IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received November 12, 2019, accepted November 20, 2019, date of publication November 28, 2019, date of current version December 16, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2956685

The Impact of Cloud-To-Ground Lightning Type on the Differences in Return Stroke Peak Current Over Land and Ocean

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This work was supported by a contract to NASA under the Defense Advanced Research Projects Agency (DARPA) Nimbus Program under Grant HR001135186.

ABSTRACT Natural cloud-to-ground (CG) lightning behaves differently over land and ocean. These differences likely reflect local variations in the speed at which storms develop over ocean, and are possibly contributed to by differences in the local aerosol composition. Earlier studies have reported statistically larger peak currents for negative CG first strokes over ocean than over land. This work focuses on differences in this relationship for first strokes, for subsequent strokes in existing channels to ground, and for subsequent strokes creating new ground contacts. This distinction will shed light on the mechanism responsible for the observed land:ocean differences, and can either support or refute the hypothesis that this difference is associated with the propagation of downward negative leaders in free space, driven by the vertical profile of electric field within and below the cloud. Results show that when compensated for detection threshold increases with increasing distance from land-based sensors, the distribution of estimated peak currents for subsequent strokes in existing (pre-ionized) channels to ground was indistinguishable from distributions for lightning that occurred inland, near shore, offshore, and in the distant ocean (~200 km offshore), with median values ranging between 14.4 and 15.1 kA. Conversely, the population of first strokes over distant ocean had much higher peak currents than those that occurred inland (median values of 23.1 kA vs. 17.3 kA, respectively), when corrected for detection threshold. These findings are consistent with the field-profile hypothesis noted above since peak currents for return strokes due to downward leaders that establish new channels (first strokes) would be impacted the most by the vertical profile of electric field near the cloud base, whereas the peak current for strokes in previously-established channels should be far less dependent on the field profile.

INDEX TERMS Electrification, lightning, ocean, peak current.

I. INTRODUCTION AND BACKGROUND

Natural cloud-to-ground (CG) lightning has been shown to behave differently over land and ocean [1]–[3]. These differences likely reflect local variations in the speed at which storms develop over ocean, and possibly the local aerosol composition. A better understanding of these differences will help identify factors that influence the widely-varying behavior of CG lightning, improve our grasp of the underlying physics of lightning processes, and quantify differences in lightning risk to people and property over land and ocean.

The associate editor coordinating the review of this manuscript and approving it for publication was Amedeo Andreotti.

An exploration of these differences requires some understanding of the nature of lightning attachment to ground, briefly described in the following paragraph. More details are available from several sources, see for example Uman and Krider [4], Uman [5], or Rakov [6].

A CG lightning flash transports electrical charge from within an electrified cloud to one or more locations on ground over a time period of about one second, through lightning processes referred to as return strokes. About 90-95% of the time, the polarity of the charge transferred to ground is negative [4], and these negative flashes are the focus of this work. The first negative return stroke in a flash forges a tortuous connection from within the cloud to the ground through a sequence of short spatial steps, referred to as stepped leaders that typically take 10's of ms to reach the ground. When the tip of the leader is within several 10's of meters of the ground, the electric field under the tip becomes large enough to initiate one or more upward connecting leaders of opposite polarity, usually from the tallest object(s) in the vicinity of the downward leader. When the upward and downward leaders connect, an ionized and highly conducting channel is established and the first return stroke begins, neutralizing charge within the channel for a few 10's of μs, with the possibility of having continuing current in the channel as it removes additional charge from within the cloud. A typical first stroke exhibits a peak current of about 30 kA, with values ranging between 5 and more than 200 kA. After a pause of several ms this sequence may begin again, resulting in an additional channel to ground, or a dart leader that propagates down a previous return-stroke channel, initiating a subsequent stroke in a new or existing channel. Based on indirect measurements using networks of ground-based electromagnetic sensors, the same-channel return strokes appear to have much lower peak currents than first strokes or subsequent strokes that establish a new channel to ground [7]. Although some negative flashes have only one return stroke, they typically have several strokes. Of these ''multi-stroke'' flashes, about half strike ground in two or more places [8], [9].

