Geological Effects on Lightning Strike Distributions

Thesis by

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Recent advances in lightning detection networks allow for detailed mapping of lightning flash locations. Longstanding rumors of geological influence on cloud-to-ground (CG) lightning distribution and recent commercial claims based on such influence can now be tested empirically. If present, such influence could represent a new, cheap and efficient geophysical tool with applications in mineral, hydrothermal and oil exploration, regional geological mapping, and infrastructure planning.

This project applies statistical analysis to lightning data collected by the United States National Lightning Detection Network from 2006 through 2015 in order to assess whether the huge range in electrical conductivities of geological materials plays a role in the spatial distribution of CG lightning. CG flash densities are mapped for twelve areas in the contiguous United States and compared to elevation and geology, as well as to the locations of faults, railroads and tall towers including wind turbines. Overall spatial randomness is assessed, along with spatial correlation of attributes. Negative and positive polarity lightning are considered separately and together.

Topography and tower locations show a strong influence on CG distribution patterns. Geology, faults and railroads do not. This suggests that ground conductivity is not an important factor in determining lightning strike location on scales larger than current flash location accuracies, which are generally several hundred meters. Once a lightning channel is established, however, ground properties at the contact point may play a role in determining properties of the subsequent stroke.
ACKNOWLEDGEMENTS

I would like to thank my supervisors Professor Sigurjon Jonsson and Professor Marc Genton for their support throughout the course of this project and for giving me the opportunity to try something unique and uncertain. I would also like to thank committee members Professor Hakan Bagci and Professor Matthew McCabe for their guidance on specific topics relevant to the project. It is a testament to the King Abdullah University of Science and Technology’s multidisciplinary approach that I could benefit from the advice of faculty in all three of the University’s divisions.

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My sincere thanks to Ron Holle and William Brooks of Vaisala (and to Vaisala itself) not only for providing the lightning data used herein, but for their patience in answering questions and responding to my many requests as I familiarized myself with the field of lightning research.

Finally, I would like to thank soon-to-be Dr. Vanessa Robitzch for her understanding and support as I toiled away on this project (and three solid semesters of coursework), and I wish her luck on her many exciting research projects in the Red Sea!
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<td>cloud-to-ground</td>
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<tr>
<td>CSR</td>
<td>complete spatial randomness</td>
</tr>
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<td>DML</td>
<td>Dynamic Measurement Limited Liability Corporation</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>IC</td>
<td>inter-cloud</td>
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<td>NLDN</td>
<td>National Lightning Detection Network</td>
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<td>USGS</td>
<td>United States Geological Survey</td>
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<td>UTM</td>
<td>Universal Transverse Mercator</td>
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INTRODUCTION

1.1 Motivation

This work was catalyzed by a rumor. In 2015, the author heard that a mineral exploration company once found an ore deposit after noting that lightning struck a particular site on a landscape more often than elsewhere. According to the rumor, exploratory drilling of the site revealed a large, conductive ore body that acted like a buried lightning rod, attracting strikes.

As reported by Robertson (2003), similar stories attribute lightning strikes to the discoveries of other geological features, including the ironstones and opals of Lightning Ridge, Australia, copper and iron deposits in Michigan, USA, and Germany’s ancient Rammelsberg Mine. None of these, however, nor the more recent rumor heard by the author, are well documented. More generally, it appears that the effects of terrestrial conductivity on lightning strike distributions have not been studied in great detail (Section 1.5). Until recently, there was no practical way to collect the relevant information on lightning strike locations.

The past few decades, however, have seen a proliferation of lightning detection networks that use electromagnetic pulses generated by lightning to record lightning locations and strike times across large areas, along with attributes of each strike that can be discerned from the waveforms of these pulses (see Section 2.1 and Cummins &
Murphy, 2009). In the United States, the establishment of the National Lightning Detection Network (NLDN) in 1988 (Orville, 2008), combined with upgrades in 1993-1994 (Cummins, 1998) and 2002-2003 (Cummins and Murphy 2009) allowed for the recording of lightning strike ground contact location with accuracies on the order of several hundred meters across much of the contiguous United States. This relatively high-resolution dataset, now accumulated over more than a decade, provides an unprecedented opportunity to analyze the effects of ground conductivity on lightning strike distribution patterns.

If lightning strike distributions or their attributes can indeed be used to detect differences in ground conductivity, this would represent a new and almost completely passive geophysical tool, with potential applications in mineral, hydrothermal and oil exploration, regional geological mapping, and infrastructure planning. Alternatively, if these distributions can be shown to be random with respect to ground conductivity, the importance of atmospheric processes in determining lightning strike locations will be underscored, and rumors such as the one told to the author can be put to rest.

1.2 Lightning Basics

This and the following section on lightning flashes (1.3) provide a brief overview of lightning useful in understanding this thesis. For a more in-depth introduction to lightning, the author recommends both Lightning: Physics and Effects (Rakov & Uman,
2003) and the more recent An Introduction to Lightning (Cooray, 2014). For ease of reading, references are mostly omitted in these two sections as the bulk of information comes directly from one or both of these sources.

Lightning is thought to strike the earth some forty-six times per second on average (Cecil, 2014). Strike rates vary considerably around the world, with densities of up to two hundred strikes per square kilometer per year in areas like Lake Maracaibo, Venezuela (Muñoz et al., 2016), to effectively zero strikes per square kilometer per year in polar regions, certain ocean regions, and parts of the Sahara Desert (Cecil, 2014). Strike rates also vary by season (ibid; Holle, 2010), and in temperate regions lightning during the winter is usually very rare or absent entirely.

A majority of Earth’s lightning does not hit the ground. Figures vary widely by region and between storm types within a given region, but a common informal estimate is that 1 in 10 instances of lightning contact the ground. Strikes that do not reach the ground are called cloud-to-cloud or inter-cloud (IC) strikes, whereas those that do contact the ground are called cloud-to-ground (CG), as shown in Figure 1. This study focuses entirely on CG strikes.

Lightning can have negative or positive polarity. A negative CG strike transfers electrons from a region of negative charge in a cloud to the relatively positively charged ground, whereas a positive CG strike transfers electrons from the relatively negatively charged ground to a zone of positive charge in a cloud (or, as per convention in atmospheric
Figure 1—A cloud-to-ground (CG) lightning strike. Note from the direction of branching that the leaders moved from the cloud toward the ground, and thus this is a typical downwards strike. *Photo credit: FreImages.com/TJ Smith.*

Physics, a positive CG strike transfers positive charge from a region of positive charge in the cloud to the relatively negatively charged ground. Due to the charge separating processes of clouds, a majority of lightning is negative, though this also depends on region, storm characteristic, and even time of year. In data provided by Vaisala for this study, the ratio of negative to positive lightning flashes ranges from 33:1 in the Lakeland, Florida study area to only 5:1 in the Duluth, Minnesota study area.

Lightning can, in rare instances, be bipolar, wherein zones of negative and positive charge in a cloud successively exploit the same channel of heated air established by an initial strike.
The direction of initial lightning propagation also varies. Lightning strikes of either polarity most commonly initiate downwards from a cloud (see Section 1.3 below), but tall, pointed objects such as communications towers are known to initiate upward strikes as well.

1.3 The Lightning Flash

Thus far, I have been using the common but informal term of lightning “strike” to refer to the occurrence of lightning. Atmospheric physicists, however, use the more specific terms flash and stroke to differentiate between what we may think of when we say a lightning strike (a flash) and the individual pulses of current (strokes) that travel along the ionized air channel established by the lightning process. One lightning flash may comprise one or more strokes. Multiple stroke lightning flashes are common, and they are the reason lightning often appears to flicker to the human observer. Throughout the rest of this thesis, I will drop the term strike and use the more specific terms flash and stroke.

