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Using Lightning Flashes to Image Thunderclouds

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Abstract

The optical energy emitted by lightning flashes interacts with the surrounding cloud medium through scattering and absorption. The optical signals recorded by space-based lightning imagers describe a convolution of lightning flash energetics and radiative transfer effects in the intervening cloud layer. A thundercloud imaging technique is presented that characterizes cloud regions based on how they are illuminated by lightning. This technique models the spatial distribution of optical energy in radiant lightning pulses to determine whether and to what extent each illuminated cloud pixel behaves like a homogeneous planar cloud layer. A gridded product is constructed that differentiates flashes that illuminate convective cells from stratiform flashes with long horizontal channels and anvil flashes whose optical emissions reflect off of nearby cloud surfaces. Producing this imagery with a rolling 15-min window allows us to visualize changes in convection with a rapid (20 s) update cycle.

Plain Language Summary

Space-based lightning imagers like the Lightning Imaging Sensor (LIS) on the International Space Station and Geostationary Lightning Mapper on National Oceanic and Atmospheric Administration's Geostationary Operational Environmental Satellites measure lightning by recording the clouds lighting up during the flash. Every flash illuminates the clouds in a different way because storm clouds are usually not a homogeneous slab but instead have differing concentrations of rain and ice from one place to another. Because light interacts with these particles, dense clouds have higher probabilities for the light to be reflected away from the sensor, and they will appear darker. We use the fact that every cloud will modify the flash in a different way to describe the cloud regions from lightning measurements. We ask whether each cloud behaves more like an irregular convective cloud, a homogeneous slab, or a case of reflections/a break in the clouds/a long horizontal lightning emitter. We then use some basic modeling of the optical signals to produce an imagery product that answers this question by highlighting each of these scenarios.

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Supporting Information:

- Supporting Information S1
- Movie S1

1. Introduction

The Geostationary Lightning Mapper (GLM; Goodman et al., 2013) on the current R-series Geostationary Operational Environmental Satellites, Lightning Imaging Sensor (LIS; Blakeslee et al., 2014) on the International Space Station (ISS), and previous space-based instruments detect lightning by recording rapid changes in optical energy leaving the cloud top. Unlike radio frequency lightning measurements that do not interact with the cloud medium surrounding the flash, scattering by cloud hydrometeors provides a significant source of attenuation and dilution of the optical lightning signals. Thomas et al. (2000) demonstrated that the LIS on the former Tropical Rainfall Measuring Mission (TRMM) satellite (Christian et al., 2000) had difficulty detecting optical signals that originated near the cloud base by comparing the optical LIS observations with very high frequency radio frequency measurements made by a Lightning Mapping Array (Rison et al., 1999). They additionally found that emissions detected by LIS in Cloud-to-Ground flashes occurred late in the discharge.

Light et al. (2001) simulated how optical lightning emissions interact with the surrounding cloud using a Monte Carlo radiative transfer model that accommodated finite and infinite cloud geometries. By tracing individual photons scattered by cloud particles, they were able to calculate the angular distribution of energy escaping the cloud top and the broadening of the optical waveforms that results from scattering. They concluded that the scattering effect can lead to an order of magnitude (or greater) difference in peak energy depending on whether the source is located on the far side or the near side of a cloud with realistic dimensions. Peterson (2014) performed radiative transfer modeling of planar cloud layers and found similar relationships between scattered optical energy and variations in cloud optical depth as well as the source location relative to the cloud top.

Modifications of optical lightning signals by intervening clouds have been observed in TRMM-LIS case studies and statistical analyses. The LIS instrument consists of a 128×128 pixel Charge-Coupled Device (CCD) array covering a cloud top area exceeding $580 \text{ km} \times 580 \text{ km}$ with a nominal sampling rate of 500 frames per second (Christian et al., 2000). The temporal and spatial resolutions of LIS enable the instrument to capture the lateral distribution of radiant energy during distinct periods of optical emission within the lightning flash duration. The LIS data set encompasses a diverse collection of optical lightning flashes that vary in size, shape, and radiance based on the energetics and evolution of the flash (Peterson et al., 2018; Peterson & Rudlosky, 2019) as well as the geometry and scattering properties of the intervening cloud (Peterson et al., 2017; Peterson & Liu, 2013). The shapes and sizes of the cloud top region illuminated by the largest optical lightning flashes (Peterson & Liu, 2011) result from cloud interactions shaping the energy distribution as much as the physical lightning processes emitting the photons (Peterson et al., 2017).

