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LONG RANGE LIGHTNING NOWCASTING APPLICATIONS FOR TROPICAL CYCLONES

Nicholas W.S. Demetriades[1], John Molinari[2], and Ronald L. Holle[1]

[1]Vaisala, Inc.
Tucson, Arizona

[2]Department of Earth and Atmospheric Sciences
The University at Albany/SUNY
Albany, New York

1. INTRODUCTION

The primary data sources for monitoring tropical cyclones beyond 625 km are (1) infrared and visible satellite imagery from geostationary satellites, (2) microwave and space-based radar imagery from polar orbiting satellites and (3) aircraft reconnaissance data. Geostationary satellite imagery is the only dataset that provides continuous monitoring of tropical cyclones far from land. Unfortunately, such imagery often does not provide detailed structural information in eyewalls and outer rainbands needed for nowcasting and forecasting tropical cyclones.

The outer limit of cloud-to-ground (CG) flash detection networks is 625 km from sensors in the U.S. National Lightning Detection Network (NLDN) and the Canadian Lightning Detection Network (CLDN). Prior studies found that CG lightning information within several hundred km of the NLDN was a useful indicator of convective outbreaks in incipient and mature hurricanes, and may signal substantial deepening of the storms (Molinari et al. 1994; 1999; Lyons and Keen 1994; Black and Hallett 1999; Cecil et al. 2002; Samsury and Orville 1994; Sugita and Matsui 2004; Demetriades and Holle 2005, 2006). However, most cases of hurricane formation and early intensification in the North Atlantic and Pacific Oceans occur outside the 625-km range of the NLDN. Vaisala is operating a VLF long range lightning detection network (LLDN) over the North Atlantic and Pacific that detects flashes thousands of kilometers from land and allows monitoring of tropical cyclones over a much larger area than the NLDN and CLDN.

The effect of vertical wind shear between 850 and 200 hPa on the number of NLDN flashes was investigated during the development of Hurricane Danny (1997). Molinari et al. (2004) found an intense lightning outbreak downshear from the center. "Downshear" indicates the half of the circulation opposite the vertical shear vector; if vertical shear is from the west, downshear represents the eastern half of the storm. Molinari et al. (2004) provided evidence that this burst of lightning brought about a downshear re-formation of the storm.

In addition, flash information in outer rainbands of tropical cyclones may provide forecasters with a valuable diagnostic tool for identifying the most intense outer rainbands. For many areas that do not experience the inner core of a tropical cyclone, outer rainbands often contain the highest wind speeds and heaviest rainfall.

Since major questions remain about how tropical cyclones form, lightning information is potentially of significant value, both for prediction and understanding of storms. This paper will describe how the LLDN operates, show examples of spatial and temporal flash distributions in tropical cyclones, and investigate the role of downshear convection in storm development.

2. LONG RANGE LIGHTNING DETECTION NETWORK (LLDN)

NLDN and CLDN wideband sensors operate in the frequency range of about 0.5 to 400 kHz where return strokes in CG flashes radiate most strongly. The peak radiation from CG flashes comes near 10 kHz in the middle of the very low frequency (VLF) band. Signals in the VLF band are trapped in the earth-ionosphere waveguide and suffer less severe attenuation than higher frequency signals. Low frequency (LF) and VLF ground wave signals from CGs are attenuated strongly, and are almost imperceptible after a propagation distance of 500 to 1000 km. However, VLF signals may be detected several thousand kilometers away after one or more reflections off the ground and the ionosphere. Detection is best when both a lightning source and a sensor are on the night side of the earth, because of better ionospheric propagation conditions at night.

