Lightning Activity in Atlantic Tropical Cyclones: Using the Long-Range Lightning Detection Network (LLDN)

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ABSTRACT

Mitigating potential disasters from land-falling tropical cyclones requires accurate forecasts of trajectory and intensity. In the last 20 years, trajectory forecasting has improved 50%, while intensity forecasts have improved little or not at all. This lack of any major advances can be partly explained by poor understanding of the physical processes behind intensity changes. Few recent studies suggest that monitoring lightning activity in tropical cyclones could help improve understanding of these processes and also help predict intensification. We studied lightning in six Atlantic tropical cyclones using the Long-Range Lightning Detection Network, which reaches 2,000 kilometers offshore of the continental U.S. With exception of tropical cyclones intensifying close to continental landfall, lightning frequency didn't show a consistent peak before the time of maximum sustained winds. On the other hand, the outer rainband-to-eyewall lightning ratio shows a clear peak 24 hours before maximum sustained winds in all of the storms. A better understanding of the physics behind the temporal behavior of the ratio is needed. Preliminary assessment of these results suggests that some lightning changes could be related to the eyewall replacement cycle. Interaction of tropical cyclones with continents could increase lightning activity and the use of a ratio is not needed to see a clear peak in lightning before maximum sustained winds. A more detailed approach about the interactions between the outer rainband and eyewall lightning activity should be conducted. Lightning in the eyewall should be compared with radar and airplane observations to observe its relationship with the eyewall replacement cycles.

1. Introduction

Tropical Cyclones (TC) are one of the deadliest and most fearsome natural phenomena on Earth. Consequently society has suffered serious property damage and loss of life due to these storms. In the USA, the effects of these phenomena are large because 50% of its population lives within 50 miles of the coast. More importantly, recent cases of rapid intensification at or near coastline have occurred with little or no warning. Accurate forecasting of both track and intensity is critical in mitigating the potential disasters that an approaching TC could cause.

Advances in research and technology have helped in the development of more precise tropical cyclone forecasts, but the majority of this progress has been made in forecasting trajectories. In the last 20 years, track forecasts have improved 50% due to better observational data and technology. In the meantime, intensity forecasting has improved little or not at all, due to deficient understanding of the physical processes leading to intensity changes. Improving intensity forecasts requires additional studies of the interactions inside tropical cyclones and with their environment.

For many years, scientists have thought that lightning activity inside hurricanes was a side effect of the storm processes and played no significant role in tropical cyclone development. However, recent studies (Price et al., 2009 and Molinari et al., 1994) have found that lightning activity could be a predictor of changes in hurricane intensity. A tropical cyclone's intensity could be affected by the convection near the storm center and its interaction with the environment and with the underlying ocean. Convection in a tropical cyclone could be associated with an increase in lightning activity inside these storms; in addition, this relationship could also increase the rate of moistening at the lower troposphere and eventually intensify the tropical cyclone.

Price et al. (2009) analyzed all worldwide hurricanes of category four and five during the 2005-2007 seasons. They found that 56 out of 58 hurricanes showed a statistically significant correlation between lightning and maximum sustained winds. More than 70% of the hurricanes analyzed had lightning activity peaking approximately 24 to 30 hours prior to the maximum wind intensities. In this research, they used the World Lightning Detection Network (WLDN) with sensors located globally. The constraint of the network is the low accuracy and detection efficiency.

Additional studies support the idea that lightning activity can be a predictor of hurricane intensity. Molinari et al. (1994) used data from the National Lightning Detection Network (NLDN) to study cloud-to-ground lightning activity inside Hurricane Andrew. The NLDN data only covers an area within 400 km of the continental U.S. coast. Due to the lack of data away from shore, Molinari et al. (1994) could study the storm only when it was close to landfall and were sometimes not able to see the whole system. They concluded that more than one hurricane needs to be studied, and that the amount of lightning activity increased or decreased depending on the part of the hurricane being investigated.

The purpose of the research described in this paper is to study how lightning activity influences intensification of tropical cyclones. The difference from previous research is that this

study uses a new and extended lightning database called the Long-Range Lightning Detection Network (LLDN).   These data are used to examine relationships with the intensification or weakening of Atlantic tropical cyclones.