This study is an initial exploration of how we might characterize the cloud layer between the emitter and the observer based on how it is illuminated by lightning. Thunderclouds observed in nature are neither homogeneous nor planar. Dense cloud regions with high concentrations of hydrometeors will extinguish photons from the sensor field of view, causing the regions to appear dark. Light can escape through thin clouds and reflect off of

nearby cloud boundaries, causing these regions to appear bright. If we can capture these effects algorithmically, then we can construct a gridded lightning-based cloud product that—when applied to operational GLM data—would provide updated imagery across the Americas and Pacific on its rapid (20-s) data production cycle.

2. The Concept of Thundercloud Lightning Imaging

During the 1980s, a U-2 operated by the National Aeronautics and Space Administration made a series of high-altitude overflights of nocturnal thunderstorms with a Vinten camera mounted on the underside of the aircraft. Vinten cameras are typically used for aerial photography of the ground but can capture lightning using an open-shutter technique. With the shutter open, the Vinten camera operates like a staring optical imager similar to LIS. The film is not exposed by the dark clouds below the aircraft. When a lightning flash occurs, the emitted radiance illuminates the cloud top and exposes the film. Images were recorded at a rate of approximately one frame per flash, either using a manual trigger controlled by the pilot, or using an automated intervalometer set to 11 s per frame. Each image described an approximately 10 km $\times$ 10 km box at cloud top level based on a nominal U-2 cruising altitude of 20 km (Vonnegut et al., 1989). These dimensions would approximate the size of one GLM pixel or a ~ 2 pixels $\times$ ~ 2 pixels box if observed by LIS.

An image recorded by the U2 Vinten camera during an overflight of a convective cell in Georgia on 11 May 1981 is shown in Figure 1. The lightning flash was embedded within the convective plume and optical radiance escapes from all sides of the cloud. However, the spatial distribution of luminosity varied with both zenith and azimuth angle unlike the simulated flashes in Plate 2 of Light et al. (2001). The footprint of the Georgia flash contains pockets of darkness embedded in the illuminated cloud that reveal the texture of the cloud top. The image is not dissimilar to a medical X-ray where a dense obstacle separates a light source from the observer. The key difference here is that it is scattering rather than absorption that primarily results in the lower energy in the dense cloud mass (Thomson & Krider, 1982).

Vonnegut et al. (1989) noted that such cases of entire convective turrets being illuminated by lightning are not uncommon. Recent examples have also been captured by astronauts on the ISS. Figure 2 shows an illuminated thundercloud image taken over Brazil in January 2011 (Nespoli, 2011). The original image shown in Figure 2a provides a digital analog to the U-2 film image in Figure 1. In Figure 2b, we convert the color table of the image to a gray scale and invert it to approximate natural cloud colors. From only the optical energy supplied by this lightning flash, we can image the illuminated cloud region well enough to distinguish convective regions and qualitatively show their spatial extent and cloud top texture.

3. Data and Methods

Radiance data from space-based optical lightning imagers can similarly be used to identify inhomogeneities in convective clouds—only at larger spatial scales than the previous U-2 and ISS examples. Instead of resolving the cloud top texture from individual convective turrets, the 4–5 km (LIS) or 8–14 km (GLM) pixels will capture differences in illumination

between convective cells, boundary clouds, anvil clouds, and stratiform clouds. The advantage that lightning imagers have over the previous cameras, however, is that they record the spatial distribution of energy in 2 ms frames rather than as an integration over the whole flash. With this fine temporal resolution, there is a reduced probability that optical emissions come from multiple emitters in different parts of the cloud.

