P1.10 INNER CORE LIGHTNING IN 2004-2007 ATLANTIC TROPICAL CYCLONES USING VAISALA'S LONG RANGE LIGHTNING DETECTION NETWORK (LLDN)

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1. INTRODUCTION

The outer limit of land-based cloud-to-ground (CG) lightning detection networks is less than 1000 km from sensors in the U.S. National Lightning Detection Network (NLDN) and the Canadian Lightning Detection Network (CLDN). This distance is determined by characteristics of the radiation emitted by the ground waves from CG flashes. While 1000 km is beyond the range of coastal meteorological radars, it is not especially far from land for monitoring rapid changes in tropical cyclone structure and intensity. The primary sources for monitoring tropical cyclones beyond this 1000-km range are (1) infrared and visible satellite imagery provided by geostationary satellites, (2) microwave and space-based radar imagery provided by polar orbiting satellites and (3) air reconnaissance data provided by National Oceanic and Atmospheric Administration (NOAA) and U.S. Air Force hurricane hunters. Geostationary satellite imagery is the only one of these datasets that provides continuous monitoring of tropical cyclones. Unfortunately, such imagery often does not provide all of the necessary detailed structural information in eyewalls and outer rainbands that meteorologists need for nowcasting/forecasting tropical cyclones.

Vaisala's NLDN has been used to study outbreaks of lightning within the eyewalls of hurricanes (Molinari et al., 1999; Lyons and Keen, 1994). Molinari et al. (1999) found that most lightning activity occurs in the outer rainbands of storms. There is a relative minimum in lightning activity in the central dense overcast and a smaller maximum in lightning activity in the eyewall. They also hypothesized a relationship between eyewall lightning outbreaks and eyewall replacement cycles. Lyons and Keen (1994) noted a large increase in eyewall lightning as 1998 Hurricane Florence made landfall in the central U.S. Gulf Coast. The NLDN has been in operation since 1989 and detects lightning within 1000 kilometers of the U.S. coastline.

More recently, Vaisala's Long Range Lightning Detection Network (LLDN) has been used to study outbreaks of lightning within the eyewalls of hurricanes (Squires and Businger, 2007; Demetriades and Holle, 2008). Squires and Businger (2007) examined eyewall lightning relationships to aircraft radar and space-based microwave imagery in Hurricanes Katrina and Rita. They found that eyewall lightning was generally located in regions with high radar reflectivity and microwave precipitation ice content signatures, and low brightness temperatures. Demetriades and Holle (2008) found that Atlantic and East Pacific tropical storms (hurricanes) tend to produce the highest (lowest) inner core (within 100 km of the storm center) lightning rates.

Vaisala's LLDN is a newer capability utilizing NLDN and CLDN sensors to detect CG lightning flashes thousands of kilometers off the coasts of North America. In addition, Vaisala's LLDN includes several long range sensors located in the North Pacific Ocean. During 2008, Vaisala expanded its long range lightning detection capabilities with the installation of additional long range sensors in the Caribbean and the western Pacific Ocean.

LLDN detection efficiency (DE) decreases with increasing distance from NLDN, CLDN and long range sensors installed in the North Pacific Ocean and Caribbean. In addition, any long range lightning detection network's DE varies as a function of time of day due to lightning signal propagation interaction with the ionosphere. Long range lightning DE is higher during the night than during the day due to better ionospheric propagation conditions at night. Since long range lightning DE, such as that provided by Vaisala's LLDN, varies as a function of location and time of day (also time of year), it introduces challenges for monitoring lightning rates within tropical cyclones that are in motion.

Demetriades and Holle (2008) have recently studied inner core lightning rates for all Atlantic and East Pacific tropical cyclones that have occurred since 2004. A lightning flash was considered to have occurred in the inner core of a tropical cyclone if it was located within 100 km of the center of the tropical cyclone, as reported by the National Hurricane Center (NHC), and within 90 minutes of the NHC reported location. As a first step toward correcting inner core lightning rates for DE, a night-time DE was applied to all time periods, regardless of time of day. This paper will discuss inner core lightning rates produced by 2004-2007 Atlantic tropical cyclones after both day and night-time DE corrections have been applied to the LLDN data that also take into account location. In addition, to better understand the relationship between inner core lightning rates and tropical cyclone landfall, inner core lightning rates are examined with respect to landfall.

