The detection of continuing current in lightning using the Geostationary Lightning Mapper and exploring its relationship to lightning initiated-wildfires

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THE DETECTION OF CONTINUING CURRENT IN LIGHTNING USING THE GEOSTATIONARY LIGHTNING MAPPER AND EXPLORING ITS RELATIONSHIP TO LIGHTNING-INITIATED WILDFIRES

by

SARAH I. FAIRMAN

A THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Atmospheric Science in The Department of Atmospheric Science to The School of Graduate Studies of The University of Alabama in Huntsville

HUNTSVILLE, ALABAMA

2020
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Submitted by Sarah I. Fairman in partial fulfillment of the requirements for the degree of Master of Science in Atmospheric Science and accepted on behalf of the Faculty of the School of Graduate Studies by the thesis committee.

We, the undersigned members of the Graduate Faculty of The University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate of the work described in this thesis. We further certify that we have reviewed the thesis manuscript and approve it in partial fulfillment of the requirements for the degree of Master of Science in Atmospheric Science in the Department of Atmospheric Science.

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Lightning with continuing current may have current durations that last for hundreds of milliseconds, resulting in continuous optical emission that coincides with the uninterrupted current flow. The space-based Geostationary Lightning Mapper (GLM) is an optical sensor that allows for the detection of continuous optical emission. GLM optical attributes associated with continuous optical emission are utilized to train a multiple logistic regression model to predict the presence of continuing current. GLM flashes that have continuous optical emission related to higher probabilities of continuing current tend to cover a longer distance, have a brighter maximum optical energy, and cover a larger maximum area over the span of the continuous optical emission. The continuing current model has a probability of detection of about 78% and a false alarm rate of about 6%. About 13.3% of flashes detected by GLM in 2018 contain continuing current. Seasonal, diurnal, and spatial analyses reveal that continuing current flashes tend to occur during the winter, at night, and over oceanic areas.
On average, the total time elapsed between a GLM flash and satellite-based wildfire was 5 to 7 days. GLM flashes closest to a satellite-detected wildfire had an average distance of about 3.3 km from a wildfire, while the closest GLM flashes with continuing current had an average distance of roughly 5.0 km from a wildfire.
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CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Introduction

Lightning is an energetic phenomenon that radiates both optically and at various electromagnetic frequencies. When a lightning discharge occurs, it either re-arranges electrical charge within a cloud or transports electrical charge to the ground. Once a lightning channel connects to the ground, it can become damaging to structures, foliage, and even the surface of the earth. The amount of damage it may cause depends on the total time the connection to the ground remains intact due to continuous charge flow to an area. As the continuous connection to the ground begins to heat up a structure due to consistent charge flow, the more likely it is for burn damage or even a fire ignition to occur. To be able to detect when a particular lightning discharge may contain a relatively longer current flow presents a potential advantage to early wildfire detection.

Before a discharge occurs, the cloud must undergo the process of electrification. As an updraft lifts graupel and ice particles in the presence of supercooled water further into the atmosphere, the graupel and ice particles begin to collide with one another resulting in the creation of charge. At this stage, the cloud becomes electrified
where positive and negative charge regions begin to form. Typically, smaller ice particles tend to gain a positive net charge during a collision and carry positive charge towards the top of the cloud as the updraft continues to lift the particles further up. A net negative charge is attached to the heaver, larger graupel particles, and the updraft is unable to lift these particles as high as the smaller, positively charged particles. Hence, a dipole charge structure is generally depicted at this point in the electrification process, where a positive charge region is established near the top of the cloud and a negative charge region forms near the bottom of the cloud (MacGorman and Rust 1998). A tripole charge structure, however, is more commonly used as a general charge structure model, and the charge region locations depend on the environmental temperature at a particular altitude (Brook et al. 1982; Krehbiel 1998).

Once the potential difference between the two charge regions is large enough, an electrical discharge occurs and charge from within the cloud is neutralized. A discharge can either remain in the cloud, termed an intracloud (IC) flash, or connect to the ground, termed a cloud-to-ground (CG) flash. The following sections provide a detailed description of a typical CG flash process and, ultimately, the relationship between lightning and wildfire initiation.

1.2 Cloud-to-Ground Lightning

There are four known types of CG lightning as seen in Figure 1.1: (a) downward negative lightning, (b) upward negative lightning, (c) downward positive lightning, and (d) upward positive lightning. Each type is categorized based on the direc-
tion of the initial leader and the polarity of charge being transferred to the ground from the cloud. Of these, negative flashes make up about 90% of global CG flashes, while about 10% of global CG flashes consist of positive lightning (Uman 1987). Since negative downward flashes are more common, this lightning type will be discussed to provide an idea of how a CG flash typically occurs.

A preliminary breakdown process associated with optical energy from within the cloud is indicative of the formation of a negative leader. Once the breakdown initiates the leader, it emerges from the cloud towards the ground in a step-like manner. As the stepped leader approaches the ground, positive leaders move upward, usually from taller objects extruding from the ground, due to an increased electric field near the surface. The downward moving stepped leader eventually makes contact with one of the upward moving positive leaders causing the large potential difference between the cloud and ground to be shorted, and thus, creating a return stroke. The resulting charge flow typically lasts for hundreds of microseconds, neutralizing the negative charge stored on the channel.

This process can be repeated if a second leader forms and travels downward. The leader may follow the same path as the first stepped leader if the previous path is still ionized, resulting in a dart leader that moves faster than a stepped leader. Otherwise, the leader will follow a new intermittent path. A subsequent stroke occurs once the dart leader undergoes an attachment process to the ground similar to the aforementioned return stroke formation. Multiple subsequent strokes may occur if conditions continue to allow for leader initiation within the cloud. On average, a CG flash may contain 3 to 5 return strokes (Rakov and Uman 2003, Table 1.1).
Figure 1.1: The four types of cloud-to-ground lightning discharges depicting the direction and polarity of the initial stepped leader. The polarity of the named discharge is dependent on the type of charge drained from the cloud. Adapted from Rakov and Uman (2003), Figure 1.1.
Many of these processes can easily be identified from the total radiated electric field due to a lightning discharge. A variety of ground-based networks have been created to measure these varying radiated electrical changes on different time scales and frequencies. The basis of measuring these processes stems from the following equation that relates the vertical component of the radiated electric field to three different terms in spherical coordinates (Uman 1987),

\[
E_z(r, t) = \frac{2}{2\pi\epsilon_0} \left[ \int_{H_B}^{H_T} \int_0^t \left( \frac{2 - 3\sin^2\theta}{cr^3} \right) \left( \frac{r - \frac{r}{c}}{r} \right) dz' \right. \\
+ \left. \int_{H_B}^{H_T} \frac{2 - 3\sin^2\theta}{cr^2} I(z', t - \frac{r}{c}) dz' \right] + \int_{H_B}^{H_T} \frac{\sin^2\theta}{cr} \frac{\partial}{\partial t} I(z', t - \frac{r}{c}) dz'
\]

where \( E_z \) is vertical component of the electric field at the surface of the earth at time \( t \) and at a horizontal distance \( r \) away from the vertical segment of interest \( z' \) that has a current \( I \) at an altitude \( z \). Additionally, \( c \) is defined as the speed of light, \( \epsilon_0 \) is the permittivity of free space, and \( \theta \) describes the angle between the point at distance \( r \) and the vertical segment \( z' \).

Equation 1.1 is comprised of the electrostatic, induction, and radiation components, respectively. The electrostatic component is related to the time integral of the current, or simply, the amount of charge on the channel, the induction component is proportional to the current itself, and the radiation component is related to the time derivative of the current. All three terms scale differently with respect to the distance \( r \) from the vertical segment \( z' \) of interest as seen in Equation 1.1. Specifically, the electrostatic component scales with distance \( \frac{1}{r^3} \), the induction component...
scales with distance $\frac{1}{r^2}$, and the radiation component scales with distance $\frac{1}{r}$. These distance relationships explain why the radiation field is the most dominant term at longer distances and shorter times, while the electrostatic field dominates at shorter distances and longer times.

1.3 Continuing Current in Lightning

As previously mentioned in Section 1.2, current flow in a typical return stroke lasts for hundreds of microseconds. However, lightning may contain current flow that lasts for tens to hundreds of milliseconds, referred to as continuing current (Brook et al. 1962; Kitagawa et al. 1962). Significantly more charge is transferred from the cloud to the surface of the earth as the connection to ground remains intact. Return strokes containing continuing current tend to have smaller initial electric field peaks than a typical return stroke (Brook et al. 1962; Rakov and Uman 1990; Rakov et al. 1994; Ferro et al. 2009). In addition, continuous charge flow is thought to occur in storms with relatively weaker updrafts, such as those over the ocean, during the winter, and at night (Goto and Narita 1995; Bitzer 2017).

1.3.1 Detection of Continuing Current

At short distances, a large charge transfer occurring for a long period of time would cause the electrostatic field to dominate the radiated electric field. In electric field data, a dominating electrostatic component is indicated by a slow change in the electric field of the same polarity as the return stroke, suggesting steady charge flow through the channel. The existence of a slow change signature allows one to infer the
occurrence of continuing current based solely on electric field data (e.g., Livingston and Krider 1978). The top panel in Figure 1.2 shows an electric field record of negative CG flash along with a photographic record of the same flash. All strokes except for the second stroke have little optical emission as seen in the photographic record accompanied by a quick electric field change that has little to no slow electric field change afterwards. However, the second stroke of the flash reveals the characteristic slow electric field change signature that lasts for about 200 ms before leveling back to a minimal change in electric field. Additionally, there is optical emission evident in the photographic record during the slow electrostatic change, suggesting a relationship between continuing current and continuous optical emission. In contrast, a discrete flash with no continuing current is pictured in the bottom panel of Figure 1.2, where there is very little optical emission associated with each stroke within the flash. Each quick change in the electric field change record has no slow electric field change after; rather, the electric field record “flatlines”, which is indicative of current flow quickly ceasing after the return stroke. Comparing these two flashes, it is quite apparent that continuing current presence may be identified by a return stroke in the electric field waveform followed by a slow electric field change or long lasting optical emission.

Since it has been established that current flow is accompanied by continuous optical emission, continuing current can be detected using video and optical sensors. Many studies have confirmed that continuous optical emission as seen in video recordings is associated with uninterrupted current flow (Kitagawa et al. 1962; Shindo and Uman 1989; Ballarotti et al. 2005; Saba et al. 2006; Biagi et al. 2007). Saba et al. (2006), in particular, found that the approximate length of both the light being emit-
Figure 1.2: Photographic, electric field, and electric field change records for a flash containing continuing current (top) and a discrete flash not containing continuing current (bottom). Adapted from Kitagawa et al. (1962), Figure 3.
ted from the visible channel and the slow electrostatic change in the electric field are strongly correlated. Because of this relationship, an estimated total duration of the current flow can be found using solely video measurements or an electric field waveform. Further, research has been done to relate the slow electric field change and continuous optical emissions as seen from space (Bitzer 2017). Bitzer (2017) analyzed time contiguous groups detected using the Lightning Imaging Sensor (LIS; Christian et al. 1992), defining five or more time contiguous groups as continuing current. Temporally contiguous frames of 1.79 ms each (Bitzer and Christian 2014) occurring near each other spatially represents light being continuously emitted from above the cloud, resulting in a continuing current measurement of at least 7 ms. In addition, ground-based measurements that reliably detected continuing current, such as high speed video or electric field change meters, are limited spatially. Specifically, a particular flash can be seen by a camera up to about 30 km away, while an array of electric field change meters with slower sampling rates may have baselines of tens of kilometers, resulting in total coverage of less than 100 km across. Various ground-based networks that cover larger spatial domains with baselines of hundreds of kilometers fail to resolve electrostatic changes associated with continuing current, limiting coverage up to a certain distance from the outermost sensors of the network. Utilizing space-based measurements means a greater potential of continuing current detection on a hemispheric scale.

A few studies attempt to define certain types of continuing current based on the temporal length of the current flow, such as very short (3 to 10 ms), short (10 to 40 ms), and long (greater than 40 ms) continuing current (Shindo and Uman
1989; Ballarotti et al. 2005; Saba et al. 2006; Lapierre et al. 2014). Current flow durations are thought to begin at 3 ms since a maximum typical return stroke current duration is assumed to last up to 3 ms (Malan and Schonland 1951; Beasley et al. 1982; Rakov et al. 1990). Also, Saba et al. (2006) found peak currents in short and long continuing current strokes are about 30% to 50% lower than peak currents of very short continuing current strokes, which supports previous findings that strokes followed by continuing current tend to have small peak fields (Brook et al. 1962; Rakov and Uman 1990; Rakov et al. 1994).

1.3.2 Negative Cloud-to-Ground Flashes

Recall from Section 1.2 that 90% of all CG flashes are thought to consist of negative CG flashes (Uman 1987). Once the downward negative leader connects to the ground, the CG stroke drains negative charge from the cloud (see Figure 1(a)). In addition, negative CG flashes contain two or more strokes 80% of the time (Rakov et al. 1994), establishing that more often than not, a particular negative CG stroke is deemed a subsequent stroke.

