16D.3 EYEWALL LIGHTNING OUTBREAKS AND TROPICAL CYCLONE INTENSITY CHANGE

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1. INTRODUCTION

The primary sources for monitoring tropical cyclones over oceanic areas are (1) infrared and visible satellite imagery provided by geostationary satellites, (2) passive microwave satellite imagery and space-based radar imagery provided by polar orbiting satellites and (3) aircraft 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 nearly continuous monitoring of tropical cyclones. Unfortunately, such imagery does not provide all of the necessary detailed structural information in eyewalls and outer rainbands that meteorologists and numerical models need for accurate nowcasting/forecasting of tropical cyclones. While images from polar orbiting satellites depict internal tropical cyclone structures, and reconnaissance aircraft provide valuable data from within the tropical cyclone, both of these platforms suffer from severe temporal and spatial sampling limitations. In addition, most tropical cyclones are outside the range of land-based radars. As a result of all of these data limitations, continuous monitoring of the internal convective structures of tropical cyclones has not been possible. Long-range lightning data over the oceans, however, offers an option to partially mitigate this problem.

Vaisala's National Lightning Detection Network (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 Hurricane Florence (1988) made landfall along 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, 2008). Squires and Businger (2008) examined eyewall lightning relationships to aircraft radar and space-based microwave imagery in Hurricanes Katrina (2005) and Rita (2005). They found that eyewall lightning was generally located in regions with high radar reflectivity and microwave precipitation ice content signatures, and low brightness temperatures.

Vaisala's LLDN utilizes NLDN and Canadian Lightning Detection Network (CLDN) sensors to detect cloud-to-ground (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.

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Demetriades and Holle (2009) applied detection efficiency corrections to inner core lightning rates produced by 2004-2007 Atlantic tropical cyclones. These corrections accounted for DE differences related to day/night propagation and location with respect to LLDN sensors. By applying DE corrections to lightning rates derived from LLDN data, Demetriades and Holle (2009) created realistic inner core lightning rates for the tropical cyclones examined in their study. They found that Atlantic tropical cyclones produce the highest inner core lightning rates during the tropical storm stage and lower inner core lightning rates during the hurricane stage. Inner core lightning was defined as all cloud-to-ground lightning within 100 km of the tropical cyclone center location reported by the National Hurricane Center (NHC), and within 90 minutes of the time of the NHC reported location.

For more information on the lightning detection efficiency 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. (2009), respectively. For more information on LLDN detection efficiency in the Atlantic basin, the reader is referred to Demetriades and Holle (2009).

Outbreaks of eyewall lightning have been observed during time periods of intensification, weakening, and little intensity change. The lack of a clear pattern to, and understanding of, eyewall lightning and storm intensity has made it difficult to use lightning information in operational settings to improve intensity forecasts. Recent research at the National Hurricane Center (NHC), University of Hawaii, and Vaisala has found recurring lightning signals during specific portions of the tropical cyclone lifecycle. Anomalous outbreaks of lightning activity frequently occur in the inner core of tropical cyclones near the end of rapid intensification and at maximum storm intensity. Rapid intensification is defined as a 30 kt increase in maximum sustained wind speed within 24 hours (Kaplan and DeMaria, 2003). This signal has been observed in many Atlantic, eastern Pacific, and western Pacific tropical cyclones. Examples will be shown from Katrina, Rita, and Wilma (all in 2005) in the Atlantic using Vaisala LLDN data that has been provided in real time to the National Weather Service. More recent examples will be shown from Rick (2009) in the eastern Pacific and Ului (2010) in the Southwest Pacific using Vaisala's new Global Lightning Dataset (GLD360).

2. VAISALA'S GLOBAL LIGHTNING DATASET (GLD360)

Vaisala's Global Lightning Dataset (GLD360) was launched in September 2009. GLD360 is the first ground-based lightning detection network capable of providing both worldwide coverage and uniform, high performance without large detection differences between daytime and nighttime conditions. The expected detection efficiency and median location accuracy of GLD360 is:

- 70% cloud-to-ground flash detection efficiency
- 5-10 km median cloud-to-ground stroke location accuracy.

