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Key Points:

- Median negative first stroke leader durations are significantly (5–11 ms) shorter for lightning occurring over ocean than those over land
- The inverse relationship between average leader duration and return stroke peak current is statistically the same over land and ocean
- We infer that shorter durations over ocean support the higher oceanic return stroke peak currents reported by lightning locating systems

Supporting Information:

- Supporting Information S1

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Negative first stroke leader characteristics in cloud-to-ground lightning over land and ocean

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Abstract We examine downward leader characteristics for negative first return strokes, along with estimated first stroke peak currents, for lightning occurring over land and ocean reported by the U.S. National Lightning Detection Network (NLDN). For the first time, to the best of our knowledge, we report independent evidence that supports the observations by lightning locating systems of higher first stroke peak currents for lightning occurring over ocean than land. We analyzed lightning occurring in five circular regions, each with 50 km diameter. In western Florida, the median stepped-leader duration was 17% shorter over ocean than over land and in eastern Florida the median durations were 21% and 39% shorter over two oceanic regions than over land. We infer that the shorter durations over ocean simply reflect the higher (25% in western Florida and 11%–16% in eastern Florida) oceanic return stroke peak currents reported by the NLDN. These findings indicate that the cloud charge structure for (at least some) oceanic storms are different than those for storms over land. The percentage of flashes that had at least one NLDN-reported negative cloud pulse prior to the first negative cloud-to-ground stroke was found to be about the same over land and ocean. Using regression analysis, we found no evidence that the relationship between leader duration and first return stroke peak current is different over land and ocean.

1. Introduction

There has been prolonged and sustained interest in the difference between characteristics of cloud-to-ground (CG) lightning occurring over land and ocean. These differences may signify underlying dissimilarities in the nature and development of deep convection over ocean versus over land, and studying these differences may help us understand how there can be nearly 2 orders-of-magnitude variation in the peak current for first strokes in CG lightning within a single large thunderstorm. Many studies [e.g., Lyons *et al.*, 1998; Orville and Huffines, 2001; Orville *et al.*, 2011; Cummins *et al.*, 2005] have examined the climatology of peak currents in CG lightning flashes using data from the U.S. National Lightning Detection Network (NLDN) and reported that the magnitudes of network-estimated peak currents for negative first return strokes (RS) are, on average, larger over the ocean than over land. This is the result of a higher proportion of high peak current negative CGs occurring over oceanic regions than over land. These observations were confirmed using other continental-scale [e.g., Poelman *et al.*, 2016] and long-range [Hutchins *et al.*, 2012; Said *et al.*, 2013] lightning locating system (LLS) data. However, this discrepancy in peak current magnitudes over land and ocean has not been found for positive RS [Orville and Huffines, 2001; Cummins *et al.*, 2005; Orville *et al.*, 2011] or for subsequent strokes in existing channels [Cummins *et al.*, 2005].

Various theories, some of which may not fully agree with inferences drawn from observations, have been proposed to explain these discrepancies and are described in detail in Cooray *et al.* [2014]. Since LLSs measure electromagnetic fields from lightning and use empirical field-to-current conversion equations to estimate peak currents from measured peak fields [e.g., Cummins *et al.*, 1998], higher reported peak currents over ocean than land could simply be due to enhanced radiation field peaks from lightning over ocean, rather than (actually) higher peak currents. Ground conductivities and surface conditions over land and ocean are different, which could cause physical differences in the attachment process that result in enhanced radiated RS peak fields. However, Rakov *et al.* [1998], based on experimental data for rocket-triggered lightning, showed that lightning peak current is not much influenced by ground conductivity. Cummins *et al.* [2005] suggested that higher RS velocity over high-conductivity saltwater could be a possible reason for higher radiation field peak over ocean than land for RS with similar peak currents. Using modeling, Cooray and Rakov [2011] showed that RS velocity is influenced only slightly by the ground conductivity. Differences in the length of upward leaders prior to RS over ocean versus land was rejected by Cooray *et al.* [2014] as a

