Polarity and energetics of inner core lightning in three intense North Atlantic hurricanes

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Abstract:

We use the World Wide Lightning Location Network (WWLLN), low frequency magnetic fields measured at Duke University, and storm intensity data (winds and central pressure) to examine the polarity and energetics of lightning within 100 km of the centers (inner core regions) of North Atlantic Hurricanes Emily, Katrina, and Rita (2005). WWLLN provides the lightning locations. Polarities, peak currents, and impulse vertical charge moment changes are derived from the Duke magnetic field measurements. In agreement with past studies, we find episodic inner core lightning outbreaks prior to and during most changes in storm intensity. A new result of our analysis indicates an increase in the relative number of positive cloud-to-ground lightning in the inner core prior to and during periods of storm weakening, which is potentially important for hurricane intensity change forecasting. Additionally, we find that the majority of inner core lightning located by WWLLN had peak currents that surpassed the threshold needed to produce optical emissions (elves) and drive electron density perturbations in the lower ionosphere (80-105 km). Since these high peak current lightning occurred in short duration outbreaks, they had an accumulated effect on the ionospheric electron density, as shown by recent modeling studies. Our results suggest that the inner core lightning in intense hurricanes might be significant drivers of perturbations in the lower ionosphere during these inner core lightning outbreaks.

1. Introduction

The intrinsically episodic cloud-to-ground lightning activity in the inner core, which comprises the eyewall and inner rainbands [Willoughby, 1988], has been associated with intensity changes in tropical cyclones in numerous studies. Lyons and Keen [1994] conducted several case studies of the lightning activity associated with North Atlantic basin tropical storms and hurricanes that occurred during the 1983-84 and 1987-88 seasons. They found that lightning was common within the outer rainbands of storms, but generally infrequent within the inner core of mature tropical cyclones. Two exceptions were Hurricanes Diana (1984) and Florence (1988). In these storms, near-eyewall cloud-to-ground (CG) lightning activity preceded periods of convection intensification. They also reported lightning associated with two large supercells that triggered closed circulation during an unnamed tropical storm in 1987. In a later study using the National Lightning Detection Network (NLDN), Samsury and Orville [1994] investigated lightning activity in Hurricanes Hugo and Jerry (1989) during an 18 hr period for each storm that included landfall. They found that Jerry had more than 20 times the number of CG lightning flashes compared with the more intense (stronger winds and lower minimum central pressure) Hugo. Most of this lightning activity was located in the rainband regions and occurring before landfall. These observations of Samsury and Orville suggested that more intense storms do not necessarily produce more lightning. The study found that about 80% of these lightning were negative CG lightning and had mean peak currents of 40-65 kA.

Molinari et al. [1994] examined CG lightning activity during Hurricane Andrew (1992) using NLDN data. They reported three distinct regimes concerning the spatial distribution of lightning activity. These three spatial regions are approximately radially distributed, with the following distinctions according to the frequency of lightning occurrence: a weak maximum in lightning activity in the eyewall, a region of minimum 40-100 km from the storm center, and a large, broader maximum in the outer rainbands 190 km from the center. As in the case studies of Hurricanes Diana (1984) and Florence (1988) [Lyons and Keen, 1994], the eyewall lightning for Andrew occurred prior to or during periods of storm intensification. These eyewall lightning were negative in polarity and occurred in a region of maximum radar reflectivity that was several kilometers inward from the highest eyewall cloud tops. Most of the positive lightning occurred in the stratiform regions, or moat between the eyewall and rainbands. Molinari et al. [1999] found similar lightning activity patterns during nine other North Atlantic basin hurricanes.

Using the satellite-borne Optical Transient Detector (OTD), Cecil and Zipser [1999] found no apparent relationship between lightning activity (cloud-to-ground and in cloud) and tropical cyclone intensity change. However, since OTD is in low-earth orbit, it observed each storm for only several minutes per day. Hence, this lack of correlation is possibly due to the satellite's very low sample rate. OTD did detect inner core lightning activity during periods of changing intensification for Hurricane Linda and Typhoon Paka, which were intense tropical cyclones in the Eastern and Western North Pacific during 1997 (see http://thunder.msfc.nasa.gov/bookshelf/docs/white_paper_driscoll.html).

Corbosiero and Molinari [2002] showed a strong correlation between the azimuthal distribution of lightning flashes and the direction of vertical wind shear using NLDN data for 35 North Atlantic basin tropical cyclones. In their analysis, the vertical wind shear was divided into 3 categories: 0–5, 5–10 and > 10 m/s. When the magnitude of the vertical shear exceeded 5 m/s, more than 90% of flashes occurred downshear in both the storm core and the outer band region (defined as the region located at 100 - 300 km from the storm center).

Cecil et al. [2002] used data from the Tropical Rainfall Measuring Mission (TRMM) satellite to investigate 45 hurricanes. They combined radar reflectivity parameters and lightning (cloud-to-ground and in cloud) data from the TRMM Lightning Imaging Sensor (LIS). Using greater ice scattering (lower 85- and 37-GHz brightness temperatures) and increased lightning frequency to indicate more intense convection, this study showed that hurricanes are dominated by stratiform rain and relatively weak convection.

There have been a number of more recent studies of lightning activity within intense tropical cyclones, which are generally in agreement with the previous studies of Lyons and Keen [1994] and Molinari et al. [1994, 1999] discussed above. Shao et al. [2005] reported inner core lightning outbursts correlated with intensity change in Hurricanes Katrina and Rita (2005) using ground-based sensors in the High Plains and Florida known as the Los Alamos Sferics Array (LASA). With data from the Vaisala Long-range Lightning Detection Network (LLDN), Demetriades and Holle [2006] and Squires and

Businger [2008] reported similar results in North Atlantic (including Katrina and Rita) and Eastern North Pacific hurricanes. Price et al. [2009] observed a statistical increase of lightning about 30 hours prior to intensification using a 10° by 10° spatial resolution and 6-hour time resolution of data from the World Wide Lightning Location Network (WWLLN) for 56 hurricanes all over the globe.

As noted above, there have only been a few previous reports of polarities and peak currents of lightning in tropical cyclones, and these observations were limited to periods when the storms approached land [Samsury and Orville, 1994; Molinari, 1999]. To date, there have been no published reports of charge moment changes, an important metric for lightning strength, in tropical cyclone lightning. Including polarity and energetic properties of lightning might lead to a clearer picture of the connection between inner core lightning and tropical cyclone intensity changes, and moreover, it could provide important information about how tropical cyclones electromagnetically couple to the middle and upper atmosphere.

