Modeling the Transmission of Optical Lightning Signals Through Complex 3-D Cloud Scenes

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Abstract Space-based lightning imagers have shown that complex cloud scenes consisting of multiple tall convective features, anvil clouds, and warm boundary layers are illuminated by lightning in many different ways depending on where the lightning occurs and how energetic it is. Modifications to the optical lightning signals from radiative transfer in the cloud medium can lead to reductions in detection efficiency and location accuracy for these instruments and can also cause some of the optical signals that are detected to have unexpected spatial energy distributions. In this study, we perform Monte Carlo radiative transfer simulations of optical lightning emissions in clouds with complex 3-D geometries to shed some light on the origins of certain irregular radiance patterns that have been recorded from orbit. We show that diffuse reflections off nearby cloud faces can explain lightning signals in nonelectrified clouds, tall clouds can result in poor optical transmission and suppressed radiances that could lead to missed events and that particularly favorable viewing conditions can cause otherwise normal lightning to produce a superbolt that is orders of magnitude brighter than the same flash seen from a different angle.

Plain Language Summary Lightning is detected from space using instruments that report rapid changes in cloud brightness from lightning illumination. However, this light can be modified by scattering and absorption in the cloud. Scattering off water drops causes portions of the signal to be diluted in space and delayed in time. What starts off as an impulsive point light source in the cloud may illuminate a region of the cloud-top that is 100 km across with a waveform that persists over significant fraction of a millisecond. Interactions between the optical lightning emissions and the cloud scene are particularly complex when the surrounding clouds do not take on a simple geometric shape. Clouds observed in nature often contain multiple vertical layers including warm boundary clouds and overhanging anvils. Understanding some of the more irregular spatial energy distributions recorded by space-based lightning sensors requires accounting for these complex geometries. In this study, we develop 3-D cloud models that approximate cloud structures found in nature and perform Monte Carlo radiative transfer simulations of how they are illuminated by lightning. In doing so, we confirm the suspected origins of irregular cloud illumination, such as reflections off of nearby cloud faces or particularly favorable viewing conditions allowing normal lightning to appear highly energetic.

1. Introduction

Pixelated lightning imagers including the Optical Transient Detector (OTD; Boccippio et al., 2000), Lightning Imaging Sensor (LIS; Blakeslee et al., 2020; Christian et al., 2000), Geostationary Lightning Mapper (GLM; Goodman et al., 2013; Rudlosky et al., 2018), and Lightning Mapping Imager (LMI; Yang et al., 2017) record the spatial distributions of optical energy that result from lightning pulses. These observed spatial radiance patterns often deviate from the simple idealized model of radiance decreasing only with radius from the center pixel. We previously reported cases of highly irregular radiance patterns where the shape of the optical pulse on the CCD imaging array followed the cloud boundaries (i.e., Figures 3 and 4 in Peterson, Deierling, et al., 2017), cases where the radiance pattern extended outward from the edge of the thunderstorm core giving an incorrect impression that these warm boundary clouds were producing lightning (Peterson, Rudlosky, et al., 2017), and cases where optical emissions were blocked from reaching orbit by certain cloud regions, resulting in “holes” in otherwise-contiguous flash footprints (i.e., Figure 1 in Peterson & Liu, 2013). Unobscured lightning sources have also been proposed as the mechanism responsible for certain lightning “superbolts” (Turman, 1977) that primarily illuminate the edge of the storm (Peterson et al., 2020).
We will show that irregularities in lightning radiance patterns result from interactions between the optical lightning emissions and complex cloud scenes. Clouds modify optical lightning signals through absorption and scattering. Thunderclouds are an optically thick medium that causes photons to undergo up to thousands or tens of thousands of scattering interactions as they transit the cloud (Plate 1 in Light, Suszczyński, Kirkland, et al., 2001). Each of these interactions may result in absorption, while the remaining light is redirected over a range of angles from its incident path. Because of this, reflections off cloud faces are diffuse rather than specular, and only a fraction of the photons incident on the cloud will transmit through it to space. The remaining light is either lost to absorption or redirected away from the space-based instrument. This multiple scattering further causes the signals that do arrive at the instrument to be broadened in space and time according to the path they took through the cloud. As clouds are invisible to Radio-Frequency (RF) signals, coordinated optical and RF measurements have been used to quantify the severity of scattering delays (Light, Suszczyński, Kirkland, et al., 2001; Suszczyński et al., 2000) and to demonstrate reduced detection capabilities for optical space-based imagers when sources occur at low altitudes in the cloud (Thomas et al., 2000).

Computational models have been employed to gain insights into how clouds modify optical lightning emissions. Thomson and Krider (1982) developed a Monte Carlo method for simulating optical transmission of transient light sources (both point sources and extended sources) through 3-D clouds of various geometries (cubic, spherical, and cylindrical). By measuring the path lengths taken by the emitted photons, they were able to further comment on typical scattering delays in the optical signals. Koshak et al. (1994) leveraged one-speed Boltzmann transport theory with diffusion approximations (essentially, treating the thundercloud as a nuclear reactor and replacing neutrons with photons) to model the waveforms that would be recorded from a high-altitude aircraft (or spacecraft) from spatially complex lightning sources after scattering through homogeneous rectangular parallelepiped clouds. Light, Suszczyński, and Jacobson (2001) took a similar Monte Carlo approach to Thomson and Krider (1982) but, similar to Koshak et al. (1994), focused on the waveforms that would be measured by on-orbit sensors. Key to the present study, Light, Suszczyński, and Jacobson (2001) concluded that the shape of the cloud and position of the lightning event in the cloud (rather than the extent or motion of the source) are the primary factors that determine the distribution of photons escaping to space.

The primary limitation to these previous studies is that they represent homogeneous clouds with simple geometric shapes. Brunner and Bitzer (2020) used Weather Research and Forecasting (WRF) simulations of thunderstorms in a cubic model geometry to improve on how clouds were represented in Monte Carlo lightning illumination simulations by permitting inhomogeneous scattering media. However, they did not consider variations in cloud geometry, and only reported the percentages of photons that escaped the upper cloud boundary—not how those photons were distributed across that boundary and thus would be imaged.

While a cylinder or even box geometry might approximate the structure of an isolated growing convective cloud, the cloud scenes monitored by LIS and GLM for lightning activity often consist of multiple convective cells with overhanging anvils that are also surrounded by warm boundary clouds (Peterson, Deierling, et al., 2017). The simplistic clouds in these former model simulations are not sufficient to describe the complex interactions between the lightning emissions and the cloud scenes where we observe the irregular radiance patterns noted previously. The need for capturing complex cloud geometries was recognized by Light, Suszczyński, and Jacobson (2001) who stated “the most realistic [cloud] shape would be some superposition of cylindrical and planar.”