possible reason that could produce higher RS peak field over ocean. Zoghzoghy *et al.* [2015], who investigated the impact of RS parameters on its magnetic field waveform using observations and modeling, found that larger LLS-reported peak radiated fields over the ocean are unlikely to result from differences in RS channel-based current risetimes, current falltimes, or RS speeds over land and ocean. They hypothesized that higher LLS-reported RS peak fields over ocean could be related to higher peak currents, potentially due to meteorological differences between land-based and oceanic thunderstorms or due to differences in the lightning attachment process over land and ocean. Chronis *et al.* [2016] proposed that higher peak currents over ocean could be due to “a physical mechanism that modulates the thundercloud potential.” These earlier studies have therefore been able to show that it is unlikely that the higher peak current estimates over ocean are a measurement artifact, but they have not provided independent evidence that the peak currents are truly higher.

In this study, we examine negative first stroke leader characteristics, first RS peak currents, and the relationship between them, for lightning occurring over land and ocean in Florida reported by the NLDN. We then discuss the possible reasons for and significance of the similarities and differences in negative first stroke leader characteristics over land versus over ocean.

2. Data

Lightning events (cloud pulses and CG strokes) reported by the NLDN during 1 September 2013 to 11 August 2015 were used in this study, as discussed in Nag and Cummins [2016]. An overview of the performance characteristics and validation techniques of modern LLSs is provided by Nag *et al.* [2015]. The performance characteristics of the NLDN validated using rocket-triggered lightning in Florida is found in Mallick *et al.* [2014a, 2014b] and Nag *et al.* [2011]. The NLDN underwent a network-wide upgrade in 2013 [Nag *et al.*, 2014] which resulted in a cloud flash detection efficiency of around 50% [Murphy and Nag, 2015]. For the period from which data are included in this paper, the NLDN sensor characteristics remained unchanged and the data were processed using the same geolocation algorithm.

We analyzed lightning occurring in five circular regions, shown in Figure 1a, each with 50 km diameter. The background colors in Figure 1a indicate the NLDN-reported average stroke density (strokes/km²/yr) over a 10 year period (2006–2015) in the Florida region. All the selected regions, except one, are centered about 50 km or less from the coastline. Due to the proximity of these regions to the eastern and western coastlines and the NLDN network geometry in the southeastern United States, the negative first stroke detection efficiency of the NLDN in these regions is expected to be about the same. Zhu *et al.* [2016a, 2016b] reported the NLDN's negative first stroke detection efficiency in the Gainesville, Florida region to be 98%. In the deeper oceanic region whose center is 125 km east of the Florida coastline near Jacksonville, the negative first stroke detection efficiency is expected to be a few percent lower than in the other four regions. However, detection efficiency for low-amplitude preliminary breakdown (PB) pulses, which are of interest in this study and often have field peaks that are an order of magnitude smaller than first RS peaks [e.g., Nag and Rakov, 2009a, Marshall *et al.*, 2014], will be substantially lower in this region than in other regions. We included this fifth region in our analysis because the average peak currents differ relatively distinctly along the land-ocean boundary in the west coast of Florida [see Nag and Cummins, 2016, Figure 3]; however, the differences are somewhat more gradual along the east coast, with a “transition zone” extending several tens of kilometers into the ocean. Further discussion on this is included in Nag and Cummins [2016]. This fifth region is selected such that it is outside this transition zone. In the four regions in the immediate vicinity of the eastern and western coastlines, the PB pulse detection efficiencies of the NLDN are expected to be similar.

NLDN-reported cloud pulses and CG strokes were grouped into flashes using a space-time grouping algorithm (see Nag and Cummins [2016, Section II] and Murphy and Nag [2015] for more details). The number of negative CG flashes reported by the NLDN in the regions on land and ocean in western Florida during 1 September 2013 to 11 August 2015 were 31487 and 23551, respectively. In eastern Florida, 27606, 7138, and 5331 negative CG flashes were reported in the regions on land, ocean, and deeper ocean, respectively. We examined the percentage of flashes that had at least one NLDN-reported negative cloud pulse prior to the first negative CG stroke and found them to be about the same over land and ocean (26% over both land and ocean in western Florida and 19% over land versus 18% over the oceanic regions in eastern Florida). Figures 1b and 1c show, for western and eastern Florida, respectively, the cumulative histograms of NLDN-reported peak currents of negative first strokes over land and ocean. Note that of the total number of