GLD360 cloud-to-ground (CG) flash detection efficiency and stroke location accuracy was recently validated over the continental United States using Vaisala's NLDN as ground truth (Demetriades et al., 2010). The time period used for the validation study was 1 December 2009 through 31 January 2010.

GLD360 CG flash detection efficiency ranged from 86% to 92% throughout the 24-hour UTC day, with little day/night variation. This variability in detection efficiency as a function of UTC time is much smaller than that observed in other existing long-range lightning detection systems. GLD360 CG stroke median location accuracy was 10.8 km.

3. METHODOLOGY

The position and maximum sustained wind speed of Atlantic hurricanes used in this study (Katrina, Rita, and Wilma) 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 positions and maximum sustained wind speeds were interpolated between consecutive 6-hourly intervals 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 LLDN DE correction was applied to the inner core lightning rates associated with Katrina, Rita, and Wilma.

The positions and maximum sustained wind speeds for Rick and Ului were obtained from real-time (not best track) NHC and UNISYS data, respectively. The methodology is the same as described above for Katrina, Rita, and Wilma, except GLD360 inner core lightning rates were not corrected for detection efficiency.

The location of inner core lightning was also calculated as a function of radius from storm center. Lightning counts were grouped into 10-km radial bins for each storm at (or near) the time of maximum storm intensity.

4. STORM ANALYSES

4.1 Hurricane Katrina (2005)

Katrina was a powerful Category 5 Atlantic basin hurricane on the Saffir-Simpson Hurricane Scale. It was classified by NHC as a tropical cyclone during 23-30 August 2005. At peak intensity over the Gulf of Mexico, Katrina had a maximum sustained wind speed of 150 kt. Vaisala LLDN data was used to monitor lightning activity within the inner core of Katrina.

Figure 1 shows a 48-hour time series of maximum sustained wind speeds and inner core lightning rates for Katrina. At 1800 UTC 28 August, Katrina reached its maximum intensity after a period of rapid intensification. A burst of anomalously high inner core lightning occurred around this time. DE-corrected, inner core lightning rates were above the 90^{th} percentile value of 200, found for Category 3 and higher hurricanes in Demetriades and Holle (2009), from 1500 to 2100 UTC 28 August.

During this time period, Figure 2 from Squires and Businger (2008) clearly shows the vast majority of this inner core lightning is located within the primary eyewall of Katrina.

4.2 Hurricane Rita (2005)

Rita was also a Category 5 Atlantic basin hurricane on the Saffir-Simpson Hurricane Scale. It was classified as a tropical cyclone during 18-26 September 2005. At peak intensity over the Gulf of Mexico, in nearly the same location as Katrina a month earlier, Rita had a maximum sustained wind speed of 155 kt. Vaisala LLDN data was used to monitor lightning activity within the inner core of Rita.

Figure 3 shows a 48-hour time series of maximum sustained wind speeds and inner core lightning rates for Rita. At 0600 UTC 22 September, Rita reached its maximum intensity after a period of rapid intensification. A burst of anomalously high inner core lightning occurred around this time. DE-corrected, inner core lightning rates were above the 90^{th} percentile value of 200 from 1500 UTC 21 September to 0600 UTC 22 September.

During this time period, Figure 4 from Squires and Businger (2008) clearly shows that, similar to Katrina, the vast majority of this inner core lightning is located within the primary eyewall of Rita.

4.3 Hurricane Wilma (2005)

Wilma was yet another Category 5 Atlantic basin hurricane on the Saffir-Simpson Hurricane Scale. It was classified as a tropical cyclone during 15-25 October 2005. At peak intensity over the northwestern Caribbean Sea, Wilma had a maximum sustained wind speed of 160 kt. Vaisala LLDN data was used to monitor lightning activity within the inner core of Wilma.

Figure 5 shows a 48-hour time series of maximum sustained wind speeds and inner core lightning rates for Wilma. At 1200 UTC 19 October, Wilma reached its maximum intensity after a period of rapid intensification. A burst of anomalously high inner core lightning occurred around this time. DE-corrected, inner core lightning rates were above the 90^{th} percentile value of 200 from 0600 to 0900 UTC 19 October.