If the signals in a single 2 ms LIS or GLM frame result from a point source emitter, then the spatial distribution of energy should resemble the simulation from Peterson (2014), shown in Figure 3. The Monte Carlo Atmospheric Radiative Transfer Simulator (MCARaTS: Iwabuchi, 2006) is used to estimate the optical energy that escapes the top of a homogeneous cloud layer from a lightning flash embedded within. A 3-D view of the scene is depicted in Figure 3a, while the plan view is shown in Figure 3b. A downward facing camera is placed at 350-km altitude that records the cloud top radiance across a 30×30 pixel box approximating the LIS view of a single flash before the TRMM satellite orbital boost. Normalized pixel radiances are reported as ratios of the maximum pixel energy to the energy of the local pixel.

The optical signals produced by this simulated flash depend on the energy of the emitter, its altitude in the cloud layer, and the prescribed scattering characteristics of the cloud. All simulations in Peterson (2014) where the lightning flash was embedded within the cloud resulted in a distribution of optical energy that depended on radius but not azimuth angle. Such results are consistent with Plate 2 in Light et al. (2001) for an infinite planar uniform-density cloud. We can therefore describe the radiance at any point along the plane in Figure 3b by fitting a mathematical model to the radiance falloff with distance from the most radiant pixel that is colocated with the emissions source.

This idealized radiance pattern can be used to gauge how clouds are illuminated by lightning in the optical measurements. We start by working under the assumption that a given optical pulse or all pulses in a stationary flash occur in planar clouds with a single point emissions source that is colocated with the most radiant event. In the LIS/GLM nomenclature, “events” are single pixels on the CCD array with a lightning detection. Pulses are approximated by features known as “groups” that describe all simultaneous triggered pixels on the array during a given 2-ms integration frame. We then compute the radiance falloff with distance by comparing the normalized radiance for each event pixel (as a fraction of the peak event radiance for the group) with the distance between the pixel and the emitter. Finally, we fit a Gaussian model to the event data that gives us an estimate for the idealized radiance pattern for the group or flash. If our assumptions are correct, then the measured and modeled radiances should agree. Regions where the radiances consistently do not agree, then, reveal information about the cloud. Dark regions (measured $\ll$ modeled radiance) suggest high extinction rates and should correspond to dense cloud regions (like the dark spots in Figures 1 and 2a).

Bright regions (measured $\gg$ modeled radiance), on the other hand, suggest either that the assumptions in our model are violated (i.e., long horizontal channels are not point sources) or that the clouds are relatively thin permitting increased transmission or additional radiance from reflections off cloud boundaries.

This is a simple initial approach that has a number of caveats. The assumption that the emitter is colocated with the brightest event in the group/flash is tenuous. Cases where there are holes in the flash footprint aligned with convective cells (i.e., Peterson & Liu, 2013) suggest that the brightest pixel (at the edge of the cell) could be 10 km or more from the emitter. Furthermore, we do not know the altitude of the source or whether it remained constant over the course of the observational period. If it is not constant, then the depth of cloud surveyed will vary from group to group. This approach also favors large flash footprints. We do not consider groups that contain fewer than six unique pixels on the LIS or GLM CCD arrays in our analyses. Finally, as the Gaussian models capture the peak radiance pixel well (0 km, 100%), we ignore the single brightest event per group in our comparisons between measured and modeled radiances. All other data points are considered.

4. Imaging a Thundercloud With a Single LIS Flash

We demonstrate the radiance modeling approach outlined in section 3 by applying it to the case of a single lightning flash observed by the LIS on the TRMM satellite. TRMM contained meteorological instrumentation for measuring the precipitation structure of thunderstorms and shower clouds. In addition to LIS. The TRMM sensor package contained several instruments for observing the precipitation structure of thunderstorms and shower clouds. These included a visible and infrared scanner (VIRS), a microwave imager, and a precipitation radar (PR). We use these coincident measurements to carefully choose a scenario with a number of features that will help demonstrate the concept of thundercloud lightning imaging:

1. Complex cloud scene (maximum – minimum infrared brightness temperature > 75 K).
2. Convective cells identified by the PR (30 dBZ > 6 km) within the flash footprint.
3. Multiple groups that illuminate large cloud top areas (group footprints >1,000 km²).
4. No notable lateral development in the flash (all group centers separated by <1 LIS pixel).