2. METHODOLOGY

In this study, inner core lightning rates for all Atlantic basin tropical cyclones that were located west of 45° west longitude were examined from 2004 through 2007. The west of 45° west longitude restriction was placed on this dataset because LLDN DE falls off to near zero for most latitudes east of 45° west longitude. This included

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the time period from when the tropical system was first designated as a tropical depression (sustained wind speeds >24 knots) to the time period when the tropical cyclone was no longer classified as a tropical depression, tropical storm or hurricane.

To better understand the effects of landfall on inner core lightning production of Atlantic tropical cyclones, inner core lightning rates were examined for the 24-hour time periods before and after landfall. To avoid including smaller islands in the landfall dataset, only tropical cyclones that made landfall in the U.S., Mexico, Canada, Hispaniola, and Cuba were included in the landfall analysis. A maximum of 54 samples were included in this analysis for any given three-hour time period within 24 hours of landfall. Not all storms were classified as a tropical cyclone for the entire 24-hour periods before and after landfall.

The position and maximum sustained wind speed of hurricanes used in this study were obtained from the best-track data produced by the NHC every 6 hours. Since a hurricane can propagate fairly long distances over a 6-hour period, the center position and maximum sustained wind speeds were interpolated between consecutive 6-hourly intervals in order to obtain 3-hour intervals for these variables.

For this study, 3-hourly CG lightning flash rates were obtained within 100 km of the center position of the tropical cyclone. This is referred to as the inner core lightning rate in this paper. Each 3-hour interval was centered on the time of each center position estimated from the best-track data. For example, CG lightning would be accumulated within 100 km of the center position from 0130 to 0430 UTC for the 0300 UTC position estimate.

Once an inner core lightning rate was obtained for a specific 3-hour time interval, a DE correction was applied. As mentioned, long range lightning DE is higher during the night than during the day due to better ionospheric propagation conditions at night. This can be seen in the DE maps for the LLDN as shown in Figures 1 and 2.

Figure 1 shows the nighttime detection efficiency (DE) of the LLDN. The dark green shading shows areas covered by >90% CG flash DE. This is the high precision region covered by the NLDN. LLDN nighttime DE can be seen dropping from 90% near the North American coast to 10-20% (red shade) thousands of kilometers into the Atlantic and Pacific Oceans.

Figure 2 shows the daytime DE of the LLDN. Since the NLDN provides the area of coverage with >90% CG lightning DE, notice that the region covered by the dark green shading (>90% DE) does not change. However, the range of the LLDN is more limited and shows the 10-20% CG DE (red shade) closer to the North American coastline.

For more information on the lightning detection model used by Vaisala and validation of Vaisala's LLDN, the reader is referred to the Appendix in Cummins et al. (1998) and Pessi et al. (in press), respectively.

DE corrections were applied to the inner core lightning count by using a distance-weighted average of the DE within 250 km of the center of the storm position, as indicated in the NHC best-track data. A relatively coarse grid (1º latitude and 2º longitude grid spacing) of DE values was used for these calculations because this was more representative of the uncertainty in DE estimates for long range lightning detection networks. Furthermore, a distance of 250 km from the center of storm position was used to help smooth the DE values and account for the uncertainty in DE at these long ranges. For example, an inner core lightning count of 10 would be multiplied by 5 if the distance-weighted, average DE value near the center of the storm was 20%. This DE correction could be very large if the tropical cyclone was far from the coast of North America. Therefore, we limited the correction to a maximum inner core lightning count multiplied by 100. For example, if the DE value near the center of the storm was less than 1%, we still only multiplied the inner core lightning count by 100 and not more than 100.

Inner core lightning rates were examined as a function of storm intensity. Tropical cyclone intensity was classified using five intensity categories (Table 1).

