

GOESR3 Final Report

Reporting Period: July 2017 – June 2020 (full 3-year period)

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Project Title: Utilizing Sub-Flash Properties of GLM to Monitor Convective Intensity with Probabilistic Guidance

Project Number: 460

Executive Summary

Rapid increases in total lightning (lightning jumps) are the result of increases in mixed-phase updraft speed and size. Recent work has developed a lightning jump algorithm to objectively identify when a storm has produced a lightning jump using lightning flash data. With the successful launch into orbit of GOES-16, the Geostationary Lightning Mapper brings a long awaited opportunity to measure lightning from space. The GLM instrument will provide sub-flash properties of lightning that directly relate to physical processes within the lightning channel and thunderstorm. Therefore, the goal of this proposal was to understand the impact of and integrate the sub-flash components from the GLM into the operational lightning jump algorithm to improve assessment of thunderstorm strength. This work has the potential take the use of lightning data for hazardous weather monitoring beyond the instrument dependent term “flash” and directly relate to basic physical quantities like radiance, energy, and size. The end result will be a GLM based lightning jump algorithm that can be utilized within the entire field of view of GOES-16 or the future GOES-S, T, and U missions.

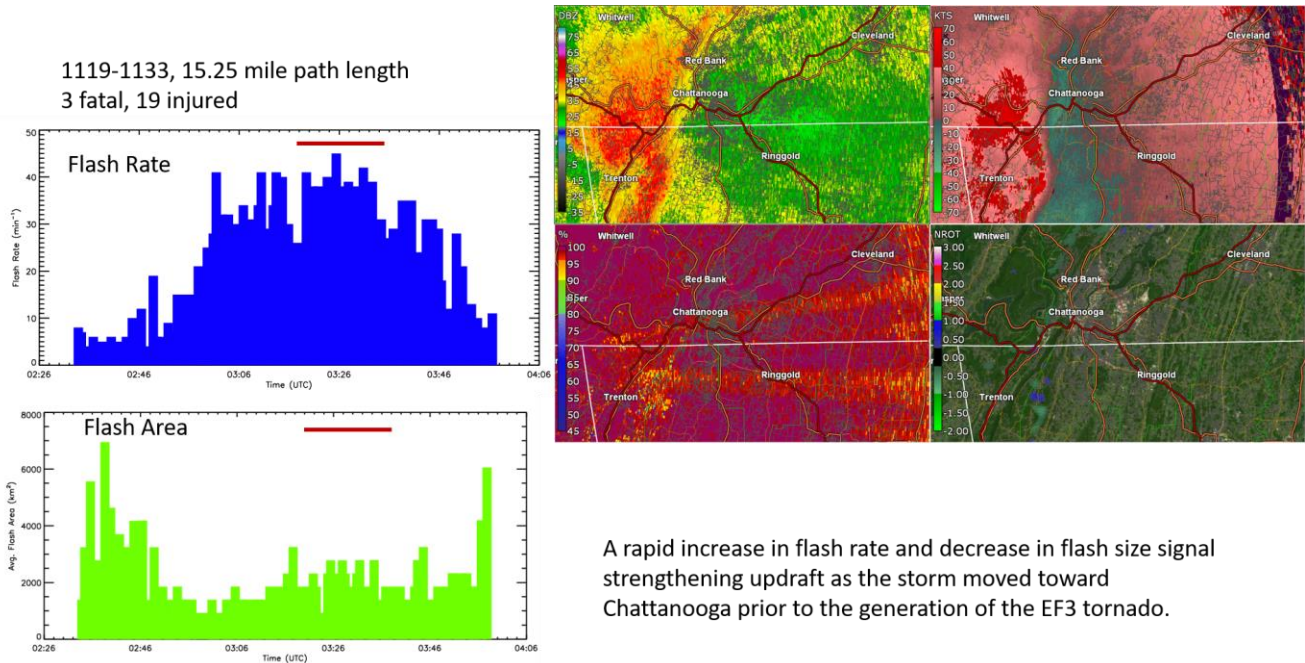
While the original pre-GLM deployment goal of this proposal was to develop a GLM tuned lightning jump algorithm, there are still challenges that exist related to GLM view angle and light extinction due to large ice water paths to create a reliable algorithm for convective prediction. That being said, there are several main outcomes that have been generated from this work, as well as, a tracking methodology which can use a combination of radar and GLM, or GLM by itself to track convective features of interest. The executive summary of this work will be split into two parts. The first part relates to the sub flash properties of storms and their application to monitoring intense convection. The second part is related to the mature storm tracking algorithm that uses a combination of radar and GLM (or can use radar or GLM alone) to track features across the field of view in time and space for convective monitoring. Between investigators Schultz, Murphy, Curtis, and Kahn, over 4000 storms were tracked from throughout the US.

1. Sub flash properties of storms in GLM

Flash extent density and average/minimum flash area fields provide utility related to updraft intensification and convective/stratiform partitioning. Numerous examples exist where GLM flash rates increase, flash size decreases just prior to severe storm manifestation. This follows idea’s we’ve formulated using lightning mapping arrays, and is very positive to see used when lightning signal is not scattered by large optical paths (see FY19 milestones).