2. Methods

a. Tropical Cyclones for this study

This study focuses on lightning activity associated with TCs during the Atlantic seasons of 2007 and 2008. Only tropical cyclones that developed into hurricanes were considered for this research. Some of the storms were chosen using the forecast intensity error which is the National Hurricane Center (NHC) defines as the absolute value of the difference between the forecast and best track intensity at the forecast verifying time. Due to time availability, we chose to work with a total of six tropical cyclones: Dean, Felix, Humberto, Gustav, Omar, and Paloma (trajectories in *Figure1*).   The seasonal description and reasons for choosing the TC are as follows:

- Atlantic Season of 2007

  For the storms during the 2007, almost twelve percent of all intensity changes qualified as rapid intensifications, which is double the climatological rate, and around four times the rate observed in the previous season. Despite these many occurrences for rapid intensification, NHC forecasts intensity errors were 25% or more above the 5-year means at all time periods except at the 24 and 36 hours. For this season we didn't use the forecast intensity error to choose the storms, but other approaches were used. Hurricanes Dean and Felix were chosen because they were the only major hurricanes in the season. On the other hand, Hurricane Humberto was chosen due to its surprising intensification and proximity to landfall.

- Atlantic Season of 2008

  The very active 2008 hurricane season had a total of eight storms that developed into hurricanes. Despite the active season, only nine percent of all intensity changes qualified as rapid intensification. Due to time constraints we needed to choose tropical cyclones based on the NHC verification reports. The majority of the storms was close to the average intensity error and set a record at 72-120 hours. The three problematic tropical cyclones in the intensity forecasting criteria were: Gustav, Omar and Paloma.

After determining which hurricanes to use in the analysis, information about their location and maximum sustained winds were needed. All of this information was obtained from the database name HURDAT, created by the Hurricane Research Division of NOAA.

Map Num	Tropical Cyclones	Cat	Duration	Average Storm Intensity Forecast Error	Average Normal Intensity Error
1	Hurricane Dean	5	2007-08-13 at 6 UTC to 2007-08-22 at 0 UTC	10, 12, 13, 14, 21, 33, and 32 kt for the 12, 24, 36, 48, 72, 96, and 120 h forecasts, respectively.	6, 10, 12, 14, 18, 20, and 22 kt for the 12, 24, 36, 48, 72, 96, and 120 h forecasts, respectively.
2	Hurricane Felix	5	2007-08-31 at 12 UTC to 2007-09-06 at 18 UTC	18, 26, 35, 53, 56 and 35 kt for the 12, 24, 36, 48, 72, and 96 h forecasts, respectively	6, 10, 12, 14, 18, and 20 kt, for the 12, 24, 36, 48, 72, and 96 h forecasts, respectively.
3	Hurricane Humberto	1	2007-09-12 at 6 UTC to 2007-09-14 at 12 UTC	18, 12, and 5 kt for the 12, 24, and 36 h forecasts	6, 10, and 12 kt, for the 12, 24, and 36 h forecasts respectively
4	Hurricane Gustav	4	2008-08-25 at 0 UTC to 2008-09-05 at 12 UTC	14, 18, 19, 21, 22, 21, and 37 kt for 12, 24, 36, 48, 72, and 96 h forecasts, respectively	7, 10, 12, 14, 18, 20, and 22 kt, for 12, 24, 36, 48, 72, and 96 h forecasts, respectively respectively
5	Hurricane Omar	3	2008-10-13 at 6 UTC to 2008-10-21 at UTC	12, 15, 19, 26, 14, and 10 kt for the 12, 24, 36, 48, 72, and 96 h forecasts, respectively	7, 10, 12, 14, 18, 20, and 22 kt,for the 12, 24, 36, 48, 72, and 96 h forecasts, respectively
6	Hurricane Paloma	4	2008-11-05 at 18 UTC to 2008-11-14 at 6 UTC	14, 20, 23, 28, 36, and 50 kt for the 12, 24, 36, 48, 72, and 96 h forecasts, respectively.	7, 10, 12, 14, 18, and 20 kt, for the 12, 24, 36, 48, 72, and 96 h forecasts, respectively.

