said 2020).

Lightning location data from two global, ground-based networks are used for comparison with GLM. Vaisala's Global Lightning Dataset (GLD360; Said et al. 2013; Mallick et al. 2014; Vaisala 2014; Said and Murphy 2016) detects waveforms in the very low frequency (VLF) range (~ 500 to ~ 50 kHz) and locates the strokes using both time of arrival and magnetic direction finding methods. The Earth Networks Global Lightning Network (ENGLN; Liu and Heckman 2012; Earth Networks 2014) operates wideband (1 Hz to 12 MHz) sensors that detect waveforms produced by both IC pulses and CG strokes, which are located using a time of arrival technique. Earth Networks then groups the strokes into flashes using spatial and temporal clustering criteria of 10 km and 0.7 s, and the reported time and location is that of the most energetic stroke in the flash (M. Stock, personal communication). Within the GLM-16 field of view, the ENGLN sensor network is most dense over the United States, southern Canada, and portions of Brazil. Previously published comparisons have reported peak location offsets of about 5–7 km for ENGLN (Bitzer et al. 2016) and 6–9 km for GLD360 (Rudlosky et al. 2017) with respect to TRMM-LIS, which itself has a persistent location bias of 5–7 km (Zhang et al. 2019). An offset map for ENGLN and GLD360 with respect to each other is in the online supplemental information (SI). While their performance throughout the GLM-16 field of view cannot be fully known due to the lack of a perfectly characterized reference dataset, these networks are the best available for broad-based coverage across the GLM domain. The total number of detections within the GLM-16 field of view during 2018 is comparable for both networks (~ 847 million for ENGLN and ~ 941 million for GLD360). Neither reference network reports reliable stroke altitudes throughout the full domain.

Each GOES-R series satellite carries an ABI with 16 spectral bands ranging from visible to thermal infrared wavelengths. The ABI cloud height algorithm (ACHA;

Heidinger 2012; GOES-R Algorithm Working Group and GOES-R Series Program Office 2018b) produces cloud-top height (CTH) estimates every 15 min based on infrared observations (at 11, 12, and 13.3 μm). The ACHA operates only in pixels for which the satellite zenith angle is less than 70°, such that slivers of the GLM-16 field of view near the limb are excluded (see SI). ABI data are not parallax corrected, with the result that GLM L2 lightning flashes are displaced radially from the cloud features from which they arise. To identify the ABI CTH associated with each GLM-16 group, we renavigate each group detected during 2018 to the ABI fixed grid using renavigation code adapted from Bruning (2019). Each group is then assigned the ABI CTH for the pixel containing the group centroid, based on the most recently completed full-disk CTH image. In less than 1% of cases, no CTH value is reported in the corresponding ABI pixel. Reasons for this may include cloud advection, scattering off the Earth surface, the lightning group being observed at a satellite zenith angle over 70°, or the group being an artifact. In these cases, the closest ABI pixel with a valid CTH is assigned to the GLM group, provided that it is within 20 km of the group centroid.

b. Matching criteria

Because both ENGLN and GLD360 report stroke data (in ENGLN's case, the strongest stroke in each flash), they are most appropriately compared with GLM-16 groups rather than to flashes or events. For this analysis, GLM-16 groups are matched to the reference data using temporal and spatial windows of ± 4 ms and 50 km from the group centroid. Of GLM-16 groups successfully matched, approximately 74% have only one candidate match from either network. For the remaining 26% of groups with more than one potential match, the reference stroke with the smallest weighted Euclidean distance (WED) from the GLM-16 group is selected as the official match. The WED calculation is patterned after Mach et al. (2007):

$$\text{WED}^2 = \left(\frac{D}{50}\right)^2 + \left(\frac{T}{4}\right)^2, \quad (1)$$

where D is the distance between the lightning locations in kilometers and T is the time between them in milliseconds. No official limit is placed on the number of GLM-16 groups that may be matched with a single reference stroke. In practice, of the reference strokes designated as official match for a GLM-16 group, approximately 87% were the official match for only one to two groups. Groups that cannot be matched with a reference stroke are excluded from the analysis.