Returning now to land:ocean differences, one avenue of study has been the difference in lightning incidence characterized by long-term lightning flash occurrence rates and within-storm rates [10]–[12]. Other studies have focused on differences in the characteristics of first return strokes in CG lightning flashes. Lyons *et al.* [13] examined the climatology of large peak current ($\geq$ 75 kA) CG lightning flashes using data from the U.S. National Lightning Detection Network™ (NLDN) and reported that the proportion of high peak current negative CG flashes occurring over oceanic regions of the northern Gulf of Mexico and off the southeastern United States coastline was ''unusually high''. Orville *et al.* [14], [15] studied the occurrence characteristics of CG lightning reported by the NLDN and the North American Lightning Detection Network (NALDN), respectively, and found that the magnitudes of network-estimated negative first-stroke peak currents were, on average, larger over the ocean than over land. These observations were confirmed using long-range lightning locating system (LLS) data [16], [17], along with shipboard electric field observations [18]. However, this discrepancy in peak current magnitudes over land and ocean has not been found for positive return strokes [14], [15], and [19]. All of these observations are based on remote measurement of electric or magnetic radiation-field in the low frequency (LF) and/or very low frequency (VLF) range that have propagated 10's of km or more from the lightning discharge location.

Until recently, the reported finding of higher peak current over ocean was questioned due to poor detection of low-current discharges outside of the (land-based) perimeter of most LLS networks, and the potential for refractive losses at and near land/ocean interfaces. Independent evidence of higher peak currents over coastal and more-distant ocean was provided in work by Nag and Cummins [3], who examined the time interval between the first detected negative cloud pulse in a flash thought to be associated with preliminary breakdown and the first negative return stroke (so-called negative stepped-leader duration) using NLDN data. They 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. They found no evidence that the relationship between leader duration and first return stroke peak current was different between regions. The authors concluded that a longer stepped-leader duration (or a slower average vertical velocity) over land could be indicative of more extensive horizontal leader propagation (radial ''wandering'') prior to reaching ground. If such horizontal propagation were within the cloud or just below the cloud base, it could be due to a more extensive lower positive charge region. Also, they suggested that 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 return stroke peak current. This finding is consistent with the hypothesis of an altered lower positive charge structure in the cloud put forward in [1]. Recent work by Shi *et al.* [20] provides additional experimental evidence of a strong positive correlation between first return stroke strength (inferred peak current) and average downward leader speed. The authors also suggest that this behavior is modulated by the relative sizes and geometry of the mid-level negative and lower positive charge regions within the cloud, resulting in within-storm variations of peak current. Given the variability and complexity of charge structure in convective updrafts of thunderstorms reported by Stolzenburg and Marshall [21], Stolzenburg *et al.* [22], there is a basis to expect that such heterogeneity can exist.

An open question for land:ocean differences is the behavior of subsequent strokes in negative flashes which fall into the two categories described above: those that produce new ground contacts (NGC strokes) and those that remain in a pre-existing ionized channel established by an earlier stroke in the flash (PEC strokes) [8]. This distinction is important because the answer will shed additional light on the mechanism for the observed land:ocean differences. More specifically, if land:ocean differences do not exist for PEC strokes, then this is consistent with the hypothesis that the difference is associated with the propagation of downward stepped leaders in free space, initiated within or below a significant negative charge region and driven by the vertical profile of electric field within and below the cloud [1], [3], and not with some inherent difference in charge density within the main negative charge region in the cloud. See Nag and Rakov [23], [24] for additional insight about the impact of cloud charge structure on initial downward leader propagation.

This distinction between first strokes and PEC strokes hinges on the unique nature of negative subsequent strokes in pre-existing channels. These strokes begin with dart leaders that travel much faster than stepped leaders [25], [26] and propagate downward from within the negative charge region [27], through any remaining positive charge region, and finally below the cloud and downward towards ground. Helpful visualizations of this behavior are provided in time-height plots of leader propagation made possible by VHF Lightning Mapping Arrays (LMA), as shown in [28] - See Fig. 4 and [29] - see Fig. 5. These images also provide clear evidence that dart leader velocity is not significantly altered as it propagates through the region between the main negative and lower positive charge regions. Unlike stepped leaders, dart leaders propagate in a previously ionized channel containing warm air [Uman and Voshall] with conductivity on the order of $\sim 10^{-2}$ S/m [30]. These channels are therefore more than 11 orders-of-magnitude more conductive than moist air near cloud edge of about 10^{-15} S/m [31]. Given these facts, the peak current of PEC strokes should be relatively unaffected by the vertical profile of the surrounding electrostatic field in the lower part of the cloud.