A recent example of this behavior is from the Easter 2020 tornado outbreak across the Southeast US. A strong mesoscale vortex approached Chattanooga TN around 11 pm EDT. Prior to this time, flash rates were below 10 per minute, and flash areas were on the order of 4000-7000 km². Then just after 11

pm EDT the flash rate ramped up to 40 flashes per minute, and the average flash size sank to below 2000 km², consistent with an intensifying updraft. Flash rate and flash size magnitudes maintained themselves for nearly 40 minutes after this ramp up/down. Then at 1119 EDT, an EF3 tornado touched down, cutting a 15 mile path length, killing 3, and injuring 19. Additional examples were present in this event across Georgia and South Carolina, where the flash rates rapidly increased prior to additional strong tornado formation.



Total optical energy seems to be variable in its response, as we've observed large increases in TOE just prior to severe weather, or no response at all. Part of this is the challenge with the field of view of GLM as outlined in Daile Zhang and Ken Cummin's work (GLM Science 2019), where there is a drop off in the minimum event energy detection with decreasing view angle. If TOE rates are to be used like flash rates for warning decisions, they will likely need to be normalized. Below is a frequency plot of 1 minute accumulated energy per GLM flash rate. Notice how a broad range of total optical energies are possible for any given flash rate.

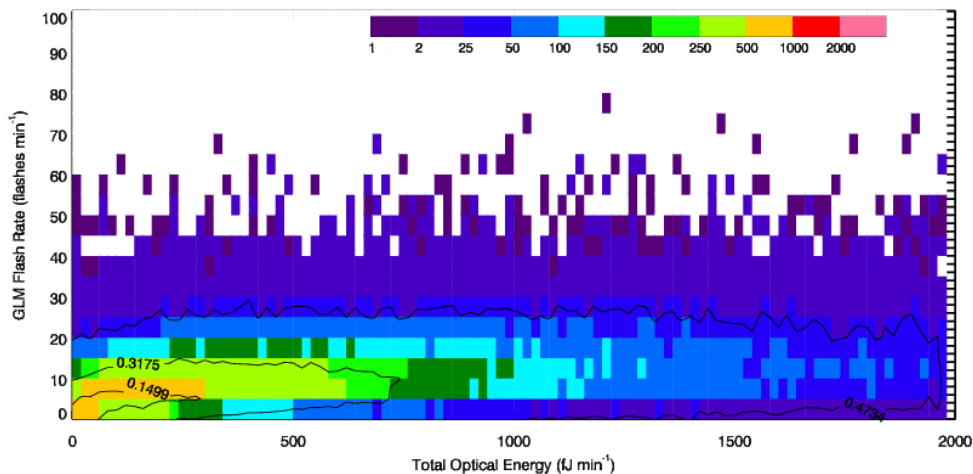


Figure 1. GLM 1 minute energy rate vs GLM flash rate for 3000+ tracked features across CONUS. Contours indicate percentage of population which fall within energy/rate parameter space.

Normalizing by flash rate reduces the energy spread observed above, and provides context to the average energy per flash observed at varying flash rates. The idea behind normalization is one can determine if there are a large number of smaller optically dim flashes contributing to the TOE signal, or a single large energetic flash. This provides some context in the fact that as the flash rate goes up, the flash area and energy per flash should decrease, consistent with flash size spectra theory outlined in Bruning and MacGorman (2013).

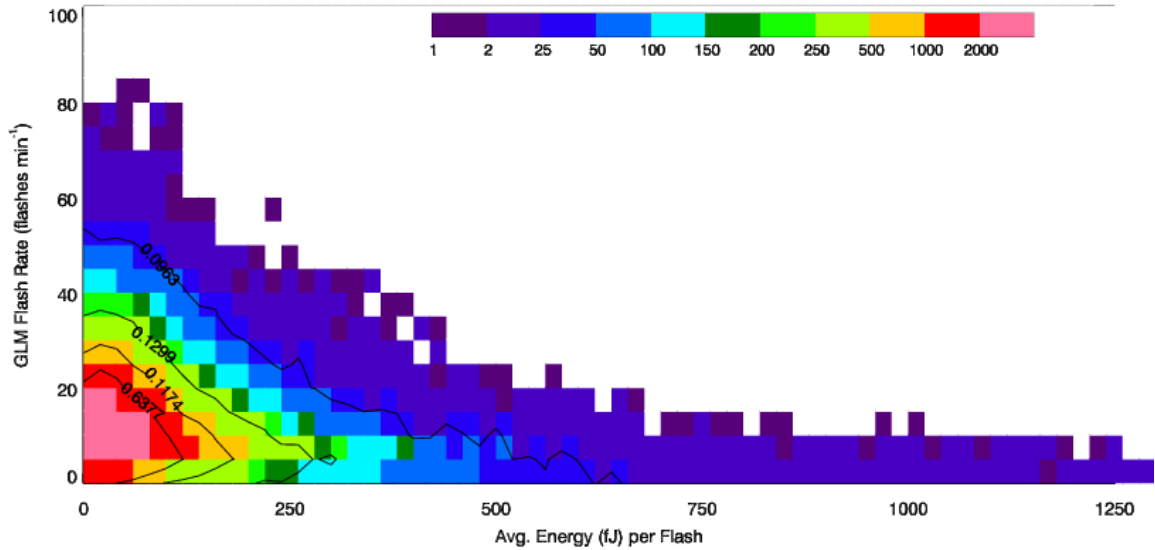


Figure 2. GLM 1 average energy per flash vs GLM flash rate for 3000+ tracked features across CONUS. Contours indicate percentage of population which fall within energy/rate parameter space.

