Flash Optical Energy from the Geostationary Lightning Mapper

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ABSTRACT: The Geostationary Operational Environmental Satellite - 16 (GOES-16) Geostationary Lightning Mapper (GLM) is evaluated for many months during the Post Launch Product Test (PLPT) phase in order to ensure that optimal products are available for both the operational forecasting and broader scientific research communities. The emphasis of the PLPT phase is to validate the GLM performance (i.e., lightning flash detection efficiency, geolocation and time-stamp accuracy) using an extensive network of independent ground-based, in-situ, and space-based reference lightning detection systems. However, another essential aspect of the PLPT phase is to obtain benchmarks of the GLM lightning optical amplitude, so that any long-term degradation in the nadir-staring GLM camera system can be realized and quantitatively assessed. This is accomplished in a straight-forward manner by collecting a very large sample of lightning flashes across many geographical regions in the GLM field-of-view so that statistically meaningful benchmarks of lightning optical amplitude (i.e., optical energy in units of femto-joules per flash) are obtained. The benchmarking is particularly important to follow-on studies that will attempt to incorporate the flash optical energy product into new derived products (e.g., energy-weighted lightning "jump" warning algorithms, and lightning nitrogen oxides production estimates).

INTRODUCTION

The optical emission from a lightning discharge is significantly multiple-scattered by the thundercloud medium and results in a diffuse cloud-top illumination that can be detected from space. High altitude aircraft observations have provided insight on the statistics of lightning cloud-top optical pulse amplitudes [Christian and Goodman 1987; Goodman et al. 1988], and detailed physical models describing the multiple scattering process have been discussed in the literature [e.g., Thomason and Krider 1982; Koshak et al. 1994].

GOES-16 GLM pixel-level lightning *event* optical energy is given simply in units of Joules (J). This has the advantage that the energy of derived products such as the *group* optical energy and the *flash* optical energy are simple sums of the fundamental event optical energies (see Mach et al. [2007] for a detailed discussion of the definitions of events, groups, and flashes). This means, for example, that small

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area bright illuminations could have the same total energy as dimmer large area illuminations. By contrast, the optical amplitude reported in the Lightning Imaging Sensor (LIS) dataset is a spectral energy density (in units of $\mu Jm^{-2}sr^{-1}nm^{-1}$) as discussed in Koshak [2010; Appendix] and is loosely referred to as a "radiance". Hence, a large optical amplitude in the LIS dataset characterizes the brightness of the flash, not the optical energy (as in the case of GLM). Therefore, the GLM dataset makes it easier to directly inter-compare the detected optical energies of two flashes, whereas the LIS dataset makes it easier to inter-compare the brightness of two flashes.

In this writing, we examine the spatial and temporal variation of the GLM-detected lightning flash optical energy. This effort initiates the process of obtaining a reliable benchmark of lightning flash optical energies that can be used in the future to detect any long-term degradation in the GLM transient response.

DATA

The GLM Level 2 (L2) dataset, composed of optical events, groups, and flashes has been under intense validation using numerous ground, in-situ, and space-based lightning detection systems during the multi-month Post Launch Product Test (PLPT) period. The GLM L2 data achieved the beta-validation level on 5 July 2017, and the provisional-validation level on 19 January 2018. In this study, a 60-day period (January 11 - March 11, 2018) is considered. The Calibration Working Group (CWG) cited January 11 as a good start time for relatively optimal data (i.e., ample ground-segment software fixes, satellite drift to East slot, and associated Instrument Navigation & Registration averaging were all completed by this time).

