1.2 **ANALYSIS OF INNER CORE LIGHTNING RATES IN 2004-2006 ATLANTIC AND EAST PACIFIC TROPICAL CYCLONES USING VAISALA'S LONG RANGE LIGHTNING DETECTION NETWORK (LLDN)**

Nicholas W. S. Demetriades * and Ronald L. Holle
Vaisala, Inc., Tucson, Arizona

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.

Outbreaks of lightning within the eyewalls of hurricanes studied by Molinari et al. (1999) had two major limitations. The first (and primary) limitation was that all storms had to have the center of circulation pass within 400 km of one of the U.S. NLDN sensors. The second limitation was that the tropical cyclone lifecycle was poorly sampled, since most were already at hurricane strength. There was little data from the tropical depression and tropical storm stages of tropical cyclones.

The Vaisala NLDN has been in operation since 1989. The Vaisala Long Range Lightning Detection Network (LLDN) is a newer capability utilizing NLDN sensors 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.

Since 1999, the LLDN dataset has provided a unique opportunity to observe lightning rates and structure within all phases of tropical cyclones over large portions of the Atlantic and East Pacific tropical cyclone basins.

* *Corresponding author address:* Nicholas W. S. Demetriades, Vaisala, Inc., 2705 East Medina Road, Tucson, AZ 85706; e-mail: nick.demetriades@vaisala.com

Demetriades and Holle (2005, 2006) have studied lightning trends within numerous tropical cyclones from 2002-2005, including hurricanes Katrina, Rita, Charley, Ivan, and Isabel. They found some similar lightning trends to those presented in the Molinari et al. (1999) study. Most notably, eyewall lightning outbreaks tended to occur during eyewall replacement cycles.

LLDN detection efficiency (DE) decreases with increasing distance from NLDN, CLDN and North Pacific Ocean sensors. 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 (2005, 2006) have recently studied inner core lightning rates in many tropical cyclones that have occurred since 2002. 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. These first analyses did not take into account the varying DE within the LLDN. This paper will discuss inner core lightning rates produced by 2004-2006 Atlantic and East Pacific tropical cyclones after night-time DE corrections have been applied to the LLDN data that also take into account location. Since the LLDN has a higher DE at night than during the day, these corrections represent realistic (conservative) estimates of inner core lightning rates within tropical cyclones during the night (day). This is the most comprehensive study of inner core lightning rates within tropical cyclones that has been studied by the scientific community to-date.

2. METHODOLOGY

In this study, the full lifecycle of all tropical cyclones that occurred in the Atlantic and East Pacific tropical cyclone basins were examined from 2004 through 2006. This included 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. Time periods during which the storm made landfall were not excluded from this study.

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.

In order to obtain eyewall lightning flash rates, Molinari et al. (1994, 1999) accumulated hourly CG lightning flash rates for all flashes that occurred within a 40 km radius around the center position of the hurricanes analyzed in their study. 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 efficiency model used by Vaisala, the reader is referred to the Appendix in Cummins et al. (1998). Validation of LLDN performance is underway and will be presented in the near future at upcoming conferences.

For this study, only a nighttime DE correction was applied to the inner core lightning counts. The nighttime DE correction was selected because the analysis was much less complex than trying to correct for DE as a function of time of day and time of year. Vaisala continues to work on refining its LLDN detection efficiency models in order to make this kind of analysis in the future.

A nighttime DE correction was applied to the inner core lightning count by using a distance-weighted average of the nighttime DE within 250 km of the center of 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 nighttime DE value near the center of the storm was 20%. This nighttime 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 nighttime 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 all 51 tropical cyclones (excluding subtropical cyclones) that occurred in the Atlantic basin from 2004 through 2006. The 3-hour, nighttime 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 on top of each other (pink and blue lines in Figure 3). Low-to-moderate inner core lightning rates (lightning counts from ~1-40) occur frequently within the H-S category (orange line in Figure 3), however high inner core lightning rates are much less frequent within the H-S category. The high frequency of low-to-moderate lightning rates in the H-S category appears 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 category 1 and 2 hurricanes (H-W category) represents a new finding concerning lightning activity within tropical cyclones. 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 zero for the H-W category and 10 for both tropical storm categories. The H-S category actually has the highest inner lightning rate of 12.

