P2.8 LONG-RANGE LIGHTNING APPLICATIONS FOR HURRICANE INTENSITY

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1. INTRODUCTION

Vaisala has been operating an experimental long-range lightning detection network (LRLDN) since 1996. This network detects cloud-to-ground (CG) lightning over oceanic and land areas that are many 1000s of kilometers from existing network sensors. Although the detection efficiency and location accuracy of the LRLDN varies with region and time of day, the data from this network provides continuous monitoring of lightning activity over a large portion of the Atlantic and Eastern Pacific tropical cyclone basins.

Outbreaks of lightning within the eyewalls of moderate-to-strong hurricanes have been studied by Molinari et al. (1999). Molinari et al. (1999) proposed that outbreaks of eyewall lightning were generally caused by either eyewall contraction or secondary eyewall replacement. This means that eyewall lightning outbreaks may be able to help forecasters nowcast hurricane intensification (eyewall contraction) or weakening (secondary eyewall replacement). Molinari et al.'s (1999) work was limited to 5 Atlantic basin hurricanes where the center of circulation passed within 400 km of one of the U.S. National Lightning Detection Network (NLDN) sensors. Sugita and Matsui (2004) performed a similar analysis on two typhoons that were within range of the Japanese Lightning Detection Network operated by Franklin Japan Corporation. Lightning does not always occur in the eyewall of a hurricane. However, when lightning does occur it may be a sign of change within the hurricane inner-core structure that could help nowcast storm intensity. In this study, we extend the work of Molinari et al. (1999) to include several category 3 or higher hurricanes as classified by the Saffir-Simpson Scale (sustained winds of 96 knots or higher) in both the Atlantic and Eastern Pacific basins from 2001 to 2003. A summary of the application of LRLDN data shortly before the landfall of Hurricane Charley will also be presented.

2. LONG-RANGE LIGHTNING DETECTION NETWORK

The sensors in the U.S. NLDN are wideband sensors that operate between about 0.5 and 400 kHz. Return strokes in CG flashes radiate most strongly in this frequency range, with their peak radiation coming at a frequency near 10 kHz in the middle of the VLF band (3-30 kHz). Signals in the VLF band propagate well in the earth-ionosphere wave guide and suffer relatively less severe attenuation than higher frequency signals. Whereas LF and VLF ground wave signals are attenuated strongly and are almost imperceptible after a propagation distance of about 1000 km, VLF signals may be detected at distances of several thousand kilometers after one or more reflections off the ground and ionosphere. Detection is best when both the lightning source and sensor are on the night side of the earth because of the better ionospheric propagation conditions at night.

The standard U.S. NLDN sensors have been part of an ongoing experimental LRLDN consisting of the combination of the U.S. and Canadian networks, the Japanese Lightning Detection Network, the MeteoFrance network, and the BLIDS, Benelux, and Central European networks operated by Siemens in Germany. This combination of networks has been shown to detect CG flashes in sufficient numbers and with sufficient accuracy to identify even small thunderstorm areas (Nierow et al., 2002). The network detects CG lightning to varying degrees over the northern Atlantic and Pacific oceans and some areas of Asia and Latin America not covered by their own lightning detection networks. Flash polarity is not detected at these long-ranges.

3. METHODOLOGY

In this study, tropical cyclones were examined only when: (1) they reached hurricane strength for at least 24 hours, (2) achieved category 3, 4 or 5 status on the Saffir-Simpson Scale at some point during their existence, and (3) had their center within an area covered by at least 10% daytime CG lightning flash detection efficiency according to Vaisala's LRLDN models. The minimum CG lightning detection efficiency threshold of 10% meant that the center of circulation for an Atlantic Basin hurricane had to be west of 65 W if the center was located south of 30 N and west of 45 W if the center was located north of 30 N. For Eastern Pacific Basin hurricanes, the center of the storm had to be located north of 20 N.

A 10% CG lightning detection threshold was chosen because it should still yield a relatively high detection efficiency for an eyewall lightning outbreak. Upon inspection of Molinari et al.'s (1994, 1999) hurricane lightning studies, the average eyewall CG lightning outbreak for Hurricanes Andrew, Elena, Hugo and Bob (1991) consisted of ~11 CG flashes. This is a conservative estimate because even within 400 km of the U.S. NLDN during the time periods in which these storms occurred, the CG lightning detection efficiency ranged between 20 and 80%. It is not an easy task to estimate the true number of CG lightning flashes per eyewall lightning outbreak. However, for the Molinari et al. (1994, 1999) studies we will assume that the average CG lightning flash detection efficiency for these four

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hurricanes was probably ~50%. Therefore, the average eyewall lightning outbreak for the hurricanes studied by Molinari et al. (1994, 1999) was ~22 flashes. Assuming a LRLDN detection efficiency of 10% and an average eyewall lightning outbreak of 22 CG flashes, the eyewall lightning outbreak detection efficiency is ~90%. It should be noted that as these storms move closer to the coastline of the U.S. NLDN, the detection efficiency increases. Coastal areas of the U.S. have a CG lightning flash detection efficiency of 90%.