We can see this in a different way by comparing energy per flash with the radar-derived Maximum Expected Size of Hail parameter below. Note how the higher MESH values correspond to lower amounts of energy per flash, which is theoretically consistent with the Bruning and MacGorman (2013) arguments for smaller flash sizes in more intense thunderstorms.

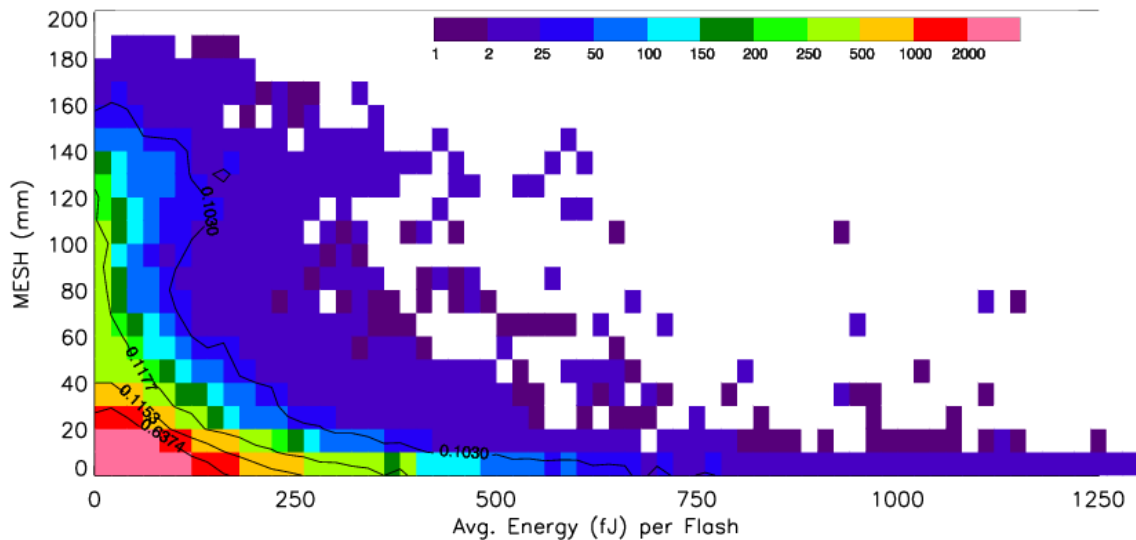


Figure 3. GLM 1 average energy per flash vs 1 minute MESH value for 3000+ tracked features across CONUS. Contours indicate percentage of population which fall within energy/rate parameter space.

2. Storm tracking algorithm using a fusion of GLM and radar for storm tracking across field of view.

A secondary goal of this proposal was to mature a radar and lightning based storm tracking algorithm outlined in Schultz et al. (2016). The team modified inputs to the tracking algorithm to accommodate the GLM flash density data (from the previously used LMA-based GLM Proxy) and started working with select GOES-R Cal/Val Campaign datasets to use the best possible position information prior to the operational rollout in January 2018. Initial results compiled in Curtis (2018) using the original storm tracking method and lightning jump algorithm in Schultz et al. 2016 and Schultz et al. 2009 to see how well the technique worked with the new GLM dataset. Results were okay from the perspective of probability of detection, but very poor for false alarm rate (FAR > 80% at times).

Upon further investigation, the tracking algorithm configuration generated variable largely varying feature sizes, which lead to artificial increases and decreases in flash rate. The culprit was the multiple levels of intensity tracking on the Vertical Integrated Liquid Flash Rate Density (VILFRD; Schultz et al. 2016) field. The segmentation algorithm in WDSS was tracking features in 20 VILFRD unit increments up to 100, and tracking on the highest VILFRD number observed. Thus, at different times the feature identification algorithm in WDSS might be jumping between two different VILFRD levels, especially if the VILFRD value was on the border of two threshold. For example, if a feature was tracking at maximum of 58 VILFRD at one time, the algorithm would identify all areas greater than 40. However, 1 minute later, this maximum may increase up to 64 VILFRD, which means the algorithm would only identify areas > 60 VILFRD. Then in the next minute, it could drop back to 55 and be using the 40 VILFRD contour for feature identification. Thus, in FY19 (Covered below) multiple configurations of storm tracking were examined to find the method that would produce the most consistent feature size and longevity for storm tracking (Murphy et al. 2019, 2020).