The first two criteria identify scenes that share aspects of the imagery in Figures 1 and 2 despite the larger LIS pixel size. Of particular interest are infrared cloud scenes that contain convective plumes surrounded by anvil cloud and possibly a lower cloud deck. The latter two factors, meanwhile, increase the probability that the observed LIS groups result from localized emission sources. Flashes that develop laterally illuminate entirely different regions as they propagate through the cloud. Thus, they would be better described as linear emissions sources along a horizontal lightning channel. Large and stationary flashes, by contrast, suggest that the measured radiance results from localized processes. This also allows us to treat all events in the flash as originating from the same source rather than identifying an independent emitter for each group.

An exceptional case found on 15 November 2011 over the state of Mato Grosso in Brazil is depicted in Figure 4. The TRMM-VIRS (Kummerow et al., 1998) 10.8- μ m (Channel 4)

infrared brightness temperatures are plotted in Figure 4a. The longwave cloud top temperatures decrease as the cloud height increases. For this reason, infrared gradients across the scene reflect the texture of the cloud top illuminated by the lightning flash. The most prominent gradient separates the warm and relatively low clouds along the western edge of the image from the colder tall clouds to the east. The 232 K contour intrudes eastward toward the center of the image dividing the expansive region with the coldest cloud top temperatures to the north from the cellular convective features to the southwest.

The lightning flash occurred near the southwestern cold cloud features (<200 K). The spatial distribution of the total optical energy from all events is shown in Figure 4b. The 232 K VIRS Channel 4 (CH4) contour from Figure 4a is preserved as a dotted line while PR features that approximate convective cells (30 dBZ at >6 -km altitude) are shown with dashed lines. Event energy is concentrated in the center of the flash footprint immediately to the east and north of the PR features. While the total radiance decreases to 50% of the maximum pixel energy over the course of 1–2 pixels in each direction from the brightest pixel, radiant energy from the flash illuminates cloud regions seven to nine pixels away from its radiance-weighted center.

The radiance falloff with distance for the flash is modeled in Figure 4c. Normalized event radiances in each group are reported as a fraction of the energy of the brightest event and plotted against their distance from this assumed emitter location. The color of the points indicates which group in the flash they belong to. The event data are fit with a Gaussian model (black line) that describes how the radiance changes over distance. The half width of half maximum for the model is 5.6 km.

We compare the measured event radiances with the radiances from our model in Figure 4d. The departure of the measured radiance from the Gaussian model should reveal cloud regions that do not behave like a horizontally homogeneous slab. Thus, the energy difference is expected to more closely resemble the infrared scene in Figure 4a than the flash energy distribution in Figure 4b. Pixels that are gray ($\sim 100\%$ measured/modeled radiance ratio) indicate cloud regions whose events either fit the model or are slightly brighter than the model. Colored pixels, on the other hand, describe pixels whose events are dimmer than the expected model radiance.

Most of the pixels within the flash footprint have measured-to-modeled radiance ratios between 70% and 120% in Figure 4d. There is no obvious pattern based on radius from the emitter as in Figure 4b. Instead, ratios across the plateau between the coldest clouds are close to parity. Pixels with measured radiances less than 50% of the modeled values are highly concentrated along the southern extent of the flash footprint. The pixels with the greatest departures from the model form clusters that are colocated with the convective PR features (dashed lines). The average measured radiances within these features are only $1/4$ or $1/5$ the radiances of the model. Measured radiances are lowest on the far side of the convective features from the emissions source. The flash footprint along its southwest boundary is also irregular, indicating that the events we see are close to the LIS detection threshold for this case. Even though the flash illuminates portions of the western lower (>256 K) cloud deck, the pixels here are not brighter than the model prediction. This

suggests that reflections are not playing a major role as we have previously noted in certain LIS flash cases (i.e., Peterson, Deierling, et al., 2017; Peterson, Rudlosky, & Deierling, 2017).

The dark convective core and lack of reflection signature off the lower cloud deck suggest that the emissions source was at a relatively low altitude below both cloud layers (perhaps as low as 5 km based on the infrared brightness temperatures). This assessment is consistent with our past observations of holes in flash footprints surrounding convective cores and the modeling work in Light et al. (2001). This case demonstrates that we can use the radiance differences to identify and define the boundaries of convective features solely from the optical lightning measurements.