The NLDN detects and processes lightning signals at long distances because the standard network sensors detect across a broad band that includes all of the VLF range. Standard NLDN sensors have been part of a long range network combining the CLDN, the Japanese Lightning Detection Network, the Meteo-France network, and the BLIDS, Benelux, and Central European networks. This combination detects CG flashes in sufficient numbers and with sufficient accuracy to identify small thunderstorm areas. The current study of tropical cyclones will use data in the North Atlantic where the nighttime detection efficiency exceeds 10% at the far reaches of the eastern Caribbean. The long range detection network is described in more detail in Murphy et al. (2006).

3. TROPICAL CYCLONE LIGHTNING NOWCASTING APPLICATIONS

Tropical depressions and tropical storms are generally more prolific lightning producers than hurricanes. Lightning activity in these weaker systems does not show a preferential spatial pattern. Figure 1 shows lightning in Tropical Storm Katrina when it was northeast of Cuba as a minimal tropical storm with sustained winds of 40 miles per hour (64 km per hour). Katrina was producing a large amount of lightning during this 30-minute time period in a number of convective clusters that covered most of the cloud mass of the storm.

In hurricanes, lightning shows preferential spatial patterns. The eyewall usually contains a weak flash maximum. There is a well-defined minimum in flashes from 80 to 100 km outside the eyewall maximum due to stratiform rain processes that dominate most of the central dense overcast (Molinari et al. 1999). The outer rain bands typically contain a strong maximum in flash density. Figure 2 shows the lightning activity within Katrina after it strengthened to a category five hurricane on the Saffir-Simpson Scale. Lightning in Hurricane Katrina shows this pattern consisting of a large eyewall lightning outbreak, very little lightning in the central dense overcast, and a tremendous amount of lightning in the outer rainbands surrounding most of the storm. There is a much more defined pattern to the lightning activity in Hurricane Katrina (Fig. 2) compared to its tropical storm stage (Fig. 1).

The lightning pattern in category five Hurricane Rita is similar to that in Katrina at that intensity, except Rita had very little lightning in its outer rainbands (Fig. 3). The similar features are a large eyewall lightning outbreak and minimal lightning activity in the central dense overcast. However, these examples show a large variability in outer rainband lightning in strong hurricanes.

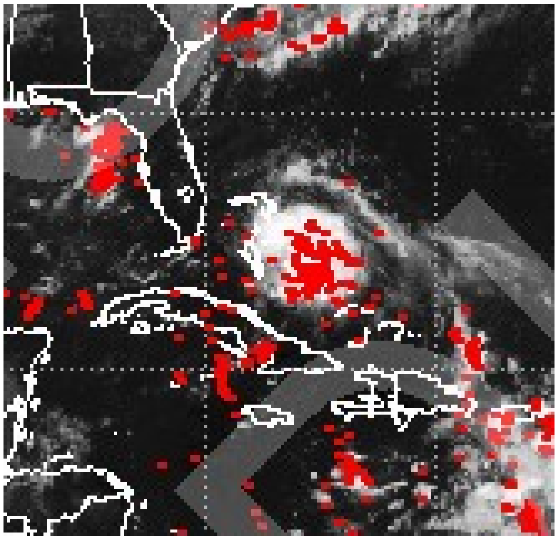

Figure 1. CG lightning (red symbols) detected within Tropical Storm Katrina between 1415 and 1445 UTC 24 August 2005. Infrared satellite image from 1445 UTC.

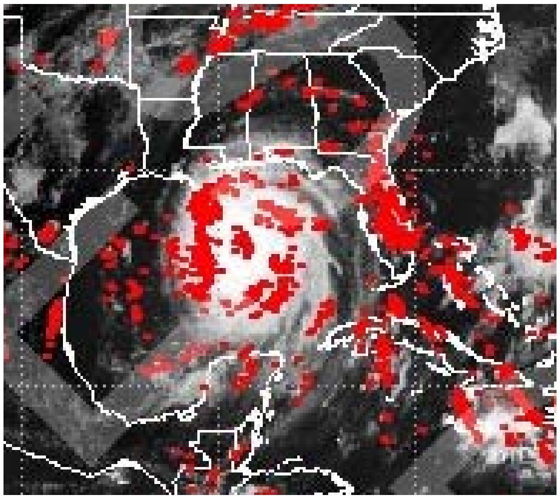

Figure 2. Same as Figure 1, between 1845 and 1915 UTC 28 August 2005. Infrared satellite image from 1915 UTC.