In this study, we ascertain which scenarios of lightning illuminating complex 3-D cloud scenes lead to the irregular radiance patterns that have been noted from orbit. We construct 3-D cloud shapes using composites of cylindrical and planar geometries represented as an x, y grid to approximate cloud structures found in nature. These clouds are input into optical Monte Carlo radiative transfer simulations that yield spatial radiance measurements from a detector above the thunderstorm in physical units. By varying the optical thickness of the cloud layer and moving the lightning source around the 3-D scene, we are able to construct artificial radiance patterns that resemble the irregular features measured from orbit—including instances of diffuse reflections caused by scattering off neighboring clouds, poor transmission leading to holes in the image, and unobscured sources from normal lightning producing superbolts.
2. Data and Methodology

In this study, we use the Monte Carlo Atmospheric Radiative Transfer Simulator (MCARaTS: Iwabuchi, 2006; Iwabuchi & Okamura, 2017) to quantify the radiance that would be measured above the thunderstorm scene from an optical point source that approximates a lightning discharge. MCARaTS is a full 3-D radiative transfer simulator that uses a forward-propagating Monte Carlo photon transport algorithm to trace the trajectories of photon packets as they make their way across the scene until they are either absorbed or leave the atmosphere. The algorithm is capable of reproducing realistic 3-D effects including complex shadows and cloud side illumination (Iwabuchi, 2006). It is also adaptable for simulating a variety of optical and infrared sources including solar, thermal emission, and localized point sources.

MCARaTS inputs include models for the atmosphere and surface, and the simulation configuration that defines the properties of any light sources and imagers present. In section 2.1, we will detail the atmospheric models that we develop to represent complex cloud geometries. In section 2.2, we will describe the remaining general MCARaTS inputs. These inputs will also be summarized for quick reference in Table 1, below. Finally, in section 2.3, we will describe the experimental configurations that will be used to examine variations in the optical radiance patterns produced by lightning.

### 2.1. Atmospheric Models With Complex Cloud Geometries

We consider five different cloud geometries that otherwise have identical vertical extents, compositions, and optical properties. To explore the dynamics of cloud geometry on measured lightning radiance, only the 3-D extent of the cloud varies between cloud types. As with Light, Susczynsky, and Jacobson (2001), we assume that each cloud consists of spherical water droplets evenly distributed throughout the cloud volume. Our cloud models will nominally be based on nonfrontal water clouds whose drops have an effective radius of 10 μm. The following sections describe the optical properties of these clouds as well as their 3-D structure.
2.1.1. Scattering Phase Functions
Since we are concerned with cloud modifications to optical lightning signals, we assume that atmospheric absorption and scattering takes place exclusively within the cloud layer. Photons in the free atmosphere will not be deflected from the forward direction or absorbed by atmospheric constituent gasses. Within the cloud layer, we assume that the phase functions for scattering interactions follow the Henyey-Greenstein approximation (van de Hulst, 1980) to the solution of the Mie scattering equations (Bohren & Huffman, 1983) below:

\[ p(\mu) = \frac{1 - g^2}{(1 + g^2 - 2g\mu)^{3/2}} \]

where \( \mu = \cos \alpha \), \( \alpha \) is the deflection angle relative to forward transport, and \( g \) is the asymmetry parameter for the cloud particles in question at the specified wavelength of the simulation.

Thomson and Krider (1982) specified an asymmetry factor of 0.84 for 10 \( \mu m \) water clouds illuminated by a near infrared (870 nm) source, while Light, Suszcynsky, and Jacobson (2001) maintained this value for red photons. For consistency with past work, we will do the same. MCARaTS requires phase functions to be specified as arrays of angle bins from 0° to 180°. For our simulations, we specify the Henyey-Greenstein solution with \( g = 0.84 \) at an angular resolution of 1° per bin.

2.1.2. Atmospheric Model
Atmospheric radiative transfer parameters are specified as 1-D vertical profiles with perturbations listed on a 3-D nested grid. Our models consist of 47 vertical layers that begin at the surface (0 km) and end at 30 km altitude. Within the lowest 10 km of the model domain, the layers are specified with a 250 m vertical resolution. The three top layers are at 10, 20, and 30 km altitude.

The 3-D grid is nested within a portion of the 1-D vertical grid. It extends from the third vertical level (500 m) to the 24th vertical level (5,750 m), adding horizontal variations to each of these layers. Within each 3-D layer, the horizontal grid is specified as a 60 x 60 element array. While the number of horizontal grid points can be modified, increasing the size of the horizontal grid beyond 60 x 60 elements causes the model to crash. We get around this issue by varying the horizontal spatial resolution of the atmospheric model. Nominally, we use a 200 m horizontal resolution, resulting in cloud scenes that are 12 km across. MCARaTS imposes a cyclic boundary condition for the 3-D model (Iwabuchi, 2006), meaning that clouds and local sources within the model domain are infinitely tiled horizontally. This facilitates simulations of side illumination in neighboring clouds, for example, from sources located at the cloud edge. However, it also permits other nearby sources to contribute to the total measured radiance.

Since we are dealing with optical sources (rather than thermal sources), the three important parameters for our simulations are the phase function (\( p \)) to be applied, the single scattering albedo (\( \omega_o \)), and the extinction coefficient (\( \sigma \)). The phase function describes the probability that a photon will be redirected in each direction following a scattering event. The single scattering albedo describes the scattering efficiency of the medium—defined as the fraction of attenuated photons that are scattered rather than absorbed. The extinction coefficient, meanwhile, quantifies the ability of light to penetrate the medium.

Each 1-D layer and 3-D grid point is assigned one of two states (within the cloud, or in the free atmosphere), and representative values for each of these parameters are prescribed based on this state. Inside the cloud, the Henyey-Greenstein phase function defined in the previous section is applied for \( p \), and 0.99996 is selected for \( \omega_o \), again based on values from Thomson and Krider (1982) for 10 \( \mu m \) water clouds illuminated by a near infrared source.