Figure 1 provides a sample of a typical day within the 60-day analysis period. The left panel shows the location of GLM-detected lightning flashes. However, there are also noise sources such as high energy electrons that trigger the GLM charged coupled device (CCD) detector, and solar-glint artifacts (and
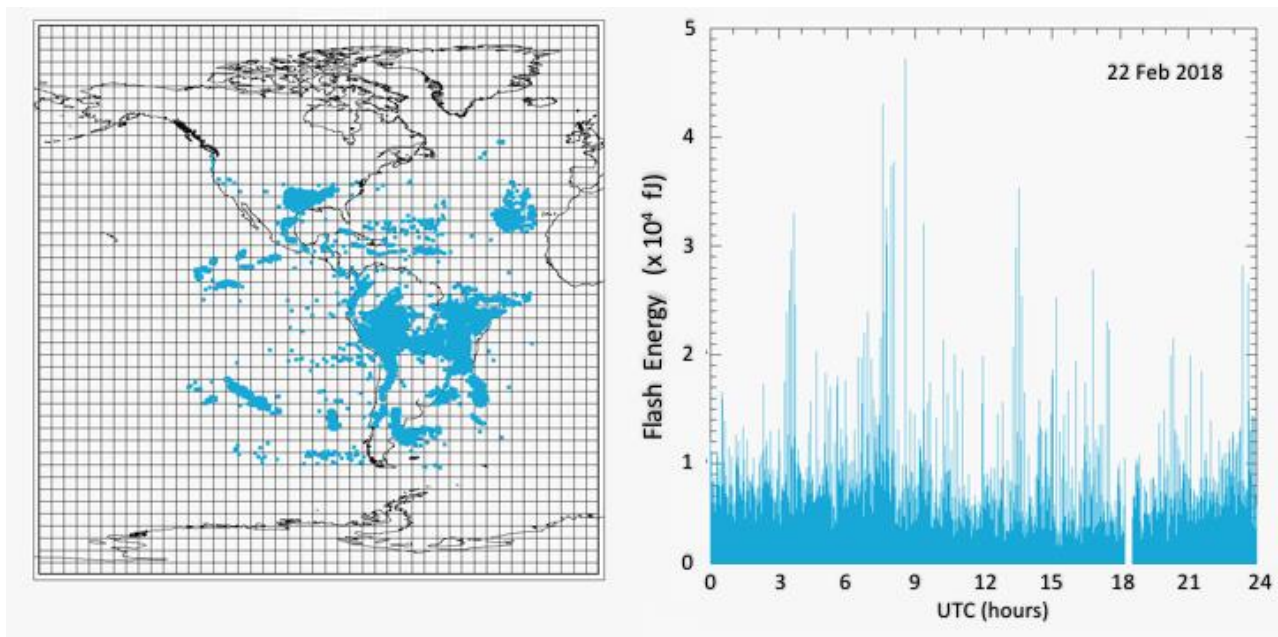

Fig. 1. Sample GLM flash, and noise, locations (left panel) and associated energies (in fJ) v. time (right panel).

associated CCD blooming) that represent false flashes. Expectations, based on analysis of Tropical Rainfall Measuring Mission / Lightning Imaging Sensor (TRMM/LIS) data suggest that GLM flash energies should only be typically one hundred to a few hundred femtoJoules (fJ) per flash, with larger values possible due to natural fluctuation [Koshak 2017]. The right panel plot in Figure 1 shows very large amplitude spikes, the largest of which are likely noise; a short data gap is also seen near 18 UTC. Progress has been made in reducing noise sources during the transitioning from the beta validation level to the provisional level, but advanced filtering methods (including a much needed "blooming filter") are still sought in order to eliminate more noise and to achieve the full maturity validation level. Therefore, the reader should keep in mind that the flash energy results presented here are still in part contaminated by noise not yet removed from the GLM dataset.