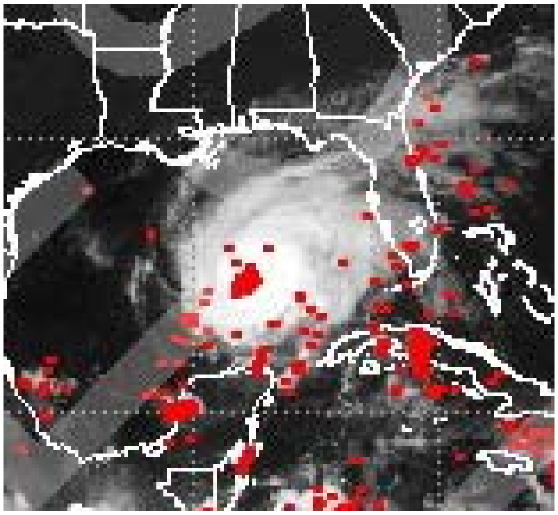

Figure 3. Same as Figure 1, except for Hurricane Rita between 0615 and 0645 UTC 22 September 2005. Infrared satellite image from 0645 UTC.

4. OUTER RAINBAND LIGHTNING

Lightning activity can help identify the most intense outer rainbands in a tropical cyclone. These rainbands often contain flooding rains and strong, gusty winds. Lightning can also show the evolution of growth and dissipation of outer rainbands as they rotate around the periphery of the storm. Figure 4 shows CG lightning detected within Hurricane Ivan as it moved toward the U.S. coast in the Gulf of Mexico. Lightning activity delineates an intense outer rainband on the east side of Ivan.

Figure 5 shows the evolution of an outer rainband as it rotates counterclockwise around the center of Hurricane Fabian on 5 September 2003. Lightning indicated that the most intense outer rainband rotated from a position located

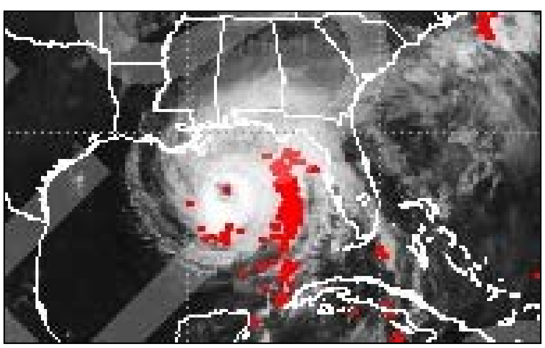

Figure 4. Same as Figure 1, except for Hurricane Ivan between 1345 and 1415 UTC 15 September 2004. Infrared satellite image from 1415 UTC.

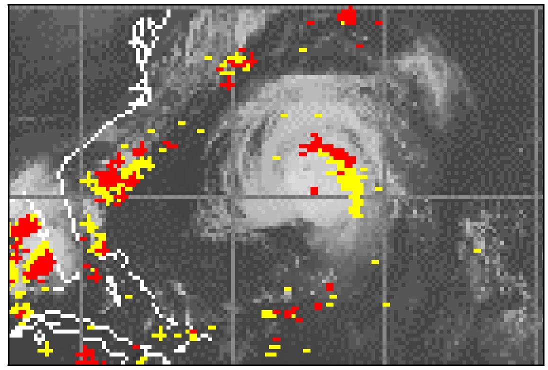

Figure 5. Long range lightning data and infrared satellite image on 5 September 2003. Lightning is from 1253 to 1553 UTC. Yellow dots are flashes detected during the first two hours, and red are from the latest hour. Infrared satellite image is from 1553 UTC.

toward the east of the center of Fabian (yellow) to the north of Fabian's center (red). In tropical depressions and storms, intense rainbands often contain the highest wind speeds and heaviest rainfall. In order to properly issue tropical depression and storm advisories and warnings, it is critical to be able to identify the location and evolution of these features.