The extinction coefficient depends on the density and liquid water content of the clouds in question and also determines the optical depth (\( \tau \)) of the cloud (the natural logarithm of the radiant power incident on the medium to the power transmitted through the medium). Light, Suszcynsky, and Jacobson (2001) constructed artificial drop size distributions by generating Gaussian functions centered on 10 \( \mu m \) and then used these drop size distributions to calculate the photon mean free path between collisions with the spherical water drops. They noted that these drop size distributions are not realistic and were selected to facilitate computations.
In this study, we instead take an observational approach to determine the cloud extinction coefficients that drive cloud optical depth. Platt (1997) parameterized aircraft observations of optical cloud characteristics according to effective drop size, water content, and atmospheric forcing. In their Figure 5, optical extinction coefficients are plotted for nonfrontal water clouds based on measurements from Stephens et al. (1978). The observed extinction coefficients ranged from >0.01 to <0.08 m$^{-1}$, while the parameterization for clouds with $r_e = 10 \mu$m drops bisects these aircraft data.

These values provide a reasonable range of extinction coefficients to consider in the present study. Light, Suszcynsky, and Jacobson (2001) and Thomson and Krider (1982) noted that typical cloud optical depths vary from 80 to 400 and thus have been simulated in the literature. An optical depth of 80 (400) corresponds to a cloud extinction coefficient of 0.015 m$^{-1}$ (0.076 m$^{-1}$) for a slab cloud in our 3-D model geometry, thus filling the range of measured values from the aircraft data presented in Platt (1997). We simulate clouds with extinction coefficients throughout this range. We neglect atmospheric absorption by the constituent gases by setting the 1-D $\sigma$ profiles to constant null values. Then, we account for extinction in the clouds by setting $\sigma$ perturbations to in-cloud points on the 3-D grid. Since the Monte Carlo model crashes when $\sigma$ perturbations are set precisely to 0, we assign a numerical fill value of $10^{-35}$ m$^{-1}$ to noncloud grid points in the 3-D model.

### 2.1.3. Complex 3-D Cloud Geometries

Five unique cloud types are constructed to account for finite/infinite geometries and the presence/absence of horizontal cloud layers at the top and bottom of the storm. The first cloud type is a simple infinite slab cloud. Such a cloud might stand in for stratiform clouds that are horizontally expansive beyond the spatial scale of illumination from optical lightning pulses. The remaining four cloud types are represented as cylinders at the center of the 3-D grid that fill all of its vertical layers. Images of these different cylinders are shown in Figure 1.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Visualization of the geometries of the finite cylindrical clouds. A wide angle (180°) camera is placed at the midlevel of the 3-D cloud domain and pointed toward the horizon. The radiance from the Cylinder (a), Cylinder + Base (b), Cylinder + Anvil (c) and Cylinder + Base & Anvil illuminated from below are imaged with a logarithmic normalization applied.
Table 2

| Configuration parameter | Experiment 1 | Experiment 2 | Experiment 3 |
|-------------------------|--------------|--------------|--------------|
| Horizontal source       | Centered     | Centered, Edge | Centered, Edge |
| Altitude                | 0 km         | 0–6 km       | 0 km         |
| Atmospheric model        | Max. cloud 80–400 | 160,320 | 400 |
| Max. optical depth       | 200 m        | 200 m        | 100 m        |
| Horizontal grid spacing  | 12 km        | 12 km        | 6 km         |
| Tiled domain size        | 12 km        | 12 km        | 6 km         |
| Surface model            | Albedo 0.0, 0.2 | 0.0, 0.2 | 0.2 |
| Imager                   | FOV full width 45° | 45° | 120° |

Figure 1 using a wide-angle (180° FOV) camera located in the midlevels of the 3-D cloud model and pointed toward the horizon. A maximum path length distance is prescribed to only show the nearest three rows of clouds. The cylinders are illuminated from below the cloud base in Figure 1, while the camera response is normalized on a logarithmic scale to emphasize dimmer portions of the image.

The radius of these cylinders is set to 15 grid points (3,000 m at the 200 m horizontal grid resolution), while the cloud-top is always located at 6 km altitude. The default case (“Cylinder” in Figure 1a) lacks additional surfaces for scattering interactions. In Figures 1b and 1d, a “base” cloud layer is added at the bottom of the cylinder. This base layer fills the bottom four vertical levels of the 3-D model and has an infinite horizontal planar geometry. In Figures 1c and 1d, an “anvil” layer is added at the top of the cylinder. This anvil layer fills the top 5 vertical levels of the 3-D model and has a cylindrical geometry with a radius of 22 grid points (4,400 m at the 200 m horizontal grid resolution).

2.2. Global MCARaTS Inputs

The global inputs to MCARaTS—the source, surface, and imager—are specified below. While MCARaTS allows localized sources within the atmospheric model domain, it is not capable of simulating a fully spherical isotropic source. To overcome this limitation, we model lightning emissions using two superimposed sources: one upward-facing point source and one downward-facing point source. We consider these light sources to be monochromatic near-infrared sources at 870 nm following Thomson and Krider (1982). These sources are assigned an optical power of $10^7$ W, consistent with the order of magnitude in optical output from return strokes (i.e., Guo & Krider, 1982).

Two surface materials are considered in this study. The first material is an idealized nonreflective surface that absorbs all incoming photon packets. None of the lightning emissions will be able to reflect off this surface to reach the satellite. The second material models rough seas as an inhomogeneous surface using a Lambertian Bidirectional Reflectance Distribution Function (BRDF) model with an albedo of 0.2. This simulated ocean surface is the surface material used in the cloud visualizations in Figure 1, and a reflection off this surface can be noted below the cloud base of the most distant row of clouds around y pixel 350 in Figure 1a.

Except for the visualizations in Figure 1, all simulations place the imager at the top of the model domain (30 km) directly above the cloud center with nadir pointing. The imager records the radiance of each pixel across its Field of View (FOV). At the 200 m horizontal grid spacing, a 45° full width FOV extends slightly beyond the edge of the horizontal model domain for the 3-D cloud directly below the imager. For runs with a broader FOV or more compact clouds, we can image multiple clouds at different off-nadir angles.

2.3. Experimental Configurations

Simulations are run to support three separate MCARaTS experiments. Aspects of the model configuration that differ between these experiments are summarized in Table 2, while the model setup is depicted in Figure 2. The source is shown as a double triangle symbol (representing the upward- and downward-directed sources). The cylinder clouds directly below the imager are superimposed on one another in this schematic drawing with their boundaries outlined in the figure. The solid line shows the overall shape of the most-complex cloud type (Cylinder + Base & Anvil), and the dashed vertical lines show the edges of the primary cylinder cloud. These cloud shapes and sources are repeated horizontally in all directions following the cyclic boundary conditions of the model.

