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Geostationary Lightning Mapper Value Assessment

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Executive Summary

This value assessment documents societal and economic benefits that can be attributed to a Geostationary Lightning Mapper (GLM) to advise future satellite architecture decisions. The report examines the use-inspired science and public benefits of space-based lightning measurements that address NESDIS mission objectives for geostationary earth and extended orbit (GEO-XO) observations. We describe operational use cases to illustrate GLM value being realized through the actions of various decision makers, and identify well documented benefit pools where the GLM adds value.

Only four years since becoming reality, the GLM is shown to be establishing a legacy of applications likely to become ubiquitous across a wide variety of meteorological domains. Operational users have eagerly embraced this new source of lightning information and incorporated it into their workflow. Over CONUS, forecasters use GLM data alongside radar to make severe weather warning decisions earlier and more confidently. The GLM also is uniquely able to monitor vast areas to identify the sustained "continuing current" lightning flashes most likely to ignite fires. This enables emergency personnel to find small and even smoldering fires before they grow, reducing forest and property loss, lowering firefighting costs, and improving air quality. Two common themes recur throughout. First, the GLM provides a freely available public source of lightning data, which is becoming more widely used as it is integrated into operational systems and web-based weather applications. Second, the GLM provides a transition from traditional single latitude/longitude point source lightning information to a rapidly-updating 2-D map that accurately portrays temporal trends and the full spatial extent of the storm threat. The GLM is broadening access to lightning information beyond those who can afford to purchase data, helping people working and recreating outdoors make more informed lightning safety decisions, leading to decreased injuries and fatalities. The GLM now provides a national and international baseline of publicly available lightning data and establishes a baseline for widespread government and industry implementation.

The GLM value will quickly multiply as the realized benefits spread; even at this early stage of adoption we document several application areas where GLM provides significant economic benefit. GLM data help fill spatial and temporal radar coverage gaps over CONUS, reclaiming a portion of an estimated $329 million annual benefit pool. This value grows considerably when considering the coverage GLM provides during radar outages (e.g., when the Puerto Rico radar was offline for months following damage from Hurricane Maria). The GLM provides great value outside CONUS by serving as a radar proxy over vast data sparse regions. It aids tropical cyclone (TC) assessment outside radar range, and the value of potential TC forecast improvements exceeds $300 million. Much of the GLM economic benefit will stem from aviation industry implementation. By observing the complete spatial footprint of total lightning flashes, GLM helps better characterize the lightning risk and increase confidence/certainty for airline flight and airport ramp operations, leading to enhanced safety, improved efficiency, and cost savings exceeding conservative estimates of $17M per year. GLM also provides situational awareness of potentially catastrophic non-meteorological events such as meteor fireballs and lightning accompanying explosive volcanic eruptions. As GLM applications mature, we will better understand and quantify the value of these benefits.

The GLM helped inspire the most recent World Meteorological Organization (WMO) Integrated Global Observing System document (WIGOS-2040) to include "lightning imagers" alongside "high-resolution multi-spectral Vis/IR imagers" and "IR hyperspectral sounders" in their recommended backbone of the future WIGOS geostationary satellite constellation (i.e., GEO-Ring). As evidenced by recent wildfires and hurricanes, a warming climate multiplies the value of satellite instruments. With a persistent, decades-long view of lightning over the Americas and neighboring oceans, GLM and its successor instruments can help assess climate change by monitoring trends of lightning-related phenomena including the distribution and intensity of thunderstorms, precipitation rates, and greenhouse gas concentrations.

The following premise statements summarize (and link to) descriptions of nine GLM application areas.

Improving Lightning Safety – The GLM improves public safety across broad segments of society, and the socioeconomic benefit continues to grow as access is gained by users traditionally unable to afford lightning data (e.g., emergency managers, event organizers, local athletics officials, and the public).

Improving Severe Thunderstorm and Tornado Warnings – Integrating GLM data into the severe weather warning process promotes earlier warning decisions, better assessment of the areal coverage of hazards, and fewer false alarms, especially during radar outages and in regions of poor radar coverage.

Improving Safety and Effectiveness of Wildfire Response – The GLM benefits the firefighting community through unique identification of continuing current lightning strikes most likely to ignite fires, better pyrocumulonimbus characterization, and thunderstorm tracking in areas lacking robust radar coverage.

Improving Short-term Model Forecasts (Data Assimilation) – Lightning data assimilation (DA) is relatively new, especially GLM DA, but early results indicate many benefits, especially for short-range forecasts of radar reflectivity, accumulated precipitation, and lightning threat in convection-allowing models.

Improving Precipitation Estimation – The GLM observations improve satellite precipitation estimates, benefiting flash flood forecasting in significant portions of the western US, Hawaii, and US territorial islands without adequate radar coverage.

Improving Tropical Cyclone Diagnosis and Warning – The GLM identifies convective tendencies below cloud top in tropical cyclones (TCs) which helps better diagnosis TC structure and evolution and aids forecasts of TC intensity change including rapid intensification.

Improving Climate Applications – GLM data offer unique insights for monitoring climate-scale variability and response in a changing climate, a close link between lightning and convective cloud properties makes it an essential indicator of inter-annual to decadal change and a key variable for validating climate models.

Value of Filling Data Gaps – The GLM's broad spatial coverage and rapid temporal updates complement radar observations over CONUS to support severe weather warning decisions, and rapidly updating GLM observations over vast (often data sparse) regions outside CONUS provide decision makers with information they need to forecast, monitor, and react to thunderstorms, cyclones, and volcanic hazards at a faster cadence than ABI.

Value of Mitigating Aviation Hazards – The GLM observes the complete spatial footprint of total lightning flashes, which helps better characterize the lightning risk and increase confidence/certainty when suspending and resuming ramp operations, leading to enhanced safety, improved efficiency, and cost savings. The GLMs broad coverage and rapid updates provide tremendous cost savings to the aviation industry through improved diagnosis and avoidance of thunderstorm hazards, especially over oceans.

1. Introduction

1.1. Purpose

This value assessment (VA) documents societal and economic benefits that can be attributed to the Geostationary Lightning Mapper (GLM) to advise future satellite architecture decisions. As NESDIS explores broader mission approaches for geostationary earth and extended orbits (GEO-XO), various analyses are required to inform the design, acquisition, development, and launch of a cost-effective, agile satellite architecture to support NOAA's mission in the coming decades. The Weather Research and Forecasting Innovation Act of 2017 also requires value assessments for any next generation observing systems with potential costs over $500 million. This GLM VA fulfills these two requirements to rationalize and prepare for a potential next generation lightning mapper. **Only four years since becoming reality, the GLM is shown to be establishing a legacy of applications likely to become ubiquitous across a wide variety of meteorological domains.**

1.2. Approach and Context

Societal and economic benefits are documented regardless of whether they can be quantified in dollars. Value comes from data use during decision making, so this study assesses the GLM value by documenting benefits to the public via decisions made by operational forecasters, private and public partners, and other end users. The GLM value is considered in the context of other available observations that provide comparable insights. Because the weather observing system is coupled, it tends to be difficult to tease out the incremental value for a single instrument. Since various instruments, technology, and processes contribute to improved decisions, a detailed analysis beyond the scope of this study is required to definitively attribute value to each aspect.

The GLM is a new capability with many applications for which economic and societal benefits are assessed. The GLM often advances us beyond thresholds where value is realized, and this VA identifies how surpassing these thresholds leads to measureable benefit. Despite widespread use of lightning datasets, the GLM remains in its infancy and much of its value is still waiting to be fully recognized. We identify well-documented benefit pools where the GLM adds value, and suggest analysis required to accurately document which fraction of this potential value is being realized.

Describing operational use cases helps illustrate GLM value through the actions of a wide variety of decision makers [both National Weather Service (NWS) and non-NWS]. Non-NWS users include both government and commercial/private sector entities. Government users include the U.S. Military, National Forest Service, Federal Aviation Administration, National Aeronautical and Space Administration, and countless local emergency management agencies. Non-government users include power utilities, broadcast stations, insurance assessors, windfarm managers, airlines, large venue managers, overseers of various outdoor recreation activities, and the public. Many NWS users have eagerly embraced this new source of lightning information and incorporated it into their workflow. The NWS Weather Forecast Office in Huntsville, AL and Hazardous Weather Testbed (HWT) in Norman, OK have led the charge, clearly demonstrating the value of GLM observations and providing excellent examples for other forecasters and forecast offices. Forecaster demonstrations at other WFOs, National Centers, and NOAA Testbeds / Proving Grounds have confirmed the GLM value for warning decision-making, providing several examples documented herein. **The GLM value will quickly multiply as these realized benefits continue to spread.**

1.3. Common Themes

Several common themes recur among the various GLM applications. Much of the GLM value comes from the broad area coverage and rapid temporal updates. These key aspects allow the GLM to address impactful spatial and temporal coverage gaps in other observing networks. The ability to observe the full spatial extent of total lightning flashes [both intra-cloud (IC) and cloud-to-ground (CG)] greatly expands the GLM applicability beyond what is possible with ground-based lightning detection networks alone. The following statements summarize two particularly game-changing and value-adding aspects of the GLM.

(1) The GLM provides a freely available public source of lightning data, which is becoming more widely used as it is integrated into operational software and web-based weather applications. The value of lightning information has been demonstrated by widespread purchases of lightning detection equipment and data from private vendors. The GLM has potential to provide huge socioeconomic benefit as access is gained by users who traditionally could not afford lightning data. Popular weather websites have eagerly adopted the GLM, broadening access beyond those with mandates to use and display satellite data products. **The GLM now provides a national and international baseline of freely available lightning data and establishes a baseline for widespread government and industry implementation.**

(2) The GLM moves from traditional single latitude/longitude point source lightning information to a rapidly-updating 2-D map that accurately portrays the full spatial extent of lightning activity. This unique ability to capture the full spatial extent of lightning over hemispheric scales more clearly illustrates links between lightning and thunderstorm meteorology, greatly expanding the applicability of these data. The GLM has observed new world records for lightning flash length (709 km) and duration (16.73 sec; Peterson et al. 2020), dwarfing previous records. **The GLM allows the threat posed by these long flashes and the electrically active regions they travel through to be clearly communicated to those most vulnerable.**

1.4. Organization

The qualitative GLM benefits are first assessed for seven application areas (Section 2). Each subsection provides background on the application, describes how the GLM benefits decision makers, and suggests methods for gathering more quantitative information. Section 3 links these applications to potential benefit pools from which the GLM is expected to draw value. Section 3.1 identifies and aggregates value that can be estimated from the preceding qualitative sections (e.g., value of filling radar coverage gaps during severe storm warning operations from Section 2.2). Section 4 summarizes our findings, Section 5 lists acronyms, and Section 6 aggregates references from the individual sections.

2. Qualitative GLM Benefits

2.1. Improving Lightning Safety

Lead: Scott Rudlosky (NESDIS/STAR)

Premise: The GLM improves public safety across broad segments of society, and the socioeconomic benefit continues to grow as access is gained by users traditionally unable to afford lightning data (e.g., emergency managers, event organizers, local athletics officials, and the public).

Discussion: This section provides background on the direct lightning threat to public safety and two examples of the GLM directly contributing to improved public safety via routine NWS operations. Annual lightning fatalities in the U.S. decreased greatly from more than 400 deaths early in the 20th century to less than 30 deaths in recent years (Cooper et al. 2016). This trend relates to increasing quality of dwellings, workplaces, schools, and other buildings with respect to lightning safety. Decreasing lightning casualties also can be attributed to a focused and sustained lightning safety education and awareness campaign across the United States. Our focus on lightning fatalities is due to sparser statistics on more frequent non-fatal lightning injuries, but as Walsh et al. (2000) noted, the protracted suffering of survivors should not be underestimated. Lightning strike survivors may not be able to continue their jobs or educational pursuits, and may be permanently disabled, compounding the economic impact.

Jensenius (2020) characterized lightning deaths in the United States and found that almost two thirds of the deaths occurred during outdoor leisure activities. From 2006 to 2019, there were 40 fishing deaths, 25 beach deaths, 20 camping deaths, and 18 boating deaths. Of the sports activities, soccer saw the greatest number of deaths with 12. Yard work (including mowing the lawn) accounted for 18 fatalities, and ranching/farming topped the work-related list with 19 deaths. Fishing and boating are especially dangerous because they occur in places more vulnerable to direct lightning strikes; the background noise from a motor or waves may limit the ability to hear thunder; and extra time may be needed to get to safety. **Coupled with proper outreach and training, the GLM helps better inform the public of their local lightning threat via improved climatologies as well as actionable real-time information.**

Lightning presents a significant hazard to the physically active population due to its pervasiveness during the times that most athletic events occur (Walsh et al. 2000). Although each person must take responsibility for his or her own personal safety during thunderstorms, people are often under the direction of others while participating in organized athletics. Athletic trainers, coaches, teachers, and game officials must receive education about the hazards of lightning and become familiar with proven lightning-safety strategies (e.g., access to real-time lightning information). **The GLM is broadening access to lightning information beyond those who can afford to purchase data, which will help athletic trainers, umpires, officials, referees, and coaches make more informed decisions.**

Large outdoor stadiums face a significant lightning vulnerability (Gratz and Nobel 2006). The usual audible and visual clues that most people rely on to assess the lightning threat may be obscured by crowd noise or impeded by the stadium structure and lighting. The National Fire Protection Association's guidelines for lightning protection lists the "risk of panic" as the number one safety concern for large venues, due to the time required to seek shelter. Stadium managers must acknowledge not just the physical threat of a direct lightning strike, but also the crowd management issues of trampling and bottlenecks in crowd flow that could pose an even greater threat to spectator safety. Stadium management must monitor any lightning activity and have an appropriate action plan in place. Whereas lightning is understood by all to be a dangerous phenomenon, the importance of seeking safe shelter and the specific time that one should vacate to safety are less well known. **GLM information is now available to any large venue manager, and the second example below demonstrates how this information is already proving actionable in collaboration with the NWS forecast office in Huntsville, AL.**

The U.S. Center for Disease Control and Prevention (CDC) outlines the occupational risks posed by lightning. The highest risk occupations are construction and building maintenance, farming and field labor, logging, explosives handling or storage, heavy equipment operation, pipefitting or plumbing, telecommunications field repair, and power utility field repair. The CDC recommended steps required for protection include checking the forecast, following the locally established program, assessing the threat, avoiding tall structures, avoiding conductive materials, and stepping away from explosives. Each of these mitigation steps require previous knowledge of the lightning threat and a means for knowing that lightning is occurring. Lightning strikes are particularly hazardous to airport ramp operations. Ramp workers must cease outdoor activities when lightning presents an imminent danger, which impacts all aspects of airport operations. Section 3.2 further describes the threat lightning poses at airports and the GLM value for mitigating this aviation-related hazard.