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 well over 100, while the H-W category has the lowest lightning rate with a value of 21. Also, notice that the H-S category starts to have much lower lightning rates at the 75th percentile. At the 90th percentile, both tropical storm categories have much higher lightning rates than the rest of the tropical cyclone intensity categories with values between 800 and 1000. At this percentile, the TD category lightning rates (332) become higher than both hurricane categories (between 150 and 200).

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 both produce non-zero lightning counts at the 38th percentile, while the H-W category does not produce its first non-zero lightning count until the 54th percentile.

Although the percentage of time periods with zero inner core lightning count appears to be relatively high for most tropical cyclone intensity categories, it is important to notice that these results show that inner core lightning occurs during the 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. EAST PACIFIC BASIN RESULTS

Inner core lightning activity was studied for all 52 tropical cyclones (excluding subtropical cyclones) that occurred in the East Pacific basin from 2004 through 2006. Time periods for storms that continued into the Central Pacific basin (or to the west of 140º W longitude) were not examined in this study. The 3-hour, nighttime DE-corrected, cumulative lightning rate results are shown in Figure 4 as a function of tropical cyclone intensity.

Similar to the Atlantic basin, the highest inner core lightning rates occur in the TS-W category (pink line in Figure 4) and the lowest inner core lightning rates occur in the H-W category (red line). Similar patterns are also shown for the TD (green line) and H-S (orange line) intensity categories. Low-to-moderate inner core lightning rates (lightning counts from ~1-300 this time) occur frequently within the H-S category, however high inner core lightning rates are much less frequent within the H-S category. The high frequency of low-to-moderate lightning rates in the H-S category appears to be related to eyewall replacement cycles (Knabb et al., 2008).

Lightning rates in the TD category generally fell between the maximum rates in the TS-W category and the minimum rates in the H-W category. Although, this time the TD lightning rate curve fell a little closer to the TS-W than the H-W curve.

The biggest difference between the Atlantic and East Pacific basins occurs for the TS-S intensity category. Inner core lightning rates were lower and much closer to the H-W category in the East Pacific. However, the TS-S category did show a tendency towards a larger percentage of 3-hour intervals with higher lightning rates than the H-W category, as lightning rates increased (from left to right on the x-axis of Figure 4).

Another way to interpret the results of Figure 4 is shown in Table 3. Since tropical cyclones in the East Pacific typically spend most of their lifetime at distances where the LLDN DE is lower than in the Atlantic basin, all the 50th percentile values were zero. Some clear differences in inner core lightning activity can be seen at the 75th and especially 90th percentiles.

At the 75th percentile, the TS-W category shows the highest lightning rates with a value of 63 and the H-W and TS-S categories show the lowest lightning rates (between 0 and 2). At the 90th percentile, the TS-W category clearly shows the highest lightning rates (500), followed by the TD category (322). A comparison between Tables 1 and 2 also shows that the 90th percentile values now follow a similar pattern for both the Atlantic and East Pacific basins, with the highest lightning rates occurring within the TS-W, TS-S and TD categories and the lowest lightning rates occurring within the two hurricane categories.

The third column in Table 3 shows that the majority of all storm intensity categories contain zero lightning counts. The percentile values at which the first non-zero lightning rates occur are much larger than in Table 2 for the Atlantic basin. Some of this difference may be attributable to different storm structure within the two tropical cyclone basins, but most of this difference is due to poorer sampling of lightning activity within tropical cyclones by the LLDN.

5. CONCLUSIONS

This study gives an unprecedented view of lightning production within the inner core of a large statistical dataset of tropical cyclones. This is 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 and East Pacific tropical cyclone basins from 2004 through 2006 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, nighttime LLDN DE corrections were applied to all 3-

hour time periods analyzed in this study. Therefore, these corrections represent realistic (conservative) estimates of inner core lightning rates within tropical cyclones during the night (day). Night-time DE corrections were chosen because correcting for a DE that varies with time of day and time of year is very complex. Vaisala continues to work on refining its LLDN detection efficiency models in order to make this kind of analysis in the future.

Atlantic and East Pacific tropical cyclones showed similar inner core lightning production; tropical storms produced the highest lightning rates and category 1 and 2 hurricanes produced the lowest lightning rates. This represents a new finding concerning lightning activity within tropical cyclones.