Tropical depressions (TD) followed the standard definition provided by NHC with maximum sustained wind speeds of less than 35 knots. Tropical storms were split into two intensity categories. The tropical storm weak (TS-W) category contained all tropical cyclones with maximum sustained wind speeds between 35 and 49 knots. The tropical storm strong (TS-S) category contained all tropical cyclones with maximum sustained wind speeds between 50 and 63 knots. Hurricanes were also split into two intensity categories. The hurricane weak (H-W) category contained all category 1 and 2 hurricanes on the Saffir-Simpson Scale or those with maximum sustained wind speeds between 64 and 95 knots. The hurricane strong (H-S) category contained all category 3, 4 and 5 hurricanes on the Saffir-Simpson Scale or those with maximum sustained wind speeds greater than 95 knots.

3. ATLANTIC BASIN RESULTS

Inner core lightning activity was studied for 66 of the 67 tropical cyclones (excluding subtropical cyclones) that occurred in the Atlantic basin from 2004 through 2007. Tropical Storm Erin (2007) was the one tropical cyclone excluded from this analysis. The 3-hour, DE-corrected, cumulative lightning rate results are shown in Figure 3 as a function of tropical cyclone intensity.

The highest inner core lightning rates occur within tropical storms. The TS-W and TS-S cumulative lightning rate curves lie very close together with TS-S producing the highest inner core lightning (blue line in Figure 3). Low-to-moderate inner core lightning rates (lightning counts from ~10-100) occur frequently within the H-S category (orange line in Figure 3), while high inner core lightning rates are much less frequent within the H-S category. Infrequent high lightning rates in the H-S category appear to be related to eyewall replacement cycles (Knabb et al., 2008).

By far, the least amount of inner core lightning activity occurs within the H-W category (red line in

Figure 3). High inner core lightning activity within tropical storms and low inner core lightning activity within hurricanes represents a newer finding concerning lightning activity within tropical cyclones (see also Demetriades and Holle 2008). Lightning activity in tropical depressions (TD category) occurs more frequently than in the H-W category, but less frequently than the tropical storm stage.

Another way to interpret the results of Figure 3 is shown in Table 2. The 50th percentile (median) of inner core lightning rates is two for the H-W category and 18-24 for both tropical storm categories. The H-S category actually has a relatively high inner core lightning rate of 16.

These differences become much larger as the 75th and 90th percentiles are examined. At the 75th percentile, both tropical storm categories have the highest lightning rates with values of 280 and 477, while the H-W category has the lowest lightning rate with a value of 43. Also, notice that the H-S category starts to have much lower lightning rates at the 75th percentile (Table 2). At the 90th percentile, both tropical storm categories have much higher lightning rates than the rest of the tropical cyclone intensity categories with values greater than 1000. At this percentile, the TD category lightning rates (585) become higher than both hurricane categories (between 200 and 300).

The third column in Table 2 shows the cumulative percentile of the first non-zero lightning rate for each storm intensity category. Again, differences are clearly shown between the H-W category and the tropical storm categories. The tropical storm categories produce non-zero lightning counts at the 29-35 percentile level, while the H-W category does not produce its first non-zero lightning count until the 47th percentile.

It is important to notice that these results show that inner core lightning occurs during the vast majority of 3-hour time periods for almost all intensity categories. It is also important to note that a percentage of these zero counts should be non-zero and are only due to a lack of LLDN DE in parts of the Atlantic basin. This is contrary to the general perception that lightning rarely occurs in the inner core (or eyewall) of tropical cyclones, especially hurricanes.

4. ATLANTIC BASIN LANDFALL RESULTS

Inner core lightning activity during the 24-hour periods before and after landfall was examined at the 25th, 50th (median), 75th and 90th percentile levels (Fig. 4). The 25th percentile values were excluded from Figure 4 because they were all near zero. The 90th percentile values were excluded from Figure 4 because they were influenced by just a few outlier events due to the relatively small sample size.

Both the 50th and 75th percentile values show that Atlantic tropical cyclones typically produce higher inner core lightning rates for the 24-hour period leading up to, and including landfall. Inner core lightning rates tend to fall off rather rapidly after landfall. This represents another new finding regarding inner core lightning activity in tropical cyclones. Contrary to the general perception that tropical cyclones usually produce more lightning during and shortly after landfall, Atlantic tropical cyclones instead produce more lightning shortly before and at the time of landfall.