Table 1: Table of the six tropical cyclones chosen for the study. Data about their lifetime, category, and forecast intensity error is provided.
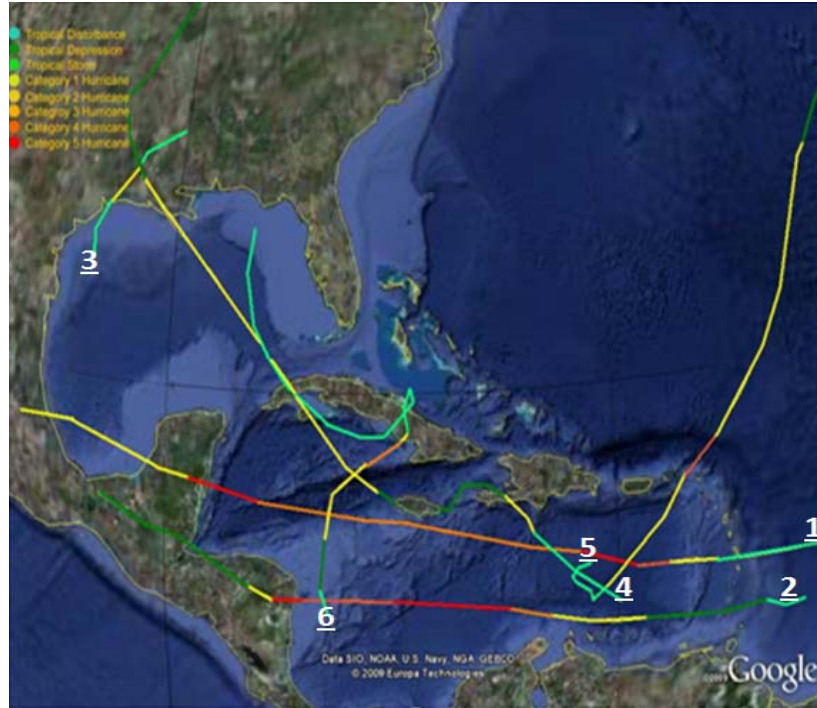
Figure1: Map showing the trajectories of all the six tropical cyclones chosen for this study. TC tracks are label and there correspondent number could be found in *table1*.

b. *Lightning Data*

In 1989, Vaisala Corporation created the National Lightning Detection Network (NLDN) providing information about the lightning strike location, time, polarity, and amplitude. The stations that provide the information for the NLDN are found across the United States and instantaneously detect the electromagnetic signals given off when lightning strikes the Earth's surface. This dataset has proven to be a useful indicator of convective outbreaks in hurricanes that are within 400km-500km of the U.S. coastal regions. However, a major problem with this dataset is that most hurricane formation and early intensification occurs outside the range of the NLDN. Due to the problem in coverage of the NLDN, a new data stream has been added to the existing network. This dataset, the Long-Range Lightning Detection Network (LLDN), can detect ground flashes 2,000km or more from the U.S. coast, covering a region from 0 ° N to 40 ° N and from 120° W to 45° W.

The LLDN accuracy is higher than many networks but it has some limitations. Lightning detection efficiency (DE) is higher during nighttime, as observed in *figure 2*, due to better conditions for ionosphere propagation. As *figure 2* shows, DE decreases as distance increases from the continental U.S. Vaisala data are reported in strokes and if a flash has several strokes the sensor usually reads the first stroke because is the one with more charge. Plots for hurricane Omar were made using the definition given by Vaisala: "For practical purposes, researchers have typically defined a flash as consisting of all CG (cloud-to-ground) discharges which occur within 10 km of each other within a one second interval" (Vaisala's NLDN Lightning Flash Data webpage). Since the majority of the strokes did not fulfill these constraints given by the flash

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definition, and after not finding a difference in trends, we decided that due to time constraints the analysis was going to be completed using strokes.
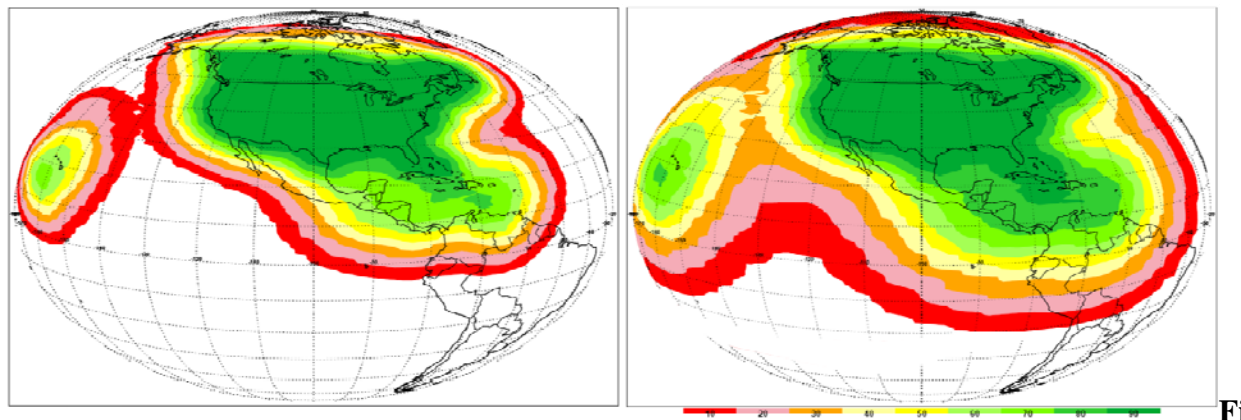