An application of this approach could be to construct a lightning-based feature data set similar to TRMM Precipitation Features (Liu et al., 2008). We previously constructed Illuminated Cloud Features from the LIS data that bound contiguous cloud regions illuminated by lightning (Peterson, Deierling, et al., 2017). Integrating the VIRS, microwave imager, and PR measurements with the LIS data over these features allowed us to assess what parts of the storm were illuminated by each LIS flash and to identify cases where lightning emissions reflected off of the sides of nearby clouds. With additional information about the heights of the light sources (e.g., from coincident very high frequency radio frequency measurements; Rison et al., 1999; Jacobson, 2003), we could screen for only low-level emissions and produce hail core features describing regions where little light reaches the cloud top. Any feature-level storm data produced by R-series Geostationary Operational Environmental Satellites will benefit from its staring geostationary view of the western hemisphere. Future work will explore this and other applications of the thundercloud imaging technique.

5. Documenting Thunderstorm Evolution With GLM Thundercloud Imagery

While section 4 characterized a cloud region illuminated by a single lightning flash, our goal is to image whole thunderstorms using every large optical pulse produced by all of its flashes. To do this, we move from LIS to GLM, which offers staring hemispheric coverage and real-time operational data. There are notable differences in detection between GLM and LIS due to thresholding and pixel size differences between the two instruments. These issues affect all LIS/GLM products, not just thunder-cloud imagery. Moreover, since the discrepancies between LIS and GLM mostly occur with the small groups from dim optical pulses that we ignore, our product is not likely to be severely affected.

We focus our analysis on a large mesoscale convective system over Rio Grande do Sul, Brazil, that was observed on 31 October 2018. This was the largest thunderstorm recorded by GLM during 2018. Advanced Baseline Imager (ABI; Schmit et al., 2005) Channel 14 (11.2 μm) infrared brightness temperatures and GLM Flash Extent Density (FED) are shown in Figure 5. GLM FEDs are integrated over the 15-min window starting at 08:45:00 UTC. A convex hull (dashed line) is also drawn around the group centroids belonging to the primary

“area of interest” (or, “area” following the LIS convention) GLM cluster feature describing the storm (Christian et al., 2000).

The area cluster feature covered a cloud top region 216,865 km² in extent, but this lightning-producing region of the storm only accounted for a portion of the larger cold anvil cloud (Figure 5a). The convective core is clearly visible in the GLM FED imagery (Figure 5b) as a line of active cells extending from west to east across the plot. The FED plateau to the south of the convective line represents horizontally expansive lightning penetrating deep into the trailing stratiform region. This complex storm system is an ideal case for testing our approach because it has both convective and stratiform flashes as well as lightning activity near the edge of the anvil cloud.

We apply our modeling approach to every GLM group over this 15-min window that contains six or more pixels. A unique model is created for every observed group that uses its specific brightest pixel location and collection of events to characterize its radiance falloff with distance. We do not fit multiple groups to the same model as we did in Figure 4. Measured and modeled energies are compared in Figure 6 as normalized energies for each group (fractions of the brightest event in the group). The two-dimensional histograms of observed radiance versus distance (Figure 6a) and measured versus modeled radiance (Figure 6b) include all types of lightning with sources at all altitudes in the cloud and from every location across the geospatial domain shown in Figure 5.

The accumulated data do not fit a single curve like the one-flash example in Figure 4d. This is desirable, as it means that the radiance data originates from a diverse set of cloud regions that we might be able to characterize. Normalized radiances are capped at 100% and the local concentration of events at this value includes both reflection cases and emitters that are not point sources. These cases correspond to events in Figure 6b that are above the 1:1 line where the observed radiance is larger than the modeled radiance. These tend to fall within a factor of 2–3 from unity and occur at all modeled energy levels. Convective pixels, by contrast, are located below the 1:1 line and frequently fall below measured-to-modeled radiance ratios of 50%.

Measured and modeled radiances from the native GLM grid are accumulated on a 0.1° grid in Figure 7. The radiances observed by GLM (Figure 7a) show horizontal lightning channels in the stratiform region, but the convective cells are less clearly defined than in the FED product (Figure 5b). Our modeled radiances in Figure 7b, meanwhile, spread optical energy across circular swaths around the assumed emitter locations. If the storm were comprised of point sources in purely planar clouds, the energy distribution in Figure 7a should resemble Figure 7b. However, this is not the case, and ratio between the two radiances in Figure 7c usually favors the modeled radiance by at least a factor of 2.