5. EYEWALL LIGHTNING OUTBREAKS

5.1 Eyewall lightning patterns

The LLDN has detected numerous eyewall lightning outbreaks in hurricanes over the Atlantic and Eastern Pacific during the past several years. The larger outbreaks tend to occur on relatively small time and space scales. Lightning bursts in hurricane eyewalls sometimes rotate cyclonically around the center of circulation for some distance before they dissipate. However, eyewall lightning outbreaks that were studied in several hurricanes since 2002 show that these outbreaks tend to preferentially occur on one side of the hurricane track. Several hours may separate consecutive bursts of eyewall lightning or these bursts may occur continually for 24-48 hours. Figure 6 shows lightning detected along the track of Hurricane Frances on 3 September 2004. The track of Frances during this 24-hour period is shown by the yellow and red line. Three eyewall lightning outbreaks can be identified as Frances moved toward the northwest. All three outbreaks occurred on the northeast side of the storm track and are shown sequentially in shades of green, orange and red.

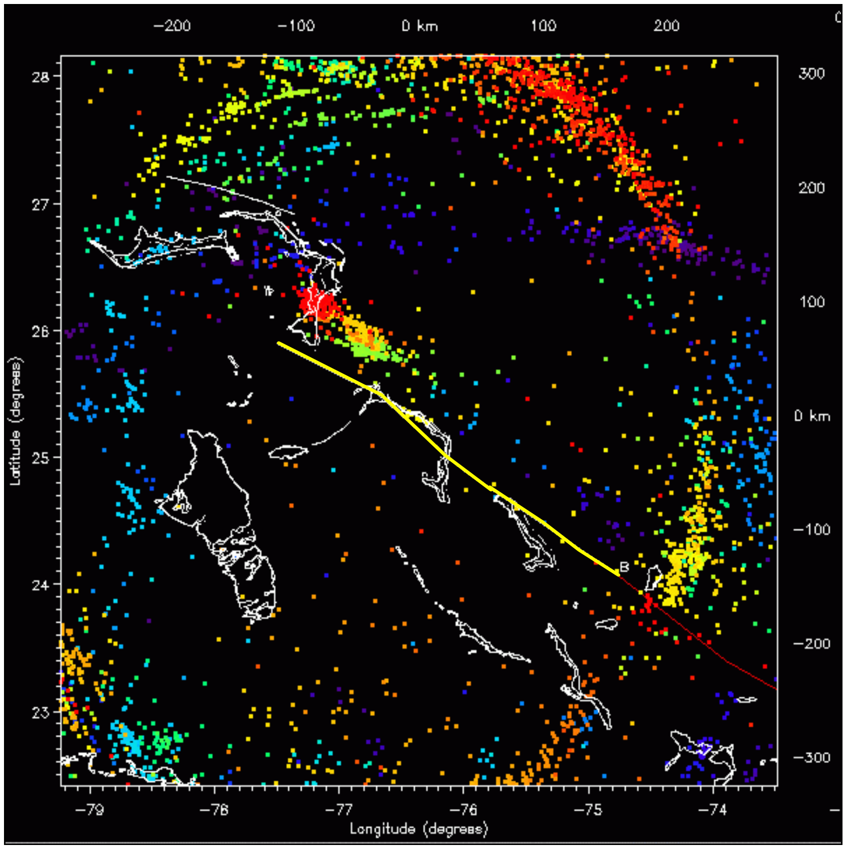

Figure 6. CG lightning detected by the LLDN in Hurricane Frances between 0000 UTC 3 September and 0000 UTC 4 September 2004. The track of the center of Frances during this 24-hour period is shown by the yellow line. Three bursts of eyewall lightning are along the right side of the track of Frances as the storm moved toward the northwest (upper left). The first burst of eyewall lightning is in green, the second burst is in orange, and the third burst is in red.