The position, maximum sustained wind speed and minimum central pressure of hurricanes used in this study were obtained from the "best-track" data produced by the National Hurricane Center (NHC) every 6 hours. Since a hurricane can propagate fairly long distances over a 6-hour period, the center position and minimum central pressure 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. Weatherford and Gray (1988) found that the typical eyewall diameter (radius) of a hurricane is between 30 (15) and 60 (30) kilometers. For this study, 3-hourly CG lightning flash rates were obtained for all flashes occurring within 60 km of the center position of the hurricane. 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 60 km of the center position from 0130 to 0430 UTC for the 0300 UTC position estimate. Increasing the time interval and radius over which rates are accumulated should not have a significant impact on this study. Concentric eyewall cycles generally occur over time intervals of at least several hours and it is the presence of an eyewall lightning outbreak that is critical, not necessarily any instantaneous rate. Also, a 60 km radius should cause little contamination from lightning occurring in other parts of the hurricane because of the relative minimum in CG lightning that occurs in the inner rainbands (Molinari et al., 1999).

4. LIGHTNING IN TROPICAL CYCLONES

New observations of CG lightning activity within numerous tropical cyclones over the Atlantic and Eastern Pacific Oceans away from land have reinforced many of the findings of Molinari et al. (1999). Tropical depressions and tropical storms are generally more prolific lightning producers than hurricanes. Lightning activity in these systems does not show a preferential spatial pattern. There may be some specific bands of lightning activity, but lightning is generally spread throughout much of the area covered by these systems. Figure 1 shows the lightning activity produced by Tropical Storm Grace between 0952 and 1252 UTC 31 August 2003. Grace was located in the Western Gulf of Mexico at this time and it was a minimal tropical storm with sustained winds between 30 and 35 knots. This system was producing tremendous amounts of lightning activity shortly before it made landfall in Southeast Texas.

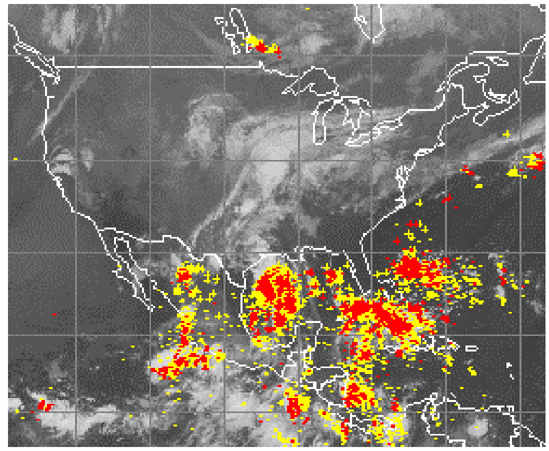

Figure 1. Long-range lightning data plotted over an infrared satellite image on 31 August 2003. The lightning data were detected over a 3-hour period from 0952 to 1252 UTC. Yellow dots represent flashes that were detected during the first two hours of this time interval and red dots represent flashes that were detected during the most recent hour of this time interval. The satellite image was produced at 1252 UTC.

Lightning does show preferential spatial patterns in hurricanes. The eyewall (or inner core) usually contains a weak maximum in lightning flash density. There is a well-defined minimum in flash density extending 80 to 100 km outside of the eyewall maximum (Molinari et al., 1999). This is due to the stratiform rain processes that generally dominate most of the region of the central dense overcast. The outer rain bands typically contain a strong maximum in flash density. Figure 2 shows the lightning activity produced by Hurricane Isabel between 0354 and 0654 UTC 15 September 2003. Isabel was located just northeast of the Caribbean, in the Western

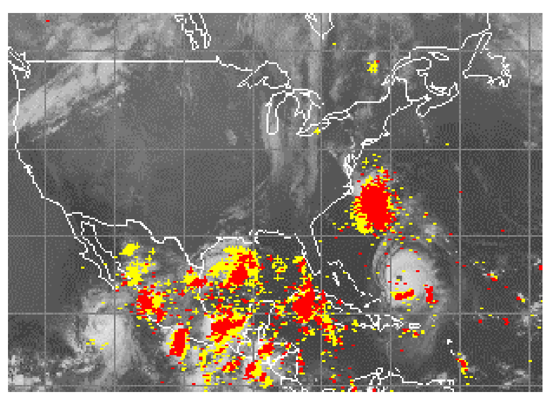

Figure 2. Same as Figure 1, except for lightning detected between 0354 and 0654 UTC 15 September 2003. The satellite image was produced at 0654 UTC 15 September 2003.

North Atlantic Ocean, and at this time it was a borderline category 4 hurricane on the Saffir-Simpson Scale with sustained winds between 120 and 125 knots. Isabel was a powerful, organized hurricane at this time with a well-defined eye. The lightning activity in Isabel shows the typical pattern for well-organized hurricanes with a few flashes located in the eyewall and a high flash density in the outer rain bands. The rain bands containing lightning were located on the southern and southeast sides of the hurricane at this time. Outer rain band lightning can be located anywhere within the periphery of a hurricane; it is not always located south and east of the center of circulation.

5. RESULTS

5.1 Hurricane Lili

Lili was a hurricane that developed southeast of the Lesser Antilles islands on the 21 September 2002. The center of Lili moved through the Caribbean and hit western mainland Cuba before continuing on a northwest path through the Gulf of Mexico, eventually making landfall in Louisiana on 3 October. Lili intensified to category 4 status on the Saffir-Simpson Scale on 2 October and reached a maximum intensity of 125 knots.

Figure 3 shows the eyewall lightning flash rate superimposed upon observations of central pressure from Hurricane Lili. On 30 September a short outbreak of lightning occurred near the center of the storm as the eyewall started to form and Lili achieved hurricane status. A second outbreak occurred early on 1 October as the eyewall started to show some decay. This decay was most likely caused by interaction with land in western Cuba. Another outbreak occurred near 2100 UTC 1 October. This lightning activity occurred during a secondary eyewall formation and replacement cycle. The NHC discussion from 0300 UTC 2 October stated “Lili appears to have just completed an eyewall replacement cycle based on the last 2 recon passes through the center.” The secondary eyewall contraction caused rapid intensification as pressures fell from ~970 to ~955 mb in 12 hours.