In this investigation, we use WWLLN (http://wwlln.net/), a real-time network that covers the entire globe, along with lightning-generated extremely low and low frequency (ELF/VLF) (3 Hz – 30 kHz) magnetic fields observed at Duke University, to study the polarity and energetics (peak currents and vertical impulse charge moments changes) of inner core lightning in Hurricanes Emily, Katrina, and Rita. WWLLN data has a distinct advantage over satellite lightning data (e.g. OTD and LIS) that only include lightning from a particular storm for a few minutes each day, and it has an advantage over data from extended regional lightning networks (e.g. LLDN) that include a limited global region. Thus, this is the first study of inner core lightning polarities, peak currents, and charge moment changes for the complete lifetime of hurricanes. Our work is a continuation of the analysis by Solorzano et al. [2008] of North Atlantic and Western North Pacific tropical cyclones using WWLLN, and our motivations are twofold: (1) Do the rates, locations, polarities, and energetics of inner core lightning relate to tropical cyclone intensity? (2) Are the peak currents and vertical impulse charge moment changes of inner core lightning in tropical cyclones large enough to drive significant perturbations in the lower ionosphere and/or produce transient luminous events (TLEs) such as elves and sprites?

2. Data sets

WWLLN provides real-time lightning locations globally by measuring the time of group arrival (TOGA) of very low frequency (VLF) radiation (3-30 kHz) emanating from lightning discharges [Dowden et al., 2002; Rodger et al. 2006]. In 2005, when Hurricanes Emily, Katrina, and Rita occurred, WWLLN was composed of between 20 and 23 active stations around the world. At least five stations had to detect radiation from a stroke for it to be accurately located. The location accuracy and efficiency of WWLLN have been estimated for certain regions of the globe by comparison to regional, ground-based lightning detection systems [Lay et al., 2004; Rodger et al., 2005, 2006, 2009; Jacobson et al., 2006]. All of these comparisons with other lightning networks showed that most WWLLN located lightning had peak currents greater than about 30 kA. Rodger et al.

[2009] used a comparison between WWLLN and the New Zealand Lightning Detection Network (NZLDN) and Monte Carlo simulation techniques to estimate the global location accuracy of WWLLN (see their Figure 5). For the North Atlantic basin, the location accuracy ranged from about 8-12 km. Comparisons with OTD and LIS lightning data suggest that the overall WWLLN efficiency was about 5-10% of cloud-to-ground lightning in this region, and comparisons with NZLDN suggest that the diurnal change in WWLLN cloud-to-ground detection efficiency was less than a factor of two (C.J. Rodger, Personal Communication). Moreover, a recent study has shown that the WWLLN detection efficiency was about 26% for parent lightning of optically confirmed TLEs over the US in 2007 [Lyons et al., 2009].

The Duke sensors used for this work were one pair of magnetic field coils sampled at 100 kHz to measure the vector horizontal magnetic field. From these data we compute the impulse charge moment change and estimate the peak current of individual lightning strokes. During some periods the data were sampled continuously, and in other periods the data were sampled in a triggered mode. The impact of this on the results is noted throughout the paper. The magnetic sensors have a flat passband of 50 Hz to 25 kHz. Absolute timing using GPS was validated to better than 20μs using NLDN data. VLF-based measurements of the azimuth to the lightning source have an uncertainty of about 2°.

Hurricane wind, pressure, and best-track data, along with storm summaries, were obtained from the National Hurricane Center (NHC; http://www.nhc.noaa.gov/pastall.shtml).

3. Method

Using the storm-track data from the NHC, we found the distance of the WWLLN located lightning events from location of the minimum central pressure for each storm. Lightning events that occurred within 100 km of the minimum central pressure were labeled as inner core lightning. The WWLLN located inner core lightning were matched with events measured by the Duke ELF/VLF system that agreed in space (within 5° azimuth) and time (within 1 ms). The lightning polarities were determined from the polarity of the ELF signal component received at Duke. The impulse vertical charge moment changes for these events were determined by processing the magnetic field waveforms according to the method of Cummer and Inan [2000]. Vertical impulse charge moment change (iM_q) is defined as the product of the cloud charge removed by vertical currents within 2 ms of the return stroke and the mean height of this removed charge. Uncertainties in these measurements are estimated to be ± 25% due to noise, calibration uncertainties, and modeling uncertainties. The charge moment changes presented here were measured with the same sensors and the same technique as measurements presented in recent work by the authors (e.g. Cummer and Lyons [2005]). The charge moment changes here can thus be directly compared to many of those in the recent literature.

Peak currents were estimated from the maximum amplitude of the received VLF signal components. Through a statistical analysis of many thousands of lightning strokes, we have found that distance-normalized peak VLF fields are proportional to NLDN-reported peak currents, enabling estimates of the peak current from our VLF data with an uncertainty of approximately ± 25%. Not all lightning located by WWLLN had clearly identifiable signals measured by the Duke system due to noise from other thunderstorms or local phenomena. For Emily, 630 of 641 WWLLN events could be measured, and for Katrina 432 of 509 events could be measured. During these storms the VLF system sampled the data continuously. For Rita, only 677 of 2359 events could be measured. The lower percentage of matches for Rita is because the Duke system was operating in a triggered rather than continuous mode during this storm. From comparisons with NLDN, we know that events with peak currents above about 30 kA (the vast majority of those located by WWLLN) are very likely to be cloud-to-ground lightning (CG). Positive polarity events with peak currents less than about 15 kA are likely to be in-cloud (IC) lightning [Cummins et al., 1998], and positive events with peak currents of 15-30 kA could be either CG or IC lightning.

4. Observations

Hurricanes Emily, Katrina, Rita were Category 5 storms on the Saffir-Simpson Hurricane Scale (SSHS; see http://www.nhc.noaa.gov/aboutsshs.shtml) that occurred during 2005 in the North Atlantic basin. Figure 1 shows WWLLN lightning data for the three hurricanes plotted in storm-centered coordinate systems for 24-hour periods. This was accomplished by finding the distance of the lightning events from the best-track location of the minimum central pressure. Figure 1 (a) shows lightning for Emily during UT day 17 July when it was a Category 5 storm in the Caribbean Sea. Figure 1 (b) shows lightning for Katrina during UT day 28 August when it intensified from a Category 3 to 5 storm in the Gulf of Mexico. Figure 1 (c) shows lightning for Rita during UT day 21 September when it intensified from a Category 2 to 5 storm in the Gulf of Mexico. In all cases, the WWLLN lightning data show the radial pattern previously observed by Molinari et al. [1999] during other North Atlantic basin hurricanes. There are three distinct regions: a weak density maximum for the eyewall (region within about 40 km of the center), a distinct area of minimum activity at approximately 80 – 200 km from the eyewall, and the main, broader maximum on the rainband region, outside the 200 km radius.