Initial evidence that negative PEC strokes do not exhibit higher peak current over ocean was provided in the work by Cummins *et al.* [19] using lightning data from the NLDN. However, this study did not control for the reduced ability of the NLDN to report low-current discharges off-shore (outside the network), and only employed a crude method for separating PEC and NGC strokes within a flash.

In this work, we describe a study of NLDN-estimated negative CG stroke peak currents over land and ocean, carefully separating-out the populations of first strokes, NGC strokes, and PEC strokes using a novel flash-grouping algorithm [32]. Distributions of peak currents derived for these populations are then compensated for reduced detection efficiency (DE) using an established DE-correction technique [33], [34].

II. INSTRUMENTS, DATA AND METHODS

The NLDN uses a network of about 100 combined time-of-arrival and direction-finding sensors operating in the VLF/LF range to locate lightning discharges throughout the conterminous U.S. [28]. It provides real-time and archived lightning data including time, location, and peak current, as well as other data-quality and waveform information. The NLDN currently geo-locates CG return strokes with a median location accuracy of about 200 meters [35] and a time accuracy to the microsecond. During the period of this study (January through November 2014), the NLDN was expected to report about 95% of all CG flashes, and about 80% of all return strokes within these CG flashes.

Modeling work by Cummins and Murphy [28] indicated that the minimum detectable peak current (50% detection) for the NLDN falls off rather rapidly outside the network. For the NLDN configuration following an upgrade in 2002-3, the estimated detection threshold off the east coast of Florida

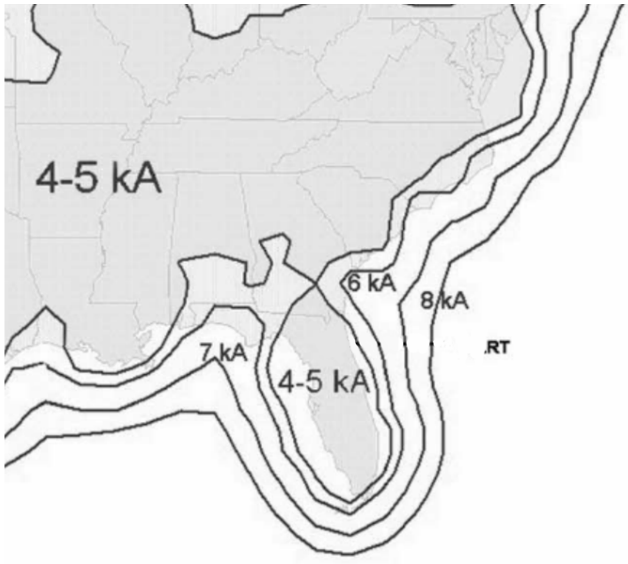

FIGURE 1. Estimated minimum detectable peak current for the U.S. NLDN in the southeast following the 2002-2003 system upgrade Adapted from Cummins and Murphy (2009), with permission.

was expected to go from 4-5 kA over the land mass to greater than 8 kA at a distance of about 100 km, as shown in Fig. 1. The sensitivity of the NLDN was improved in mid-2013 to increase detection of cloud pulses produced by both CG and intra-cloud (IC) flashes [35]. This upgrade will also have improved the offshore performance somewhat for the 2014 data employed in this work. This performance fall-off needs to be considered when studying land:ocean differences in estimated peak current.

The NLDN stroke-level data were used in this study, after being grouped into CG flashes by Vaisala's flash grouping algorithm [Cummins et al, 1998]. These data were accumulated into four spatial regions near Kennedy Space Center (KSC), Florida as shown in Fig. 2. These regions were

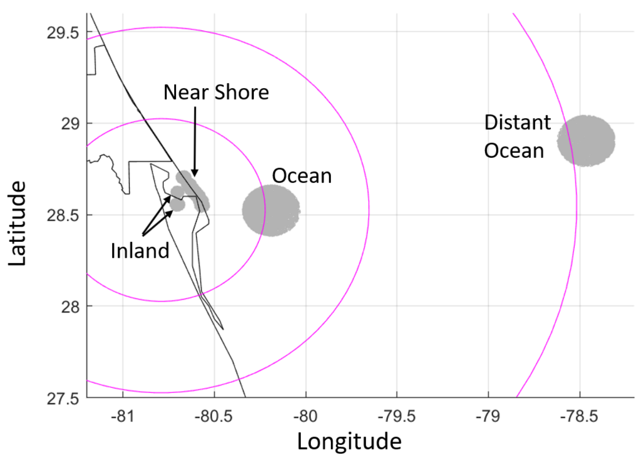

FIGURE 2. Cloud-to-ground return stroke location for the four regions evaluated in this study.