Shortly after this time period another eyewall lightning outbreak occurred during the time that a secondary eyewall formation was speculated by NHC. The NHC discussion from 0900 UTC 2 October stated “Aerial reconnaissance data showed a fairly rapid central pressure fall…to about 954 mb just before 0600 Z…but a later dropsonde from a NOAA aircraft of 955 mb suggested that the central pressure had leveled…this is probably temporary…and some short-term fluctuations in strength are likely due to internal processes such as eyewall replacement cycles.”

A final outbreak of eyewall lightning occurred between 1500 UTC 2 October and 0600 UTC 3 October. This outbreak contained the largest eyewall lightning rates recorded in this study and in Molinari et al. (1994, 1999). Flash rates peaked at over 600 per 3-hour interval. This outbreak was not only associated with the development of an outer eyewall, it was also associated with an unexplained rapid weakening that dropped Hurricane Lili from a category 4 storm to a category 2 storm within 12 hours. The NHC discussion from 2100 UTC 2 October stated “Lili is showing signs of peaking…as the aircraft and satellite imagery indicate the beginning of an outer eyewall that will likely bring a halt to the current intensification.”

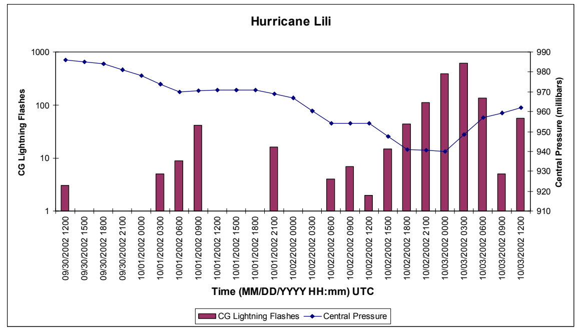

Figure 3. 3-hour CG lightning rates detected within 60 km of Hurricane Lili’s center superimposed on Lili’s central pressure. CG lightning rates are indicated by purple bars with values located on the left y-axis and central pressure is indicated by the blue line with values located on the right y-axis.

5.2 Hurricane Isidore

Isidore developed near the northern South American coast on 14 September 2002. The center of Isidore moved through the Caribbean and made landfall in western mainland Cuba with sustained winds of 75 kts. Isidore intensified further before making landfall in the Yucatan Peninsula as a category 3 hurricane with sustained winds of 110 kts. Isidore re-emerged over the Gulf of Mexico and made landfall for a third and final time as a tropical storm along the Louisiana coast on 26 September. On 21 September Isidore intensified to category 3 status and reached a maximum intensity of 110 knots.

Figure 4 shows the eyewall lightning flash rate superimposed upon observations of central pressure from Hurricane Isidore. On 19 September a moderate outbreak of lightning occurred near the center of the storm as the eyewall started to form and Isidore achieved hurricane status. A couple of large eyewall lightning outbreaks occurred on 20 September. Both of these occurred as the center of Isidore was near Cuba, however the second peak lightning rate at 1500 UTC occurred during the formation of a secondary eyewall. The NHC discussion from 1500 UTC 20 September stated “There are indications in the radar imagery and flight-level data that Isidore has a concentric eyewall structure.”

Eyewall lightning rates remained low, but fairly steady between 2100 UTC 20 September and 1200 UTC 21 September. A concentric eyewall structure was confirmed again at 0900 UTC 21 September. The NHC discussion from 0900 UTC 21 September stated “The recon aircraft reports concentric eyewalls of 15 and 25 n

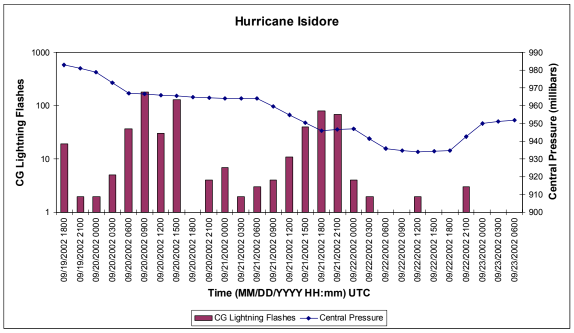

Figure 4. Same as Figure 3, except for Hurricane Isidore.

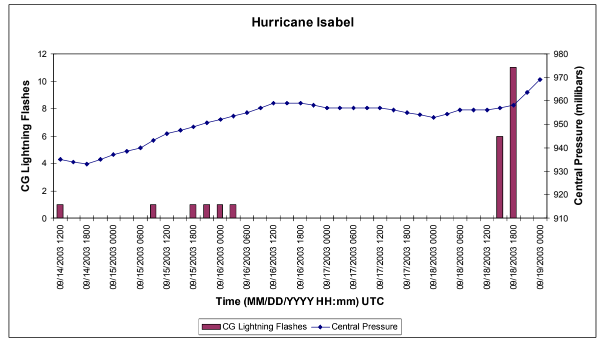

Figure 5. Same as Figure 3, except for Hurricane Isabel.

mi diameters." Between 0600 and 1800 UTC 21 September Hurricane Isidore underwent rapid intensification as the central pressure fell from 964 mb to 946 mb. This was most likely caused by the secondary eyewall replacing the primary eyewall and subsequent contraction of the secondary eyewall. Another large outbreak of eyewall lightning occurred at the time that rapid intensification ceased in Isidore. Lightning rates peaked at 79 at 1800 UTC 21 September. The end of this rapid intensification period was caused by the formation of another secondary eyewall. The NHC discussion from 2100 UTC 21 September stated "Earlier today…a recon plane observed a smaller eye and a double max wind band structure. Both the Cancun radar and satellite data showed an outer convective ring surrounding the eye. Then…the minimum pressure leveled off around 946 mb. This suggests that Isidore was going through an eyewall cycle or replacement. This is probably the reason that the rapid deepening observed earlier has temporarily ended."