5. CONCLUSIONS

This study gives an unprecedented view of lightning production within the inner core with a large statistical dataset of tropical cyclones. Following the work of Demetriades and Holle (2008), this continues to be the most comprehensive study of tropical cyclone inner core lightning rates that has been studied to date.

Inner core, 3-hour lightning rates were examined within all tropical cyclones from the Atlantic tropical cyclone basin from 2004 through 2007 using Vaisala's LLDN. Using any long range lightning detection network to examine lightning activity within storms presents some challenges, since DE is higher at night than during the day due to better ionospheric propagation conditions at night. For this reason, LLDN DE corrections were applied to all 3-hour time periods analyzed in this study.

Atlantic tropical cyclones produce the highest inner core lightning rates during the tropical storm stage and the lowest inner core lightning rates during the hurricane stage. This represents a newer finding concerning lightning activity within tropical cyclones (see also Demetriades and Holle 2008).

Although Atlantic major hurricanes (categories 3, 4 and 5 on the Saffir-Simpson Scale) produced high inner core lightning rates infrequently, they appear to be related to eyewall replacement cycles (Knabb et al., 2008).

Inner core lightning rates were also examined with respect to landfall. Atlantic basin tropical cyclones produce more inner core lightning during the 24-hour period leading up, and including landfall, than they do during the 24-hour period after landfall. This represents another new finding concerning lightning activity and tropical cyclones.

6. REFERENCES

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Table 1. Maximum sustained wind speeds for each of the five tropical cyclone intensity categories used in this study.

Tropical cyclone intensity category	**Maximum sustained wind speeds**
Tropical depression (TD)	<35 knots
Tropical storm – weak (TS-W)	35-49 knots
Tropical storm – strong (TS-S)	50-63 knots
Hurricane – weak (H-W)	64-95 knots
Hurricane – strong (H-S)	>95 knots

Table 2. Statistics for all Atlantic basin tropical cyclones from 2004 through 2007. Column one shows the tropical cyclone intensity category. Column two shows the cumulative percentile of the first non-zero lightning count. Columns three, four, and five show the 50th percentile, 75th percentile, and 90th percentile 3-hour lightning counts, respectively.

Tropical cyclone intensity category	**Sample size**	**Percentile of first non-zero lightning count**	**50th percentile**	**75th percentile**	**90th percentile**
Tropical depression (TD)	480	42%	3	100	585
Tropical storm – weak (TS-W)	658	35%	18	280	1248
Tropical storm – strong (TS-S)	446	29%	24	477	1765
Hurricane – weak (H-W)	512	47%	2	43	276
Hurricane – strong (H-S)	373	29%	16	76	200