Solorzano et al. 2008 studied the temporal and spatial evolution of lightning in hurricanes Katrina and Rita and showed the WWLLN results agreed well with results from LASA [Shao et al., 2005] and LLDN [Demetriades and Holle, 2006; Squires and Businger, 2008]. Here we examine the polarities, peak currents, and vertical impulse vertical charge moments changes of inner core lightning (within 100 km of the minimum pressure) in Emily, Katrina, and Rita. Inner core lightning events can be seen in Figure 1 (events within 100 km of the origin of each panel). We are currently investigating rainband lightning (beyond 100 km from the minimum pressure) in these storms and plan to present these results in future publications.

Figures 2, 3 and 4 show the temporal evolutions of polarities (b panels), peak currents (c panels), and impulse vertical charge moment changes (d panels) in Emily, Katrina, and Rita. These figures also show the maximum sustained winds (1-minute averages in knots) and minimum central pressure data to indicate storm intensity (a panels). As shown by Solorzano et al. 2008 and studies using other networks [Shao et al. 2005; Demetriades and Holle, 2006; Squires and Businger, 2008], inner core lightning outbreaks tended to occur prior to and during intensity change in these storms. The new observation in Figures 2 (b), 3 (b), and 4 (b) is the polarity of these inner core lightning (black bars are negative CG lightning, red bars positive CG lightning, and blue bars are the percent of positive lightning). Most of these lightning were negative in polarity for most outbreaks. Notable exceptions were usually just prior to or during periods of storm weakening. For instance, during Emily (Figure 2 and Table 1) 44% of lightning were positive during the outbreak on 15 July when it weakened from a Category 4 to 2 storm in the Caribbean Sea and 47% of the lightning were positive during 16-18 July when it weakened from Category 5 to 1 storm prior and during landfall on Yucatan Peninsula

Similar temporal patterns are observed for Katrina and Rita. During Katrina (Figure 3 and Table 2) positive lightning became more prevalent (29% to 41%) during 28-29 August when it weakened from a Category 5 to 3 storm prior to landfall in Louisiana. For Rita (Figure 4 and Table 3) there was a higher percentage of positive CG lightning after landfall on 24 September when it weakened from a Category 3 to 1 storm. Importantly, we must be cautious in comparing Rita with Emily and Katrina, since the Duke system was operating in triggered mode during Rita and only recorded waveforms for about 30%

of the WWLLN located inner core lightning. Note that this 30% is likely the fraction with the highest peak currents, resulting in peak VLF fields that exceeded the system trigger threshold.

The c panels of Figures 2, 3 and 4 show the temporal evolution of inner core lightning peak currents (I_{pk}). WWLLN is most sensitive to I_{pk} amplitudes greater than about 30 kA, and based on our detection efficiency estimated for this region, our results represent the top 5-10% of the largest peak current inner core CG lightning. That said, the majority of peak currents were above 50 kA and many were above 100 kA, which is further shown by the histogram of peak currents for the entire duration of all three storms in Figure 5. The c panels of Figure 2, 3 and 4 show no clear relationship between I_{pk} magnitude and storm intensity for these hurricanes. The d panels of Figures 2, 3 and 4 show the temporal evolution of inner core lightning vertical impulse charge moment changes (iM_q). Just as for the peak currents values, there is no clear relationship between iM_q amplitudes and storm intensity for these hurricanes. The majority of iM_q amplitudes were less than 50 C-km in magnitude, which is further shown in Figure 5.

Figure 6 shows the spatial distribution of polarities, peak currents, and vertical impulse charge moment changes for inner core lightning in storm-centered coordinates integrated for the complete lifetimes of Emily, Katrina, and Rita. No clear relationships between polarity, I_{pk}, or iM_q and location relative to the storm center are apparent for these hurricanes. For Emily and Katrina, most inner core lightning were within about 40 km of the storm center and were likely located in the primary eyewall cloud. The lightning outside of about 40 km in the inner core were located in the inner rainbands and stratiform regions (see Willoughby [1988] for a discussion of inner core structure). In Rita, lightning were less concentrated near the best-track storm center. There appears to be a dense area of lightning in the south-west quadrant, which might indicate that best-track storm location was in error when these lightning occurred.

5. Discussion

We observe an increase in the relative amount of positive cloud-to-ground lightning just prior to and during most periods of storm weakening in the three hurricanes investigated. Based on previous comparisons of the Duke magnetic field measurements and NLDN data, the high peak fields of these events suggest that the vast majority (>90%) of them were indeed positive CG lightning. However, since WWLLN only locates the highest peak current cloud-to-ground lightning (greater than 30 kA) in these storms, we must be cautious in interpreting these results. Indeed, additional polarity studies should be conducted on a larger number of storms using other lightning networks and WWLLN to confirm our findings. Nonetheless, an increase in positive lightning before and during storm weakening was clearly observed in all three hurricanes we examined, which suggests that real-time polarity observations could prove useful for intensity forecasting.

We do not identify particular locations within the inner core that were preferred by positive lightning (Figure 6). The positive discharges were dispersed throughout the inner core region, not just located outside of the eyewall. Thus, we cannot say that positive lightning was located in stratiform regions, as previously reported by Molinari et al. [1999]. In future works, we intend to combine our polarity results with radar data (ground-, satellite- and airborne-based) in order to investigate the convective structures associated with positive lightning, which might provide insight on the connection between positive discharges and weakening stages.

The peak current and vertical impulse charge moment change observations have implications for the production of transient luminous events (TLEs; e.g. elves and sprites) and lightning-driven perturbations in the lower ionosphere. Modeling and remote observations suggest that elves are the result of electromagnetic pulses (EMPs) generated by large peak current lightning return strokes (both negative and positive polarity) exciting and ionizing the lower ionosphere at 90-100 km [Taranenko et al., 1993a; Fernsler and Rowland, 1996; Inan et al., 1997; Barrington-Leigh and Inan, 1999]. Barrington-Leigh and Inan studied 86 events detected by NLDN with peak currents greater than 38 kA and observed correlated elves for 52% of these using a photometric array, and for peak currents above 57 kA, all 34 NLDN flashes had correlated elves. A more recent study [Cheng et al., 2007] generally agreed with these results, setting the threshold for EMP induced conductivity perturbations in the ionosphere at about 40-60 kA. Thus, it may be likely that a significant fraction of all WWLLN-detected cloud-to-ground lightning are producing elves, since the network is most sensitive to peak currents greater than about 30 kA. Although, to date, there have been very few reports of electrical perturbations and TLEs above tropical storms. Two notable exceptions include satellite measurements of a transient electric field disturbance above Hurricane Debbie (1992)

[Burke et al., 1992] and video imaging of a gigantic jet above Tropical Storm Cristobal (2008) [Cummer et al., 2009].