Example Use Case #1: Operational Utility of GLM Flash Extent Density on June 1 (2018)

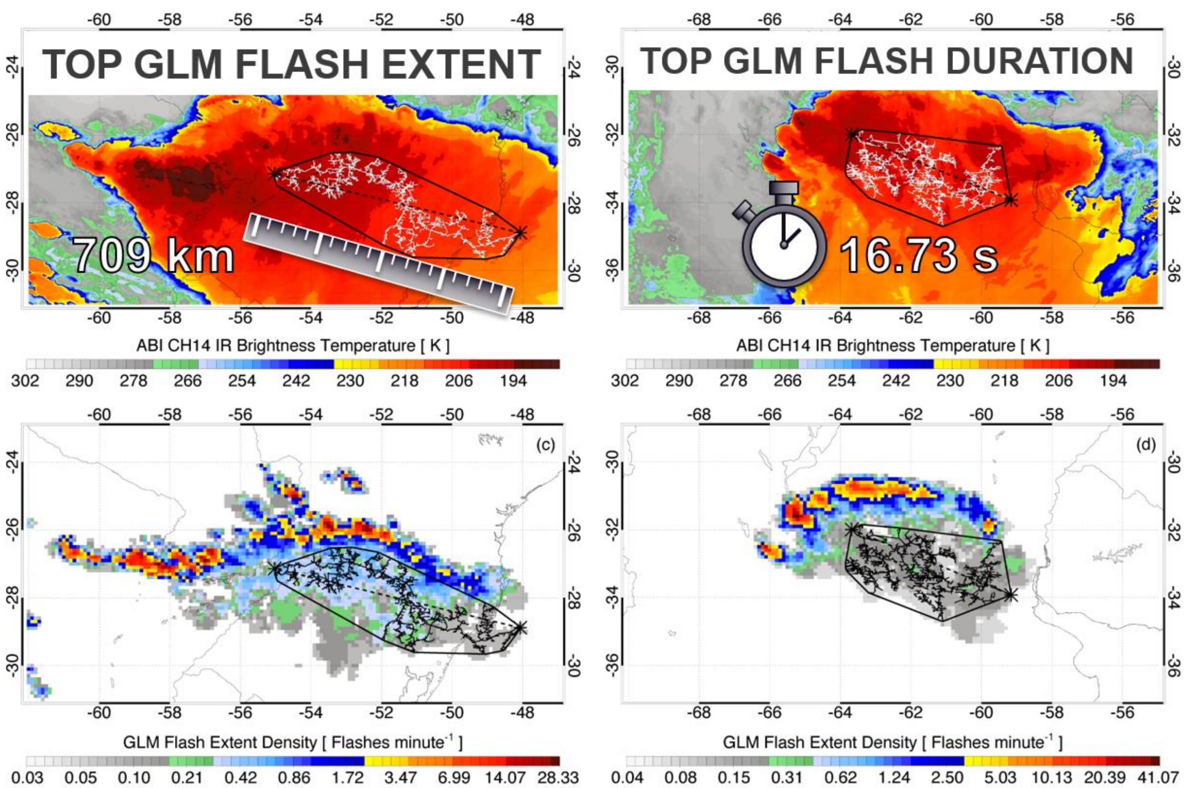
Paraphrased from https://nasasport.wordpress.com/2018/06/07/operational-utility-of-glm-flash-extent-density-on-june-1/

NWS Huntsville provided on-site weather support for a large outdoor country music concert in Cullman, Alabama on Friday, June 1. A small multi-cell cluster of thunderstorms developed approximately 30 miles to the west and moved steadily east, putting forecasters and public safety officials on alert. Forecasters at both the NWS office and the concert used GLM to evaluate the threat to almost 30,000 people. Fortunately, the initial cluster of storms to the west essentially “split”, with one updraft gaining dominance to the south, and the rest weakening. There were some “long flashes” extending far to the north from the southern storm, and far to the south from the northern storm. The storm to the south produced a great deal of lightning, but thanks to the GLM Flash Extent Density product, forecasters were able to determine that the concert would not be affected. The northern storm regained strength and GLM Flash Extent Density (FED) showed several flashes moving into the 10 nautical mile range ring. However, forecasters were able to combine GLM FED information with GOES-16 IR and Multi-Radar/Multi-Sensor radar data to determine that the storm was moving away. With our legacy of using LMA data for almost 15 years, NWS Huntsville forecasters have embraced GLM FED data eagerly.

Example Use Case #2: Using GLM for Airport Weather Warnings

Paraphrased from https://nasasport.wordpress.com/2018/06/15/using-glm-for-airport-weather-warnings/

NWS Huntsville issues Airport Weather Warnings (AWWs) for Huntsville International Airport (KHSV) and Northwest Alabama Regional Airport (Muscle Shoals; KMSL). AWWs are issued for the threat to personnel working outside the terminal and neighboring operations. One criteria for AWW issuance is the threat of cloud-to-ground lightning within 5 miles. On May 30, a relatively small line of thunderstorms developed over northeast Mississippi and tracked to the east, producing a few pockets of straight-line wind damage along the way. The GLM FED data were most useful later in the event, after the line passed east of KHSV and the Huntsville metro area. The convective updrafts weakened and lightning along the line generally decreased–but flashes within the trailing stratiform region did not. The FED product really illustrated the spatial threat simply and effectively, especially when combined with the NLDN data. **GLM helped forecasters acquire and retain situational awareness of these trailing stratiform "long flashes", which helped with AWW extension/reissuance.** As a result, the airport weather warning for Huntsville was re-issued until the trailing stratiform region cleared the airport and the threat subsided.



Peterson et al. (2020) found that the GLM has detected thousands of flashes exceeding the previously certified world records for lightning flash length (km) and duration (sec). The image above illustrates the newly certified world records for the greatest horizontal extent (709 ± 8 km; 441 ± 5 mi) and greatest duration (16.730 ± 0.002 sec) of individual lightning flashes. More recently, Peterson reported the following…

- **Megaflashes can individually put down up to 100 CGs!!**
- **Larger megaflashes more likely to have more CGs = greater per-flash impact to the public**
- **CGs in larger megaflashes occur over 80% of the flash extent = no safe place outdoors**
- **Megaflashes can be only lightning in the previous hour = the 30/30 rule doesn't apply**

2.2. Improving Severe Thunderstorm and Tornado Warnings

Lead: Kristin Calhoun (OAR/NSSL)
Contributors: Scott Rudlosky, Christopher Schultz, Eric Bruning

Premise: Integrating GLM data into the severe weather warning process promotes earlier and easier warning decisions, better assessment of the areal coverage of hazards, and fewer false alarms, especially during radar outages and in regions of poor radar coverage.

Discussion: Severe storms and associated hazards have cost the United States more than 228 billion dollars in the last 20 years (NCEI: https://www.ncdc.noaa.gov/billions/events/US/2000-2020). Several factors including population spread, vulnerability, and climate change have resulted in an annual increase in the number of billion dollar severe storm events. From 2000-2010, the United States averaged to 2-4 such events annually. Since 2015, the US has averaged more than 8 events annually. During the first five months of 2020 alone, 10 individual billion dollar events from severe storms totaling more than $17 billion in damage occurred across the contiguous United States.

An initial GLM objective was increased lead time for tornadoes and other severe storm hazards (GLM PORD, 2018). While the GLM imagery is still not fully integrated into the operational product delivery stream for the National Weather Service, through the use of advanced training and pushing the data through local data managers at individual forecast offices, NWS forecasters are now including GLM data in the warning-decision process. NWS forecasters use GLM data in conjunction with data from other sources (including WSR-88D radars) to:

1) Make the decision to warn earlier and easier. GLM has proven important in the decision to warn or not to warn (or ending warnings), reducing unnecessary coverage and false alarms.
2) Determine the areal coverage of a warning or hazard.
3) End current warnings sooner once storms decrease in intensity (see Sutter and Erickson 2010).

The rapid update times of the GLM data (20 sec nominally, and 1 min within NWS operations) allows forecasters to visualize the rapid intensification of thunderstorms early in their development at a faster cadence than radar volume scan updates (average volume scan is close to 5 min). This unique, rapidly updating system provides invaluable information that forecasters have already integrated into their warning decision process to better understand internal storm dynamics at critical decision points (NASA SPORT, 2019; Goss 2020). In NOAA Proving Grounds and Testbeds, forecasters have shown similar consideration and use of the GLM data, integrating products such as flash extent density, minimum flash area, and total optical energy into their severe weather warning and analysis procedures (Calhoun, 2018; Calhoun, 2019). During severe weather activity, forecasters used the GLM data “to monitor and identify new updrafts and storm glaciation”, “identify convective trends”, and “to get lead time on convective development" (Calhoun, 2019). All of these comments confirm the ability of forecasters to make warning decisions earlier and more decisively when using GLM data alongside radar.

An example from the NWS forecast office in Huntsville, AL illustrates the integration of GLM data into the severe weather warning process and shows it to be especially valuable during radar outages and regions of poor radar coverage. Ravenscraft, a warning forecaster at the Huntsville office, used the gridded 1-minute flash extent density to assess rapid intensification of storms and successfully issue tornado warnings on 11 Jan 2020 during an outage of the local WSR-88D radar (Goss, 2020). As noted in the article by Goss, Ravenscraft had previously seen how the GLM flash extent density was used successfully in the tornado warning process on 16 Dec 2019, explaining that **"If we start to see these lightning jumps, and we see these updrafts grow, especially combined with the surge in the line we can see on radar, then there's a good chance we're going to end up with a tornado."** This previous experience gave her the confidence to use the GLM data on 11 Jan 2020 to reissue a tornado warning when the flash extent density from GLM depicted an increased density collocated with the updraft region. This process began the alert chain and kept people sheltered prior to a tornado in Marshall County, AL that produced EF2 damage including at an elementary school (Goss, 2020).

Additional examples from multiple NWS offices depict similar stories, particularly for tornadoes that develop within quasi-linear convective systems (QLCS). Using the same GLM Flash Extent Density product as Ravenscraft above, Cobb (2019) noted multiple use cases at the Tulsa, OK office where the GLM total lightning information was incorporated in both the warning decision and corresponding threat communication. As the Science Operations Officer responsible for training at the Tulsa office, Cobb analyzed in detail the GLM characteristics associated with QLCS tornadoes on 18 May 2019. He, like Ravenscraft above, noted the rapid increase in flash density (or lightning jump) followed by consistently high values of flash extent density at the location of the updraft region and subsequent tornado. Early in the event on 18 May 2019, the Meteorologist-In-Charge of the local office communicated in NWS chat with regional partners that: "GOES lightning data has just jumped from 36 to 102... thats a big jump... in the isolated cell moving into the SE Corner of Choctaw Co.... that suggests rapidly increasing severe weather potential... new SVR coming for that cell."

As shown in these example, the GLM has value when used in conjunction with radar data, but the value increases immensely in the absence of radar data or in regions with poor radar coverage. The number of missed tornado warnings increases with increasing distance from the radar (Brotzge and Erickson 2010), so GLM data can have a significant impact on warning decisions in poor radar coverage regions. Additionally, when used in conjunction with radar data, forecasters are able to **make warning decisions earlier** and **with increased confidence** when storm trends match across multiple sensors and platforms (Calhoun 2018, 2019). Furthermore, the GLM data also promotes more accurate (and earlier) conclusions of severe weather warnings. A decreasing lightning density combined with an increasing flash area pattern that fits their training on storm physics, allows forecasters to conclude or avoid reissuing unnecessary severe weather warnings.

As a dataset that captures internal storm dynamics, GLM data is beginning to have an impact on machine learning and automated intelligence (AI) applications for severe weather forecasting. Lightning data has already shown improvement in the accuracy of these AI algorithms by reducing the false alarm rate while also increasing the lead time (Cintineo et al., 2018). As the only source of lightning data with geospatial coverage freely available to private, academic, and other research institutions, GLM data provides both a unique and widely accessible dataset to promote machine learning research and applications.

Early results of new research from the ProbSevere team indicates that the GLM greatly benefits an experimental deep-learning algorithm that reports the “probability of intense convection” (i.e., Cintineo et al.). Their findings show value in the GLM data, especially offshore, that has yet to be realized more broadly. Other research under development in the NASA Frontier Development Laboratory examining “Lightning and Extreme Weather” certifies the ability of **GLM data alone** to predict the likelihood of severe weather at a specific location (Ahmed et al., 2020). Using eight different variables from the GLM, this time series-based convolutional-kernel model correctly classified tornado and severe weather reports while reducing false alarms for warned thunderstorms. The inherent value of GLM data will continue to grow as it is incorporated into more severe storm assessment and data-fusion algorithms. The spatial coverage of the GLM and the insights it provides into internal storm dynamics can be used alone or in conjunction with other gridded data to produce more accurate decision support guidance through AI of value to both NWS forecasters and end-users across other sectors. Feature importance and permutation tests will better indicate the GLM value within AI, but the initial studies are exceedingly promising.