A final small outbreak of eyewall lightning occurred as Isidore was making landfall on the Yucatan Peninsula.

5.3 Hurricane Isabel

Isabel developed west of the northwest coast of Africa on 6 September 2003. The center of Isabel propagated to the west-northwest passing to the northeast of the Caribbean Islands. Isabel made landfall on the North Carolina coast on 18 September as a category 2 hurricane with sustained winds of 90 knots. On 11 September Isabel intensified to category 5 status on the Saffir-Simpson Scale and reached a maximum intensity of 145 knots.

Isabel had already reached its maximum intensity before reaching the 10% CG lightning detection efficiency contour off the coast of the U.S. Figure 5 shows the eyewall flash rate superimposed upon observations of central pressure from Hurricane Isabel during the period of analysis. One eyewall lightning flash was detected near 1200 UTC 14 September as the storm was about to undergo a fairly rapid weakening stage. Another eyewall lightning outbreak occurred between 0900 UTC 15 September and 0300 UTC 16 September. There was only a total of 5 CG flashes detected, however they occurred during a time period of concentric eyewall formation. The NHC discussion at 0900 UTC 15 September stated "The aircraft has also reported well-defined concentric wind maxima."

Isabel maintained a fairly steady central pressure between 1200 UTC 16 September and 0900 UTC 18 September. During this time period, no eyewall lightning was detected in this storm. This is in agreement with the Molinari et al. (1999) hypothesis that hurricanes undergoing little change in intensity will not exhibit eyewall flashes. A final outbreak of eyewall lightning occurred between 1500 and 1800 UTC 18 September. This outbreak was probably initially caused by concentric eyewall formation before being influenced by landfall. The NHC discussion at 0900 UTC 18 September stated "WSR-88D radar data from Morehead City shows what looks like a classic concentric eyewall formation…with a poorly-defined ring of convection near the center and a stronger ring 40-50 nm out."

5.4 Hurricane Kenna

Kenna developed off the southwest coast of Mexico, in the Eastern Pacific Ocean on 22 October 2002. The center of Kenna propagated toward the northwest before making a turn to the northeast and making landfall as a category 4 hurricane near San Blas, Mexico. On 24 October Kenna intensified to category 5 and reached a maximum intensity of 145 knots.

Kenna did not reach the 10% CG lightning detection efficiency contour until 4.5 hours before landfall at 1630 UTC 24 October. The analysis period was extended to include the 12 hours leading up to Kenna's propagation across the 10% detection efficiency contour. Figure 6 shows the eyewall flash rate superimposed upon observations of central pressure from Hurricane Kenna from 0000 to 1200 UTC 25 October.

This 12-hour period of analysis included a critical part of the lifecycle of Hurricane Kenna. One of the largest outbreaks of eyewall lightning found in this study occurred as a secondary eyewall formed in Kenna. The NHC discussion from 0900 UTC 25 October stated "Kenna continues to display a small well defined eye.

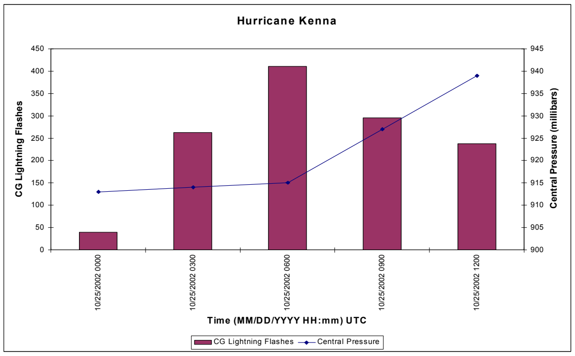

Figure 6. Same as Figure 3, except for Hurricane Kenna.

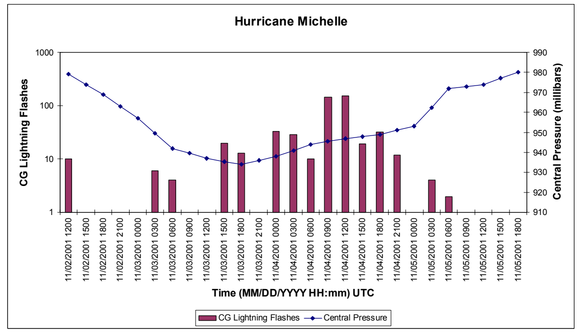

Figure 7. Same as Figure 3, except for Hurricane Michelle.

There is a suggestion of concentric eye walls and cloud tops have cooled significantly during the last six hours." The next NHC discussion from 1500 UTC 25 October stated "A microwave pass at 0429 Z showed concentric eyewalls." The development of a secondary eyewall signaled the end of the rapid intensification phase of Kenna and rapid weakening ensued. Eyewall flashes reached a maximum rate of 410 per 3-hour interval during this secondary eyewall development phase. Kenna was similar to Hurricane Lili in that a large eyewall lightning outbreak occurred during the development of a secondary eyewall and rapid weakening ensued. Sustained winds in Kenna dropped from 145 to 120 kt in the 10.5 hours preceding landfall.