Figure 2: These maps show Vaisala's Long Range Lightning Detection Network (LLDN) detection efficiency (DE). The one to the left represent the daytime DE and the one to the right represents the nighttime DE.

c. *Plots creation*

Lightning data were divided into six-hour intervals to match HURDAT data. Each interval was filtered in grids containing data four degrees away from the location of the hurricane eye in all cardinal directions. We then calculated the radius of the lightning from the eye in kilometers and obtained the total counts of lightning strokes at intervals of 20 km.

To observe the location of lightning inside the hurricane we created spatial plots showing the latitude and longitude of the strokes. The plots of location were created only for rapid intensification (RI) periods as defined by NHC. Rapid intensification is defined as a period of 24 hours with sustained winds changes higher than 30 knots (34.5 mph). Enhanced infrared images from the Cooperative Institute for Research in the Atmosphere (CIRA) webpage were compared with each location plot created.

Total counts of lightning at each six hour interval for the track of each storm were compared with maximum sustained winds for the same intervals throughout the TC. Due to the results obtained in the location and total counts plots, we decided to plot an outer rainband-to-eyewall lightning ratio for comparison with sustained winds for each TC. For this research the eyewall was defined as any lightning activity within 40 km or less in radius from the HURDAT eye coordinates. The outer rainband included any lightning activity 160 km or more in radius from the HURDAT eye coordinates.

Results and Discussion

a. *Lightning location*

Hurricane Gustav is the only TC showing a clear spatial lightning structure during the maximum sustained winds (*see figure 3*). All of the cases present lightning activity increasing in

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the eyewall around the time of maximum sustained winds, but with many visual lightning strikes in the outer rainband location. Some TCs have an appearance of lightning in the eyewall a little bit earlier than others but not that much difference. The only mayor differences in lightning location and structure were found in Hurricane Paloma, as seen in *figure 5*.
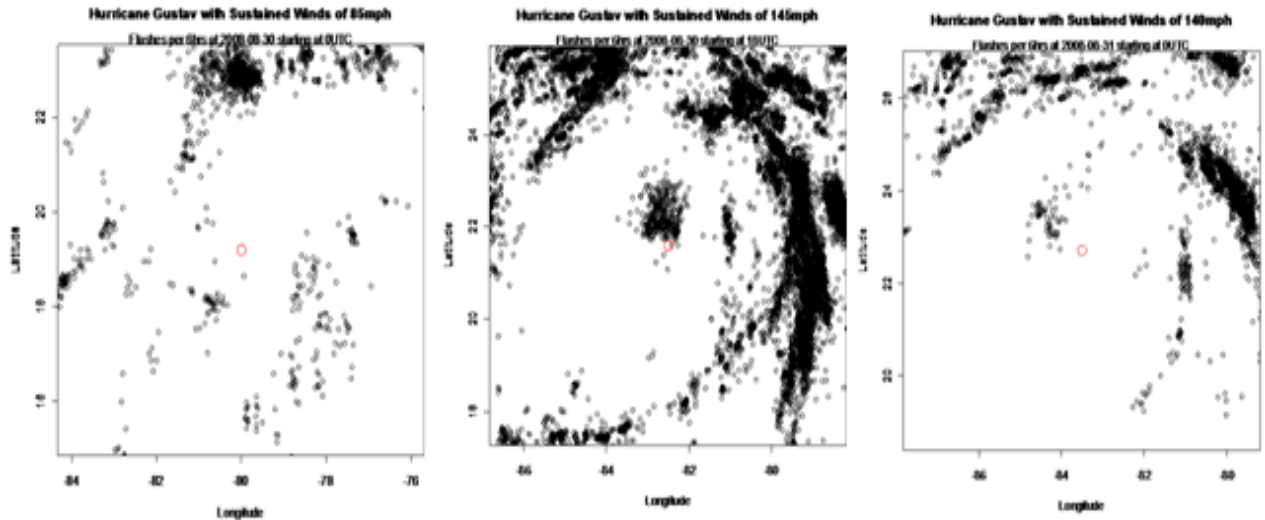