selected to represent varying relationships associated with the coastline near KSC:

Distant Ocean	(~200 km east of KSC)
Ocean	(~35 km east of KSC)
Near-shore	(along the Florida Coast near KSC)
Inland	(over Merritt Island)

For each of these locations, the negative CG strokes were classified as first-in-flash (FIF) strokes, subsequent strokes creating a new channel to ground (NGC), and subsequent strokes in a pre-existing channel (PEC). The spatial clustering and classification algorithm was developed using both the location of the individual discharges and their individual location uncertainties (confidence ellipses) that are provided as part of the NLDN dataset [32]. This two-stage algorithm first clusters well-located strokes into likely ground-strike locations based on a k-means approach using Euclidian distances, similar to the work by Pédeboy [36]. Any remaining strokes in the flash with large location uncertainty are evaluated to determine if size and spatial orientation of their uncertainty, embodied in their confidence ellipses, allows them to be confidently clustered with an established ground strike location. If not, then those strokes are thought to establish a new ground contact. See [23] for further details. In this analysis, the clustering parameters were selected in order to have high confidence that "true" NGC strokes were not included in the PEC stroke classification, thereby minimizing contamination of the population of PEC-classified strokes. This likely biases the population of NGC strokes, but this population is not central to this work. An example of a clustered flash from the 2014 dataset is provided in Fig. 3. This flash had 7 return strokes that were clustered into four ground strike locations, resulting in one first stroke, three NGC strokes, and three PEC strokes. The confidence ellipses in this figure encircle regions with an estimated 50% probability of containing the true strike location [37].

Normalized cumulative peak current distributions were produced for each of the four regions and three classifications. These "reverse cumulative" distributions were accumulated from the highest magnitude to lowest magnitude, in order to (1) most-clearly show the loss of low current discharges off-shore, and (2) to allow for graphical determination of the true median value following compensation for the "loss" of low-current discharges.

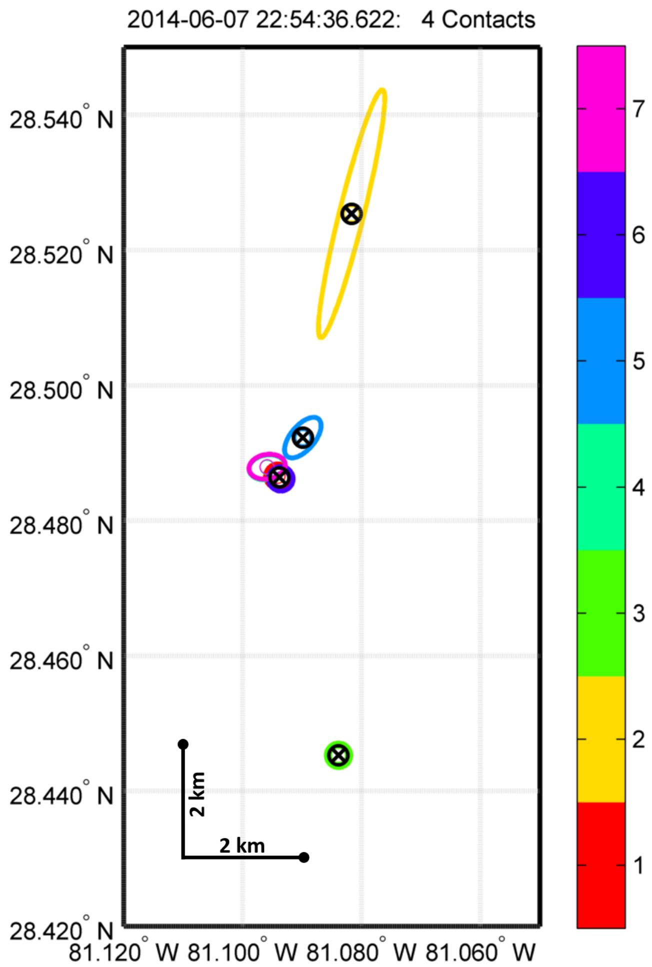

FIGURE 3. Estimated ground-strike locations (circled X) for a seven-stroke negative CG flash with 4 ground contacts and three strokes in pre-existing channels. Colors indicate the stroke index within the flash. Ellipses indicate the median location uncertainty for each stroke.