4.4 Hurricane Rick (2009)

Rick was a Category 5 hurricane on the Saffir-Simpson Hurricane Scale that occurred in the eastern North Pacific basin. It was classified as a tropical cyclone during 15-21 October 2009. At peak intensity, Rick had a maximum sustained wind speed of 155 kt. Vaisala GLD360 data was used to monitor lightning activity within the inner core of Rick.

Figure 6 shows a 48-hour time series of maximum sustained wind speeds and inner core lightning rates for Rick. At 0300 UTC 18 October, Rick reached its maximum intensity after a period of rapid intensification. A burst of anomalously high inner core lightning occurred in and around this time. Uncorrected, inner core lightning rates were above the 90^{th} percentile value of 200 from 2100 UTC 17 October to 0600 UTC 18 October.

4.5 Tropical Cyclone Ului (2010)

Ului was a Category 5 Southwest Pacific basin tropical cyclone on the Saffir-Simpson Hurricane Scale. It was classified as a tropical cyclone during 11-20 March 2010. At peak intensity, Ului had a maximum sustained wind speed of 140 kt. Vaisala GLD360 data was used to monitor lightning activity within the inner core of Ului.

Figure 7 shows a 48-hour time series of maximum sustained wind speeds and inner core lightning rates for Ului. At 0000 UTC 14 March, Ului reached its maximum intensity after a period of rapid intensification. A burst of anomalously high inner core lightning occurred in and around this time. Uncorrected, inner core lightning rates were above the 90^{th} percentile value of 200 at 0000 UTC 14 March.

5. RADIAL DISTRIBUTION OF INNER CORE LIGHTNING

The radial distribution of inner core lightning was examined for all 5 storms at the time of maximum storm intensity and the end of rapid intensification. For Wilma, the radial distribution of inner core lightning is shown three hours earlier because it was the only storm where its lightning rates dropped significantly at the time of maximum storm intensity.

Katrina, Rita, Wilma, and Ului all showed a peak of inner core lightning activity within 40 km of the storm center at (or very near) the time of maximum storm intensity (Fig. 8). In fact, most of the inner core lightning within these four storms was located within 50 km of the storm center. Rick was the one exception, with a peak of inner core lightning at 60-70 km from the storm center and a large fraction of its inner core lightning beyond 50 km.

6. SUMMARY

Outbreaks of eyewall lightning have been observed during time periods of intensification, weakening, and little intensity change. The lack of a clear pattern to, and understanding of, eyewall lightning and storm intensity has made it difficult to use lightning information in operational settings to improve intensity forecasts. Recent research at the National Hurricane Center (NHC), University of Hawaii, and Vaisala has found recurring lightning signals during specific portions of the tropical cyclone lifecycle. Anomalous outbreaks of lightning activity (according to results from Demetriades and Holle, 2009) frequently occur in the inner core of tropical cyclones near the end of rapid intensification and at maximum storm intensity. This signal has been observed in many Atlantic, eastern Pacific, and western Pacific tropical cyclones.

Several tropical cyclones were used to examine this lightning signal in more detail. They were Katrina (2005), Rita (2005), and Wilma (2005) in the Atlantic basin, Rick (2009) in the eastern Pacific basin, and Ului (2010) in the Southwest Pacific basin. Inner core lightning was defined as 3-hourly lightning rates within 100 km of the storm center. Vaisala LLDN data was used to examine inner core lightning in Katrina (2005), Rita (2005), and Wilma (2005). A new Vaisala lightning dataset, GLD360 was used to examine inner core lightning in Rick (2009) and Ului (2010).

The positions and maximum sustained wind speeds for Katrina (2005), Rita (2005), and Wilma (2005) were obtained from the best track data produced by the NHC. The positions and maximum sustained wind speeds for Rick and Ului were obtained from real-time (not best track) NHC and UNISYS data, respectively.

These 5 storms span three tropical cyclone basins (Atlantic, eastern Pacific, and Southwest Pacific). All of them underwent a period of rapid intensification and reached Category 5 status on the Saffir-Simpson Hurricane Scale at their peak intensity.

