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Characteristics of Negative Cloud-to-Ground Lightning over Land and Ocean

Amitabh Nag
Department of Physics and Space Sciences
Florida Institute of Technology, Melbourne, Florida, USA
anag@fit.edu

Kenneth L. Cummins
Department of Atmospheric Sciences
University of Arizona, Tucson, Arizona, USA

***Abstract*—We examined peak currents and magnetic field risetimes for negative return strokes occurring over land and ocean in Florida reported by the U.S. National Lightning Detection Network (NLDN). The risetimes were measured by a single NLDN sensor located less than two kilometers from the coastline in Florida. We analyzed lightning occurring in five circular regions, each with 50 km diameter. 69% and 72% of the flashes over land and ocean, respectively, contained both NLDN-reported cloud pulses and CG strokes in western Florida. In eastern Florida, 59% of the flashes over land and 49% and 46% of the flashes over the two oceanic regions contained both NLDN-reported cloud pulses and CG strokes. 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. The median NLDN-reported negative first stroke peak current over ocean was found to be higher than that over land. The median threshold-to-peak, 10-to-90%, and 10-to-50% magnetic field risetimes were found to be somewhat longer and the median 50-to-90% risetime slightly shorter for return strokes occurring over ocean than those for return strokes over land.**

Keywords: negative cloud-to-ground lightning; return strokes; characteristics; magnetic fields, risteime, peak current; oceanic lightning

I. Introduction

Various studies have reported differences between the characteristics of cloud-to-ground (CG) lightning return strokes occurring over land and ocean. Lyons et al. [1998] examined the climatology of large peak current ($\geqslant$ 75 kA) CG lightning flashes using data from the U.S. National Lightning Detection Network (NLDN) and reported the proportion of high peak current negative CGs occurring over the oceanic regions of the northern Gulf of Mexico and off the southeastern United States coastline was "unusually high". Orville and Huffines [2001] and Orville et al. [2011] studied the occurrence characteristics of CG lightning reported by the U.S. National Lightning Detection Network (NLDN) and North American Lightning Detection Network (NALDN), respectively, and found that the magnitudes of network-estimated negative return stroke peak currents are, on average, larger over the ocean than over land. These observation were confirmed using long-range lightning locating system (LLS) data by Hutchins et al. [2012] and Said et al. [2013]. However, this discrepancy in peak current magnitudes over land and ocean has not been found for positive return strokes [Orville and Huffines, 2001; Cummins et al., 2005; Orville et al., 2011].

Nag and Rakov [2014] reported that, for positive return strokes and propagation over relatively long distances (ranging from about 10 to 160 km) over land, the peak electric field derivative (dE/dt) is considerably smaller and the dE/dt half-peak width is much longer than those for both positive [Cooray et al., 2004] and negative [Krider et al., 1996] return strokes reported in the literature for the case of propagation over salt water. Interestingly, Nag and Rakov's values are comparable to those reported by Heidler and Hopf [1998] for propagation over a few kilometers over land, for which propagation effects due to finitely conducting soil were expected to be relatively small. This implies that there may be a discrepancy between the values of peak electric field derivative and dE/dt half-peak width for positive return strokes occurring over land versus salt water related to the source, as opposed to propagation effects. On the other hand, Cummins et al. [2005] examined NLDN-reported risetimes of both positive and negative first strokes and found them to be not much different for lightning over land and ocean. However, Cummins et al.'s study was done using network reported risetimes without accounting for differences in propagation paths (between return stroke locations and various sensors in the network) and sensor thresholding effects.