Figure 3: Plots of lightning location for Hurricane Gustav at before maximum sustained winds(left), during maximum sustained winds (right) and after maximum sustained winds (right). The red circle indicates the location of the eye at those intervals.
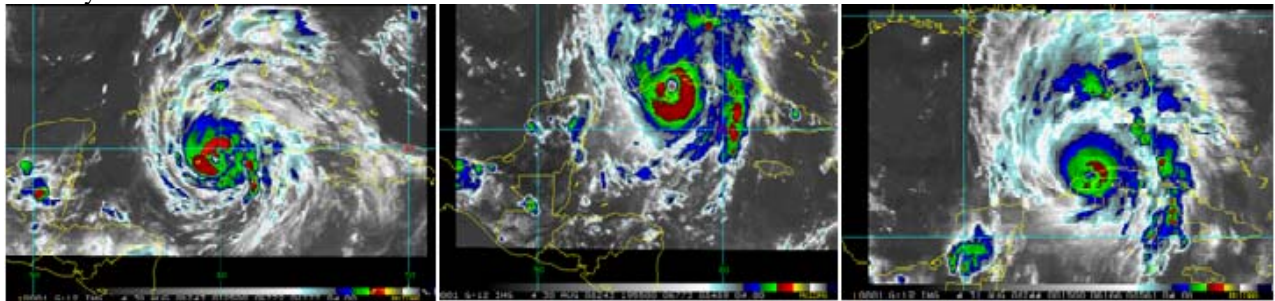

Figure 4: Enhanced Infrared Imagery for Hurricane Gustav at before maximum sustained winds(left), during maximum sustained winds (right) and after maximum sustained winds (right). Helps see the structure of the TC to understand the location of lightning in *figure 3*

As most of the figures show, the majority of the time the lightning activity is in the eyewall of the storm. A clear structure of lightning activity in the outer rainband location can be seen at all times throughout the whole rapid intensification periods studied.
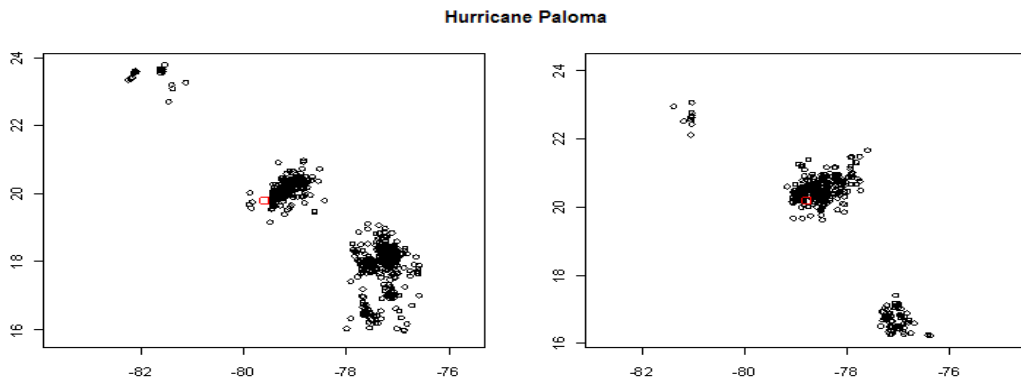
Figure 5: Plots of lightning location for Hurricane Paloma at before maximum sustained winds (left), during maximum sustained winds (right). The red circle indicates the location of the eye at those intervals.

b. *Total Count of Lightning*

Total lightning count for each interval in the whole trajectory of the storm shows an apparent discrepancy in the results. Hurricane Humberto (*figure 7*) is the only TC showing a clear peak in total storm lightning activity less than 24 hours before the maximum sustained winds. The total and average amount of lightning activity is considerably higher than other storms.
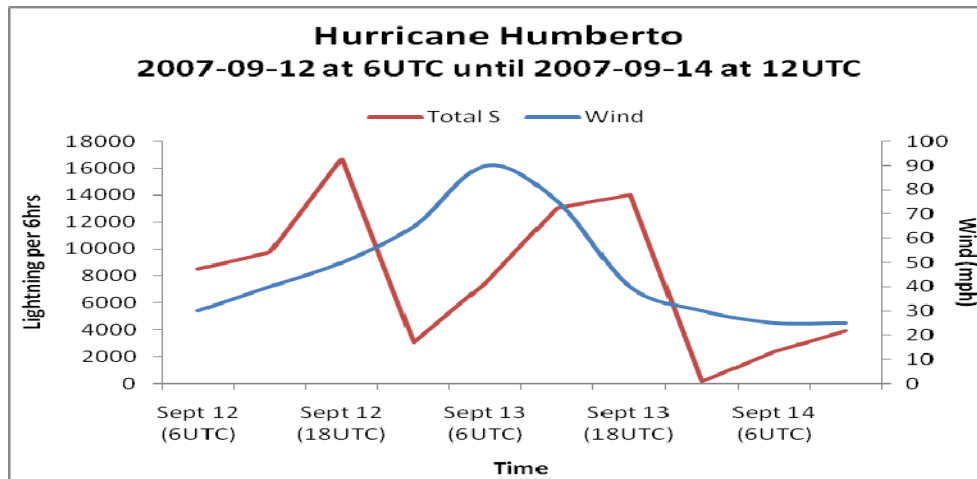