For these tropical cyclones, anomalous outbreaks of inner core lightning occurred from 15 hours before maximum storm intensity to 3 hours after maximum storm intensity. This signal was most consistent from the 3 hours preceding maximum storm intensity to the time of maximum storm intensity (Figs. 1, 3, 5-7).

Katrina, Rita, Wilma, and Ului all showed a peak of inner core lightning activity within 40 km of the storm center at (or very near) the time of maximum storm intensity (Fig. 8). In fact, most of the inner core lightning within these four storms was located within 50 km of the storm center.

Overlays of inner core lightning on NOAA P-3 (or WP-3D) lower fuselage radar reflectivity during times of these anomalous outbreaks clearly show that the vast majority of lightning is located in the primary eyewall of these storms (Figs. 2 and 4 from Squires and Businger, 2008).

The global coverage and uniform, high performance of Vaisala's GLD360 provides exciting opportunities to observe and learn more about these inner core lightning signatures and other potential lightning signatures. GLD360 lightning data has the potential to improve tropical cyclone nowcasts/forecasts across the globe.

7. REFERENCES

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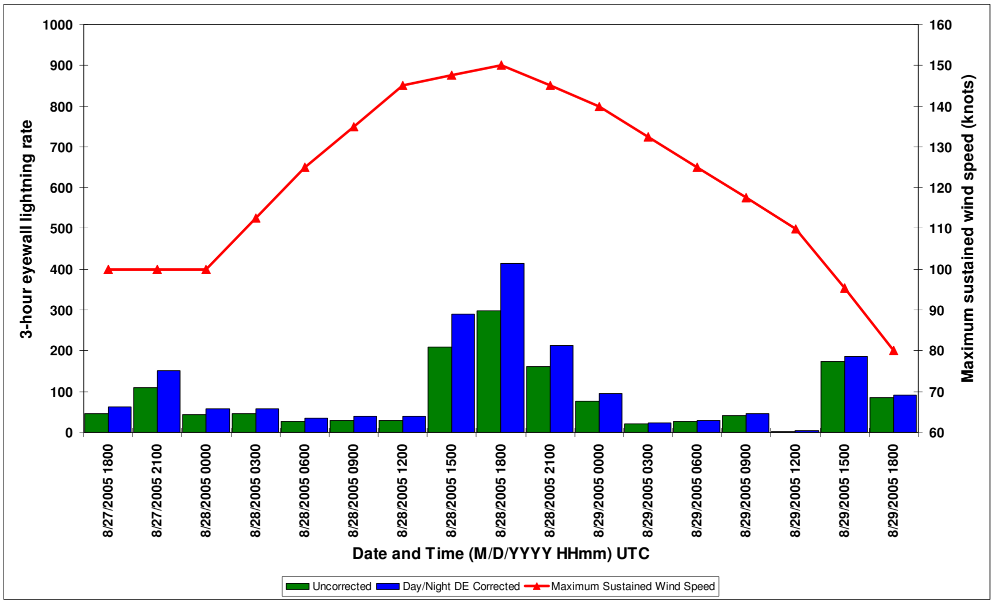

Figure 1. Time series of maximum sustained wind speeds and 3-hour inner core lightning rates for Hurricane Katrina from 1800 UTC 27 August to 1800 UTC 29 August 2005. Maximum sustained wind speeds are shown by the red curve with values on the right-hand y-axis. Uncorrected (Day/Night DE Corrected) Vaisala LLDN inner core lightning rates are shown as green (blue) bars with values on the left-hand y-axis. Rapid intensification ended and maximum storm intensity was achieved at 1800 UTC 28 August.