Various theories, some of which may not fully agree with inferences drawn from observations, have been proposed to explain some of these discrepancies. 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 be due to enhanced radiation field peaks from lightning over ocean. Ground conductivities and surface conditions over land and ocean are different, which could cause physical differences in the attachment process over land and ocean. Such differences can cause, in theory, radiated return stroke peak fields to be enhanced over ocean versus over land due to differences in return stroke channel-base current characteristics such as its peak value and velocity. 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 return stroke velocity over high-conductivity-saltwater could be a possible reason for higher radiation field peak over ocean than land for return strokes with similar peak currents. Using modeling, Cooray and Rakov [2011] showed that return stroke velocity is influenced only slightly by the ground conductivity. Differences in the length of upward leader prior to return stroke over ocean versus land was rejected by Cooray et al. [2014] as a possible reason that could produce higher return stroke peak field over ocean. Higher return stroke peak field over ocean could be related to multiple closely-spaced pulses (probably multiple upward leaders) that can occur just prior to attachment, as observed by Murray et al. [2005]. The absence of sharp objects over ocean and hence, higher electric field over water, as well as higher conductivity of salt water compared to that of land, resulting in faster current risetimes, have been proposed by Heidler and Hopf [1998] as reasons that could explain the disparity of dE/dt characteristics over land and ocean. Zoghzoghy et al. [2015], who investigated the impact of return stroke 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 return stroke channel-base current risetimes, current falltimes, or return stroke speeds over land and ocean. They hypothesized that higher LLS-reported return stroke 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.

In this study, we examine the first stroke peak current of negative CG lightning occurring over land and ocean reported by the NLDN. We also examine the magnetic field risetime of negative first strokes occurring in these regions measured by a single NLDN sensor located less than two kilometers from the coastline in Florida. Finally, we discuss the possible reasons for and significance of the similarities and differences in first stroke characteristics over land and ocean.

II. DATA

Lightning events (cloud pulses and CG strokes) reported by the NLDN during September 1, 2013 to August 11, 2015 were used in this study. 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, b] and Nag et al. [2011a]. 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, 2014]. For the period from which data is included in this paper, the NLDN sensor characteristics remained unchanged and the data were processed using the same geolocation algorithm.

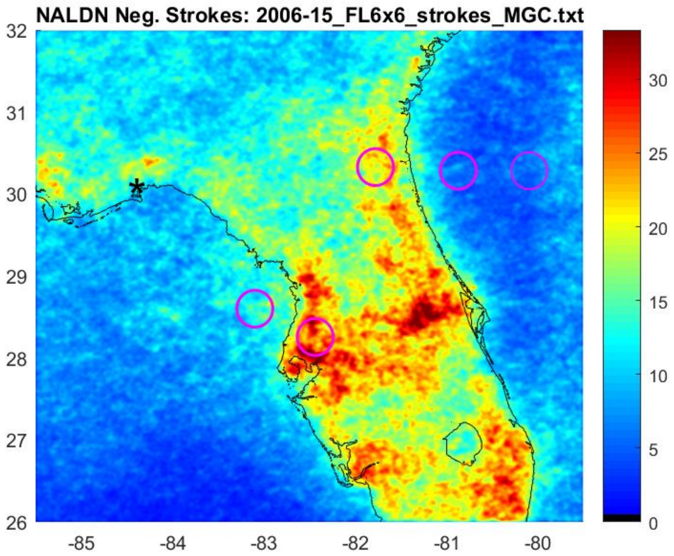
We analyzed lightning occurring in five circular regions, shown in Figure 1, each with 50 km diameter. The locations (latitude, longitude) of the center points of these regions are shown in table below Figure 1. The background colors indicate the NLDN-reported average stroke density (strokes/km^2/year) over a ten year (2006-2015) period in the Florida region. The black asterisk on the Florida pan-handle coastline indicates the location of the NLDN sensor used to measure the risetimes discussed in Section III B. All the selected regions, except one, are centered 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, b] 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. Detection efficiencies for cloud pulses and flashes in this region, on the other hand, will be substantially lower than those in the others, due to the average peak field of cloud pulses being an order of magnitude or more smaller than that for first strokes. The reason for selecting this fifth region is discussed in Section III A. In the four regions in the immediate vicinity of the eastern and western coastlines, the cloud flash detection efficiencies of the NLDN are expected to be similar.