It is thought about 30-50% of all negative CG flashes contain long continuing current (Rakov and Uman 2003). Further, subsequent strokes in negative CG flashes tend to be followed by continuing current, rather than the first stroke in a multiple stroke flash or the only stroke in a single stroke flash (Rakov and Uman 1990). Additionally, in a multiple stroke flash, the first stroke tends to initiate a small charge transfer while the following stroke induces a larger charge transfer, or in other words, continuing current (Brook et al. 1962). Deeper analysis of the relationship between
subsequent strokes and continuing current production has shown mean peak current values in subsequent strokes were lower than that of the first stroke (Shindo and Uman 1989; Saba et al. 2006). In addition, Saba et al. (2006) reported mean continuing current durations in subsequent strokes were generally lower than continuing current durations of the first stroke. Therefore, it can be expected that continuing current is more likely to follow a subsequent stroke in a negative CG flash than the initial stroke or a single stroke flash.

From a physical standpoint, a negative CG flash that is followed by continuing current is thought to neutralize surplus charge from more mature areas of the cloud where untouched charge regions reside, while a typical negative CG flash with no continuing current neutralizes solely the charge on the channel (Krehbiel et al. 1979). However, a recent study compared the growth of the positive leader within the cloud versus the continuing current duration from electric field data (Lapierre et al. 2014). The study identified continuing current presence in negative CG flashes did not affect the positive leader growth rate within the cloud, suggesting that there must be some mechanism other than channel growth into negative charge regions that determines continuing current occurrence.

1.3.3 Positive Cloud-to-Ground Flashes

Positive CG flashes lower positive charge from the cloud to the ground (see Figure 1(c)) and make up about 10% of global CG flashes (Rakov 2003). Additionally, positive CG flashes are the dominant flash type during wintertime thunderstorms (Takeuti et al. 1978; Brook et al. 1982; Orville et al. 1987), as well as the trailing
stratiform regions of mesoscale convective systems (MCSs; Engholm et al. 1990). Both cold season storms and the trailing stratiform regions of MCSs are considered relatively shallow compared to convective summertime storms with strong updrafts, suggesting that weaker updrafts may play a role in positive CG production.

Some of the earliest research involving continuing current states that positive CG flashes tend to initiate a long lasting current (Rust and MacGorman 1981; Fuquay 1982; Beasley et al. 1983; Rust et al. 1985). Further, positive CG flashes are thought to be comprised of fewer return strokes than negative CG flashes (Nag and Rakov 2012). Nag and Rakov (2012), in particular, reported 81% of positive CG flashes contained a single stroke. In addition, Fuquay (1982) had a sample of 75 positive CG flashes, and each flash was comprised of a single stroke followed by continuing current.

Other studies have looked into the physical formation and structure of a positive CG flash. Activity within the cloud as shown in electric field data often precedes a positive CG flash for hundreds of milliseconds (Rust and MacGorman 1981; Fuquay 1982). These same studies also found that positive CG flashes produce long, horizontal channels within the cloud, often kilometers long. The long horizontal channels may relate to a finding from Lapierre et al. (2017), which concluded that negative leader growth within the cloud while a positive CG is connected to the ground injects a large amount of current into the channel, thus retaining current flow.
1.3.4 Intracloud Lightning

In some instances, a leader forms within a cloud but does not at any point connect to the ground and drain charge from the cloud; rather, charge quickly rearranges within the cloud, causing a discharge known as IC lightning (Kitagawa and Brook 1960; Bils et al. 1988; Shao and Krehbiel 1996). An IC flash consists of both an early (or active) stage and a late (or final) stage. The early stage consists of frequent large amplitude pulses as seen in electric field data, which is indicative of an upward moving negative leader propagating toward the positive region of the cloud. Once the negative leader reaches the positive region, the late stage commences. A bi-level breakdown process occurs where the leader connects the two charge regions and charge is rearranged within the cloud. The late stage coincides with a decrease in pulses as seen in electric field data. Pulses throughout the late stage are thought to be related to streamer activity within the cloud, or in other words, K-changes (Kitagawa and Brook 1960; Thottappillil et al. 1990).

Only one previous study mentions the possibility of continuing current presence during an IC flash (Proctor 1983). The study identifies a portion of the late stage of a single IC flash where an established IC channel had no recoil streamer activity and no extension of the channel. The lack of streamers and a pause in channel growth led to the conclusion of constant charge flow through the channel and, thus, continuing current presence. However, no further studies to date mention continuing current in relation to IC flashes, so it remains unclear if the late stage of an IC flash may contain current flow similar to current flow in a CG flash.
1.4 Relationship between Lightning and Wildfires

One of the main threats a CG flash poses to nature is the chance of initiating a wildfire. As a return stroke occurs, the resulting current flow can heat an object, such as a tree, past its combustion temperature. If a stroke is followed by a long continuing current, the tree would be exposed to a high temperature for a sufficient amount of time, thus igniting the tree (Rakov 2003).

Specifically, past research suggests that positive CG flashes may be the prime flash type to initiate forest fires (Fuquay et al. 1967, 1972). This is mainly due to positive CG flashes being linked to the production of continuing current. While it may be true that a positive CG flash is typically followed by continuing current, similar research presented data where negative CG flashes initiated the majority of forest fires (Flannigan and Wotton 1991; Duncan et al. 2010). It has been suggested in these studies that stroke multiplicity in a negative CG flash is an important factor in predicting wildfire initiation. A possible theory for the significance of stroke multiplicity is explained by Rakov and Uman (1990), which states negative CG strokes are more likely to contain continuing current if they are a subsequent stroke rather than the first stroke in a flash. However, a more recent study has found that neither polarity or a higher multiplicity is shown to initiate a wildfire with a higher probability (Pineda et al. 2014). It should be noted that none of the aforementioned studies include a continuing current metric when relating lightning to a fire initiation. Hence, there remains a hypothesis that continuing current presence and large charge trans-
fers heighten the chance of wildfire ignition due to lightning (Latham and Williams 2001).

Factors unrelated to lightning properties can also increase the probability that a CG flash may initiate a wildfire, such as atmospheric conditions, fuel moisture and type, and precipitation rates. Some studies investigated the trends of the dewpoint depression and temperature differences aloft, inferring that high instability and high dewpoint depressions promote conditions for wildfire potential (Rorig and Ferguson 1999, 2002). Further, precipitation presence and amounts are significant when determining fuel and surface moisture, which can greatly affect the chances for a fire ignition. Therefore, past research is apt to define dry lightning that makes a connection to the ground when little or no precipitation has fallen within a certain amount of time (Rorig and Ferguson 1999, 2002; Dowdy and Mills 2012). In addition, dry fine fuels, such as dead grass, leaves, and needles, are thought to play an important role in the probability of an ignition (Dowdy and Mills 2012). Although multiple atmospheric and surface elements can affect whether or not lightning can start a fire, the longevity of current flow during a CG also needs to be considered when determining which flash may have caused an ignition.

1.5 Motivation

Bitzer (2017) characterized all continuous optical emission as seen by LIS lasting at least 10 ms as continuing current flashes. Developing a more robust method to further filter out optical emission unrelated to continuing currents can allow for a more reliable method by decreasing the detection of false events. It also may seem
beneficial to include a ground-based network to be sure flashes characterized as continuing current indeed have continuous optical emission associated with CG flashes. However, creating a continuing current detection technique from solely space-based data, such as the Geostationary Lightning Mapper (GLM; Goodman et al. 2013), results in potential continuous detection of continuing current flashes over a larger field of view of both North and South America and surrounding oceans. A model of this type would create a continuing current probabilistic approach independent of ground-based networks. Additionally, remote areas where no ground-based sensors are present are still included within the GLM coverage.

The ability to include continuing current probabilities as an additional metric in predicting lightning-initiated wildfires is another advantage to this study. Continuing current is often mentioned when introducing a wildfire study, but it is rarely included when determining which flash may have initiated a wildfire from a population of flashes. This is often due to the fact that some type of ground-based network is used to match flashes to a given wildfire location, and the majority of these networks lack the capability to detect continuing current. Developing a method to match GLM flashes to wildfires can introduce a continuing current characteristic in the lightning-initiated wildfire prediction. In addition, the GOES-16 and GOES-17 satellites allow for additional data to be utilized within the same field of view. As a result, wildfire products can then be incorporated to further relate GLM flashes with continuing current to fires seen on satellite imagery.

This study aims to build a more robust continuing current detection method dependent on various optical attributes from GLM data. CG strokes that contain con-
tinuous optical emission in high speed video are utilized to confirm continuing current presence in electric field slow channel waveforms, and any continuous optical emission as seen from GLM are then characterized as continuing current based on current durations estimated the electric field waveforms. Once the model is developed, GLM flashes are then matched to satellite-detected wildfires from the Advanced Baseline Imager Level-2 Fire/Hotspot Characterization (FHC) product. Matched GLM flashes are ingested into the continuing current model and characterized as flashes with or without continuing current. A wide variety of spatial and temporal constraints are employed to optimize a continuing current metric when selecting GLM flashes that could have ignited a fire represented by a FHC pixel. Multiple GLM flashes may occur near a FHC pixel, and choosing simply the closest flash in space or time may not be an appropriate approach. Applying the continuing current model to GLM flashes that matched to a FHC pixel can aid in filtering out flashes with low continuing current probabilities, and thus, resulting in smaller population of candidate flashes that may have ignited a fire.
CHAPTER 2

THE DETECTION OF CONTINUING CURRENT IN LIGHTNING
USING THE GEOSTATIONARY LIGHTNING MAPPER

2.1 Introduction

A lightning flash typically contains discrete return strokes in which current flow lasts for hundreds of microseconds (Malan and Schonland 1951; Beasley et al. 1982; Rakov et al. 1990). However, the current in a return stroke may last for hundreds of milliseconds and is known as continuing current (Brook et al. 1962; Kitagawa et al. 1962). Continuous optical emission from a return stroke accompanies the continuing current flow as seen in various video recordings (Kitagawa et al. 1962; Shindo and Uman 1989; Ballarotti et al. 2005; Saba et al. 2006; Biagi et al. 2007). Lightning containing continuing current has been found to occur frequently in wintertime and nighttime storms (Goto and Narita 1995; Bitzer 2017). Since flashes with continuing current have been related to the initiation of forest fires (Fuquay et al. 1967; Latham and Williams 2001), it is advantageous to identify the presence of continuing current to enable decision makers and emergency personnel to potentially improve response times to lightning-initiated wildfires.
The majority of ground-based lightning detection networks have limited capabilities to detect continuing current. Very high frequency (VHF) sensing systems with frequencies around 60 to 66 MHz, such as lightning mapping arrays, are sensitive to fast in-cloud or CG breakdown and leader processes produced during channel development (Rison et al. 1999; Krehbiel et al. 2000; Thomas et al. 2000). The VHF impulses represent the time derivative of the current, where processes that occur have a quick surge in current. The peak intensity VHF impulse within an 80 µs window is modeled as a point source, where multiple sources over a span of hundreds of milliseconds can lead to a detailed spatial and temporal structure of a discharge. Due to mapping only the most intense VHF impulses, processes caught on lower frequencies, such as current flow, are missed. Very low frequency/low frequency (VLF/LF) networks with frequencies between 3 to 300 kHz that cover a larger domain, such as the National Lightning Detection Network (NLDN), can detect VLF/LF signals related to large transient currents that can propagate up to thousands of kilometers, including return strokes and K changes (Cummins and Murphy 2009); however, the VLF/LF frequencies coupled with baselines of 300-350 km affects the ability to retrieve the characteristic continuing current electric field waveform from a discharge (Cummins and Murphy 2009). Very low frequency/low frequency (VLF/LF) networks that are more sensitive with smaller baselines of tens of kilometers, such as the Huntsville Alabama Marx Meter Array (HAMMA; Bitzer et al. 2013), can capture the slow electrostatic change waveform associated with continuing current, but the sensors comprising the array typically cover an area of approximately 50 km across the domain. This limits the spatial domain up to roughly 50 km from the outermost sen-
sor before there is difficulty in identifying an electrostatic change in the electric field waveform (Lin et al. 1979; Shindo and Uman 1989). Magnetic field measurements, however, do have the capability to detect long-lived currents at ultra low frequencies (~0.1 to 200 Hz) up to 500-2000 km away from the sensors due to the magnetic field decay of $\frac{1}{r}$ versus the the electric field decay of $\frac{1}{r^3}$ (Cummer and Füllekrug 2001; Ross et al. 2008). These sensors could be used to detect continuing current across a larger spatial domain compared to a VLF/LF electric field change network, but measurements beyond roughly 2000 km from the outermost sensors would receive a weaker magnetic field signal and, thus, an unclear current signature in the magnetic field waveform. Many studies have used video recordings to determine continuing current presence by measuring the temporal length of continuous optical emission (Kitagawa et al. 1962; Shindo and Uman 1989; Ballarotti et al. 2005; Saba et al. 2006; Biagi et al. 2007). However, relying solely on ground-based high speed video observations to identify continuing current limits the spatial domain to tens of kilometers around the camera. Developing a method to detect continuing current using a space-based optical sensor, such as the Geostationary Lightning Mapper (GLM; Goodman et al. 2013), grants continuous hemispheric coverage for continuing current detection over a larger field of view.

There has been previous work that attempted to detect continuing current in lightning using a space-based optical sensor. Specifically, data from the Lightning Imaging Sensor (LIS; Christian et al. 1992), aboard the Tropical Rainfall Measuring Mission satellite, has shown that 11.2% of LIS flashes contain continuing current, assuming that all optical emission that lasted 10 ms or longer (or roughly five
LIS groups) was indicative of continuing current presence (Bitzer 2017). However, other optical properties collected by space-based instrumentation, such as total optical energies and optical areas, to refine continuing current identification were not explored. This work supported the notion that although oceanic, wintertime, and nighttime storms tend to exhibit lightning less frequently compared to land-based, summertime, and daytime storms, lightning in these types of storms are more likely to contain flashes with continuing current.