We expect to see increased visibility and value over the coming years as the GLM data are integrated into more algorithms. New technology on a next generation GLM that improves the spatial and temporal resolution and allows for lowering of the exceedance thresholds should further improve the GLM’s ability to resolve lightning trends that are indicative of severe storms.

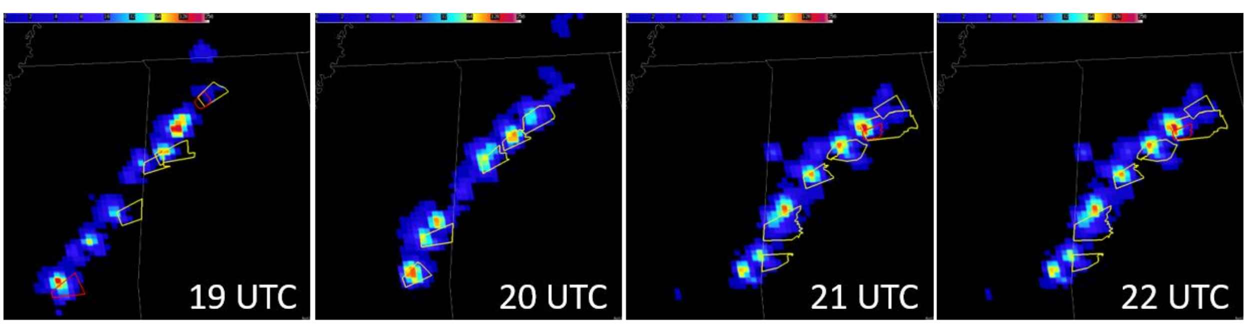


Image: Warmer colors in the Flash Extent Density indicate the most frequent GLM flashes, with maxima typically collocated with severe thunderstorm (yellow) and tornado (red) warning polygons. When used in conjunction with radar data, these lightning trends allow forecasters to make warning decisions earlier and more confidently.

2.3. Improving Safety and Effectiveness of Wildfire Response

Lead: Chris Schultz (NASA/MSFC)
Contributors: Nick Nauslar, Robyn Heffernan, Aviva Braun, Phillip Bitzer, Peter Roohr

Premise: The GLM benefits the firefighting community through unique identification of continuing current lightning strikes most likely to ignite fires, better pyrocumulonimbus characterization, and thunderstorm tracking in areas lacking robust radar coverage.

Discussion: While human-caused fires are more frequent (84%), lightning-initiated wildfires account for 56% of the total acreage burned in CONUS (Balch et al. 2017). This is due to many of the lightning-ignited fires occurring in less populated areas resulting in delayed detection and the need to bring resources in from other areas. *Nearly half of lightning-ignited fires are not observed until one or more days after the lightning ignites the fuels*. Mapping potential fire starts using the GLM data provides a means to identify smaller fires before they grow, mitigating property loss and firefighting costs. This section identifies four main areas in which GLM provides added value to the firefighting community and those working to identify fire starts, and highlights the August 2020 wildfire outbreak in California to demonstrate how GLM value might be realized during less extreme cases.

(1) Identifying long continuing current (LCC) and Wildfire Ignitions

Continuing current is the most critical lightning parameter for igniting wildfires (Latham and Williams 2001). Recent studies by Fairman and Bitzer (2020) and Bitzer (2017) revealed that the GLM can identify continuing current flashes. When combined with other information (land surface, precipitation, fuel, etc.), identifying potential hotspot locations becomes possible. Nearly 48% of fires within a study by Schultz et al. (2019) were not reported/identified by satellite until 1 or more days after their lightning ignition. Lightning ignited fires can go unnoticed for more than a week, such as the High Park Fire in 2012 west of Fort Collins CO. Faster response allows fires or hotspots to be caught before they rapidly grow during more conducive conditions, which helps reduce property loss, firefighting expense, and smoke-induced air quality impacts.

Wide-baseline ground-based lightning detection networks are unable to observe continuing current. However, Vaisala Inc. used methods similar to Bitzer (2017) to combine information from the GLM and their National Lightning Detection Network (NLDN; Cummins and Murphy 2009) to pinpoint the locations of continuing current flashes. From Goss (2020), "The GLM can see this type of sustained flash—from 10 to several hundred milliseconds long—but can resolve its location only to around 64 square kilometers. Vaisala is testing software that takes these broad GLM data points and combines them with NLDN data to narrow down the location to 200 meters. That's information that emergency management personnel could use to go investigate potentially smoldering locations before they catch". This recently released commercial product demonstrates the private sector generating added value from NOAA observations.

(2) Pyrocumulus/Pyrocumulonimbus Identification and Tracking

Intense fires can produce large plumes of heat and smoke that can generate their own lightning and ignite additional fires (e.g., Rudlosky and Fuelberg 2011, Lang et al. 2014, Capital Weather Gang 2018). GLM lightning observations can serve as a diagnostic for the magnitude of the charge separation within the plume, providing information critical to diagnosing the intensity of updrafts and downdrafts. The GLM maps the extent of electrification in the cloud, providing additional detail on the transition from pyrocumulus to pyrocumulonimbus, and the structure of the pyrocumulonimbus cloud (e.g., Peterson et al. 2017, Lareau and Clements 2016). The 2020 Hogg Fire in Northern California provides a recent example where GLM-observed lightning in the pyrocumulonimbus cloud (Active Norcal, July 20, 2020) was tracked using the GLM-based tracking methods from Schultz et al. (2016) and Murphy et al. (2020).

(3) Situational Awareness to Promote Firefighter Safety

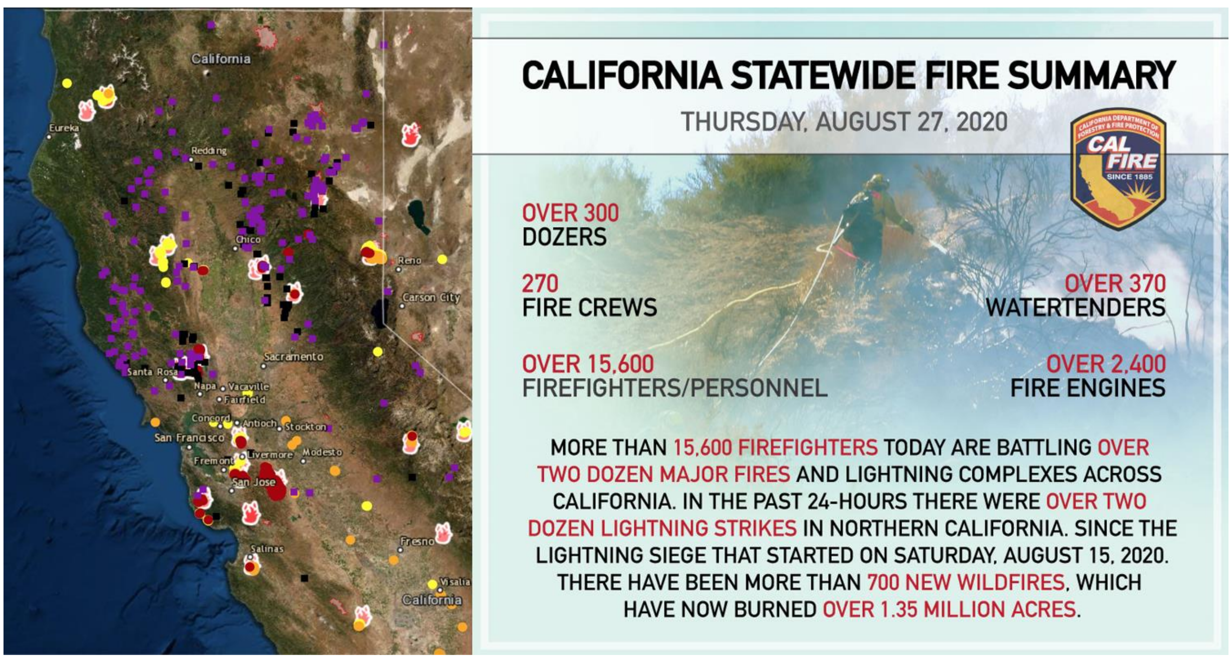
The GLM observes the full spatial extent of total lightning (IC and CG) which provides improved situational awareness to firefighters. Identifying IC flashes can provide firefighters with 2-5 min advanced warning relative to ground-based network detections (NASA Marshall Space Flight Center Emergency Operations Center, personal communication). By showing the full spatial extent of lightning within electrified clouds, the GLM provides a more complete picture than point data from the ground-based networks (e.g., Schultz et al. 2017, Stano et al. 2019). Knowing the full spatial extent helps anticipate CG lightning strikes, which pose a direct safety threat to firefighters and a secondary threat via new fire starts.

Although ground-based networks capture most CG flashes and some IC flashes, the GLM adds value by identifying missed flashes and depicting the areal extent. By mapping the spatial footprints of all lightning flashes, the GLM helps track convection in areas lacking robust radar coverage. Storm tracking is vital to determining storm motion, especially in situations where fires are ongoing and sudden shifts in thunderstorm intensity and downdraft generation can produce variable winds that affect firefighting efforts and drastically shift fire lines (e.g., Waldo Canyon Fire 2013; Johnson et al. 2014). The GLM provides early awareness of the potential for erratic winds generated by pyrocumulonimbus, and helps instantaneously characterize the updraft/downdraft state in preparation for potential wind shifts. Storm tracking also allows incident commanders to reduce risk when vectoring in aircraft resources.

(4) Forensics

GLM helps authorities and insurance companies determine the existence of convection during investigations of fire cause as well as for confirming whether lightning caused power outages, injury in remote areas, or prove existence of convection that could be associated with high thunderstorm winds, hail, or tornadoes. Continuing current also can damage sensitive equipment, and insurance companies may disagree about damage payment if ground based networks do not report a CG near a home or facility. In these cases, the GLM helps better inform about the timing and intensity of lightning in the area.

Goss (2020) described an example of ongoing research seeking to incorporate this complementary information into an actionable tool. “Going one step further (beyond identifying continuing current), one group is trying to take these data and create automated wildfire detection algorithms. Chris Schultz is a research meteorologist at NASA’s Short-term Prediction Research and Transition Center, or SPoRT, in Huntsville. He recently led a team that looked at how long an area might smolder before catching fire after it has been struck by lightning. In a paper published last year, they found that half of causal flashes occurred the same day as the fire, but the rest were tracked largely between 2 and 5 days before the fire was spotted—one fire in New Mexico didn’t catch until 12 days after the causal lightning strike [Schultz et al., 2019]. “The end goal is to develop an algorithm where you have all the inputs of precipitation, storm type, and land surface and soil moisture that forecasters look for as assessment of the fire danger,” said Schultz, “and then as thunderstorms roll through you can evaluate the likelihood of a fire” from a lightning strike, even if it doesn’t ignite for a week.”



Extreme lightning-ignited wildfire outbreak that began during August in California illustrates the immense potential value of GLM wildfire applications. During August 15-27, 2020, more than 12,000 lightning strikes ignited over 700 new wildfires. Lightning ignited so many fires that many could not even be assessed before growing out of control. In less extreme cases, wildland fire managers have more time to gather information and make more informed decisions. The GLM will add value by influencing these decisions, which could provide a basis for documenting the value added.

Rodriguez et al. (2020) recently showed that “Massive wildfires (i.e., megafires) produce enough heat to generate powerful updrafts that are as strong as those observed during tornadic supercell thunderstorms. Weather radar data show that these updrafts are as strong as 130 mph (209 km/hr) and extend for miles above the surface. These updrafts can trigger fire-generated thunderstorms and pose a threat to aircraft flying in the vicinity of large wildfires”. “Strong inflow winds replace the evacuated updraft air which has a profound impact on fire spread, and updrafts of this magnitude can loft large burning debris capable of initiating spot fires that merge to form mass fire”.

2.4. Improving Short-term Model Forecasts (Data Assimilation)

Lead: Amanda Back

Premise: Lightning data assimilation (DA) is relatively new, especially GLM DA, but early results indicate many benefits, especially for short-range forecasts of radar reflectivity, accumulated precipitation, and lightning threat in convection-allowing models.

Discussion: GLM's image-based datasets differ fundamentally from the data produced by ground-based lightning detection systems, so new methods are being developed to assimilate these data. In particular, the flash extent density (FED, Bruning et al., 2019) is a pixel-based alternative to the densities derived from ground-based systems that yields additional insight into convective activity. Storm electrification is not directly included in many mesoscale or convection resolving NWP systems, so the path to lightning (GLM) data assimilation remains open to innovation. Recent studies have presented various approaches to relate GLM lightning densities to model state variables:

- Apodaca and Zupanski (2018) related GLM density to column-maximum vertical updraft, which was a function of the state variables horizontal velocity, specific humidity, and temperature. They also demonstrated a forward operator for convection-allowing models, based on the McCaul et al. (2009) lightning threat diagnostic, which relates GLM centroid density to the vertical flux of precipitating ice hydrometeors at -15°C and column-integrated graupel.
- Allen et al. (2016) and Kong et al. (2020) demonstrated a different set of operators relating the GLM FED to column-integrated graupel quantities.
- Back et al. (2020), Chen et al. (2020), and Vendrasco et al. (2020) all assimilated GLM (FY-4A) by converting flash densities to proxy 3D radar pseudo-observations using statistical relationships.
- Fierro et al. (2019) and Hu et al. (2020) demonstrated various benefits by converting flash centroid densities to pseudo-observations of water vapor for GLM assimilation (e.g., improved short-term forecast of accumulated rainfall, composite radar reflectivity, and individual storm tracks).