The only major difference between the Atlantic and East Pacific basins was the inner core lightning rates of the TS-S category (strong tropical storms). These storms produced high lightning rates in the Atlantic and relatively low lightning rates in the East Pacific. This difference may be attributable to the following factors: (1) structural differences between Atlantic and East Pacific strong tropical storms, (2) smaller sample size of strong tropical storms in the East Pacific when compared to the Atlantic, and (3) strong tropical storms spending more time outside of effective LLDN detection range in the East Pacific due to typical storm motion and lifecycle differences between the Atlantic and East Pacific.

Atlantic and East Pacific major hurricanes (categories 3, 4 and 5 on the Saffir-Simpson Scale) also showed similar trends in inner core (eyewall) lightning activity. A large fraction of 3-hour time periods contained low-to-moderate (~1-300 flashes) CG lightning rates and only a small fraction of 3-hour time periods contained high (>300 flashes) CG lightning rates. These low-to-moderate inner core lightning rates appear to be related to eyewall replacement cycles (Knabb et al., 2008).

6. REFERENCES

Cummins, K.L., M.J. Murphy, E.A. Bardo, W.L. Hiscox, R.B. Pyle, and A.E. Pifer, 1998: A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network. *Journal of Geophysical Research*, **103**, 9035-9044.

Demetriades, N.W.S., and R.L. Holle, 2005: Long-range lightning applications for hurricane intensity. Preprints, Conference on Meteorological Applications of Lightning Data, January 9-13, San Diego, California, American Meteorological Society, 9 pp.

—, and —, 2006: Long range lightning nowcasting applications for tropical cyclones. Preprints, 2nd Conference on Meteorological Applications of Lightning Data, January 29-February 2, Atlanta, Georgia, American Meteorological Society, 9 pp.

Knabb, R., J. Cangialosi, C. Lauer, B. Maher, M. Willis, N.W.S. Demetriades, and R.L. Holle, 2008: Operational applications of long range lightning data at the National Hurricane Center. Preprints, 3rd Conference on Meteorological Applications of Lightning Data, January 20-24, New Orleans, LA, American Meteorological Society.

Molinari, J., P.K. Moore, V.P. Idone, R.W. Henderson, and A.B. Saljoughy, 1994: Cloud-to-ground lightning in hurricane Andrew. *Journal of Geophysical Research,* **99,** 16665-16676.

—, —, and —, 1999: Convective structure of hurricanes as revealed by lightning locations. *Mon. Wea. Rev.*, 127, 520-534.

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 2006. 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 50^{th} percentile, 75^{th} percentile, and 90^{th} percentile 3-hour lightning counts, respectively.

Tropical cyclone intensity category	**Sample size**	**Percentile of first non-zero lightning count**	**50^{th} percentile**	**75^{th} percentile**	**90^{th} percentile**
Tropical depression (TD)	522	49%	1	54	332
Tropical storm – weak (TS-W)	684	38%	10	167	833
Tropical storm – strong (TS-S)	525	38%	10	180	942
Hurricane – weak (H-W)	577	54%	0	21	186
Hurricane – strong (H-S)	335	30%	12	55	156

Table 3. Statistics for all East Pacific basin tropical cyclones from 2004 through 2006. 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 50^{th} percentile, 75^{th} percentile, and 90^{th} percentile 3-hour lightning counts, respectively.

Tropical cyclone intensity category	**Sample size**	**Percentile of first non-zero lightning count**	**50^{th} percentile**	**75^{th} percentile**	**90^{th} percentile**
Tropical depression (TD)	603	62%	0	27	322
Tropical storm – weak (TS-W)	560	54%	0	63	500
Tropical storm – strong (TS-S)	270	76%	0	0	280
Hurricane – weak (H-W)	354	74%	0	2	111
Hurricane – strong (H-S)	151	60%	0	19	124