This study focuses on developing a more robust method of predicting continuing current presence within satellite-based optical data so no additional lightning detection systems are required. To achieve this goal, various ground-based networks are utilized to construct a data set consisting of lightning strokes and their estimated current durations. Continuous optical emission durations in cloud-to-ground (CG) strokes are measured using high speed video recordings, and the optical emission durations are compared to simultaneous electric field waveforms to confirm the presence of the characteristic slow electrostatic change during the continuous luminosity. Identifying the electrostatic continuing current signature in electric field data allows for the characterization of continuing current strokes on days GLM data are available. GLM data with optical emission present during the slow electrostatic change in the electric field are then saved, and GLM attributes describing continuous optical emission within a GLM flash are ingested into a logistic regression model. Results and applications for this particular continuing current model are then discussed.
2.2 Instrumentation and Methods

2.2.1 High Speed Video

A Photron SA-X2 with an 18 mm or 28 mm lens was used to record flashes between 29 April 2014 and 19 September 2017, and a total of 50 CG strokes were utilized from the recorded flashes. Frame rates ranged from 12 500 fps to 40 000 fps. For the purpose of capturing discharges with continuous optical emission that may last for hundreds of milliseconds, frame rates of 12500 fps were sufficient to record continuing currents with a time resolution of 80 $\mu$s while frame rates faster than 40 000 fps were not necessary. To be considered for analysis, each video was required to contain a visible channel with the total amount of light being emitted in its entirety and a clear connection to ground.

All videos in this study were recorded in the cupola of the National Space Science and Technology Center (NSSTC) on the University of Alabama in Huntsville (UAH) campus. There was about a 270 degree clear field of view of the west, north, and east of the building with a limited view of the south. Once a flash occurred, a trigger system consisting of a simple photodiode detected the presence of light which was deemed the “trigger time.” Prior to the trigger time, a fixed number of frames were saved, while the remaining number of frames after the trigger time were dependent on a user-selected resolution and frame rate. Additionally, a GPS IRIG system was connected to the camera to obtain accurate UTC timing of each frame to one microsecond.
The videos were analyzed frame-by-frame to determine the total duration of channel luminosity. First, the pixels in each frame were totaled and plotted with time to create a light curve, as shown in an example flash in Figure 2.1(a). The frame consisting of a return stroke will typically contain many bright pixels, and therefore, manifests as the local maxima in the light curve, e.g., at approximately 29 ms in Figure 2.1(a). The brightest frame after the connection to ground was considered to be the initial time of the current; however, this assumption will slightly underestimate the actual current duration since the initial time of current will occur when the leader makes a connection to the ground. Next, the total pixel values in each frame prior to any luminous stepped leader processes leading up to the return stroke were averaged and labeled as the background. To determine the final time of the optical emission from the channel, the post return stroke frames were split into 8 ms segments, and the total pixel values in each segment were averaged. Once an 8-ms segment reached the background threshold, the segment was split into even smaller segments until an approximate time of where the curve returned to the averaged background threshold (e.g., the final time of the current) was determined. In Figure 2.1(a), the light curve reached the final time of the current at around 197 ms; hence, the estimated total current duration was about 168 ms. Although the light curve approached the background threshold around 80 ms, the channel illuminated again after this time. A surge in current and luminosity has been observed to periodically occur following a return stroke with continuing current, termed an M-component (Malan and Schonland 1947). To recognize an M-component optically, the initial brightness of the return stroke tends to fade, and within about 15 ms of the initial field peak of the return
stroke (Thottappillil et al. 1990), the channel reilluminates. The brightening of the channel indicates an increase in charge transferring through the channel due to fast negative breakdown within the cloud (Mazur et al. 1995).

### 2.2.2 Huntsville Alabama Marx Meter Array (HAMMA)

HAMMA is comprised of VLF/LF ground-based electric field change meters sensitive to frequencies between 1 Hz and 400 kHz with baselines of ~15 km (Bitzer et al. 2013). A time constant of 100 ms is chosen to allow for measurements at the lower end of the frequency range while still retrieving radiation of higher frequencies. Specifically, HAMMA is capable of capturing both the electrostatic and radiation...
components of the electric field. Hence, simultaneous analysis of both charge movement and time rate of change of the current of a discharge is possible. In addition, HAMMA is roughly centered around the NSSTC, which makes it possible to easily compare data with the high speed video.

To identify continuing current following a return stroke in a VLF/LF waveform, a slow electric field change of the same polarity as the return stroke occurs for up to hundreds of milliseconds, representing steady charge flow during this time (Kitagawa et al. 1962; Livingston and Krider 1978; Shindo and Uman 1989). The time between the return stroke and the point in the waveform where the slope becomes consistently very close to zero can be used to estimate the total duration of the continuing current (Lapierre et al. 2014). Prior to analysis, HAMMA data was “dedrooped” (Sonnenfeld et al. 2006) to remove the instrument response on the data, as well as to display a summation of the signal response assuming the time of the first data point is zero. Additionally, observing HAMMA data in this manner reveals a clearer distinction between the slow, steady change during current flow and no charge movement (e.g., a near-zero slope of the electric field). To compare the total optical emission durations from high speed video to the electrostatic change from HAMMA, a linear fit approach similar to Lapierre et al. (2014) was conducted on each available “dedrooped” HAMMA waveform to estimate the continuing current length. Specifically, the linear fit of the interstroke interval was calculated, and the resulting time where the HAMMA waveform was within 0.1% of the linear fit was labeled as the final time of the continuing current duration. For example, the electrostatic change for the positive CG flash in Figure 2.1(b) reaches a near-zero slope as the charge
ceases to flow around the same time as the light curve in Figure 2.1(a) approaches the background threshold and less light is being emitted from the channel. Note that the linear fit approach appears to overestimate the current duration in relation to the light curve in this example.

Each of the 50 CG strokes captured on high speed video were chosen since HAMMA data were also available during each stroke. The data from the closest HAMMA sensor to the stroke without a saturated signal was selected for evaluation since the electrostatic component of the electric field decays with distance $\frac{1}{r^3}$ Lin et al. (1979); Shindo and Uman (1989). NLDN stroke-level data were used to provide an approximate location of each CG stroke since NLDN detects CG strokes of either polarity with a detection efficiency of 60-80% and a median location error of approximately 0.5 km (Cummins and Murphy 2009). The distance between each sensor and CG stroke were then able to be estimated.

Current durations estimated from optical emission in high speed video and the electrostatic change from HAMMA have a correlation of 0.95 (Figure 2.2). The high correlation value suggests that estimating the length of continuing current in a stroke using either method is comparable. Past results from Saba et al. (2006) support that a correlation of this magnitude is to be expected for continuing current longer than 100 ms. The current durations estimated from the electric field tend to be longer than those from high speed video, especially when durations are below $\sim$40 ms. Saba et al. (2006) also investigated short continuing currents between 10 to 40 ms and very short continuing currents below 10 ms, stating that either method is appropriate for short and long continuing currents greater than 10 ms, but high speed video may be better
suited for estimating very short continuing current below 10 ms. This study found a correlation of 0.95 between the 34 strokes with both estimated current and luminosity durations above 10 ms; however, a correlation of -0.27 was calculated between the 4 strokes with both electric field and high speed video durations below 10 ms. Although the sample size for very short continuing currents was small, it still agrees with the previous study that high speed video may be better suited for estimating very short continuing currents due to the lack of a clear slow field change in the electrostatic with very short currents.

2.2.3 Geostationary Lightning Mapper (GLM)

The GLM (Goodman et al. 2013) is a space-based optical sensor that was recently launched on the GOES-16 and GOES-17 satellites, and its 1372 x 1300 pixel charge-coupled device (CCD) focal plane records transient optical pulses at the 777.4 nm neutral oxygen emission line triplet (Christian et al. 1989) continuously over the western hemisphere. Optical emission can be detected at any time of day throughout the field of view. The spatial resolution varies from about 8 km at nadir to 14 km near the edge of the field of view. To be considered a lightning event, an illuminated pixel must exceed a variable background difference threshold. This accounts for a varying background signal and has been utilized as a measurement approach on the LIS (Christian et al. 1992).

Once a pixel exceeds the background difference threshold and passes several noise filters, the total amount of optical energy over a ~2 ms time frame is termed an event. Events that are adjacent to each other within the same frame comprise a
Figure 2.2: A scatterplot of continuing current durations as seen from high speed video and durations estimated from HAMMA waveforms with $N = 50$ and $R = 0.95$. The red line represents the 1:1 line for reference.

group. Groups that occur within a particular set of temporal and spatial constraints are clustered together to make up a flash. The current GLM operational Lightning Cluster-Filter Algorithm (LCFA) sorts groups within 330 ms in time and 16.5 km in space using the weighted Euclidean distance between groups into a flash (Goodman et al. 2010, 2013). Flashes represent a series of optical pulses and processes that provides an initial basis for relating optical emissions and various storm energetics Peterson et al. (2018); Peterson and Rudlosky (2019). Analyzing multiple groups
within a flash may lead to a deeper understanding of optical processes that last longer than a 2-ms group but shorter than the total flash duration, such as gigantic jets (Boggs et al. 2019), leader processes (Peterson 2019), and continuing currents (Bitzer 2017).

Since previous work utilized LIS data to characterize flashes with continuing current (Bitzer 2017), comparing the limitations of both the LIS and GLM should be discussed. First, the LIS (Christian et al. 1992) had a 128 x 128 CCD focal plane that recorded transient optical pulses over a field of view of roughly 600 km x 600 km and a pixel resolution of about 4.5 km. The LIS had a low-earth orbit which resulted in an observing time of ~90 s at a given point on the earth’s surface and total coverage included the areas between latitudes -35° to 35°. The key differences between the LIS and GLM instruments are the spatial resolution of the pixels and the total area within each respective field of view. The GLM has continuous hemispheric coverage due to being in geostationary orbit, but the smallest pixel sizes are roughly double the size of a LIS pixel. The LIS being in low-earth orbit results in smaller pixel sizes while viewing a particular point on Earth for only ~90 s. Pixel sizes up to roughly 14 km along the edge of GLM’s field of view could result in smaller lightning processes that exceed the background threshold to illuminate a single large pixel, while the same small lightning process that exceeds the LIS background threshold could illuminate a single LIS pixel of about 4.5 km. The differences in the spatial resolution may affect the resulting footprint during continuous optical emission. For example, a GLM flash that illuminates two GLM pixels on the edge of the field of view would have a footprint of roughly 28 km, yet the LIS could potentially see the same lightning
discharge propagate across approximately seven LIS pixels. Further, continuous optical emission in LIS may last longer due to the smaller spatial resolution, potentially retaining pixels that exceed the background threshold at a smaller spatial scale that GLM would be unable to detect within its larger pixel area. However, it should be noted that less frames are included to determine the variable background threshold in LIS compared to GLM. This provides a chance for GLM to catch dimmer and spatially smaller optical processes that occur within its larger pixel area. A small, optically bright discharge detected by LIS but not detected by GLM would likely consist of a temporally short, optically energetic flash within a pixel area of roughly 4.5 km that would not be bright enough to surpass GLM’s background threshold.

The GLM operational LCFA Level-2 flash-level data consists of a variety of fields including initial and final flash times, latitude and longitude for flash centroid, flash identifier, total number of groups within the flash, flash footprint, total flash optical energy, and flash quality flag. While the fields describe the flash spatial, temporal, and optical properties, the flash quality flag field reports a potential issue may have occurred in sorting the flash, where each flash has a “good” or “degraded” quality flag. There are three instances where a GLM flash would be considered degraded. In particular, if a flash is comprised of events that may be out of order temporally, comprised of more than 101 groups, or exceeds a duration of 2,998 ms, the flash will be labeled as degraded (Goodman et al. 2010; GOES-R Series Program Office 2017; Peterson 2019). This presents an issue where ongoing flashes may be artificially split due to these fixed constraints. Flashes containing a degraded flag are
likely part of a bigger flash, where the actual flash is longer temporally than reported in the operational data.

The previous comparison between high speed video and electrostatic measurements show that when a visible channel connecting to the ground exhibits continuous optical emission, continuing current is simultaneously occurring; however, time-contiguous GLM groups are not necessarily always related to continuous current flow to the ground. For instance, take the beginning of an intracloud (IC) flash as shown in Figure 2.3. There are frequent large amplitude pulses at the start of the flash in Figure 2.3(a), which is indicative of the early (or active) stage of an IC flash (Bils et al. 1988). This early stage is associated with 21 time-contiguous GLM groups in Figure 2.3(b), so ongoing optical emission occurs for \( \sim 42 \text{ ms} \). In the early stage of an IC, the frequent radiation pulses in the electric field represent an upward moving negative leader propagating toward the positive region that establishes an upward channel prior to bi-level breakdown (Bils et al. 1988; Shao and Krehbiel 1996). Since the upward moving negative leader has not yet made a connection to the positive region of the cloud, it can be assumed that there is no steady current flow during the continuous optical emission as seen by GLM during the early stage of an IC flash. One previous study attempted to relate IC flashes and continuing current (Proctor 1983), where the IC channel contained no recoil streamers and was not extended during the continuing current. However, it remains unclear if current flow in the final stage of IC flashes is of similar nature to continuing currents in channels connecting to the ground. This study considers time-contiguous GLM groups associated with an initial IC leader to not be continuing current.
Figure 2.3: (a) HAMMA waveform, (b) GLM groups plotted with time, and (c) a zoomed-in portion of the pulses associated with IC leader activity within the red box in plot (a) of an IC flash from 27 April 2017 at 06:55:55 UTC. Note that plot (b) contains a logarithmic scale on the y-axis.