III. RESULTS AND DISCUSSION

The as-measured peak current distributions for the three stroke types are shown in Fig. 4. The Inland dataset is viewed as the reference set because the NLDN detection efficiency is the highest in this area (See Fig. 1). The distributions for the other three regions are plotted as black bars on top of these reference distributions (wider grey bars). The nonparametric two-sample Kolmogorov-Smirnov test was used to test the significance of the hypothesis that that the pairs of distributions are statistically indistinguishable. We view p-values greater than 0.05 as indicating non-significant differences between the distributions; for this work all p-values were either less than 0.001 or greater than 0.20. All Near-Shore distributions (FIF, PEC, and NGC) were indistinguishable from the Inland distributions, all having p-values greater than 0.3. For the Ocean region, only the PEC distributions were indistinguishable. Since the PEC distribution includes the lowest-current strokes, this finding indicates that the NLDN DE is not compromised at this modest distance from shore (see Fig. 2). On the other hand, all three Distant Ocean distributions were significantly different ($p<0.001$) than the Inland distributions, with major differences for the low-current strokes. This supports concerns about the loss of low-current strokes over distant ocean as shown in Fig. 2. This issued is addressed in the analysis that follows.

Fig. 5a shows the "reverse" cumulative distributions for PEC strokes, for each of the four regions. The distributions for Ocean, Near Shore, and Inland are nearly identical. The small deviations for the Inland curve above 19 kA are due to the small number of observations in this dataset (total of 866 strokes). The Distant Ocean curve is distinctly