Table I shows a summary of the all NLDN-reported flashes that occurred in the five regions during September 1, 2013 to August 11, 2015. NLDN-reported cloud pulses and CG strokes were grouped into flashes using a space-time grouping algorithm [e.g., Murphy and Nag, 2015]. All cloud pulses within 20 km and 1 second and CG strokes within 10 km and 1 second of the first event (pulse or stroke) in a flash and an interpulse or interstroke interval of 500 ms or less were defined as belonging to the same flash. CG flashes in which the first return stroke was negative was classified as a negative CG flash. We divided CG flashes into two categories, flashes consisting of NLDN-reported CG strokes only and those consisting of NLDN-reported cloud pulses and CG strokes. 69% and 72% of flashes over land and ocean, respectively, contained both cloud pulses and CG strokes in western Florida. In eastern Florida, 59% of the flashes over land and 49% and 46% of the flashes over the two oceanic regions consisted of cloud pulses and CG strokes. We also 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 the 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).

III. ANALYSIS AND RESULTS

A. *Negative First Stroke Peak Currents*

Cumulative histograms of peak currents for negative first strokes over land and ocean in western and eastern Florida are shown in Figure 2 and the statistics are summarized in Table II. Note that, of the total number of negative CG flashes occurring over land and ocean shown in Table I, only those with NLDN-reported first stroke peak currents of 4 kA or more were included in Figure 2 and Table II. 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 return stroke peak currents lower than 5 kA. It is likely that a



Region	Center point		Description
	Latitude	***Longitude***	
Land over western Florida	28.254°	-82.438°	Centered about 30 km from coastline near Spring Hill, Florida.
Ocean near western Florida	28.600°	-83.100°	Centered about 45 km off shore near Spring Hill, Florida.
Land over eastern Florida	30.285°	-80.094°	Centered about 35 km from coastline near Jacksonville
Ocean near eastern Florida	30.329°	-81.779°	Centered about 50 km off shore near Jacksonville
Deeper ocean near eastern Florida	30.285°	-80.094°	Centered about 125 km off shore near Jacksonville

Figure 1. Map showing the 50-km diameter circular regions over land and ocean in which NLDN-reported cloud pulses and cloud-to-ground return strokes were analyzed. The background colors indicate the NLDN-reported average stroke density (strokes/km^2/year) over a ten year (2006-2015) period in the Florida region. Locations (latitude, longitude) of the center points and description of the regions are included in the adjoining table. The black asterisk on the Florida pan-handle coastline indicates the location of the NLDN sensor used to measure the risetimes discussed in Section III B.

large fraction of the lightning events classified by the NLDN as negative first strokes and having peak currents less than 4 kA are cloud pulses misclassified by the NLDN, and have been excluded from this analysis.