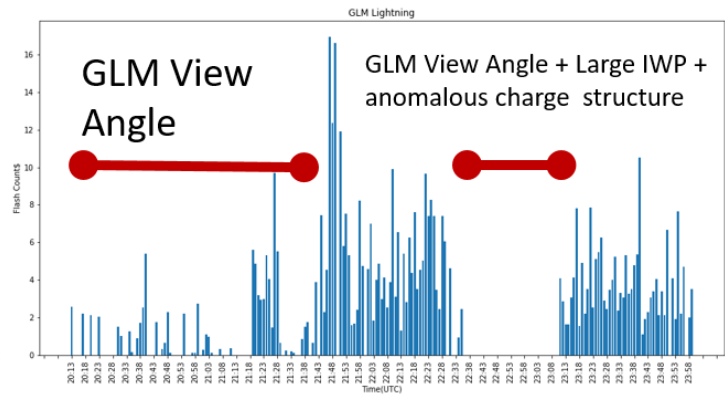
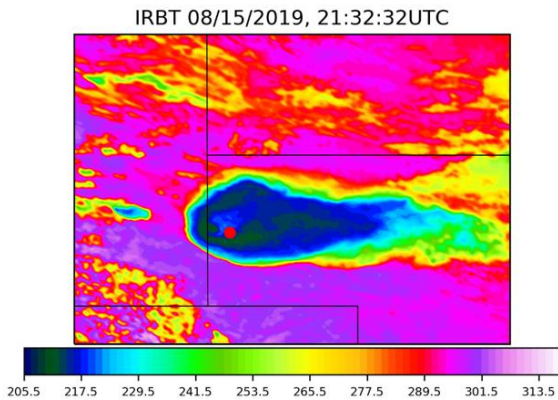
Additionally, we wanted to test the algorithm beyond just use for severe convection. Thus, Kahn (2020) examined less organized convection associated with wildfire production in the Western US, where radar voids/blockage is more prevalent. Using the original Schultz et al. (2016) method, almost all of the 54 wildfire events were missed from a feature tracking perspective. These storms were much smaller in size compared to the typical tracking method (65 km² vs 162 km²). Thus in lesser convective regimes it might be beneficial to track on a smaller flash size. When this minimum area was reduce to 65 km², 36 of the 54 fire starting thunderstorms were tracked for more than 30 minutes, providing a coherent feature to track for impact based decision support. Thus an operational implementation of the tracking algorithm may need to be tuned to the problem of the day to maximize the tracking capability within the GOES-R field of view.

Final Year Milestones (FY19) and Project Deliverables

Assessment of storm days continued between 1 July 2019-30 June 2020.

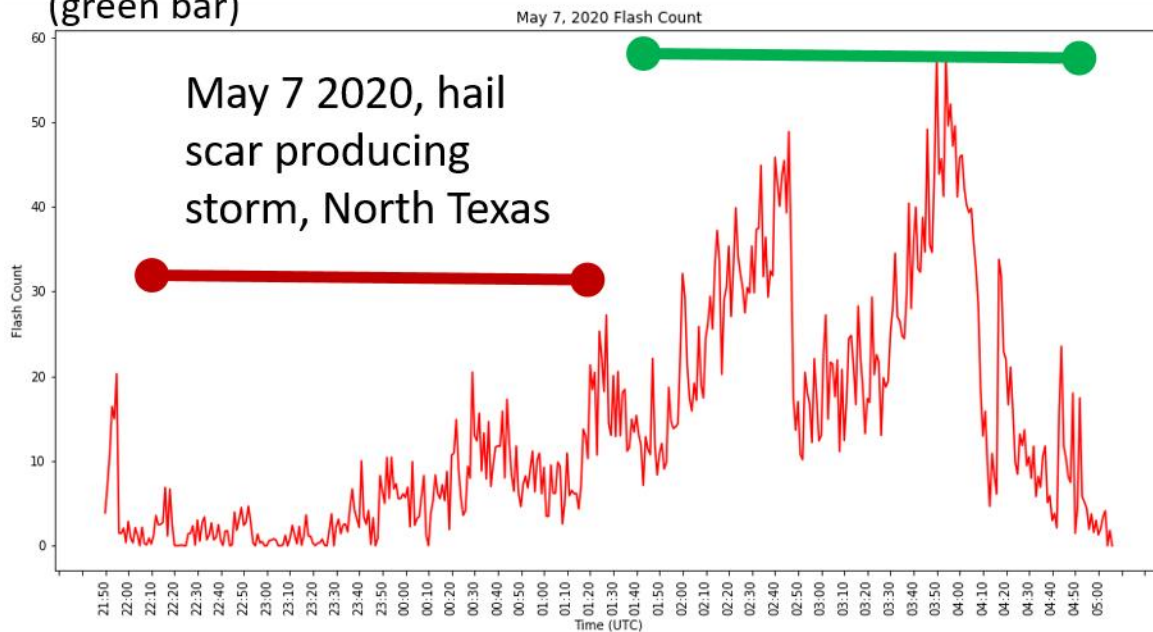
In addition to the various severe weather events across the CONUS during the last year, one of the foci was on hail related cases to quantify the behaviour of the lightning rates in these systems. The goal was to attempt to quantify the loss in signal as an indicator of signal, given the idea that a storm must first ramp up before the ice water path attenuation takes over and limits the signal. We had a varying degree of success in quantifying this aspect at night, but the day time was a challenge. Below are two examples of large hail producing storms over Nebraska and Texas where IWP and view angle were apparent.