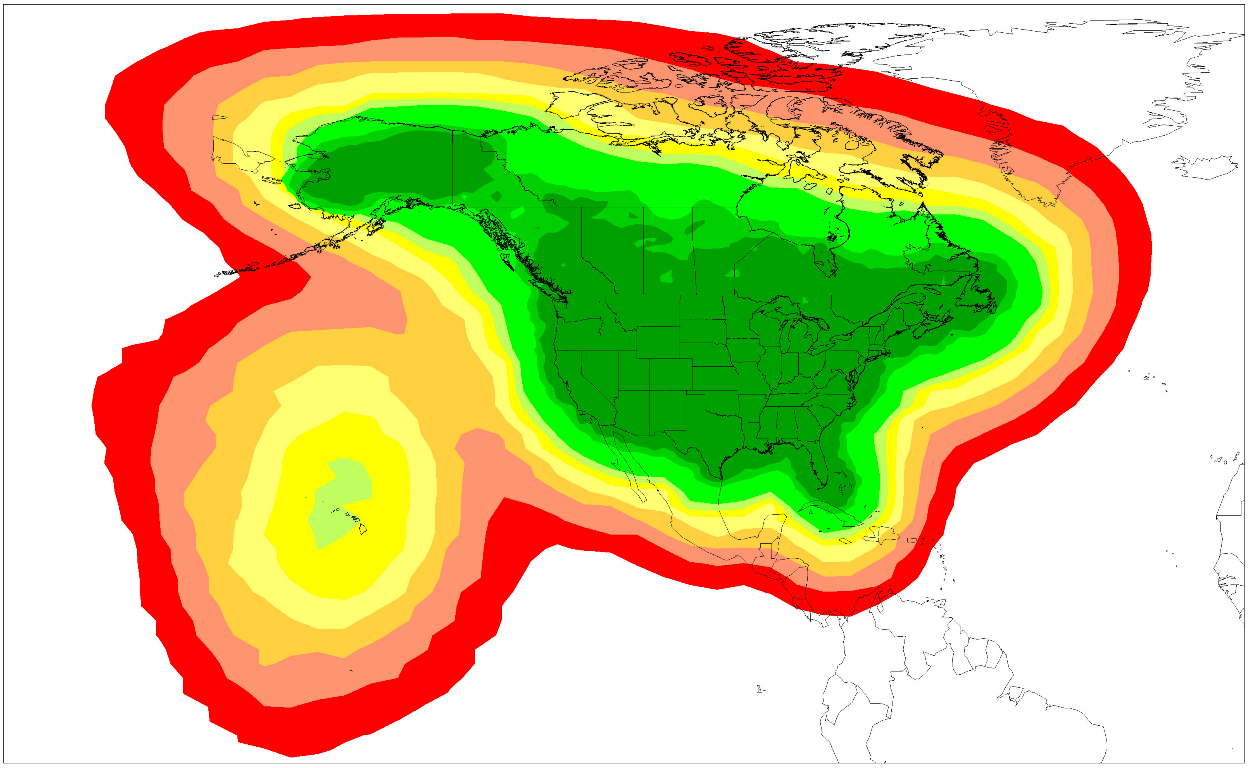

Figure 1. Vaisala LLDN nighttime detection efficiency (DE) for the period of this study (2004-2006). Shaded colors represent 10% increments of CG lightning flash DE, starting from >90% for the dark green shade to 10-20% for the red shade.

