2010
21st International Lightning Detection Conference
19 - 20 April • Orlando, Florida, USA
3rd International Lightning Meteorology Conference
21 - 22 April • Orlando, Florida, USA

Assessing Relations Between Changes in Tropical Cyclone Intensity and Lightning Patterns Using GIS Based Methods

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1. Background

Forecasting the path and intensity of tropical cyclones (TCs) continues to perplex scientists and forecasters alike. Although track forecasts have improved considerably in recent decades, there has been little improvement in intensity forecasts. Previous research has suggested that lightning activity is related to storm intensity. Some studies have indicated that lightning bursts in a TC's inner core may be a precursor to storm intensification (e.g., Lyons and Keen 1994) while others found that lightning is more common during or after rapid intensification (Molinari et al. 1994, 1999; Squires and Businger 2007). Still others have shown that lightning bursts can occur before, during, and after intensity change (Samsury et al. 1994). Most previous efforts have focused on a relatively small number of storms in near-coastal areas using data from the National Lightning Detection Network (NLDN).

Vaisala's recently developed Long Range Lightning Detection Network (LLDN) now allows us to examine lightning in storms that are well offshore. Our use of LLDN is important since Khain et al. (2009) hypothesized that increased lightning in tropical cyclones may be related to aerosol intrusion from nearby landmasses. Our TC sample includes twenty-one tropical storms and hurricanes that encompass a variety of intensities. Tools such as the Earth Systems Research Institute's ArcGIS software allow us to visually observe and analyze lightning data in non-conventional ways. This paper discusses our methods as well as preliminary findings regarding inner core lightning in tropical cyclones and its potential role in storm intensity.

2. Methods

Storm sample

LLDN data were gathered for each storm in our sample. The LLDN consists of sensors from the NLDN, the Canadian Lightning Detection Network (CLDN) and long-range sensors in the North Pacific and Caribbean (Demetriades and Holle 2008). We limited our study to the years 2004 and after due to an NLDN system upgrade during the 2002 and 2003 hurricane seasons. Demetriades and Holle (2008) used LLDN data during 2004 through 2007 in some of their research. Twenty-one Atlantic Basin storms were chosen from 2004 through 2008, including tropical storms as well as weak and intense hurricanes. We emphasized storms that impacted North America and/or spent much of their time over the western Atlantic Ocean and Caribbean Sea where LLDN detection efficiencies are relatively large.

Lightning density and time series plots

Flash density plots were developed to visualize lightning trends along a storm's path. Three hour storm locations were linearly interpolated from NHC best track 6 h positions. LLDN stroke data were gathered for each 3 h position. Strokes were converted to flashes and limited to within 100 km of each 3 h storm position. This radial threshold is consistent with previous research that concentrated on lightning activity in the inner core region (Demetriades and Holle 2008).

The resulting flash data and storm location information were plotted in ArcGIS. Once the lightning data were populated into GIS, each flash was joined to a 6 h position, yielding a flash count at each 6 h position for each storm's duration. Because flashes were deduced from 3 h positions, 6 h flash counts include flashes from 3 h leading up to the position time to 3 h after the time of the storm position. For example, a storm position at 0600 UTC would include flash data from 0300 to 0900 UTC. This provides the most accurate assessment of flashes at a given time.

The GIS software includes a spatial analyst toolset to conduct simple spatial operations. One of these is a kernel density algorithm that we used to calculate the 0-100 km along-track flash density for each storm in the sample. Density contours were plotted on an equal area projection to preserve the relative sizes of density areas. Observing both storm intensity and its surrounding flash density can provide clues on the convective pattern of the storm at a given time.

The next step was to obtain flash count information for each storm and place it into a database. Each storm position included data for latitude, longitude, date and time, pressure, wind speed, and inner core flash count. Data positions were limited to areas where the LLDN night time detection efficiency (DE) was ~ 50% or greater (see Fig. 1). This domain corresponds to the area west of 70°W longitude and north of 15°N latitude. All positions north of 40°N were removed because lightning activity associated with storms at these latitudes was rare, and storms often became extra-tropical. We did not apply corrections to the lightning data to account for varying detection efficiencies.

Land effects were considered by deleting all 6 h periods when the storm was over land. Previous studies have shown that as tropical cyclones interact with land, lightning activity often increases, particularly in the outer rainband region (Cecil et al., 2001, Khain et al. 2009). However, we also have noted increases within the inner core region. We did not remove observations when the eye was near, but not over land. Thus, some land influence will be observed in our later results; however, these will be noted as they occur.