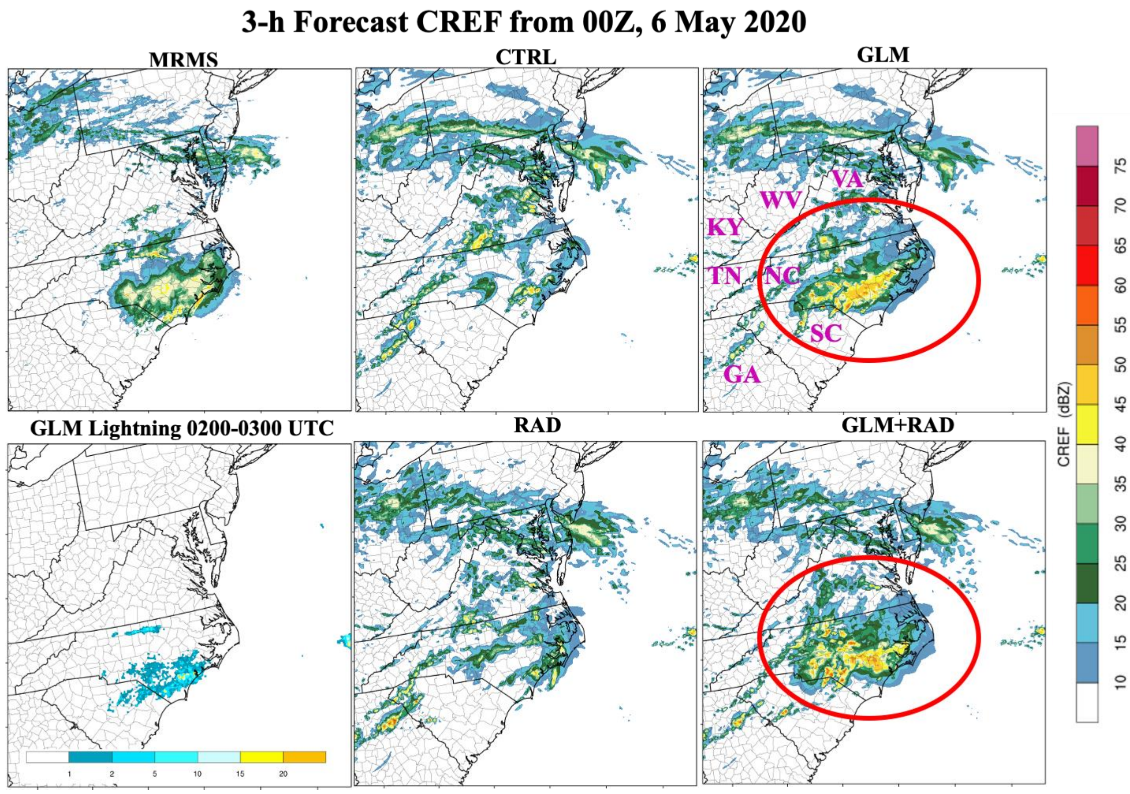
GLM DA has been shown beneficial with and without radar. Chen et al. (2020) found that assimilating lightning data from a geostationary satellite mapper improved accumulated precipitation forecasts over 1-6 hours in a case study of severe weather that produced flash flooding in a mountainous, radar-deprived region. In a case with radar data available, the authors found that a configuration assimilating radar data and a configuration assimilating GLM-derived proxy radar data provided comparable skill. Fierro et al. (2019) and Hu et al. (2020) also noted similar performance between configurations assimilating lightning data and those assimilating radar data, for both the accumulated precipitation and radar reflectivity forecasts up to 3 hours. Additionally, Hu et al. (2020) noted increased skill overall when both GLM and radar reflectivity were assimilated together. Vendrasco et al. (2019) found a degradation in performance when replacing radar data with proxy data from GLM in a pair of case studies; however, the configuration assimilating GLM still had considerably higher skill than a configuration assimilating neither radar nor lightning. Apodaca and Zupanski (2018) used a pseudo-GLM product derived from ground-based lightning observations to study a case outside radar range, and found greatly improved 3-hr lightning threat forecasts. Allen et al. (2016) also used pseudo-GLM data from ground-based detecting systems to conclude that GLM ingest would provide benefit where radar coverage lacks. Kong et al. (2020) performed similar DA experiments using real GLM data, assessing their forecasts against both radar reflectivity and lightning observations, and found that GLM assimilation improved representation of both the location of storm cores and the extent of the storms.

GLM DA has been shown to further improve forecasts in areas where radar data are available and assimilated. Fierro et al. (2019) noted that adding GLM assimilation caused storms to be accurately represented earlier in the forecast. Hu et al. (2020) also found an increase in probability of detection, assessed against radar reflectivity, by combining GLM and radar assimilation. Most studies conducted to date have not assessed the skill of GLM assimilation against, or alongside, that of other lightning observations. However, the preliminary findings of Back et al. (2020) showed that GLM added skill to a configuration of the experimental High Resolution Rapid Refresh (HRRRX), run by NOAA GSL, into which lightning data from a ground-based detecting network were already assimilated. The addition of GLM data in 30 model initializations over a 3-day period produced a notable increase in probability of detection, assessed against radar reflectivity observations, without increasing the false alarm ratio, for 1-3 hour forecasts. During these experiments, the real-time HRRRX was able to assimilate these additional data while producing forecasts at its usual rate due to the prompt delivery of the GLM datasets.

GLM data are expected to be assimilated in the HRRRX's real-time configuration the first-generation Rapid Refresh Forecast System (RRFS), a convection-allowing component of the Unified Forecasting System, when it becomes operational in about 2023. The mesoscale lightning assimilation strategy of Apodaca and Zupanski (2018) is also expected to be incorporated into the global FV3-based UFS model in a future release (Apodaca, private communication, 2019), and the ECMWF is currently developing the framework to assimilate lightning observations from their Lightning Imager instrument when it becomes available in 2022 (Lopez 2016). Another expected benefit is improvements to environmental state following GLM DA. For instance, under-forecast instability could be improved in the RAP 0 hr analysis when greater lightning rates are assimilated as a proxy for the true instability. The model covariances pick up on this, and in turn, better forecasts improve severe weather watch accuracy, especially in highly uncertain/contingent cases.

Economic benefit of improved model initialization and forecast accuracy will be realized when the results of the aforementioned research reaches operational models and impacts operational decisions. A few example application areas expected to benefit from GLM-related improvements to short-range weather forecasts include the following:

- Increased lead time and improved accuracy of NWS severe weather watches (flooding, tornadoes, wind, and hail), leading to better receptiveness of warnings and improved public safety.
- GLM DA will benefit the transition to warn-on-forecast, leading to enhanced accuracy of NWS-issued severe weather warnings, including lower false alarm rates.
- Reducing losses from hail (e.g., automobiles can be moved to avoid large losses, agricultural losses can be mitigated on small scales in response to weather forecasts).
- Predicting weather favorable to the onset or spread of wildfires, including a Fire Weather Index product in development for use in the NOAA SPC's Fire Weather Outlook.



Preliminary results from the 2020 Hazardous Weather Testbed Spring Forecast Experiment reveal GLM DA improvements regardless of radar coverage (Hu et al. 2020, Fierro et al. 2020).

2.5. Improving Precipitation Estimation

Lead: Bob Kuligowski (NOAA/NESDIS/STAR)

Premise: The GLM observations improve satellite precipitation estimates, benefiting flash flood forecasting in significant portions of the western US, Hawaii, and US territorial islands without adequate radar coverage.

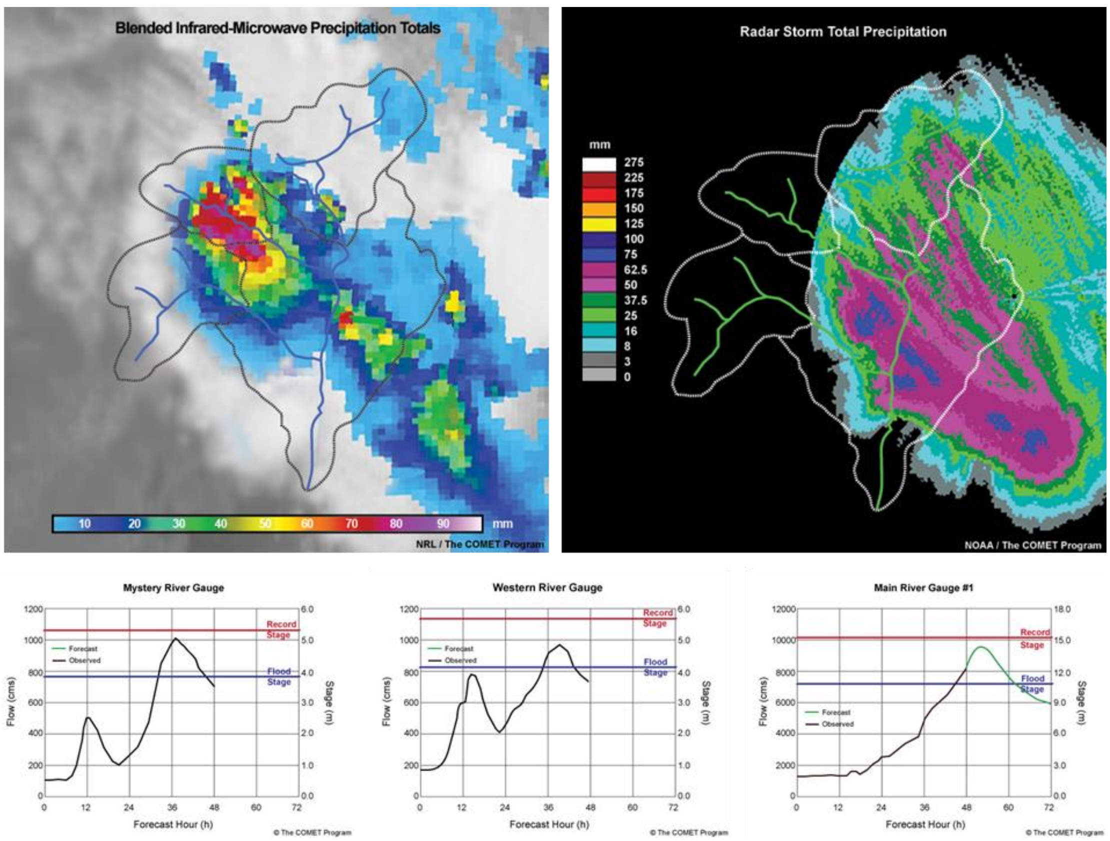
Discussion: Although much of the CONUS has adequate radar coverage, satellite estimates of rainfall still provide valuable information in radar-poor regions such as the western United States, the Rio Grande Valley (where the Mexican portion of the basin lacks coverage), and islands such as Hawaii and Puerto Rico. This is particularly true for flash floods where information is needed quickly in order to maximize the time available for public response. Initial unpublished analyses indicate that the GLM can improve the accuracy of the GOES-R satellite rainfall estimates. Including observations from the GLM (specifically, 2-km gridded Flash Extent Density and Total Optical Energy) in the operational Enterprise GOES-R Rainfall Rate Product will improve skill that will lead to improved forecasts (longer lead time and greater accuracy) of flash flooding in radar-poor regions. This section describes how improved satellite precipitation estimates are expected to provide value through improved flash flood forecasting.

Significant portions of the western US, Hawaii, and US territorial island possessions lack adequate radar coverage to support flash flood forecasting. In these regions, forecasters are often left with partial views of the storms, commonly missing information in the lowest levels. While heavy rain associated with deep convection can still be detected in these instances, shallow convection will not and neither will the enhancement of rain in areas of complex terrain via the "seeder-feeder" mechanism [i.e., orographic precipitation-enhancement in which precipitation from an upper-level precipitating cloud (seeder) falls through a lower-level orographic stratus cloud (feeder) capping a hill or small mountain]. In areas of complex terrain, radar coverage is further compromised because installing the radar in lower elevations (which is cheaper and easier to maintain) means that higher terrain around the radar will block the beam from seeing behind it, while installing it in higher elevations will make the beam even higher with range.

Even when only focusing on those regions with poor radar coverage, the annual cost of flash flooding is still quite high. According to the NCEI Storm Events Database, during the 10-year period from May 2010 through April 2020 flash floods in the western United States and floods in the Rio Grande Valley, Hawaii, and US territorial possessions totaled $21.66 billion in property damage (crop damage was not included), resulting in 142 deaths. Hurricane Maria in Puerto Rico produced $18.26 billion of this total (and 20 deaths), but even removing this event leaves an average of $340 million in damages and 12 deaths per year in regions with poor radar coverage. In the case of Hurricane Maria, the GLM provided crucial coverage for several months during the recovery efforts helping substitute for the heavily damaged radar. Most flash flood damage cannot be avoided; e.g., buildings cannot be moved out of the way. Using Figure 4 of Carsell et al. (2004), a warning time of 30 minutes or more can reduce total damage by approximately 5%. We chose 30 min because flash floods are rapid-response events and longer increases in warning time are not realistic. Applying this multiplier to the total would give an average annual avoidable property damage estimate of $17 million in regions with poor radar coverage.