“Holes” like we saw in Figure 4 are not common features in the measured- to-modeled radiance ratio product in Figure 7c. This is because low- altitude cases are uncommon compared to high-altitude emitters that do illuminate the hail cores. Attenuation increases with the cloud depth between the emitter and the top of the cloud. This causes GLM detections to favor sources originating in the upper portion of the storm. Though convective

cells are less likely to produce “holes” in the imagery, micro-physical inhomogeneities still add texture to convective regions that persists over time and responds to changes in storm kinematics. We see this texture in Figure 7c.

GLM measurements of convective pixels typically only attain 50% (or less) of their modeled energies, but there are single pixels or rows of pixels in particular regions that reach or exceed the model. These bright regions suggest that there is some aspect of the cloud scene that permits more energy to escape the cloud top than the model predicts. Bright pixels often result from reflections off of lower cloud layers, which cause the cloud pixels surrounding a typical dark convective cell to light up. We do not see this during the mature stage of the Brazilian mesoscale convective system depicted in Figure 7c, but it can be observed earlier in the life history of the thunderstorm. Figure 8 shows the measured and modeled radiances across the same region at 02:45:00 UTC—6 hr before the imagery in Figures 6 and 7. A single isolated cell can be noted north of the primary convective line. The GLM detections along its western flank (Figure 8a) are brighter than the model prediction (Figure 8b) leading to a local maximum in the radiance difference product (Figure 8c) that reached 200% (yellow) at its center. The extent of the lightning hazard in these reflection cases is smaller than what the GLM data suggest. This signature of bright pixels at cloud edges in the radiance difference product can be used to differentiate between thunderclouds and reflections.

Bright pixels can also be caused by long horizontal lightning channels. Our model assumes that light is emitted by a point emissions source. If the source is linear and extends many kilometers, then the radiance falloff with distance will vary by azimuth angle as well as elevation angle. The radiance will decrease laterally from the horizontal channel, but not in the direction of the channel, and the radiances produced by a point source model will be too low along the channel. We see this throughout the stratiform region in Figure 7c, but the linear features of white (~100%) and yellow (>200%) pixels are most visible along its southern flank. Linear sources may also explain some of the measured radiances that meet or exceed the model in the convective line (particularly on the eastern flank that falls outside of the convex hull of the area feature), as anvil flashes can also extend laterally over considerable horizontal distances (Kuhlman et al., 2009).

GLM measurements also exceed the model when there is a break in the clouds that allows more energy to reach the satellite than expected. Such features can be distinguished from linear emitters by animating the storm. Long horizontal flashes are over in a second and occur at a low rate, but relatively transparent cloud regions will change on convective time scales (i.e., minutes to an hour). If bright regions persist between 15-min time steps in the imagery, then they are the result of scattering in the cloud, not single lightning flashes.

The radiance difference product reveals all of these scenarios in single 15-min integrations, but they are most evident when animated in time. A key benefit of GLM is that it provides continuous observations on a 20-s update cycle. Twenty seconds is not a sufficient amount of time to produce imagery for all but the highest flash rate storms, but we can resolve incremental changes in convection by using a rolling 15-min window that updates every 20 s as new GLM data comes in. The ABI, by comparison, provides full-disk cloud imagery on a

15-min update cycle in its normal operating mode. As a result, there are only 96 ABI full disk data files per day for each spectral band. The rolling window for the GLM imagery preserves the 20-s update cycle to produce 4320 daily frames. Movie S1 in the supporting information is created using this approach and it clearly shows cellular advection in the developing storm system on time intervals that would fall between ABI scans.

6. Conclusions

Space-based optical lightning measurements are used to characterize the layer of clouds that separates the lightning emissions source from the cloud top. Lightning flashes embedded within the thundercloud radiate optical energy that scatters through the uppermost cloud layer according to its geometry, optical depth, and scattering properties. This is why dense convective plumes stand out as dark spots in high-resolution aircraft and ISS images of lightning, why low-resolution LIS flash footprints are often irregularly shaped and follow cloud boundaries, and why lower boundary clouds far from the lightning discharge can be illuminated through reflections off their surfaces.