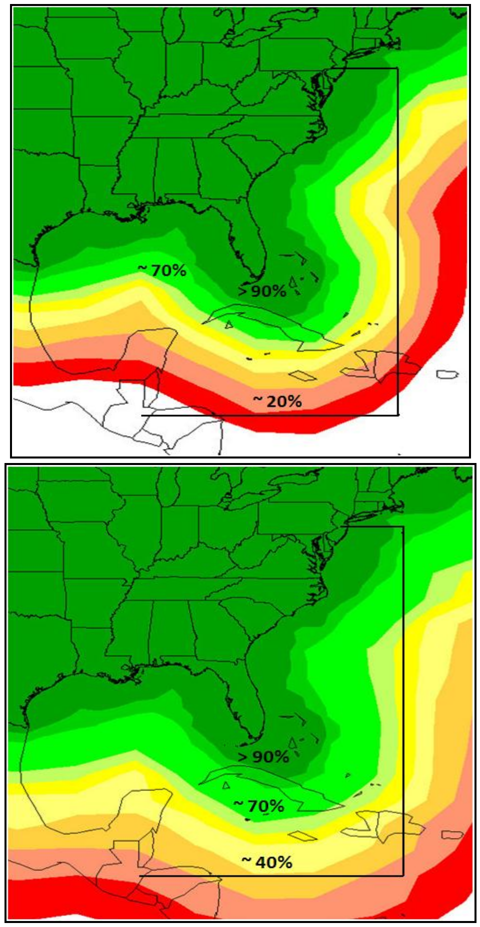


Figure 1. Top: LLDN DE during the day (dark green ~ 90%, red ~ 10%). Bottom: LLDN DE during the night (dark green ~ 90%, red ~ 10%). After Demetriades and Holle (2008). The study domain is delineated by black lines.

Time series plots of lightning and minimum central pressure were produced for each storm to view relationships between these variables. We also examined correlations between lightning and various parameters such as storm type, pressure change, and wind speed. A summary of average flash rates per storm type also was created.

3. Results

Several case studies are presented first to show the variability in our sample. These cases focus on a range of storm categories and display differing lightning trends and patterns. The

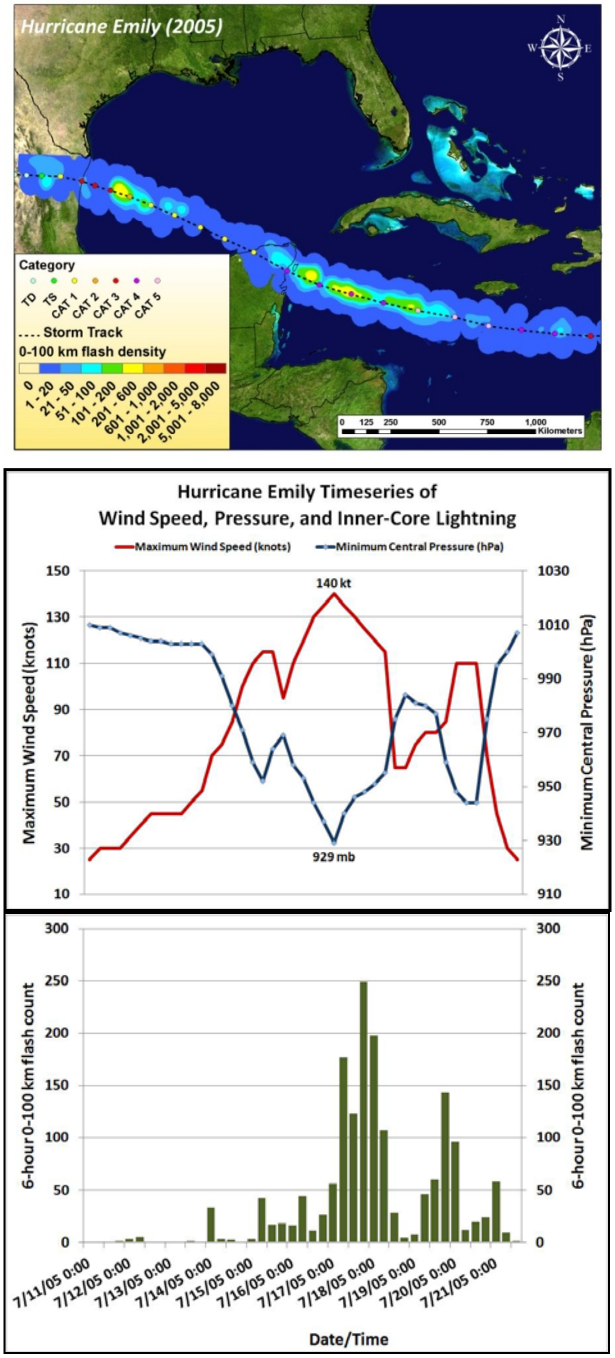


Figure 2. Top: LLDN inner core lightning density (flashes km^{-2}) for hurricane Emily (2005) displaying 6 h positions, intensity, and flash density. Middle: Time series of pressure (hPa) and peak wind speed (kt) at 6 h intervals Bottom: 6 h LLDN flash count between 0-100 km of the storm center.

analyses assess lightning during periods of rapid intensification, peak intensity, and weakening. This approach is similar to that of Squires and Businger (2007) who examined category 5 hurricanes Katrina and Rita during the 2005 Atlantic hurricane season.

Hurricane Emily (2005)

Emily was an intense category 5 hurricane with winds as strong as 140 kt (160 mph). It is the earliest category five storm on record for a given season, (Franklin and Brown 2006). One caveat to studying this storm is the relatively small DE over the region where it tracked (Fig. 1), with values ranging from 20 to 30% prior to landfall on the Yucatan. DE does improve as the storm moves closer to the North American coastline. The time series plots (Fig. 2) show that lightning tends to increase as pressure decreases. Through the first period of intensification, a lightning burst occurs after peak intensity (929 hPa) with a slowly increasing flash rate during intensification. As the storm deepens, inner core convection likely increases, as does flash activity. Black and Hallet (1998) found a strong relation between TC intensity and the deep convection that supports lightning. Lightning activity decreases as the storm crosses the Yucatan on 18 July beginning at 0600 UTC. Once the storm emerges into the southern Gulf of Mexico, it re-strengthens with a secondary flash peak as the pressure falls. However, this time the lightning burst precedes peak intensity. Lyons and Keen (1994) saw a similar pattern, with lightning preceding periods of robust intensification. Flash counts generally are smaller than for other hurricanes with similar characteristics, possibly due to DE between 30% and 40% early in its life. Nonetheless, the large fluctuations in Emily's lightning suggest DE is not solely responsible.