Cho and Kurdzo (2020) evaluated the value of radar data for flash flood casualty reduction. In the United States, operational flash flood warning decisions rely primarily on the concept of flash flood guidance (FFG; Ostrowski et al. 2003). The basic idea is that the forecaster looks for accumulated quantitative precipitation estimation (QPE) to exceed the FFG rain accumulation threshold in a given catchment basin when issuing a flash flood warning; decision support tools such as the Flash Flood Monitoring and Prediction system aid the forecaster in this process (Clark et al. 2014). When heavy rains cause flash floods, in order to issue timely warnings, forecasters mostly use multisensor precipitation estimator (MPE) products for comparison with FFG thresholds. Waiting for flow-level measurements from stream gauges delays the decision, and many potential flash flood areas are in ungauged headwaters. MPE ingests radar, rain gauge, and geostationary satellite data; with rain gauge data used to help correct biases in the radar and satellite estimates. The dominant MPE contributor is radar QPE, while satellite QPE is mainly used to fill gaps in radar coverage (Kitzmiller et al. 2013). Forecasters have started to consult short-term rainfall nowcasts as well (Ahnert et al. 2012), and the GLM shows great promise for helping to advance the warn-on-forecast concept.

Cho and Kurdzo (2020) showed unambiguously that better radar coverage of the causative rainfall leads to improved flash flood warning statistics. They also established that the casualty rate decreases by 44% when a flash flood warning is present. Their study combined these two effects to generate benefit estimates on a high-resolution spatial grid. The present WSR-88D network was shown to provide over $300 million per year in flash flood casualty reduction. There is a modest remaining benefit pool of $13 million per year for coverage improvements, which is indicative of the effective coverage provided for flash flood warning purposes by the current weather radar network. Inclusive of all aspects of flash flood warning POD improvements, including better radar QPE, the maximum benefit pool is $69 million per year. Improvements made possible by the GLM could reclaim some fraction of this radar coverage benefit pool (e.g., 2% would be $1.38 million). Section 3.1 provides additional details on GLM benefits related to filling radar coverage gaps (both poor coverage and routine / unplanned outages).



“Flood Forecasting Case Study” training module illustrates the role satellite QPE can play in flash flood forecasting (http://ftp.comet.ucar.edu/memory-stick/hydro/basic_int/case_study/print.htm). Supplementing satellite QPE using GLM will significantly improve rainfall estimates during convective precipitation, especially in regions lacking radar coverage. The GLM also detects thundersnow, which is indicative of heavy snowfall in shallow winter storms that are more susceptible to radar coverage gaps.

2.6. Improving Tropical Cyclone Diagnosis and Warning

Lead: Stephanie Stevenson (NOAA/NHC)
Contributors: Mark DeMaria (NOAA/NHC), Scott Rudlosky (NOAA/NESDIS)

Premise: The GLM clearly conveys convective patterns below cloud top in tropical cyclones (TCs) which helps better diagnosis TC structure and evolution and aids forecasts of TC intensity change including rapid intensification.

2.6.1. Background

Observations are critical for analyzing TC location, intensity, and size, and for forecasting these parameters. TC observations often are limited to those from satellites due to their occurrence away from land-based observation platforms. GLM is a unique dataset that aids TC analysis and forecasting. Traditionally, geostationary satellite imagery has been used to observe TC cloud top patterns, and microwave imagery from polar-orbiting satellites has provided insight into the convective structure below the cloud tops. The lightning detected by GLM provides insight into the vigor and pattern of convection below the cloud tops in TCs, and unlike microwave imagery, is able to do so continuously from geostationary orbit.

Ground-based lightning detection networks are capable of capturing lightning over the oceans, but they are inherently biased toward the detection of one type of lightning (cloud-to-ground) and exhibit a non-uniform detection of in-cloud lightning depending on the distance from a land-based sensor. Data from the inner core of Hurricane Maria (2017) during its rapid intensification depicts this important difference in flash detection efficiency, with the ground-based system only detecting 3% of the flashes detected by GLM (Fierro et al. 2018). GLM is the only network that provides continuous detection of total lightning (cloud-to-ground + in-cloud) across the tropical Atlantic and eastern and central Pacific basins. The GLM flash area and optical energy measurements also provide spatial and temporal information on the convective evolution not captured by other lightning networks.

2.6.2. GLM applications in tropical cyclones

a. Forecasting intensity change, including rapid intensification

Improvements to TC intensity forecasts continue to be a focus within the operational and research communities. Rapid intensification is a particularly challenging subset of such forecasts which can be devastating if occurring near landfall. During the GLM era, Hurricanes Laura (2020), Michael (2018), and Harvey (2017) have most clearly demonstrated the devastating impacts of rapid intensification near shore. Sustained winds in these storms increased by more than 40 mph in the 24 h prior to landfall. Section 104 of the *Weather Research and Forecasting Innovation Act of 2017* specifically tasks NOAA with planning and maintaining “a project to improve hurricane forecasting, including the prediction of rapid intensification and track of hurricanes”.

Several studies have noted a relationship between increased inner-core or rainband lightning activity and TC intensity change (Lyons and Keen 1994; Molinari et al. 1994; Squires and Businger 2008; Pan et al.

2010; Jiang and Ramirez 2013; Zhang et al. 2015; Stevenson et al. 2016; Ranalkar et al. 2017; Xu et al. 2017; Stevenson et al. 2018). In some cases, lightning bursts preceded rapid intensification (e.g., Stevenson et al. 2014). Using a statistical-based method that determines the probability of rapid intensification, DeMaria et al. (2012) demonstrated that the weight of the lightning input was comparable to the weight of other factors used to determine rapid intensification in operational TC forecasting models. They suggested that the lightning provided independent information and had the potential to improve forecasts of rapid intensity changes.

Hurricanes Michael (2018) and Dorian (2019) are two recent cases where the maximum sustained wind speed increased by 30 to 35 knots 24 hours prior to landfall (Beven et al. 2019; Avila et al. 2020). GLM captured a significant amount of lightning in the eyewall of both of these hurricanes prior to and during the rapid intensification. Early research on Hurricane Dorian also shows added value in the GLM lightning flash area and optical energy fields for determining whether lightning is associated with intensification. These unique fields are not available from ground-based lightning networks. The National Hurricane Center (NHC) is currently developing a real-time rapid intensification forecasting aid that incorporates GLM observations.

b. Monitoring structure beneath the cloud tops

TC structural changes beneath the cloud tops can also influence the TC intensity, yet these can be difficult to diagnose with geostationary satellite imagery and often require microwave imagery from polar-orbiting satellites, in-situ aircraft observations, and/or radar data. For example, Stevenson (2018) and Squires and Businger (2008) found evidence that lightning may be useful for identifying secondary eyewall formation and eyewall replacement cycles, which can result in TC intensity fluctuations.

The cirrus canopy often obscures the structure of convection below the cloud tops in TCs. GLM can monitor the nature of convection below the cirrus canopy, which is useful for tracking center locations, monitoring storm dissipation, and analyzing convective symmetry of the eyewall. Vagasky (2017) documented a ring of eyewall lightning that is commonly found in strong TCs. Some researchers have suggested using these features to track the TC center.

c. Monitoring convection in landfalling tropical cyclones

For forecasters responsible for issuing short-fused warnings for tornadoes during hurricane landfall, situational awareness of individual storms and circulations in the outer rainbands is key. Though flash rates are often weak in tropical systems, the production of any storm charge is typically associated with stronger updrafts capable of producing tornadic activity (e.g., McCaul et al. 2004; Spratt et al 1998). The presence of total lightning information (such as detected by GLM), even when infrequent, can be an important signal to operational forecasters responsible for warning decisions.

d. Data assimilation into numerical models

The potential benefits of GLM data assimilation into numerical weather prediction (NWP) models for TC forecasting has yet to be fully explored. NWP models often struggle to initialize the TC inner core without in-situ aircraft observations. Several studies have shown reduced TC intensity forecasts errors, ranging from 20-40%, when airborne Doppler radar observations are assimilated (Zhang et al. 2011; Zhang and

Weng 2015; Tong et al. 2018). While not TC-focused, others have shown improvements to short-term convective forecasting over land when assimilating the GLM flash extent density (see Section 2.4). It is possible that GLM data assimilation over the data-sparse oceans would allow NWP models to better analyze the inner-core convective structure, leading to forecast improvements comparable to those observed when assimilating airborne Doppler observations.

2.6.3. Value assessment

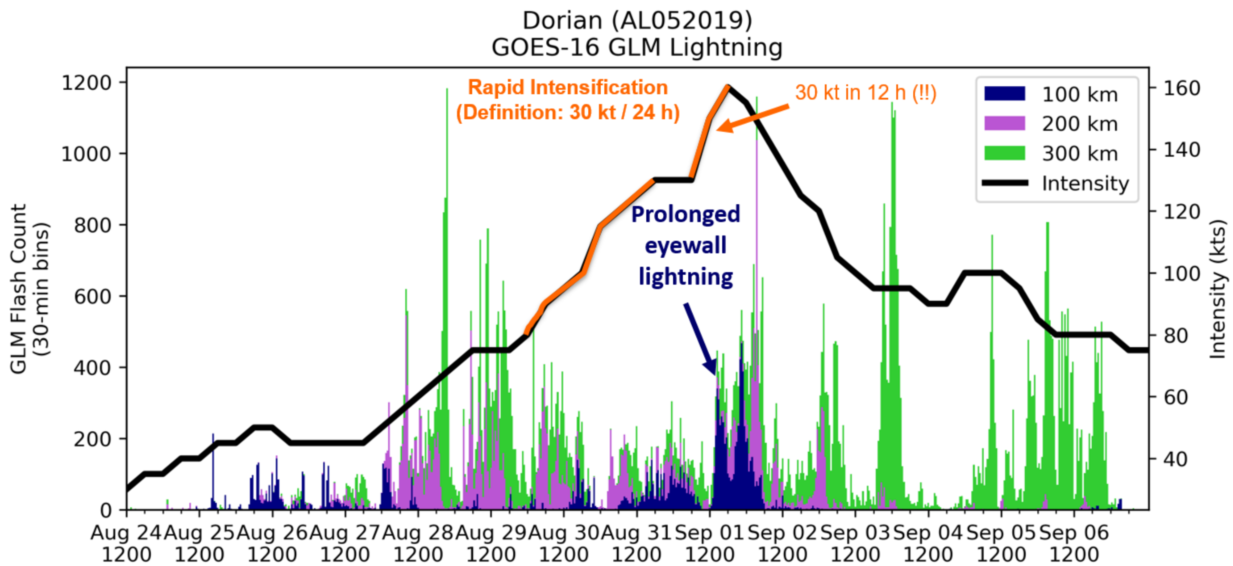
Assessing the economic value of GLM for TCs is complicated by factors beyond quantifiable improvements to the TC forecasts since social science also plays a role. The economic impact of TCs is highly dependent not only on the TC track, intensity, and size, but also on the population and building structure quality upon landfall, as well as the actions of decision-makers and public in response to the forecast.

Sutter and Ewing (2016) summarize the current state of knowledge on the economic value of improving hurricane forecasts. They found that the value of reducing loss of life ranges from $250 million to $1 billion annually, with only a fraction of that attributable to improved forecasts. Preparations in the hours or days ahead of a storm, including evacuations and temporary property loss reduction measures, also have economic value. Sutter and Ewing (2016) suggest that TC intensity has more value than track in these preparations, thus any improvements in TC intensity forecasts from GLM may lead to a greater lead time and reduced costs in storm preparation activities.

Sutter and Ewing (2016) stated that hurricane damage averaged $14 billion annually in the U.S. since 1990. The NOAA National Centers for Environmental Information (NCEI)'s U.S. Billion-Dollar Weather and Climate Disasters database suggests that this number has increased over the last decade (2010-2019), averaging $44.2 billion annually (adjusted for inflation). In the last 3 years (2017-2019), annual costs were estimated much higher at $111.7 billion due to high impact events, some of which intensified quickly before landfall [e.g., Hurricanes Harvey (2017), Michael (2019), Laura (2020), and Sally (2020)]. Similar to the decade average, the Congressional Budget Office estimated $54 billion in expected annual damages from hurricane winds and storm-related flooding. If even a small fraction of this money could be saved by better preparations from improved intensity forecasts, it could provide a large economic benefit. Additional economic benefits likely exist for countries in the Caribbean and Latin America that are impacted by TCs forecast by NHC, though values of that impact remain to be discovered.

While landfalling TCs certainly impact the public and economy more, TCs also have economic impacts over water. Cargo and cruise ships are affected by the track, size, and intensity of TCs. TCs in the Gulf of Mexico can also impact the energy sector, and as Considine et al. (2004) showed, the oil and gas industry valued the 2-day forecasts for this region around $8 million per year in the 1990s, with an additional $15 million in value for forecast accuracy improvement of 50%. Updated values for the energy sector and attributable economic impacts to the shipping and tourism sectors should be examined.

In summary, the GLM can provide value in TC assessment, particularly for forecasting intensity changes, monitoring structure beneath the cloud tops, and helping to initialize the inner-core in numerical models. TCs significantly impact the economy and can cause billions of dollars in damages. The quantifiable value of GLM applied to TCs remains difficult to determine due to the infancy of its integration into the TC forecasting process, and future studies should examine the GLM impact on forecast accuracy along with the value of any improved forecasts.



Eyewall lightning in Hurricane Dorian prior to landfall had everyone's attention, including NHC forecasters. Nearly continuous eyewall lightning was observed for several hours predominately in the northern eyewall (front right quadrant). This eyewall lightning ceased when the inner eyewall began to weaken, suggesting the GLM may help monitor eyewall replacement cycles (ERCs).