5.5 Hurricane Michelle

Michelle developed near the eastern coast of Central America on 29 October 2001. The center of Michelle propagated northward and then made a turn toward the northeast making landfall as a category 4 hurricane in Cayo Largo, Cuba. Michelle reached category 4 status on 4 November and reached a maximum intensity of 120 knots.

The first eyewall lightning outbreak occurred on 2 November as Michelle developed an eyewall structure and attained hurricane status (Fig. 7). A couple of eyewall lightning outbreaks occurred on 3 November. The first of these was associated with continuing intensification of the storm, although the intensification rate lessened following the lightning outbreak. The second appeared to be associated with some vertical wind shear affecting the system. Eyewall lightning rates rose to moderate levels early on the 4 November. This was apparently associated with a concentric eyewall cycle. The NHC discussion from 0300 UTC 4 November stated "Fluctuations in intensity are very common with intense hurricanes and are normally associated with eyewall cycles…which Michelle appears to be undergoing."

A large burst of eyewall lightning occurred shortly after the moderate burst that was probably caused by concentric eyewall formation. CG lightning rates reached 152 per 3-hour near 1200 UTC 4 November. This increase in lightning rates was associated with increasing vertical wind shear that began to affect Michelle. Eyewall lightning continued as Michelle made landfall in Cuba at 1800 UTC 4 November.

5.6 Hurricane Erin

Erin developed off the northwest coast of Africa on 1 September 2001. The center of Erin propagated west-northwestward for several days and then made a turn to the northwest. Erin passed to the northeast of Bermuda and then took a turn toward the northeast and eventually became extratropical. Erin reached category 3 on 9 September and reached a maximum intensity of 105 knots.

Hurricane Erin produced few eyewall lightning flashes within 60 km of its center of circulation throughout its lifetime (Fig. 8). The first eyewall lightning flashes were detected as deep convection wrapped around the center of the storm as it attained hurricane status. The only other lightning flash detected within 60 km of the center took place on 14 September as the eye became asymmetric and the storm began moving over cooler waters. However, concentric eyewalls were detected during the end of 10 September and the beginning of the 11 September. The NHC discussion from 0300 UTC 11 September stated "Airborne radar imagery from a NOAA Hurricane Research Division P-3 flight very late this afternoon showed that Erin has a concentric eyewall structure. This was confirmed by double peaks in both the flight-level winds and surface winds reported by the stepped-frequency microwave radiometer…SFMR…instrument onboard the P-3."

Since the diameter of the primary eyewall of Erin was rather large (~30 nm), the radius used to gather flashes was expanded to 100 km in order to see if any flashes were detected in the secondary eyewall (the diameter of the secondary eyewall was not mentioned in the NHC discussions). Two lightning flashes were detected between 90 and 100 kilometers from Erin's center shortly after the report of concentric eyewalls on 11 September (Fig. 9). Infrared satellite imagery showed that these flashes were located on the inner parts of the central dense overcast and not located near outer rain bands. Since lightning flashes are rare within

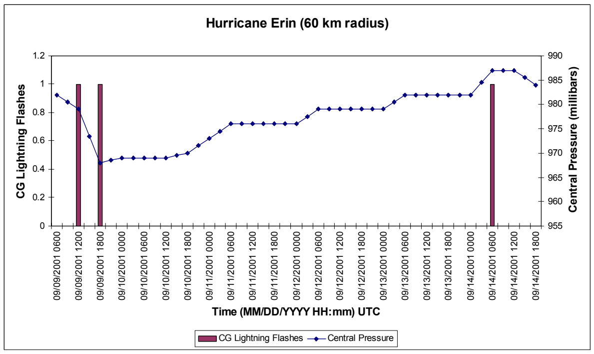

Figure 8. Same as Figure 3, except for Hurricane Erin.

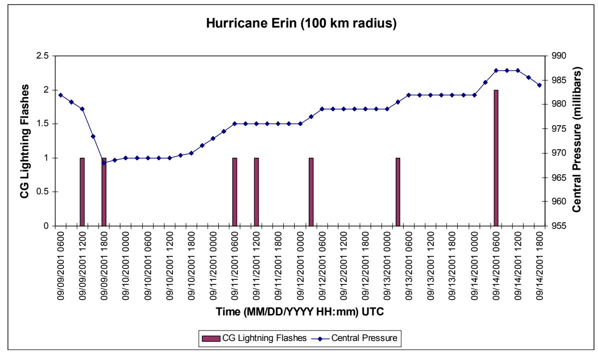

Figure 9. Same as Figure 3, except for all lightning flashes within 100 km of the center of Hurricane Erin.

inner rain bands located in the central dense overcast, these flashes were interpreted as occurring within the secondary eyewall. Two other flashes occurred early on 12 and 13 September. Interestingly, these flashes occurred at short time intervals of rapid weakening that were surrounded by a fairly steady storm intensity.

During most of the time periods when Erin was holding steady in intensity, there was a lack of eyewall lightning.

5.7 Hurricane Juliette

Juliette developed off the southern coast of Mexico in the Eastern Pacific Ocean on 21 September 2001. The center of Juliette initially propagated to the west-northwest before making a turn to the north-northwest making landfall in San Carlos, Mexico on Baja California. Juliette attained category 4 status on 25 September and reached a maximum intensity of 125 knots.