Within a GLM flash, optical emission that lasts for many consecutive frames may be temporally limited due to the way GLM detects an optical event, a limitation that also applied to LIS (Christian et al. 1992; Bitzer 2017). The estimated background is determined by continuously averaging the CCD output from the previous several frames (GOES-R Series Program Office 2017). When there is a constant source of light, each frame increases the averaged background estimate, resulting in a higher background difference threshold the signal from an illuminated pixel must pass. Once the background difference threshold is raised high enough, the optical signal would no longer be considered a potential lightning event as the signal would be too low. Therefore, GLM may underestimate the duration of the continuous optical emission, although it should be noted that GLM is less likely to “self-quench” than LIS since GLM uses more frames to estimate background than LIS.
2.3 Results and Discussion

2.3.1 Predicting Continuing Current

Data were collected during the GLM Calibration and Validation Field Campaign in which HAMMA and GLM data from the GOES-16 satellite were readily available. A total of 288 CG strokes on 22 April 2017 and 27 April 2017 representing current duration estimations ranging from 0.5 ms to 417.2 ms were collected, where at least one GLM group was associated with each CG stroke. Continuing current processes should be well represented in the data set despite the CG strokes only being collected over a span of two days due to the large number of discharges that occurred on both days. In order to remain confident that the electrostatic component evident in the electric field waveform is related to the stroke of interest, all strokes chosen for analysis were confirmed by hand to be characterized as CG and isolated over the HAMMA domain (i.e., no other simultaneous lightning activity occurring nearby). Stroke locations were estimated using NLDN, and any NLDN strokes 50 km or beyond a HAMMA sensor were not included in the analysis. There were also 78 initial upward leaders during the active stage of IC flashes that were categorized as not having continuing current. GLM groups associated with IC flashes during the final stage were not considered in the as a relationship between IC flashes and continuing currents have not been confirmed. The maximum number of time-contiguous GLM groups associated with each stroke and initial IC leader were then manually collected. GLM groups that occurred between the return stroke pulse and the following return stroke pulse, or the end of electrostatic change, were considered for each stroke, and
GLM groups occurring during the initial IC pulses were collected. In the instance where multiple sets of the same number of time-contiguous GLM groups were associated with a stroke or IC leader, where GLM events did not reach the background difference threshold for at least one frame between the sets of GLM groups, the first set of GLM groups in time was chosen for analysis in an attempt to gather the GLM groups that were temporally closest to the return stroke or IC leader.

A variety of GLM attributes were calculated from each set of time-contiguous GLM groups within the 366 manually classified CG strokes and initial IC leaders. Some GLM attributes were found to be highly correlated (with values of 0.80 or higher) with the maximum group optical energy, including mean group optical energy, standard deviation group optical energy, difference between maximum and minimum group optical energies, and total optical power. To avoid redundancy, maximum group energy was retained while the remaining highly correlated parameters were no longer included as inputs to the model.

Utilizing a multiple logistic regression model, the probability that continuing current may occur within a particular flash is calculated depending on each coefficient and predictor. In this case, predictors are the variety of GLM attributes calculated for each maximum set of time-contiguous groups within a GLM flash (e.g., the first column in Table 2.1). The CG strokes were labeled as having continuing current or not having continuing current based on the estimated electric field durations, while initial IC leaders were labeled as no continuing current. In this study, continuing current was defined to have an estimated current duration of 10 ms or greater. Since GLM may underestimate the total continuous optical emission duration, there may be instances
Table 2.1: The GLM group attributes collected for the logistic regression model. A scale factor to normalize each GLM attribute prior to any calculation and their coefficient values are shown.

<table>
<thead>
<tr>
<th>GLM Attribute</th>
<th>Scale Factor</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Distance between Two Groups</td>
<td>—</td>
<td>0.1412</td>
</tr>
<tr>
<td>Maximum Group Footprint</td>
<td>$10^{-1}$</td>
<td>0.0022</td>
</tr>
<tr>
<td>Maximum Group Optical Energy</td>
<td>$10^{15}$</td>
<td>0.0435</td>
</tr>
<tr>
<td>Maximum Number of Contiguous Groups</td>
<td>—</td>
<td>-0.1344</td>
</tr>
<tr>
<td>Median Group Optical Energy</td>
<td>$10^{15}$</td>
<td>-0.0545</td>
</tr>
<tr>
<td>Total Group Optical Energy</td>
<td>$10^{15}$</td>
<td>-0.0001</td>
</tr>
<tr>
<td>Intercept</td>
<td>—</td>
<td>-1.9408</td>
</tr>
</tbody>
</table>

where strokes that contain continuing current may only contain one or two GLM groups. A typical return stroke with no continuing current (e.g., current durations less than 3 ms) may also contain a maximum of one or two GLM groups due to the 2 ms frame integration and the light potentially splitting across two frames (Bitzer and Christian 2014). To be confident that the logistic regression was trained with strokes properly characterized as having continuing currents, very short continuing current strokes (e.g., current durations between 3 and 10 ms (Saba et al. 2006; Lapierre et al. 2014)) were considered as strokes with no continuing current since estimating very short current durations were shown to be better suited using high speed video rather than electric field measurements. Therefore, the model was trained by characterizing current durations of 10 ms or greater as continuing current.

Some statistics were determined to gain a better understanding of the differences in the GLM attributes between the 152 CG strokes with continuing current (e.g., current durations longer than 10 ms) and 72 IC leaders Table 2.2 since both distributions tend to exhibit continuous optical emission in GLM data. On average,
continuous optical emission within CG strokes with continuing current have a larger maximum GLM group footprint, cover a larger distance, and have higher optical energies than continuous optical emission associated with initial IC leaders.

The data set was split in half to create both a training and testing subset, where each subset consisted of a combination of 183 CG strokes and IC leaders. Depending on the GLM attribute, a scale factor was applied to normalize the GLM attribute values to ensure they were of the same order. The coefficients for the multiple logistic regression model from the training subset are listed in Table 2.1. The intercept represents the odds ratio of continuing current if every GLM attribute were to equal zero. Since a GLM flash will always contain at least one group equating to non-zero GLM attributes, the intercept effectively has no meaning. Each coefficient value ultimately affects the probability of continuing current, where a positive coefficient value with a larger magnitude increases the chance of a higher probability of continuing current, and a negative coefficient with a larger magnitude increases the chance of a lower probability of continuing current. In this case, the maximum distance between two GLM groups and the maximum number of time-contiguous GLM groups both greatly affect the probability of continuing current. The maximum distance between two GLM groups is the best single predictor for a high continuing current probability within a GLM flash, while the maximum number of time-contiguous GLM groups is indicative of a lower probability of continuing current. While a higher number of time-contiguous GLM groups seems like an ideal single predictor for continuing current, other sub-flash processes, such as those that occur during an IC flash, are also associated with several time-contiguous GLM groups. About 31.5% of the continuing
Table 2.2: The mean, median, and standard deviation values of the GLM group attributes calculated from the maximum length of optical emission within each of the 152 CG strokes with continuing current and 78 initial IC leaders.

<table>
<thead>
<tr>
<th>GLM Attribute</th>
<th>CG Strokes with Continuing Current</th>
<th>Initial IC Leaders</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Median</td>
</tr>
<tr>
<td>Maximum Number of Time-Contiguous Groups</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Maximum Distance between Two Groups (km)</td>
<td>11.3</td>
<td>8.1</td>
</tr>
<tr>
<td>Maximum Group Footprint (km$^2$)</td>
<td>924</td>
<td>882</td>
</tr>
<tr>
<td>Maximum Group Optical Energy (J)</td>
<td>$3.14 \times 10^{-13}$</td>
<td>$1.44 \times 10^{-13}$</td>
</tr>
<tr>
<td>Median Group Optical Energy (J)</td>
<td>$2.88 \times 10^{-14}$</td>
<td>$1.89 \times 10^{-14}$</td>
</tr>
<tr>
<td>Total Group Optical Energy (J)</td>
<td>$1.02 \times 10^{-12}$</td>
<td>$3.82 \times 10^{-13}$</td>
</tr>
</tbody>
</table>
current strokes (i.e., with current durations of 10 ms or more) used to train the model are accompanied by less than five time-contiguous groups, which affects the maximum number of time-contiguous GLM groups coefficient.

The calculated coefficients were then applied to the test data set, and the probability that a particular set of time-contiguous groups within a GLM flash contains continuing current was calculated. A receiver operating characteristic (ROC) curve was used to determine an optimal threshold to consider which resulting probabilities were deemed as having continuing current (Figure 2.4). Although utilizing a lower threshold, such as 0.125, as the threshold provided a high probability of detection (POD) of 96%, the probability of false detection (e.g., false alarm rate; FARate) was rather high at 76%. This threshold may have caught all of the continuing current flashes, but the FARate indicated many flashes being incorrectly predicted as having continuing current. As shown in Figure 2.4, higher thresholds until ~0.33 may be chosen while retaining a fairly high POD around 0.80 and a lower FARate between 5% and 10%. Using 0.33 as the threshold, as seen in Table 2.3, reveals a POD of approximately 78% was attained while decreasing the FARate to 6%. Further, utilizing higher thresholds lower the FARate even more, but the POD decreases at a much faster rate at thresholds higher than 0.33. For example, setting 0.50 as a threshold lowered the POD to around 71% while the FARate decreased to about 5%. An appropriate threshold can be chosen depending on a given application. Since a higher threshold would lower the amount of false alarms, it could be ideal to use for climatologies to be sure no flashes with a low probability of continuing current are
Figure 2.4: A ROC curve for various thresholds from the test subset. The “no skill” line is shown in red. The square, star, and diamond represent the 0.125, 0.33, and 0.50 thresholds, respectively.

included in an analysis; however, a lower threshold may be optimal for operational use to gain confidence that flashes that have continuing current are minimally missed.

2.3.2 Applications

There were 379,160,390 total flashes detected by GLM in 2018, and of these, 365,337,632 flashes (96.3%) were not flagged with a degraded quality flag. To remain consistent with the ROC analysis, it was assumed that flashes with continuing cur-
Table 2.3: Contingency table where $N = 183$ and probabilities greater than or equal to 0.33 are considered to be continuing current flashes. Statistics include percent correct ($PC$) = 0.8743, false alarm rate ($FARate$) = 0.0577, false alarm ratio ($FARatio$) = 0.0882, probability of detection ($POD$) = 0.7848, and critical success index ($CSI$) = 0.7294.

<table>
<thead>
<tr>
<th></th>
<th>Observed Continuing Current</th>
<th>Observed No Continuing Current</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Continuing Current</td>
<td>62</td>
<td>6</td>
<td>68</td>
</tr>
<tr>
<td>Predicted No Continuing Current</td>
<td>17</td>
<td>98</td>
<td>115</td>
</tr>
<tr>
<td>Total</td>
<td>79</td>
<td>104</td>
<td>183</td>
</tr>
</tbody>
</table>

Current had an estimated probability of 0.33 or higher. There were 53,640,665 flashes (14.2%) of the total flashes detected by GLM that contained continuing current, while 48,483,409 flashes (13.3%) of the flashes not labeled as degraded were characterized as continuing current flashes. Results where GLM flashes with a degraded quality flag were included introduces the issue where a temporally larger flash artificially split into multiple flashes may be counted more than once, and therefore, may be counted as a continuing current flash several times. To prevent this, results herein do not include degraded quality flag flashes.

Figure 2.5 shows the flashes that contain continuing current binned into $1^\circ \times 1^\circ$ bins. It should be noted that the majority of the flashes with degraded quality flags reside along the edges of the GLM field of view. Areas with relatively high counts of flashes with continuing current include northern South America, regions of Central America, and along the western coast of Mexico. Most of these listed regions agree with past results with LIS (Figure 4; Bitzer 2017); however, the continuing current hot spot off of the eastern coast of North America is not as apparent using GLM. To investigate further, a select random sample area within this region was chosen, and
Figure 2.5: Distribution of flashes with continuing current in 2018 within the GLM field of view. Bins that contain less than 500 flashes with continuing current are not included. GLM flashes with a degraded quality flag are also not included.
GLM flashes with more than five time-contiguous groups were gathered and sorted between those with and without continuing current. Although GLM flashes with five or more time-contiguous groups occur in this region (i.e., the GLM flashes exhibit continuous optical emission similar to LIS flashes), the remaining GLM attributes utilized in the continuing current model are generally smaller compared to flashes that contain continuing current in this same region Table 2.4. Flashes occurring off of the eastern coast of North America with five or more time-contiguous groups, small distances between groups, small optical energies, and small optical footprints compared to the distributions between confirmed CG strokes with continuing current and initial IC leaders suggests that these flashes may be associated mainly with initial IC leaders rather than CG strokes with continuing current.