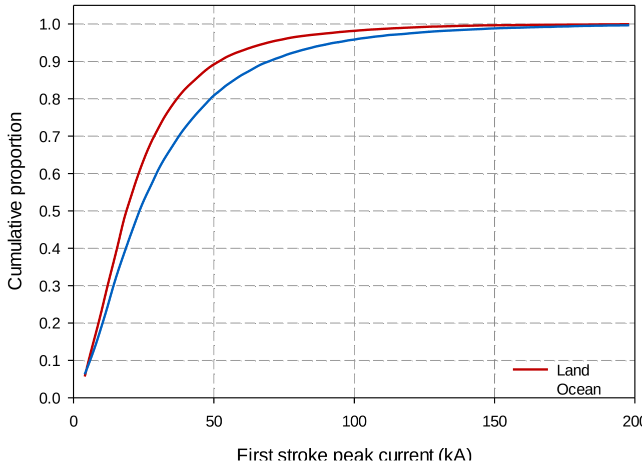
The median peak currents over land and ocean in western Florida are 20 kA and 25 kA, respectively. In eastern Florida, the median peak currents are 19 kA over land and 21 kA over the ocean region centered 50 km off shore, respectively. Figure 3 shows a map of the NLDN-reported average peak current over a ten year (2006-2015) period in the Florida region. It can be seen that while the average peak currents differ relatively distinctly along the land-ocean boundary in the west coast of Florida, the differences are somewhat more gradual along the east coast with a transition region extending several tens of kilometers into the ocean. The reason for the existence of this "transition zone" is not completely understood, and could be due to thunderstorms electrified over land along the east coast of Florida moving toward the east onto the ocean due the direction of prevailing winds. Such thunderstorms might then retain the characteristics of land-based storms in the coastal region causing the peak current differences between land and ocean to be more gradual along the east coast. Tyahla and Lopez [1994] investigated peak current distributions in two coastal regions in Florida and did not notice more intense field changes from oceanic lightning, indicating that the transition may be more gradual in some regions like Florida. This is consistent with the observations of Orville and Huffines [2001] (see for example, their Fig. 13) of a "transition zone" along the eastern Florida coastline in which the median peak currents over ocean were the same as that over nearby land. In order to get away from this "transition zone" we selected the deeper oceanic region whose center is 125 km east of the Florida coastline near Jacksonville, as discussed in Section II. The median and arithmetic mean (AM) peak current in this region

TABLE I. SUMMARY OF THE ALL NLDN-REPORTED FLASHES THAT OCCURRED IN THE FIVE REGIONS IN FLORIDA SHOWN IN FIGURE 1 DURING SEPTEMBER 1, 2013 TO AUGUST 11, 2015.

Flash type	Land (western Florida)	Ocean (western Florida)	Land (eastern Florida)	Ocean (eastern Florida)	Deep ocean (eastern Florida)
All CG flashes	31487	23551	27606	7138	5331
CG strokes only	9820	6587	11264	3625	2893
CG strokes and IC pulses (%)	21667 (69)	16964 (72)	16342 (59)	3513 (49)	2438 (46)
At least one negative IC pulse prior to CG (%)	8075 (26)	6190 (26)	5160 (19)	1254 (18)	937(18)

TABLE II. SUMMARY OF NLDN-REPORTED PEAK CURRENTS FOR NEGATIVE FIRST STROKES THAT OCCURRED IN THE FIVE REGIONS IN FLORIDA SHOWN IN FIGURE 1 DURING SEPTEMBER 1, 2013 TO AUGUST 11, 2015. ONLY STROKES WITH NLDN-REPORTED FIRST STROKE PEAK CURRENTS OF 4 KA OR MORE ARE INCLUDED.

	Land (western Florida)	Ocean (western Florida)	Land (eastern Florida)	Ocean (eastern Florida)	Deep ocean (eastern Florida)
Minimum (kA)	4	4	4	4	4
Maximum (kA)	297	443	258	343	312
Median (kA)	20	25	19	21	22
Arithmetic Mean (kA)	27	34	25	31	34
Standard Deviation (kA)	23	32	21	30	35
Sample Size	28328	21156	26167	6944	5320