These examples are being analyzed in conjunction with other groups in hopes to develop methods to extract signals due to view angle and large IWP. Fellow investigators like Rutledge et al. 2020 and Thiel et al. 2020 (both JGR in press or soon to be in press) highlight additional storms and view angle problems.



Above left: Channel 13 IR temperature image at 2132 UTC on 15 August 2019 over Western NE. **Above right:** GLM flash rate as tracked by VILFRD method. Note low flash rates throughout the storms lifetime with periods of little to no activity while large hail > 2.54 mm fell and land surface scarring was observed during this period. We know lightning was present during the period because we've compared with the Colorado LMA.

Reduced GLM DE during daylight (red bar), increased DE as sun set (green bar)



Above: Flash rate trend in a large hail producing supercell that generated surface scarring across north Texas on 7 May 2020.

Storm tracking outcomes from 2019-2020

VILFRD is a unitless quantity that merges both radar and GLM lightning data into one variable. Identifying and tracking storm cells using VILFRD inherently incorporates the location of lightning into the feature ID process, which is unique to other methods that may only rely on radar derived variables. Due to this, it is hypothesized that the use of VILFRD would be advantageous, especially for lightning applications research. For example, a feature defined using only radar reflectivity may not include lightning that falls outside of a reflectivity contour. In this case, the feature footprint from which information is drawn to classify a storm would be missing potentially valuable flash data. This is especially a concern when considering the spatial extent of lightning detected by the GLM.

The goal of the research is to transition and optimize the VILFRD ID and tracking method from Schultz et al. (2016) for use with the operational GLM data stream. In doing this, an automated and objective thunderstorm ID and tracking system is created which can provide situational awareness to forecasters of the intensity, organization, and evolution of thunderstorms.

Initial observations from the thunderstorm and tracking ID method from Schultz et al. (2016) when used in conjunction with operational GLM data:

- Non-consistent tracked feature boundary size
- Due to the spatial nature of GLM, there were often instances where lightning was falling outside of the tracked feature contour
- "Missed" portions of VILFRD not consistently being identified

Considering the above observations, application concerns could be:

- Non-consistent feature boundary size could result in fluctuating statistical bucket from which storm information is drawn
- Missing of flashes outside of the feature boundary – implications on total flashcount for a feature (this can affect applications such as identifying lightning jumps, lightning intensification trends, etc.)
- Missing strong regions of tracked storms in proximity to other nearby clusters

A few changes were implemented to try to address these concerns. At the beginning of the research, operational GLM data had just become available, so these observations were made using a few selected case days, where a case day includes storms identified and tracked within a specified domain size and time window. As a result of these initial observations, three "new" VILFRD ID & tracking method were configured, as well as one non-vilfrd method for an extra point of comparison. This non-VILFRD method has been used in the past to ID and track storms for application of the lightning jump. The methods were tested on a large sample database to assess performance of the new methods compared to the original configuration. All new methods included no modifications to the VILFRD formulation itself, only on how the quantity is tracked in WDSSII using w2segmotion. They are below:

- 1) Original method: ID storms using VILFRD starting at values of 100, incrementing by 20 down to a floor value of 20 VILFRD.
- 2) 7010 method: ID storms using VILFRD starting at values of 70, incrementing by 10 down to a floor value of 20 VILFRD.
- 3) Original smoothed method: ID storms using VILFRD starting at values of 100, incrementing by 20 down to a floor value of 20 VILFRD. Use a percent filter (90%) on VILFRD to dilate the fields.
- 4) 7010 smoothed method: ID storms using VILFRD starting at values of 70, incrementing by 10 down to a floor value of 20 VILFRD. Use a percent filter (90%) on VILFRD to dilate the fields.
- 5) Standard method: ID storms using the 35 dBZ isosurface -10°C.

The large database is made up of 15 (273 hours) case days. The total number of storms tracked is dependent on the feature ID method, however it ranges from 612 – 1442 storms/tracked features.

(Also of note that a database is being built of tracked days – currently it has 70 case days (where one case day could have anywhere from ~10-200 tracked features/storms).

Initial Results of method performances on large database:

Number of tracked features:

Original	7010	Original Smooth	7010 Smooth	Standard
753	824	1343	1442	612

Average feature duration (mins)

Original	7010	Original Smooth	7010 Smooth	Standard
64.98	63.23	64.93	65.32	72.56

Average flash density (flashes per min/size of feature)

Original	7010	Original Smooth	7010 Smooth	Standard
.04337	.04445	.03442	.03441	.02254

Average size/min of a tracked feature (km)