To gain a better idea of the frequency of continuing current flashes, the ratio of continuing current flashes to total flashes in each $1^\circ \times 1^\circ$ bin is calculated. Again, Figure 2.6 shows trends generally similar to previous continuing current work (Figure 6; Bitzer 2017), where the highest continuing current ratios are present over oceanic areas. This further supports that flashes that occur over the ocean are more likely to contain continuing current relative to flashes over land. Although the trends appear similar, the actual ratio values are approximately 30% smaller than previously reported with LIS. Applying the same methodology as Bitzer (2017) to the GLM flashes in 2018 yielded 88,126,089 (24.1%) of flashes not labeled as degraded contained five or more time-contiguous groups. Since the logistic regression model incorporates more optical properties than just the number of time-contiguous groups within each flash, and any continuous optical emission associated with IC activity is
Table 2.4: The mean, median, and standard deviation values of the GLM group attributes from flashes with (N = 91,809) and without (N = 343,001) continuing current that have five or more time-contiguous groups within the sample area off of the eastern coast of North America in 2018.

<table>
<thead>
<tr>
<th>GLM Attribute</th>
<th>Continuing Current</th>
<th></th>
<th>No Continuing Current</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Median</td>
<td>St. Dev.</td>
<td>Mean</td>
</tr>
<tr>
<td>Maximum Number of Time-Contiguous Groups</td>
<td>11</td>
<td>9</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Maximum Distance between Two Groups (km)</td>
<td>9.5</td>
<td>6.3</td>
<td>8.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Maximum Group Footprint (km²)</td>
<td>659</td>
<td>493</td>
<td>512</td>
<td>236</td>
</tr>
<tr>
<td>Maximum Group Optical Energy (J)</td>
<td>$1.37 \times 10^{-13}$</td>
<td>$8.70 \times 10^{-14}$</td>
<td>$2.01 \times 10^{-13}$</td>
<td>$2.13 \times 10^{-14}$</td>
</tr>
<tr>
<td>Median Group Optical Energy (J)</td>
<td>$2.04 \times 10^{-14}$</td>
<td>$1.37 \times 10^{-14}$</td>
<td>$2.36 \times 10^{-14}$</td>
<td>$1.27 \times 10^{-14}$</td>
</tr>
<tr>
<td>Total Group Optical Energy (J)</td>
<td>$3.61 \times 10^{-13}$</td>
<td>$1.91 \times 10^{-13}$</td>
<td>$5.32 \times 10^{-13}$</td>
<td>$7.06 \times 10^{-14}$</td>
</tr>
</tbody>
</table>
deemed as not continuing current when training the model, the results include less continuous optical emission associated with IC flashes. This explains why the GLM logistic regression model estimates lower ratios of continuing current flashes relative to flashes with at least five time-contiguous groups. It should be noted that some GLM artifacts are not mitigated by filtering out GLM flashes labeled with degraded quality flags in Figure 2.6. Specifically, the box-like area with lower continuing current ratios streaking east of the Bahamas represents artifacts caused by the boundaries of the GLM CCD subarrays known as Real Time Event Processors. Since these artifacts do not appear in Figure 2.5, the total number of GLM flashes in these areas increase, are not labeled as continuing current, and therefore affect the continuing current ratio in each bin. Hence, the small ratios east of the Bahamas have many GLM flashes occurring within this boundary relative to the surrounding areas. Solar artifacts, such as glint and solar intrusions, and flashes with larger event pixels off nadir are also apparent over oceanic areas along the edges of the GLM field of view. There are both very high and very low continuing current ratios on the edges over both the Atlantic Ocean and Pacific Ocean. Although excluding flashes with a degraded quality flag should minimize flashes associated with solar artifacts, flashes that typically occur at the end of the artifact detection that do not exceed the quality flag artificial thresholds will not be flagged as degraded. The solar artifacts are very apparent in Figure 2.6 since they occur in areas with little to no lightning, and excluding bins with less than 500 total GLM flashes eliminates most of the artifacts on the edges of the field of view.
Figure 2.6: The ratio of continuing current flashes to total flashes using GLM in 2018. Bins with less than 100 total flashes are not included. GLM flashes with a degraded quality flag are also not included.
The seasonal variation of flashes with continuing current and all flashes seen by GLM in 2018 are explored. A subset of flashes within a spatial domain between latitudes 30° to 45° and longitudes -115° to -80° are collected to represent the seasons in North America, similar to Bitzer (2017). As seen in me GLM artifacts are not mitigated by filtering out GLM flashes labeled with degraded quality flags in Figure 2.7, the trend in flashes with continuing current are comparable to (Figure 7; Bitzer 2017). The percentage of continuing current flashes is higher during the North American winter months while frequency of flashes with no continuing current is low. In contrast, the frequency of flashes with no continuing current peaks during the North American summer months, and the percentage of flashes with continuing current is low. However, due to LIS being positioned in low-Earth orbit with an observation time over each area of about 90 s (Christian et al. 1992), temporal resolutions finer than a monthly scale could not be used. Since the GLM continuously monitors the western hemisphere, a finer time scale could be implemented. A biweekly averaging was chosen to minimize noise apparent in finer temporal scales.

The diurnal variation of GLM flashes with and without continuing current shows similar trends to that of LIS (Figure 8; Bitzer 2017); however, there are a few key dissimilarities due to the different approaches in continuing current detection. As seen in Figure 2.8, flashes with continuing current peak during both nighttime and daylight hours, as does flashes with no continuing current. Results from LIS show that more flashes with continuing current occur during nighttime hours rather than during day. At first glance, Figure 2.8 reveals the opposite since the peak in flashes with continuing current during the daylight hours is larger than during the
nighttime; however, the ratio of continuing current flashes to total flashes remains higher at night than during the daytime, which agrees with the result from LIS where a flash occurring at night is more likely to have continuing current.

### 2.3.3 Discussion

Accounting for optical properties other than the length of the continuous optical emission within a GLM flash improves the confidence that continuing current is being detected rather than a different sub flash process, such as an initial IC leader. Applying the same methodology as Bitzer (2017) to the GLM data set results in
Figure 2.8: Flashes with continuing current (solid) and flashes with no continuing current (dashed) as seen by GLM converted to local hour. The flashes with no continuing current are scaled down by a factor of 6. GLM flashes with a degraded quality flag are not included.

24.1% of GLM flashes contain five or more time-contiguous groups. A much higher percentage using the same methodology suggests that simply labeling all continuous optical emission as continuing current can likely lead to an overestimation of the number continuing current flashes. Additionally, continuing current flashes where GLM detects only a portion of the continuous optical emission that lasts less than 10 ms (i.e., less than five time-contiguous groups) can still be assigned a continuing current
Table 2.5: The GLM group attributes collected for the logistic regression model for CG strokes only. A scale factor to normalize each GLM attribute prior to any calculation and their coefficient values are shown.

<table>
<thead>
<tr>
<th>GLM Attribute</th>
<th>Scale Factor</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Distance between Two Groups</td>
<td>—</td>
<td>0.1688</td>
</tr>
<tr>
<td>Maximum Group Footprint</td>
<td>$10^{-1}$</td>
<td>-0.0005</td>
</tr>
<tr>
<td>Maximum Group Optical Energy</td>
<td>$10^{15}$</td>
<td>0.0213</td>
</tr>
<tr>
<td>Maximum Number of Contiguous Groups</td>
<td>—</td>
<td>1.1832</td>
</tr>
<tr>
<td>Median Group Optical Energy</td>
<td>$10^{15}$</td>
<td>0.0074</td>
</tr>
<tr>
<td>Total Group Optical Energy</td>
<td>$10^{15}$</td>
<td>-0.0085</td>
</tr>
<tr>
<td>Intercept</td>
<td>—</td>
<td>-3.3601</td>
</tr>
</tbody>
</table>

probability using the model. Flashes of this nature account for roughly 37.9% of the continuing current flashes detected by GLM in 2018.

A POD of approximately 78% with a low FARate of about 6% provides confidence that continuing currents are being detected without relying on any supplemental data, such as flash type classification or electrostatic measurements. This can be helpful for lightning that occurs in remote areas and locations where ground-based networks have little to no coverage. It can be speculated that the continuing current model can be performed on retrieved data from the GLM aboard the GOES-17 satellite, which covers much of the Pacific Ocean, as well as an overlapping view of the Pacific Northwest in North America with the GOES-16 GLM. However, if there is knowledge of the flash classification prior to training a logistic regression model (i.e., it is known that flash is a CG or an IC), then the skill of the model to detect continuing current slightly improves. Utilizing the 288 manually classified CG strokes from the original data set and training a multiple logistic regression model on 144 of these CG strokes, the coefficients of each GLM attribute shift with the maximum
Table 2.6: Contingency table for CG strokes only, where \( N = 144 \) and probabilities greater than or equal to 0.63 are considered to be continuing current flashes. Statistics include percent correct \((PC) = 0.8819\), false alarm rate \((FARate) = 0.0400\), false alarm ratio \((FARatio) = 0.0517\), probability of detection \((POD) = 0.7971\), and critical success index \((CSI) = 0.7639\).

<table>
<thead>
<tr>
<th></th>
<th>Observed Continuing Current</th>
<th>Observed No Continuing Current</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Continuing Current</td>
<td>55</td>
<td>3</td>
<td>58</td>
</tr>
<tr>
<td>Predicted No Continuing Current</td>
<td>14</td>
<td>72</td>
<td>86</td>
</tr>
<tr>
<td>Total</td>
<td>69</td>
<td>75</td>
<td>144</td>
</tr>
</tbody>
</table>

number of time-contiguous groups becoming the largest coefficient (Table 2.5). The remaining GLM attributes remain in the model, but the coefficients do not provide nearly as much weight as the maximum number of time-contiguous groups. Further, a contingency table for this model using 0.63 as the threshold to distinguish between predicted strokes with and without continuing current reveals a prediction with approximately 4% of false alarms while retaining a high POD of about 80% (Table 2.6). As with the previous model, an optimal threshold is chosen to retain a high POD with a low FARate, where 0.63 provides ideal percentages for model performance statistics. However, there is a slightly lower POD of around 72% with no false alarms when simply categorizing CG strokes with five or more time-contiguous groups as continuing current Table 2.7.

Although there is no known method in which GLM can classify individual flashes as CG or IC, matching GLM flashes to ground-based networks that detect CG strokes and flashes can provide an opportunity to implement a CG-only continuing current model. Applications for this type of model include implementing a continuing current parameter in lightning-initiated wildfire analyses. Since a flash must be a CG
Table 2.7: Contingency table for CG strokes only, where N = 144 and flashes with a maximum of five or more time-contiguous groups are considered to be continuing current flashes. Statistics include percent correct (PC) = 0.8471, false alarm rate (FARate) = 0.0, false alarm ratio (FARatio) = 0.0, probability of detection (POD) = 0.7179, and critical success index (CSI) = 0.7179.

<table>
<thead>
<tr>
<th></th>
<th>Observed Continuing Current</th>
<th>Observed No Continuing Current</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Contin</td>
<td>56</td>
<td>0</td>
<td>56</td>
</tr>
<tr>
<td>Continuing Current</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predicted No Cont</td>
<td>22</td>
<td>66</td>
<td>88</td>
</tr>
<tr>
<td>Continuing Current</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>78</td>
<td>66</td>
<td>144</td>
</tr>
</tbody>
</table>

A flash to ignite a fire at the surface, utilizing the CG-only model can increase the confidence that a flash associated with a lightning-initiated wildfire contains continuing current, especially due to a higher POD compared to the original continuing current model.

Applying a continuing current model to GLM flashes can also aid in filtering out other optical phenomena detected by GLM that may be mistakenly characterized as continuing current. For instance, bolides are large meteors that burn up as they enter Earth’s atmosphere and can be detected by GLM and sorted as lightning flashes (Jenniskens et al. 2018; Rumpf et al. 2019). They typically contain many GLM groups, have higher energies later in the flash, have straight-line trajectories during their entry into the atmosphere, and compared to lightning, have smoother, less sporadic light curves with time that can last for many seconds. If there is a bolide associated with continuous optical emission that potentially lasts for seconds, the continuing current model will likely estimate a low probability of continuing current. Further, as small bolides are considered to be harder for GLM to detect, a small bolide likely will not be mislabeled as a flash with continuing current since its trajectory may
occur within one GLM pixel (Rumpf et al. 2019), and the continuing current model is heavily weighted by the maximum distance between two GLM groups during the continuous optical emission. To investigate, GLM optical emission associated with 9 confirmed bolides from Rumpf et al. (2019) were ingested into the continuing current model. It should be noted that most of the GLM flashes associated with a bolide were labeled with a degraded quality flag since they were split due to exceeding the artificial temporal thresholds for a GLM flash. Despite the quality flag label, roughly 94% of the GLM flashes that occurred during a bolide event had a continuing current probability of about 8% or less, while 75% these GLM flashes showed a 0% probability of continuing current. Merging the split flashes together improved the results, where each of the 9 bolides received a continuing current probability of approximately 0%. Bolide characteristics and corresponding GLM flash continuing current probabilities are shown in Table 2.8.