Figure 7: Total lightning count for Hurricane Humberto compared to the sustained winds

The other five TCs don't show a clear peak in total lightning well before the maximum sustained winds. *Figure 8* is an example, using Hurricane Gustav, showing that some storms have the total lightning activity peak at the same time as the maximum sustained winds. Other plots are noisier, as seen in *figure 9,* and a clear prediction of which lightning peak will be the one preceding the intensification is not well seen. We also plan to investigate whether the lightning counts from the LLDN for the TC's traversing the Southern Caribbean may be under sampled, due to range-dependent issues there.
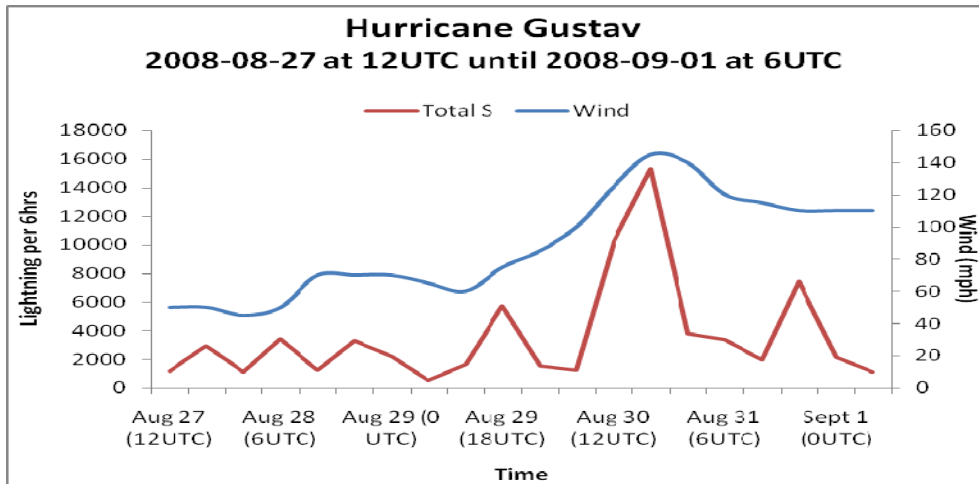
Figure 8: Total lightning count for Hurricane Gustav compared to the sustained winds
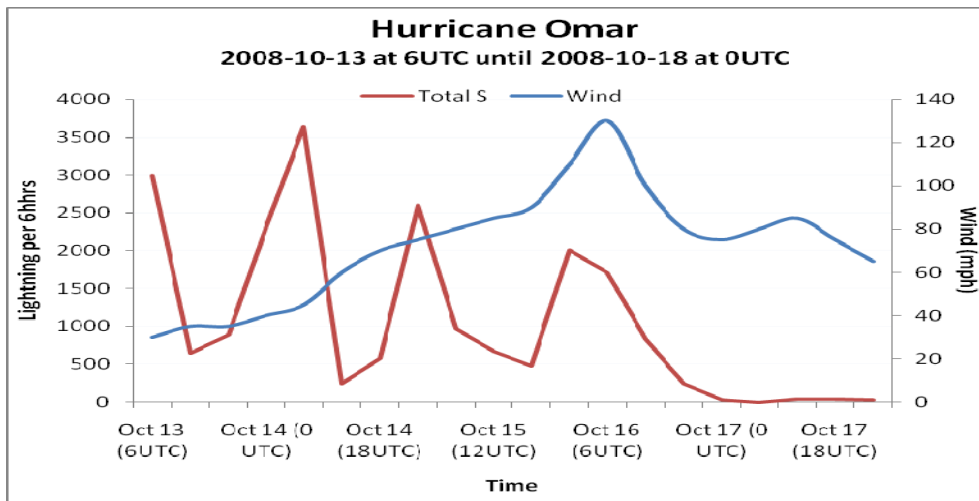