Original	7010	Original Smooth	7010 Smooth	Standard
322.9	236.0	355.5	293.2	517.4

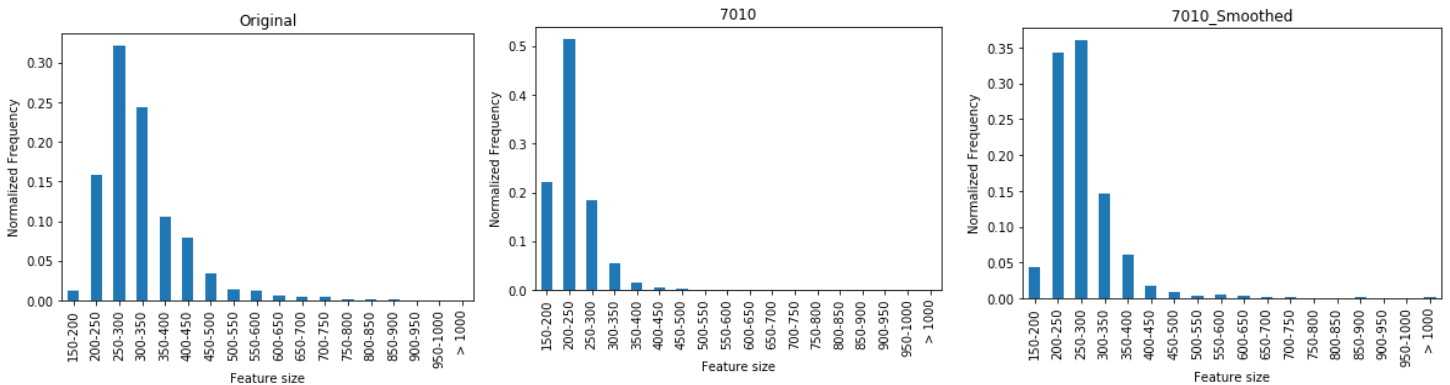
Average change in size/min (km)

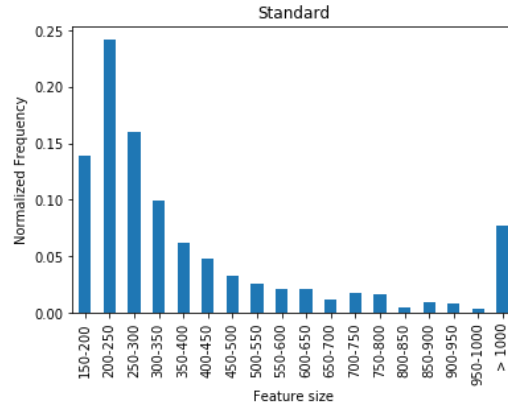
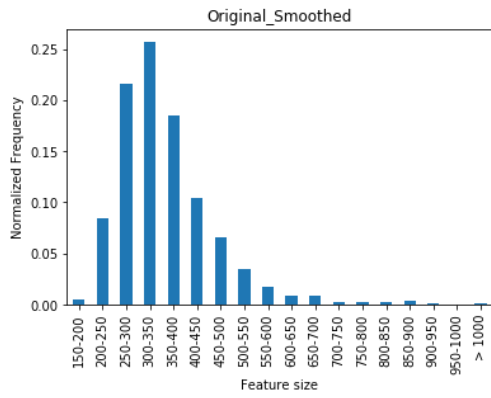
Original	7010	Original Smooth	7010 Smooth	Standard
54.15	42.66	67.13	55.30	45.41

Average change in flashcount/min:

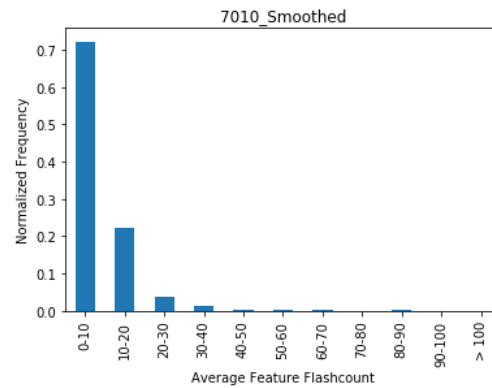
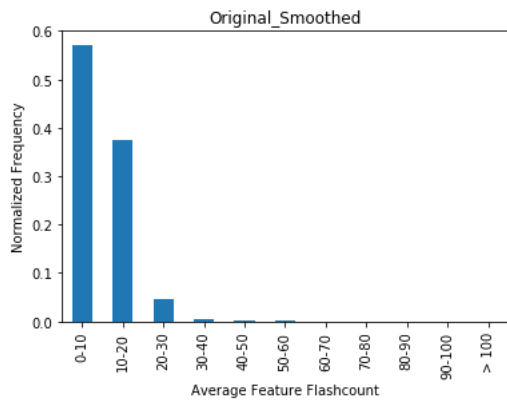
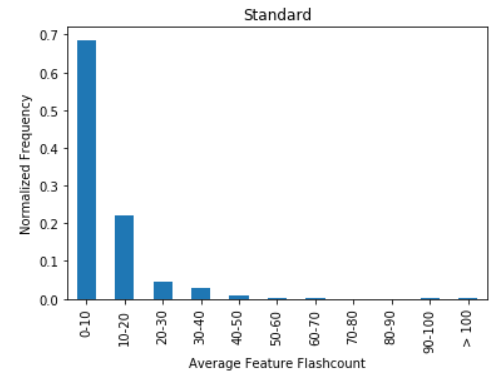
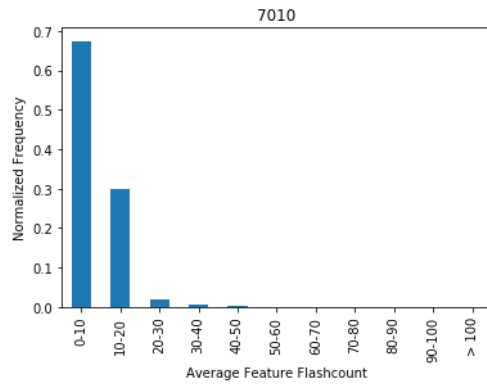
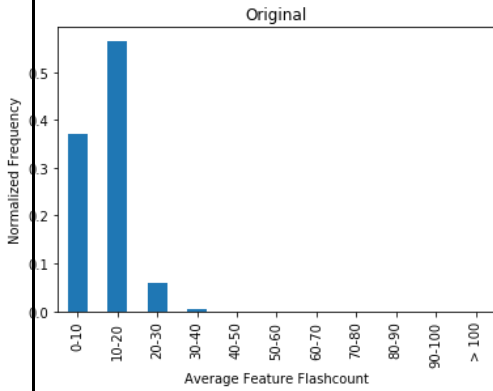
Original	7010	Original Smooth	7010 Smooth	Standard
4.0107	3.1859	4.2268	3.7083	3.1190