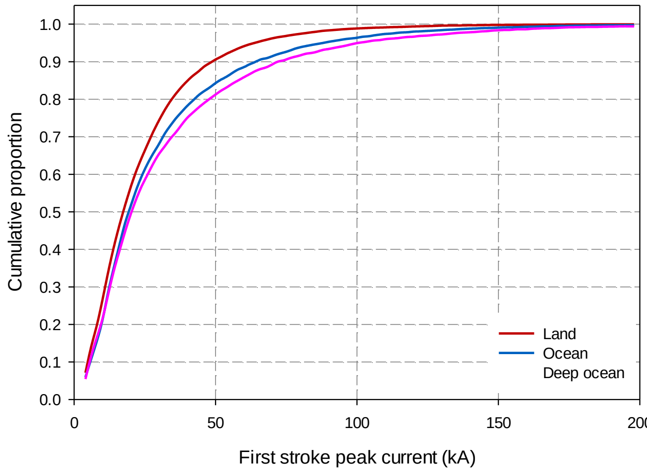


Figure 2. (a) Cumulative first stroke peak current distribution over land and ocean in western Florida. (b) Cumulative first stroke peak current distribution over land, ocean, and deep ocean in eastern Florida. Only a small percentage of events have peak currents above 200 kA and are not shown in these histograms.

are 22 kA and 34 kA, respectively, versus 19 kA and 25 kA, respectively, over land in eastern Florida. Any bias introduced in the dataset over the deeper-oceanic region due to NLDN's detection efficiency being marginally lower in this region relative to the other oceanic region in the east closer to the coastline would result in smaller proportion of low peak current strokes being reported in the deeper oceanic region. From Figure 2b it can be seen that 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 differences in the NLDN's detection efficiency.

Our result of higher average LLS-reported return stroke peak current over ocean than over land is consistent with those reported in previous studies [Orville and Huffines, 2001, Cummins et al., 2005, Orville et al., 2011, Hutchins et al., 2012; and Said et al., 2013].

B. *Negative First Stroke Risetime*

We examined the threshold-to-peak, 10-to-90%, 10-to-50%, and 50-to-90% risetimes of negative first-stroke magnetic fields measured by an U. S. NLDN sensor located about 2 km from the coastline near Carrabelle, Florida. As shown in Figure 1, this geometry results in similar propagation distances and nearly identical sensor arrival direction for the two regions. Of the negative first strokes that occurred in the selected regions in western Florida over land and ocean (see Figure 1), the sensor measured threshold-to-peak and 10-to-90% risetimes for 3421 strokes over land and 4306 strokes over ocean. Note that, for all selected strokes in our dataset, the sensor threshold was lower than 10% of the return-stroke peak field.

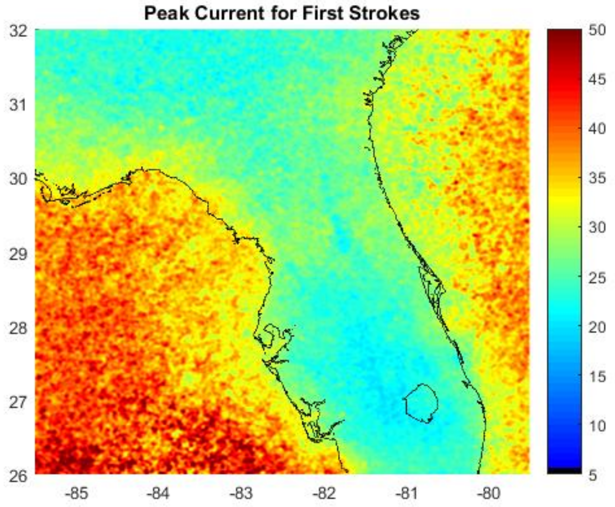


Figure 3. NLDN-reported average peak current over a ten year (2006-2015) period in the Florida region.

The upper limit of the frequency bandwidth at –3 dB of an NLDN sensor is about 400 kHz [Nag et al., 2011b]. The step response 10-to-90% risetime of an NLDN sensor is 750 ns. So we expect this bandwidth limitation to affect the measurement of shorter (< 1 μs or so) risetimes. However, the focus of this analysis is not to examine the magnitudes of the negative first stroke risetimes themselves, but to compare the risetimes of strokes occurring over land versus over ocean measured by the same coastal sensor in a specific region (western Florida).