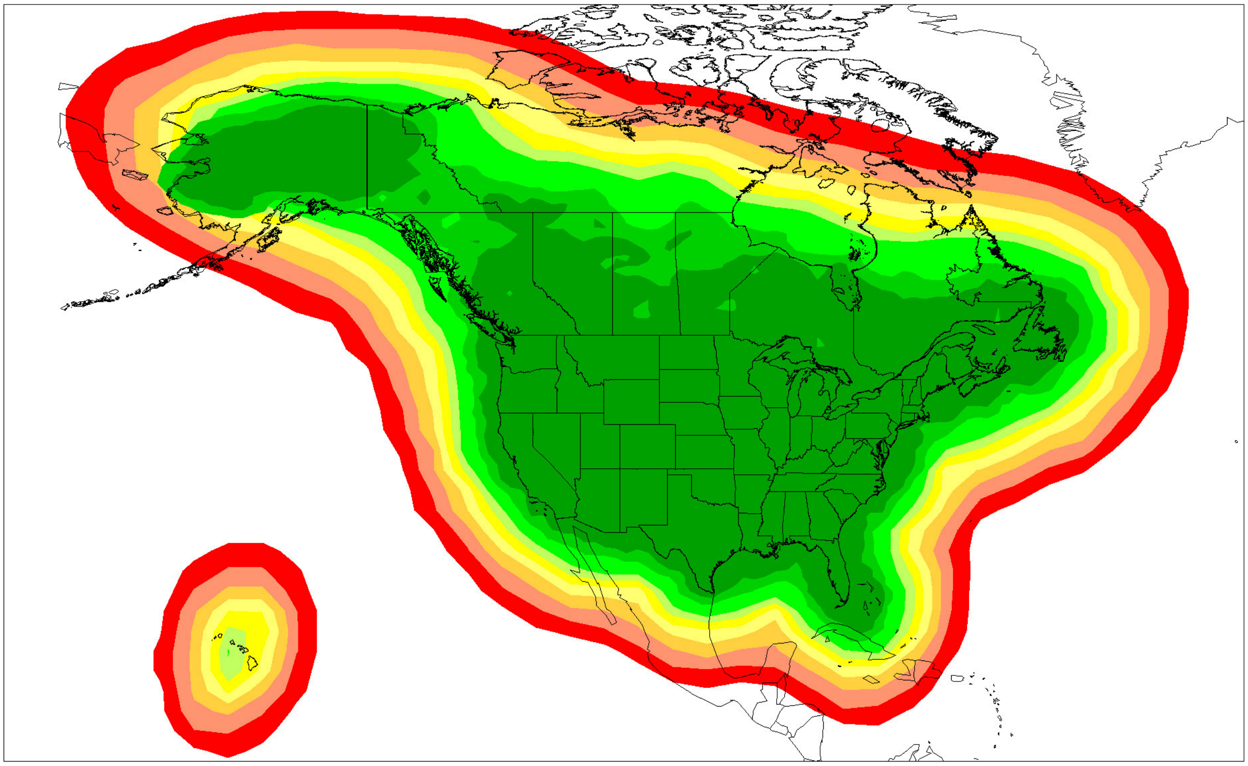

Figure 2. Vaisala LLDN daytime detection efficiency (DE) for the period of this study (2004-2006). Shaded colors represent 10% increments of CG lightning flash DE, starting from >90% for the dark green shade to 10-20% for the red shade.