We consider two possible horizontal positions for the source in each experiment. The source may be centered within the cloud (as in Figure 2a), or it may be located at the edge of the cloud (as in Figure 2b). In the latter case, the source is placed in the center of the cloud in the model y axis and at 1.8 grid points from the edge of the primary cylindrical cloud in the model x axis (i.e., 360 m from the cylinder edge at the 200 m horizontal model resolution).
Experiment 1 (section 3.1) examines how the radiance patterns recorded by the imager above the cloud change for each cloud type according to the chosen cloud extinction coefficient and optical depth. In this experiment, we place the lightning source at the surface \((z = 0 \text{ m})\) directly below the center of the cloud, and then record the radiance that is detected by the imager at 30 km altitude directly above the source.

Experiment 2 (section 3.2) chooses an optical extinction coefficient from the first experiment to represent optically thick clouds and then examines how the radiance patterns vary with source altitude, and source horizontal position. The source is free to move up and down the dotted vertical lines in Figure 2 between 0 and 6 km altitude with a vertical step of 100 m.

Experiment 3 (section 3.3) leverages the tiled nature of the 3-D model domain to examine how the radiance patterns recorded by the nadir-pointing imager vary with the off-nadir angle of the cloud and source. The imager FOV is increased to a full width of 120°, while the horizontal grid spacing of the 3-D cloud model is reduced to 100 m between grid cells. This allows us to compare the radiance from multiple clouds illuminated by identical lightning sources at various points across the instrument FOV when the source is located at either the center or the edge of the storm core.

Figure 2. Experimental setup showing the location of the light source (double triangle) and imager (eye symbol) in the cylindrical cloud geometries when (a) the source is located at the geometric center of the cloud, and (b) the source is located near the edge of the primary cylinder. Solid lines outline the outer boundaries of the slab and most complex cylindrical clouds while dashed lines show the primary cylinder radius. Dotted lines indicate the range of altitudes where the light source may be positioned.

Figure 3. The radiance of the cloud directly over the source (source pixel: solid lines) and the maximum scene radiance (dashed lines) from a surface-level \(10^9 \text{ W} \) source over a (a) nonreflective surface and (b) simulated ocean surface illuminating each cloud geometry (colors) with varying cloud extinction coefficients and optical depths.
3. Results

3.1. Experiment 1: Radiance Variations With Cloud Extinction Coefficient and Optical Depth

In the first experiment, we place our $10^9$ W optical source below the cloud base at the geometric center of the storm and record the radiance patterns that result from simulations with different cloud extinction coefficients. This changes the optical depth of the cloud region that optical energy must transit to reach the imager. Figure 3 shows how the recorded radiance from the imager pixel colocated with the source (termed “source pixel”): solid lines, and the brightest pixel across the scene (dashed lines) varies with the prescribed cloud extinction coefficient for each of our cloud geometries over a nonreflective surface (Figure 3a) or over the simulated ocean surface (Figure 3b). The received radiance from the center of the cloud decreases from $\sim 1$ W m$^{-2}$ sr$^{-1}$ at a total vertical optical depth of 80 to $\sim 0.003$ W m$^{-2}$ sr$^{-1}$ at a total vertical optical depth of 400. The center pixels are slightly brighter over the reflective ocean surface than over the nonreflective surface, as a portion of the downward-directed energy is reflected upward toward the satellite. Only slight differences can be noted between the cylindrical cloud types, while the slab geometry is slightly brighter than the other clouds at optical depths below $\sim 250$.

Because the model reports monochromatic radiance in physical units, we can put these values into perspective by comparing them with past observations of natural lightning. Christian and Goodman (1987) measured lightning from a high-altitude aircraft and reported peak radiances per flash over a range from $< 0.02$ to 0.3 W m$^{-2}$ sr$^{-1}$ and radiances from all pulses that extend down to $< 0.005$ W m$^{-2}$ sr$^{-1}$. While key differences exist between these observations and our model in terms of source power (they estimated a median of $10^8$ W, a factor of 10 less than our model source), source altitude/extent, and cloud height, it is promising that the model radiances have a similar numerical range compared to these observations.

However, the center pixel directly over the source is only the brightest pixel in the scene when the cylindrical clouds have small optical depths. At optical depths around 200–250 (depending on cloud geometry), the dashed curves in Figure 3 show the scene maximum radiance begin to diverge from the solid curves that denote the source pixel radiance. For runs over the nonreflective surface, only the Cylinder + Base clouds and Cylinder + Base & Anvil clouds diverge from the central pixel brightness in this range. Cylinder and Cylinder + Anvil clouds gain bright pixels displaced from center starting at optical depths >350. Meanwhile, all cylindrical (i.e., nonslab) clouds over the simulated ocean surface gain bright pixels displaced from center at optical depths between 200 and 300. The simulations in Figures 3a and 3b are otherwise identical—only with a different surface material. Yet the brightest pixels from finite clouds in Figure 3b are universally brighter than the brightest corresponding pixels in Figure 3a at the largest optical depths, and these pixels have more than 10 times the radiance of the central pixel over the source.

To demonstrate why this is occurring, Figures 4–6 depict the radiance patterns produced by each cloud type for runs corresponding to an optical depth of 160 (Figure 4) and 320 (Figure 5) over a nonreflective surface, and an optical depth of 320 over a simulated ocean surface (Figure 6). The first five panels plot the radiance across the 3-D model domain in imager angular coordinates with the cloud type in question named in the plot title. Radiance are normalized according to the brightest pixel in each image. Dashed circles are drawn to show the diameters of the primary cylindrical cloud (at its base) and the cylindrical anvil cloud (where present). The geometric center of the cloud is indicated with asterisk symbols. The final sixth panel shows scene-normalized radiance cross sections through the center of each image along the x axis. These cross sections are also indicated in the first five panels with horizontal dashed lines.

The clouds with the lower optical depths (Figure 4) are all brightest over the source and have radiance patterns that decrease radially with similar Gaussian curves out to near the edge of the primary cylindrical cloud (Figure 4f). The spatial radiance distributions diverge starting at this radius according to cloud geometry. While the cylindrical cloud (Figure 4b) drops immediately to the model noise floor, clouds with a planar base (Figure 4c) have a secondary peak at the maximum cloud radius. If an overhanging anvil is present (Figures 4d and 4e), it can block radiance from reaching the imager, but illumination along its edges still produce a secondary radiance peak.
These radiance patterns change as we increase the cloud extinction coefficient and optical depth. The clouds in Figure 5 with maximum optical depths of 320 produce radiance peaks (Figure 5f) in the same locations as the previous cloud (Figure 4f), but the cloud edges can rival or even exceed the central peak radiance. This is compounded by diffuse reflections off the rough oceanic surface in Figure 6b where even the simple Cylinder geometry is brightest around its edges. The ocean surface behaves like the base layer in Figures 6c and 6e, expanding the radiance pattern outward from cylindrical cloud.