Figures 4a, b, c, and d show, respectively, the histograms for the threshold-to-peak, 10-to-90%, 10-to-50%, and 50-to-90% risetimes. Note that, the horizontal axis is truncated at 20 μs in Figures 4a and b and at 10 μs in Figures 4c and d, as only a small fraction of strokes had risetimes above these values. Also note that by definition, the threshold-to-peak magnetic field first stroke risetime that we report is different (shorter) than the zero-to-peak risetime of that stroke. Over land, the median risetimes were, 4.8 μs, 3.5 μs, 1.8 μs, and 1.4 μs, respectively, while over ocean they were 5.0 μs, 3.7 μs, 2.1 μs, and 1.3 μs, respectively. The median threshold-to-peak, 10-to-90%, and 10-to-50% risetimes were somewhat longer over ocean than over land, while the median 50-to-90% risetime was slightly shorter over ocean than over land. Interestingly, from Figure 4c, we see that a significantly larger fraction of strokes had 10-to-50% risetimes between 1.2 and 2.0 μs over land than over ocean and a significantly larger fraction of strokes had 10-to-50% risetimes between 2.8 and 5.0 μs over ocean than over land.

Various factors can influence the measured magnetic field return stroke risetimes differently over land than over ocean. The effect of propagation of the lightning electromagnetic signals over 5-55 km (which is the distance between the various points in the selected land-based circular region in western Florida and the coast line, see Figure 1) over land in Florida before taking a path over salt water while traveling to the NLDN sensor will tend to increase risetimes from lightning measured over land. Additionally, the propagation path to the sensor for lightning occurring over land is longer than for lightning occurring over ocean. (The distances between the NLDN sensor and the center of the circular regions over land and ocean are 282 and 208 km, respectively). Uman et al. [1976] reported that for typical first strokes, zero-to-peak and 10-to-90% risetimes increased by more than 1 μs in propagating over 200 km over Florida soil. Willett et al. [1990] reported a significant attenuation in lightning return stroke electromagnetic radiation field spectra above 10 MHz due to propagation over 45 km of salt water. In our data, we find that all risetimes, other than the 50-to-90%, are somewhat longer for lightning occurring over the ocean than over land. The slightly shorter 50-to-90% risetime over ocean than over land could be a result of propagation loss differences, given that this risetime corresponds to the fast-rising portion of the return stroke current (and resulting field) waveform. So, after propagation effects are accounted for, it is possible that return-stroke field risetimes (especially, the 10-to-50% risetime) over ocean may actually be notably longer than those over land.

Next, if over ocean, there is a larger proportion of strokes having higher peak currents than over land, then the average risetime values over ocean may be longer. This is because, while risetime and return stroke peak currents have been found to be not correlated in rocket-triggered lightning [Fisher et al., 1993], generally speaking, strokes with higher peak currents could have longer risetimes. Note that triggered-lightning strokes studied by Fisher et al. [1993] are similar to subsequent strokes in natural negative CG lightning, while our data is comprised of natural negative first strokes. Another factor that could influence the threshold-to-peak risetimes is that, over ocean, a larger proportion of strokes have higher peak fields than those occurring over land in our dataset. This would result in a bias toward longer risetimes over the ocean than over land because the threshold value above which the NLDN sensor measures the return stroke waveform will be earlier in the waveform for return strokes associated with larger fields. The 10-to-90% risetimes, which are longer over ocean than over land in our dataset, are, however, not affected by the sensor threshold because, as stated above, for all strokes in our dataset, the sensor threshold was lower than 10% of the return-stroke peak field.