Impressive eyewall lightning signatures were also produced by Hurricane Rita as it became a category five hurricane on 21 September 2005. At times, Rita produced significant eyewall lightning that surrounded almost the entire eyewall (Fig. 7). Eyewall lightning outlines the northeast, northwest and southwest portions of the eyewall of Rita during this time period. In this case, lightning data could have been used to show that strong convection, and by implication large latent heat release, was simultaneously occurring through about 75% of the eyewall.

Eyewall lightning tends to occur when the inner core of the hurricane is undergoing a change in structure and intensity. Lightning helps to identify intense convective cores with larger updraft speeds embedded in the eyewalls of hurricanes. These lightning outbreaks may be strongly, and perhaps uniquely, associated with tall precipitation features, often called hot towers, that form in hurricane eyewalls. In favorable environments for hurricane intensification, these tall precipitation features are often associated with rapid intensification of hurricanes. Vaisala continues to collaborate with the tropical meteorology community to determine how often eyewall lightning outbreaks are associated with tall precipitation features within hurricane eyewalls.

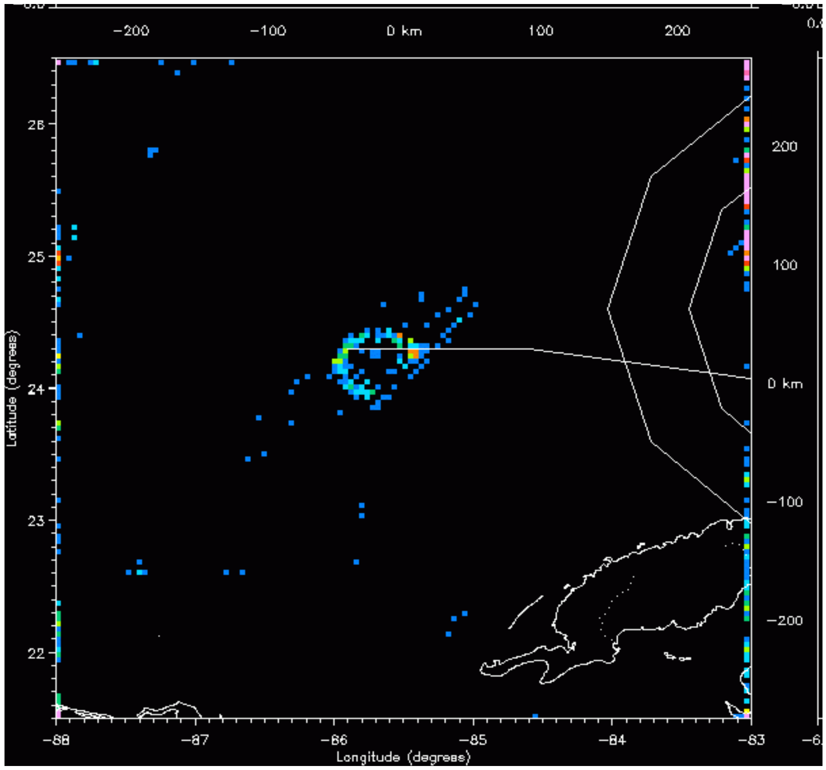

Figure 7. Lightning flash densities detected in Hurricane Rita between 1430 and 1500 UTC 21 September 2005. Light blue (pink) represents one flash (greater than 10 flashes) per 16 square kilometer area for the time interval shown. The track of Rita as it moved into the Gulf of Mexico northwest of Cuba is shown by the white line. The National Hurricane Center estimated center position of Rita at 1500 UTC 21 September 2005 is shown at the west end of the white line.