Here, we see the basis for holes in the lightning radiance patterns observed from space. If the radiance of these central pixels falls below the minimum sensitivity of the instrument, then it will only resolve the bright ring.
around the edge of the cloud. Figure 6c is particularly illustrative of what such a radiance pattern would look like in the lightning imager measurements. Pixels that correspond to shortcuts that the photons can take to avoid transmitting through the full optical depth of cloud will light up while the storm core remains dark. The implication of this is that poorly transmissive clouds not only reduce the detection efficiency of the instrument but also the location accuracy—as the pixels at the edge of the cloud are considered to have produced the optical impulse in question, when the source was actually located within the thunderstorm core.

3.2. Experiment 2: Radiance Variations From Source Altitude

In the second experiment, we place our point source at various altitudes within each cloud geometry and then compare the radiance patterns recorded by the imager. Figures 7a–7e compare the radiance from the...
pixel corresponding to the source location (solid lines) and the maximum scene radiance (dashed lines) for a centered (black) or edge (blue) optical source over a nonreflective surface. Radiance is shown along the lower x axis, while normalized radiance relative to an unobscured source located at the cloud top is shown along the upper x axis. Figure 7f, then, computes the half width of half maximum (HWHM) in the resulting radiance pattern at each altitude and cloud type starting at 1500 m.

The radiance-altitude profiles show that the most rapid change in scene radiance occurs within the top 1 km of the cloud medium. When the source is located near the cloud top, the peak radiance is colocated with the source. Moreover, comparing the centered source curves (black) with the edge source curves (blue) suggests that this does not depend on the horizontal position of the source in the cloud. High-level sources behave as though they were embedded in slab clouds, while their increased pixel radiances from having concentrated

Figure 6. As in Figure 5, but for a surface-level source over a reflective simulated ocean surface. Cloud overall optical depths are still 320. Radiance extends outward from the cloud edge due to the rough reflective surface being illuminated.
optical energies (Figure 7f) less diluted by the cloud medium provide a detection advantage over lower altitude sources with the same optical power.

As the source is moved lower in the cloud, the curves for all finite cylindrical cloud geometries (Figures 7b–7e) eventually separate. First, centered sources start to produce greater radiances than edge sources, indicating additional energy loss from the instrument field of view when high-level sources are placed near the edge of the scattering medium. Then, at a lower altitude, the source pixel loses its distinction as the brightest location in the scene. Edge sources are only dimmer than their centered counterparts when the sources are located near the cloud top. As the sources are moved lower into the cloud, edge sources lose less energy with increasing cloud optical depth than the centered sources. The brightest pixels that illuminate Cylinder + Base clouds, in fact, become brighter as the source is lowered from 4 km altitude to 2 km altitude. This causes the blue edge source curves to eventually overtake the centered source curves. For the lowest source altitudes, sources near the edge of the cloud are always brighter than sources located at its center.

The radiances from low-altitude sources are also affected by surface reflections. Figure 8 shows the same radiance altitude profiles as Figure 7, but for a reflective ocean surface. As we saw in Figure 6, surface-level centered sources below optically thick clouds can generate scene-maximum radiances that...
are up to an order of magnitude brighter than the same source and cloud type over a nonreflective surface. This only occurs while the source is at low altitudes. If the source is located in the middle to high levels of the cloud, the curves in Figures 7 and 8 are nearly indistinguishable. The altitude where ocean surface reflections becomes a second-order effect is near the middle of the cloud at 3 km.

Figure 7. Radiance profiles as in Figure 7, but for sources at various altitudes over a nonreflective ocean surface.

Figure 8. Radiance profiles as in Figure 7, but for sources at various altitudes over a reflective ocean surface.

The altitudes where the curves in Figures 7 and 8 separate and the specific behavior of the edge source curves depend on the geometry of the cloud considered. For centered source runs, the scene maximum radiance curves separate from the source pixel radiance curves at ~2 km altitude. Figure 9 shows the radiance patterns from 2 km centered sources over a nonreflective surface in each cloud type (Figures 9a–9e) and a cross section through the center of the scene (Figure 9f) following the convention of Figures 4–6 (though note that the radiance in Figure 9f is normalized relative to an unobscured nadir source rather than the maximum scene radiance). While the central peak colocated with the source is still the most prominent feature, radiance at the edge of the overall cloud footprint rivals this central peak in clouds with a base layer (Figures 9c and 9e). The same runs over a reflective ocean surface add this edge ring to Cylinder and Cylinder + Anvil clouds (as we saw in Figures 6b and 6d) but otherwise generate similar radiance patterns. In this way, the ocean surface behaves like a base layer below the cloud, directing photons to the imager along paths that are not accessible through clear air—resulting in greater low-level scene-maximum radiances below these thick clouds than the nonreflective surface runs.

The altitudes where these outer peaks overtake the central peak can be seen in the HWHM curves in Figures 7f and 8f. HWHM increases as sources are moved away from the cloud top. For sources above the cloud, this is due to reflections off the uppermost cloud boundary. For sources within the cloud, this is
due to increased scattering interactions. Midlevel sources (i.e., ~3 km altitude) have their radiant energy diluted over a large area through scattering, and this causes both a severe reduction in the maximum pixel radiance (only ~0.01% of an unobscured source) and large HWHM values (off-nadir angles of ~5° for our imager configuration and measurement geometry). However, when the outer peak becomes more radiant than the inner peak, the HWHM suddenly increases because the HWHM algorithm is looking for the half maximum at radii beyond the peak radiance location. Ordered from highest to lowest altitude, this jump occurs in the simulated ocean surface runs (Figure 8f) first in Cylinder + Base clouds, then Cylinder + Base & Anvil clouds, then Cylinder clouds, and finally Cylinder + Anvil clouds. It does not occur with slab clouds and is also absent for the nonreflective surface runs (Figure 7f) that lack a base layer. For illumination from centered sources to be strongest at the cloud edge, there must be some

Figure 9. Radiance patterns as in Figure 3, but from a centered source located at 2,000 m altitude above a nonreflective surface illuminating clouds with an overall optical depth of 400. Normalized radiances in panel (f) are shown as a percent of the radiance from an unobstructed source at nadir rather than the scene maximum radiance.
reflective medium beyond the primary cylindrical cloud to direct the photons up toward the imager—either a lower cloud deck or a rough reflective surface.