Figure 1. (a) Map showing the 50 km diameter circular regions over land and ocean used in this study. The background colors indicate the NLDN-reported average stroke density (strokes/km²/yr) over a 10 year (2006–2015) period in the Florida region. Cumulative first stroke peak current distributions over land and ocean in (b) western and (c) eastern Florida. Only first strokes with NLDN-estimated peak currents of 4 kA or more are included. Only a small fraction (<0.2%) of events have peak currents of 200 kA or greater and are not shown in these histograms. Min = Minimum, Max = Maximum, AM = Arithmetic Mean, and SD = Standard Deviation. Unit for all statistical parameters except “Count” shown in Figures 1b and 1c is kiloamperes.

negative CG flashes occurring over land and ocean, only those with NLDN-reported first stroke peak currents of 4 kA or more were included in Figures 1b and 1c, in order to exclude misclassified cloud pulses. Cooray and Rakov [2012] estimated that the minimum first stroke peak current lies in the range of 3 kA to 1.5 kA with the most probable value being about 2 kA. However, there are no direct measurements of first RS peak currents lower than 5 kA. The median peak currents over land and ocean in western Florida are 20 kA and 25 kA, respectively. In eastern Florida, the median peak currents are 19 kA over land and 21 kA over the oceanic region centered 50 km off shore. The median peak current in the deeper oceanic region in eastern Florida is 22 kA. Any bias introduced in the data set over the deeper oceanic region due to lower detection efficiency relative to the other oceanic region would result in smaller proportion of low peak current strokes being reported in the deeper oceanic region. From Figure 1c it can be seen that this effect is minimal since the cumulative histograms for peak current over the two oceanic regions in eastern Florida agree very well with each other up to a peak current of 16 kA, before they diverge at higher peak currents. This indicates that the differences in the average peak currents are due to a higher proportion of high peak current events occurring over the deeper oceanic region than over the oceanic region closer to the coastline, rather than simply differences in the NLDN’s detection efficiency. Our result of higher average LLS-reported first RS peak current over ocean is consistent with those reported in previous studies (cited in section 1).

3. Duration of Negative Stepped Leader

In an effort to observe the impact of higher first RS peak currents using a parameter that is dependent on peak current but is not subject to the assumptions employed in the NLDN peak current estimates, we examined the time interval between the first detected negative cloud pulse in a flash and the first negative RS (negative stepped-leader duration). Of the negative CG flashes that had at least one negative cloud pulse prior to the first negative stroke, we selected for this analysis those flashes in which the first stroke peak current was 4 kA or more (see discussion in section 2). Additionally, since we were interested in the time interval between pulses radiated by sources within or immediately below cloud (PB pulses) and the first stroke, we excluded stepped-leader pulses occurring close to (few hundred meters above) ground or ocean surface (which are generally classified as cloud pulses by the NLDN). So flashes in which the first NLDN-reported negative cloud pulse occurred less than 1 ms [Rakov and Uman, 2003, chap. 4] prior to the first stroke were not included in this analysis. Finally, we have excluded flashes where the time interval between the first detected negative cloud pulse and the first RS was more than 200 ms, as it is likely that such a cloud pulse is not part of PB in a “regular” downward moving negative stepped leader. Only about 3 to 5% of Florida stepped leaders are expected to have durations longer than 90 ms [Rakov and Uman, 1990; Nag, 2007]. Note that the selection criteria discussed here help to reduce the number of non-PB cloud pulses included in our data set. Interestingly, the percentage of negative CG flashes occurring over land versus over ocean

Figure 2. Histograms for negative stepped-leader duration (time interval between the first negative cloud pulse in a flash and the following first RS) in 5 ms bins for lightning occurring over land and ocean in (a) western and (b) eastern Florida. Unit for all statistical parameters except “Count” shown in Figures 2a and 2b is milliseconds.

in our data set that met the above criteria were nearly the same (22% over both land and ocean) in western Florida and similar (17% over land and 16% over the two oceanic regions) in eastern Florida.