Juliette approached the 10% lightning detection efficiency contour on 26 September, allowing lightning analysis to take place between 1800 UTC 26 September and 0000 UTC 28 September. Figure 10 shows no eyewall flashes within Juliette during this time period. However, 2 and, at times, 3 concentric eyewalls existed in Juliette during this time period. The NHC discussion from 0300 UTC 27 September stated "An Air Force reserve hurricane hunter aircraft indicated this evening that Juliette has three concentric eyewalls…a rather uncommon occurrence."

The radius around Juliette's center was increased to 100 km and then 200 km and still no eyewall lightning was found. This was the only hurricane analyzed in this study that contained concentric eyewalls with no eyewall lightning detected.

5.8 Hurricanes Fabian and Kate

Fabian was a hurricane that developed off the northwest coast of Africa on 27 August 2003. The center of Fabian propagated to the west-northwest for several days before taking a turn to the north. Fabian passed just to the west of Bermuda as a category 3 hurricane on 5 September. It then took a turn toward the northeast and became extratropical. Fabian attained category 4 status on 31 August and reached a maximum intensity of 125 knots.

Kate was a hurricane that developed in the southern North Atlantic Ocean on 25 September 2003. The center of Kate meandered around the central North Atlantic for several days before turning toward the northeast and becoming extratropical. Kate attained category 3 status on 3 October and reached a maximum intensity of 110 knots.

Concentric eyewalls were not detected in Hurricanes Fabian and Kate. However, figures showing the eyewall flash rate superimposed upon observations of central pressure were created for both hurricanes (not shown). Both Fabian and Kate contained periodic eyewall lightning outbreaks. Most of these were associated with a change in the structure of the eyewall during the weakening phase of both storms. Most of the intensification phases of these storms took place while they were in areas with less than 10% CG lightning detection efficiency. Eyewall lightning outbreaks occurred during times when NHC observed a ragged eye, an elongated eye, a dry air intrusion or vertical wind shear. Eyewall lightning often occurred during times of vertical wind shear, however it was not detected in a continuous manner throughout the time periods containing vertical wind shear. Why eyewall lightning outbreaks occurred sporadically and not continuously thoughout the shearing phases of these storms is not known.

5.9 Hurricane Charley

Charley developed just east of the Windward Islands on 9 August 2004. The center of Charley propagated to the west-northwest through the Windward Islands into the Caribbean Sea. Charley then turned to the north and made landfall as a category 1 hurricane in western mainland Cuba between 0300 and 0900 UTC 13 August. After crossing Cuba, Charley rapidly intensified and turned to the north-northeast making landfall near Charlotte Harbor, Florida at ~2030 UTC 13 August. Charley attained category 4 status on the Saffir-Simpson Scale shortly before landfall and reached

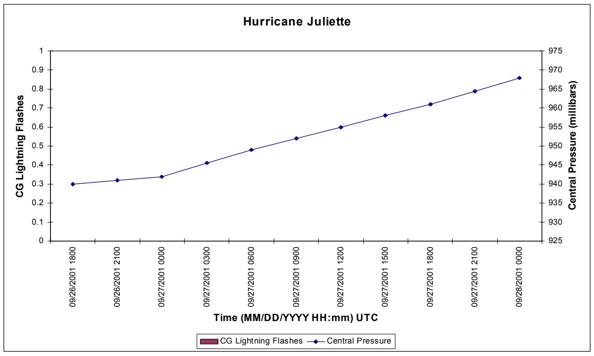

Figure 10. Same as Figure 3, except for Hurricane Juliette.

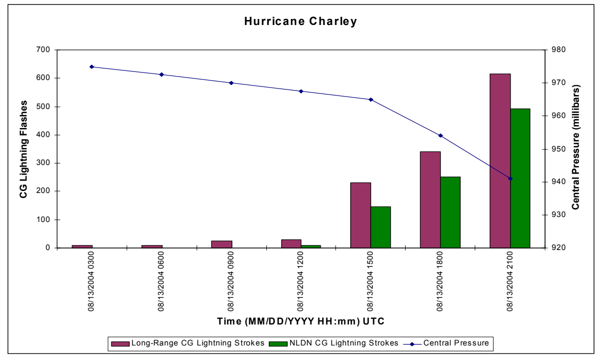

Figure 11. Same as Figure 3, except for LRLDN and U.S. NLDN lightning flashes within 60 km of the center of Hurricane Charley.

a maximum intensity of 125 knots.

Charley provided a unique opportunity to apply the hypotheses put forth in Molinari et al. (1994, 1999) and the results found in this paper to a real-time situation. The rest of this study was completed shortly before Hurricane Charley developed in the Atlantic basin.

Eyewall lightning data from Hurricane Charley was analyzed for the 19 hours preceding landfall in Florida. Data were not analyzed before this time period due to high center position error estimates by the NHC and poor LRLDN geometry relative to Charley's position on 11-12 August. Figure 11 shows the eyewall flash rate as detected by both the LRLDN and the U.S. NLDN superimposed upon observations of central pressure from Hurricane Charley. Low-to-moderate rates of eyewall lightning occurred as Charley intensified at a moderate rate between 0300 and 1200 UTC. Charley started to move into NLDN range at ~0600 UTC. Some of the benefits of LRLDN data can be seen as 3-hour lightning rates as measured by the LRLDN were detected earlier and at larger values than the U.S. NLDN. For example, the NLDN did not detect an eyewall lightning flash between 0130 and 0430 UTC and only detected 2 eyewall flashes between 0430 and 1030 UTC. By comparison, the LRLDN detected 9 eyewall flashes between 0130 and 0430 UTC and 34 eyewall flashes between 0430 and 1030 UTC.