The AM zero-to-peak and 10-to-90% risetimes for 105 negative CG first strokes occurring over land and propagating over distances of 1 to 20 km over land in Florida reported by Master et al. [1984] were 4.4 and 2.6 μs, respectively. Their electric field measurements were recorded on an instrumentation tape recorder with the upper limit of the frequency bandwidth at –3 dB being at 1.5 MHz (versus 400 kHz for the NLDN sensor used in this study). Their AM 10-to-90% risetime is appreciably shorter than the corresponding value of 4.1 μs for negative first strokes occurring over land and propagating over distances of 5 to 55 km over land and then 250 km over salt water in the dataset analyzed here. For 4 negative first strokes occurring over land and propagating over distances of 46 to 48 km over land in Florida, Nag et al. [2012] reported geometric mean zero-to-peak and 10-to-90% risetimes of 6.5 and 3.6 μs, respectively, and AM risetimes of 7.0 and 4.0 μs, respectively. Their geometric mean and AM 10-to-90%

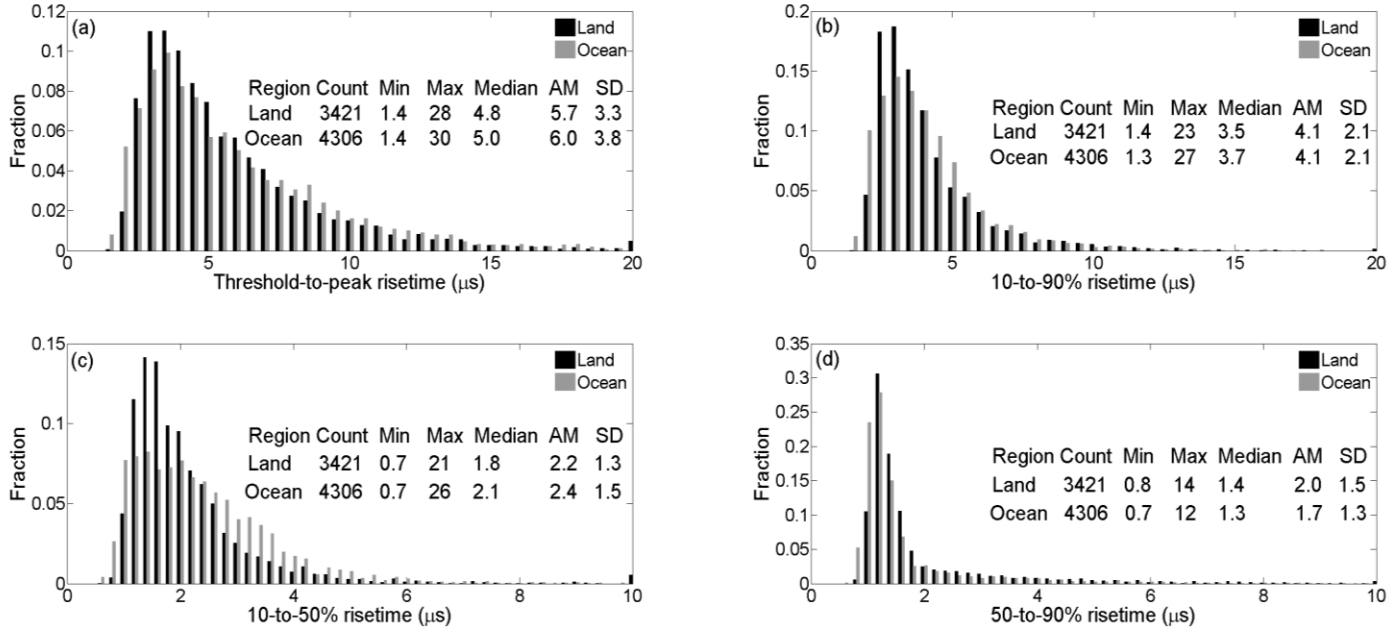


Figure 4. Histograms for (a) threshold-to-peak, (b) 10-to-90%, (c) 10-to-50%, and (d) 50-to-90% risetimes. Note that the horizontal axis is truncated at 20 μs in Figures 4a and b and at 10 μs in Figures 4c and d, as only a small fraction of strokes had risetimes above these values.

risetimes (3.6 and 4.0 μs, respectively) are similar to, respectively, the median and AM 10-to-90% risetimes (3.5 μs and 4.1 μs, respectively) for negative first strokes occurring over land in our dataset.