Hurricane Wilma (2005)

Wilma is the strongest Atlantic hurricane on record, with a minimum central pressure of 882 hPa and maximum sustained winds of 160 kt (180 mph). Wilma initially was located in an area of small DE (Fig. 1). Some of the largest flash counts occur when Wilma was a tropical storm strengthening to a hurricane (Fig. 3). There were slow pressure falls and erratic movement during this period. Flash density naturally is greater for slow moving systems since convective elements remain over a location for longer periods.

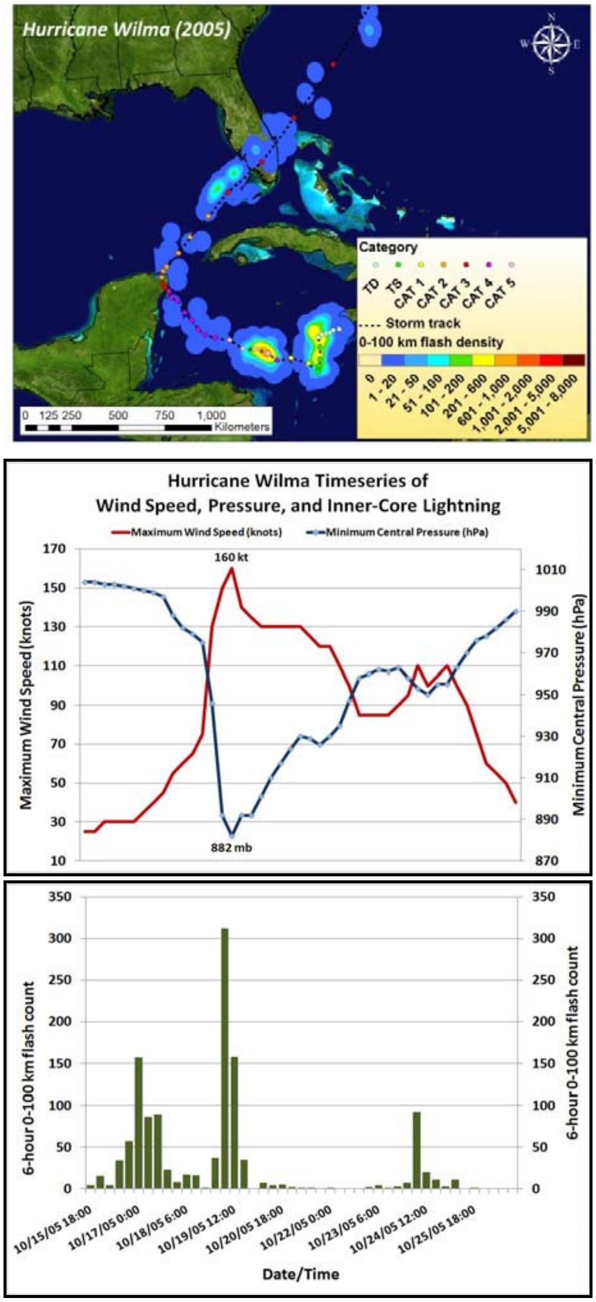


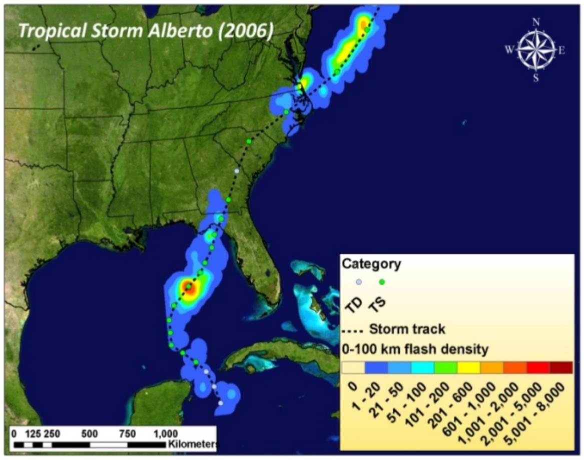
Figure 3. Top: Plot of LLDN inner core lightning density for hurricane Wilma (2005) displaying 6 h positions, intensity, and flash density (flashes km^{-2}). Middle: Time series of pressure (hPa) and peak wind speed (kt) in 6-h intervals Bottom: 6 h LLDN flash count between 0-100 km of the storm center. LLDN flash count within 100 km of the storm center.