As the primary eyewall of Charley contracted and the storm rapidly intensified from 965 to 941 mb, eyewall flash rates increased dramatically. LRLDN (NLDN) eyewall flash rates increased to 230 (146) and 340 (251) at 1500 and 1800 UTC, respectively. At this same time, a secondary eyewall developed around the primary eyewall. The primary and secondary eyewalls of Hurricane Charley can be seen in the radar base reflectivity data from the Tampa Bay WSR-88D at 1813 UTC (Fig. 12). LRLDN data superimposed on infrared satellite imagery from 1515 UTC shows a burst of eyewall lightning on the western side of the eye of Charley (Fig. 13). The high flash rates at 2100 UTC may be at least partially due to the landfall of Charley at ~2030 UTC.

Comparisons of LRLDN and NLDN data from Charley show that the LRLDN provided reliable data that have more than sufficient detection efficiency and location accuracy to be used in eyewall lightning applications. The NLDN provides high detection efficiency and location accuracy across the continental U.S. Over land, the median location accuracy for CG lightning strokes is 500 m and the detection efficiency is over 90% (Cummins et al., 1998; Kehoe and Krider, 2004). The detection efficiency and location accuracy of the NLDN decreases with increasing distance from the U.S. coastline, however the more stringent lightning location algorithms used in the network provide a higher resolution dataset that helps to verify the LRLDN dataset near coastal areas.

6. DISCUSSION

One of the main goals of this paper was to extend the work of Molinari et al. (1994, 1999) to include a greater number of major hurricanes at greater distances from the U.S. mainland coastline. This study included 8 major hurricanes from the Atlantic basin and 2 major hurricanes from the Eastern Pacific basin. Nine of the ten storms shown in this paper produced eyewall lightning at some point during their lifecycle. Eyewall lightning rates varied from only a couple per 3-hour interval to over 600 per 3-hour interval.

The results of this paper support some of the hypotheses put forth in Molinari et al. (1999). Eyewall lightning outbreaks in a weakening, steady, or slowly deepening hurricane typically are an indication of eyewall contraction and rapid intensification. An outbreak of eyewall lightning in a hurricane that has been rapidly deepening for some time typically indicates that a secondary eyewall is forming and the rapid intensification period is about to end. Also, a lack of eyewall lightning typically existed when the hurricanes remained at a fairly steady intensity. Molinari et al. (1999) only had eyewall cycle information for 1 of the 5 hurricanes they analyzed. Due to NHC archiving, we had access to detailed forecast discussions throughout the lifetime of these 10 major hurricanes. Seven of the 10 hurricanes had verified concentric eyewall structures as documented by microwave satellite, radar or aircraft reconnaissance data. Of the 3 remaining storms, a concentric eyewall cycle was discussed, but not verified,

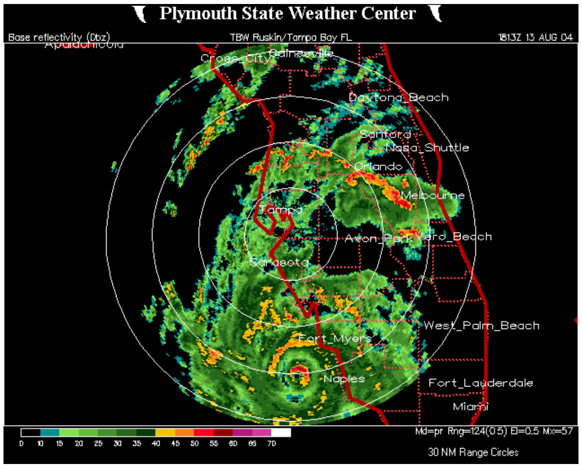

Figure 12. Tampa Bay WSR-88D radar base reflectivity image from 1813 UTC 13 August 2004. The center of Hurricane Charley is located just off the southwest coast of Florida. The secondary eyewall is visible as a ring of higher reflectivity surrounding a ring of lower reflectivity, surrounding the primary eyewall. Image courtesy of the Plymouth State Weather Center located at vortex.plymouth.edu.

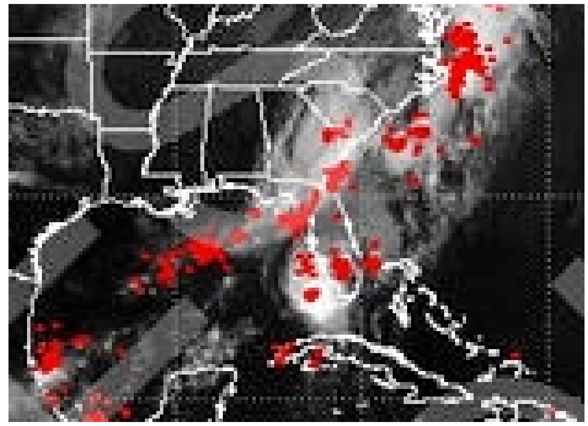

Figure 13. LRLDN lightning flashes superimposed on an infrared satellite image from 1515 UTC 13 August 2004. LRLDN flashes detected between 1445 and 1515 UTC are plotted in red. Eyewall lightning flashes are located in the central dense overcast of Hurricane Charley off the southwest coast of Florida.

by NHC in Hurricane Michelle and NHC never mentioned a concentric eyewall cycle in Hurricanes Fabian and Kate.