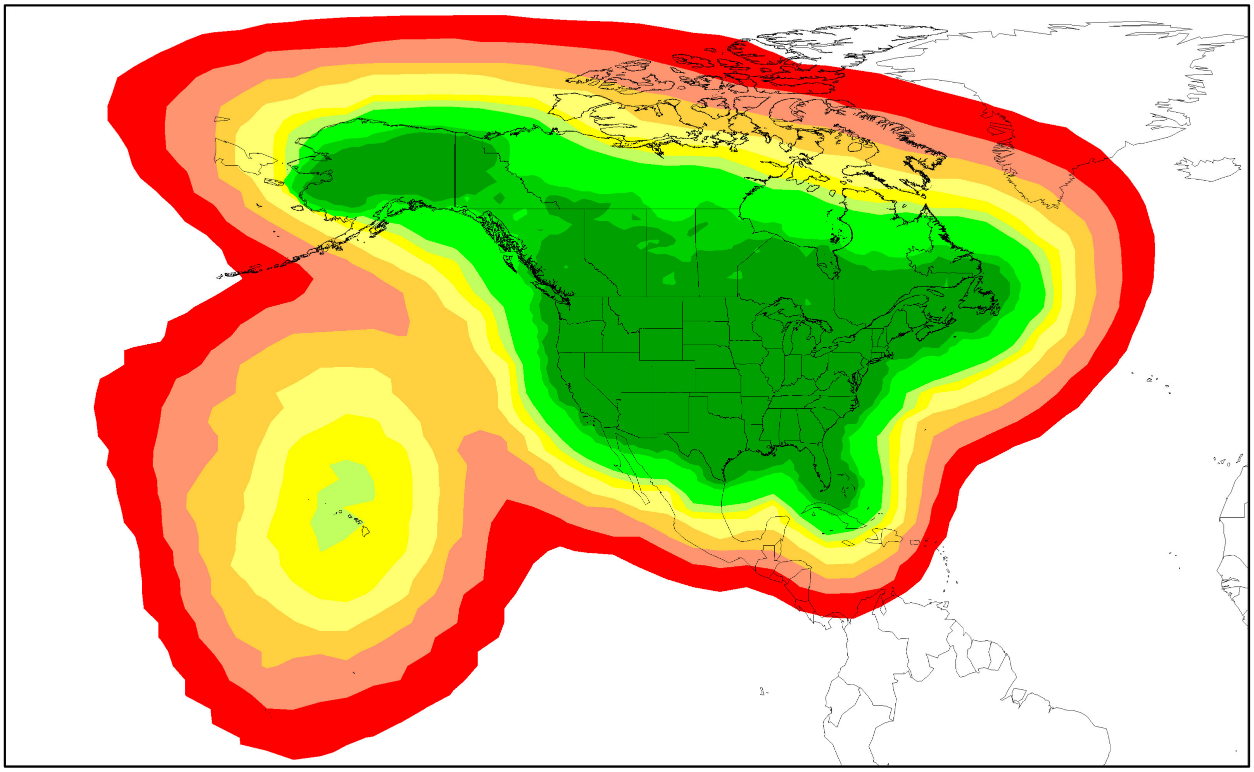

Figure 1. Vaisala LLDN nighttime detection efficiency (DE) for the period of this study (2004-2007). Shaded colors represent 10% increments of CG lightning flash DE, starting from >90% for the dark green shade to 10-20% for the red shade. Please see Pessi et al. (in press) for updated DE figures.