RESULTS AND DISCUSSION

Flash Energy Statistics

Figure 2 shows the frequency distribution of the GLM flash optical energies (in units of fJ). A total of over 45 million (flashes plus noise sources) occurred. The GLM *flash* False Alarm Rate (FAR) mission requirements specification is that it be below 5% (over a 24-hr period across the GLM field-of-view), and the actual flash FAR performance is still under investigation within the PLPT process.
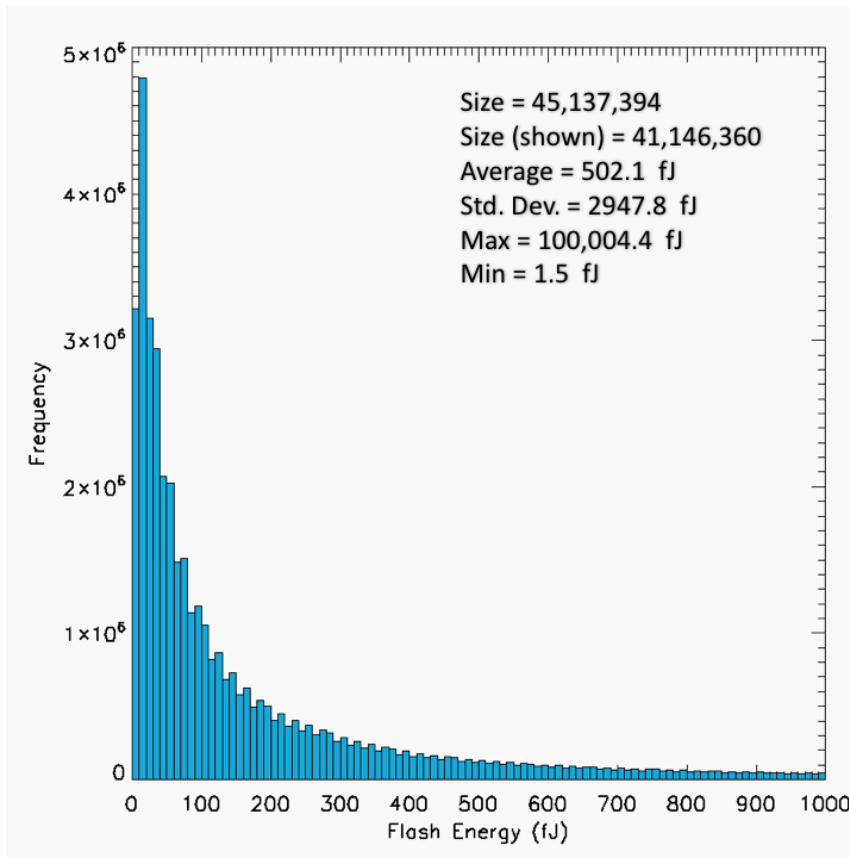

Size = 45,137,394
Size (shown) = 41,146,360
Average = 502.1 fJ
Std. Dev. = 2947.8 fJ
Max = 100,004.4 fJ
Min = 1.5 fJ

Fig. 2.   Distribution of flash energies in the 60-day analysis period. Noise sources bias the results.