Out of a total of 12 secondary eyewalls mentioned in NHC discussions, 10 were accompanied by eyewall lightning outbreaks within 60 km of the storms' center. Ten of these twelve secondary eyewalls were verified by radar, satellite and/or aircraft observations. However, one of the two verified secondary eyewalls occurred in Hurricane Erin and when the radius was increased from 60 to 100 km, 2 eyewall flashes were observed. The radius probably needed to be increased in Hurricane Erin because of its large diameter primary eyewall. Taking this into account, 11 of the 12 (92%) concentric eyewall cycles were accompanied by eyewall lightning outbreaks. Eyewall lightning may have existed, but gone undetected in Hurricane Juliette due to low flash rates. The probability of detecting an eyewall lightning outbreak would drop dramatically if the total flash count for an eyewall lightning outbreak in Juliette dropped much below the 11 flashes discussed in Section 3 of this paper. However, eyewall lightning may not have existed during the concentric eyewall cycle of Hurricane Juliette because it was moving over increasingly colder waters at the time the concentric eyewalls were observed. The colder waters could have stabilized the atmosphere to the point that the updrafts necessary to produce lightning could not be sustained.

Eyewall lightning outbreaks could be valuable information for forecasters because of the rapid intensification changes that can take place during concentric eyewall cycles and the difficulties in observing these features. Currently, there is no way to continuously monitor secondary eyewall formation throughout the lifetime of a hurricane. In order to receive ground-based radar data, the storm center needs to be close to coastal areas. Microwave satellite imagery is only available a couple of times a day due to the polar earth orbiting satellites on which these instruments reside. Aircraft reconnaissance data is only available when hurricane hunters fly through a hurricane.

Another interesting observation was that the 3 highest eyewall lightning flash rates were associated with storms that underwent secondary eyewall formation and rapid weakening or rapid intensification. Hurricanes Lili, Kenna and Charley all had 3-hour eyewall flash rates over 300 during a concentric eyewall cycle. Hurricane Lili weakened from category 4 to category 2 and Hurricane Kenna weakened from category 5 to a low-end category 4 on the Saffir-Simpson Scale during these outbreaks. Hurricane Charley strengthened from a category 2 to a category 4 storm during its high eyewall lightning flash rate.

Observations from this study suggest that eyewall lightning outbreaks occur whenever there is a change in the dynamical structure of the eyewall or center of circulation. These outbreaks were often observed when the eyewall became ragged or elongated in shape or dry air started to intrude on the storm center. They also occurred when the hurricanes came under the influence of increased vertical wind shear. This often led to the ragged or elongated eyewall shapes. Eyewall lightning outbreaks were also frequently observed during landfall.

Another important finding was that outbreaks of lightning often occur near a tropical cyclones' center as it intensifies from a tropical storm to a hurricane. NHC discussions often mentioned the importance of convection developing or wrapping around the storm center during its transition stage from a tropical storm to a hurricane. When this convection develops around the storm center it is usually accompanied by eyewall lightning. Hurricanes Lili, Isidore, Michelle and Erin all contained eyewall lightning outbreaks as they strengthened from a tropical storm to a hurricane. Eyewall lightning often continued as these hurricanes intensified and the primary eyewall contracted. Eyewall contraction in general appears to produce lightning, regardless of whether it is the primary or a secondary eyewall.

7. CONCLUSIONS

LRLDN data may provide forecasters with a valuable diagnostic tool for observing concentric eyewall cycles and other important dynamic changes in the core of a hurricane. Eyewall lightning outbreaks occurred in 11 of the 12 concentric eyewall cycles found in this study. This is important for forecasters because concentric eyewall cycles are often obscured on visible and infrared satellite imagery. The instrumentation currently used to identify these features can not continuously monitor hurricanes. These include ground-based radar, microwave satellite and air reconnaissance data.

Eyewall lightning outbreaks also occurred during the initial intensification stage of a hurricane and when the eyewall dynamical structure changed. These dynamical structure changes occurred when the eyewall became ragged or elongated in shape, when vertical wind shear increased and/or when dry air intruded into the storm center.

8. REFERENCES

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

Kehoe, K.E., and E.P. Krider, 2004: NLDN performance in Arizona. *Proceedings, 18th International Lightning Detection Conference*. Helsinki, Finland, June 7-9, 8 pp.

Molinari, J., P. Moore, and V. Idone, 1999: Convective structure of hurricanes as revealed by lightning locations. *Mon. Wea. Rev.*, **127**, 520-534.

----------, P.K. Moore, V.P. Idone, R.W. Henderson, and A.B. Saljoughy, 1994: Cloud-to-ground lightning in Hurricane Andrew. *J. Geophys. Res.*, **99**, 16665-16676.

Nierow, A., R.C. Showalter, F.R. Mosher, and T. Lindholm, 2002: Mitigating the impact of oceanic weather hazards on transoceanic flights. *Proceedings, 17th International Lightning Detection Conference*, Tucson, AZ, October 16-18, 4 pp.

Sugita, A., and M. Matsui, 2004: Lightning in typhoons observed by JLDN. *Proceedings, 18th International Lightning Detection Conference*. Helsinki, Finland, June 7-9, 4 pp.

Weatherford, C. and W.M. Gray, 1988: Typhoon structure as revealed by aircraft reconnaissance. Part II: Structural variability. *Mon. Wea. Rev.*, **116**, 1044-1056.