2.7. Improving Climate Applications

Lead: Steve Goodman (GOES-R)
Contributors: William Koshak (NASA/MSFC), Eric Bruning (TTU)

Premise: GLM data offer unique insights for monitoring climate-scale variability and response in a changing climate, a close link between lightning and convective cloud properties makes it an essential indicator of inter-annual to decadal change and a key variable for validating climate models.

2.7.1. Background

One primary GLM mission objective is to "Accumulate a long-term database to track decadal changes in lightning activity" (GLM PORD, 2018). This climate objective is important because potential changes in thunderstorm activity, including severe convective storms, may be monitored through changes in lightning activity, and linked to modulation of earth's electrical balance as measured in the global circuit. The GLM extends the 20+ year NASA Earth Observing System Lightning Imaging Sensor (LIS) time-series (1997-Present, with a short gap) for the next 2+ decades (Goodman et al., 2007; Cecil et al., 2014; Albrecht et al., 2016; Blakeslee et al., 2020). The WMO and GCOS (Aich et al., 2018; WMO GCOS, 2019) identified lightning as an Essential Climate Variable (ECV, Bojinski et al., 2014) owing to the availability of the LIS data from low earth orbit (LEO) and the geostationary lightning data from the GOES-R series GLM (Goodman et al., 2013), with expected contributions from the EUMETSAT MTG-Lightning Imager (Dobber and Kox, 2016), Chinese Meteorological Agency Fengyun-4 Lightning Mapping Imager (Yang et al., 2016), and complementary information from ground-based lightning networks.

2.7.2 Relevance

Clouds: The close linkage between lightning and convective cloud properties and precipitation makes it a useful indicator for observing changes in climate and extreme storms. A 7-year study of the most intense storms on earth using passive microwave, active radar, and LIS observations from the Tropical Rainfall Measuring Mission (TRMM) shows a clear sensitivity of the most extreme lightning flash rates to the vertical depth of high reflectivity > 40 dBZ and low brightness temperatures at 37 and 85 GHz, indicating strong updrafts and the presence of precipitation-sized ice and hail (Zipser et al., 2006). They note that such intense storms are distributed quite differently from rainfall, and provide new metrics for global models to more accurately simulate the types and modes of convection as a component of the climate system. Lightning's unique sensitivity to mixed phase processes in deep convection makes it a useful addition to methods for improving characterization of mixed phase clouds: a noted area of climate model uncertainty (Korolev 2017). A new WMO International Cloud Working Group (ICWG) initiative presented at the CGMS-48 meeting is looking at potential contributions from lightning observations for a more accurate characterization of thunderstorms and context for cloud climatologies such as the widely used International Satellite Cloud Climatology Project (ISCCP, Rossow and Schiffer, 1999) and the planned follow-on for a higher spatial-temporal resolution ISSCCP - Next Generation (ISCCP-NG) cloud climatology using the new generation of operational multi-spectral geostationary imagers.

Lightning Climatology and Inter-annual Variability: The occurrence, distribution, seasonal, and inter-annual variability of lightning and thunderstorms around the globe are closely linked to the Earth's climate, while the climate is strongly influenced by the general circulation of the atmosphere (e.g., Hadley circulation, Rossby waves, Madden-Julian Oscillation, polar lows and fronts, extra-topical Jetstream, among the major features). Lightning also has been shown to be globally linked to the continental land masses and their topography. Observations from space (Christian et al., 2003, Goodman et al., 2007; Cecil et al., 2014; Albrecht et al, 2016; and Blakeslee et al, 2020) as well as ground-based networks (e.g., Virts et al., 2013) generally agree. However, the total lightning (IC and CG) properties are best observed from space and provide unique information on the energetics (Beirle, et al., 2014; Chronis et al., 2017; Holzworth et al., 2019), duration, and spatial extent (e.g., Peterson et al., 2020) of lightning flashes not observable from the ground. The most energetic flashes can be found over the coastal-open ocean, whereas long duration and horizontally extensive discharges are more common in the stratiform precipitation region during the mature-decaying phase of mesoscale convective systems (MCSs; Peterson et al., 2019). Long flashes propagating from the convective line into and throughout the trailing stratiform rain may extend hundreds of miles with dozens of strikes to ground. **Such flashes, numbering over five million in 2019 (Peterson, 2019), are especially hazardous to outdoor workers and those participating in outdoor recreation activities.**

The MCS, a regional, long-lived (i.e., long-track) and often nocturnal weather system, is known to produce a significant fraction of the warm season heavy rainfall throughout the world. Velasco and Fritsch (1987), and others have showed that the El Niño-Southern Oscillation (ENSO) can modulate the synoptic and mesoscale environments over the Americas, which in turn can influence the number and tracks of MCS, as well as the convective activity and precipitation patterns across the tropical and subtropical Americas. They found that the number of MCS storm-tracks and rainfall doubled during the 1982/83 El Niño event. Goodman and MacGorman (1986) found that the typical MCS produced cloud-to-ground lightning flash rates exceeding 1000 hr^{-1} for nine or more hours with as much as 25% of the annual lightning strikes at a single location caused by the passage of just a single MCS. **Space-based optical instruments like the GLM are presently the only tool able to fully characterize the spatial extent of lightning within these massive systems throughout their lifetime.**

During the 1997-1998 ENSO event, which is notable for being the strongest event since the 1982/83 El Niño, Goodman et al (2000) found the most significant year-to-year changes in lightning frequency worldwide occurred along the Gulf Coast and within the Gulf of Mexico basin during the Northern Hemisphere winter (DJF). Within a broad swath across the northern Gulf basin there was a 100–150% increase in lightning days year-to-year and a nearly 200% increase in total hours with lightning. The increase in lightning activity during ENSO occurred in association with a 100% increase in the number of synoptic scale cyclones that developed within or moved through the Gulf basin. The primary variables controlling these enhancements in thunderstorm activity are the position and strength of the jet stream. In a related study Hamid et al. (2001) found convective rainfall suppressed near the Western Pacific regions and the Maritime Continent including Indonesia, yet the lightning activity during the El Niño period increased in contrast (on the average by 57%). As observed by the Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor and Precipitation Radar, the convective storms during the El Niño were more intense. This was supported by the evidence that the El Niño storms had greater vertical development and ice phase precipitation. The inter-annual variability (and predictability) of convective storms, lightning, precipitation, and flooding are all of great societal interest in understanding the variability and change of extreme weather and its impacts.

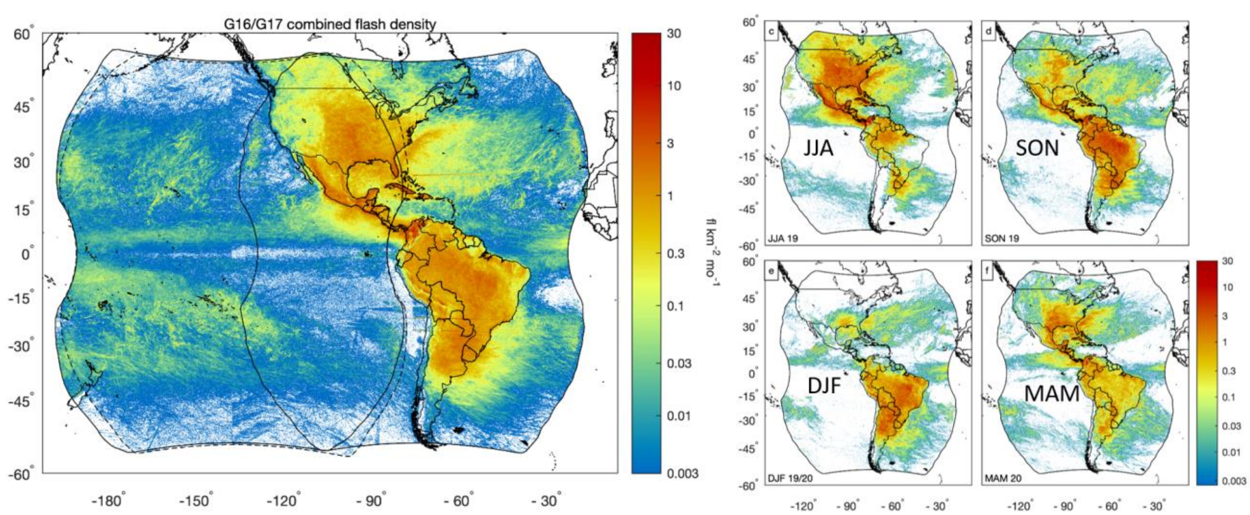
<u>Aerosols and Greenhouse Gases</u>: Lightning affects the global climate directly serving as a major natural source of nitrogen oxides (NOx), an important greenhouse gas (Price, 1997). The GLM offers a new capability to probe lightning/climate inter-relationships and improve air quality forecasts (Allen and Pickering, 2002; Pickering et al., 2020), thereby supporting the National Climate Assessment (NCA) [Koshak et al., 2015]. In particular, GLM can be used to estimate lightning nitrogen oxides (LNOx) since trace quantities of NOx affect greenhouse gas concentrations (e.g., ozone). A simple LNOx retrieval model for this already exists employing GLM Flash Optical Energy, proportional to total flash energy and which in turn is proportional to the flash LNOx production (Koshak, 2017). The first GLM estimates of LNOx/flash vary both spatially and seasonally with the peak in LNOx/flash in winter (shallower clouds, lower flash rates, higher +CGs ratio). These are consistent with the earlier results found with TRMM/LIS over 17+ year period using the same retrieval model.

<u>Societal Impacts</u>: For the period 2003-2012, Koshak et al (2015) examined the cloud-to-ground and in-cloud lightning (from the NLDN and TRMM/LIS, respectively) and found lightning-caused fatalities and injuries, and the number of lightning-caused wildland fires and burn acreage trended downward. However, crop and personal-property damage costs increased. Although the CONUS-averaged dry-bulb temperature trended upward during the analysis period (i.e., a period of warming), the CONUS-averaged

wet-bulb temperature (a variable that is better correlated with lightning activity) trended downward. They estimated the following societal and economic impacts:

- 1.454 fatalities and 9.044 injuries per million CG flashes (human health)
- \$6,696 in crop damage per million CG flashes (agriculture)
- \$38,919,976 in home-owners' insurance claims per million CG flashes (personal property)
- 440.6 wildland fires and 122,940 acres burned per million CG flashes (forestry)

Climate Change: Price and Rind (1994), using cloud top height as a proxy for lightning flash rate in the Goddard Institute for Space Studies (GISS) General Circulation Model (GCM), predicted an increase in lightning as a result of a warmer climate. Two climate change experiments were conducted: one for a 2xCO_2 climate (representing a 4.2°C global warming) and one for a 2% decrease in the solar constant (representing a 5.9°C global cooling). The results suggest a 30% increase in global lightning activity for the warmer climate and a 24% decrease in global lightning activity for the colder climate. Several subsequent studies support the positive correlation between lightning amount and temperature (Williams, 1999, 2005; Reeve and Toumi (1999); Price, 2008; and Romps et al., 2014). These reports, based on observations and climate models, describe the climate-change science impacts and also help to interpret the findings of the U.S. Global Change Research Program and the Intergovernmental Panel on Climate Change (IPCC). Price (2008) suggests, in addressing the question "Will lightning activity increase in a warmer world?", that since the majority of global lightning activity occurs in the tropics, changes in future global lightning activity will depend on changes in the tropical climate. They suggest that the thunderstorms that do occur will be more explosive, resulting in more lightning activity. Romps et al. (2014), using a lightning-based proxy proportional to Convective Available Potential Energy and precipitation applied to 11 climate models, found that CONUS lightning strikes were predicted to increase by 12 ± 5% per degree Celsius of global warming and as much as 50% over the rest of this century. Lightning is a good target variable for climate model validation, where there is a need to improve treatment of the mixed-phase precipitation processes to which lightning is most sensitive. For these reasons, GLM data will provide great value for monitoring climate-scale interannual variability, and any pattern shifts in a warming climate.



Above images from Rudlosky and Virts (MWR manuscript conditionally accepted) illustrating the first 18 months of coincident GOES-16 and GOES-17 GLM coverage (December 2018 – May 2020).

3. Quantitative Value Estimates

3.1. Value of Filling Data Gaps

Lead: Chad Gravelle (NWS/SRH)
Contributors: Scott Rudlosky (NESDIS/STAR)

3.1.1. Contiguous U.S. (CONUS) Applications

Premise: The GLM's broad spatial coverage and rapid temporal updates complement radar observations over CONUS to support severe weather warning decisions.

Value Estimate: This section details the role the GLM plays in filling spatial and temporal radar coverage gaps over CONUS. By augmenting radar analysis with GLM observations, forecasters have naturally begun finding ways to mitigate radar coverage issues. Although the GLM does not resolve much of the detail provided by radar (e.g., horizontal and vertical resolution of particle distribution and winds), near uniform coverage and rapid temporal updates add value during severe weather warning operations (i.e., tornado, wind, hail, and flash flood). Radars are inherently range dependent and forecasters often are tasked with tracking storms as they traverse regions of varying radar coverage. The GLM provides a baseline for tracking and interrogating these storms regardless of their radar-relative location. Radars also scan volumes through successive elevation scans, adding latency to the observations. The rapidly-updating low-latency GLM observations have been shown to marginally increase warning lead time by helping forecasters avoid waiting for additional elevation scans. Forecasters also can avoid issuing unnecessary warnings if decreasing lightning trends conflict with the delayed radar representation of storms.