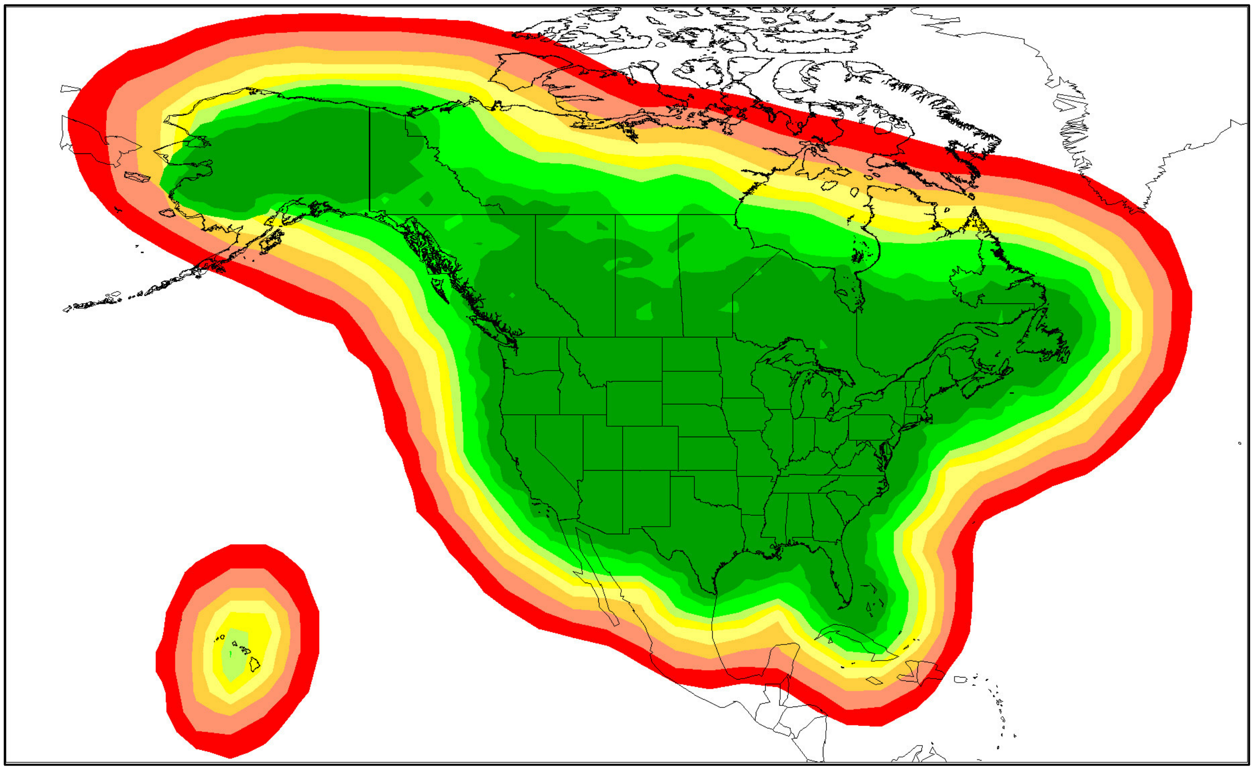

Figure 2. Vaisala LLDN daytime detection efficiency (DE) for the period of this study (2004-2007). Shaded colors represent 10% increments of CG lightning flash DE, starting from >90% for the dark green shade to 10-20% for the red shade. Please see Pessi et al. (in press) for updated DE figures.

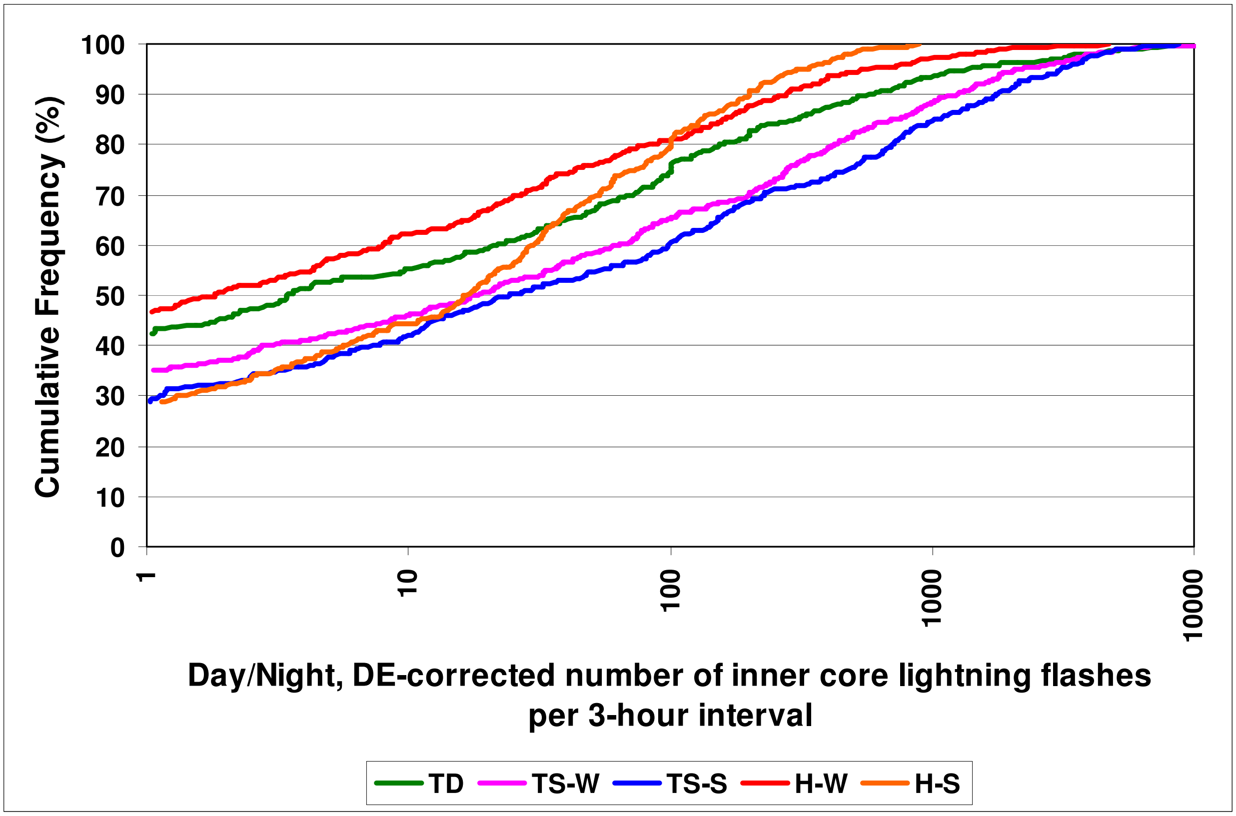

Figure 3. Cumulative 3-hour inner core lightning rate distributions as a function of tropical cyclone intensity for all Atlantic basin tropical cyclones from 2004 through 2007.