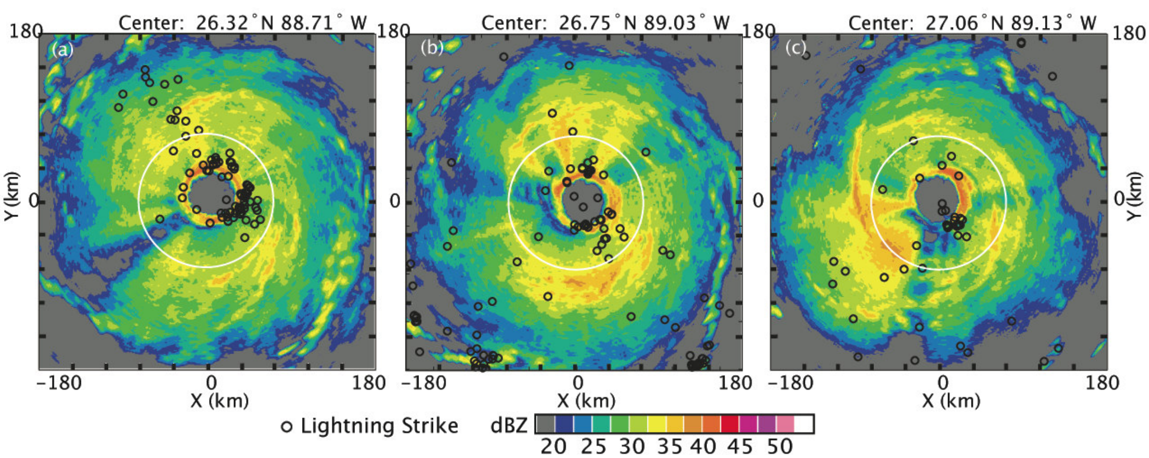

Figure 2. NOAA P-3 lower fuselage radar reflectivity taken of Hurricane Katrina on 28 August while the aircraft was near storm center, at an altitude of ~ 2,300 m. The nominal effective range of the LF radar is shown using the 70 km range ring (white circle). Overlaid onto these images are Vaisala LLDN lightning strike locations (black circles) for a 20-m time period centered on the time of the image. a) 1752 UTC, b) 2036 UTC, and c) 2324 UTC. (Figure 13 from Squires and Businger, 2008)

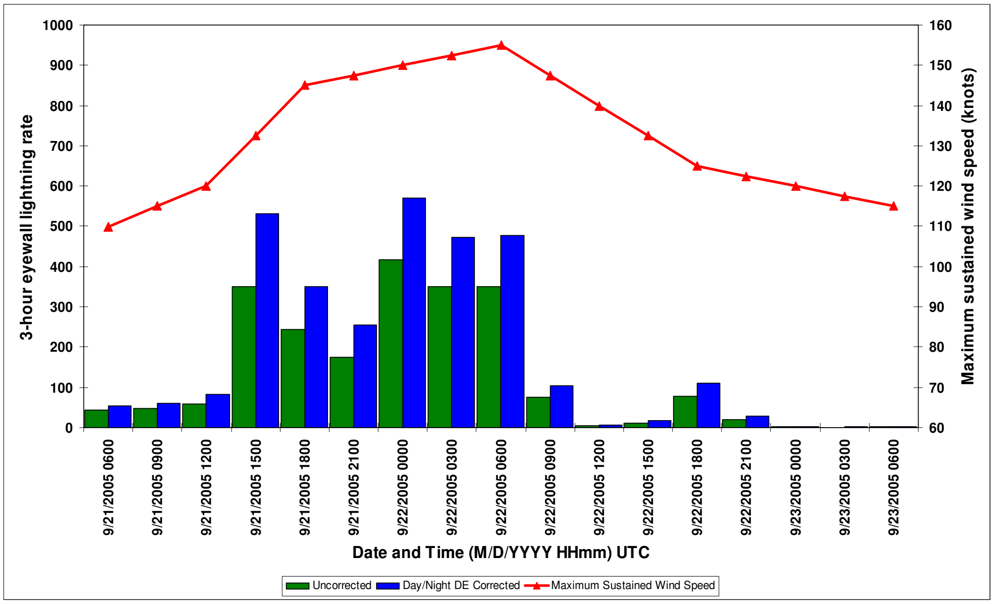

Figure 3. Same as Figure 1, except for Hurricane Rita from 0600 UTC 21 September to 0600 UTC 23 September 2005. Rapid intensification ended and maximum storm intensity was achieved at 0600 UTC 22 September.