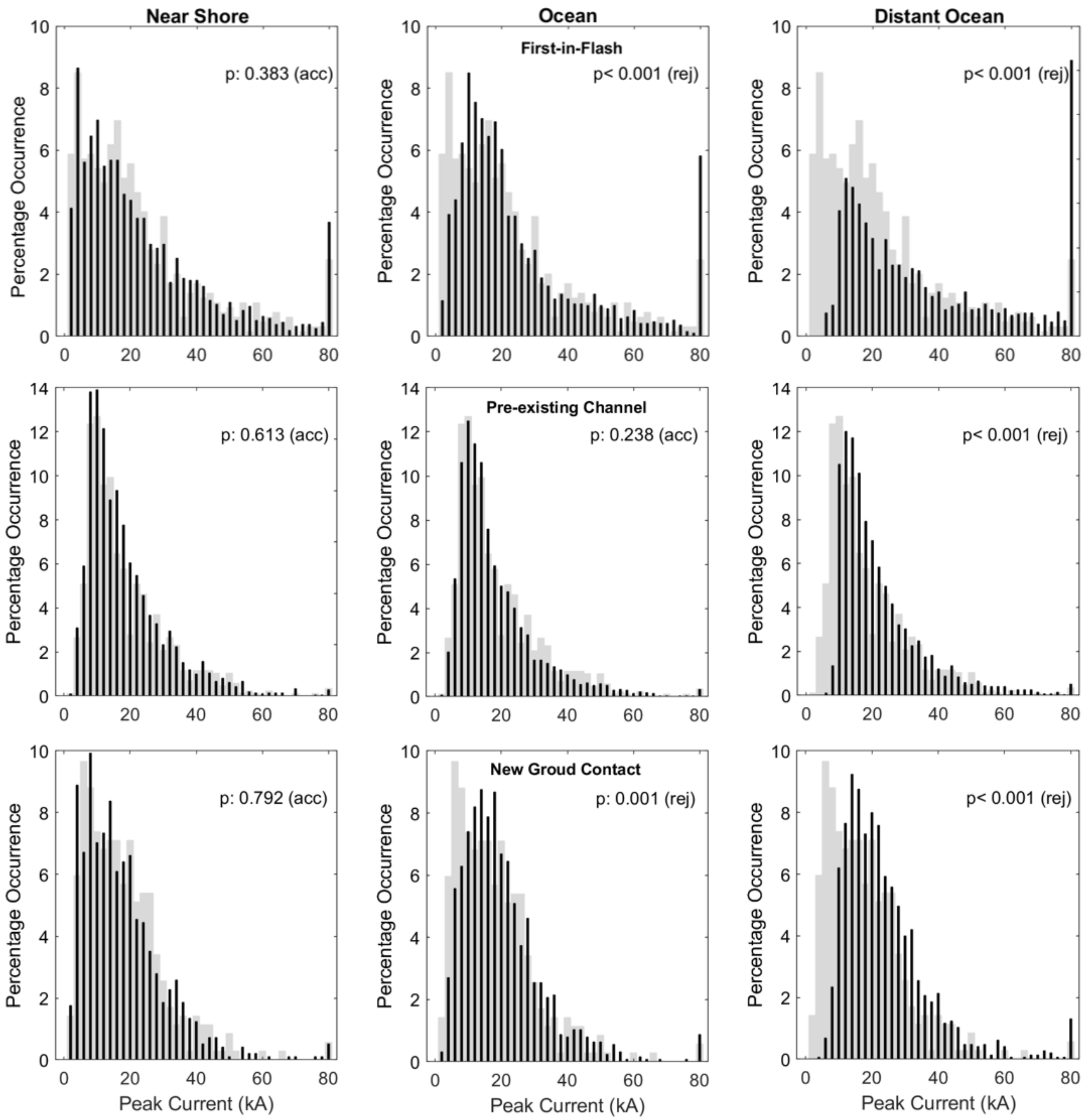

FIGURE 4. Peak current distributions for first-in-flash return strokes (top row), return strokes in pre-existing channels (middle row), and return strokes making new ground contacts (bottom row). The distributions for Near Shore (left column), Ocean (middle column) and Distant Ocean (right column) are plotted as black bars on top of the associated distributions measured inland (wide grey bars). All currents > 80 kA are accumulated in the 80 kA histogram bin. The p-values greater than 0.05 indicate that the distributions are not statistically distinguishable using the two-sample Kolmogorov-Smirnov test. All p-values are either less than 0.001 or greater than 0.2.

different, with no strokes having peak currents less than about 7-8 kA. Measured mean and median values are included, demonstrating the nearly-identical statistics for all regions except for Distant Ocean.

If we assume that the primary source of this difference for Distant Ocean is the inability to report low-current strokes at this distance of about 150-200 km from the coastline, then a simple scaling of the cumulative distribution by the relative fractional DE should make the higher-current portion of this distribution match the others. Fig. 5b shows the result of scaling the Distant Ocean distribution by 0.77. Note that the adjusted values above 10 kA are now visually

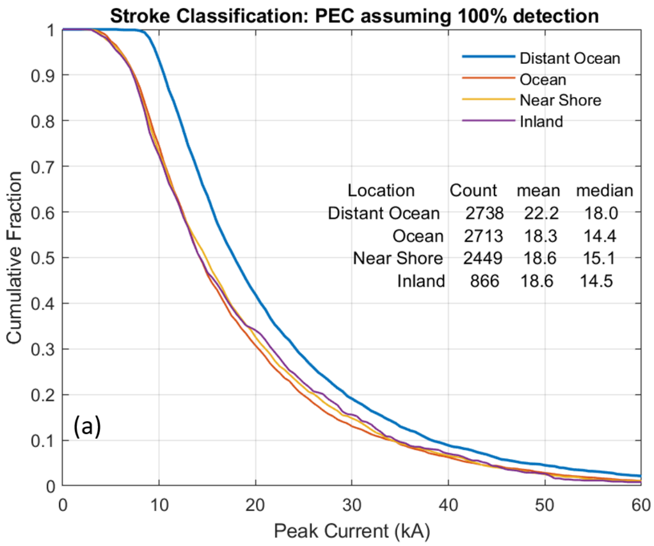

FIGURE 5. Cumulative peak current distributions for return strokes in pre-existing channels. (a) uncorrected normalized distributions; (b) same as (a) but with Distant Ocean distribution corrected for non-detected strokes with peak currents below about 8 kA (77% DE).