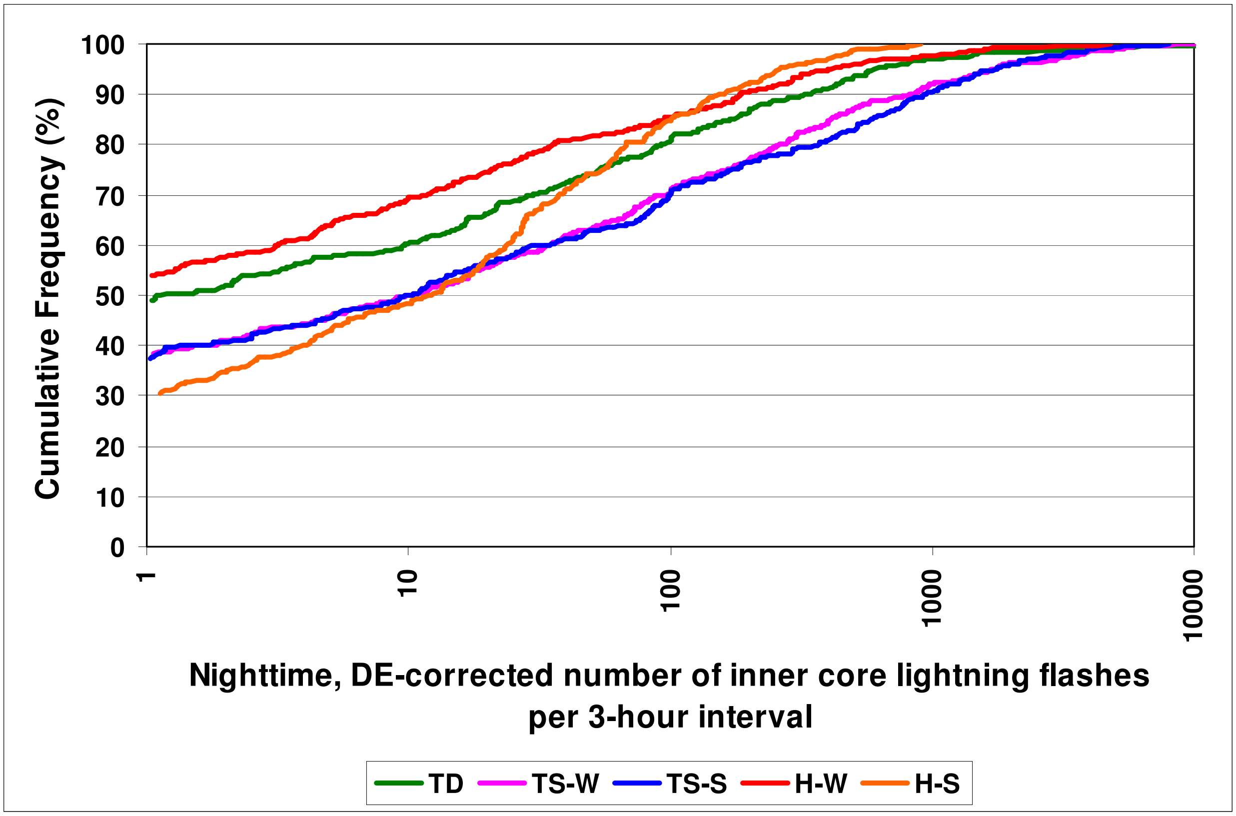

Figure 3. Cumulative 3-hour inner core lightning rate distributions as a function of tropical cyclone intensity for all Atlantic basin tropical cyclones from 2004 through 2006.

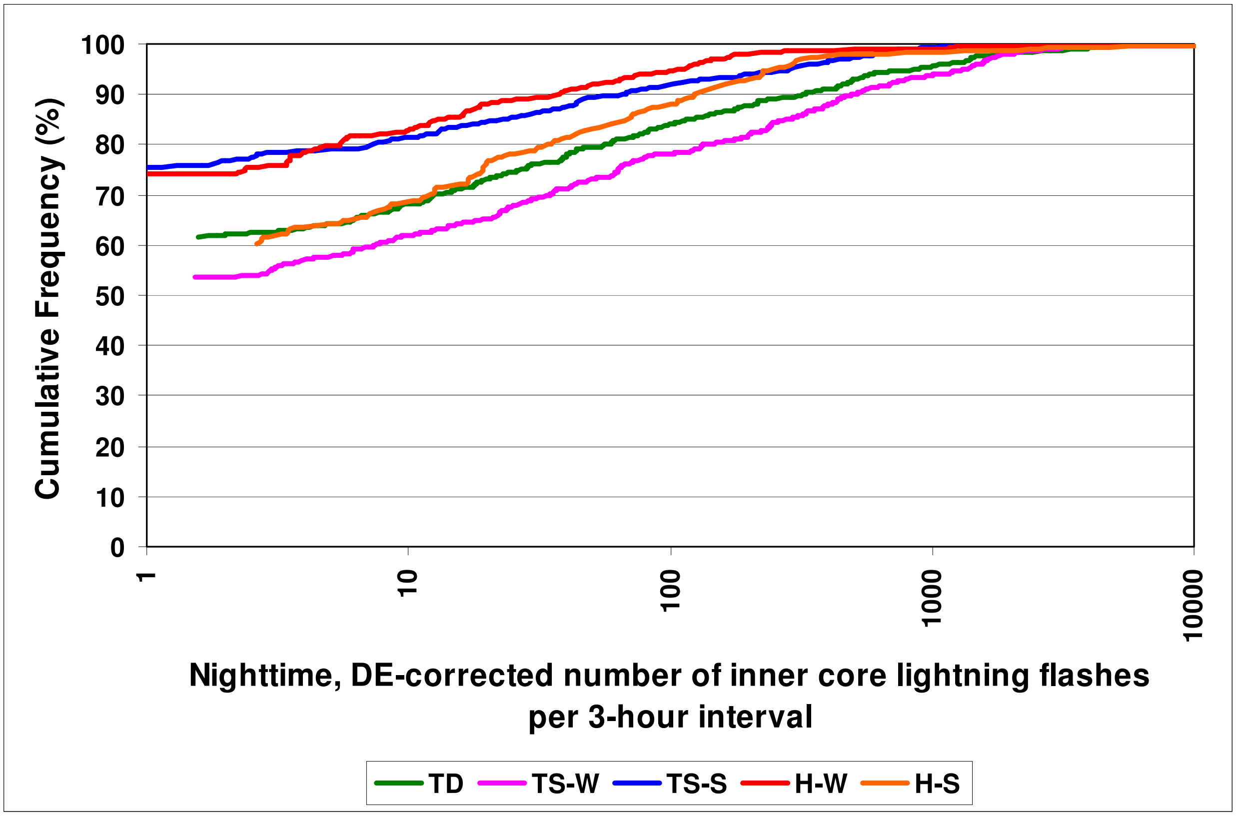

Figure 4. Cumulative 3-hour inner core lightning rate distributions as a function of tropical cyclone intensity for all East Pacific basin tropical cyclones from 2004 through 2006.