Lightning begins with charge separation in a cloud (Figure 2). While the specifics of this process are not fully understood and various mechanisms are still debated, a common view holds that the accumulation of super-cold water droplets on icy agglomerations known as graupel results in a net charge on the graupel. The polarity of this charge depends on temperature. At temperatures between roughly -10°C to -25°C, this process
apparently delivers a negative charge to the graupel particles, while leaving surrounding ice crystals with a positive charge. According to the theory, gravity then provides the mechanism for overall charge separation as graupel particles are larger, heavier, and have less surface area per unit volume than the ice particles, and thus they carry their negative charge downward.

Figure 2—Highly simplified schematic of graupel-induced charge separation in a cloud. Light, positively charged ice crystals are carried upwards on strong updrafts whereas larger, denser, negatively charged graupel particles fall downwards. Photo credit: Freimages.com/George Lioio

However it occurs, charge separation results in electric field gradients between zones of differing charge. These field gradients may produce leaders, channels of ionized gas in which electrons move to one end. The formation of leaders is also poorly understood and actively debated.
Within a cloud, a leader forms a bipolar conductive channel. In the case of a negative cloud-to-ground flash, the positive end of the leader commonly spreads within regions of negative charge in the cloud while the negative end moves downwards towards the ground as a stepped leader, so-called because it propagates through cool air in quick, short pulses (whereas a positive leader, or a negative leader moving through an established conductive channel, moves continuously).

The attraction of lightning to objects on the ground is perhaps best understood in terms of electrical potential. As the highly negative leader approaches the ground, it establishes a conductive channel that brings the potential of the negatively charged zone in the cloud closer to the relatively positive ground, increasing the gradient of the electric field as the distance between leader and ground decreases. Tall objects on the ground are particularly subject to this gradient increase as they carry the ground potential to a higher elevation (for example, see Figure 15 in Section 4.6). Pointed, conductive objects locally distort electrical fields, causing a charge accumulation at their tips that can induce the formation of additional leaders (Figure 3). These positive upward leaders (also known as connecting leaders) move toward the incoming stepped leader, further increasing the electric potential gradient. At some distance, known as the strike distance, this gradient reaches a critical value and the charge jumps from the stepped leader to the upward leader, establishing a continuous conductive channel from cloud to ground. Strike distances are typically small, on the order of tens of meters for lightning hitting objects near the ground, and they may be an important factor in
considering the potential effects of ground conductivity on strike distribution (Section 4.5).

Figure 3—Upward leaders rising from wind turbines. Note that the leaders shown here are precursors to upward lightning, rather than the typical, brief upward leaders that form in response to an approaching downward leader from a cloud. From: Montanyà et al., 2014.

With a conductive channel established, a rapid cascade of downward moving electrons propagates upward from the point of contact and into the charged zone of the cloud. This event is known as the return stroke, and it quickly depletes the local charge reservoir within the cloud. The intense discharge of energy in the return stroke is the brightest part of the lightning flash. It explosively heats surrounding air to values of around 30,000 degrees Celsius, creating the pressure waves we hear as thunder.

The positive end of the initial bipolar leader, inside the negatively charged zone of the cloud, may have branched extensively throughout this zone while the negative leader
propagated downwards to the ground. These positive branches can disconnect. When
this happens, the sudden depletion of charge in the negative zone caused by the return
stroke can activate the negative end of a disconnected leader. This new negative
leader, called a **recoil leader**, propagates within the cloud back into the recently
depleted area where the negative zone was.

If a recoil leader connects with the hot, conducting channel established by the return
stroke, it becomes a **dart leader**, travelling rapidly towards the ground along the same
channel as the initial stroke. When the dart leader contacts the ground, a subsequent
return stroke is established, draining the area of charge accessed by that particular
branch of the initial positive leader. This can happen multiple times, and thus as
mentioned earlier a single lightning flash can have multiple strokes. Subsequent return
strokes are generally smaller in magnitude than the initial return stroke.

Positive cloud-to-ground lightning behaves similarly, but with the negative leader
propagating within a zone of positive charge inside the cloud and the positive leader
extending towards the ground. Due to their physical differences (a positive leader is
characterized by a relative absence of electrons, whereas a negative leader is formed by
the electrons themselves), positive leaders often move in a continuous fashion, and thus
the term “stepped leader” generally applies to a negative downward leader. In
addition, negative leaders within the cloud do not disconnect in the same manner as
positive leaders, so recoil leaders are much less likely to form during positive lightning
events, and thus positive flashes with multiple strokes are relatively rare.
In addition to multiple strokes, a single lightning flash can and often does have multiple ground contact points.

1.4 Ground Conductivity

Earth’s surficial materials cover a wide range of electrical conductivity values. Bedrock alone can vary from conductivities of 10-100 siemens per meter in certain massive sulphide deposits and graphitic zones down to $10^{-5}$ siemens per meter for certain unweathered igneous rocks and carbonates (Palacky, 1987), a span of seven orders of magnitude (Table 1). These are rough guides, however—depending on factors like weathering state (ibid), porosity and water content (e.g. Robinson et al., 2003), itself linked to porosity, these values can change drastically. Massive sulphides are also known which have very low conductivity, and weathered surface materials can have conductivities similar to graphite (Palacky, 1987).

Water also varies considerably in conductivity depending on its state and ionic content—salt water can overlap with highly conductive massive sulphides in its conductivity, whereas fresh water is less conductive and frozen permafrost can be as resistive as limestone and igneous rocks (ibid).

Further complicating the picture are overburden, soil, vegetation and anthropogenic infrastructure. Railroad ties, for example, have conductivities of $4.4 \times 10^6$ siemens per
Table 1—Common ranges of conductivity values observed in earth materials. Adapted from Palacky, 1987.

meter (Hill et al., 1999), more than four orders of magnitude above some of the most conductive geological materials.

1.5 Previous Work

Very little work has been done examining the effects of terrestrial conductivity on lightning strike distributions.

One early laboratory test suggested a tendency for positive lightning strikes to steer towards a metallic (“iron ore”) vein hosted in a relatively non-conductive medium (sand), whereas negative strikes were observed to contact the ground surface randomly regardless of conductivity differences (Norinder & Salka, 1949). Unfortunately, the reported results of this testing (Figure 4) are not quantified, and thus the significance of
the effect is somewhat ambiguous. It is also important to note that such laboratory testing effectively creates a long spark, which is not necessarily analogous with the propagation of a downward leader at much larger scales in actual lightning (Berger, 1967). If anything, these tests might offer insight into the final connecting behavior of a downward leader as it comes within its strike distance of upward leaders rising from the ground (see Figure 15 in Section 4.6).

![Diagram](image)

**Figure 4**—Results from Norinder & Salka (1949), showing a tendency for laboratory generated sparks to steer towards an “iron ore” vein in a sandy medium.

A later study, similar in motivation to the current study, analyzed lightning location data recorded from 1992 through 2000 in Alberta, Canada in light of local geology, but was hampered by uncertainties of up to 6.5 kilometers in lightning location accuracy and was thus unable to arrive at any firm conclusions (Robertson, 2003).
In 2008, a team of researchers analyzed lightning location densities in southern Brazil with respect to different soil types based on metal content of the soils, finding no correlation (Bourscheidt et al., 2008b).