Geographical Distribution of Counts and Energy

The large (45M+) flashes were also examined geographically as shown in Figure 3. Note in the left panel of Figure 3, which gives flash counts, that most flashes occurred over the S. American landmass (as expected since the 60-day analysis period is during the Northern Hemisphere winter). The grid cell resolution is 4º x 4º in latitude and longitude, and the overall pattern of flash counts traces out the basic GLM field-of-view. The right panel shows the mean flash energy within each grid cell; i.e. the sum of the flash energies in a grid cell divided by the flash count in the grid cell. Hence, the right panel plot in Figure 3 represents the geographical distribution of the mean flash energy (in units of fJ/flash).
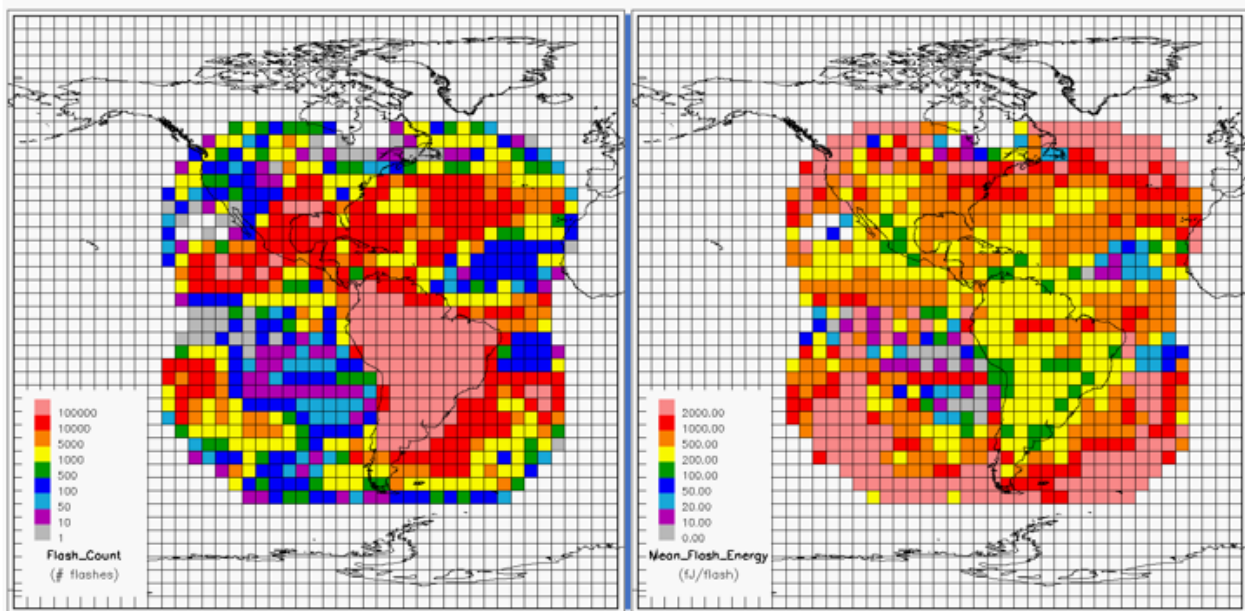

Fig. 3.   Distribution of flash counts (left) and mean flash energy (right) in the 60-day analysis period.

There are interesting geographical variations in the mean flash energy, and it is difficult at this stage to unravel, or even identify, all effects. However, where the flash count is sufficiently large, one typically sees larger flash energy over ocean than over land (e.g., flash energy is mostly larger over the Atlantic Ocean than over the S. America landmass) and this tendency agrees with the TRMM/LIS findings in Beirle et al. [2014]. There also appears to be an increase in flash energy near the limb of the GLM field-of-view. The large energy values at high latitudes over the N. American landmass helps clarify that there is in fact a limb effect since in this case the emission is not from oceanic lightning. The limb effect appears to be due to the fact that the instrument minimum detectable energy increases towards the limb (because of smaller pixel size, and less source throughput through the GLM narrow bandpass filter). But, other factors could be at play (e.g., the enhancement near the limb might in part be due to GLM detecting side-cloud lightning optical emissions, or bare channel emissions from below cloud-top, that are larger than the usual cloud-top lightning emissions). Motivation to examine the geographical variation of mean flash energy came from recent related analyses of TRMM/LIS observed optical energy densities (personal communications, D. Zhang and K. Cummins of the University of Arizona).