Direct stroke-to-group comparisons indicate that GLM-16 lags the reference data by about 0.8 ms

FIG. 2. (a) Histogram of temporal offsets (ms) between GLM-16 groups matched with reference networks ENGLN and GLD360 using criteria described in section 2b. The histogram has been scaled such that the plotted values sum to 1. Negative offsets indicate that GLM-16 lags the reference data. (b) Two-dimensional histogram of distance offsets (km) between GLM-16 groups and the reference networks as a function of distance (km) from the satellite subpoint, with each column scaled to sum to 1. The black line shows the peak distance offset. Distance offsets are calculated from the group centroid to the stroke location.

(Fig. 2a). This lag is due in part to cloud multiple scattering in the near-IR (Koshak et al. 1994; Light et al. 2001a,b; Boeck et al. 2004). The broadly peaked distribution is due to GLM's 2-ms frame duration as well as signal intensity. When flashes contain multiple strokes or pulses, some of these will be detected by GLM and not by the reference networks, and vice versa. Peak distance offsets (the metric used for official GLM calibration/validation activities) between GLM-16 and the ground networks are less than 5 km for groups that are less than 6000 km from the satellite subpoint but increase sharply near the limb (Fig. 2b), an observation that will be investigated more thoroughly in the following sections. These histograms, along with a sensitivity study using matching windows of ± 8 ms and 100 km (not shown), demonstrate that

FIG. 3. For the original lightning ellipsoid ($e_1 = 16$ km and $p_1 = 6$ km), (a) the peak distance offset of GLM-16 groups (km; colors) and shift required to best match the reference networks (vectors), and (b) number of groups (10^4) matched with the reference networks per $3^\circ \times 3^\circ$ grid box. For clarity, vectors in (a) are plotted for every other grid box.

the matching windows applied in this study are appropriate for capturing the range of reasonable observed offsets. It is also important to note that results from the ground networks (detected at very low to high frequencies) and GLM will not always align well spatially because radio and optical frequency emissions from the lightning channel are based on different physical processes. In addition, clouds are transparent to radio emissions, but strongly multiple scatter optical emissions.

3. Improving location accuracy by changing the lightning ellipsoid

Originally, the GOES ground system assumed the emitter height configuration shown in Fig. 1a; i.e., an ellipsoid at an equatorial height of $e_1 = 16$ km sloping down to a polar height of $p_1 = 6$ km. The poleward extent of the GLM-16 domain is approximately 54° latitude, such that the lowest assumed emitter height in the field of view was about 9 km. The performance of this configuration is shown in Fig. 3a. Colored shading indicates the peak (i.e., modal) distance offset between GLM-16 and the reference networks in each $3^\circ \times 3^\circ$ grid box. (Note that the $3^\circ \times 3^\circ$ gridding was chosen to strike a balance between larger grid boxes, which increase the sample size within each box and thus reduce noise, and smaller grid boxes, which offer more flexibility in representing real geographic patterns in the emitter height.) The closest agreement is observed over much of the North and South American continents and the northwestern Atlantic, where the distance errors peak at 5 km or smaller (i.e., approximately half the

GLM-16 pixel resolution near nadir). The distance errors generally increase with distance from the satellite subpoint and are largest in the northwestern, northeastern, and southwestern lobes of the field of view, where they range up to 20–30 km or more. Comparatively smaller errors are observed in the southeastern lobe, where intense convective systems initiated over the steep slopes of the South American terrain grow upscale and propagate eastward over the Atlantic (Rasmussen and Houze 2011). Overall, only 33% (11%) of grid boxes at distances more than 6000 (7000) km from the satellite subpoint have peak distance errors of 7 km or smaller, or approximately half the GLM-16 pixel resolution near the limb.

The vectors in Fig. 3a depict the mean latitude difference and mean longitude difference between individual GLM-16 groups and their matched reference strokes; i.e., they depict the shift required to best match the ground networks. These vectors are predominantly oriented toward the limb, indicating that the GLM-16 groups have been originally geolocated too close to nadir. That is, the emitter heights assumed by the original lightning ellipsoid are systematically too high, a problem that is exacerbated during the local winter season when thunderstorms are typically shallower in vertical extent (not shown).