Most recently, members of the private Texas-based company Dynamic Measurement, LLC (DML) have produced several conference articles and a presentation reporting strong correlations among both cloud-to-ground lightning distributions and lightning stroke characteristics with geological conductivity and even lunar tidal pull (Nelson et al., 2013; Haggar et al., 2014; Haggar & Nelson, 2014; Haggar et al., 2015a; Haggar et al., 2015b), while stating that infrastructure like modern wind turbines, commonly accepted to increase lightning activity (e.g. Eriksson, 1978; Golde, 1978), have a relatively minor influence on lightning strike distributions (Nelson et al., 2013). The company recently acquired a patent for their method of inferring ground conductivity from lightning stroke characteristics (Denham et al., 2016). These commercial endeavors are discussed further in Section 4.7.

1.6 Project Areas

Twelve regions in the continental United States were selected for this study (Figure 5). Following initial exploratory data analysis, each of these regions was examined with more rigorous tests to analyze flash distributions and flash densities in light of geological
lithology, faults, and conductive anthropogenic features, specifically railroads, communications towers and windmills.

Geographic extents for each study area, along with the primary motivation for its selection, are summarized in Table 2.

Figure 5—Approximate study area boundaries (black) plotted over flash densities for the contiguous United States. Boundary coordinates for each study area are listed in Table 2. Flash density figure from Vaisala, used with permission. In the text, the study areas are referred to as follows:

1: Coosa, Alabama 7: DeWitt County, Texas
2: Ouachita, Arkansas 8: Colorado County, Texas
3: Lakeland, Florida 9: Sevier, Utah
4: Jefferson, Idaho 10: Willis, Virginia
5: Duluth, Minnesota 11: Iron Mountain, Wyoming
6: Pecos, New Mexico 12: Yellowstone, Wyoming
<table>
<thead>
<tr>
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<th>Latitude</th>
<th>Longitude</th>
<th>Primary Rationale for Selection</th>
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<tr>
<td>North</td>
<td>South</td>
<td>West</td>
<td>East</td>
</tr>
<tr>
<td>1 - Coosa, Alabama</td>
<td>33°10' N</td>
<td>86°40' W</td>
<td>86°00' W</td>
</tr>
<tr>
<td>2 - Ouachita, Arkansas</td>
<td>34°39' N</td>
<td>94°26' W</td>
<td>92°48' W</td>
</tr>
<tr>
<td>3 - Lakeland, Florida</td>
<td>28°12' N</td>
<td>82°57' W</td>
<td>81°10' W</td>
</tr>
<tr>
<td>4 - Jefferson, Idaho</td>
<td>44°12' N</td>
<td>112°50' W</td>
<td>111°36' W</td>
</tr>
<tr>
<td>5 - Duluth, Minnesota</td>
<td>47°52' N</td>
<td>92°14' W</td>
<td>91°26' W</td>
</tr>
<tr>
<td>6 - Pecos, New Mexico</td>
<td>35°20' N</td>
<td>106°10' W</td>
<td>105°03' W</td>
</tr>
<tr>
<td>7 - Colorado County, Texas</td>
<td>29°53' N</td>
<td>96°50' W</td>
<td>96°13' W</td>
</tr>
<tr>
<td>8 - Dewitt County, Texas</td>
<td>29°06' N</td>
<td>97°50' W</td>
<td>97°13' W</td>
</tr>
<tr>
<td>9 - Sevier, Utah</td>
<td>39°46' N</td>
<td>113°27' W</td>
<td>112°11' W</td>
</tr>
<tr>
<td>10 - Willis, Virginia</td>
<td>37°46' N</td>
<td>78°50' W</td>
<td>78°00' W</td>
</tr>
<tr>
<td>11 - Iron Mountain, Wyoming</td>
<td>41°49' N</td>
<td>105°33' W</td>
<td>104°57' W</td>
</tr>
<tr>
<td>12 - Yellowstone, Wyoming</td>
<td>44°46' N</td>
<td>111°03' W</td>
<td>110°15' W</td>
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Table 2—Study area boundaries with basic selection rationale.
METHODS

2.1 Data Collection

All lighting data used in this study were collected by the company Vaisala using their National Lightning Detection Network (NLDN) in the United States. This network employs electromagnetic sensors to detect broadband atmospheric radio pulses, often called sferics, that are produced by lightning activity. A combination of time-of-arrival techniques, broadly similar to those used in seismology, and direction finding techniques are used across multiple stations to locate lightning strokes and, in the case of CG strokes, their ground contact locations (Cummins & Murphy, 2009). Following upgrades to the NLDN in 2002-2003, median location accuracies for CG strokes across much of the contiguous USA are thought to be 500 m or less (ibid).

Not all lightning flashes are detected by the NLDN. Model estimates suggest that 60-80% of strokes and 90-95% of flashes (defining flash detection as detection of one or more of its constitutive strokes) are detected by the NLDN following its 2002-2003 network upgrades (Cummins & Murphy, 2009).

Properties of lightning strokes can be deduced from the waveforms of their respective sferics. This includes differentiating between IC and CG strokes, determining polarity, estimating peak electric current levels of a stroke, and calculating the rise time from establishment of a lightning channel through its peak current (Cummins & Murphy,
2009). But differentiating between IC and CG lightning can be difficult, particularly for positive strokes with low current amplitudes. A field-based campaign performed in 2003-2004 found that roughly ninety percent of positive CG strokes with amplitudes under ten kiloamperes reported by the NLDN were in fact IC strokes, whereas above twenty kiloamperes fewer than ten percent of reported positive CG strokes were actually IC (Biagi et al., 2007). Based on these results, in April 2006 Vaisala began truncating CG positive stroke data at a minimum value of fifteen kiloamperes (Cummins & Murphy, 2009). Another field-based study, which during 2005 examined 376 flashes from three separate storms in a region with high positive lightning activity, found that fifty-four percent of CG strokes reported by the NLDN were in fact IC, and that among these misclassified events, fifty-nine percent were assigned the wrong polarity (Fleenor et al., 2009). Had the fifteen kiloampere cut-off been applied in 2005, only thirty percent of strokes would have been misclassified (Cummins & Murphy, 2009).

Nonetheless, uncertainty exists in the lightning data, particularly in strokes with low current amplitudes.

In August 2015, Vaisala applied upgrades to the NLDN that increase their confidence in the ability to distinguish positive CG strokes from IC strokes, and thus began reporting values below fifteen kiloamperes once again (Ron Holle, personal communication 2016).
2.2 Lightning Data

Vaisala provided lightning stroke location data recorded by the NLDN for twelve areas in the continental United States (Table 2 and Figure 5), spanning the period from January 1, 2006 through December 31, 2015 inclusive. Each data file lists seven properties for each stroke: The date and time to millisecond precision in UTC, the latitude and longitude of the ground contact point in decimal degrees to four decimal places (corresponding to roughly 10 meter precision), the peak current magnitude in kiloamperes (from which polarity is easily deduced by the sign of the current), the rise time to peak current in microseconds, and the location accuracy of the stroke record in kilometers, reported as the length of the semi major axis of a fifty percent probability ellipse.

Vaisala truncates rise times greater than 30 microseconds in order to limit the size of their data stream. Such events are rare, and should not affect this analysis.