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Diurnal Variation

We have found the mean flash energy within each Local Time hourly bin. Performing this analysis over the entire 60-day period ensures that large noise events will adversely influence the overall diurnal pattern. To correct for this, we side-step some of the noise by just considering averaging over a selected 3-day period that appears (from the daily map flash location plots) to have less noise. To remove additional noise, we apply a maximum flash energy filter; i.e., we analyze only those flashes in the 3-day period having flash energy $\leq$ 5000 fJ, $\leq$ 1000 fJ, or $\leq$ 500 fJ. The results for the selected 3-day period (Feb 22-24, 2018) are provided in Figure 4. Note that when energy filters are applied, the results are qualitatively similar to the diurnal variation of the TRMM/LIS flash "radiance" data product provided in Chronis and Koshak [2017].
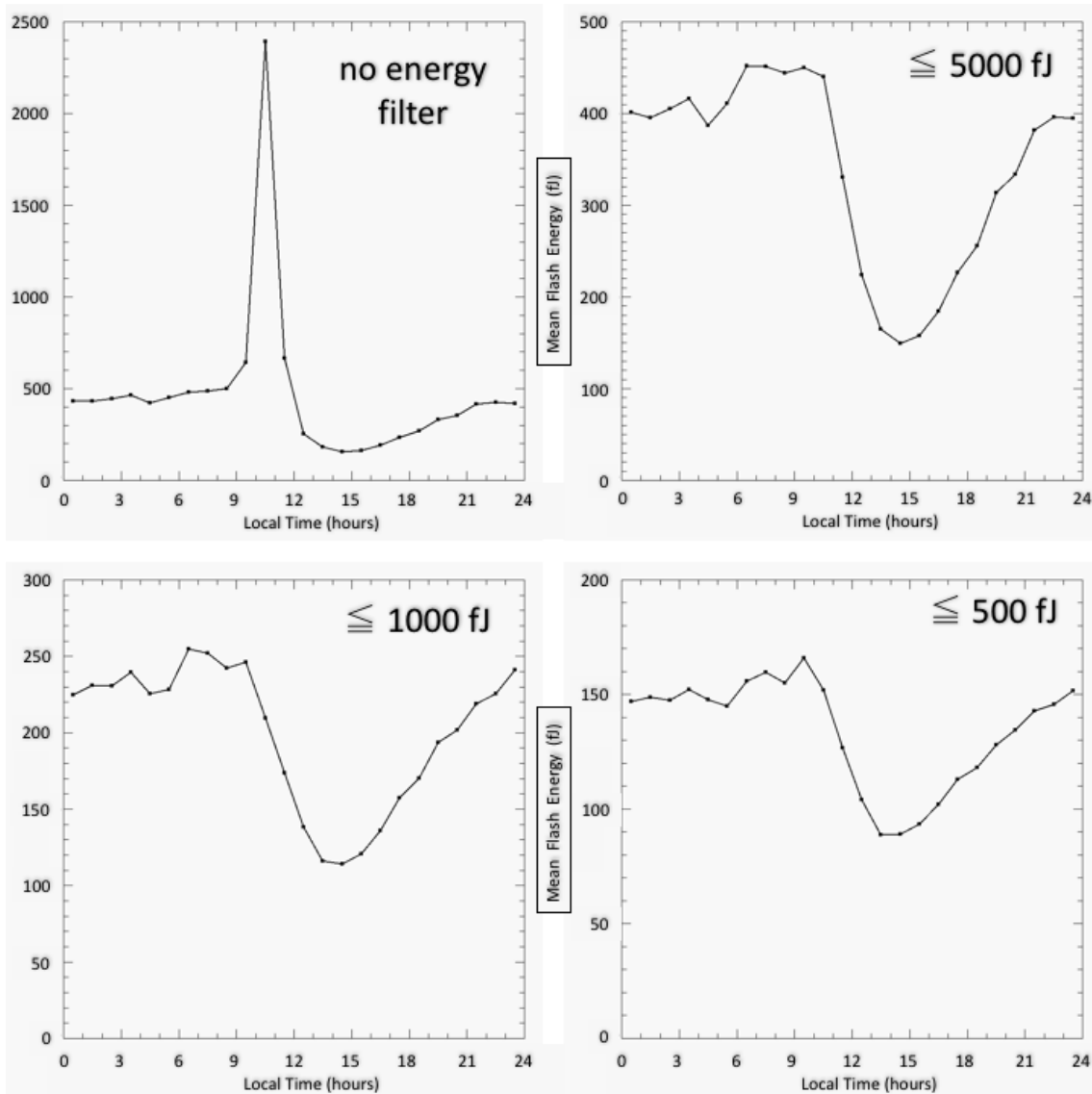

Fig. 4. Sample diurnal variation of the 3-day (Feb 22-24, 2018) mean flash energy v. local time.