2.4 Conclusions

A multiple logistic regression model was developed to predict the presence of continuing current in lightning using optical data from the GLM. Continuing current durations could be measured from electric field data since there was a 0.95 correlation with durations recorded from high speed video, while high speed video was better suited for current durations below 10 ms. Training the logistic regression with both CG strokes and initial IC leaders revealed that continuous optical emission within a GLM flash associated with higher probabilities of continuing current tend to cover a longer distance, a brighter maximum optical energy, and a larger maximum area over
Table 2.8: Nine bolides from Rumpf et al. (2019) and the total number of GLM flashes that occur during each bolide, the GLM flash times of each flash with a non-zero continuing current probability, the corresponding continuing current probability for each flash, and the resulting continuing current probability when merging all GLM flashes that occur within each bolide into one flash. If the bolide had no flashes with a continuing current probability greater than zero, then the first GLM flash is listed.

<table>
<thead>
<tr>
<th>Bolide Date</th>
<th>Total Number of GLM Flashes</th>
<th>GLM Flash Time (UTC)</th>
<th>Non-zero Continuing Current Probability</th>
<th>Merged Continuing Current Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>08 May 2018</td>
<td>6</td>
<td>02:27:13.274</td>
<td>0.035</td>
<td>0.000</td>
</tr>
<tr>
<td>01 November 2018</td>
<td>3</td>
<td>18:36:45.143</td>
<td>0.013</td>
<td>0.000</td>
</tr>
<tr>
<td>03 November 2018</td>
<td>1</td>
<td>12:36:21.269</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>11 November 2018</td>
<td>1</td>
<td>07:58:29.952</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>12 November 2018</td>
<td>3</td>
<td>04:58:15.594</td>
<td>0.075</td>
<td>0.000</td>
</tr>
<tr>
<td>15 November 2018</td>
<td>5</td>
<td>08:02:44.400</td>
<td>0.415</td>
<td>0.000</td>
</tr>
<tr>
<td>20 November 2018</td>
<td>2</td>
<td>12:17:52.712</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>22 November 2018</td>
<td>2</td>
<td>13:10:46.655</td>
<td>0.024</td>
<td>0.000</td>
</tr>
<tr>
<td>01 February 2019</td>
<td>13</td>
<td>18:17:08.795</td>
<td>0.073</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18:17:11.550</td>
<td>0.005</td>
<td></td>
</tr>
</tbody>
</table>
the span of the continuous optical emission. Further, continuous optical emission that occurs during initial IC leader activity tend to have smaller optical energies, cover a shorter distance, and a smaller maximum area compared to CG strokes that contain continuing current.

About 14.2% of the total flashes detected by GLM in 2018 contain continuing current, and 13.3% of all GLM flashes that were not flagged as degraded are considered to have continuing current. Roughly 24.1% of flashes with no degraded quality flag exhibit continuous optical emission for 10 ms or longer, which suggests that assuming a GLM flash with continuous optical emission is a continuing current flash will lead to an overestimation in the total number of continuing current flashes. High counts of flashes with continuing current occurred in northern South America, regions of Central America, and along the western coast of Mexico. A previously noted continuing current hot spot off of the eastern coast of North America that was shown in LIS data was not as apparent with the GLM continuing current model. Analyses revealed that the majority of GLM flashes with continuous optical emission within this area off of the eastern coast of North America had, on average, small distances between groups, small optical energies, and small optical footprints. Since GLM flashes with continuous optical emission that cover a large distance spatially, contain larger optical energies, and exhibit a larger maximum area tend to have continuing current according to the continuing current model, the data suggests that east coast CONUS flashes may mainly be associated with initial IC leaders. The model further supports that flashes with continuing current tend to occur more often over the ocean, at nighttime, and during the winter season.
It was shown that if flash type classification is known, the model improves in detecting continuing current in CG flashes. The GLM attributes also shift in weight when trained with confirmed CG flashes, where the maximum number of time-contiguous groups becomes the most important parameter in predicting continuing current presence. Since lightning with continuing current are known to cause wildfires, GLM flashes with higher probabilities of continuing current may be used to gain a better idea of which GLM flash may have started the fire. This can improve response times as a probability of continuing current can be generated quickly, even in remote areas and locations without ground-based lightning detection network coverage. Although, matching with ground-based lightning networks when available could potentially refine the probability of ignition as the flash could be assigned a flash type.
CHAPTER 3

EXPLORING THE RELATIONSHIP BETWEEN CONTINUING CURRENT IN LIGHTNING AND LIGHTNING-INITIATED WILDFIRES

3.1 Introduction

One major threat lightning poses to nature is the chance of igniting a wildfire once a discharge connects to the ground. About 16% of wildfires were initiated by lightning in the continental United States between 1992 and 2012, and although human-caused fires made up the majority of ignitions in this particular study, lightning-caused wildfires burned up to 56% of the total burned acreage within the same 20-year time frame (Balch et al. 2017). Being able to improve the response time to an ignition location can help prevent the fire from spreading further, resulting in less damage and acreage burned.

Continuing current presence and large charge transfers heighten the chance of wildfire ignition due to lightning (Latham and Williams 2001). As a lightning stroke makes a connection to the ground, the resulting current flow can heat an object, such as a tree, past its combustion temperature. If a stroke is followed by a long continuing current, the fuel would be exposed to a high temperature for a sufficient
amount of time, thus igniting the fuel (Fuquay et al. 1972; Latham and Schlieter 1989; Latham and Williams 2001). Past research suggests that positive cloud-to-ground (CG) flashes may be the prime flash type to initiate forest fires, which is mainly due to positive CG flashes being linked to the production of continuing current (Fuquay et al. 1967, 1972; Latham and Williams 2001). It has been found that about 75% of positive CG flashes may contain a long continuing current of at least 40 ms (Saba et al. 2010), while negative CG flashes are followed by a long continuing current roughly 30% of the time (Rakov and Uman 1990). Despite the notion that a positive CG is more likely to initiate a wildfire, research investigating the relationship between flash polarity and wildfire initiation found negative CG flashes initiated the majority forest fires (Flannigan and Wotton 1991; Duncan et al. 2010). It has been suggested in these studies that stroke multiplicity in a negative CG flash is an important factor in predicting wildfire initiation. A possible theory for the significance of multiplicity has been negative CG strokes are more likely to contain continuing current if they are a subsequent stroke rather than the first stroke in a flash (Rakov and Uman 1990). However, a more recent study has found that neither polarity or a higher multiplicity are strong indicators that a particular flash initiates a wildfire (Pineda et al. 2014).

Previous studies have attempted to match lightning measurements from ground-based networks to several methods of fire detection, such as simple fire observations (Schultz et al. 2019; MacNamara et al. 2020) and fire detection via satellite imagery (Peterson et al. 2010; Bar-Massada et al. 2012; Fusco et al. 2016). Various metrics were investigated, such as spatial distance and temporal differences between the fire observations and lightning. Ground-based lightning detection networks used to in-
vestigate lightning-initiated wildfires typically consist of a very low frequency/low frequency (VLF/LF) sensors, where time-of-arrival techniques are used to determine the location of the strike and various flash characteristics, including flash type, multiplicity, polarity, and peak amplitudes, are included in the data output. Ground-based lightning VLF/LF networks used in previous studies, such as the National Lightning Detection Network (NLDN; Cummins and Murphy 2009) and similar networks (Peterson et al. 2010; Dowdy and Mills 2012; Pineda et al. 2014), lack the capability to detect continuing current at long distances. The electric field decay of $\frac{1}{r^3}$ limits the detection of continuing current to approximately 50 km from each sensor (Lin et al. 1979; Shindo and Uman 1989), and since the aforementioned VLF/LF networks typically consist of baselines of 300-350 km between each sensor (Cummins and Murphy 2009), continuing current detection can not be consistent across the spatial domain. Magnetic field measurements allow for continuing current detection at distances up to 2000 km from a sensor since the magnetic field decay is $\frac{1}{r}$ (Cummer and Füllekrug 2001; Ross et al. 2008). While these types of sensors may be ideal since they could cover a larger spatial domain, the continuing current signatures still become weaker with distance, making them unreliable beyond the outermost sensors. Utilizing space-based optical sensors for lightning detection, such the Geostationary Lightning Mapper (GLM) aboard the GOES-16 satellite, allows for continuous hemispheric coverage of lightning, as well as the potential to determine whether or not a discharge may have continuing current (Bitzer 2017). Further, the Advanced Baseline Imager (ABI) on the same GOES-16 satellite can provide similar coverage and consistent overlap so comparisons between the GLM and ABI can be made.
This study utilizes GLM group-level characteristics to match GLM flashes to satellite-detected wildfires. The probability of continuing current of each matched GLM flash is then calculated and considered when determining which flash may have initiated the fire. General statistics of all flashes matched to the fire are determined depending on differences in spatial and temporal constraints, as well as which flashes may or may not have continuing current. Continuing current probabilities, spatial variations, and temporal characteristics are then taken into consideration when choosing which GLM flashes that were most likely to have caused each wildfire.

3.2 Data and Methods

3.2.1 Fire Observations

Fire observations from 2018 were collected from the Geospatial Multi-Agency Coordination (GeoMAC) website, which provided past fire locations and perimeters in the United States (GeoMAC 2018). Fires from 2018 were chosen to be sure both ABI and GLM data were available for the analysis. It should be noted that as of April 30, 2020, the GeoMAC has been decommissioned and transitioned into the National Incident Feature Service. The fire observations were either labeled as naturally-caused or human-caused, and there were 390 fires that were deemed as naturally-caused in this database for 2018. Information about the fires included date, time, latitude, longitude, and total burned acreage. It is important to note that the time provided within the data indicates the time that the report was given, not necessarily the time of the fire ignition.
3.2.2 Advanced Baseline Imager (ABI)

The Advanced Baseline Imager (ABI) is a 16-band radiometer aboard the GOES-16 satellite (Schmit et al. 2005, 2017). More spectral bands in the visible, near infrared, and infrared wavelengths are available compared to previous GOES generations, as well as improved temporal and spatial resolution, radiometric properties, and performance. The ABI Level-2 Fire/Hotspot Characterization (FHC; Schmidt et al. 2013; GOES-R Series Program Office 2017) product is built on the previous GOES Wildfire Automated Biomass Burning Algorithm (WF-ABBA; Koltunov et al. 2012) and prior infrared techniques (Matson and Dozier 1981) to detect sub-pixel temperature anomalies. The FHC product utilizes the 3.9 $\mu$s, 11.2 $\mu$s, and 12.3 $\mu$s infrared bands to detect active fires with a horizontal spatial resolution of 2 km and temporal resolution over the continental United States of 5 minutes. The 3.9 $\mu$s and 11.2 $\mu$s bands are both required for the FHC algorithm to run since the sensitivity of the 3.9 $\mu$s band to high temperature sub-pixel anomalies compared to the less sensitive 11.2 $\mu$s band determines fire presence. The 12.3 $\mu$s band is used to identify opaque clouds, and the visible shortwave 0.64 $\mu$s band is also used when available during the daytime to aid in cloud detection so both high temperature and smoke anomalies can be easier to detect.

Various statistical techniques are applied to potential FHC pixels to filter out false alarms caused by viewing angle, sun glint, and surface types (e.g., water versus vegetation). Corrections are also made for water vapor attenuation, surface emissivity, solar reflection, and semi-transparent clouds to further eliminate potential false
alarms. Calculations are then made for fire size, temperature, and fire radiative power to describe each sub-pixel entity. The values attained from these calculations determine if a FHC pixel continues through additional thresholds to reduce as many “non-fire” FHC pixels as possible and further direct the characterization of the FHC pixel once all thresholds have been applied. Each FHC pixel can be flagged as either processed, saturated, cloudy, high probability, medium probability, or low probability depending on the sub-pixel temperature estimates. A processed FHC pixel represents valid estimates for fire size and temperature are reached. A saturated flag is determined before any filtering is implemented, resulting in a fire temperature solution that is not reached due to high temperature readings from both the 3.9 μs and 11.2 μs bands. A cloudy flag is set to a FHC pixel when valid fire size and temperature values are estimated, but opaque clouds are present in the 12.3 μs band resulting in a high albedo calculation. The high, medium, and low probability FHC pixels are dependent on various thresholds that are determined by the estimated temperatures, background surface temperatures, and their differences from both the 3.9 μs and 11.2 μs bands. It should be noted that low probability FHC pixels are not often used by end users as an indicator of a valid fire (Schmidt et al. 2013). The ABI FHC product is used since the metrics can be applied with GLM data throughout the field of view of the GOES-16. Further, this study utilizes processed, saturated, cloudy, and high probability FHC pixels to be confident a fire is present at the time the earliest FHC pixel.
3.2.3 Geostationary Lightning Mapper (GLM)

As a space-based optical sensor, the GLM (Goodman et al. 2013) continuously records transient optical pulses over the western hemisphere on its 1372 x 1300 pixel charge-coupled device (CCD) focal plane. An illuminated pixel must be greater than the variable background difference threshold before it is considered a potential lightning event. Employing a background difference threshold allows optical emission to be detected during any time of day and night. The time resolution of the GLM is ~2 ms, and the spatial resolution of a GLM pixel increases from approximately 8 km at nadir to about 14 km along the edge of the field of view.

The GLM data is organized into a parent-child hierarchy of events, groups, and flashes, where events are the children of groups and groups are the children of flashes (Goodman et al. 2013). The illuminated pixels that surpass the variable background difference threshold, in addition to several noise filters, are labeled events. When adjacent events occur within the same time frame, they comprise a group. Groups that occur within the weighted Euclidean distance of 16.5 km and the temporal bounds of 330 ms are then sorted into a flash (Goodman et al. 2010, 2013). The locations of both groups and flashes are radiance-weighted centroids, meaning the centroid locations are dependent on higher event or group optical energies, respectively.