Table 4 lists the number of inner core lightning events in Emily, Katrina, and Rita that surpassed 40 kA in magnitude, the approximate threshold for elve production according to the works of Barrington-Leigh and Inan [1999] and Cheng et al. [2007]. Hundreds of inner core lightning for each hurricane were above this threshold for elve production. Importantly, as shown in Figures 2, 3, and 4, these high peak current lightning tended to occur in short duration episodes, with tens to hundreds of high peak current lightning occurring in a few hours. Recent modeling work by Lay et al. [2009], which is based on earlier studies by Taranenko et al. [1993b] and Rodger et al. [2001], has shown that lightning strokes can have an accumulated effect on the lower ionosphere. According to Lay et al., multiple high peak current lightning strokes that occur near in space and time, like the inner core lightning studied here, drive EMPs that have an additive non-linear effect on the electron density of the lower ionosphere. Hence, our results suggest that the inner core regions of intense hurricanes might drive strong electron density perturbations in the lower ionosphere during these lightning outbreaks.

We should point out that tropical cyclones are not the most active lightning producers on globally. Even the most electrically active tropical cyclone is a weak lightning producer compared to a continental mesoscale convective system, where lightning cloud-to-ground flash rates can exceed 10,000/hr (see for example Zipser et al., [2006]). Most tropical cyclones are probably more similar to a typical mesoscale convective system in terms of lightning activity, even when considering higher peak current events.

Sprites are driven by large charge moment change lightning, which are predominantly positive in polarity [Boccippio et al., 1995]. These lightning generate a large quasi-static electric field above the thundercloud, which leads to breakdown seen as sprites [Pasko et al., 1997]. Table 4 lists the number of inner core lightning events in Emily, Katrina, and Rita that surpassed 350 C-km in magnitude, the approximate threshold for prompt, or short-delayed, sprite initiation based on an investigation of sprites over the US High Plains by Cummer and Lyons [2005]. Only a few events surpassed this vertical impulse charge moment change threshold. However, many sprites are dominantly produced by continuing current charge moment change [Li et al., 2008] in lightning with only modest impulse charge moment changes. Determining whether the inner core regions of intense hurricanes are or are not active sprite producers will require detailed analysis of the charge moment change on times scales longer than 2 ms.

There has been very little systematic investigation of TLEs above tropical cyclones. We examined the TLE-database from the ISUAL instrument aboard the FORMOSAT satellite, and we found no TLEs above Hurricanes Emily, Katrina, and Rita. We have also initiated a search for ISUAL observed TLEs in all tropical cyclones globally since 2004. These results will be presented in future publications.

6. Conclusions and future work

We find episodic inner core lightning outbreaks prior to and during most changes in storm intensity (winds and central pressure) in Hurricanes Emily, Katrina, and Rita, which is in strong agreement with past investigations [Molinari et al., 1994, 1999; Squires and Businger, 2008; Solorzano et al., 2008]. As a novel result, we find that the relative number of positive cloud-to-ground (CG) lightning increased in the inner core prior to and during periods of storm weakening. This change in the temporal distribution of positive CG lightning might prove useful for forecasting hurricane intensity change. However, since WWLLN only locates the highest peak current lightning in these storms, further studies are needed to support this result. No relationship between the location of negative and positive CG lightning and storm intensity is found, and we find no apparent correspondence between spatial and temporal distributions of energetic magnitudes (I_{pk} and iM_q) and storm intensity.

Another new finding is that the majority of inner core lightning located by WWLLN had peak currents that surpassed the threshold needed to produce elves and drive electron density perturbations in the lower ionosphere (80-105 km), but very few of these lightning had vertical impulse charge moment changes that were large enough to initiate short-delayed sprites. Since these high peak current lightning occurred in short duration outbreaks in a localized region in the inner core, there could have been an additive effect on the lower ionosphere due to EMPs from these multiple lightning events. Our results suggest that these hurricanes might be significant drivers of electron density perturbations in the lower ionosphere during these inner core lightning outbreaks.

In the near future, we intend to combine our polarity results with radar data in order to investigate the convective structures associated with positive lightning, which might explain why positive discharges are predominant during weakening stages. Additionally, work is currently underway to study polarity and energetics of lightning in rainband regions outside the inner core. Finally, to test the role of tropical cyclone inner core lightning as drivers of electron density perturbations in the lower ionosphere, we propose that future observational campaigns (e.g. optical and radar studies) of the middle and upper atmosphere be conducted in the vicinity of tropical cyclones.

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Figure Captions

Figure 1. WWLLN lightning data for Hurricanes Emily (a), Katrina (b), and Rita (c) plotted in storm-centered coordinate systems for 24-hour periods.

Figure 2. Temporal evolution of inner core lightning in Hurricane Emily. (a) Maximum sustained winds (1-minute averages in knots shown as blue circles) and minimum central pressure (green squares). (b) Lightning activity within 100 km of the best-track storm center binned in 3-hr intervals (black bars are negative CG lightning, red bars are CG positive lightning, and blue bars are percent positive lightning) (c) A spectrogram of peak currents (I_{pk}) using 3-hr by 40 kA bins. (d) A spectrogram of vertical impulse charge moment changes (iM_q) using 3-hr by 40 C-km bins. The color bar indicates the number of lightning events in each bin, and dark red represents 10 or more events. Events with I_{pk} and iM_q magnitudes greater than 400 kA (C-km) are included in the 360-400 kA (C-km) bins.

Figure 3. Temporal evolution of inner core lightning in Hurricane Katrina (see Figure 2 caption for details).

Figure 4. Temporal evolution of inner core lightning in Hurricane Rita (see Figure 2 caption for details).

Figure 5. Histogram of peak current and impulsive vertical charge moment changes for inner core lightning in Hurricanes Emily (a), Katrina (b), and Rita (c). Events with I_{pk} and iM_q magnitudes greater than 400 kA (C-km) are included in the 350-400 kA (C-km) bins.

Figure 6. Spatial distribution of inner core lightning in Hurricanes Emily (a, b, and c), Katrina (d, e, and f), and Rita (g, h, and i) in storm-centered coordinates for the entire duration of each storm. Panels a, d, and g show polarity (negative CG lightning are black and positive CG lightning are red). Panels b, e, and h show peak current (I_{pk}) magnitudes (0-50 kA are blue, 50-100 kA are green, and greater than 100 kA are magenta). Panels c, f, and i show impulsive vertical charge moment change (iM_q) magnitudes (0-175 C-km are blue, 175-350 C-km are green, and greater than 350 C-km are magenta).

Table 1. Percent of positive cloud-to-ground lightning for inner core lightning outbreaks in Hurricane Emily.