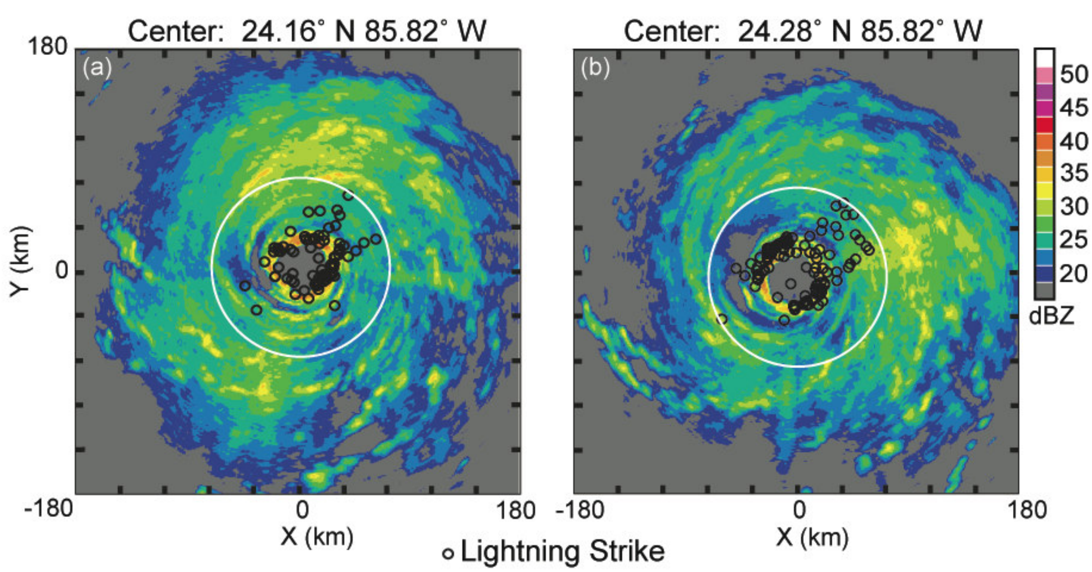

Figure 4. NOAA WP-3D lower fuselage radar reflectivity taken on 21 September while aircraft was located within the center of Hurricane Rita, at an altitude of 2,700 m. The nominal effective range of the LF radar is shown using the 70 km range ring (white circle). Superimposed onto each image is 20 minutes of Vaisala LLDN lightning data (black circles) centered on the time of the image. a) Reflectivity at 1523 UTC, with strike locations from 1513 UTC to 1533 UTC. b) Reflectivity at 1602 UTC, with strike locations from 1552 UTC to 1612 UTC. (Figure 4 from Squires and Businger, 2008)