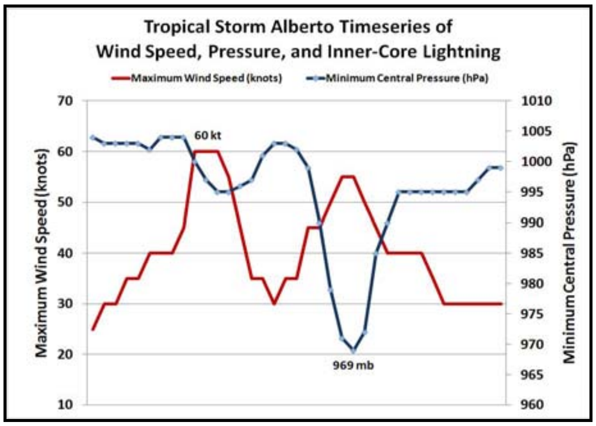
As the storm begins a period of rapid intensification, with pressure plunging 97 hPa in just 12 h, there first is a lull in lightning activity. Wilma's main lightning burst occurs just prior to peak intensity of 882 hPa. This relates well to the findings of Squires and Businger (2007) who suggested that lightning bursts often occur during rapid intensification. Even though the storm remains in the category 4 to 5 range, inner core lightning decreases quickly after 12 h of strengthening.

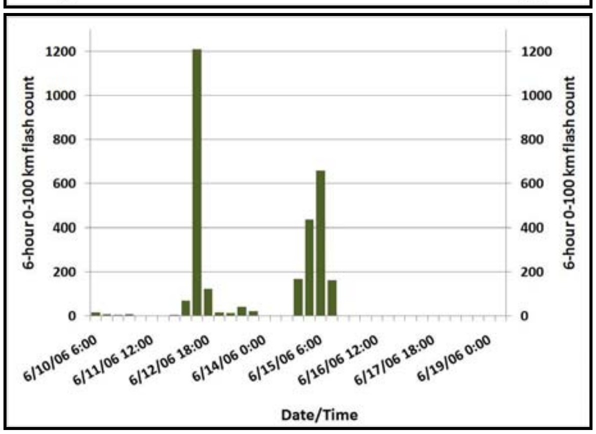
As Wilma approaches the South Florida coast, lightning increases as the storm undergoes a brief period of intensification. Fig. 3 shows that the majority of these flashes remain on the northwest side of the circulation. The mechanisms leading to asymmetric flash-density patterns are not well understood, but may be due to trough interaction (Hanley et al. 2001, Hanley 2002) and/or vertical wind shear (Corbosiero and Molinari 2002, 2003, Molinari et al. 2004). We will not address those possibilities here, but will report them in the future. Wilma displayed its greatest lightning activity both during and after periods of RI.

Tropical Storm Alberto (2006)

Alberto is the only one of our 21 TCs that remained a tropical storm during its entire lifetime. Nonetheless, one should note the large flash counts in the time series (Fig. 4). The previous two cases exhibited peak flash activity in the hundreds; however, Alberto exhibits flash counts well into the thousands. Previous research has shown that tropical storms produce more lightning than depressions or hurricanes, both strong and weak (Cecil and Zipser 1998, Demetriades and Holle 2008). Alberto also displays large fluctuations in peak flash activity. The first peak occurs as the storm strengthens from a 45 kt to a 60 kt tropical storm. This only corresponds to a maximum pressure drop of 4 hPa over 6 h, nowhere near the rapid intensification threshold of 42 hPa in 24 h. The density plot indicates that interaction with land was not a factor in this anomaly since the storm was over the open Gulf of Mexico at the time.







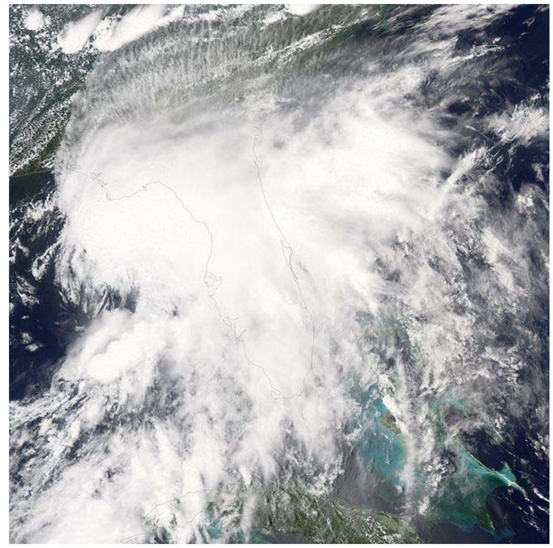


Figure 4. Top: Plot of LLDN inner core lightning density for tropical storm Alberto (2006) displaying 6 h positions, intensity, and flash density (flashes km^{-2}). Middle two: Time series of pressure (hPa), peak wind speed (kt) at 6 h intervals, and 6 h LLDN flash count within 100 km of the storm center. Bottom: Visible satellite image at 1833 UTC 13 June 2006.

Tropical storms often contain disorganized areas of showers and thunderstorms. In the case of Alberto, a large area of convection on the storm's northeast side (Fig. 4) leads to an increase in flash activity. The lightning burst is correlated with a small drop in pressure. Despite continued pressure falls during the following 12 h, flash counts diminish rapidly to below 200 flashes km-^{2}. As the storm makes landfall over the Florida Big Bend, very few flashes occur. The next peak in flash activity is associated with the absorption of the storm into a trough off the U.S. East Coast. This corresponds with a transition to an extra-tropical storm on 14 June (Avila and Brown, 2006). It is no surprise that lightning activity increases as frontal convection develops within the system. The largest increase in flash count occurs during a period of small pressure change. Cecil and Zipser (1998) found a similar relationship when analyzing a large sample of tropical cyclones. They concluded that storms undergoing small intensity changes are associated with the largest increase in inner core flashes.