Time Period (UT)	Intensity Change	Number of Lightning	Percent Positive
11 Jul. 00:00 – 11 Jul. 06:00	Strengthen	28	21%
11 Jul. 12:00 - 12 Jul. 09:00	Strengthen	148	20%
12 Jul. 21:00 – 13 Jul. 06:00	Strengthen	2	0%
13 Jul. 18:00 – 14 Jul. 06:00	Strengthen	97	26%
14 Jul. 15:00 – 15 Jul. 06:00	Strengthen	49	33%
15 Jul. 06:00 – 15 Jul. 21:00	**Weaken**	**39**	**44%**
15 Jul. 21:00 – 16 Jul. 09:00	Strengthen	47	23%
16 Jul. 18:00 – 18 Jul. 12:00	**Weaken**	**195**	**47%**
18 Jul. 21:00 – 19 Jul. 09:00	Strengthen	9	22%
19 Jul. 18:00 - 20 Jul. 00:00	Strengthen	4	0%
20 Jul. 21:00 – 21 Jul. 03:00	**Weaken**	**2**	**50%**
11 Jul. 00:00 – 22 Jul. 00:00 (Entire Storm)	NA	630	32%

Table 2. Percent of positive cloud-to-ground lightning for inner core lightning outbreaks in Hurricane Katrina.

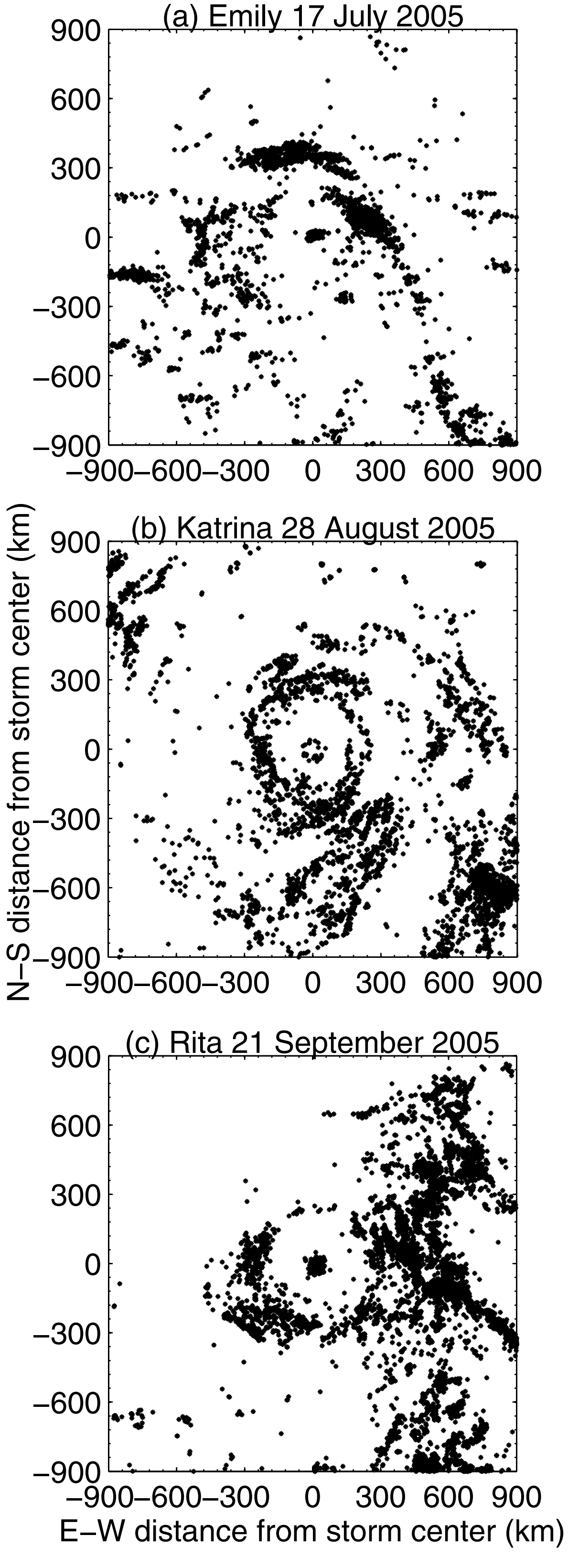
Time Period (UT)	Intensity Change	Number of Lightning	Percent Positive
24 Aug. 00:00 – 24 Aug. 21:00	Strengthen	42	14%
25 Aug. 09:00 – 26 Aug. 00:00	Strengthen	115	17%
26 Aug. 00:00 – 26 Aug. 06:00	**Weaken**	**62**	**6%**
26 Aug. 06:00 – 27 Aug. 00:00	Strengthen	134	20%
27 Aug. 21:00 – 28 Aug. 03:00	Strengthen	27	11%
28 Aug. 12:00 – 28 Aug. 21:00	**Strengthen/ Weaken**	**27**	**41%**
28 Aug. 21:00 – 29 Aug. 03:00	**Weaken**	**10**	**40%**
29 Aug. 12:00 – 29 Aug. 21:00	**Weaken**	**14**	**29%**
24 Aug. 00:00 – 30 Aug. 00:00 (Entire storm)	NA	432	18%

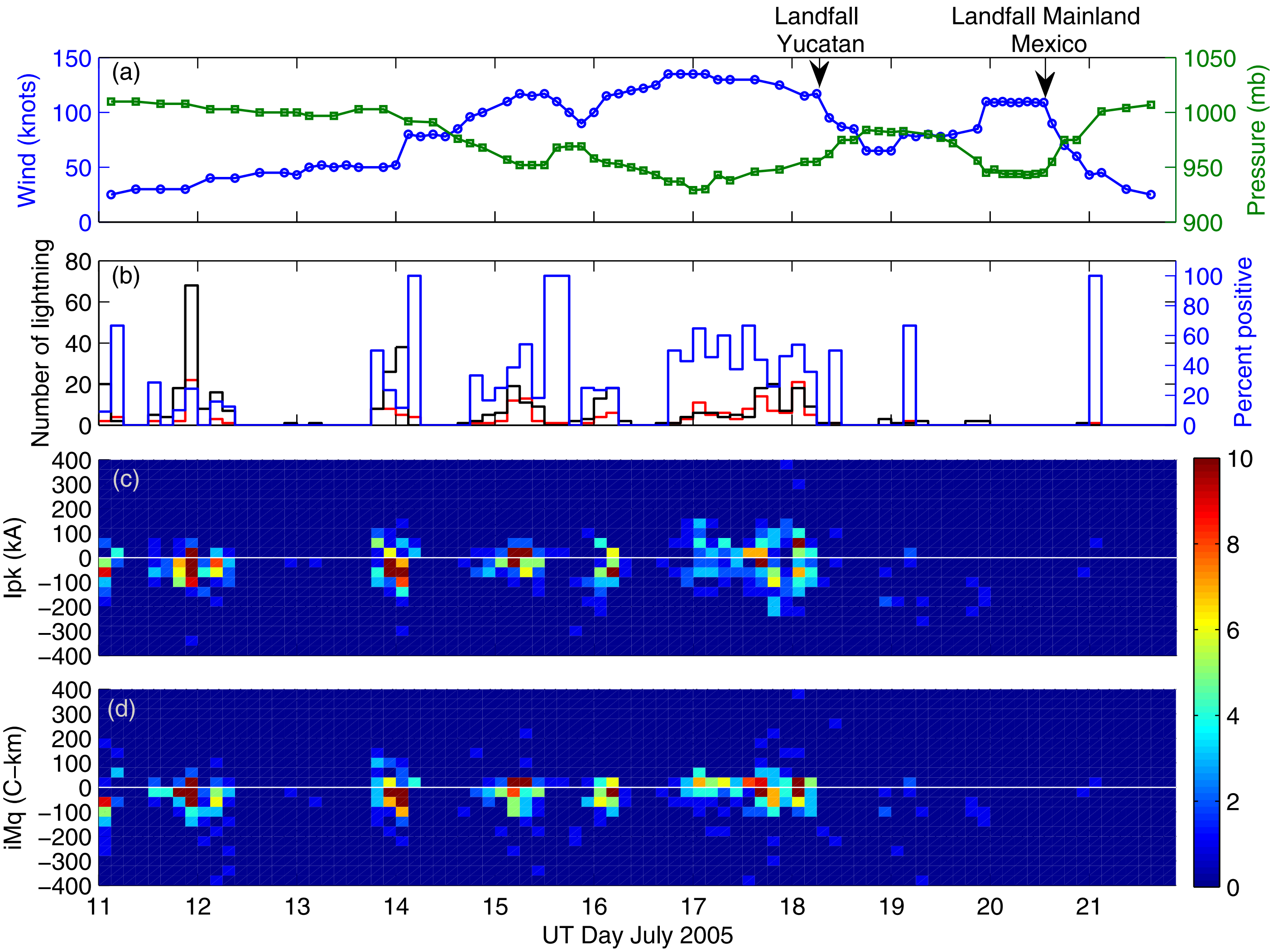
Table 3. Percent of positive cloud-to-ground lightning for inner core lightning outbreaks in Hurricane Rita.