As an example of Vaisala data, Figure 6 shows the plotted locations of positive flashes and density of negative flashes for the Jefferson, Idaho study area.
Figure 6—An example of plotted Vaisala data spanning 2006 through 2010 in Jefferson, Idaho. Positive flashes are blue, with older events colored navy blue and more recent events grading to cyan. Negative flashes are too numerous to show at this scale, so they are represented by a heat map, with red corresponding to the highest densities. Note the red area in the southeast corner of the study area—this is caused by a large wind farm on the underlying ridges. Imagery courtesy of TerraMetrics, obtained through Google Earth.
2.3 Data processing

Unless otherwise specified, all data processing and subsequent analyses were performed using R (R Core Team, 2014), along with visualization in Google Earth and using data provided by Google Maps.

In order to remove potential noise at any location, strokes with fifty percent probability ellipses exceeding one kilometer on their semi-major axis were excluded from analyses. It is possible that this could introduce a bias, particularly if some characteristic of these poorly located strikes also makes them most susceptible to influence from ground conductivity. But given the large uncertainty in their locations, it would presumably be difficult nonetheless to infer any localized effects from these strikes. On average, this meant removing one eighth of the strikes in a given study area.

Individual flashes—which can comprise multiple strokes—were determined by grouping strokes that occurred within two thousand meters and one half second of each other. This is similar to the NLDN’s practice of grouping strokes that occur within ten kilometers and one half second of each other (Cummins and Murphy 2009), but with tighter spatial restrictions imposed to help differentiate between multiple strokes along a single channel and multiple widely-spaced ground contacts from a single flash. The effectiveness of this differentiation technique is unknown, but separating multiple contacts from multiple flashes along a single stroke would prove useful in assessing preferred strike locations, as each separate ground contact location within a flash is determined in part by competing upward leaders.
For lightning stroke attribute analysis, rise times shorter than and equal to one microsecond and rise times greater than and equal to thirty microseconds were removed. Some very small reported rise times (as low as zero microseconds) are possibly erroneous, and created outliers in the data as well as infinite rise rates. Values at thirty microseconds are artifacts of Vaisala’s practice of truncated reported rise times above that threshold.

2.4 Ripley K and Besag’s L Functions

Ripley’s K function provides a means of testing an observed point pattern for complete spatial randomness. By comparing point densities observed around data points to the overall density of the process, one can get a sense of whether a point pattern is clustered, random, or ordered.

The K function is defined as the expected value of points within a radius \( r \) divided by the intensity \( \lambda \) of the process:

\[
K(r) = E[... |r|] / \lambda
\]

For complete spatial randomness (CSR), the expected value is simply the intensity of the process multiplied by the area of the circle defined by \( r \):

\[
E[... |r|] = \lambda \pi r^2
\]

\[
\therefore K(r) = \pi r^2
\]
For ease of interpretation, Besag’s L transformation can be applied (Besag, 1977).

Besag, noting that the above K function depends only on distance $r$, normalized it to $r$:

$$L(r) = \sqrt{K(r)/\pi}$$

Thus, under CSR:

$$L(r) - r = 0$$

Assuming stationarity, a positive Besag values suggest clustering, whereas negative values suggest repulsion between points as seen in an ordered grid pattern.

Each study area was divided into ten by ten kilometer sub areas, and Besag’s L function was plotted for each using the “Lest” function in R’s “spatstat” package (Baddeley & Turner, 2005). Positive and negative flashes were also separated and analyzed independently, and the two flash types were checked for spatial interdependence using Besag’s L function applied to the point locations of one while counting the points of the other.

Edge effects were accounted for using Ripley’s isotropic correction (François, 1999), wherein values are scaled according to the fraction of the circle defined by $t$ falling within the study area.
2.5 Mark Variograms

Lightning flash location data, combined with attributes measured from associated electromagnetic waveforms, represent marked point processes in that each point in the spatial point pattern is accompanied by information which is not just sampling from a random spatial field (Wälder & Stoyan, 1996). To test for spatial continuity of these attributes, which might be influenced by ground conductivity, mark variograms were used.

These mark variograms were generated for various attributes of each strike using the “markvario” command in the R package “spatstat” (Baddeley & Turner, 2005). Similar to variograms, mark variograms test the degree of spatial variance among point values at differed distance ranges. As with Ripley K functions, edge effects must be accounted for.

Total current, rise time, rise rate, time of strike and stroke multiplicity were considered separately for both negative and positive flashes. Stroke multiplicity was calculated as described in Section 2.3 whereas rise rate is simply the peak current of a stroke divided by its rise time. To ease computational burden and to better identify localized effects, each study region was broken down into ten kilometer by ten kilometer cells which were analyzed separately from each other.
2.6 Gridded Flash Counts

Lightning flash counts were tallied by breaking down each study area into a square grid of 250 by 250 meter cells. The latitude and longitude location of each point were converted to the UTM coordinates of their corresponding UTM zones in WGS 84 using the R packages “sp” (Pebesma & Bivand, 2005; Bivand et al., 2013) and “rgdal” (Bivand et al., 2015). As this re-projection generally tilts a rectangle defined by latitude and longitude, creating wedges without data on the edges of a square plot, the edges of the grid in excess of integral multiples of 250 meters were discarded symmetrically. The value of each grid cell in the count maps is simply the number of lightning flashes contained within.

2.7 Gridded Stroke Attributes

Using the same 250 by 250 meter grid structure defined above (Section 2.6), peak current, rise time and rise rate (defined in Section 2.5) for each stroke in a given grid cell were averaged, as well as stroke multiplicity values for each flash within a grid cell. The variance of each attribute within each grid cell was also calculated.
2.8 Flash Density by Geology

Geological maps of each relevant state were obtained as shapefiles from the United States Geological Survey’s “Preliminary integrated geologic map databases for the United States” compilation project (Ludington et al., 2005; Stoeser et al., 2005; Nicholson et al., 2005; Dicken et al., 2005a; Dicken et al., 2005b). The original map scales of these data range from 1:100,000 to 1:1,000,000 (ibid), and thus the smallest mapped rock units are on the order of one hundred meters across. Geology data was loaded into R using the “maptools” package (Bivand & Lewin-Koh, 2016), cropped using the “raster” package (Hijmans, 2015), and re-projected to UTM for area calculations using the “sp” package (Pebesma & Bivand, 2005; Bivand et al., 2013).

Flash densities for each unit were computed using the R package GISTools (Brunsdon & Chen, 2014) by summing flash locations falling within the boundaries of each lithology (ROCKTYPE1 in the USGS data). Ninety-five percent confidence intervals were calculated for a spatial Poisson point process with intensity set by the overall density of strikes in the corresponding study area using the “stats” package in R (R Core Team, 2014).
2.9 Flash Density by Elevation

The National Elevation Dataset, compiled by the United States Geological Survey, provides a seamless elevation raster for the contiguous United States at one third of an arc second resolution, or roughly ten meters per pixel (USGS, 2016a). Elevation values for each flash were assigned from this dataset using the “extract” function in the “raster” package in R (Hijmans, 2015), and compared to the total area at each elevation to get densities. Results were binned for plotting at different intervals for different study areas, depending on the total topographic range in a given area.

2.10 Flash Density by Distance to Towers

Tower location information was obtained as shapefiles from the U.S. Federal Communications Commission's (FCC’s) International Bureau Filing System (USGS, 2003a) and Antenna Structure Registration program (USGS, 2003b), which requires all antennae structures above two hundred feet tall (sixty one meters) to be registered. Site checking of FCC records using Google Earth showed that locational errors between fifty and one hundred meters were common, and in a few instances, no antennae structure could be found in satellite imagery for the location. In other cases, unreported towers are likely present as the data form a snapshot of registered tower locations in November 2003, and are thus two to twelve years outdated. Nonetheless, these records serve as good indicators of existing antennae positions. Industrial wind turbine locations for the entire
United States were provided by the USGS (Diffendorfer et al., 2013), and location records proved accurate on inspection in Google Earth to within meters, with no missing records observed. With the 2013 data, it is possible that some towers were constructed during the study period.