The radiance patterns from edge sources are most complex when the sources are located in the midlevels of the cloud where the photon packets can access reflective surfaces across the 3-D scene to find shortcuts to the imager. Figure 10 demonstrates the impact of these diffuse reflections on the radiance patterns from horizontally offset lightning sources. In this case, the source is placed at 3.8 km altitude over a nonreflective surface near the point where the blue curves separate in Figures 7b–7e. Due to the cyclic nature of the 3-D model domain, clouds and localized sources are repeated horizontally. Thus, the right side of the cloud is primarily illuminated by the visible source, while the left side of the cloud is primarily illuminated by the source in the next tile to the left (outside of the instrument FOV).

Figure 10. Radiance patterns as in Figure 9, but for an edge source located at 3,800 m altitude above a nonreflective surface illuminating clouds with an overall optical depth of 400.
For the slab cloud (Figure 10a), the radiance pattern is only influenced by the visible source. The radiance cross section (black line in Figure 10f) decreases from the source location and remains near 0% at x pixels below ~5 degrees. The finite cylindrical clouds have a radiance peak over the source, but their radiance patterns and cross sections are irregular compared to the slab cloud case. For a simple cylindrical cloud (Figure 10b), the radiance peak over the source is bounded by the cloud edge, causing the primary peak in the cross section (Figure 10f) to be sharper on its right side. Meanwhile, a second prominent peak is visible along the left side of the cloud from radiance produced by the source in the adjacent tile reflecting off the cloud face to reach the imager.

Adding a base cloud layer (Figure 10c) provides a more effective reflective surface for directing the lightning emissions toward the imager. The reflection off top of the base layer is more radiant than the primary peak colocated with the source (where the photons still must transit a relatively thick cloud layer to reach the imager). The neighboring point source still illuminates the west edge of the cylindrical cloud, resulting in a total of three peaks in the imager x cross section in Figure 10f. Performing the same runs over a reflective simulated ocean surface (not shown) adds this behavior to the other cloud types that lack this base layer.

If we, instead, add an anvil to the top of the cylindrical cloud (Figure 10d), then the radiance peak over the source is not shifted as notably inward as in Figure 10b (though the same effect applies at the edge of the wider anvil cloud). This case results in two peaks in the radiance cross section in Figure 10f: the source peak, and the left edge of the anvil cloud reflecting radiance from the next source over. The source peak is the brighter of the two peaks.

Finally, adding a lower base layer and an upper anvil cloud to the simple cylinder cloud (Figure 10e) combines all of these effects. While a dim peak exists over the source that has nearly the same width as the slab cloud peak in Figure 10a, the most radiant source is located beyond the edge of the anvil cloud where diffuse reflections off the top of the base layer transmit photons directly to the imager. This edge peak is the brightest of any peak in Figure 10f that comes from a cloud with a finite geometry. Peak transmission to space from these edge sources in finite cloud geometries is only 23% (Cylinder) to 55% (Cylinder + Base & Anvil) of the radiance of a homogeneous slab cloud. The remaining optical emissions that would be detected from above in an idealized cloud are lost from being redirected away from the imager.

The radiance patterns in Figures 9 and 10 show that increasing the complexity of the cloud scene provides more opportunities for the radiance pattern to diverge from the Gaussian spatial radiance distributions seen in slab clouds—especially when sources are offset from the geometric center of the cloud. These variations in the observed radiance patterns result from specific aspects of the cloud scene that can be identified in the spatial distribution of optical radiance. This supports the idea that we can make inferences about cloud geometry and structure based on how the clouds are illuminated by lightning.

### 3.3. Experiment 3: Radiance Variations From Look Angle

The first two experiments consider how clouds directly below the imager are illuminated by lightning sources. In the third experiment, we expand the imager FOV while decreasing the horizontal grid spacing of the cloud model to image multiple clouds illuminated by surface-level sources over a simulated ocean surface at various points across the scene.

Radiance patterns from centered lightning sources are shown in Figure 11 for each of our cloud geometries. Because the imager has a square shape with each axis (x and y) covering 120°, the corner pixels (outside of the inner dashed circle) extend out beyond this nominal angular FOV. The horizon below the camera (~75° from nadir) can be noted in the corners of the image (outer dashed line) where the illuminated clouds seem to disappear from the image. Each of the images in Figures 11a–11e are normalized relative to the brightest pixel in the image, as before. However, instead of a cross section through the center of the image, the final panel (Figure 11f) shows the peak radiance in each ring corresponding to a particular off-nadir angle normalized relative to the radiance of an unobstructed nadir source.

A common feature for all finite cylindrical cloud types (Figures 11b–11e) is that the center cloud that we examined in Experiments 1 and 2 is the least radiant cloud in the scene. Clouds that are not located at nadir provide more shortcut paths that photons can take to the imager. As a result, less of the radiance is diluted or extinguished from the instrument FOV. The radial distribution of peak radiance (Figure 11f) is similar for all cloud types for the first three peaks (up to ~45°). Within this range, the peak radiance from all cloud tiles
(except the cloud at nadir) is approximately the same and does not notably increase with the off-nadir angle of the cloud in question.

However, not all cloud tiles in the image achieve these peak radiance values. Particularly along the central x and y axes in Figures 11b–11e, the clouds near the edge of the nominal x and y FOV (60°) have their radiance blocked by the top of the neighboring cloud closer to the center of the image. This blocking is especially important for cloud types with anvil layers (Figures 11d and 11e) because the cylindrical anvils at the cloud top have an increased diameter compared to the primary cylindrical cloud.

Figure 11. Radiance patterns (a–e) from multiple cloud tiles illuminated by centered surface-level sources (with a 100 m horizontal grid spacing) above a simulated ocean surface. The imager FOV has been increased to 120°. The radii corresponding to the nominal imager FOV (inner) and horizon (outer) are indicated with dashed circles. Radial cross sections of peak radiance (radial dashed line in panels a–e) for each cloud type are shown in (f) as a function of off-nadir angle. The edge of the nominal imager FOV is indicated with a dashed vertical line in panel (f). As in Figures 9 and 10, radiance is normalized relative to an unobscured cloud-top source at nadir.
These competing factors—the relative visibility of the source and blocking by neighboring clouds—cause the angular peak radiance distributions for each cloud type to diverge at off-nadir angles beyond 45°. The key factor for how the radiance distributions behave after this point is whether the cloud geometry has a base layer. If no base layer is present, then the peak radiance begins to increase with off-nadir angle, as the source is less obscured when the cloud is viewed from the side. Anvil clouds (if present) are more effective at blocking radiance at large off-nadir angles than narrow cylinders. Thus, the Cylinder cloud type (blue line in Figure 11f) reaches a maximum peak radiance between the nominal (60°) and overall (75°) edge of the imager FOV that is 4× brighter than any other cloud type, while the Cylinder + Anvil cloud type (red line) angular peak radiance distribution decreases.