The first step toward addressing this bias involved investigating the use of lower lightning ellipsoids. These ellipsoids were defined by various combinations of equatorial height ($e_2 = 12, 13, \dots, 16$ km) and polar height ($p_2 = 3, 4, \dots, 6$ km), for a total of 19 alternate configurations. All GLM-16 group data for the first

FIG. 4. Mean distance offset (km) between reference lightning data and GLM-16 groups renavigated using ellipsoids defined by various combinations of equatorial height (e_2) and polar height (p_2). Statistics are shown for (a) all GLM groups and (b) groups more than 6000 km from the satellite subpoint. Note that the color scale differs between panels.

5 months in GOES-East position (January–May 2018) were renavigated from their locations under the original lightning ellipsoid ($\text{lat}_1, \text{lon}_1$ for e_1, p_1) to a series of new locations ($\text{lat}_2, \text{lon}_2$ for e_2, p_2), then matched anew with lightning observations from the reference networks using the same criteria described in section 2b. In each case, the number of successful matches changed by less than 1%, illustrating the stability of our chosen spatio-temporal matching criteria. The geographic distribution of matched groups (Fig. 3b) is broadly consistent with the expected climatological pattern of lightning occurrence in the Western Hemisphere. The mean distance errors for each combination of e_2 and p_2 are shown in Fig. 4 for the full domain and for groups near the limb. Based on this analysis, a lower ellipsoid of $e_2 = 14$ km

and $p_2 = 6$ km (Fig. 5a) produced the best statistical location accuracy throughout the field of view. This configuration was recommended in June 2018 and was eventually implemented in the GOES-R series Ground System for GLM-16 in October 2018 (i.e., lookup table parameter update PR.07.01.00) and for GLM-17 in December 2018 (PR.07.03.04). Note that the ellipsoid configuration that would produce the best statistical accuracy for groups more than 6000 km from the satellite subpoint is considerably lower ($e_2 = 12$ km, $p_2 = 4$ km; Fig. 4b).

The performance of this lower ellipsoid is shown in Fig. 5b. Distance errors near the limb noticeably decrease under this configuration: the percentage of grid boxes more than 6000 (7000) km from the satellite

FIG. 5. As in Figs. 1a and 3a, but for the lower lightning ellipsoid ($e_2 = 14$ km and $p_2 = 6$ km).

subpoint with peak distance errors less than 7 km increases to 42% (14%) overall. Despite this improvement, however, peak distance errors of 15–25 km or larger are still observed at some locations near the limb. The outward-pointing orientation of the offset vectors indicates that systematic parallax errors remain, which cannot be addressed within the current lightning ellipsoid framework without degrading the location accuracy over the rest of the domain (cf. Figs. 4a and 4b). An attempt to further mitigate these parallax errors requires the development of a more flexible emitter height framework, i.e., one which varies not just as a function of latitude. The following section describes this approach.

4. Improving location accuracy using an optimal assumed emitter height

To represent the real variations in lightning illumination height as observed by GLM-16, the emitter height used in geolocation should be allowed to vary geographically and seasonally (see section 1). For this reason, all GLM-16 groups recorded for the first full year of GOES-East observations were re-navigated from their locations under the original lightning ellipsoid ($\text{lat}_1, \text{lon}_1$ for e_1, p_1) to a series of new locations ($\text{lat}_2, \text{lon}_2$) that vary as h_2 varies in 0.5 km increments: $h_2 = 1.0, 1.5, \dots, 17.0$ km. Here, h_2 represents the candidate emitter altitude above the surface of Earth, where once again the Earth surface is modeled by WGS84. The re-navigated groups were then matched anew with lightning stroke data from the reference networks; as before, the total number of matches varies by less than 1% regardless of which emitter height is assumed. The candidate value of h_2 that produced the smallest mean location error at a given location for a given month was designated the optimal assumed emitter height. For example, Fig. 6a compares the emitter heights applied for the example midlatitude location of Washington, D.C., under the original ellipsoid (12.1 km) and lower ellipsoid configurations (10.9 km) with the monthly optimal assumed emitter height for a $3^\circ \times 3^\circ$ grid box over the same site. The optimal emitter height varies by about 6 km throughout the year; values are lowest, about 6.5–7.5 km, during the boreal winter season and increase during spring to a maximum of 11.5–12.5 km during the local summer. For this site, application of the original lightning ellipsoid provides nearly the best possible location accuracy during summer. However, during winter even the lower ellipsoid overestimates the actual emitter height by about 4 km, producing a parallax-related bias of 4 km in addition to the inherent GLM variability. The contrast between ellipsoid-derived and optimal emitter height is even starker at sites near the limb such as Seattle in the northwestern United

FIG. 6. Monthly lightning emitter height (km) for a $3^\circ \times 3^\circ$ grid box over (a) Washington, D.C., and (b) Seattle, based on the original ellipsoid ($e_1 = 16$ km and $p_1 = 6$ km), the lower ellipsoid ($e_2 = 14$ km and $p_2 = 6$ km), and the optimal emitter height. Also shown is the monthly number of groups matched with the reference networks.