Figure 9: Total lightning count for Hurricane Omar compared to the sustained winds

    c.   *Outer Rainbands-to-Eyewall Ratio*

Since the lightning frequency plots were noisy and the lightning location plots were showing changes in the lightning activity of the outer rainbands compared to the eyewall, we decided to calculate the outer rainband-to-eyewall ratio. There is a consistent peak in this lightning activity ratio before the maximum sustained winds (*figures 10-12*). *Figure 10* shows a little noise in the beginning due to problems with the first rapid intensification of the hurricane creating difficulty with lightning data. The only outlier in these plots was in Hurricane Paloma (*figure 12*) which has various lightning peaks before the intensification of the storm, perhaps related to its interaction with the island of Cuba.
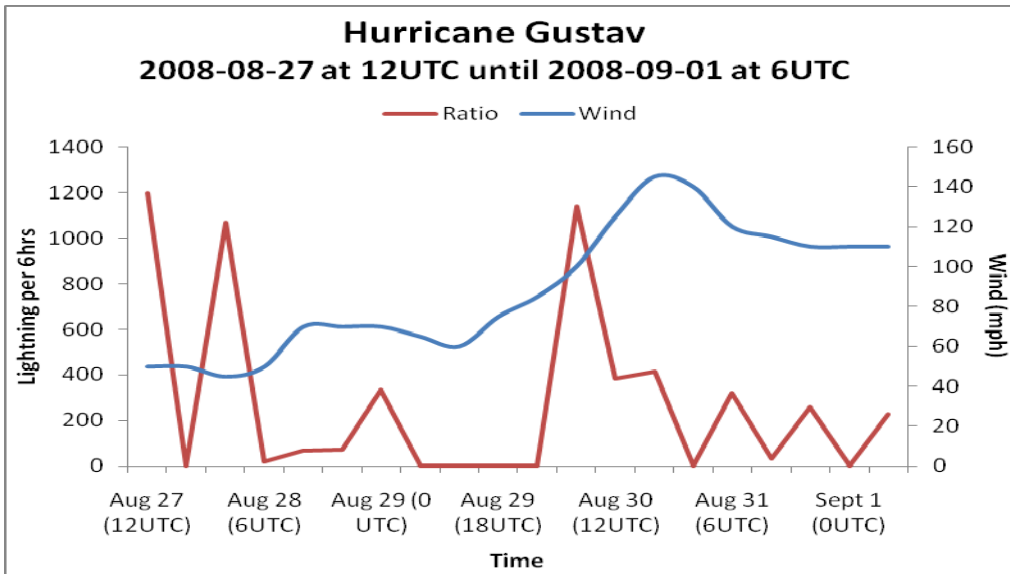
Figure 10: Outer Rainbands-to-eyewall lightning activity ratio for Hurricane Gustav compared to sustained winds.
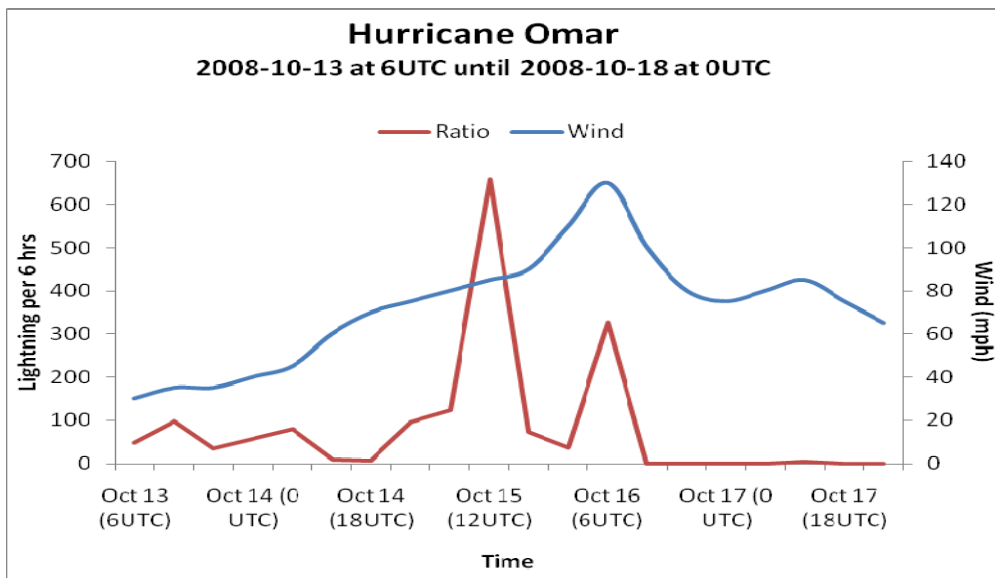