Distance to point rasters were generated with a 50 m cell size using the “raster” package in R (Hijmans, 2015), and compared to point densities for lightning flashes. Areas were calculated by binning distance ranges and multiplying each binned count by the area of each cell in the raster.

2.11 Flash Density by Distance to Faults

Fault shapefile information accompanied geological data obtained from the United States Geological Survey’s “Preliminary integrated geologic map databases for the United States” compilation project (Ludington et al., 2005; Stoeser et al., 2005; Nicholson et al., 2005; Dicken et al., 2005a; Dicken et al., 2005b). The original map scales of these data range from 1:100,000 to 1:1,000,000 (ibid), and thus only significant faults appear in the data. Fault data was loaded into R using the “maptools” package (Bivand & Lewin-Koh, 2016), cropped using the “raster” package (Hijmans, 2015) and converted to UTM using the “sp” package (Pebesma & Bivand, 2005; Bivand et al., 2013). Each study area was then rasterized at fifty meter resolution, with the distance
to the nearest fault assigned as the raster cell value. Lightning strikes were assigned
distances to faults using these values, and binned at one hundred meter intervals.

2.12 Flash Density by Distance to Railroads

Railroad location data was obtained from the United States Geological Survey’s National
Transportation Dataset (USGS, 2016b). Processing in R followed the same steps as
above for faults.
RESULTS

3.1 Ripley’s K Functions

Figure 7 shows Besag L corrected plots of Ripley’s K functions for Coosa, Alabama and Ouachita, Arkansas, each broken down into ten kilometer by ten kilometer segments. The figure demonstrates various features seen throughout the project areas.

In the Coosa, Alabama data, several plots depart upwards from the ninety five percent confidence interval between 250 meters and 300 meters from zero, a similar distance to reported lower location accuracy of the NLDN data (Cummins, 2009). The upward departure indicates flash clustering at this scale. By the one kilometer mark, roughly half of the plots exceed this bound, and the ongoing upwards slopes indicate clustering across various scales. Only one plot in the study area runs below the zero mark, suggesting that flashes there are more evenly distributed than random, though the effect is small and within confidence bounds of CSR. Also of note is the sharp negative departure near zero distance—this is an artifact of the finite density of the lightning locations, as there is an average minimum distance between points.
Figure 7—Ripley K function plots after Besag’s L correction, wherein a zero value denotes CSR. Each line corresponds to a 10 by 10 kilometer region within the study area. Colors are assigned by latitude. The grey rectangle denotes 95% confidence bounds based on 39 trials of CSR for a similar flash density.
Ouachita, Arkansas comprises a larger study area and thus more ten kilometer by ten kilometer plots are shown. Though the figure is somewhat chaotic, there are several points to note. First, most of the plots fall within the confidence bounds for CSR. Of those that don’t, some rise quickly and then level off, others rise more or less continuously, and several, including the black line that rises most sharply from the origin, peak around the 250 to 300 meter range and then drop back towards values more typical of CSR. These results are discussed further in Section 4.1.

Through Ripley K testing, no significant spatial interdependence was observed between negative and positive flashes.

3.2 Mark Variograms

To test whether the attributes of lighting flashes—namely peak current, rise time, rate of rise time and stroke multiplicity—have any dominant spatial dependence, mark variograms were constructed. Figure 8 offers a roughly representative sample of overall results across study areas, measured here in the Coosa, Alabama study area in the ten kilometer by ten kilometer region surrounding the Coosa graphite deposit. As can be seen, each variogram almost immediately reaches a sill, suggesting that the point attributes are not strongly correlated in space. One possible exception to this is shown by the positive stroke rise rate plot, which increases with increasing distance.
Figure 8—Mark variograms for flash attributes in the ten by ten kilometer zone surrounding the Coosa, Alabama graphite deposit. The top four figures show negative flashes, whereas the bottom four show positive flashes. Mark variograms are plotted using both Ripley’s isotropic correction (black – François, 1999) and the translation method (dotted red – Osher, 1987) to account for edge effects.
3.3 Flash Density by Elevation

Gridded flash densities reveal a strong but variable influence of topography on flash distributions. Figure 9 juxtaposes flash density maps for the Pecos, New Mexico and Ouachita, Arkansas study areas with their digital elevation models. Plots of average flash densities for different elevation ranges are also shown. These two areas have more rugged topography than other study areas, and thus associated topographical effects are more readily visible in the maps. For overall legibility of the average flash density plots, several high-density values (roughly double the maximum density value shown) corresponding to communications towers on topographic highs were excluded.

In both density maps, features of the corresponding digital elevation models can be identified. High flash densities generally correlate with specific topographical highs, whereas local topographic lows (gullies and stream channels) are particularly notable for their lower lightning densities.
Figure 9—Total flash density values with respect to elevation for a subset of the Ouachita, Kansas study area (left) and the Pecos, New Mexico study area (right). The top figures are scatterplots of flash density vs. elevation, with darker blue points corresponding to larger total areas for a given elevation (and thus lower expected variance in a result). The middle figures map observed flash densities with 250 meter by 250 meter grid cell resolution. For visibility, flash densities in these plots are truncated at 30 and 15 flashes per grid cell for the Ouachita and Pecos areas respectively. The bottom figures show corresponding digital elevation models.
3.4 Flash Density by Geology

Widespread, direct measurements of geological conductivity in most of the study areas are unknown to the author. However, given the wide range of conductivity values between different bedrock lithologies, it seems plausible that if ground conductivity influences the spatial distribution of lightning, different geological units might be subject to different strike densities when other conditions are the same.

Figure 10 shows lightning strike densities for each of the geological units in the Coosa, Alabama study area over the ten years from 2006 through 2015, along with the associated geological map. Densities vary broadly between plots, more so than would be expected given a CSR point process based on observed Poisson p values. All units can be observed exceeding their ninety five percent confidence intervals based on CSR in either direction. Similar results were observed across the other study areas. In Coosa, the exception to this is quartzite, which exceeds the CSR ninety five percent confidence interval in seven of the ten years, and never falls below. This unit forms a pronounced ridge in the relatively flat and low-lying northwestern corner of the study area.
Figure 10—Flash densities by rock type for the Coosa, Alabama study area. The map in the top left shows geology, with graphitic schist units colored black, sandstone colored light blue, and the Coosa graphite deposit marked by a red dot. The top center map shows the DEM for the region, with lighter colors corresponding to higher elevations. Annual histograms highlight graphitic schists and quartzite units using the same coloring as the geological map. Flash density units are flashes per square meter per decade.
3.5 Flash Density by Distance to Towers

Figure 11 demonstrates the effect of tall, conductive anthropogenic structures on lightning flash distributions. Towers and windmills generally produce an increase in lightning activity, as illustrated by the peaks in flash densities along the left sides of the plots. The effect appears to be constrained to the nearest 250 meters.

Figure 11—Flash densities vs. distance to towers. Ouachita, Arkansas shows the most pronounced trend, with a strong contribution from the 325-meter-tall Gurdon Arkansas Education Television Tower (33° 54’ 26.73” N, 93° 06’ 46.61” W), which averaged more than ten flashes and thirty strokes per year throughout the ten-year study period. Other areas exhibit similar trends, with the highest flash densities within several hundred meters of towers.
It is not readily apparent from gridded positive flash density maps, which are somewhat sparse in all study areas, that positive strikes cluster around towers (for example, Figure 6). From plots of distance vs. density, however, it can be seen that both flash types indeed have higher densities near towers, though the effect is not as strong for positive strikes. The discrepancy is likely a result of the relatively low density of positive strikes.