If a base layer is present, however, then the angular peak radiance distributions do not notably increase beyond off-nadir angles of 45°. The various peaks in these distributions (corresponding to unique cloud
tiles) maintain their off-nadir values from angles <45°. It should be noted that these trends are only valid for the cloud tile spacing and measurement geometry considered by these simulations. Radiance certainly changes significantly with off-nadir angle when the imager is located at higher altitudes.

Figure 12 depicts the radiance patterns that result from sources placed near the right edge of the primary cylindrical cloud. Blocking by neighboring clouds is particularly important when the source is located at the edge of the storm. Tiles where entire cloud volumes separate the source from the imager remain dark—including most of the right side of the imager FOV. However, this blocking is not evident in Figures 12b and 12d because it is overshadowed by extremely bright pixels in the tiles to the left of center. These pixels have a direct sight line on the lightning source. When the base layer is present, it dilutes the optical emissions from the offset source, causing the peak radiance profiles for the Cylinder + Base and Cylinder + Base & Anvil cloud geometries in Figure 12f to behave in a similar manner to the slab cloud geometry (black curve)—only at a greater radiance due to its thin vertical extent. Without this base layer, the Cylinder and Cylinder + Anvil cloud geometries record the unimpeded radiance from the source. Indeed, the maximum values in their angular peak radiance distributions (blue and red curves) nearly reach 100% of the radiance of an unobscured nadir source.

We are essentially describing the conditions that allow ordinary lightning to be measured as a superbolt. Having this direct unobscured sight line on the source can cause the peak radiance to be 5 orders of magnitude brighter than the same exact source below a cloud layer—either on the edge of the storm but below a base layer of warm cloud, or centered in the storm core (Figure 11). Since superbolts are defined as being 2–3 orders of magnitude brighter than typical lightning, this scenario may allow normal lightning to contribute significantly to the sample of superbolts recorded from space by optical instruments. In on-orbit measurements, the source would not be a single point at the surface but rather an illuminated dendritic network of ionized lightning channels extending into the cloud. As a result, the whole edge of the cloud would be illuminated instead of a single pixel on the imaging array. We referred to examples of this scenario as “anvil superbolts” in Peterson et al. (2020) because they mostly illuminated the nonraining anvil and boundary clouds surrounding the storm core.

This is not the only scenario where a superbolt can arise, however. A population of “stratiform superbolts” was also noted in Peterson et al. (2020) where particularly radiant lightning emissions originated from homogenous stratiform clouds identified by coincident precipitation radar data. These layered clouds would behave similarly to the Slab cloud in Figure 12a. Figure 12f indicates that the observed radiance in such a cloud does not depend on look angle. These events are bright because the optical source is particularly energetic (e.g., a +CG accessing a horizontally expansive network of lightning channels), the illumination occurs at an altitude in the cloud where the optical thickness of the layer above is limited, or a combination of the two. Shortcut paths like we see in Figures 12b and 12d may be the cause of anvil superbolts, but they are not the likely cause of stratiform superbolts.

4. Conclusion

This study uses optical Monte Carlo radiative transfer simulations with complex 3-D cloud scenes to explain the origins of irregular lightning radiance patterns that have been observed from orbit—including “holes” in the middle of otherwise-contiguous illuminated cloud regions, lightning that wraps around storm edges or seems to occur entirely in a warm boundary cloud that is probably not electrified, and particularly intense lightning signals from storm edges (“anvil superbolts”). We approximate the shapes of natural stormclouds by combining cylindrical and slab cloud geometries. While a purely cylindrical cloud might approximate growing convection, tall convection with an overhanging anvil is simulated by adding a second cylinder with a greater diameter at the top layers of the cloud. Warm boundary clouds, then, are simulated by adding an infinite slab cloud to the bottom of the primary cylinder.

These clouds are illuminated by localized point sources that approximate lightning emissions, and the radiance patterns measured by an imager above the cloud are examined. By varying the optical thickness of the clouds and moving the point source around the cloud scene, we are able to explore the dynamics of cloud illumination and identify scenarios that result in the irregular radiance patterns of interest.
We confirm that diffuse reflections off of nearby cloud faces (particularly lower warm boundary clouds) are an important factor that determines how the radiance measured from above is distributed spatially across the scene. When the source is located below a thick storm cloud, the brightest illumination in the scene is from “shortcuts” that the optical signals can take to reach the imager without scattering through the entire cloud depth. This is important because midlevel sources reflecting off a base layer or low-level CG sources might appear to be located outside of the storm core when the primary peak directly over the source is attenuated, reducing location accuracy. Moreover, particularly thick clouds almost entirely attenuate this peak, resulting in the “hole” features noted in observations. Even though overhanging anvils are a “shortcut” due to their limited optical depth compared to the full cylinder, they still extinguish the signals from low-level sources and can form holes by reflecting radiance back toward the Earth.

On the other extreme, certain viewing geometries can lead to particularly favorable shortcut paths where the imager can view a source located at the edge of the storm directly without significant modification by the clouds. Because the measured radiance decreases exponentially in the first ~1 km of cloud between the source and sensor, the radiance from such an unobstructed source is up to 5 orders of magnitude brighter than the same source viewed from a different angle. Thus, a normal lightning source that is observed along this particularly favorable sight line can easily be labeled as a superbolt—and this appears to be the origin of our “anvil superbolts” that primarily illuminate the edges of the parent thunderstorm. This scenario does not explain stratiform superbolts that occur embedded within slab-like stratiform clouds.

These results show that increasing the complexity of the cloud scene provides more opportunities for complex interactions with the lightning emissions leading to irregularities in the resulting radiance pattern measured from above the storm. However, when the clouds can be represented as slab layers (e.g., stratiform clouds or high-altitude sources), radiance profiles can be approximated with Gaussian curves. These findings support the idea that we can infer cloud structure based on how the clouds are illuminated by lightning (i.e., how the radiance pattern diverges from an idealized state).

Data Availability Statement

The MCARaTS model used in this study may be acquired from Iwabuchi (2004), while the cloud models that serve as input data are located at Peterson (2020).