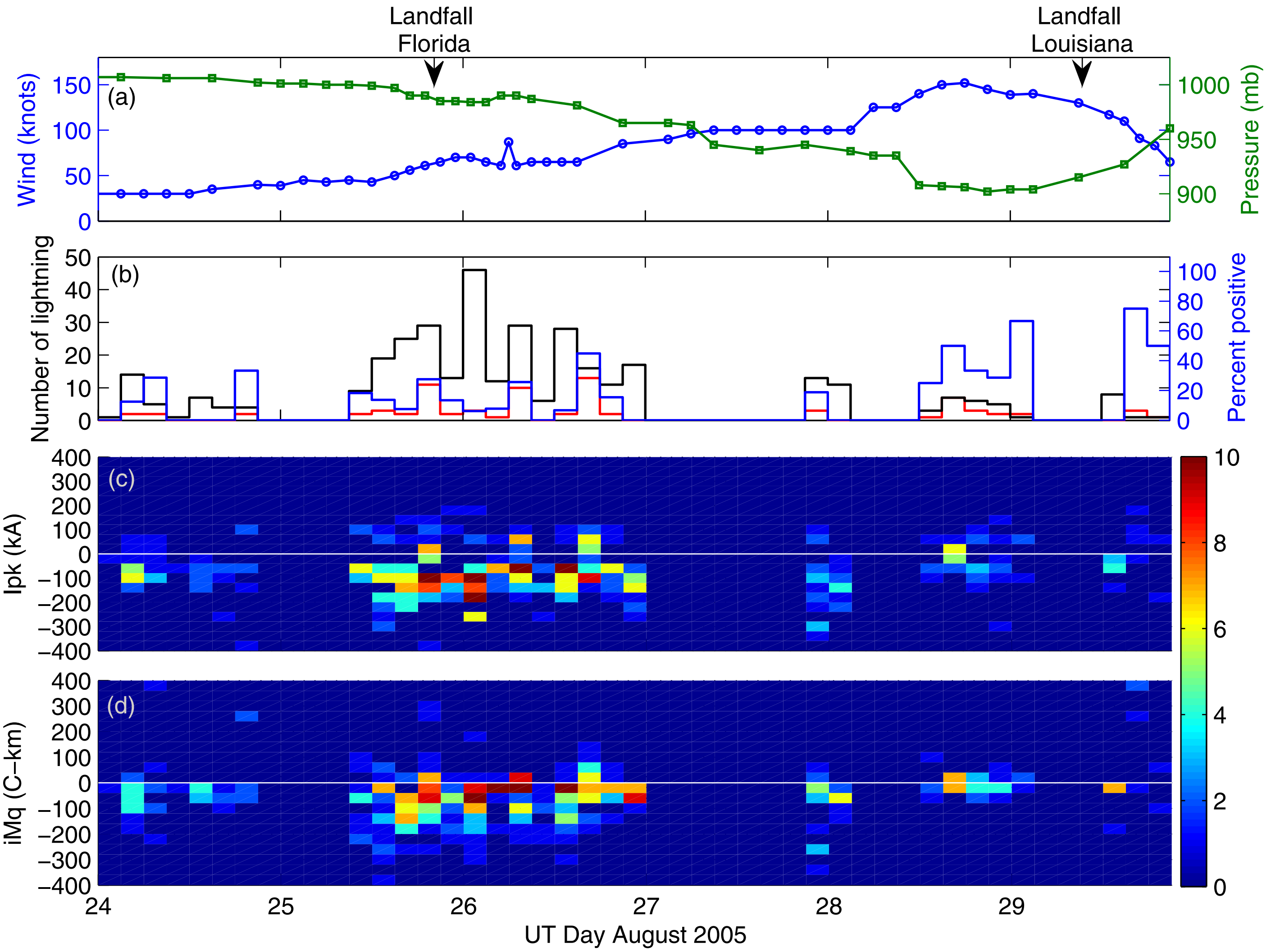
Time Period (UT)	Intensity Change	Number of Lightning	Percent Positive
18 Sep. 06:00 – 18 Sep. 12:00	Strengthen	18	13%
18 Sep. 18:00 – 19 Sep. 00:00	Strengthen	17	0%
19 Sep. 12:00 – 20 Sep. 09:00	Strengthen	372	14%
20 Sep. 12:00 – 20 Sep. 18:00	Strengthen	56	11%
20 Sep. 21:00 – 21 Sep. 06:00	Strengthen	55	20%
21 Sep. 09:00 – 22 Sep. 03:00	Strengthen	91	20%
22 Sep. 03:00 – 22 Sep. 12:00	**Weaken**	**40**	**5%**
22 Sep. 15:00 – 22 Sep. 21:00	**Weaken**	**5**	**0%**
24 Sep. 12:00 – 24 Sep. 21:00	**Weaken**	**16**	**94%**
18 Sep. 00:00 – 25 Sep. 00:00 (Entire storm)	N/A	677	16%