Cho and Kurdzo (2019) recently developed and applied a geospatial model for calculating weather radar benefits for tornadoes. Their "fraction of vertical volume observed" measure of radar network coverage takes into account the near-range cone of silence, the far-range loss of low-level coverage due to Earth's curvature, as well as terrain blockage and ground height variability. The model was instrumental in establishing an unambiguously positive correlation between radar coverage and tornado warning performance. Relative to a CONUS without weather radars, the current baseline provides ~$490 million in tornado benefits annually (Cho and Kurdzo 2019). The remaining benefit pool (i.e., value that could be realized) is about $260 million per year, split roughly evenly between coverage- and rapid-scanning-related gaps. Adding rapid-scanning capability achieves far greater cost reduction than improving radar coverage. Just upgrading the existing radars with rapid scanning yields about the same benefit (~$100 million per year) as blanketing the CONUS with perfect radar coverage. Most of the rapid-scan benefit derives from tornado warning FAR reduction, which is especially important because Tornado warning FAR is high (~0.72) relative to other severe weather warnings. If the connection between casualty reduction and longer lead times is established, the benefit estimates for rapid scanning rise further.

Along with the substantial value realized through filling routine radar coverage gaps, the GLM plays an important role during planned or unplanned radar outages. The challenges associated with the aging

WSR-88D network leads to loss of individual radars often at inopportune times (i.e., during lightning and severe weather occurrence). These outages can be part of routine maintenance (e.g., ongoing NEXRAD Service Life Extension Program) or caused by unforeseen circumstances (e.g., lightning or severe winds impacting the radar, power outages). An ongoing pedestal replacement program has been causing 2-3 week planned outages when forecasters are required to rely on neighboring radars and other datasets (e.g., MRMS, GLM) during forecast and warning operations. We have begun analyzing the radar-relative occurrence of lightning and the relation to radar status for all CONUS WSR-88Ds. Early results suggest that less than half (~42%) of all CONUS lightning occurs within 100 km of WSR-88D radars during May – July 2020. This student-led study aims to document the radar relative occurrence of lightning along with the frequency of lightning during radar outages to better assess the actual GLM value (see next version).

Our goal moving forward will be to accurately document which fraction of this potential value is presently being realized. For now, we document the potential benefit pools where GLM value is realized:

- Although ground-based lightning observations can fill radar coverage gaps and augment poor coverage, tremendous value comes from the U.S. government owning its own lightning dataset (U.S. government lightning data purchases are on the order of ~$5 million per year; NOAA, DoD, DOE, BLM, NASA).
- Future analyses should seek to attribute value to GLM by quantifying the minutes saved on each end of severe weather warnings, number of unnecessary warnings avoided, and reduction in unnecessary warning coverage area. For now, we note the $260 and $69 million per year benefit pools identified by Cho and Kurdzo (2019, 2020) for improved tornado and flash flood warnings associated with radar network improvements, and assert that the GLM helps realize some fraction of that value.

3.1.2. Outside CONUS (OCONUS) Applications

Premise: Rapidly updating GLM observations over vast (often data sparse) regions provide decision makers with information they need to forecast, monitor, and react to thunderstorms, cyclones, and volcanic hazards at a faster cadence than ABI.

Value Estimate: GLM value is realized OCONUS through improved short term model forecasts (Section 2.4), improved satellite precipitation estimates (Section 2.5), improved tropical cyclone forecasting (Section 2.6), and supporting aviation assets in route (Section 3.2.2). Two additional applications are:

<u>Monitoring Maritime Convection</u>

Roughly 30% of the U.S. population (~94 million people) live in counties adjacent to the Atlantic Ocean, Gulf of Mexico, and Pacific Ocean, which underscores the importance of monitoring maritime convection. Since radar coverage quickly diminishes offshore, the GLM data provide tremendous value for forecasters monitoring and warning on storms in near-shore waters. For example, in the presence of deep convection the GLM FED product is well correlated with plan-view radar reflectivity at the -20 C isotherm and base reflectivity. Therefore, the GLM imagery provides valuable information for monitoring maritime storms both near-shore and over the open water. Trillions of dollars of commerce flow in and out of U.S. ports each year, commercial and recreational fisherman make extensive use of the near shore waters, and offshore oil and gas platforms are vulnerable to inclement weather. Forecasters with the responsibility of monitoring maritime convection can leverage the same trending information deployed during severe weather warning operations over land. In many cases, in the absence of radar, the GLM is the only quantitative tool available to diagnose convective intensity. The GLM also allows forecasters to detect and monitor convective intensity and coverage upstream (outside radar range) as storms approach the U.S. (e.g., the monsoon approaching the southwest).

Detecting Volcanic Eruptions

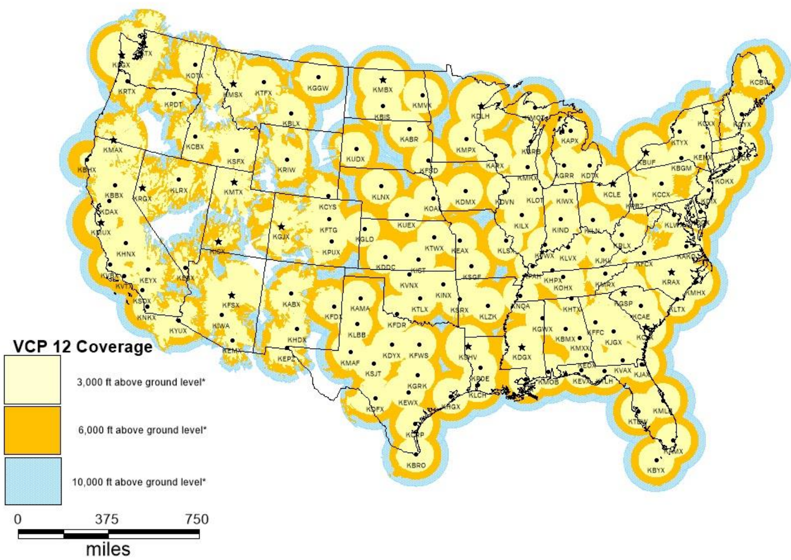
Pavolonis et al. (2020) described how the GLM can aid in the detection of volcanic eruptions and characterization of their plumes. Volcanic clouds can affect weather and are a major aviation hazard, so routine volcanic cloud monitoring is critical. The Advanced Baseline Imager (ABI) and GLM are extremely valuable for detecting, tracking, and characterizing volcanic clouds, including volcanic ash, which is the constituent that poses the greatest overall hazard. The VOLcanic Cloud Analysis Toolkit (VOLCAT) allows users at Volcanic Ash Advisory Centers to quickly determine if automated alert correctly capture an eruptive event. If alerts are verified through human expert analysis of ABI imagery, possibly in combination with information of other data sources, a volcanic ash advisory is issued. Volcanic Ash Advisory Center feedback indicates that the alerts are an important complement to routine manual interrogation of ABI imagery. In the future, the alerts will be used to automatically initiate model-generated forecasts of ash dispersion and transport. The tool will also be extended to include SO2 alerts and GLM-derived information on lightning.

Explosive volcanic eruptions often generate lightning via a series of complex and not yet fully understood mechanisms (McNutt and Williams, 2010). The GOES-R GLM, which uniquely complements ground-based measurements of lightning, may lead to improved eruption detection and characterization. On 3 June 2018, Fuego volcano in Guatemala had a series of explosive events that generated lightning. GLM observed flashes for the first explosive event, which commenced around 18:00 UTC. While analysis is ongoing, certain attributes (e.g. total optical energy) of the GLM observed lightning in the 3 June 2018 Fuego events differed from the surrounding meteorological convection, but additional analysis is needed. The combination of the GLM and ABI provides novel insights on volcanic eruptions and volcanic cloud behavior, and continued analysis of GLM observed volcanic lightning is encouraged.

Our goal moving forward will be to accurately document which fraction of this potential value is presently being realized. For now, we document the potential benefit pools where GLM value is realized:

- Radars provide ~$1 billion in annual value over CONUS (tornadoes, floods, etc., Cho and Kurdzo 2019, 2020), so the GLM contributes considerable value by serving as a radar proxy offshore.
- Detecting, tracking, and characterizing volcanic clouds helps better characterize the distribution of ash in the atmosphere, helping airplanes avoid potential catastrophe.

- GLM data assimilation shows comparable results to radar assimilation, suggesting great GLM value offshore (especially as convective allowing models cover larger spatial domains).
- GLM provides value for TC assessment outside of radar range, particularly for forecasting intensity changes, monitoring structure beneath the cloud tops, and helping to initialize the inner-core in numerical models. Sutter and Ewing (2016) estimated the value of potential TC forecast improvements, finding that lives saved in the U.S., property damage avoided through temporary measures, and the international benefits categories could easily exceed $100 million per year each. GLM related TC forecast improvements are expected to realize some fraction of this value.



Left: WSR-88D Radar Coverage below 10,000 ft AGL

Below: Weather-related radar damage

Hurricane Maria required FEMA/NWS San Juan to use GLM as a radar replacement to help the restoration crews avoid lightning, and as a proxy for heavy rainfall while the radar was restored.

3.2. Value of Mitigating Aviation Hazards

Lead: Scott Rudlosky (NOAA/NESDIS/STAR)
Contributors: Randy Bass (FAA), Amanda Terborg (AWC), and Brian Pettegrew (AWC)

Summary: Thunderstorms incur great costs on the aviation industry that the GLM can help reduce by providing a reliable source of accurate, timely, and freely available lightning information. GLM integration into existing procedures provides measurable socioeconomic benefits. The GLM supports the safety and efficiency of both 1) ramp operations and 2) airplanes en route (and on approach), and this section estimates the GLM value associated with this.

3.2.1. Supporting ramp safety and efficiency (CONUS)

Premise: The GLM observes the complete spatial footprint of total lightning flashes, which helps better characterize the lightning risk and increase confidence/certainty when suspending and resuming ramp operations, leading to enhanced safety, improved efficiency, and cost savings.

Value Estimate: GLM observations increase the confidence of aviation stakeholders charged with characterizing the lightning hazard as a basis for improving the safety of outdoor personnel and minimizing avoidable operational inefficiencies. The operator dilemma is that the costs of flight delays are immediately recognizable as real money lost, while the cost of the lightning risk remains virtual until somebody actually gets hurt (Steiner et al. 2016). The perception of risk depends on the lightning information used, with uncertainty in lightning detection efficiency directly inducing some unknown risk to the operator (Steiner et al. 2016).

Steiner et al. (2015) raised awareness of the magnitude of ramp closure impacts and the complexity of the ramp closure decision-making process. Airline and airport stakeholders employ safety rules that are reactive to a first lightning strike within a critical radius to halt outdoor work and start a waiting period (Bass 2019). Subsequent lightning strikes within that critical radius reset the waiting period clock. The ramp closure decision-making process is burdened with uncertainties, especially related to the measurement and processing of lightning data, and the safety procedures and effectiveness of implementation (Steiner et al. 2015). Lightning data exhibited uncertainty related to the measurement technique (sensor type), network detection efficiency (sensor configuration), and data processing (locating flashes and classifying IC versus CG). Missed or misplaced lightning strikes occur, which yield safety risks and/or operational inefficiencies (e.g., unnecessary ramp closures).

Steiner et al. (2016) showed that ramp closure delays vary significantly, both from one airport to the next for similar types of weather scenarios as well as for one event to the next at the same airport. The delays largely depend on lightning ramp closure characteristics and impact timing relative to traffic demand. Annual cost estimates per airport for these isolated ramp closure delays range from \$1M (New York/EWR/LGA/JFK, Chicago/ORD/MDW, Dallas/DFW, Denver/DEN airports) to \$8M (Atlanta/ATL, Orlando/MCO airports), although these estimates can easily vary by a factor of two depending on the lightning source and safety procedures used.

The risk to human life posed by lightning is difficult to monetize but important to document. Steiner et al. (2016) evaluated the effectiveness of implementing ramp closures for two airline stakeholders during June – August 2014. Using their framework, the lightning risk effectively mitigated by Stakeholder A (B) equated to approximately $6M ($10M). These risk values are for one airport over one convective season.

Our goal moving forward will be to accurately document which fraction of this potential value is presently being realized. For now, we describe the potential benefit pools where GLM value is realized:

- Based on Steiner et al. (2016), we guess that lightning related ramp closures cost on average $2 million per airport multiplied by 35 Operational Evolution Partnership (OEP) airports (= $70 million). If the GLM has reduced unnecessary ramp closures by 5% (may or may not actually have), this results in an estimated annual value of $3.5 million. With improved tools and training the GLM contribution to reducing unnecessary ramp closures could easily double. Shortening the duration of ramp closures provides additional benefit for the GLM to help realize.
- Generalizing the limited Steiner et al. (2016) analysis to a full year over varied geography, we guess that the lightning safety risk effectively mitigated per airport is ~$5 million, multiplied by 35 Operational Evolution Partnership (OEP) airports (= $175 million). If the GLM accounts for just 10% of that value (remaining value attributed to radar, ground lightning networks, display/analysis tools, forecasters), the estimated value is $17.5 million annually. Although this value is not fully realized, it shows the magnitude of the benefits provided by better characterizing the lightning hazard and deploying tools to efficiently communicate the information.

3.2.2. Supporting safety and efficiency in route (mostly OCONUS)

Premise: The GLMs broad area coverage and rapid updates provide tremendous cost savings to the aviation industry through improved diagnosis and avoidance of thunderstorm hazards, especially over oceans.

Estimated Value: The GLM benefits aviation assets en route and on approach through improved air traffic control and increased pilot awareness. Routing remains centralized over the contiguous U.S. (CONUS), where pilot requests are considered and granted based on many factors. Pilots have more flexibility outside CONUS (OCONUS), where re-route requests are approved more easily. An early value assessment for a proposed GLM listed four operational benefits categories, including “Improvements in information provided to commercial airlines on hazardous convective weather, particularly over oceanic regions where current sensor coverage is limited” (Weber et al. 1998). They estimated the oceanic aviation benefit for a GLM type sensor to be $16M per year in more efficient routing and reduction of injury from turbulence encounters. The total benefit in determining the location, severity, and extent of thunderstorms in Terminal, Enroute, and Oceanic flights was estimated at $23M per year. Since the GOES-East and West GLMs cover vast stretches of the ocean sparsely covered by other instruments, much of this benefit is already being realized.