References

Blakeslee, R. J., Lang, T. J., Koshak, W. J., Buechler, D., Gatlin, P., Mach, D. M., et al. (2020). Three years of the lightning imaging sensor onboard the international space station: Expanded global coverage and enhanced applications. Journal of Geophysical Research: Atmospheres, 125, e2020JD032918. https://doi.org/10.1029/2020JD032918

Boccippio, D. J., Koshak, W., Blakeslee, R., Driscoll, K., Mach, D., Buechler, D., et al. (2000). The optical transient detector (OTD): Instrument characteristics and cross-sensor validation. Journal of Atmospheric and Oceanic Technology, 17, 441–458. https://doi.org/10.1175/1520-0469(2000)017<0441:TOTDIO>2.0.CO;2

Iwabuchi, H. (2004). Algorithm theoretical basis document (ATBD) for the lightning imaging sensor (LIS). (pp. 82–129). New York: John Wiley.

Iwabuchi, H., & Bitter, P. M. (2020). A first look at cloud inhomogeneity and its effect on lightning optical emission. Geophysical Research Letters, 47, e2020GL087094. https://doi.org/10.1029/2020GL087094

Christian, H. J., & Goodman, S. J. (1987). Optical observations of lightning from a high-altitude airplane. Journal of Atmospheric and Oceanic Technology, 4, 704–711. https://doi.org/10.1175/1520-0426(1987)004<0701:OOOLFA>2.0.CO;2

Goodman, S. J., Blakeslee, R. J., Koshak, W. J., Mach, D., Bailey, J., Buechler, D., et al. (2013). The GOES-R geostationary lightning mapper (GLM). Atmospheric Research, 125–126, 34–49. https://doi.org/10.1016/j.atmosres.2013.01.006

Guo, C., & Krider, E. P. (1982). The optical and radiation field signatures produced by lightning return strokes. Journal of Geophysical Research, 87(C11), 8913–8922. https://doi.org/10.1029/JC087iC11p08913

Christian, H. J., & Goodman, S. J. (1987). Optical observations of lightning from a high-altitude airplane. Journal of Atmospheric and Oceanic Technology, 4, 704–711. https://doi.org/10.1175/1520-0426(1987)004<0701:OOOLFA>2.0.CO;2

Iwabuchi, H. (2004). MCARaTS. Retrieved September 08, 2020, from https://sites.google.com/site/mcarats/home

Iwabuchi, H. (2006). Efficient Monte Carlo methods for radiative transfer modeling. Journal of the Atmospheric Sciences, 63, 2324–2339. https://doi.org/10.1175/jas3755.1

Iwabuchi, H., & Okamura, R. (2017). Multispectral Monte Carlo radiative transfer simulation by using the maximum cross-section method. Journal of Quantitative Spectroscopy and Radiative Transfer, 193, 40–46. https://doi.org/10.1016/j.jqsrt.2017.01.025

Koshak, W. J., Solakiewicz, R. J., Phanord, D. D., & Blakeslee, R. J. (1994). DiFusion model for lightning radiative transfer. Journal of Geophysical Research, 99(D7), 14,361–14,371. https://doi.org/10.1029/94JD00022

Light, T. E., Suszcynsky, D. M., & Jacobson, A. R. (2003). Coincident radio frequency and optical emissions from lightning, observed with the FORTE satellite. Journal of Geophysical Research, 108(D22), 28,223–28,231. https://doi.org/10.1029/2003JD003721

Acknowledgments

This work was supported by the US Department of Energy through the Los Alamos National Laboratory (LANL) Laboratory Directed Research and Development (LDRD) program under project number 20200529ECR. Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear Security Administration of US Department of Energy (Contract No. 89233218CNA000001).
Light, T. E., Suzyczynsky, D. M., Kirkland, M. W., & Jacobson, A. R. (2001). Simulations of lightning optical waveforms as seen through clouds by satellites. *Journal of Geophysical Research,* 106(D15), 17,103–17,114. https://doi.org/10.1029/2001JD900051

Peterson, M. (2020). Cloud models used in lightning radiative transfer simulations. *Journal of Geophysical Research: Atmospheres,* 125, 13,370–13,386. https://doi.org/10.1029/2019JD031087

Platt, C. M. (1997). A parameterization of the visible extinction coefficient of ice clouds in terms of the ice/water content. *Journal of the Atmospheric Sciences,* 54, 2083–2098. https://doi.org/10.1175/1520-0469(1997)054<2083:APOTVE>2.0.CO;2

Rudlosky, S. D., Goodman, S. J., Virts, K. S., & Bruning, E. C. (2018). Initial geostationary lightning mapper observations. *Geophysical Research Letters,* 46, 1097–1104. https://doi.org/10.1029/2018GL081052

Stephens, G. L., Paltridge, G. W., & Platt, C. M. R. (1978). Radiation profiles in extended water clouds, III. Observations. *Journal of the Atmospheric Sciences,* 35, 2133–2141. https://doi.org/10.1175/1520-0469(1978)035<2133:RPIEWC>2.0.CO;2

Susyczynsky, D. M., Kirkland, M. W., Jacobson, A. R., Franz, R. C., Knox, S. O., Guillen, J. L. L., & Green, J. L. (2000). FORTE observations of simultaneous VHF and optical emissions from lightning: Basic phenomenology. *Journal of Geophysical Research,* 105(D2), 2191–2201. https://doi.org/10.1029/1999JD900993

Thomas, R., Krehbiel, P. R., Rison, W., Hamlin, T., Boccippio, D. J., Goodman, S. J., & Christian, H. J. (2000). Comparison of ground-based 3-dimensional lightning mapping observations with satellite-based LIS observations in Oklahoma. *Geophysical Research Letters,* 27(12), 1703–1706. https://doi.org/10.1029/1999GL010845

Thomson, L. W., & Krider, E. P. (1982). The effects of clouds on the Light produced by lightning. *Journal of the Atmospheric Sciences,* 39, 2051–2065. https://doi.org/10.1175/1520-0469(1982)039<2051:TEOCOT>2.0.CO;2

Turman, B. N. (1977). Detection of lightning superbolts. *Journal of Geophysical Research,* 82(18), 2566–2568. https://doi.org/10.1029/JC082i018p02566

van de Hulst, H. C. (1980). *Multiple Light Scattering,* vols. 1 and 2. Academic. San Diego, CA: Academic Press.

Yang, J., Zhang, Z., Wei, C., Lu, F., & Guo, Q. (2017). Introducing the new generation of Chinese geostationary weather satellites, Fengyun-4. *Bulletin of the American Meteorological Society,* 98, 1637–1658. https://doi.org/10.1175/BAMS-D-16-0065.1