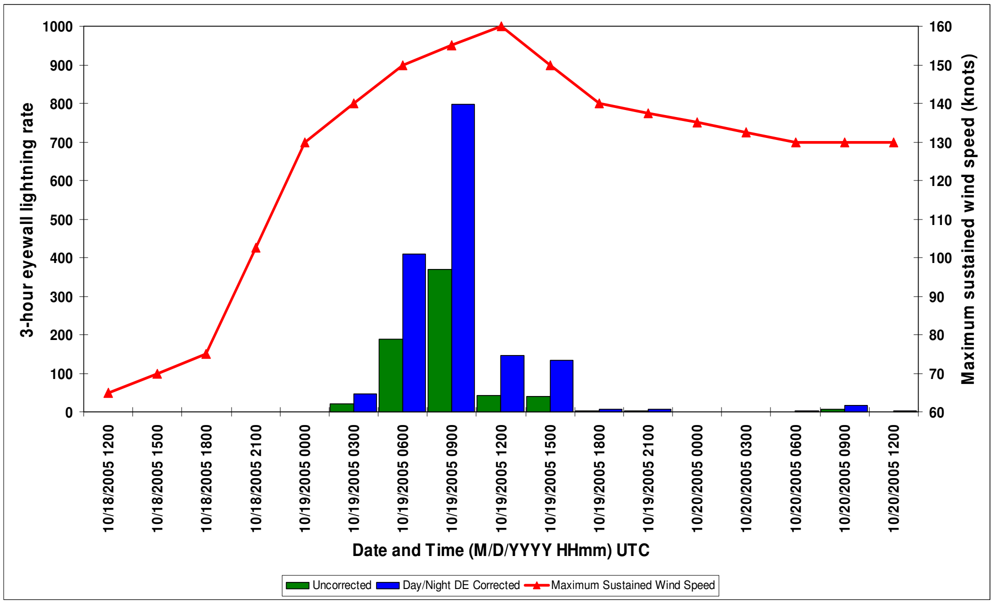

Figure 5. Same as Figure 1, except for Hurricane Wilma from 1200 UTC 18 October to 1200 UTC 20 October 2005. Rapid intensification ended and maximum storm intensity was achieved at 1200 UTC 19 October.

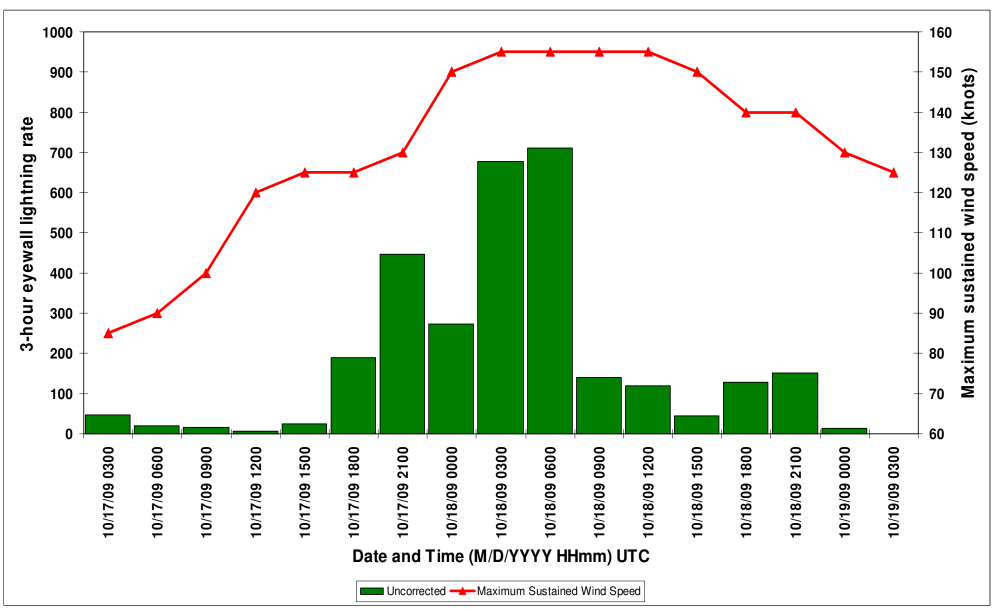

Figure 6. Time series of maximum sustained wind speeds and 3-hour inner core lightning rates for Hurricane Rick from 0300 UTC 17 October to 0300 UTC 19 October 2009. Maximum sustained wind speeds are shown by the red curve with values on the right-hand y-axis. Uncorrected GLD360 inner core lightning rates are shown as green bars with values on the left-hand y-axis. Rapid intensification ended and maximum storm intensity was achieved at 0300 UTC 18 October.