3.6 Flash Density by Distance to Faults

Faults often serve as conduits for electrically conductive groundwater, and in some areas are associated with the development of graphite-rich shear zones, which are also conductive (Palacky, 1987). For this reason, comparing lightning flash densities to fault proximity may provide a means of detecting the effects of heterogeneous geological conductivity on flash distributions.

As Figure 12 shows, however, no obvious correlation between mapped faults and strike densities was detected in the survey. Pecos, New Mexico and Duluth, Minnesota show flat density distributions typical of most other areas, indicating no correlation between the two variables. Coosa, Alabama shows a slight trend of decreasing densities away from the fault for the first 2.5 kilometers. This effect, however, is minor, and it may be an artifact arising from the fact that mapped faults in this area are concentrated in higher regions, where exposure is better and thus faults can be found. Jefferson, Idaho has the most dramatic distribution, with a pronounced decreasing trend in strike
densities for the nearest 10-12 kilometers to faults. Here, however, the effect is almost
certainly due to a mapping bias, as no faults are mapped in the central, flood basalt
filled Snake River Valley. The highest strike densities in the Jefferson area occur around
wind farms in the mountainous southeast of the study area, which corresponds to the
region where roughly half of the mapped faults of the study area occur (the other half
are in the mountains of the northwest corner, which does not have wind farms nor the
associated high flash densities). It is thus likely that the combined presence of high
mapped fault densities and abundant wind turbines accounts for the trend.

Figure 12—Flash densities vs. distances to faults. Each point is colored with respect to total area
available to calculate density, with lighter blues using less area and thus subject to higher
variance.
Interestingly, for both the Jefferson and the Coosa study areas, positive flash densities show no correlation with fault densities. In Jefferson, this is consistent with the earlier observation that positive flash densities are not drastically increased by the presence of the wind farm.

3.7 Flash Density by Distance to Railroads

Given that faults are variably conductive, subjectively and selectively mapped, and only partially exposed on surface, it is not particularly surprising that their analysis failed to show any obvious trends. Even if a well-exposed section of fault were highly conductive and had an effect on lightning flash patterns, it might be masked in such a broad analytical approach by an abundance of other less conductive or buried faults without such an effect. As such, the test was repeated on a highly conductive, completely and accurately located and well-exposed feature: railroads.

The results are tallied in Figure 13, and despite the better exposure of railroads, the results are broadly similar to the fault data. In Jefferson, Idaho, the high flash densities around the wind farm in the southwest result in an apparent trend of increased lightning density as distance from the rail increases (note that this is the same cause, but opposite effect of the higher wind farm flash values on the fault analysis due to the faults’ locations in the mountains and the railroads’ locations in the valleys). Pecos, New Mexico exhibits a similar trend as the railroads there bypass the highest flash
densities in the mountainous center of the study area. Coosa, Alabama and Duluth, Minnesota both display a high degree of variance in densities near railroads, but overall are relatively flat.

Figure 13—Flash densities vs. distance to railways. Each point is colored with respect to total area used in calculating density, with lighter blues using less area and thus subject to higher variance.

3.8 Attribute Maps

For most study areas, attribute maps appear largely random, with a few outlying values corresponding to towers and the presumably unique characteristics associated with the
upward lightning rising from those towers. This agrees with the mark variogram results of Figure 8.

The Lakeland, Florida study area, however, is a notable exception, as the attribute maps are clearly not random, but instead show a spatial correspondence to certain surface features. Figure 14 compares average rise rates and rise time variance for the region to satellite imagery obtained from Google Earth. The white spots (highest rates) in the rise time plot correspond to communications towers. Interestingly, ground checking of these spots using Google Earth revealed towers that are not apparent in the gridded flash density plots. Dark regions (lowest rates) appear to correlate well with thickly forested swamps. There is also a general trend for higher rise rates towards the Gulf of Mexico in the west of the study area. Rise time variances in the lower plot do not share the strong correspondence with towers and forested swamps, but they do reveal another trend in the form of a broadly curved, concave west linear feature at around 380000 meters East, with higher rise time variances immediately east of this feature. This feature does not appear to correlate with elevation or with any obvious feature in the satellite imagery.
Figure 14—Grid averaged rise rates (top) and rise time variances (bottom) for the Lakeland, Florida study area. Rise rates are capped at 12 MA/s. The city of Tampa Bay is visible in the left center of the map. Grid units correspond to UTM Zone 17N, with Easting on the bottom and Northing on the left axis. Satellite imagery courtesy of Landsat, sourced from Google Earth.
DISCUSSION

4.1 Spatial Randomness

The Ripley K functions in Figure 8 clearly indicate at least some clustering on scales ranging from the locational accuracy limit of the NLDN through at least 1.5 kilometers. Given the dependency of flash density on elevation, some of this clustering might well be expected from topography within the study areas, and this appears to check out. In the Ouachita data, almost all plots exceeding the ninety five percent confidence intervals for CSR come from the northern half of the study area, where pronounced linear ridges cause obvious patterns in the data (Figure 9). These plots tend to rise and level out, or continue rising depending on the scale of the spacing between the linear mountain ridges in the area. The clustering effect of communication towers is also apparent. The steep black line rising almost immediately from the origin in Figure 7 corresponds to the subplot enclosing the 325-meter-tall Gurdon Arkansas Education Television Tower (33° 54’ 26.73” N, 93° 06’ 46.61” W), likely one of the most lightning-struck objects in the United States, averaging more than ten flashes and thirty strokes per year throughout the ten-year study period. Note that this clustering is localized. Beyond one kilometer the plot returns to a reasonable range for CSR. Topographically flat, low lying sub regions contribute the rest of the plots in Figure 7, which fall within the confidence interval calculated for CSR. Thus, when topography and tall structures are not a factor, flash locations appear to be completely random.
Although it is not shown in the figures, Ripley K functions for shorter time intervals have a higher degree of clustering. This is likely due to a high degree of variability of strike density from year to year, as a single storm in one part of a study area can show a strong influence on that year’s spatial distribution, but such discrepancies are reduced as more data is accumulated.

4.2 Attribute Correlation

The Lakeland, Florida study area attribute maps (Figure 14) show a correspondence between strike attributes and location, with heavily forested, presumably freshwater swamps corresponding to distinct zones of low rise rates. Accordingly, stroke rise times are notably higher in these zones as well. It may be that such swamps are less conductive, and thus when a current channel is established between a charge zone in the cloud and such a swamp the charge cannot drain as quickly as it would in another area.

The vegetation itself appears to be important in the effect, as freshwater lakes towards the east end of the study area do not show similar lows in average rise rates—in fact, several lakes show isolated high cell values. Thus, an alternative explanation might be that the plants themselves account for lower rise rates through an atmospheric effect induced by transpiration. Plant transpiration accounts for three quarters of land-based water vaporization (Caemmerer & Baker, 2007). Cloud charging and thus lightning
activity is affected by varying levels of water vapor (Rakov & Uman, 2003). So it may be that the excess water vapor from highly transpirative swamp forests affects cloud charge structures in such a way as to lessen the rise rates of strokes originating in those clouds. Or, it may be that this water vapor affects conductivity of plasma in the lightning channel once a stroke is established.