States (Fig. 6b): here, the lower ellipsoid height of 9.7 km is higher throughout the year than the optimal emitter height, which ranges from 6–8 km during local summer down to 2.5–4.5 km during the winter. Overestimating the actual emitter height by 6 km would produce a parallax-related bias of over 17 km at this location during the winter.

Maps of optimal assumed emitter height are shown in Fig. 7 for two contrasting months: February and August 2018. Both maps exhibit extrema near the satellite subpoint at $(0^\circ, 75.2^\circ\text{W})$, where the family of geolocation solutions is very similar regardless of what emitter height is applied. As boresight angle increases and the emitter height assumption plays a more significant role, geographic patterns emerge. During February (austral summer; Fig. 7a), optimal emitter heights are highest over northern South America and the equatorial Atlantic (14–17 km) as well as southern South America

FIG. 7. Optimal assumed emitter height (km) for GLM-16 for (a) February and (b) August 2018. Interpolation using a spring metaphor is applied for grid boxes with fewer than five successful matches with the ground networks during the month. Also shown is mean ABI cloud-top height associated with GLM-16 groups during (c) February and (d) August 2018, with no interpolation applied.

and near-coastal regions to the east (11–14 km). Local maxima are also observed over the subtropical northeast Pacific, the southeastern United States and Gulf of Mexico, and the Gulf Stream. Optimal emitter heights are lowest over the northwestern, northeastern, and southwestern lobes of the field of view, where they range as low as 1–4 km. During August (boreal summer; Fig. 7b), optimal emitter heights are highest over the intertropical convergence zone (ITCZ) latitudes over South America and the Atlantic as well as off the eastern coast of Brazil (15–17 km), and heights over the central and eastern United States range from 11 to 14 km. During this season, the lowest heights are over the southern Pacific (3–4 km). Thus, the optimal emitter height maps reflect the established meteorological

patterns, with the deepest convection in the equatorial belt and summertime continental regions, as well as the expected lower emitter heights near the limb where GLM can detect side-cloud illumination.

Broadly similar geographic patterns, including low cloud-top heights near the limb, are also observed in maps of the mean ABI-derived cloud-top heights associated with GLM-16 groups (Figs. 7c,d). The most significant differences between the optimal assumed emitter heights and ABI cloud-top heights occur near the satellite subpoint, for reasons discussed above, and in areas with little or no genuine lightning such as the subtropical highs (see SI), where GLM-16 artifacts such as those documented by Rudlosky et al. (2019) can coincide with low-level clouds. Further investigation of the relationship

FIG. 8. As in Fig. 3a, but offsets are calculated when (a) optimal assumed emitter height for the current month and (b) optimal assumed emitter height for months ± 1 are applied. See text for details.

between the ABI cloud-top height and the optimal emitter height is certainly warranted, but is beyond the scope of this paper. Note also from Figs. 7a and 7b that the optimal emitter heights for a given latitude band can vary by 5–10 km during a given month. This further confirms that the lightning ellipsoid, which applies a single emitter height at each latitude band, cannot adequately represent the real variations in lightning illumination altitudes observed by GLM-16.

Maps analogous to those in Figs. 7a,b were derived for all months in 2018. The performance of these optimal assumed emitter heights when applied to the geolocation of GLM-16 groups is shown in Fig. 8. For Fig. 8a, the optimal emitter heights were applied during the same month for which they were derived—i.e., the heights shown in Fig. 7a were applied to groups observed during February 2018, etc. The location errors produced near the limb in this analysis are much smaller than those in Fig. 5b. Approximately 77% (71%) of grid boxes more than 6000 (7000) km from the satellite subpoint have peak location errors of 7 km or smaller when the optimal emitter height for the current month is applied to the GLM-16 group geolocation. The residual offset vectors in Fig. 5b are primarily oriented perpendicular to the axis of parallax correction.