The investigation of the diurnal variation of flash energy is a relatively new topic, and so potential biases in the diurnal patterns are still being examined. The Chronis and Koshak [2017; Fig. 6a] study concluded that the diurnal pattern is driven more by the (inverse) relationship between thundercloud flash rate and flash energy than by other potential biases (e.g., instrument threshold setting increases for brighter cloud background, and any biases associated with the sample sizes employed in the analysis). In addition, note that the diurnal variation over land and ocean technically differ [Chronis and Koshak 2017], but Figure 4 shows the diurnal variability from a combination of land and oceanic flashes.

Bench-Marking Long-Term Daily Mean Flash Energy

Finally, Figure 5 provides the daily mean flash energy across the entire 60-day analysis period. This serves as the initial estimate for bench-marking the GLM flash energy. However, since the analysis in Koshak [2017]
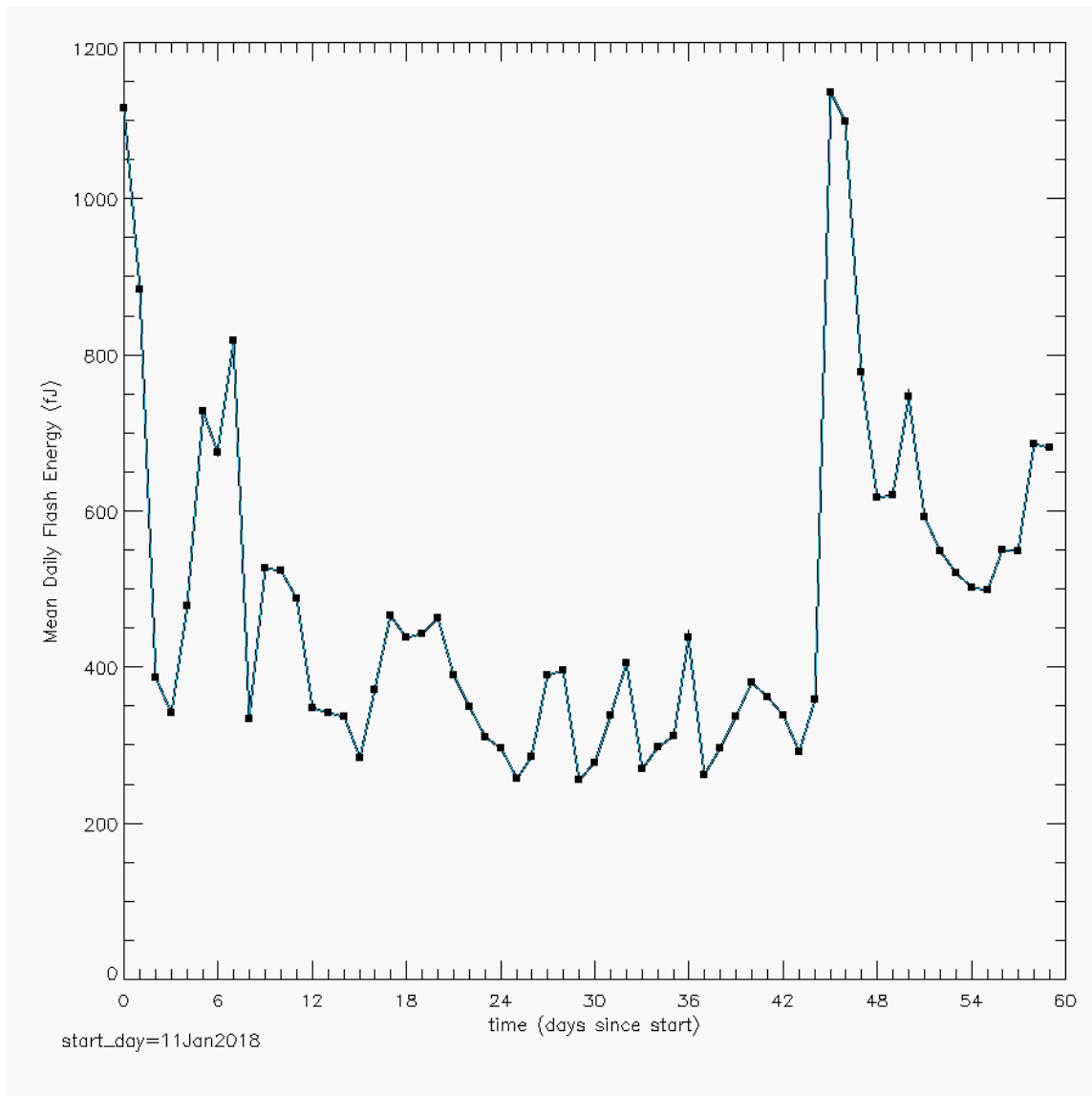