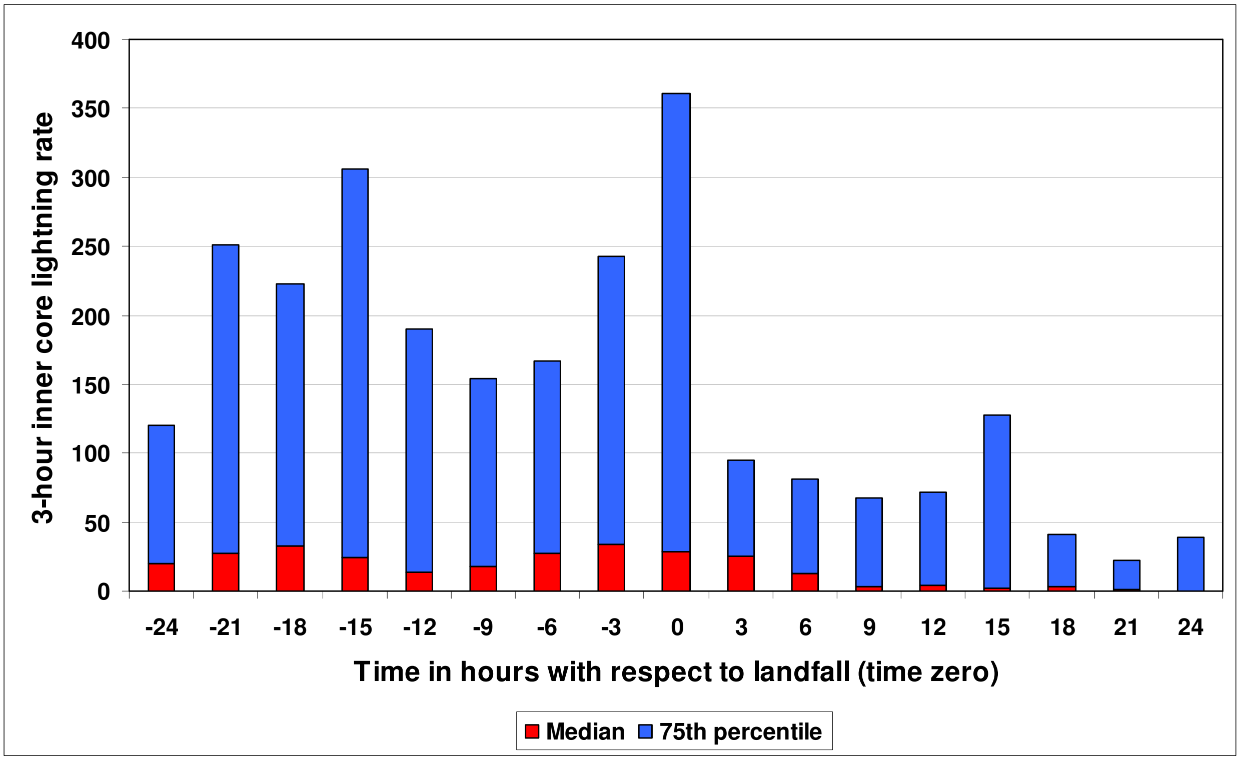

Figure 4. Median and 75th percentile, 3-hour inner core lightning rates for the 24-hour periods before and after landfall for Atlantic basin tropical cyclones from 2004 through 2007. Only landfalls in the U.S., Mexico, Canada, Hispaniola, and Cuba were included in this dataset. Time with respect to landfall is shown on the x-axis and 3-hour inner core lightning rates are shown on the y-axis.