However, given the clear resolution in Figure 14 of observations of the effect on scales less than one kilometer, it seems more likely that a ground-based phenomenon like conductivity is responsible, as increased atmospheric humidity would be spread by wind and blur the attribute distribution. The idea that the effect is ground-based, and even conductivity-based, is further supported by observations of fulgurites, which are glassy structures created by lightning discharge through sand and other ground material. Fulgurite paths show that lightning current unsurprisingly travels preferentially along more conductive layers in soil, and along conductive objects in the ground (Fisher, 1994). This demonstrates that conductivity differences do play a role in lightning induced currents in the ground, and thus it is not a large jump to infer ground conductivity might well play a role in electrical current properties of a lightning stroke as well.

A second feature of note in the Lakeland, Florida study area is the long, curved feature running roughly north to south in the bottom of Figure 14, formed by a sharp increase in the variance observed in rise times for each grid cell. The cause of this feature is not obvious. It does not appear to reflect elevation, nor does it correspond to any clear
features in satellite imagery. It may represent an atmospheric phenomenon related to weather patterns moving in off the Gulf of Mexico, or, if ground conductivity is involved, it might relate to a freshwater/saltwater interface in near-surface groundwater.

Despite the correspondences observed in the Lakeland study area, the other study areas appear mostly random with respect to attribute distribution, both in their mark variograms and their gridded attribute plots. This may simply be because such strong, large-scale conductivity contrasts are not found in these areas. An exception, however, is the Pecos, New Mexico study area, which sees generally slow rise rates and higher rise times in its central mountainous zone. This could be related to the elevation itself and associated atmospheric processes, to differences in geological conductivity between the largely igneous mountains and sedimentary surroundings, to vegetation (the mountains are forested whereas the valley are open), or to something else entirely. Further investigation of this effect and the Lakeland effects are certainly warranted.

4.3 Elevation

Various effects of elevation on lightning occurrence have been documented previously. Reap (1986), for example, demonstrated a strong correlation between elevation and lightning activity in the western United States, thought to be due to an increase in atmospheric conductivity with increasing altitude. Similar correlation has been corroborated elsewhere (e.g. Bhavika, 2007, Smorgonskiy et al., 2013). Other studies
suggest that topographic controls such as slope and aspect can also be important in lightning development, particularly as they relate to regional weather patterns (Fosdick & Watson, 1995; Boursesidet et al., 2008a; Vogt & Hodanish, 2014; Muñoz et al., 2016).

The data in Figure 9 appear consistent with these studies. In addition to supporting the idea that flash density increases with elevation, the figure demonstrates the importance of local topographical features in dictating the distribution CG ground contact points. Thus there are both large scale and localized effects of topography.

It also shows that the correlation between density and altitude depends on additional factors. In the New Mexico data, for example, the highest mountain ridges along the north end of the study area have low strike densities, whereas lower ridges along the eastern flank of the mountain range and even the plains in the southwest corner of the study area have higher densities. This is likely a result of the influence of topography on regional weather patterns, blocking the movement and development of thunderstorms over peaks surrounded by other peaks while enhancing storm activity in certain low-lying areas adjacent to mountainous regions depending on direction. This pattern is consistent with those observed in New Mexico by Fosdick & Watson (1995).

As topography and elevation clearly affect lightning flash distributions, they should be considered in any analysis of lightning distribution patterns.
4.4 Geology

The results of geological density measurements suggest that broad-scale geology does not play a role in determining the contact location of cloud-to-ground lightning flashes. The Coosa, Alabama study area was initially selected based on its geology, particularly the presence of long linear units of graphitic schist—including one of the largest known graphite ore bodies in the United States (Wilson et al., 2015)—which should exhibit a strong conductivity contrast with surrounding felsic gneisses (Palacky, 1987). As Figure 10 shows, however, the schists and the gneisses have similar overall strike densities. They also vary similarly from year to year, likely due to their spatial proximity, which highlights the importance of annual weather patterns in determining strike densities. In the Coosa study area, effects of geology could be masked by vegetative overburden as the region is forested, and conductivity contrasts might also be masked by weathering—oxidized red soils are apparent in Google Earth’s imagery of the area. Nonetheless, as geological units in other study areas also lack strong correlations, it is likely that geology is not an important factor.

There is one exception to this, exemplified by quartzite in the Coosa, Alabama study area. Where units resistant to erosion form topographically prominent features, they will get hit by lightning more often based the previously discussed effects of elevation (Berger, 1967) and possibly shape (Eriksson, 1978). And although it was not observed, the opposite could well be true for units most susceptible to erosion. Of course, these effects have little to do with electrical conductivity.
4.5 Towers, Faults and Railroads

The observed increase in flash densities around towers (Figures 6 and 11) and the tendency of towers to stand out on gridded flash density maps demonstrate that lightning can indeed be used to detect the presence of certain objects. However, as these densities are much higher than those of surrounding areas, it seems that rather than “capturing” or attracting lightning that would otherwise strike nearby, the towers themselves are responsible for initiation of much of this excess lightning in the form of upward flashes. This is consistent with established understanding of the role of tall, grounded objects in lightning discharge, as observed by Berger (1967), Golde (1978) and others. The absence of a ring of lower flash density values around towers resulting from redirection of downward leaders towards towers lends further support to this idea (although if such a low-density feature did exist it might well be masked by the locational uncertainties of flashes hitting a given tower). Thus the observed clustering around towers suggests that any redirection of downward leaders occurs at a scale small enough that its spatial effects are obscured by the locational accuracy of the NLDN. This might also apply to any redirection towards low-lying features such as conductive fault zones and railroads, if any redirection exists at all.

Accordingly, density plots with respect to distance from railroads and faults are almost ubiquitously flat (Figures 12 and 13), and where they are not, the observed effects are readily explained by topography or tower locations (e.g. Pecos, New Mexico and
Jefferson, Idaho). Any influence of conductive features on lightning strike distributions must therefore be limited in extent. These conductive surface features do not appear to be generating any upwards lightning, as in the case of tall towers, nor do they appear to be redirecting lightning at any scale beyond that of the locational accuracy of the dataset. Assuming that railroads can be treated analogously to other conductive features on the Earth’s surface, the absence of any effect of railroads on strike distributions is perhaps the strongest empirical evidence in this study against conductive, flat-lying surface features playing a role in the spatial distribution of lightning flash contact locations. Such features would include conductivity differences in geology, overburden and groundwater.

Previous work supports these findings. Lalande et al. (2002), for example, demonstrate that the ability of a conductive object to produce a stable upward leader depends not only on the strength of the electric field gradient but also non-linearly on the object’s height, with low-lying objects at a particular disadvantage. Bourscheidt et al. (2008b) found no influence of metal content in soils on lightning flash distributions in Brazil.

4.6 Theoretical considerations

Both positive and negative downward cloud-to-ground lightning flashes initiate in the atmosphere as a result of charge separation within clouds (Rakov & Uman, 2003). It follows, then, that the spatial distribution of strike *initiation* points would be
independent of underlying ground, except as that ground influences relevant weather. Downward leader propagation is likely also strictly atmospheric for most of its trajectory (ibid, and further evidenced by the lack of large-scale ground-based attractors in the present study). Thus any influence of ground conductivity on flash locations, if present, is probably limited to the formation of upward leaders and the final attachment process of the downward leader. This would explain the lack of large-scale effects observed in this study.