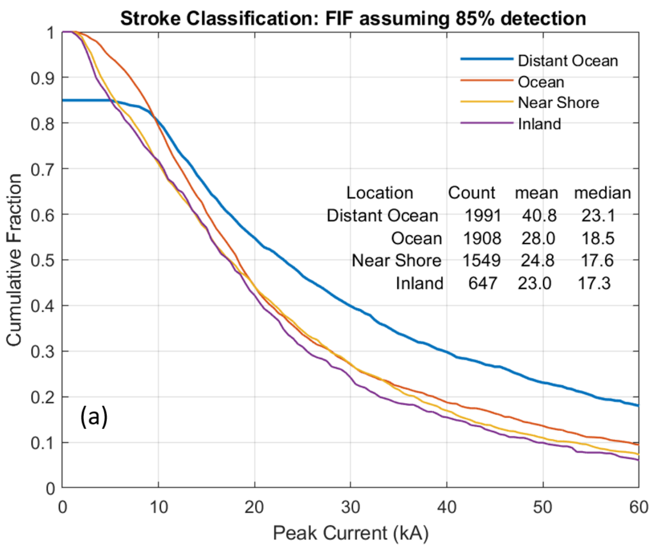

FIGURE 6. Cumulative peak current distributions for (a) First-in-Flash strokes; (b) New Ground Contact strokes. For both panels, the Distant Ocean distribution is corrected for non-detected strokes with peak currents below about 8 kA.

indistinguishable from the other three curves. This technique for correcting for DE was first reported by Cummins and Bardo [38] and was applied to correct the lightning flash density by Murphy and Holle [33]. When low-current strokes (<10 kA) were excluded from the Kolmogorov-Smirnov test for this PEC dataset the p-value was 0.53, indicating a non-significant difference. This result makes it clear that the underlying distribution of peak currents for strokes in pre-existing channels is not dependent on the occurrence over land or ocean, at least in this region, with a "corrected" median value (cumulative fraction at 0.5) of 14.9 kA. This lack of "land:ocean differences" for PEC strokes was first suggested by Cummins *et al.* [19], and further explained by Cooray *et al.* [1]. This earlier work did not provide a convincing way to confirm this result.

Separate analyses of negative first strokes (FIF) and NGC are shown in Figs. 6a and 6b, respectively. For these figures, the "as measured" mean and DE-compensated median values for Distant Ocean are included. The compensated median values can also be read directly off the graphs and are 23.1 kA for the FIF strokes and 18.5 for the NGC strokes. The Deep Ocean distribution for first strokes is clearly different from the others, with a much larger fraction of strokes above 20 kA, and larger mean and median values, consistent with the references cited above. The Distant Ocean distribution for NGC strokes indicates slightly higher peak currents in

TABLE 1. Summary of peak current characteristics in four regions.

	Pre-existing Channel			First-in-Flash			New Ground Contact		
Region	Count	Mean	Median	Count	Mean	Median	Count	Mean	Median
Distant Ocean	2738	22.2	14.9	1991	40.8	23.1	1450	24.4	18.5
Ocean	2713	18.3	14.4	1908	28.0	18.5	1256	20.5	17.4
Near Shore	2449	18.6	15.1	1549	24.8	17.6	967	18.2	15.0
Inland	886	18.6	14.5	647	23.0	17.3	352	18.1	15.8

the median, but the differences are quite modest. Overall, the strokes that create a new channel (NGC strokes) have peak current slightly larger than PEC strokes, but smaller than first strokes. Thus the ordering of peak current magnitudes over the ocean are consistent with the video-based findings over land reported by Biagi et al. [7] and the references therein.

Table 1 contains the negative stroke counts, along with the mean and median magnitudes of the NLDN-estimated peak current values for the four regions. There is no meaningful way to correct the mean values because a calculation of the mean requires knowledge of the full population (all currents), so these values are as-measured. However, the median values are taken from the corrected distributions in Fig. 5.

IV. SUMMARY AND CONCLUSION

This study explored land:ocean differences in NLDN-estimated peak current for first strokes, for subsequent strokes in existing channels to ground, and for subsequent strokes creating new ground contacts. Results show that when compensated for detection threshold increases with increasing distance from land-based sensors, the distribution of peak currents for subsequent strokes in existing (pre-ionized) channels to ground was indistinguishable from distributions for lightning that occurred inland, near shore, offshore, and in the distant ocean ($\sim$200 km offshore). These strokes in pre-exiting channels are unlikely to be affected by the vertical profile of electric fields near the cloud base. Conversely, the population of first strokes over distant ocean had much higher peak currents than those that occurred inland (median values of 23.1 kA vs. 17.3 kA, respectively), when corrected for detection threshold. These findings are consistent with the hypothesis that thunderstorm charge structure is different over land and ocean, assuming that this difference will influence the propagation and charge density of downward negative leaders in free space, driven by the vertical profile of electric field within and below the cloud.

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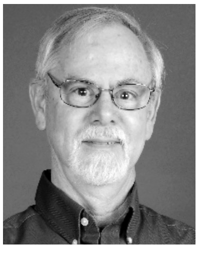

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