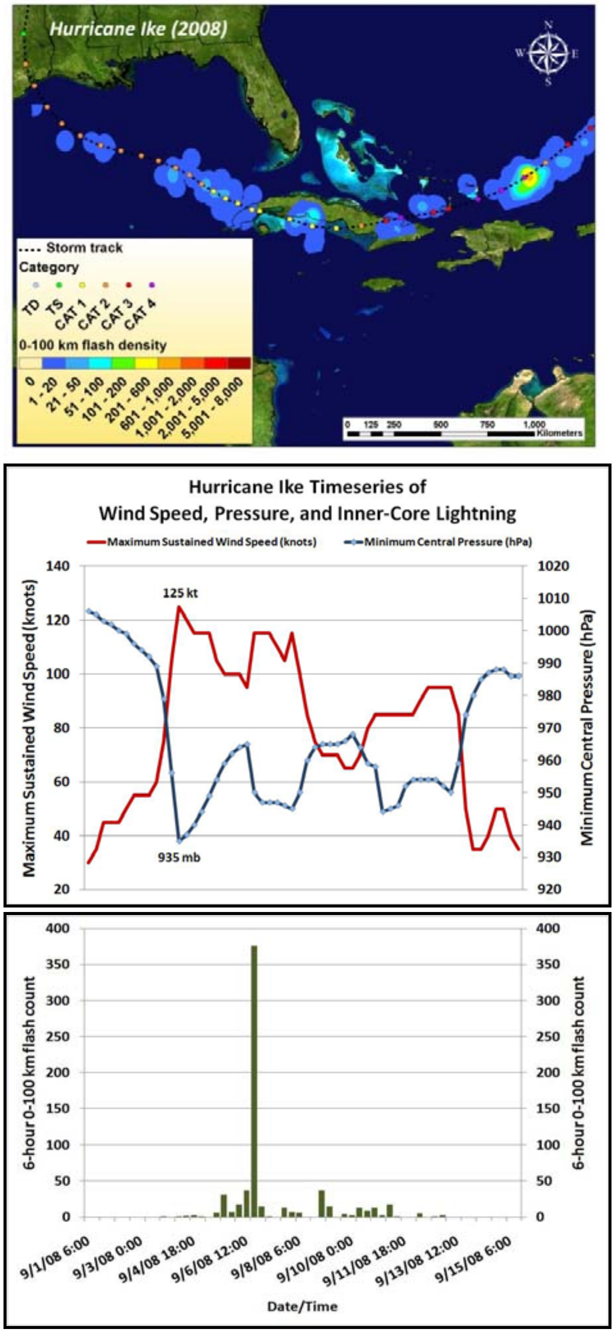


Figure 5. Top: Plot of LLDN inner core lightning density for hurricane Ike (2008) displaying 6 h positions, intensity, and flash density (flashes km^{-2}). Middle: Time series of pressure (hPa) and peak wind speed (kt) at 6 h intervals Bottom: 6 h LLDN flash count within 100 km of the storm center.

Hurricane Ike (2008)

Ike is the largest TC in our sample. Despite its size, Ike initially displays marginally small flash rates, partly due to the poor DE in its region of origination. The time series of pressure and wind speed (Fig. 5) shows a period of rapid intensification early in Ike's life, with pressure falling from 989 hPa at 1200 UTC 3 September to 935 hPa just 12 h later as a category 4 hurricane. With such rapid deepening, an enhanced lightning flash count might be expected; however, flash rates are abnormally small. Although this partly can be attributed to missed flashes due to small DEs in the area, one might expect at least a small increase in lightning. Ike produces few inner core flashes at the time of peak intensity.

As Ike continues westward, it weakens to category 2 intensity in response to northeasterly wind shear (Berg 2009). This period is characterized by flash counts and pressure that increase simultaneously. The maximum count of 376 flashes in a 6 h period occurs just after a maximum in pressure on 6 September; The pressure then quickly decreases. In this case, the greatest flash rate occurs just after the pressure begins to fall. Molinari et al. (1999) found that lightning bursts may occur at the beginning of rapid intensification or at the onset of an eyewall replacement cycle. In fact, according to Berg's (2009) report on Ike, reconnaissance data support an eyewall replacement cycle at this time. Two minor peaks in lightning activity are evident in association with land interactions, but flash rates still remain relatively small as the storm impacts Cuba. By the time Ike emerges into the eastern Gulf of Mexico, the storm is large and disorganized. The wind field then expands, making it difficult for the storm to tighten its circulation and significantly re-intensify (Berg 2009). A small maximum in flash density occurs immediately after Ike's interaction with Cuba, associated with a slow strengthening to category two status. The storm's large and disorganized nature keeps inner core convection at a minimum; thus, flash counts remain small through landfall on the Texas coast.

Composite Studies

Although case studies are a good way to analyze lightning patterns on a storm by storm basis, they do not provide generalized information about lightning in TCs. Therefore, we next present composite results from our complete dataset of 21 storms that includes both the aforementioned tropical storm and hurricanes.

We tabulated average flash rates for each intensity category (Table 1). The categories were tropical depressions (TD), tropical storms (TS), category 1 and 2 hurricanes (CAT 1 & 2), and category 3 and higher hurricanes (CAT 3+). This categorization was performed every 6 h for each storm. A summary of the results is given in Table 1.

Table 1. Summary of average flash rates and standard deviations of flash rates for each type of tropical cyclone, including the total number of 6 h samples for each category.