From Figure 2 we see that the median and arithmetic mean (AM) stepped-leader durations were 30 ms and 44 ms, respectively, over land and 25 ms and 40 ms, respectively, over ocean in western Florida. In eastern Florida, the median/AM stepped-leader durations were 28/43 ms over land, 22/36 ms over ocean, and 17/31 ms over the deeper oceanic region. In both western and eastern Florida, the average stepped-leader durations are significantly shorter over ocean than over land. In western Florida, it is 17% shorter over ocean than over land and in eastern Florida the median durations are 21% and 39% shorter over the oceanic and deeper oceanic regions, respectively. We note that there may be a small bias toward shorter NLDN-reported stepped-leader durations over the deeper oceanic region due to lower detection efficiency for low-amplitude pulses occurring early in the PB pulse train. This will result in a PB pulse occurring later in the train being reported as the first pulse in a flash. However, this bias would be less than a millisecond since the typical duration of PB pulse trains is a few to several milliseconds [e.g., Nag and Rakov, 2009a; Zhu et al., 2015] and the largest pulses in a PB pulse train typically occur in the first half of the pulse train duration [e.g., Nag and Rakov, 2009a]. While we could not find any other studies that examined the stepped-leader durations (time interval between PB pulses and the negative first stroke) separately for lightning occurring on land and ocean, various studies [e.g., Nag and Rakov, 2008; Baharudin et al., 2012; Marshall et al., 2014; Zhu et al., 2015] have reported geometric mean or median negative stepped-leader durations for lightning in Florida to be in the range of 19–37 ms, consistent with our findings.

Figures 3a–3c show scatterplots of the negative stepped-leader duration versus RS peak current in the analysis regions. Generally speaking, RS with peak currents higher than 60–80 kA tend to have stepped-leader durations of 20 ms or less in all regions. Our results are similar to those of Zhu et al. [2015] who, for 222 negative CG flashes, reported that most flashes with short (≤ 6 ms) PB-to-RS intervals were associated with high NLDN-estimated RS peak currents. Further, our results are also consistent with those of Zhu et al. [2016c] who reported that the PB-to-RS interval was found to decrease with increasing RS peak currents for 3077 negative first strokes with peak currents equal to or greater than 50 kA occurring in an area including both land and ocean in and around Florida. In Figure 3d, the median leader duration for different ranges of NLDN-estimated peak current (I_p bins) are shown for the five regions considered here. The data were first treated to exclude extreme outliers (those with values outside $\pm$ three standard deviations of the untrimmed medians). The number of outliers excluded ranged from 2.9 to 3.3% of the respective data sets for the five regions. The I_p bins are relatively narrow (3 kA) for lower peak currents, and wider (as wide as 25 kA) for higher peak currents. In order to produce the nonlinear regression shown in Figure 3d, we used the median stepped-leader duration (Δt_{SL}) for data from all regions, at center points of each I_p bin. This approach has

Figure 3. Scatterplot of negative stepped-leader duration in milliseconds versus negative first stroke peak current in kiloamperes for lightning occurring over (a) land and ocean in western Florida, (b) land and ocean in eastern Florida, and (c) land and deep ocean in eastern Florida. (d) Scatterplot of the median leader duration in milliseconds (Δt_{SL}) for different peak current bins versus the middle value of each peak current bin (I_p) color coded by region. The equation relating Δt_{SL} and I_p using data from all regions is shown along with the determination coefficients (R^2) for each region. The 99% confidence intervals (solid lines) for (e) western and (f) eastern Florida, along with the median leader durations for each I_p bin color coded by region. See text for details. Note that the horizontal and vertical axis limits are different in Figures 3a–3c versus 3d–3f.