Figure 15 offers a qualitative look at the moment before a negative downward leader connects with upward leaders by jumping the strike distance and establishing the return stroke channel. The figure is a simplified cartoon; in reality the attachment process depends on a wide range of factors including leader velocities, charge distributions in and strength of the downward leader, object geometries and relative positions and remains an active area of research (Becerra, 2008). The cartoon in Figure 15 is a variation of the “rolling sphere” method used in lightning strike protection system design and assessment, wherein an imaginary sphere of radius r representing an expected strike distance given a downward leader’s intensity is rolled over the object to be protected in order to determine the most likely strike points (Horvath, 2012).
Figure 15—Conceptual, simplified sketch of electric fields (grey lines) and leader formation (blue) above conductively heterogeneous ground immediately prior to negative CG attachment A) in the presence of tall structures, based on concepts in Cooray (2014) and Lalande et al. (2002), and B) on flat, exposed terrain. The circle around the downward leader represents the strike distance. Note in A) that due to the equipotential surface of the earth, the conductive feature in the ground (black) has no effect on the electric field gradient, which is commonly understood to be necessary in leader formation (e.g. Lalande et al., 2002). Unless, as in B), conductive ground is more efficient at forming upward leaders by some other means, it should have no effect on lightning strike locations even at the relatively small scales of the attachment process. However, if the downward leader causes a rapid shift in subterranean electric fields, then conductive zones might be expected to build positive charge more quickly and thus at surface be more likely to form leaders than more resistive ground. Such a process is purely speculative, however, and not based on observations made in this study. It would also need to be extremely efficient to compete with leaders forming directly underneath a downward leader.
In Figure 15A, note the effect of tall, grounded objects on the electric field. These objects bring the positive ground charge to a higher altitude, distorting the otherwise planar gradient of the electric field. The downward leader does the same thing with the negative charge zone of the cloud, bringing it closer to the ground. This compresses the overall gradient of the electric field, possibly steering the downward leader(s), and certainly allowing for the initiation and propagation of upward leaders. As taller objects see more field compression in this manner, they form these leaders more readily.

Leaders are highly conductive, and so they further propagate the ground electrical potential towards the downward leader. When an upward leader reaches the strike distance of the downward leader, the gap between it and the downward leader closes rapidly, and the return stroke channel is established.

Because conductive features in the ground are flush with the ground, they do not cause any such distortion in the electric field, and thus they are not selectively subject to the increased electrical field gradients seen by taller objects that initiate leaders.

Figure 15B considers the case of a planar surface with an exposed, conductive vein, similar to the laboratory setup of Norinder and Salka (1949). Given random propagation of the downward leader, the importance of the strike distance in leader selection is readily apparent. To capture a downward leader descending adjacent to a given conductive feature, the conductive feature would have to produce an upward leader much more efficiently than surrounding Earth surface materials. The model also
suggests that a downward leader with a larger strike distance would be more likely to find an upward leader from a conductive feature if such a leader were present, as the downward leader’s sphere of strike distances would present a flatter profile to the ground, thus approaching more potential upward leader sites.

Thus, if locational accuracies of lightning networks are improved to distances lower than the average strike distances of downward leaders (requiring at least an order of magnitude improvement over current accuracies), and if any such effects are actually present, they should then begin to appear in the spatial distribution data. Accounting for the strike distance of each stroke might yield conductive features such as railroads, faults, or certain exposed ore bodies. Even in such a scenario, however, given the worldwide paucity of flat, conductively heterogeneous ground devoid of overburden, infrastructure or thick vegetation yet within a zone of at least low to moderate lightning activity, such analysis may prove to have limited relevance for geophysical exploration of bedrock.

4.7 Commercial Considerations:

As the researchers behind the company DML make claims regarding lightning strike distributions that are not entirely congruent with the results of this study, a review of these claims seems warranted. The company offers geophysical interpretation of subsurface conductivity and oil prospectivity based on lightning strike distribution data,
including attribute data. A key claim is that lightning strike locations are more related to
geology and shallow earth currents than to any effects of topography, vegetation or
infrastructure (Haggar et al., 2015b). However, these claims are not well supported by
the case studies that DML presents.

In Nelson (2013), for instance, a map is shown of eight stroke locations near a line of
wind turbines in Texas. The strokes cover one hour of lightning activity during March 8,
2010, with three strokes occurring within two hundred meters of the turbines, three
more within four hundred meters of the turbines, and a final two strokes within eight
hundred meters of the turbines. Despite the fact that all of these strokes fall within
common error ellipse ranges for NLDN data from the wind turbines, and without
reference to or refutation of previous, well-documented work such as Eriksson (1978),
Golde (1978) or Montanyà et al. (2014), this is deemed strong evidence that tall
structures do not influence lightning distributions. Given NLDN location errors,
however, all eight of these strikes could very well have hit the towers.

Elsewhere, DML publications appear to be subject to the so-called Texas sharpshooter
fallacy, wherein data are cherry-picked to find patterns that appear to support a given
hypothesis, while contradictory data are ignored. An example of this can be found in
Haggar et al. (2015a), where channels of the Bayou Lacombe and the Big Branch
tributary are overlain on stroke density and attribute maps to show correlation, though
the features do not stand out independently and could easily be interpreted in many
other ways without the benefit of the overlay.
Nonetheless, the company has done some interesting, pioneering and potentially valuable work. What is perhaps DML’s most intriguing result is presented in Haggar & Nelson (2014). Average strike rise time and rate of rise time values are plotted for a coastal Louisiana wetland that is punctuated by three circular salt dome islands—Avery Island, Weeks Island and Cote Blanche Island—each roughly three kilometers in diameter. Such attribute-based spatial analysis is the basis of DML’s recent patent (Denham, 2016). In plots of both attributes, the islands appear anomalous in relation to the rest of the data, and the anomalies conform closely to the shapes and positions of the salt islands. Salt is a strong insulator, and the surrounding salt water should make a good conductor (Palacky, 1987), so a contrast in conductivity values could be expected here. The results suggest that the rise time of a lightning stroke may be influenced by the impedance of the ground it strikes. The elevation of the islands, up to 39 meters in the case of Weeks Island, offers another possible explanation for the attribute anomalies.

These findings appear consistent with the patterns observed in the Lakeland, Florida study area (Section 4.2), particularly in that areas of forested swamp display the lowest rise rates. It is unusual, however, that the salt dome islands display higher rise rates than saltwater mangroves, which one would expect to be more conductive.

As it stands, until these effects are better understood, the author recommends against basing any costly exploration decisions on lightning distribution data, and an healthy
degree of caution, due diligence and skepticism before making similar decisions based on lightning attribute data.
CONCLUSIONS

This study did not encounter strong evidence supporting an influence of ground conductivity on the spatial distribution of CG lightning flash ground contact points. Results primarily suggest the opposite—that no such influence exists. This does not constitute empirical proof against such influence, but it does demonstrate that any related effects, if present, are minor.

The primary drivers of lightning strike distribution appear to be elevation and topography, coupled with local and regional weather trends. Tall, isolated objects, particularly communications towers, wind turbines and transmissions towers, have a strong influence on local flash densities in that they trigger upwards lightning which would not otherwise occur, but there is no evidence to suggest they affect distribution of downward flashes on scales larger than current lightning detection locational accuracies.

This study demonstrates, however, that certain ground features—particularly wooded wetlands—can show a distinct influence on lightning stroke attributes. This influence may be a result of ground conductivity, and it is not obviously present in most of the study areas. Whether such influence could be practically applied for exploration purposes remains to be seen.
REFERENCES


Horvath, T. (2012). The protected space proved to be an undefined term. *International Conference on Lightning Protection (ICLP), Vienna, Austria*. 