IV. Discussion

Our results show that NLDN-reported negative first stroke peak currents are, on average, larger for lightning occurring over ocean than over land, which is consistent with previous studies [Orville and Huffines, 2001, Cummins et al., 2005, Orville et al., 2011, Hutchins et al., 2012; and Said et al., 2013]. Measured magnetic field risetimes over land and ocean appear to be only slightly different. However, after accounting for propagation effects, it is possible that return-stroke field risetimes over ocean are notably longer than those over land. Note that the greatest difference between land and ocean is for the 10-to-50% risetime, which overlaps with the slow front portion of the return stroke field waveform. Hence, longer risetimes over ocean could be due to longer slow fronts in the field waveforms that are generally linked to the attachment of upward and downward leaders. Also, the downward leader may have to progress much closer to the surface over ocean than over land to initiate upward leaders due to the lack of tall and pointed objects such as vegetation and man-made structures on the ocean surface. This may lead to somewhat longer return stroke risetimes (at least in the slow front portion of the waveform) due to the relative inefficiency of producing upward leaders over ocean than over land. Interestingly, Schoene et al. [2009], who examined characteristics of (negative subsequent) return stroke currents in rocket-triggered lightning, reported that the 10%-to-90% current risetimes for strikes to power line (geometric mean 1.2 μs) and for strikes to earth (geometric mean 0.4 μs) were significantly different, indicating a dependence of current risetime on the electrical properties of the strike object. Using a return stroke model, Cooray and Rakov [2011] show that the peak time derivative (dI/dt) of strokes terminating on poorly conducting ground (like land in Florida in this study) is significantly lower than that for the case of highly conducting ground (like ocean in this study). So, in addition to the propagation effects discussed in Section III B, the slightly shorter 50-to-90% risetime over ocean versus over land in our dataset could also be attributed to such ground conductivity differences. In summary, it appears that differences exist between negative first stroke risetimes for lightning occurring over land and ocean, but further observations and modeling are needed to provide clear reasons for such differences.

While the various factors determining the return stroke risetime could be different for negative and positive lightning, for completeness, we add that an inference of shorter dE/dt half-peak width (duration of the initial dE/dt pulse is equivalent to the field risetime) for positive return strokes over ocean than over land can be made from observations in the literature [Heidler and Hopf, 1998; Cooray et al., 2004; Nag and Rakov, 2014].

V. Summary

We examined the characteristics of lightning occurring over land and ocean in Florida reported by the NLDN during September 1, 2013 to August 11, 2015. For the period from which data is 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, each with 50 km diameter. 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. 69% and 72% of the flashes over land and ocean, respectively, contained both NLDN-reported cloud pulses and CG strokes, in western Florida. In eastern Florida, 59% of the flashes over land and 49% and 46% of the flashes over two oceanic regions contained both NLDN-reported cloud pulses and CG strokes. 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.

The median NLDN-reported negative first stroke peak current over land in western and eastern Florida was 20 and 19 kA, respectively, versus 25 and 21 kA in regions over ocean in western and eastern Florida, respectively. The median peak current for return strokes occurring in a region farther off shore in eastern Florida was found to be 22 kA, which is slightly higher than that for return strokes occurring in the oceanic region closer to the coastline. This result (higher average peak currents over ocean versus land) is in good agreement with that found in previous studies [Orville and Huffines, 2001, Cummins et al., 2005, Orville et al., 2011, Hutchins et al., 2012; and Said et al., 2013]. The median threshold-to-peak, 10-to-90%, and 10-to-50% magnetic field risetimes were found to be somewhat longer and the median 50-to-90% risetime slightly shorter for return strokes occurring over ocean than those for return strokes over land. After accounting for propagation effects, it is possible that return-stroke field risetimes (especially, the 10-to-50% risetime) over ocean are notably longer than those over land.

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