Avg Feature Size Distributions:

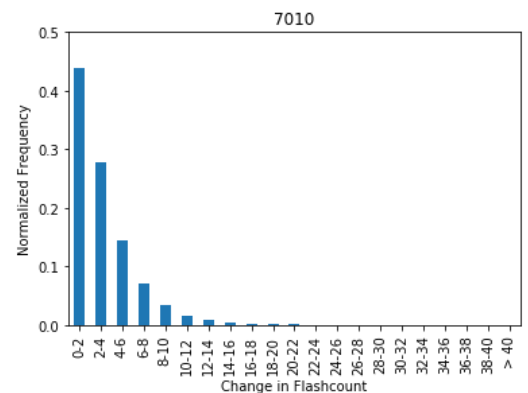
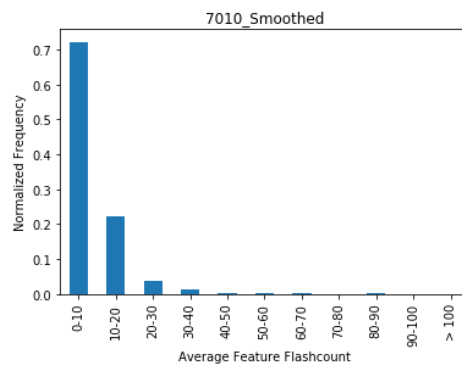
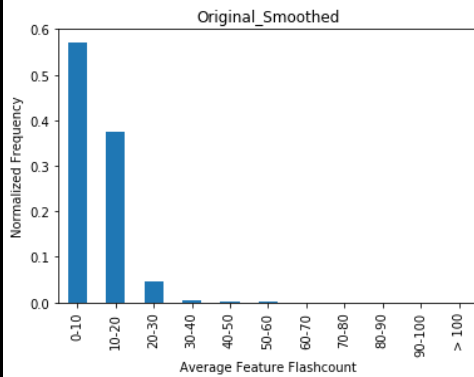


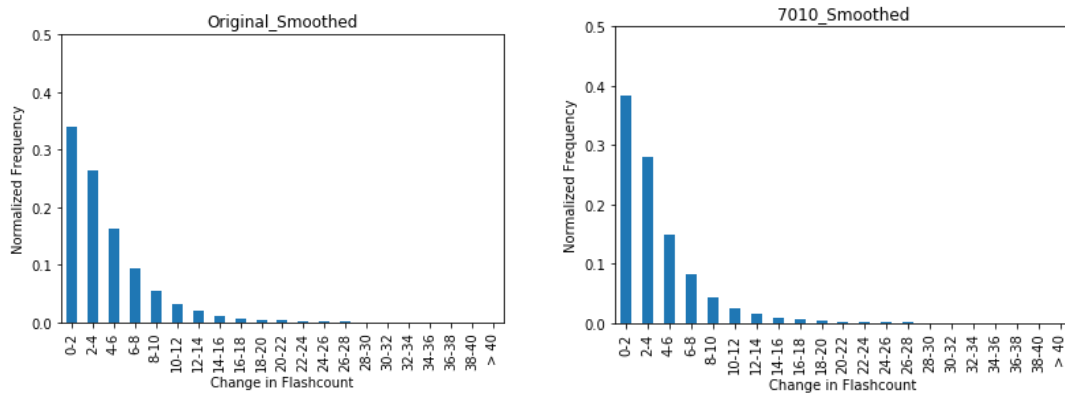


Avg Feature Flashcount Distributions:



Change in Feature Flashcount/min Distributions:





Initial results indicate that the 7010 methods do create a more stable feature contour boundary, but capture slightly less lightning. Both dilated methods cause there to be an increase in the actual number of storms tracked. Future work needs to determine if there is benefit to using a method that produces a more stable feature boundary even at the cost of losing flashes within the contour. It also needs to be determined why the dilated methods cause an increase in the number of features tracked. A noticeable result is that the standard method resulted in some very large tracked features – indicating VILFRD methods likely do a better job at isolating/separating individual storm cores in large areas of convection. Also, the total summed number of flashes/min over all storms is much less for the standard method.