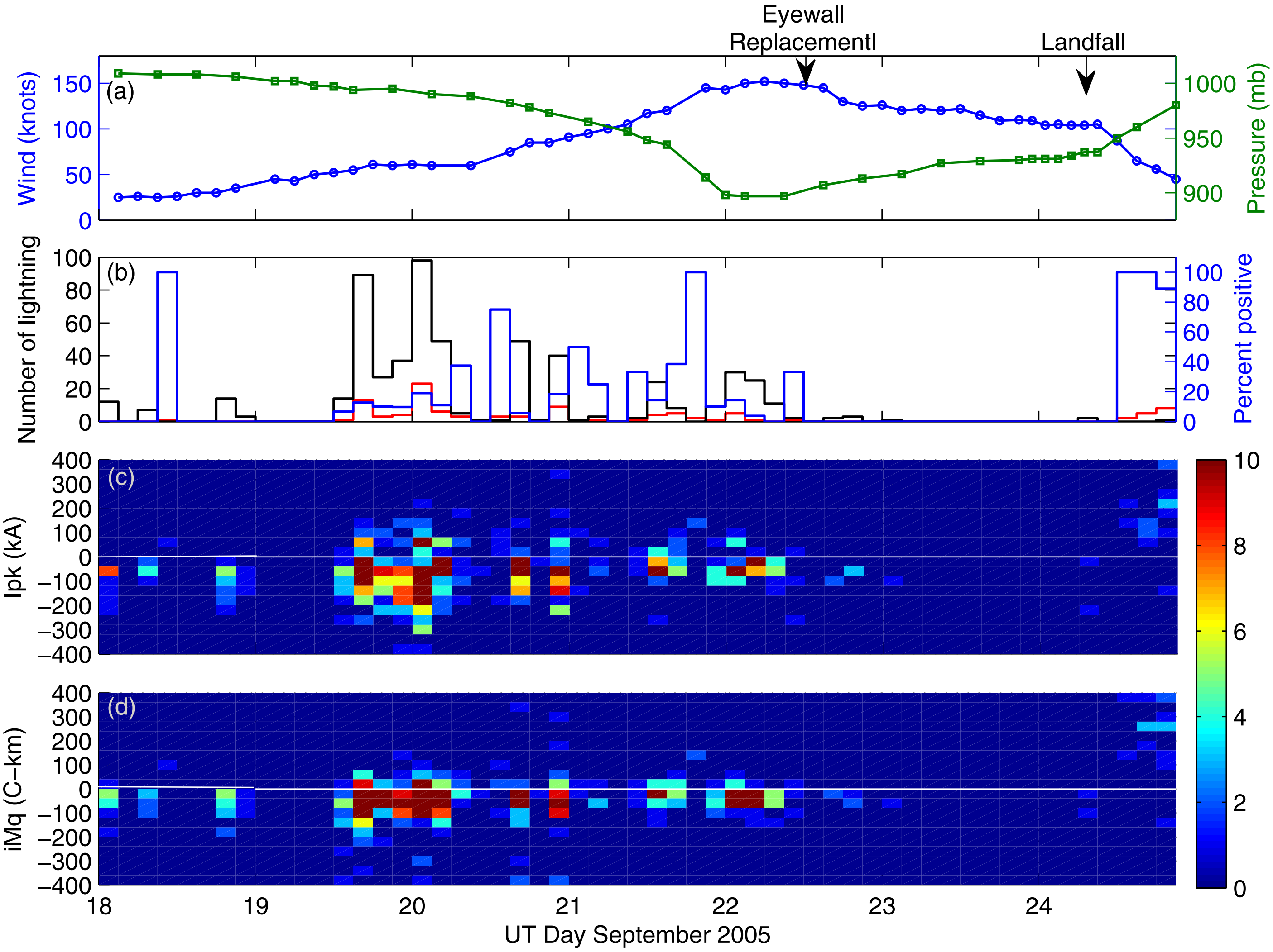
Table 4. Number of inner core lightning peak currents (I_{pk}) above elve thresholds and impulse vertical charge moment changes (iM_q) above short-delayed sprite thresholds.

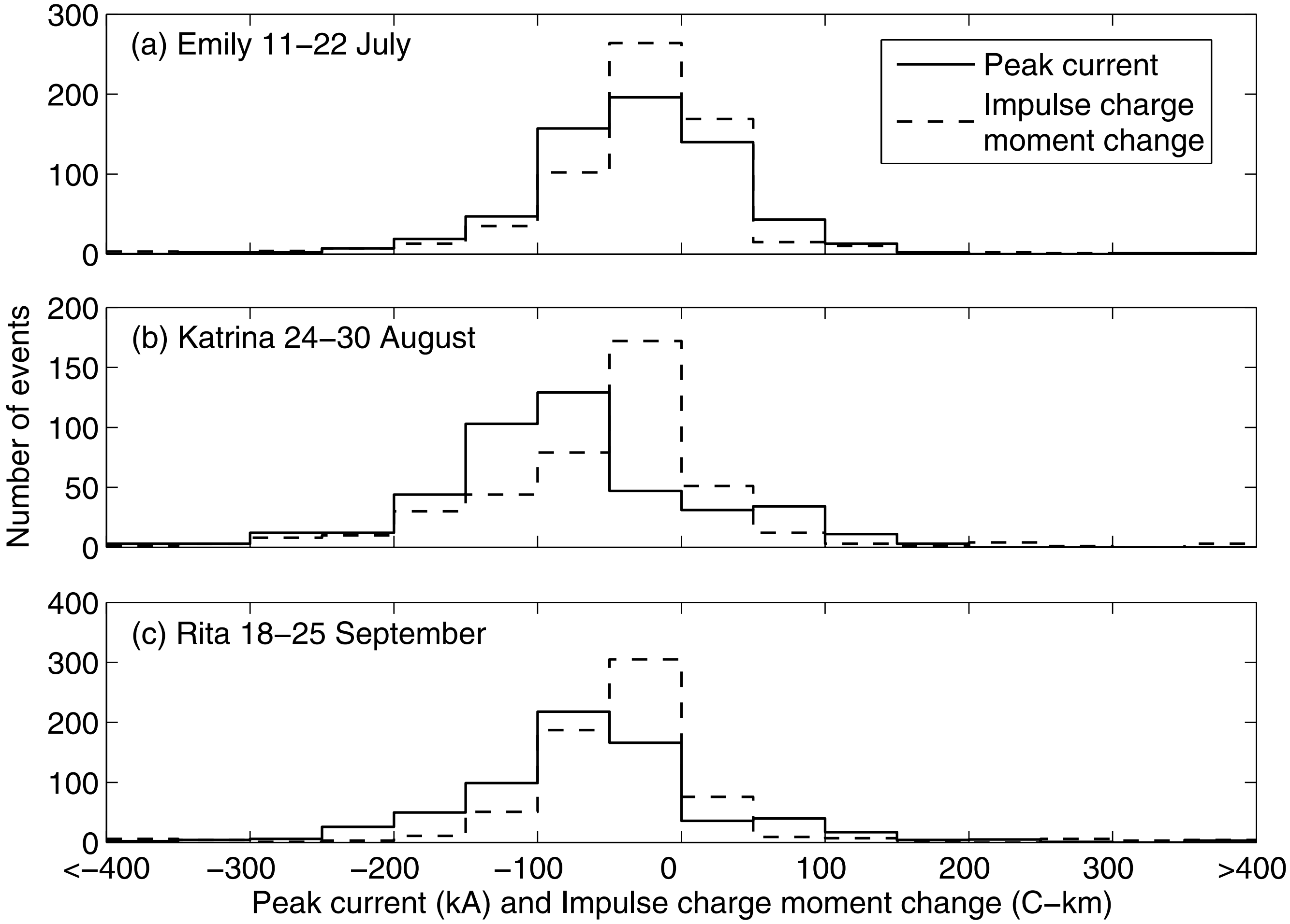
Hurricane	$\|I_{pk}\| > 40$ kA		$\|iM_q\| > 350$ C-km	
	Negative	Positive	Negative	Positive
Emily	275	88	3	1
Katrina	328	57	1	3
Rita	467	83	6	4