Fig. 5. Daily mean flash energy for the 60-day analysis period (no flash energy filtering performed).

suggests, based on TRMM/LIS observations, that a typical GLM flash energy should be a hundred (or hundreds) of femtoJoules, it is advisable to conduct the same analysis as in Figure 5, but to apply a maximum energy filter ($\leq$ 5000 fJ) in order to at least avoid large noise spikes in the data. The result is plotted in Figure 6. Whereas the mean (and standard deviation) from all flashes is 502.1 fJ (2947.8 fJ) for Figure 5 (i.e., see Figure 2), the values associated with Figure 6 are 297.7 fJ (560.1 fJ). Note that the huge standard deviation (2947.8 fJ, indicative of large noise sources) was reduced to 560.1 fJ from this energy filtration. We are reasonably confident that the energy filter removes a substantial amount of noise and relatively little (if any) actual lightning, so that the results in Figure 6 represent a better bench-marking than in Figure 5. However, these are only preliminary "quick-looks" and it is likely that the results in Figure 6 are still on the high-side due
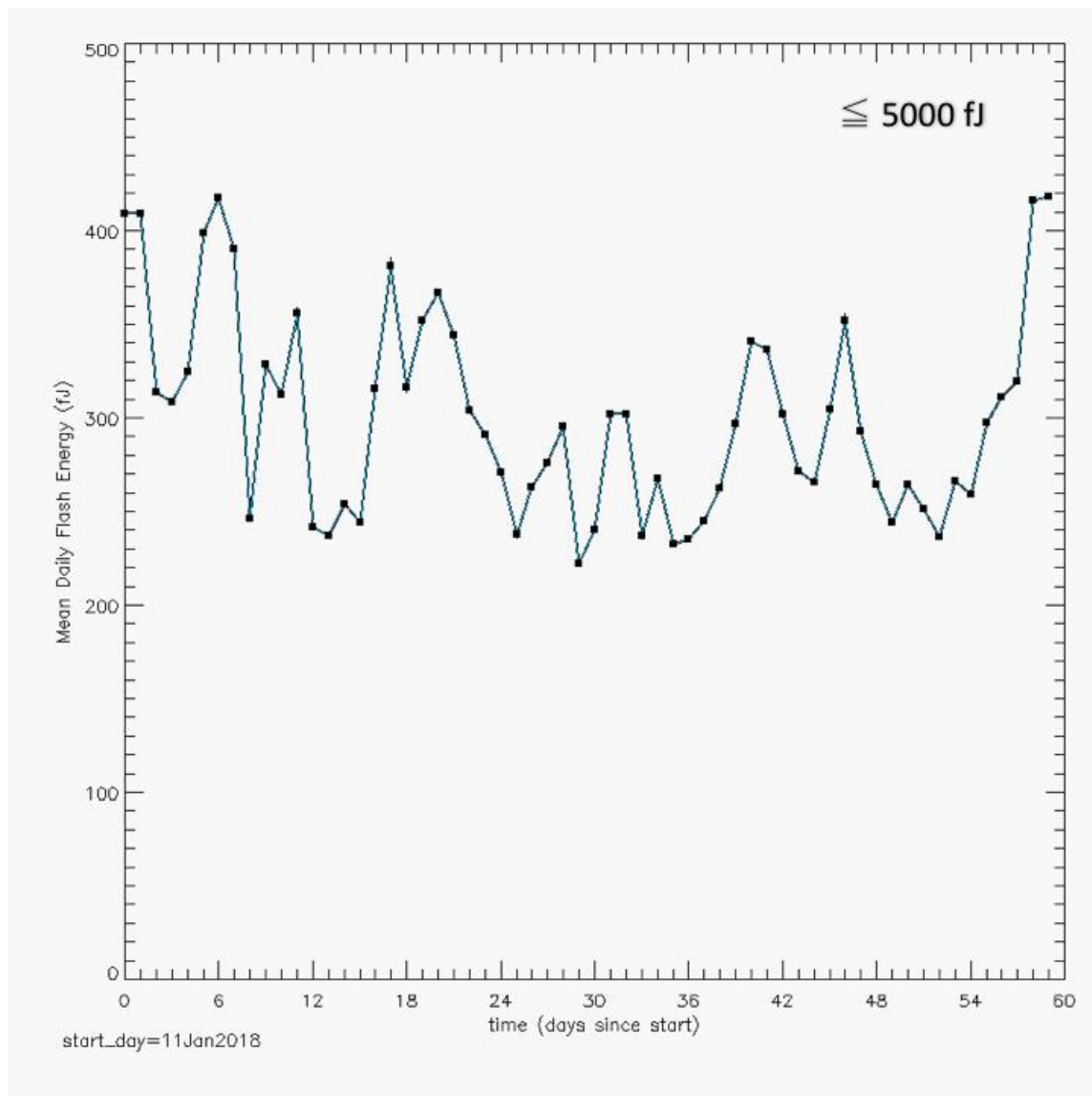