5.2 Hurricane Rita

Rita developed north of the Dominican Republic on 18 September 2005. Rita propagated to the west and attained hurricane status at 1500 UTC 20 September just south of the Florida Keys. Twelve hours later, Rita was a category five hurricane with sustained winds of 175 miles per hour (282 km per hour) and a minimum pressure of 897 mb (hPa), the fourth lowest ever recorded in the Atlantic. Rita eventually turned northwest and made landfall as a category three hurricane east of Sabine Pass, Texas at 0730 UTC 24 September.

A time series of minimum central pressure and eyewall lightning rates from Rita shows bursts of eyewall lightning during rapid intensification (Fig. 8). Eyewall lightning rates were defined as the number of lightning flashes detected by the Vaisala LLDN within 100 km of the center (from the National Hurricane Center) per three-hour interval.

The first large eyewall lightning outbreak started at 1500 UTC 19 September as three-hour rates rapidly increased from under 100 to over 400 (Fig. 8). These large lightning rates continued until 0600 UTC 20 September, and peaked with the largest eyewall lightning rate during the storm of 1340 flashes at 0000 UTC 20 September. Rita rapidly intensified from the time of the peak, and attained hurricane status at 1500 UTC 20 September. Shortly after Rita attained hurricane status, another very large eyewall lightning outbreak occurred with a peak three-hour rate of 997 flashes at 2100 UTC 20 September. This second major eyewall lightning outbreak occurred as the storm began to intensify at a higher rate with the central pressure dropping from 973 to 956 mb (hPa) between 21 UTC 20 September and 0900 UTC 21 September. A third large eyewall lightning outbreak occurred at 1500 UTC 21 September when 820 flashes were detected. This outbreak was coincident with the beginning of the most rapid intensification of the storm as the pressure dropped an average of 3.9 mb (hPa) per hour from 15 UTC 21 September to 03 UTC 22 September. At the end of this rapid intensification, Rita's minimum central pressure was 897 mb (hPa). As Rita's intensification ceased, eyewall lightning rates increased once more to values between 300 and 500 from 0000 to 0600 UTC 22 September. This final large increase in lightning rates may be the first sign of secondary eyewall formation. The 0900 UTC 22 September National Hurricane Center Forecast Discussion mentioned that a secondary eyewall was forming in Rita, which is consistent with some of the findings of Molinari et al. (1999) and Demetriades and Holle (2005).

6. VERTICAL WIND SHEAR EFFECTS

A promising analysis is to relate flashes with respect to storm structure as indicated by the vertical shear between 850 and 200 hPa (Molinari et al. (2006). Hurricane Claudette (2003) showed unprecedented behavior between 0600 and 1200 UTC 10 July when it unexpectedly developed from a disorganized tropical storm to a hurricane. Then it weakened just as quickly, returning to marginal tropical storm intensity by 1800 UTC the same day. Claudette did not achieve hurricane intensity again for several days, although it remained over warm water. Of interest is whether long range lightning data provide some insight into the behavior of the storm.

Vertical wind shear represents a key variable in tropical cyclone intensity change. Shelton (2005) showed that vertical wind shear was strong from the southwest and west-southwest during most of the lifetime of TS/Hurricane Claudette. The distribution of lightning flashes with respect to the storm center and to the vertical wind shear was calculated for an eight-day period as Claudette moved from the Caribbean to the Texas coast. The goal was to confirm that the long range data show results comparable to those of Corbosiero and Molinari (2003) using the NLDN coverage area. Within 100 km of the center, 92% of flashes were downshear, with a downshear-left maximum. Between the 100 and 200 km radii, almost 97%