An initial thundercloud lightning imaging technique is introduced that models the spatial distribution of optical radiance measured by the lightning imager as though it were a point emitter embedded in a planar cloud layer. The modeled radiances are then compared with observations in order to determine whether individual cloud pixels behave like inhomogeneous convective clouds (measured $\ll$ modeled radiance), homogeneous planar clouds (measured $\approx$ modeled radiance), or cases of reflections/increased transmission/long horizontal channel emitters (measured $\gg$ modeled radiance).

Mapping the difference between the measured and modeled radiances reveals cloud top texture in convective regions. These features persist over multiple 15-min periods and trace how convective cells develop within the larger storm system. Reflections, breaks in the clouds, and long horizontal lightning channels can also be easily identified as bright spots in the imagery.

We use a rolling 15-min window to generate updated cloud imagery every 20-s (the minimum update interval for GLM). This allows us to document convective development between 15-min ABI full disk scans. This product complements existing cloud and lightning imagery and may have uses in operations for evaluating the lightning hazard and monitoring thunderstorm evolution (particularly during ABI outages).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Key Points:

- Lightning optical energies measured from orbit depend on the energetics of the flash and scattering in the cloud medium
- By modeling optical lightning signals and comparing with recorded pixel energies, cloud layer scattering effects can be revealed
- A method of using optical lightning data to image thunderclouds is presented that highlights cloud features in the lightning imager data

Figure 1.

U-2 Vinten camera image of lightning illuminating a convective cloud over Georgia in 1981.

Figure 2. International Space Station image of lightning illuminating a convective cloud in 2011 (a) in original color, and (b) with an inverted grayscale color palette to highlight cloud top texture in the lightning imagery.

Figure 3.

A Monte Carlo radiative transfer simulation of a lightning flash embedded in a cloud layer depicted as (a) a schematic of the model setup with the lightning flash as a point source and the camera located directly above the flash at 350-km altitude, and (b) the resulting spatial radiance pattern in model pixel coordinates.

Figure 4.

An example case of a large and stationary LIS flash illuminating a complex cloud scene. (a) VIRS CH4 infrared brightness temperature across the scene. (b) The spatial distribution of total LIS radiance. (c) The normalized pixel radiance of the events in each group (as a fraction of the maximum) plotted against the distance from the brightest pixel in the group. A Gaussian fit is shown as a solid line. (d) The ratio of the modeled radiance for each pixel to the observed pixel radiance. Dashed lines in (a), (b), and (d) denote precipitation radar convective features while dotted lines show the 232 K VIRS CH4 T_b contour. VIRS = visible and infrared scanner; LIS = Lightning Imaging Sensor.

Figure 5. Geostationary Operational Environmental Satellites 16 satellite observations of a large mesoscale convective system on 31 October 2018. (a) Advanced Baseline Imager Channel 14 (11.2 μm) infrared brightness temperature, and (b) GLM Flash Extent Density integrated over a 15-min period starting at 08:45:00 UTC. A convex hull is drawn around the GLM groups belonging to the primary thunderstorm area of interest to show the overall extent of lightning in (a). GLM = Geostationary Lightning Mapper.

Figure 6. Two-dimensional histograms comparing the normalized observed event radiance for the Brazilian mesoscale convective system in Figure 5 to (a) the distance from the brightest event in each group, and (b) the normalized modeled event radiance. Constant ratio lines from 1:1 to 10:1 are shown in (b). GLM = Geostationary Lightning Mapper.

Figure 7.

GLM total measured (a) and modeled (b) radiances for the Brazilian mesoscale convective system in Figure 5 at 08:59:40 UTC. The measured-to-modeled radiance ratio is shown in (c) with pixels that have measured $\gg$ modeled radiances (at least 200%) shaded yellow.

GLM = Geostationary Lightning Mapper.

Figure 8.

As in Figure 7, but during an earlier stage of the Brazilian mesoscale convective system at 02:45:00 UTC showing reflections near the edge of the isolated northernmost cell.