The improvements shown in Fig. 8a demonstrate that the optimal assumed emitter height is capable of providing location accuracy superior to any lightning ellipsoid. However, in practice the emitter heights applied to GLM data must be determined a priori, without the postprocessing optimization described in the previous paragraphs. In other words, we must assess the performance of the optimal emitter height by applying it to

GLM-16 groups detected during an independent time period. To accomplish this, the optimal emitter heights were applied to GLM-16 data from months ± 1 —i.e., the optimal maps for January and March (but not February) 2018 were applied to groups observed during February 2018, etc. The analysis thus retained the seasonal cycle while providing a more stringent test of optimal emitter height performance. The results (Fig. 8b) still represent a marked improvement over the ellipsoid performance in Fig. 5b. This improvement is illustrated in Fig. 9 as the difference in peak location error between Figs. 5b and 8b. The improvement is most significant in the northeastern,

FIG. 9. Improvement in GLM-16 geolocation accuracy when optimal assumed emitter height is applied, represented as the difference (km) in peak location error between Figs. 5b and 8b.

FIG. 10. As in Fig. 3a, but offsets are calculated for GLM-16 groups from January to August 2019 when (a) optimal assumed emitter height for the current month and (b) optimal assumed emitter height for the same month in 2018 are applied. The total number of matched GLM-16/reference network pairs for January–August 2019 is around 667 million. See text for details.

northwestern, and southwestern lobes of the field of view, where the largest errors are currently observed (Fig. 5b). For groups more than 6000 (7000) km from the satellite subpoint, the percentage of grid boxes having peak location errors of less than half a pixel increases to 57% (50%).

As a further performance test, the optimal assumed emitter heights derived for each month from January to August 2018 were applied to GLM-16 groups detected in January–August 2019 (i.e., the optimal heights for January 2018 were applied to groups observed during January 2019, etc.). The performance of the optimal emitter height maps in year +1 is comparable to their performance in months ± 1 (cf. Figs. 8b and 10b), and for groups more than 6000 (7000) km from the satellite subpoint, the percentage of grid boxes having peak location errors of less than half a pixel increases from 47% (25%) using the lower ellipsoid configuration to 61% (35%) using the optimal emitter height from the previous year. While preliminary given that only eight months of data were available for testing, this result suggests that the optimal assumed emitter heights for one year have predictive utility for future years.

5. Conclusions and future work

In the absence of near real-time observations of cloud-top heights in the GLM geolocation processing chain, the geolocation of lightning flashes observed from geostationary orbit requires an a priori assumption of the height at which the illumination is viewed by GLM (the

“emitter height,” where the emitter is the radiant entity observed by GLM and is a cloud, a bare lightning channel, or a reflection from Earth’s surface). Unlike previous low-Earth-orbiting lightning sensors for which a constant emitter height was applied, the GLM L2 processing permits the emitter height to vary with latitude, originally from 16 km at the equator down to 6 km at the poles (i.e., the “lightning ellipsoid”). When applied to GLM-16 data over the American continents, this assumption locates lightning strokes to within approximately half a pixel accuracy over the majority of these landmasses. However, it also produces parallax-related location errors of 20–30 km or more near the limb (Fig. 3), where the actual emitter height is significantly lower than the ellipsoid (Fig. 6) due in part to side-cloud illumination and below-cloud lightning channel detection. To address these location biases, the performance of alternate lightning ellipsoids was tested (Fig. 4), and a lower ellipsoid defined by 14 km (equator) and 6 km (poles) was implemented for both GLM-16 and GLM-17. This lower ellipsoid, which is still in use operationally at the time of this writing, improves location accuracy near the limb, but significant parallax errors remain (Fig. 5).

We empirically derive monthly maps of optimal assumed emitter height for GLM-16, defined as the emitter height that produces the smallest mean location error for each grid box. The optimal emitter heights at a given location can vary by 6 km or more during the year, and their geographic and seasonal variations reflect known meteorological patterns (Figs. 6 and 7). Application of

the optimal emitter height improves GLM-16 location accuracy near the limb by as much as 10–15 km (Figs. 5, 8 and 9). When the optimal emitter heights are applied to months ± 1 (i.e., an independent time period) instead of the month for which they were derived, about 57% (50%) of grid boxes more than 6000 (7000) km from the satellite subpoint have peak location errors of better than half a pixel (Fig. 8b).