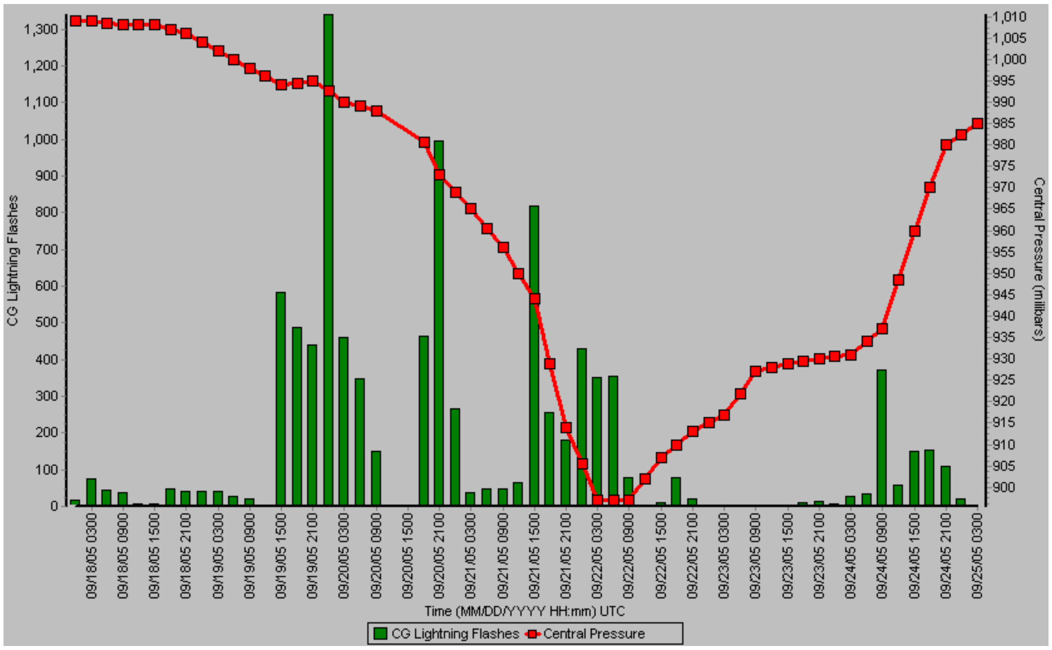

Figure 8. Three-hour CG lightning rates detected within 100 km of Hurricane Rita's center superimposed on Rita's central pressure. CG lightning rates are indicated by green bars with values located on the left y-axis and central pressure is indicated by the red line with values located on the right y-axis.

of flashes were downshear, with a downshear-right maximum. These results closely match those of Corbosiero and Molinari (2003; their Figure 7) for strong-shear cases like Claudette. This provides evidence that the long range data contain information as useful as that provided by the NLDN, but with the obvious advantage of a much greater range.

Figure 9 shows a time series of the number of flashes indicated by the long range network within 100 km of the center. Only 8-12 July 2003 is shown, centered on the time that hurricane intensity was achieved. Also shown is the time variation of minimum central pressure. During the first two days of study (8-9 July), fewer than 60 total flashes per hour occurred within 100 km of the center. The storm did not substantially change intensity during this time. Early on 10 July, a substantial outbreak produced more than 150 flashes in one hour, and the storm began to deepen. Between 0700 and 1000 UTC on the 10th, a second large outbreak occurred. The storm rapidly deepened during this time and reached hurricane intensity at 1200 UTC. The lightning thus provided some advanced and coincident indication of the development.