Storm Type	Avg Flash Rate	Std Dev	Comparison	Sample Size
TD	*126.48*	*368.13*	*~ 3 x mean*	*52*
TS	*235.98*	*477.49*	*~ 2 x mean*	*148*
CAT 1 & 2	*86.86*	*215.06*	*~ 2.5 x mean*	*119*
CAT 3+	*63.34*	*98.18*	*~ 1.5 mean*	*93*

Results show that tropical storms generally produce the most lightning. This finding is consistent with previous research (Demetriades and Holle 2008, Cecil and Zipser 1998). The TD and TS categories exhibit the greatest standard deviations of flashes, meaning that there is large variability among the observed flash counts. TD and TS systems usually are poorly organized, characterized by discrete convective elements, some of which may be outside the 0-100 km range at certain times, and inside this range at others. Weak hurricanes (Categories 1 and 2) display the next greatest average flash rates, less than half that of tropical storms. Finally, the strongest hurricanes produce the smallest inner core flash rates. Inner core lightning within major hurricanes is concentrated in the eyewall region where deep convection forms.

One should note the small standard deviations in flash activity for hurricanes. The value is only ~ 1.5 times the average flash rate, instead of ~ 3 times the flash rate for tropical depressions and ~ 2 times the flash rate for tropical storms. Since strong hurricanes usually are well organized, this may cause lightning flash rates to remain relatively constant, except during lightning bursts.

In addition to average flash rates, we were interested in how well lightning activity is related to other storm parameters. We calculated correlations between lightning and variables relating to hurricane intensity. In addition to considering lightning that is concurrent with the storm intensity data (time of the position ± 3 h), flashes preceding and lagging the intensity data also were examined. Preceding flashes occur 6 h before the TC's position time, while lagging flashes occur 6 h after the position.

Fig. 6 contains results when the flash information is centered on the period of pressure change. Each storm position is treated separately regardless of its peak lifetime intensity. That is, while a tropical storm, the data are placed in that intensity category (TS). Hurricanes were split into two categories--categories 1 and 2, and categories 3 and greater.

We first consider lightning versus pressure change for all data periods and all storms. Fig. 6 shows flashes concurrent with 6 h pressure change. A weak correlation ($r^2 = 0.19$) with a negative sloping trendline suggests that lightning activity usually increases as pressure falls. Fig. 7 displays flashes that precede the 6 h pressure change. In this case, there is virtually no correlation ($r^2 = 3\times10^{-5}$) between lightning and pressure change with a nearly horizontal trendline. With a correlation so close to zero, it seems that lightning activity is a poor indicator of subsequent intensification. Fig. 8 shows lightning that lags the 6 h pressure change. Lagging lightning exhibits better results than preceding lightning, with $r^2 = 0.013$. The negatively sloping trendline reiterates that pressure falls generally are associated with enhanced lightning.

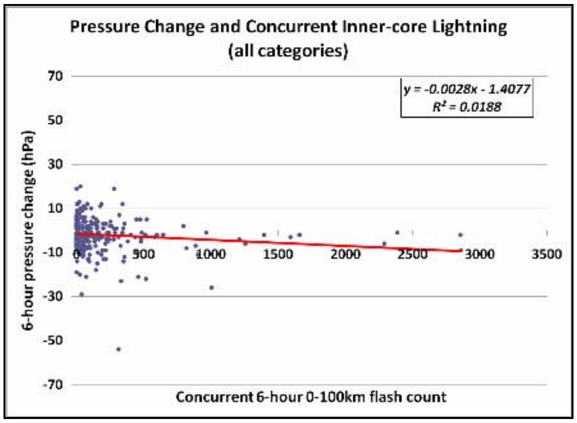


Figure 6. Scatter plot of 6 h pressure change and concurrent inner core lightning with trendline and coefficient of determination (r^2)

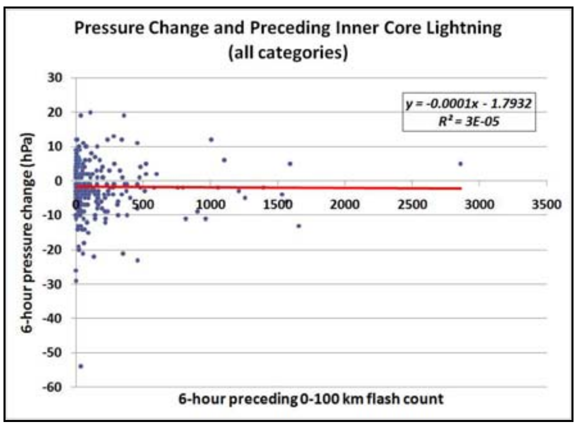


Figure 7. Scatter plot of 6 h pressure change and preceding inner core lightning with trendline and coefficient of determination (r^2)

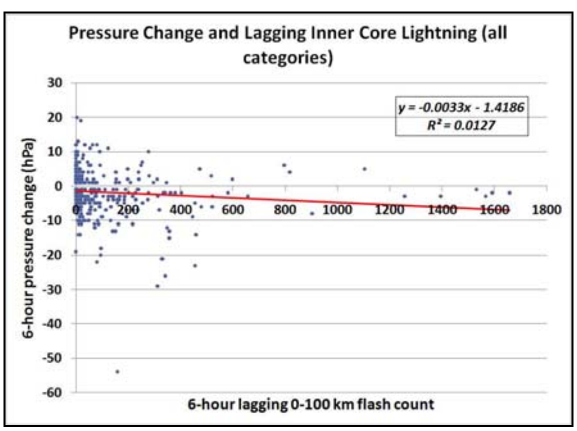


Figure 8. Scatter plot of 6 h pressure change and lagging inner core lightning with trendline and coefficient of determination (r^2)

In all three cases the correlations are insignificant. Concurrent lightning displays the greatest relation to pressure fluctuation, but with a correlation of only r = 0.13. Such small values indicate that strong relationships between pressure falls and lightning are doubtful.