Fig. 6. Daily mean flash energy for the 60-day analysis period (with the 5000 fJ filter applied).

to residual noise. Official bench-marking will be done using a longer analysis period and the best (final validation maturity level) reprocessed data with optimally mitigated noise sources.

CONCLUSIONS

This paper has provided the first detailed look at the geographical and temporal variation in GLM lightning flash energies across the GLM field-of-view over a 60-day (Southern Hemisphere summertime) period. Over 45 million sources (i.e., legitimate flashes plus noise sources) have been analyzed, and the frequency distribution of the source energy and associated statistics have been provided. Given that GLM is still on the pathway to a full maturity validation level and that noise (e.g., high energy electrons, solar glint/blooming) has not yet been optimally mitigated, the flash energy statistics presented here should still be viewed as noise-biased. For example, by removing sources having energies above 5000 fJ (a reasonable approach for removing much more noise than flashes) the mean source energy drops from 502.1 fJ to 297.7 fJ. Nonetheless, it should be noted that significant progress has been made in mitigating noise sources in the process of transitioning from the beta validation level to the provisional validation level, and this progress is expected to continue.

The geographical distributions of flash energy presented in this paper are interesting. As expected, flashes over the ocean appear more energetic on average than over the land, in agreeance with results from previous studies. However, there also appears to be an increase in mean flash energy as one approaches the limb within the GLM field-of-view. This appears to be due to the fact that the instrument minimum detectable energy increases towards the limb. However, other complicating factors also come into play, such as the effect of side-cloud (and/or below cloud) detection of flashes near the limb.

Plots of the diurnal variation of mean flash energy were also provided. This is a relatively new and interesting topic wherein the main drivers leading to the diurnal pattern are not clearly identified and are not well understood, but some reasonably justified explanations have been suggested [Chronis and Koshak 2017]. Given that the GLM diurnal variation results presented here are noise-biased, and were not segregated based on whether the flash occurred over land or ocean, the GLM results still look qualitatively similar to the basic TRMM/LIS results in Chronis and Koshak [2017].

Finally, we provided a preliminary bench-marking of the daily mean flash energy across the 60-day analysis period. Of course, these noise-biased preliminary results will be replaced by official bench-marking results after the noise is optimally mitigated along the pathway to the full maturity validation level. The bench-marking process is vital for quantitatively assessing any long-term degradation in the GLM transient channel.

ACKNOWLEDGMENTS

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