The optimal assumed emitter heights presented in this paper were derived based on the first year of provisional GLM-16 data from GOES-East position. This imposes sample size limitations for areas with low lightning density (Figs. 3b, and 6; see also SI)—including many of the oceanic regions near the limb that are the focus of this study. Lightning occurrence during a single year may also not be representative of the actual climatological occurrence, although the performance of the optimal emitter heights from 2018 when applied during 2019 indicates substantial year-to-year consistency (Fig. 10). The optimal emitter heights will be refined over the next few years as more GLM-16 data are gathered, in order to increase the sample size and to ensure that the maps are representative of the climatological emitter height patterns. Analogous maps will also be derived for GLM-17. The full parallax correction methodology provided here has been formally submitted in the form of an algorithm discrepancy report (ADR) with associated lookup tables (LUTs) for intended implementation by the GLM ground system or in the gridded quality-controlled GLM products (Bruning et al. 2019).

The analysis in this paper focused on the geographical and seasonal variations of the emitter height. It is also expected that emitter height will vary diurnally. As an example, the optimal assumed emitter height was calculated for 3-h intervals during August 2018. The diurnal cycle over Washington, D.C. (Fig. 11), is well defined, peaking at 13 km during late afternoon, with a secondary maximum of 11.5 km after midnight and a minimum of 9–10 km during the morning. The peak-to-peak difference of 4 km is smaller than the 6-km variations observed with the annual cycle at this location (Fig. 6a). While a thorough investigation of the diurnal cycle is not possible with one year of data, this analysis indicates that diurnal variability in emitter height may not be trivial. It remains to be seen whether applying a diurnally varying as well as seasonally varying optimal assumed emitter height would further improve GLM-16 location accuracy.

Acknowledgments. KV was supported by a NASA Postdoctoral Program appointment at Marshall Space Flight Center. The authors gratefully acknowledge

FIG. 11. The 3-hourly optimal assumed emitter height (km) for a $3^\circ \times 3^\circ$ grid box over Washington, D.C., during August 2018.

Clem Tillier for providing the GLM event renavigation script used in this study, Doug Mach for background information on LIS, Michael Stock for information on the ENGLN network, and Michael Peterson and three anonymous reviewers for their thoughtful and thorough feedback that significantly improved the paper. GLM data are accessible through the National Oceanic and Atmospheric Administration (NOAA) Comprehensive Large Array-data Stewardship System (CLASS; class.noaa.gov), and monthly optimal detection height maps may be obtained from www.nsstc.uah.edu/data/katrina.virts/GLM/parallax. Earth Networks and Vaisala Inc. collected and provided the ENGLN and GLD360 data, respectively, to the Global Hydrology Resource Center (GHRC) as part of GLM cal/val activities.

REFERENCES

- Albrecht, R. I., S. J. Goodman, D. E. Buechler, R. J. Blakeslee, and H. J. Christian, 2016: Where are the lightning hotspots on Earth? *Bull. Amer. Meteor. Soc.*, **97**, 2051–2068, <https://doi.org/10.1175/BAMS-D-14-00193.1>.
- Bateman, M., and D. Mach, 2020: Preliminary detection efficiency and false alarm rate assessment of the Geostationary Lightning Mapper on the GOES-16 satellite. *J. Appl. Remote Sens.*, **14**, 032406, <https://doi.org/10.1117/1.JRS.14.032406>.
- Bitzer, P. M., J. C. Burchfield, and H. J. Christian, 2016: A Bayesian approach to assess the performance of lightning detection systems. *J. Atmos. Oceanic Technol.*, **33**, 563–578, <https://doi.org/10.1175/JTECH-D-15-0032.1>.
- Boeck, W. L., D. M. Suszcynsky, T. E. Light, A. R. Jacobson, H. J. Christian, S. J. Goodman, D. E. Buechler, and J. L. L. Guillen, 2004: A demonstration of the capabilities of multisatellite observations of oceanic lightning. *J. Geophys. Res.*, **109**, D17204, <https://doi.org/10.1029/2003JD004491>.