several advantages over an analysis of means using least squares regression that employs all individual observations. First, the full data set includes outlier values that, in our case, cannot be controlled because individual lightning waveforms are not available for inspection. This technique mitigates the impact of outliers. Further, the use of medians for each I_p bin prevents the final regression from being heavily influenced by the relative occurrence of CG strokes in different I_p bins. Additionally, the variable I_p bin length accommodates a more rapid change in stepped-leader durations in the lower I_p bins and also assures that statistically acceptable numbers of observations (>10) are present in the higher I_p bins. The relationship between Δt_{SL} in milliseconds and the center point of each peak current bin (I_p) in kiloamperes, assuming that it is independent of region, is given by

$$\Delta t_{SL} = 193 I_p^{-0.48} - 11 \quad (1)$$

Also, for comparison purposes, we show in Figure 3d the median leader durations for each I_p bin color coded by region. The determination coefficients for each of the five regions separately range from 0.87 to 0.97 (see Figure 3d), indicating that equation (1) describes the relationship between stepped-leader duration and RS peak current well for each region. This supports our assumption that the relationship between stepped-leader duration (which is determined in part by leader vertical velocity) and first RS peak current (which likely depends upon leader line charge density) is not significantly affected by regional differences. Note that studies using high-speed video measurements of negative leaders [e.g., Campos *et al.*, 2014] have shown that leaders may have irregular speed variation as they approach ground. Stepped-leader durations reported in this study allow us to only make inferences about the average velocity at which each leader progresses vertically downward. Note also that Kodali *et al.* [2005] show the estimated line charge density for dart leaders to be positively correlated with return stroke peak currents in rocket-triggered lightning, which we assume to be also the case for stepped leaders and first strokes in natural lightning.

Figures 3e and 3f show, for western and eastern Florida, respectively, the 99% confidence intervals (solid lines) along with the median values for each I_p bin, color coded by region. Given the highly skewed (toward long durations) distributions of leader durations for the lower current I_p bins (see Figures 3a–3c), and the small number of observations in some of the I_p bins (as few as 10 in some cases), we elected to employ a distribution-free technique to determine the confidence intervals. For each I_p bin in each region, the

statistical distribution of median durations was estimated by drawing 10,000 randomly selected sample sets (without replacement within a sample set) from the combined population of observations from all regions, where the number of samples in each set matched the number of observations in the associated I_p bin. The two-sided 99th percentile limits are then determined directly from 10,000 point statistical distributions. For the western Florida observations (Figure 3e), all the medians are within the narrow confidence intervals, or extremely close. For the eastern Florida observations (Figure 3f), the confidence intervals for the ocean and deep ocean are much wider due to fewer observations. A number of the deep-ocean medians fall outside the confidence intervals. We interpret this as being a reflection of the relatively small bias due to lower detection efficiency in this distant region, as discussed earlier in this section.

4. Discussion

In our analysis, we found that the median negative stepped-leader duration is significantly shorter over ocean than over land. This indicates a faster negative leader vertical velocity over ocean, on average. The median differences are large enough (11 ms or 39% shorter over deep ocean) that they cannot be due to leader acceleration close to the ocean surface alone. Over land, a longer median stepped-leader duration (slower vertical velocity, on average) could indicate more extensive horizontal leader propagation prior to reaching ground. If such horizontal propagation were within the cloud, it could be due to a more extensive lower positive charge region [e.g., Coleman *et al.*, 2008; Nag and Rakov, 2009b]. Experimental data show that negative ground flashes in Florida often neutralize a small positive charge at altitudes of 1 to 3 km in addition to the larger main negative charge higher in the cloud [Jacobson and Krider, 1976], indicating that the positive charge region may play a significant role in generating ground flashes. Nag and Rakov [2009b] hypothesized that when the lower positive charge region (in a typical thundercloud with tripolar charge structure) is small or absent, the initiation of negative leader is essentially not assisted by the lower positive charge region and such initiation would generally require a stronger negative charge source. This concept is depicted in terms of the associated electric fields in Figure 3 of Nag and Rakov [2016] and an adapted version is included in the supporting information of this paper as Figure S1. Between the main negative and lower positive charge centers, the vertical components of electric field vectors due to the two charge regions are in the same direction and hence the electric field is enhanced in this region. This electric field enhancement will not occur if the lower positive charge region is small or absent, and to produce electric fields required for the initiation of the negative leaders, a relatively large main negative charge region will be needed. In the region immediately below the lower positive charge center, the vertical electric field vectors are in opposite directions, and hence, the field is reduced. In the absence of a significant lower positive charge region, this field reduction immediately below the charge layers will not occur, perhaps resulting in a higher negative leader vertical velocity. The above discussion supports the hypothesis that in clouds electrified over the ocean, a larger main negative charge region and a smaller lower positive charge region could result in negative leaders with higher leader tip potential and a higher line charge density which propagate downward with a faster average vertical velocity. The primary role of the RS current is to neutralize the leader charge, and the peak current is likely related to the line charge density in the few hundred meters of the leader channel immediately above the attachment point. So a faster leader vertical velocity over ocean than over land would likely be associated with higher negative RS peak current.