Figure 11: Outer Rainbands-to-eyewall lightning activity ratio for Hurricane Omar compared to the maximum sustained winds.
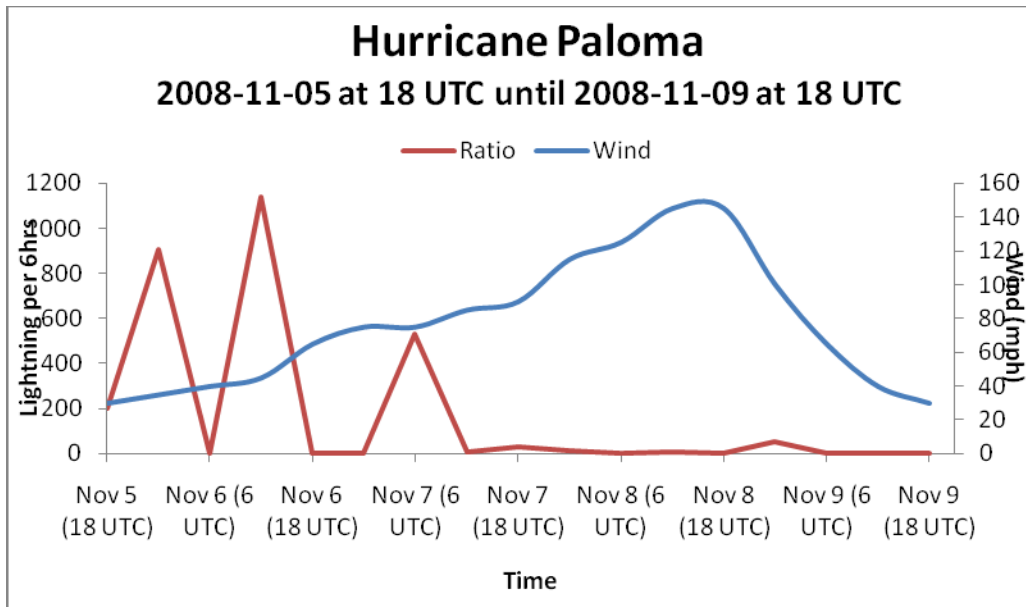
Figure 12: Outer Rainbands-to-eyewall lightning activity ratio for Hurricane Paloma compared to sustained winds.

3. Conclusion

Lightning activity in hurricanes could be an indication of important and poorly-measured microphysical process interacting with the tropical cyclone. Despite other research, total counts of lightning in almost all of our cases didn't present a clear peak before the maximum sustained winds. Hurricane Humberto was the only TC with considerable high lightning activity and a clear peak before the maximum sustained winds. This storm was the only TC intensifying close to the continental USA, and its interaction with land could have caused the changes.

Pollutants from the continent could have been one important factor for this increase in lightning activity inside Hurricane Humberto. It has been observed in recent studies, that over land more than the ocean, pollutants could create stronger thunderstorms by delaying rain and increasing the cloud to higher altitudes. A study about the interaction of pollutant aerosols with TCs approaching continental USA should be pursued to have a better understanding of the possible reaction with the lightning activity inside these phenomena.

Lightning plots indicate increased activity in the eyewall during maximum sustained winds, and in the right outer rainband relative to the storm's motion. Some storms showed some activity in the eyewall before the maximum sustained winds. An hourly assessment of the eyewall lightning is needed during those time of increase in eyewall's lightning activity. The peak in lightning in the eyewall could be an indication of eyewall replacement, but not a good predictor of intensification, since it's occurring at the same time of the strengthening of the storm.

Our research suggests a clear peak approximately 24 hours before the maximum sustained winds. Hurricane Paloma had a rather different and noisier ratio than the other storms, and this could be explained by the lightning location plots for this storm. Hurricane Paloma made landfall close to the mountains in Cuba, and this interaction created an unusually low count

in the outer rainband and normal counts on the eyewall. This difference could be a suggestion that an interaction between eyewall and outer rainband is occurring before the maximum sustained winds.

A physical explanation of why the ratio is peaking before the maximum sustained winds needs to be studied in detail. The interactions with land are giving us an idea that microphysical processes could be a key part on a development of tropical cyclones. Future studies should take in consideration the effects on the hurricane intensity of constraints such as: microphysical processes; interaction with the surrounding storm environment (including Saharan dust outbreaks); and the effects of pollutant and natural aerosols.

4. References

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