- Bruning, E. C., 2019: glmttools. Zenodo, <https://doi.org/10.5281/zenodo.2648658>.
- , and Coauthors, 2019: Meteorological imagery for the Geostationary Lightning Mapper. *J. Geophys. Res. Atmos.*, **124**, 14 258–14 309, <https://doi.org/10.1029/2019JD030874>.
- Christian, H. J., and Coauthors, 1999: The Lightning Imaging Sensor. *Proc. 11th Int. Conf. on Atmospheric Electricity*, Guntersville, AL, International Commission on Atmospheric Electricity, 726–729.
- Dell'Aquila, A., P. M. Ruti, and A. Sutera, 2007: Effects of the baroclinic adjustment on the tropopause in the NCEP-NCAR reanalysis. *Climate Dyn.*, **28**, 325–332, <https://doi.org/10.1007/s00382-006-0199-4>.
- Earth Networks, 2014: Earth Networks Global Lightning Network. Global Hydrology Resource Center Distributed Active Archive Center. Subset used: January 2018–April 2019, accessed 1 May 2019, <http://www.earthnetworks.com/Products/TotalLightningNetwork.aspx>.
- Fueglistaler, S., A. E. Dessler, T. J. Dunkerton, I. Folkins, Q. Fu, and P. W. Mote, 2009: Tropical tropopause layer. *Rev. Geophys.*, **47**, RG1004, <https://doi.org/10.1029/2008RG000267>.
- Gottelman, A., P. Hoor, L. L. Pan, W. J. Randel, M. I. Hegglin, and T. Birner, 2011: The extratropical upper troposphere and lower stratosphere. *Rev. Geophys.*, **49**, RG3003, <https://doi.org/10.1029/2011RG000355>.
- GOES-R Algorithm Working Group and GOES-R Series Program Office, 2018a: NOAA GOES-R series Advanced Baseline Imager (ABI) level 2 cloud top height (ACHA). NOAA National Centers for Environmental Information. Subset used: January–December 2018, accessed 15 August 2019, <https://doi.org/10.7289/V5HX19ZQ>.
- , 2018b: NOAA GOES-R series Geostationary Lightning Mapper (GLM) level 2 lightning detection: Events, groups, and flashes. NOAA National Centers for Environmental Information. Subset used: January 2018–August 2019, accessed 1 September 2019, <https://doi.org/10.7289/V5KH0KK6>.
- Goodman, S. J., and Coauthors, 2013: The GOES-R Geostationary Lightning Mapper (GLM). *Atmos. Res.*, **125–126**, 34–49, <https://doi.org/10.1016/j.atmosres.2013.01.006>.
- Heidinger, A., 2012: ABI cloud height, version 3.0. NOAA Algorithm Theoretical Basis Doc., 79 pp., https://www.star.nesdis.noaa.gov/goesr/documents/ATBDs/Baseline/ATBD_GOES-R_Cloud%20Height_v3.0_July%202012.pdf.
- Koshak, W. J., R. J. Solakiewicz, D. D. Phanord, and R. J. Blakeslee, 1994: Diffusion model for lightning radiative transfer. *J. Geophys. Res.*, **99**, 14 361–14 371, <https://doi.org/10.1029/94JD00022>.
- Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson, 1998: The Tropical Rainfall Measuring Mission (TRMM) sensor package. *J. Atmos. Oceanic Technol.*, **15**, 809–817, [https://doi.org/10.1175/1520-0426\(1998\)015<0809:TTRMMT>2.0.CO;2](https://doi.org/10.1175/1520-0426(1998)015<0809:TTRMMT>2.0.CO;2).
- Light, T. E., D. M. Suszcynsky, and A. R. Jacobson, 2001a: Coincident radio frequency and optical emissions from lightning, observed with the FORTE satellite. *J. Geophys. Res.*, **106**, 28 223–28 231, <https://doi.org/10.1029/2001JD000727>.
- , —, M. W. Kirkland, and A. R. Jacobson, 2001b: Simulations of lightning optical waveforms as seen through clouds by satellites. *J. Geophys. Res.*, **106**, 17 103–17 114, <https://doi.org/10.1029/2001JD900051>.