To predict the presence of continuing current using GLM data, the continuous optical emission within each GLM flash is analyzed. Particular GLM attributes from the longest run of time-adjacent groups within a flash are collected and are ingested into a multiple logistic regression model (Table 1; Fairman and Bitzer 2020, in review).
The model has a probability of detection of around 78% and a false alarm rate about 6%. Based on the ROC analysis in Fairman and Bitzer (2020), GLM flashes with continuing current probabilities greater than or equal to 0.33 are considered to have continuing current.

3.2.4 Fire and Flash Analysis

To confirm that the fire observations were naturally-caused and associated with lightning, GLM flashes were matched to the provided fire observation locations. To match the GLM flashes, GLM group centroids within 30 km of the FHC location were identified, and the parent flashes of each group within the spatial bounds were considered a matched GLM flash. GLM groups can be roughly categorized as the equivalent to ground-based strokes and pulses (Goodman et al. 2013), which is demonstrated in previous satellite-based work that used the Lightning Imaging Sensor (Christian et al. 1992) groups to match to ground-based networks employed spatial and temporal constraints of 20 km and 10 ms, respectively (Bitzer et al. 2016; Zhang et al. 2016). Therefore, matching GLM flashes to a fire location at the group-level is considered to be roughly similar to matching ground-based strokes or pulses to a fire.

A fire observation was considered to be lightning-caused if at least one GLM parent flash had at least one group that occurred within 30 km of the fire observation location and up to 14 days prior to the observation time to account for holdover times (Schultz et al. 2019). Of the 390 naturally-caused fires, 384 (98.5%) fire observations had at least one GLM group within these spatial and temporal bounds. Next, the date of the earliest GLM flash in time associated with each fire observation within
the constraints was recorded, and FHC pixels were searched 30 days after the earliest GLM date within 10 km of the fire observation. This approach accounts for FHC pixels that could have manifested either prior to or after the fire observation, as well as taking into account whether the FHC pixel happened after the earliest GLM flash that occurred near the fire observation location.

There were 342 (89.1%) fire observations that matched with at least one processed, cloudy, or high probability FHC pixel within 10 km of the fire observation (Figure 3.1). The FHC pixel that occurred earliest temporally was considered the FHC pixel associated with the fire, and if more than one pixel occurred at the earliest time, all pixels were recorded. None of the fire observations matched to a saturated
FHC pixel, which agrees with the fact that an elevated saturated temperature of 400 K or greater in the 3.9 $\mu$s band limits the number of FHC pixels flagged as a saturated pixel to less than 5% of all FHC pixels (Schmidt et al. 2013). Although the spatial resolution of a FHC pixel is 2 km, FHC pixels within 10 km of a fire observation were considered to account for the fact that the fire observation location may not have been the exact initiation point of the fire.

Next, GLM flashes were matched to the location of each FHC and occurred up to 14 days prior to each FHC pixel to, again, account for the maximum possible holdover time (Schultz et al. 2019). If there were multiple FHC pixels matched to a fire observation, the averaged latitudes and longitudes of all matched FHC pixels were considered the FHC location. Note that the closest GLM group locations within each FHC pixel location were considered when spatial constraints were adjusted. Utilizing GLM group locations over parent flash locations accounted for parent flashes that consist of multiple groups and may have propagated closer to the FHC pixel location. Figure 3.2 provides an example FHC pixel within the data set revealing the closest GLM group locations to the FHC pixel (Figure 3.2(a)) and the corresponding GLM parent flash locations (Figure 3.2(b)). In this particular example, there were roughly 34% of the GLM parent flash locations outside of the 30 km spatial bound with continuing current probabilities of 0.33 or greater that contain at least one group location within 30 km. If GLM flash centroids were used to match to a FHC pixel instead, then the GLM flashes with a flash centroid location outside of the spatial bounds but with at least one group centroid location within the spatial bounds would not have been included in the analysis.
A variety of metrics such as the distance and total time elapsed between a particular discharge and FHC pixel are investigated to determine if trends utilized in past ground-based network studies are apparent when analyzing potential trends in matched GLM parent flashes with continuing current. Since previous papers have looked at ground-based flashes closest in both space and time, adding a continuing current metric allows for a more robust method when determining which flash may have caused the fire.

3.3 Results

3.3.1 Matching Approach

The differences in flash characteristics when matching a GLM flash centroid to a FHC pixel versus finding the closest GLM group within a parent flash to a FHC pixel are explored. Of the 322 FHC pixels that had at least one GLM group cen-
troid within 30 km of each pixel, only one pixel had no GLM flash centroid matches. Figure 3.3 shows the distributions of the closest matched GLM flash centroids and GLM group centroids, respectively. When matching using GLM group centroid locations, the mean continuing current probabilities of the GLM parent flashes was about 0.27, where using flash centroid locations resulted in an average continuing current probability of 0.21. The distances between the closest GLM group centroids were, on average, about 1 km closer to the FHC pixel location than the closest GLM flash centroid locations. This result further supports the reasoning to use GLM group centroid locations to match to a FHC pixel, since a close GLM group suggests a possible stroke occurring near the FHC location while the GLM flash centroid represents the radiance-weighted location of all groups within the flash (Goodman et al. 2013).

3.3.2 All Matched GLM Parent Flashes

General statistics of the continuing current probabilities, total time elapsed, and the distance between the closest group in a GLM parent flash to the FHC pixel are analyzed from all of the groups matched to a FHC pixel to gain a better understanding of how an estimate of a continuing current probability can improve the process of determining which GLM parent flash initiated a wildfire. First, the total number of GLM parent flashes that matched to a FHC pixel varies based on which spatial constraint is utilized. Of the 342 FHC pixels that matched to a fire observation, there were 322 FHC pixels where at least one GLM group occurred within 30 km of its location and prior to the earliest FHC time. The total number of FHC pixels that matched to at least one GLM group decreases as the spatial constraint decreases,
Figure 3.3: Distributions of the characteristics of the closest GLM flash centroid locations or GLM group centroid locations matched to each FHC pixel within 30 km, showing (a) continuing current probabilities, (b) distances between the GLM flash centroid location or closest GLM group centroid location within each flash and the FHC pixel in kilometers, and (c) total time elapsed from the GLM flash or GLM parent flash to the FHC pixel in days. There were 321 FHC pixels that matched to at least one GLM flash centroid, and there were 322 FHC pixels that matched to at least one GLM group centroid.

where roughly 94% of pixels have at least one GLM group match within 30 km and about 77% FHC pixels match to at least one GLM group within 5 km of the pixel location (Table 3.1). However, about 88% of FHC pixels have at least one GLM group with a parent flash with a continuing current probability of 0.33 or greater within 30 km, while approximately 59% of FHC pixels matched to at least one GLM group with a parent flash continuing current probability of 0.33 or greater within 5 km of the FHC pixel location (Table 3.2).

On average, the continuing current probabilities of all GLM parent flashes where the closest group matched to a FHC pixel within the 30 km spatial bounds is about 0.19 and increases to about 0.23 for GLM parent flashes with the closest
Table 3.1: The total number of FHC pixels (i.e., fires) that have at least one GLM group within each respective spatial constraint of the FHC pixel location. The mean, median, and standard deviation values of the total number of GLM parent flashes matched to a FHC pixel are also shown.

<table>
<thead>
<tr>
<th>Spatial Constraint</th>
<th>Number of Fires</th>
<th>Mean GLM Flashes</th>
<th>Median GLM Flashes</th>
<th>St. Dev. GLM Flashes</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 km</td>
<td>322</td>
<td>995</td>
<td>253</td>
<td>1,654</td>
</tr>
<tr>
<td>15 km</td>
<td>305</td>
<td>349</td>
<td>95</td>
<td>610</td>
</tr>
<tr>
<td>10 km</td>
<td>290</td>
<td>193</td>
<td>54</td>
<td>347</td>
</tr>
<tr>
<td>5 km</td>
<td>263</td>
<td>73</td>
<td>22</td>
<td>131</td>
</tr>
</tbody>
</table>
Table 3.2: The total number of FHC pixels (i.e., fires) that have at least one GLM group with a parent flash continuing current probability $\geq 0.33$ within each respective spatial constraint of the FHC pixel location. The mean, median, and standard deviation values of the GLM parent flashes with a continuing current probability $\geq 0.33$ matched to a FHC pixel are also shown.

<table>
<thead>
<tr>
<th>Spatial Constraint</th>
<th>Number of Fires</th>
<th>Mean GLM Flashes</th>
<th>Median GLM Flashes</th>
<th>St. Dev. GLM Flashes</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 km</td>
<td>300</td>
<td>132</td>
<td>36</td>
<td>247</td>
</tr>
<tr>
<td>15 km</td>
<td>267</td>
<td>56</td>
<td>16</td>
<td>104</td>
</tr>
<tr>
<td>10 km</td>
<td>250</td>
<td>34</td>
<td>9</td>
<td>64</td>
</tr>
<tr>
<td>5 km</td>
<td>203</td>
<td>17</td>
<td>6</td>
<td>30</td>
</tr>
</tbody>
</table>
Figure 3.4: Distributions of the characteristics of all GLM parent flashes with continuing current probabilities of 0.33 or greater within various spatial constraints of a FHC pixel, showing (a) continuing current probabilities, (b) distances between the closest GLM group within each flash and the FHC pixel in kilometers, and (c) total time elapsed from the GLM parent flash to the FHC pixel in days. The total number of FHC pixels with at least one matched GLM parent flash with continuing current within 30 km, 15 km, 10 km, and 5 km are 300, 267, 250, and 203 flashes, respectively.

The average time between all matched GLM parent flashes and the manifestation of each respective FHC pixel within 30 km and 5 km is roughly 6.3 days and 5.9 days, respectively. Only including GLM parent flashes with continuing current probabilities of 0.33 or greater slightly affects the mean total time elapsed between all matched GLM parent flashes and each FHC pixel, as shown in Figure 3.4(c), where the total time elapsed is 6.5 days and 6.1 days, respectively.
3.3.3 Comparison to Previous Methods

Previous methods determined whether a particular flash initiated a wildfire based on distance from the fire, the amount of time between the flash and the fire, or some combination of both distance and time elapsed. Specifically, some studies have either considered which ground-based lightning flashes occurred near the fire observation location within a relatively larger time bound (e.g., within 10 km and up to 14 days; Schultz et al. 2019) or which flashes occurred earliest in time within a relatively closer spatial bound (e.g., within 5 km and up to 3 days; Dowdy and Mills 2012). Both approaches can be applied in addition to considering continuing current probabilities of each flash to further narrow down potential flashes that ignited the fire. Optimizing one of these approaches over the other may not necessarily be the right approach when picking which flash may have caused the fire; rather, the distance between the closest GLM group within a parent flash and FHC pixel, the amount of time elapsed between the GLM parent flash and FHC pixel, and the continuing current probability of the GLM parent flash should be considered when deciding which flash may have caused the fire.

There could be several GLM parent flashes with the closest group location within each spatial constraint to the FHC pixel, as well as multiple GLM parent flashes that occurred right before the FHC pixel time within a particular spatial bound. Applying the continuing current model to each of these parent flashes can further filter matched GLM parent flashes to narrow down which flash could have ignited the fire. To gain a better idea of how the continuing current model can filter
out matched GLM parent flashes, Figure 3.5(a) shows one processed FHC pixel from the dataset and the matched GLM parent flash locations. Figure 3.5(b) provides a comparison when matching the closest GLM group in both time and space, where three parent flashes occur within an hour of the flash closest to the FHC pixel time. This approach is employed in this example since no GLM parent flashes occurred within an hour of the FHC pixel time. The GLM parent flash with highest probability of continuing current is the farthest from the FHC pixel, so if the closest GLM parent flashes in time were only considered, the continuing current model can help a user decide which of the three GLM flashes may have ignited the fire. Without applying a spatial or temporal constraint beforehand, the continuing current model can filter out several flashes with low continuing current probabilities. In this particular example, 881 GLM flashes matched to the FHC pixel, and 116 of the flashes (≈13.2%) had continuing current probabilities of 0.33 or greater. Further, 24 GLM flashes (≈2.7%) had continuing current probabilities of 0.90 or greater.