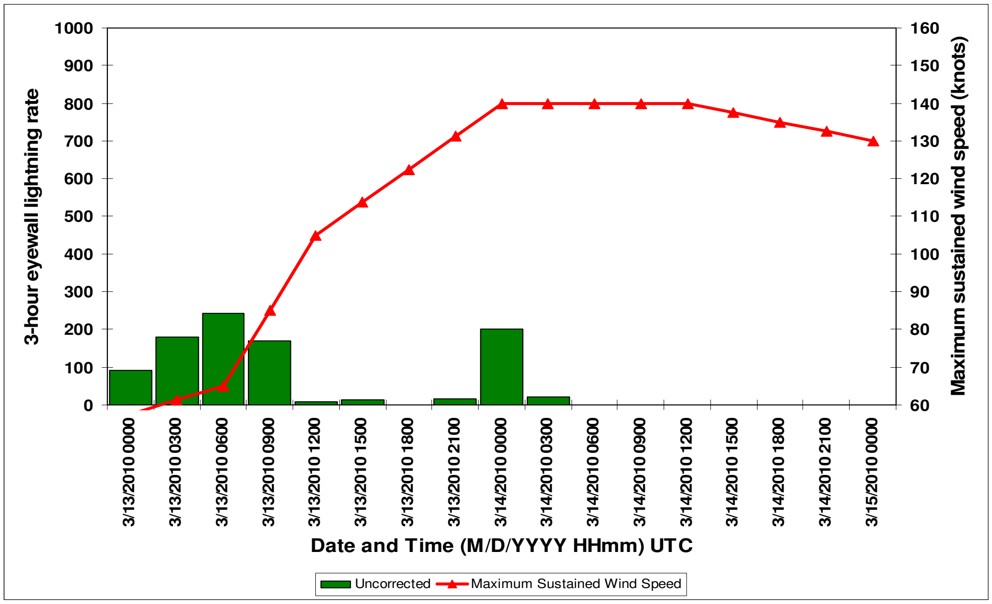

Figure 7. Same as Figure 6, except for Tropical Cyclone Ului from 0000 UTC 13 March to 0000 UTC 15 March 2010. Rapid intensification ended and maximum storm intensity was achieved at 0000 UTC 14 March.

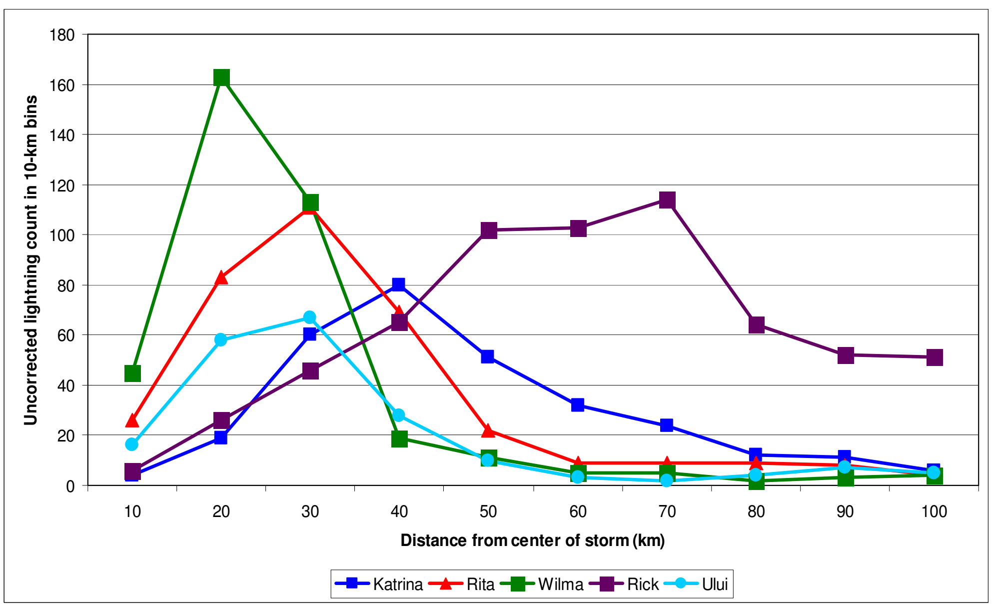

Figure 8. The radial distribution of inner core lightning at the time of maximum storm intensity, and the end of rapid intensification, for Katrina (2005), Rita (2005), Rick (2009), and Ului (2010). For Wilma (2005), the radial distribution of inner core lightning is shown three hours earlier because it was the one storm where its lightning rates dropped significantly at the time of maximum storm intensity. Lightning counts were grouped into 10-km radial bins. Distance from the center of the storm is shown on the x-axis. Uncorrected (Vaisala LLDN and Vaisala GLD360) lightning counts are shown on the y-axis. Each storm is shown in a different color with the color key located at the bottom of the figure.