The results for only the TD and TS periods (Fig. 9) generally are the same as those for all categories combined. Correlations are slightly better (r^2 = 0.036), and the more negatively sloped trendline again suggests that greater flash rates are concurrent with larger pressure falls. Although r^2 is greater than before, it remains very small

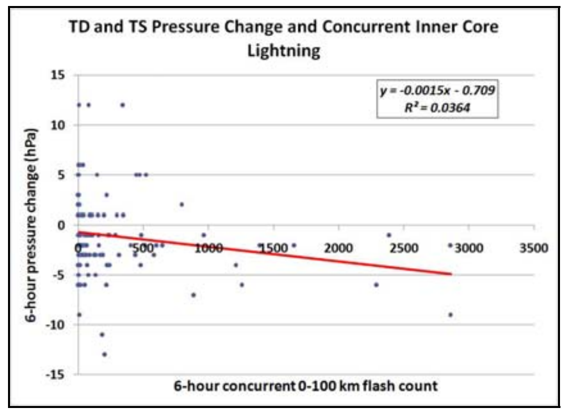


Figure 9. Scatter plot of 6 h pressure change and concurrent inner core lightning for tropical storms and tropical depressions with the trendline and coefficient of determination (r^2)

Scatter plots for preceding and lagging flashes with respect to 6 h pressure change for the TD/TS category (not shown) reveal even smaller correlations than the concurrent case (Fig. 9).

We examined weak and strong hurricanes separate from the overall sample to see if there was a stronger signal between lightning and pressure change. Figs. 10 and 11 show 6 h pressure change and concurrent inner core lightning for weak (category 1 and 2) and strong (category 3+) hurricanes, respectively. Weak hurricanes display stronger correlations (r^2 = 0.08) and a more negatively sloped trendline than strong hurricanes (r^2 = 0.02). However, in both cases, the correlations are much too small to be considered useful in relating pressure change to lightning.

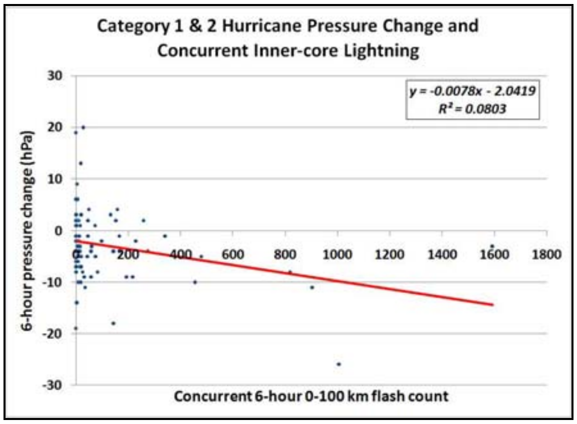


Figure 10. Scatter plot of 6 h pressure change and concurrent inner core lightning for category 1 and 2 hurricanes with the trendline and coefficient of determination (r^2)

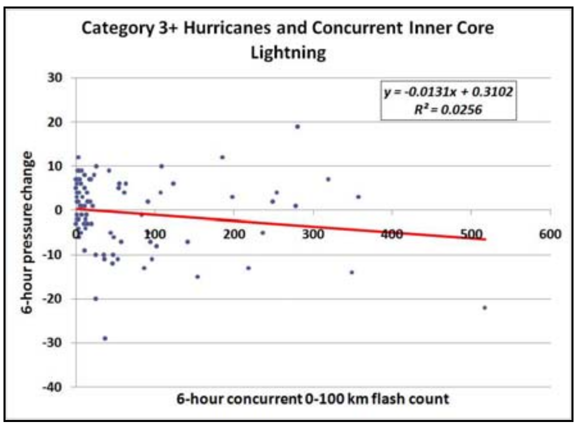


Figure 11. Scatter plot of 6 h pressure change and concurrent inner core lightning for category 3+ hurricanes with the trendline and coefficient of determination (r^2).

Weak hurricanes display the greatest correlation between pressure and lightning (r^2 = 0.08), followed by tropical storms and depressions, and intense hurricanes. Each category exhibits a negatively sloped trendline suggesting that pressure falls, not rises, are associated with greater flash rates. Analysis of each separate category produces results that are similar to those of the sample as a whole with continued weak correlations between pressure change and inner core lightning flash rates.

Periods of rapid intensification, hereafter RI, also were considered separately to determine if there is a relationship between RI and concurrent, preceding, or lagging inner core lightning. RI is defined by the National Weather Service as a pressure drop of 42 hPa or more in 24 h or less. This is equivalent to approximately 10 hPa during a 6 h period.