To further compare with previous methodologies, the properties of the GLM parent flashes with the maximum continuing current probabilities of all matched parent flashes to each FHC pixel are explored. It should be noted that multiple GLM parent flashes consisting of the same maximum continuing current probability matched to a single FHC pixel were possible. On average, there were roughly 1 to 6 flashes that had the same maximum continuing current probabilities match to a FHC pixel, depending on the spatial constraint utilized. The median total time elapsed between a parent flash with continuing current is more consistent at around 6.7 days for the spatial constraints between 30 km and 10 km, while the mean total time elapsed
Figure 3.5: The (a) GLM flash locations, (b) GLM flashes closest to the FHC pixel time, (c) GLM flashes with continuing current probabilities of 0.33 or greater, and (d) GLM flashes with continuing current probabilities of 0.90 or greater that were matched to the processed FHC pixel from 07 August 2018 at 23:02:26.3 UTC shown in the center of each plot in red. The gray circles moving outward represent distances of 10 km, 20 km, and 30 km from the FHC pixel location, respectively.

for these three spatial bounds are between 6.9 days and 6.1 days. However, for GLM parent flashes with a group within 5 km of a FHC pixel, the total time elapsed drops with a mean and median of around 5.3 days and 4.7 days, respectively. Plots representing the maximum continuing current probabilities are omitted due to the fact that median maximum continuing current probability for each spatial constraint was 1.00. Although, the maximum continuing current probability distributions for each
Table 3.3: The mean, median, and standard deviation values of the same characteristics shown in Figure 3.3 of the closest GLM group centroid locations matched to each FHC pixel within 30 km with parent flash continuing current probabilities of at least 0.33.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean</th>
<th>Median</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of Continuing Current</td>
<td>0.73</td>
<td>0.75</td>
<td>0.24</td>
</tr>
<tr>
<td>Distance (km)</td>
<td>5.0</td>
<td>2.4</td>
<td>6.3</td>
</tr>
<tr>
<td>Time Elapsed (days)</td>
<td>5.1</td>
<td>4.1</td>
<td>4.2</td>
</tr>
</tbody>
</table>

of the spatial bounds were still investigated. Approximately 2% of GLM flashes with a group within 30 km did not have a maximum continuing current probability of 1.00, while roughly 26% of flashes with a group within 5 km had a maximum continuing current probability of 1.00.

Since previous methods typically determined that a flash closest to a fire in space is most likely to have caused a fire, the statistics of GLM parent flashes with a group closest to each FHC pixel are investigated. Of the 322 FHC pixels with at least one GLM parent flash matched within 30 km, the mean and median continuing current probabilities of the GLM parent flashes with the closest group to a FHC pixel are 0.27 and 0.12, respectively. The mean and median distances between the closest group within each GLM parent flash and the FHC pixel are 3.3 km and 1.1 km, respectively. Finally, the mean and median values of the total time elapsed between the GLM parent flashes with the closest group to the FHC pixels are 5.1 days and 4.7 days, respectively. Table 3.3 explores the continuing current probabilities, spatial, and temporal properties of the closest GLM groups with parent flash continuing current probabilities of 0.33 or greater. The most notable difference between the two distributions is the increase in both the mean and median distances between the
closest GLM groups and the FHC pixel. This suggests that the closest GLM group matched to a FHC pixel, on average, may not be associated with continuing current, which further supports that simply selecting the parent flash of the closest GLM group matched to a FHC pixel may not be the most appropriate approach.

3.4 Discussion

To determine which lightning flash may have caused the fire, properties in addition to simply finding the closest flash in space or time need to be considered. Finding the earliest flashes in time may not necessarily be the most appropriate approach as the time of the FHC pixel does not exactly indicate the initial start time of the fire. Further, as seen throughout this study, employing a variety of spatial constraints may result in multiple flashes satisfying the chosen bounds. Even selecting the closest flash in space may be arbitrary in a sense, as there are, on average, 73 GLM parent flashes had the closest group match to a FHC pixel within 5 km, where some group centroid locations may be just tens to hundreds of meters away from each other.

In addition, using the closest GLM group centroid location to determine if a parent flash has matched to a FHC pixel rather than the flash centroid location is demonstrated to be the ideal approach. Due to GLM groups being roughly analogous to a stroke or K-change process, a close GLM group to a FHC pixel could indicate a potential stroke process near the FHC pixel location. A flash centroid location close to the FHC pixel could also indicate a location of a stroke process, but since the centroid location is the radiance-weighted location of all the groups within a flash,
the flash centroid location is only likely to be close to a stroke process if GLM detects
the stroke being the optically brightest part of the flash. Otherwise, GLM groups
may have occurred during a stroke process, but the flash centroid location would
be affected by optically brighter groups within the flash. Further, both the mean
and median distances between the closest GLM group and FHC pixel increase as
the spatial constraint increases. This suggests that several flashes surround the FHC
pixels within each spatial constraint rather than a few outliers occurring sporadically,
and a smaller constraint should be used when matching GLM groups to a FHC
pixel, similar to matching space-based groups to ground-based lightning networks in
previous studies (Bitzer et al. 2016; Zhang et al. 2016).

Utilizing the continuing current model can aid in narrowing down which parent
flash may have initiated a wildfire. In the instances where multiple parent flashes
have a group within a certain distance from a FHC pixel, parent flashes with higher
continuing current probabilities can be assumed to be more likely to have started
the fire versus parent flashes with lower continuing current probabilities. Since GLM
parent flashes with a group that occurs within 30 km of a FHC pixel with continuing
current tend to be, on average, about 3.3 km away from a FHC pixel and occur
roughly 5.1 days prior to the FHC pixel, these characteristics should be taken into
consideration when selecting a potential GLM parent flash candidate that may have
initiated a wildfire rather than selecting the GLM parent flash with minimum values
for either constraint. Selecting the closest GLM group within a parent flash that
has a continuing current probability of 0.33 or greater versus any continuing current
probability further suggests that simply picking the closest GLM group to the FHC
pixel is not necessarily a correct approach. However, the closest GLM group with a parent flash with continuing current tended to still occur, on average, within roughly 5.0 km of the FHC pixel with a median distance of about 2.4 km. Although the closest GLM group may not be associated with a GLM parent flash with continuing current, a parent flash with continuing current still typically had its closest GLM group within 5.0 km.

Further investigating the temporal characteristics of matched GLM parent flashes can help aid in future methodological improvements when matching lightning to lightning-initiated wildfires. The results reveal that, on average, a FHC pixel manifests approximately 6 to 7 days after a GLM parent flash, independent of a high or low probability of continuing current and each of the utilized spatial constraints. Further, the median time elapsed between each GLM parent flash and a FHC pixel is roughly 5 to 7 days. Both of the mean and median values remain consistent when choosing to investigate the entire population of GLM parent flashes matched to a FHC pixel or focusing on a single parent flash matched to a FHC pixel. This suggests that searching for GLM flashes up to 14 days from the FHC pixel time is too large of a window. However, a more detailed analysis into time elapsed and the specific FHC pixel flags that manifest first may be useful in determining a more robust approach since a temporal parameter may be more dependent on ABI characteristics, such as the estimated fire temperature solutions and albedo approximations.

It should be noted that the continuing current model was trained on data from the GLM on the GOES-16 satellite. Due to several fires occurring on the edge of the GOES-16 field of view, matched GLM parent flashes in these areas have larger pixel
sizes of up to 14 km at nadir, which may affect the continuing current probabilities of GLM flashes. In other words, with a coarser resolution on the edges of the field of view in the GLM data, some flashes may report longer distances between two groups during continuous optical emission. Since this parameter affects the outcome of a high continuing current probability the most, there may be more false alarms along these areas. Figure 6 in Fairman and Bitzer (2020) reveals higher continuing current ratios in the Pacific Northwest, alluding to more continuing current flashes occurring in this region compared to other areas throughout the CONUS. As seen in Figure 3.1, much of the FHC pixels in this study occur in the Pacific Northwest, so the matched GLM parent flashes in this area may have an inflated number of continuing current flashes matched to a FHC pixel. However, the GLM aboard the GOES-17 satellite includes the western half of CONUS in its field of view, so areas such as the Pacific Northwest do not reside along the edges of the GOES-17 field of view. Fire-prone areas in the western CONUS may benefit more utilizing the GLM data from GOES-17, but proceed with caution as the continuing current model may need to be retrained using GOES-17 data, as well.

3.5 Conclusion

Fire observations deemed naturally-caused from 2018 were collected, where 98.5% of the observations were confirmed to be associated with lightning. Next, about 89.1% of the fire observations were matched to ABI Level-2 FHC product pixels. GLM groups were matched to the earliest FHC pixel in time associated with each fire, and the parent GLM flashes of each group were ingested into a continuing current model.
to provide a continuing current probability of each parent flash in addition to spatial and temporal properties in the analyses of lightning-initiated wildfires.

On average, it takes about 5 to 7 days between a GLM parent flash occurrence and the manifestation of a FHC pixel, independent of the continuing current probability of the GLM parent flash and the distance between the closest GLM group within the parent flash and the FHC pixel. The total time elapsed property may be more dependent on the FHC pixel flag type; in other words, the methodology of detecting an estimated fire size, temperature, and cloud cover solution in the ABI Level-2 FHC product may affect this parameter more than continuing current presence and the closest GLM group distance from the pixel. Selecting the GLM parent flashes of the closest GLM group to each FHC pixel in space showed that the mean and median distances between the pixel and closest GLM group was roughly 3.3 km and 1.1 km, respectively. Only accounting for GLM parent flashes with continuing current resulted in mean and median distance values of 5.0 km and 2.4 km, suggesting that selecting the closest GLM group in time may not necessarily be the right approach. However, GLM parent flashes with continuing current remained spatially close to a FHC pixel. This suggests that considering all GLM groups within a small spatial constraint of at least 5.0 km in addition to the continuing current probabilities of 0.33 or greater is a more appropriate approach in determining with parent flash may have initiated a fire.

Incorporating additional parameters, such surface type, moisture, and atmospheric conditions at the time of a lightning discharge, can further refine the probability of a lightning-caused ignition (Rorig and Ferguson 1999, 2002; Dowdy and Mills 80
Continuing current presence generally provides context in terms of how likely a lightning channel remains in the contact with the surface. Although, if a particular surface type is prone to ignition or little to no precipitation has fallen recently in time resulting in a dry fuel at the time of a lightning strike, then continuing current probabilities may not play as much of a role in lightning-initiated wildfire prediction since any length of charge flow to the surface would have a high chance of ignition. However, future work needs to explore supplemental environmental parameters further to determine if GLM parent flashes with higher continuing current probabilities are more likely to initiate a wildfire versus lower continuing current probabilities.
A more robust approach compared to previous methods of predicting continuing current in lightning using space-based optical attributes was developed. Ground-based lightning data from high speed video and electric field change meters were utilized to manually collect 50 CG strokes and estimate their current durations. A correlation of 0.95 between the two methods of estimating the current durations was found. Once GLM groups associated with 360 manually classified combination of CG strokes and initial IC leaders were identified, the model was trained and tested where continuing current was defined as at least 10 ms and not associated with initial IC leader activity. The GLM continuing current model has a POD of about 78% and FARate of roughly 6%, while the POD increases to about 80% and FARate decreases to approximately 4% if the flash is known to be a CG flash.

Roughly 13.3% of GLM flashes in 2018 had continuing current compared to 24.1% of GLM flashes containing continuous optical emission for at least 10 ms (or five GLM groups). Simply defining continuing current as any continuous optical emission lasting at least 10 ms in space-based optical data may lead to an overestimation in the total amount of continuing current flashes. Further, utilizing various GLM attributes
beyond the temporal length of continuous optical emission allows for GLM flashes that are associated with continuing current in electric field data but do not have continuous optical emission durations as seen by GLM for at least 10 ms to generate continuing current probabilities. GLM flashes of this nature made up about 31.5% of the entire training and testing dataset, while roughly 37.9% of GLM flashes in 2018 contained continuing current while having a maximum length of continuous optical emission of less than 10 ms.

While the GLM continuing current model accounted for continuous optical emission associated with initial IC leaders, there remains the chance that high continuing current probabilities generated from the model may still be associated with IC flashes. In other words, the late stage of an IC flash may contain continuous optical emission that lasts longer than any continuous optical emission associated with the early stage. Previous work suggested that an IC flash might exhibit continuing current processes during the late stage, where no streamer activity or channel extension occurred in ground-based measurements (Proctor 1983). Since GLM flashes with continuous optical emission during the late portion of an IC flash may be assigned high continuing current probabilities, the use of the model introduces a potential initial approach to explore IC flashes in depth and investigate whether or not the GLM continuous optical emission attributes behave similarly to those associated with continuing current in CG flashes. The model may finally allow an expansion on the early work of continuing current possibly being present in the late stage of an IC flash and potentially create a new approach to collect these types of flashes efficiently.
Matching the ABI Level-2 FHC product to fire observations across CONUS in 2018 reveals that about 89.1% of lightning-caused wildfire observations are matched to at least one processed, cloudy, or high probability FHC pixel. Applying the GLM continuing current model to GLM parent flashes matched to FHC pixels provides insight on a more appropriate method when determining which GLM parent flash may have caused a wildfire. On average, about 5 to 7 days elapses between the GLM parent flash time of closest GLM group and the FHC pixel manifestation. Further, the mean and median distance values between the closest GLM group within 30 km and each FHC pixel are 3.3 km and 1.1 km, respectively. Although, focusing only on GLM parent flashes within 30 km with continuing current probabilities of 0.33 or greater results in mean and median distance values of 5.0 km and 2.4 km. This result is contextual, where the GLM parent flash with the closest group may not necessarily be the flash that initiated the wildfire. However, the closest GLM group of the GLM parent flashes with continuing current still occurs within a relatively small distance from the FHC pixel of at least 5.0 km, on average. It should be noted that the parent flash of the closest GLM group with continuing current does not necessarily have the highest possible continuing current probability, as well, with an average probability being 0.73.

Adding a continuing current metric when determining which lightning discharge may have initiated a wildfire is just one of many parameters that needs to be considered. Several surface, atmospheric, and environmental conditions at the time of a potential ignition should also be taken into account. A high continuing current probability may not be as significant if a particular fuel type is prone to ignition or
little to no precipitation was present at the time of the storm. Future work should ex-
plore the variations in continuing current probabilities and specific conditions where
a current probability may be of more significance in wildfire initiation.
REFERENCES