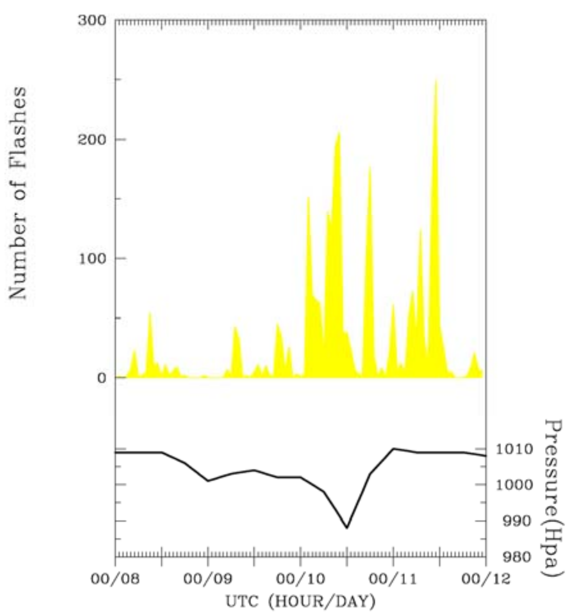

Figure 9. Hourly flash count (shaded) from the long range lightning network within 100 km of the center of Tropical Storm/Hurricane Claudette during 8-12 July 2003. Also shown is the time variation of minimum central pressure.

Conversely, after the storm began to weaken, additional outbreaks occurred late on 10 July and on 11 July that clearly did not relate to deepening. In order to investigate this further, we examine only the lightning occurring left of the vertical wind shear vector in Figure 10. The rationale for this choice is as follows: Reasor et al. (2004) showed that tropical cyclones can successfully resist the negative effects of vertical wind shear by tilting to the left of the shear vector. This produces maximum upward displacement of a circulating air parcel, and thus deep convection and lightning, at the same location. We hypothesize the following: a tropical cyclone with lightning mostly left of the vertical wind shear shows the storm is successfully resisting shear and more likely to deepen; in contrast, a storm with lightning mostly to the right of shear is less able to resist shear and more likely to weaken. Figure 10 provides support for this hypothesis. Large lightning outbreaks occur left of shear during deepening and right of shear during non-deepening time periods.

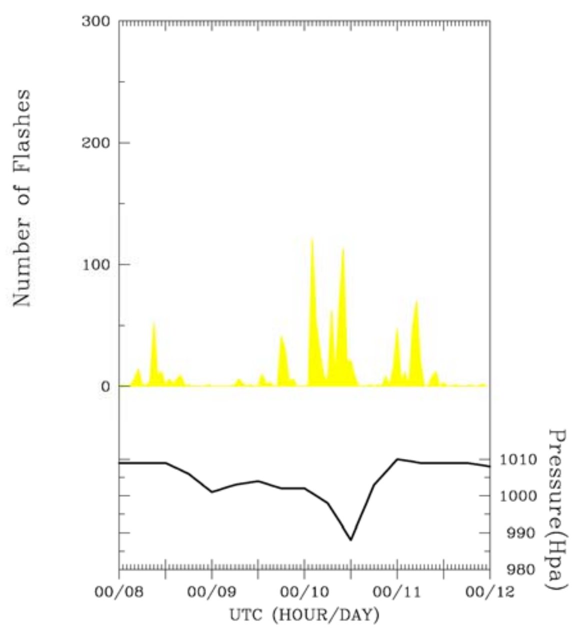

Figure 10. As in Figure 9, but only for the number of flashes occurring to the left of the vertical wind shear vector.

7. CONCLUSIONS

Real-time lightning data over a large portion of the North Atlantic and Eastern Pacific tropical cyclone basins is being provided by Vaisala's LLDN. The data allow forecasters to monitor the evolution of strong convective structures in the eyewalls of tropical cyclones. Lightning should also help identify and track the most intense outer rainbands. In addition, not only the frequency of lightning, but also its distribution with respect to vertical shear, appear to provide information as to whether a storm is about to deepen. This hypothesis will be tested with additional long range data in tropical cyclones.

For areas outside the inner core, and in weaker tropical cyclones, intense rainbands often contain the highest wind speeds and heaviest rainfall. In order to issue the appropriate advisories and warnings, forecasters need to be able to follow the evolution of strong convective features not only in the eyewalls, but also in the outer rainbands of tropical cyclones. Vaisala LLDN data may provide the best opportunity to follow these important features over data-sparse oceanic areas.

7. ACKNOWLEDGEMENT

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