Klein et al. (2009) noted that the impact of convective weather on air traffic can in part be mitigated by reroutes, not just ground delays, and that the latest generation of short-term convective forecast products brings higher forecast accuracy and potential for further delay reduction. The percentages of avoidable delays and avoidable cancellations attributable to terminal weather forecast inaccuracy amount to 12.2% and 6.9% of their respective totals (Klein et al. 2009). The estimated total annual cost of such avoidable delays and cancellations is on the order $400-450M per year, with local thunderstorms accounting for 1.6% of total avoidable weather delays ($7.2 million annually in direct operating costs). These estimates are for direct operating costs of scheduled air carriers only; adding costs to other segments of the aviation industry, as well as passenger costs, would further increase the potential benefit pool estimate.

Forster et al. (2016) provided background on the convective threats to aviation. Pilots always prefer to avoid thunderstorms and their accompanying phenomena (e.g., turbulence, icing, heavy precipitation, hail, and lightning). En route, and especially during nighttime over the ocean, the onboard weather radar is often the only tool for diagnosing convective weather. The reliable range of the onboard radar is limited to ~150 nautical miles (corresponding to about 20 min of flight time) and can only scan a limited sector in front of the aircraft. Pilots often cannot see thunderstorms behind or beside the aircraft, which becomes critical during avoidance maneuvers. Ice crystals in anvil clouds and blow off cirrus from thunderstorms are another problem, as they cause only weak radar returns and can mask convective cells. The cyclical and often short lived nature of thunderstorms provides another source of uncertainty for assessing the thunderstorm threat. These constraints make it difficult for pilots to find the safest possible route through regions with thunderstorm activity and increase the stress level in the cockpit. The results are detours leading to increased fuel burn, delays, and diversions, as well as inadvertent flights through convective cells, with all resulting in considerable costs.

While technological advances work their way into cockpits, pilots make use of alternative means for obtaining real-time weather information (e.g., internet connected tablets). The FAA Weather Technology in the Cockpit (WTIC) team recently conducted a cost/benefit analysis during a demonstration of the Remote Oceanic Meteorology Information Operational (ROMIO). ROMIO sent near-real-time convective weather information to cockpits during transoceanic flights. Several U.S. airlines participated over the 2+ year demonstration. The weather information was developed using satellite imagery, GLM and other lightning data, and models to show the locations of convection as well as echo top heights. A cost benefit analysis conducted by Virginia Tech revealed that the ability to "see" convective weather well ahead of current weather radar on the plane resulted in an average of 10-minute earlier weather deviations, with an average savings of 355 pounds of fuel and 1110 pounds of greenhouse emission savings. The results show that the annual savings derived from the ROMIO Demo could reach $5.54M in the Atlantic Ocean and $1.35M in the Pacific Ocean.

Early evaluations of the FAA Offshore Precipitation Capability (OPC; Veillette et al. 2018) suggest that the GLM provides great benefit over the data sparse oceanic regions. An FAA Traffic Management Unit (TMU; Houston/ZHU) routinely uses the OPC display to make strategic decisions on the opening and closing of airways in the Gulf of Mexico. Timely airspace closures allow aircrews to properly fuel for the routing as opposed to reactionary deviations that can lead to diversions. The OPC data also facilitates speedy opening of airways as the TMCs can confidently decide to open a route, communicate it to the users, and quickly reroute flights.

GLM observations benefit the NWS Aviation Weather Center (AWC) forecast products, which flow downstream to NWS offices and a wide variety of aviation stakeholders (both on- and offshore). Total lightning (GLM) observations support AWC forecasts by updating at a sub-radar volume scan temporal frequency; providing information beyond CG observations – with IC typically preceding the initial CG strike in a storm; providing information on the intensity of storm updrafts; and providing the spatial extent of the electrified cloud, especially extending into the stratiform region of storms (Terborg and Stano 2017). Many AWC products are targeted at the general aviation community, broadening the impact of GLM information beyond the larger airports and airlines.

Our goal moving forward will be to accurately document which fraction of this potential value is presently being realized. For now, we describe the potential benefit pools where GLM value is realized:

- Present cost savings realized through better diagnosis and avoidance of thunderstorms offshore brought on by the GLMs broad coverage and rapid updates is estimated to be at least the same order of magnitude as the ROMIO demonstration (estimated annual value of $5 million).
- GLM benefits stemming from improved NWS/AWC forecast products and their impacts downstream (e.g., FAA TMUs, airline dispatch centers) provide an estimated annual value of $5 million (through reduced fuel burn, delays, diversions, and inadvertent flights through storms.
- The GLM has the unique ability to contribute to the reduction of lightning strikes to aircraft since it can identify electrified cloud regions that are not well-characterized by ground-based systems. Future analyses will investigate whether the GLM results in a quantifiable reduction in the frequency of lightning strikes to aircraft. For example, decreasing the commercial aircraft strike rate from ~1/yr/aircraft to less than 0.8/year would provide great value.

The GLM will benefit a recently commissioned FAA assessment of lightning strikes to aircraft. Much remains to be learned regarding the conditions under which planes are struck, and which measures can be taken to reduce the risk.

4. Summary

Only four years since becoming reality, the GLM is shown to be establishing a legacy of applications likely to become ubiquitous across a wide variety of meteorological domains. The GLM has met its original mission objectives and found use beyond. It now provides a national and international baseline of freely available lightning data, establishing a baseline for widespread government and industry implementation. The GLM moves from traditional point sources of lightning information to a rapidly-updating 2-D map that accurately portrays the full spatial extent of lightning activity. Many operational users (e.g., NWS) have eagerly embraced this new source of lightning information and incorporated it into their workflow. Despite widespread use, the GLM remains in its infancy with much of its value still waiting to be fully realized. The GLM value will quickly multiply as the realized benefits spread.

The GLM is broadening access to lightning information beyond those who can afford to purchase data, which helps many users make more informed decisions. Coupled with proper outreach and training, the GLM better informs the public of their local lightning threat via improved climatologies as well as actionable real-time information. The GLM allows the threat posed by record-breaking long lightning flashes and the electrically active regions they travel through to be clearly communicated to those most vulnerable. NWS forecasters use the GLM to acquire and retain situational awareness of these long flashes, which helps with Airport Weather Warning extension and reissuance. These "Megaflashes" can individually strike ground up to 100 times, often covering 80% of their spatial footprint, and can be the only lightning within an hour, challenging the widely accepted 30/30 rule for lightning safety.

Used in conjunction with radar data over CONUS, the GLM allows forecasters to make warning decisions earlier and more confidently when storm trends match across multiple sensors and platforms. One forecaster noted "If we start to see these lightning jumps, and we see these updrafts grow, especially combined with the surge in the line we can see on radar, then there's a good chance we're going to end up with a tornado." Early GLM data assimilation (DA) results indicate many benefits, especially for short-range forecasts of radar reflectivity, accumulated precipitation, and lightning threat in convection-allowing models. This suggests that GLM DA can benefit the transition to warn-on-forecast, leading to enhanced accuracy of NWS-issued severe weather warnings. Machine learning research at the NASA Frontier Development Laboratory examining "Lightning and Extreme Weather" recently certified the ability of GLM data alone to predict the likelihood of severe weather at a specific location.

The GLM also serves as a radar proxy over vast OCONUS regions. Since radar coverage quickly diminishes offshore, the GLM data provide tremendous value for forecasters monitoring and warning on storms in near-shore waters. Roughly 30% of the U.S. population (~94 million people) live in counties adjacent to the Atlantic Ocean, Gulf of Mexico, and Pacific Ocean, which underscores the importance of monitoring maritime convection. The GLM clearly conveys convective patterns below cloud top in tropical cyclones (TCs) which helps better diagnosis TC structure and evolution and aids forecasts of TC intensity change including rapid intensification.

The GLM is a new capability with many economic and societal benefits. Since the weather observing system is coupled, it tends to be difficult to tease out the incremental value for a single instrument. Various instruments, technology, and processes contribute to improved decisions, so a detailed analysis beyond the scope of this study is required to definitively attribute value to each aspect. Instead, we describe operational use cases to illustrate GLM value being realized through the actions of a wide variety of decision makers, and identify well documented benefit pools where the GLM adds value. Future analyses will work to document which fraction of this potential GLM value is being realized.

Studies estimating the value of weather radar data provide a good baseline for evaluating the GLM value. Weather radars provide ~$1 billion in annual value over CONUS, with remaining benefit pools of $260 and $69 million per year for improved tornado and flash flood warnings associated with radar network improvements. Upgrading the existing radars with rapid scanning yields about the same benefit (~$100 million per year) as blanketing the CONUS with perfect radar coverage. Although ground-based lightning observations can fill radar coverage gaps and augment poor coverage, tremendous value comes from the U.S. government owning its own lightning dataset.

With Aviation comprising 5.2% of the U.S. GDP ($488 billion), much of the economic benefit from GLM will stem from implementation by this industry. Rough value estimates for the costs of weather-related ramp closures, lightning safety risk effectively mitigated, improved diagnosis and avoidance of thunderstorms offshore, and better NWS/AWC forecast products and their impacts downstream exceed $70 million, $175 million, $5 million, and $5 million, respectively. The GLM also contributes the unique ability to reduce lightning strikes to aircraft since it can identify electrified cloud regions that are poorly characterized by ground-based systems. Future analyses will investigate whether the GLM results in a quantifiable reduction in the frequency of lightning strikes to aircraft. For example, decreasing the commercial aircraft strike rate from ~1/yr/aircraft to less than 0.8/year would be very valuable.

Our analysis suggests that the GLM likely provides many times more value OCONUS than over CONUS. GLM data assimilation shows comparable results to radar assimilation, suggesting great GLM value offshore (especially as convective allowing models cover larger spatial domains). The GLM aids TC assessment outside of radar range, particularly for forecasting intensity changes, monitoring structure beneath the cloud tops, and helping to initialize the inner-core in numerical models. The value of potential TC forecast improvements exceed $100 million each for lives saved in the U.S., property damage avoided through temporary measures, and the international benefits categories. GLM related TC forecast improvements are expected to realize some fraction of this value.

As evidenced by the ongoing wildfires in California, a warming climate multiplies the value of satellite instruments. GLM data offer unique insights for monitoring climate-scale variability and response in a changing climate. The close link between lightning and convective cloud properties makes it an essential indicator of inter-annual to decadal change and a key variable for validating climate models. Performance improvements are expected for the next two GLMs (GOES-T and –U), and future analyses will more directly investigate the potential increased value from full integration of present knowledge, and the increased value made possible by an instrument redesign (e.g., 4x4 km resolution at nadir, improved temporal resolution of 1 ms, and broader coverage extending to higher latitudes).

5. Acronyms

ABI	Advanced Baseline Imager
AWWs	Airport Weather Warnings
BLM	Bureau of Land Management
STAR	Center for Satellite Applications and Research
FY-4A	Chinese Meteorological Agency Fengyun-4 Lightning Mapping Imager
CG	Cloud-to-ground
CONUS	Contiguous U.S.
CONUS	Contiguous US
DA	Data assimilation
DoD	Department of Defense
DOE	Department of Energy
ENSO	El Niño-Southern Oscillation
ECMWF	European Centre for Medium-Range Weather Forecasts
OPC	FAA Offshore Precipitation Capability
WTIC	FAA Weather Technology in the Cockpit team
FAA	Federal Aviation Administration
FED	Flash Extent Density
FFG	Flash flood guidance
GCM	General Circulation Model
GEO-XO	Geostationary earth and extended orbits
GLM	Geostationary Lightning Mapper
GCOS	Global Climate Observing System
GISS	Goddard Institute for Space Studies
HWT	Hazardous Weather Testbed
HRRRX	High Resolution Rapid Refresh
IPCC	Intergovernmental Panel on Climate Change
ICWG	International Cloud Working Group
ISCCP	International Satellite Cloud Climatology Project
IC	Intra-cloud
ISCCP-NG	ISSCCP - Next Generation
LIS	Lightning Imaging Sensor
LNOx	Lightning nitrogen oxides
LCC	Long continuing current
LEO	Low earth orbit
MCSs	Mesoscale convective systems
MRMS	Multi-radar multi-sensor
MPE	Multisensor precipitation estimator
NASA	National Aeronautic and Space Administration
NCEI	National Centers for Environmental Information
NCA	National Climate Assessment

NESDIS	National Environmental Satellite, Data, and Information Service
NHC	National Hurricane Center
NLDN	National Lightning Detection Network
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
Nox	Nitrogen oxides
NCWCP	NOAA Center for Weather and Climate Prediction
NWP	Numerical weather prediction
AWC	NWS Aviation Weather Center
SPC	NWS Storm Prediction Center
OEP	Operational Evolution Partnership airports
OCONUS	Outside CONUS
QPE	Quantitative precipitation estimation
QLCS	Quasi-linear convective systems
RRFS	Rapid Refresh Forecast System
RAP	Rapid refresh model
ROMIO	Remote Oceanic Meteorology Information Operational
TCs	Tropical cyclones
TRMM	Tropical Rainfall Measuring Mission
CDC	U.S. Center for Disease Control and Prevention
US	United States
VA	Value assessment
WFOs	Weather Forecast Offices
WSR-88D	Weather Surveillance Radar – 88D
WMO	World Meteorological Organization

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