- Liu, C., and S. Heckman, 2012: Total lightning data and real-time severe storm prediction. *Conf. on Meteorological and Environmental Instruments and Methods of Observation*, Brussels, Belgium, World Meteorological Organization, P5 (10), https://www.wmo.int/pages/prog/www/IMOP/publications/IOM-109_TECO-2012/Session5/P5_10_Liu_Total_Lightning_Data_and_Real-Time_Severe_Storm_Prediction.pdf.
- Mach, D. M., 2020: Geostationary Lightning Mapper clustering algorithm stability. *J. Geophys. Res. Atmos.*, **125**, e2019JD031900, <https://doi.org/10.1029/2019JD031900>.
- , H. J. Christian, R. J. Blakeslee, D. J. Boccippio, S. J. Goodman, and W. L. Boeck, 2007: Performance assessment of the Optical Transient Detector and Lightning Imaging Sensor. *J. Geophys. Res.*, **112**, D09210, <https://doi.org/10.1029/2006JD007787>.
- Mallick, S., and Coauthors, 2014: Evaluation of the GLD360 performance characteristics using rocket-and-wire triggered lightning data. *Geophys. Res. Lett.*, **41**, 3636–3642, <https://doi.org/10.1002/2014GL059920>.
- Murphy, M. J., and R. K. Said, 2020: Comparisons of lightning rates and properties from the U.S. National Lightning Detection Network (NLDN) and GLD360 with GOES-16 geostationary lightning mapper and advanced baseline imager data. *J. Geophys. Res. Atmos.*, **125**, e2019JD031172, <https://doi.org/10.1029/2019JD031172>.
- Peterson, M., S. Rudlosky, and W. Deierling, 2017: The evolution and structure of extreme optical lightning flashes. *J. Geophys. Res. Atmos.*, **122**, 13 370–13 386, <https://doi.org/10.1002/2017JD026855>.
- Rasmussen, K. L., and R. A. Houze Jr., 2011: Orographic convection in subtropical South America as seen by the TRMM satellite. *Mon. Wea. Rev.*, **139**, 2399–2420, <https://doi.org/10.1175/MWR-D-10-05006.1>.
- Rudlosky, S. D., M. J. Peterson, and D. T. Kahn, 2017: GLD360 performance relative to TRMM LIS. *J. Atmos. Oceanic Technol.*, **34**, 1307–1322, <https://doi.org/10.1175/JTECH-D-16-0243.1>.
- , S. J. Goodman, K. S. Virts, and E. C. Bruning, 2019: Initial Geostationary Lightning Mapper observations. *Geophys. Res. Lett.*, **46**, 1097–1104, <https://doi.org/10.1029/2018GL081052>.
- Said, R., and M. Murphy, 2016: GLD360 upgrade: Performance analysis and applications. *24th Int. Lightning Detection Conf. and Sixth Int. Lightning Meteorology Conf.*, San Diego, CA, Vaisala, <https://www.vaisala.com/sites/default/files/documents/Ryan%20Said%20and%20Martin%20Murphy.%20GLD360%20Upgrade%20Performance%20Analysis%20and%20Applications.pdf>.
- , M. B. Cohen, and U. S. Inan, 2013: Highly intense lightning over the oceans: Estimated peak currents from global GLD360 observations. *J. Geophys. Res. Atmos.*, **118**, 6905–6915, <https://doi.org/10.1002/JGRD.50508>.
- Schmit, T. J., M. M. Gunshor, W. P. Menzel, J. J. Gurka, J. Li, and A. S. Bachmeier, 2005: Introducing the next-generation Advanced Baseline Imager on GOES-R. *Bull. Amer. Meteor. Soc.*, **86**, 1079–1096, <https://doi.org/10.1175/BAMS-86-8-1079>.
- Vaisala, 2014: Global Lightning Dataset GLD360. Global Hydrology Resource Center Distributed Active Archive Center. Subset used: January 2018–April 2019, accessed 1 September 2018, <https://www.vaisala.com/en/products/data-subscriptions-and-reports/data-sets/gld360>.
- Zhang, D., K. L. Cummins, P. Bitzer, and W. J. Koshak, 2019: Evaluation of the performance characteristics of the Lightning Imaging Sensor. *J. Atmos. Oceanic Technol.*, **36**, 1015–1031, <https://doi.org/10.1175/JTECH-D-18-0173.1>.