Discussion of operational transition readiness for any project outcomes

The most operational ready part of this project is the storm tracking. We are presently running autonomously within the Hazardous Weather Testbed, generating features using the radar/GLM combination and the GLM only parts of this tracking method. Validation of feature size and duration will occur later this fall once we've collected a large enough sample size to validate.

The project team feels that a need for the operational community is a quality flag to identify challenges due to view angle. Other GLM challenges can be understood (say large ice water paths, which can be supplemented by radar and satellite), and might be able to be taken advantage of (i.e., IWP signal loss means increasing potential for large hail).

Positively, we've taken these outcomes (flash occurrence, size, optical output) and applied knowledge to other hazards (thundersnow, volcanic eruptions, lightning safety) by utilizing other funding sources to perform the research. Thus we've been extending the rate, area, and energy information related to severe convection, and extending it to other hazards to understand how these parameters might provide insight into the cloud's microphysical structure.

Harkema, S. S., C. J. Schultz, E. B. Berndt, and P. M. Bitzer. 2019: Geostationary Lightning Mapper Flash Characteristics of Electrified Snowfall Events. *Weather and Forecasting*, **34**, 1571–1585, <https://doi.org/10.1175/WAF-D-19-0082.1>.

Schultz, C. J., R. E. Allen, K. M. Murphy, B. R. Herzog, S. A. Weiss 2020: Investigation of cloud-to-ground flashes in the Non-Precipitating Stratiform Region of a Mesoscale Convective System on 20 August 2019 and Implications for Decision Support Services. *Weather and Forecasting*, accepted pending minor revision.

Schultz, C. J., V. P. Andrews, K. D. Genareau, and A. R. Naeger, 2020: Observations of Lightning in Relation to Transitions in Volcanic Activity During the 3 June 2018 Fuego Eruption. *Scientific Reports*, Accepted pending minor revision.

Additional Information

1. Interaction with operational partners – We've been working with local WFO's to highlight the use of GLM for severe weather and use of the GLM Sub-flash properties for other applications to

December 19th QLCS tornado event and storm tracking/warning application:

<https://nasasport.wordpress.com/2019/12/17/storm-tracking-and-monitoring-with-the-geostationary-lightning-mapper-glm/>

January 11th, 2020 QLCS tornado event with radar outage:

<https://nasasport.wordpress.com/2020/01/31/the-utilization-of-glm-during-the-january-11th-tornado-event/>

March 3rd, 2020 Nashville Tornado (collaboration with NWS Nashville's Krissy Hurley, Dan Hawblitzel

<https://nasasport.wordpress.com/2020/03/03/a-first-look-at-glm-observations-of-the-supercell-thunderstorm-responsible-for-tornadoes-in-tennessee-on-march-2-3-2020/>

2. Conference/workshop participation – GLM Science Team Meeting, NWA Annual Meeting, AMS Annual Meeting. Had planned for AMS Severe Local Storms, but that was pushed to 2021.

Schultz, C. J., K. M. Murphy, L. D. Carey, P. M. Bitzer, K. M. Calhoun, and E. C. Bruning, 2019: Characterization of optical energy output in thunderstorms to enhance severe thunderstorm identification. *44th National Weather Association Annual Meeting*, Huntsville, AL.

Murphy, K. M., L. D. Carey, C. J. Schultz, N. Curtis, 2019: Automated and Objective Thunderstorm Identification and Tracking using Operational Geostationary Lightning Mapper (GLM) Data. *44th National Weather Association Annual Meeting*, Huntsville, AL.

Murphy, K. M., L. D. Carey, C. J. Schultz, N. Curtis, 2020: Automated and Objective Thunderstorm Identification and Tracking using Operational Geostationary Lightning Mapper (GLM) Data. *100th AMS Annual Meeting*, Boston, MA.

3. Outside project publicity – Continue to discuss results on the NWS Total Lightning Working Group call, and the JTTI calls which involve NWS forecasters. Specifically, our work with the NWS Huntsville office in training them how to use GLM for severe warning operations, and its utility in two warning ops was highlighted in AGU EOS and the NASA SPoRT blog.

EOS Article: Goss, H., 2020: Lightning Research Flashes Forward, Eos, 101, <https://doi.org/10.1029/2020EO142805>, Published on 24 April 2020.

4. Journal articles – Two articles are in preparation related to the storm tracking analysis and the sub flash property characteristics within severe and non-severe convection.

Two theses were outcomes of this work as well.

Curtis, N., 2018: An Analysis of the Lightning Jump Algorithm using the GOES-16 Geostationary Lightning Mapper. U. Alabama-Huntsville, 101 pp.

Kahn, D., 2020: Characterization of Wildfire Producing Storms Utilizing Satellite, Radar, and Lightning Datasets. U. Alabama-Huntsville, 116 pp.

Key Graphics

Included in Text because it was easier.