Another possible explanation for shorter average stepped-leader durations over ocean could be a significantly lower altitude negative charge region over ocean than over adjacent flat land. This is not the case for the regions considered here, based on temperature estimates at different atmospheric pressure values during the convective season (obtained from the North American Regional Analysis).

Four different hypotheses regarding the origin of the lower positive charge region are reviewed by Rakov and Uman [2003, p. 88]. The lower positive charge region can be associated with (a) graupel, which, according to the graupel-ice cloud electrification mechanism, charges positively at temperatures warmer than the reversal temperature; (b) positive charge deposited in the cloud by lightning; (c) upward transport of positive charge produced by corona at ground surface; and (d) positive screening layer at the lower cloud boundary. Cooray *et al.* [2014] suggest that the corona mechanism is expected to be less efficient over oceans than over land and also suggests that the presence of trace quantities of sodium chloride in cloud water and the collision of graupel and ice crystals result in negative charging of graupel at all temperatures below 0°C [Jayaratne *et al.*, 1983], which would inhibit the development of the lower positive charge region.

It is possible that in land-based thunderstorms, a more turbulent and intense-convection driven mixing of graupel, ice particles, and other charged hydrometeors occurs within the thundercloud, resulting in opposite polarity charge pockets in relative proximity [e.g., Rakov and Uman, 2003, chap. 3; Bateman et al., 1999], producing the locally enhanced fields needed for lightning initiation. We speculate that such “turbulent mixing” of cloud charge particles could be lacking in thunderclouds electrified over oceans, resulting in less “lumpy” charge distributions and with more extensive main negative charge regions necessary to produce higher peak current strokes. Interestingly, similar arguments about cloud charge structure were used by Chronis et al. [2015] to explain diurnal variations in first stroke peak currents for CG lightning over land. Additional measurements and observations (including broadband field measurements in conjunction with low frequency and very high frequency mapping LLS data) could help gain further insight into if and how the vertical electrical profile within and under oceanic thunderstorms may be different than land-based ones and how this may affect lightning leader characteristics.

5. Summary

We examined the negative first stroke leader characteristics and first RS peak currents for lightning reported by the NLDN in five circular regions (each with 50 km diameter) over land and ocean in Florida during 1 September 2013 to 11 August 2015. The percentage of flashes that had at least one NLDN-reported negative cloud pulse prior to the first negative CG stroke was found to be about the same over land and ocean. We examined the time interval between the first detected negative cloud pulse in a flash and the first negative RS (negative stepped-leader duration) and found that in western Florida, the median stepped-leader duration was 17% shorter over ocean than over land and in eastern Florida the median durations were 21% and 39% shorter over the oceanic and deeper oceanic regions, respectively, than over land. We found no evidence that the relationship between leader duration and first RS peak current is different over land and ocean. A longer stepped-leader duration (or a slower average vertical velocity) over land could indicate more extensive horizontal leader propagation prior to reaching ground. If such horizontal propagation were within the cloud, it could be due to a more extensive lower positive charge region. A faster average negative leader vertical velocity over ocean would likely be associated with higher vertical fields near the cloud base, a higher leader tip potential, and a higher line charge density, leading to a higher first RS peak current. These findings provide, for the first time, independent evidence that supports higher first stroke peak currents over ocean, particularly well offshore (deep ocean), that does not rely on assumptions employed to produce peak current estimates by ground-based LLSs.

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