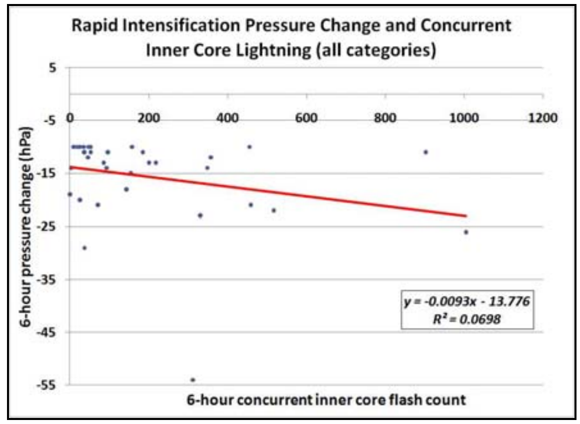


Figure 12. Scatter plot of 6 h pressure change during periods of RI versus concurrent inner core lightning with the trend line and coefficient of determination (r^2).

Fig. 12 shows a small correlation (r^2 = 0.07) between concurrent lightning and 6 h periods of RI with a negatively-sloped trendline. This suggests that as a storm deepens, the inner core convection becomes more vigorous. This may enhance lightning production through charge separation processes associated with stronger vertical motion. Black and Hallet (1994) found that hurricanes experiencing RI exhibit relatively strong vertical motions that influence the storms' microphysical properties and produce enhanced lightning. Cecil et al. (2002a) also suggested that the presence of lightning in tropical cyclones indicates "vigorous" convection. Our results show a weak negative correlation between RI and lightning. Correlations are slightly larger for the lagged case (r^2 = 0.10) and much smaller for the preceding case (r^2 = 0.006), but once again neither shows a significant relation between RI and inner core lightning activity. These values again demonstrate that preceding lightning is a very poor predictor of future intensification.

Table 2. Summary of r^2 for each storm category and preceding, lagging, and concurrent 6 h periods.

Period	All	TD-TS	Hurr 1-2	Hurr 3+	RI
Preceding	~0.00	~0.00	0.02	~0.00	0.01
Lagging	0.01	0.01	0.01	0.15	0.1
Concurrent	0.02	0.04	0.08	0.03	0.07

Table 2 is a summary of r^2 values for each storm category and time period in our dataset. Overall, correlations are very small, with the strongest relationships between pressure change and lagging 6 h inner core lightning. Concurrent flashes show the second highest r^2 values, with preceding lightning exhibiting a near 0 correlation in all categories. These results suggest that lightning is a poor predictor of future intensity, and that in fact, inner core lightning more often may be a product of intensification rather than a predictor of it.

Lagging correlations are greatest for the strong hurricane (cat 3+) and RI categories. The majority of inner core lightning in well-developed hurricanes is confined to the eyewall region. Previous research has described the convective structure of a hurricane as two maxima in flash activity, in the inner core and outer rainband regions, separated by an area of weak electrical activity in the inner rainband (e.g., Molinari et al. 1998, Cecil et al. 2002a, b). Our correlations may be greater for strong hurricanes and periods of RI because many RI periods occur when hurricanes are most intense which induces more convection in the inner core.

Correlations between concurrent lightning and 6 h pressure change are greatest for the weak (category 1 and 2) hurricanes and RI periods. Similar to the previous case, hurricanes generally are more organized and have a more convective inner core region which promotes lightning. RI associated with hurricanes often is associated with convective bursts in the inner core region that can increase lightning activity.

In summary, our results show that relationships between preceding inner core lightning and intensification are essentially non-existent. Although there are very small correlations for weak hurricanes and RI periods, they are much smaller than those of the concurrent and lagging cases.

4. Conclusions

Inner core lightning processes in tropical cyclones still are poorly understood. Previous research has not found conclusive relationships between lightning and storm intensity. Instead of a case study approach, we used a sample of 21 storms along with data from the LLDN network in an attempt to make more general conclusions about the role of lightning in TCs.

Individual case studies showed how lightning varies along a TC's path. Plots of lightning density provided a visual representation of the placement of lightning bursts with respect to storm position and intensity. Using the lightning density plots and time series of wind speed, pressure, and inner core flash counts, simple comparisons were made between these parameters.

A summary of flash rates showed that tropical storms and tropical depressions typically produce more lightning than hurricanes. Hurricanes displayed smaller average flash rates and smaller standard deviations. These results are consistent with previous research.

Results showed that pressure change was only very weakly negatively correlated with concurrent, preceding, and lagging inner core flash count, suggesting that lightning increases as a storm's pressure decreases for all categories of storm intensity. This relation was somewhat more pronounced when hurricanes were considered.

Rapid intensification periods exhibited slightly better correlations with lagging lightning than preceding or concurrent lightning, suggesting that large pressure falls support increased flash rates. Preceding flashes mostly were uncorrelated with decreasing pressure.

Lagging flashes generally were better correlated with pressure change than concurrent or preceding lightning. Table 2 indicated almost no correlation between preceding inner core lightning and pressure change, and only very weak relations between concurrent and lagging flashes and pressure.These very slight correlations strongly suggest that inner core lightning is not a reliable indicator of future storm intensity.

Future research will focus on correcting flash counts in regions of small DE. This will allow more storms to be included in our sample, including those in the Eastern and Central Atlantic. The roles of wind shear and microphysics also will be assessed, incorporating model and satellite observations into the dataset. Observations may be updated to include 3 h flash counts in addition to 6 h counts. These efforts hopefully will improve our understanding of both the structure and temporal evolution of lightning in tropical cyclones.

Acknowledgements

This research was sponsored by NASA grant NNX09AC43G.

We thank the Vaisala Thunderstorm Group for supplying lightning data (LLDN) and helpful comments during this research.

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