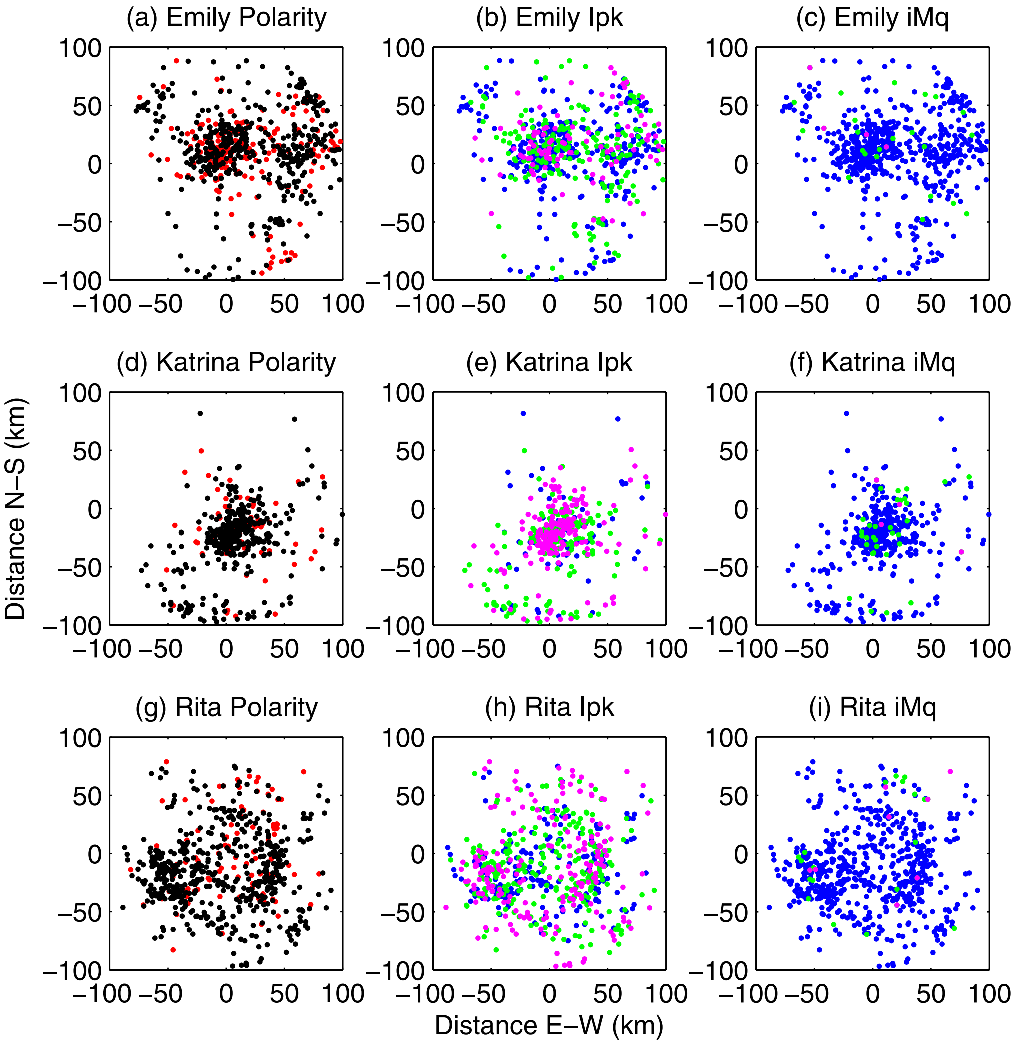

(a) Emily 17 July 2005
(b) Katrina 28 August 2005
(c) Rita 21 September 2005
900
600
300
0
−300
−600
−900
−900−600−300 0 300 600 900
N−S distance from storm center (km)
E−W distance from storm center (km)


Landfall
Yucatan
Landfall Mainland
Mexico
(a)
Wind (knots)
0
50
100
150
Pressure (mb)
900
950
1000
1050
(b)
Number of lightning
0
20
40
60
80
Percent positive
0
20
40
60
80
100
(c)
Ipk (kA)
400
300
200
100
0
−100
−200
−300
−400
(d)
iMq (C−km)
400
300
200
100
0
−100
−200
−300
−400
0
2
4
6
8
10
11
12
13
14
15
16
17
18
19
20
21
UT Day July 2005


Landfall
Florida
Landfall
Louisiana
(a)
Wind (knots)
Pressure (mb)
0
50
100
150
900
950
1000
(b)
Number of lightning
Percent positive
0
10
20
30
40
50
0
20
40
60
80
100
(c)
Ipk (kA)
400
300
200
100
0
−100
−200
−300
−400
(d)
iMq (C−km)
400
300
200
100
0
−100
−200
−300
−400
0
2
4
6
8
10
24
25
26
27
28
29
UT Day August 2005


Eyewall
Replacementl
Landfall
(a)
Wind (knots)
Pressure (mb)
0
50
100
150
900
950
1000
(b)
Number of lightning
Percent positive
0
20
40
60
80
100
(c)
Ipk (kA)
400
300
200
100
0
-100
-200
-300
-400
(d)
iMq (C-km)
0
2
4
6
8
10
18
19
20
21
22
23
24
UT Day September 2005


(a) Emily 11–22 July
(b) Katrina 24–30 August
(c) Rita 18–25 September
Peak current
Impulse charge moment change
Number of events
Peak current (kA) and Impulse charge moment change (C–km)
<–400
–300
–200
–100
0
100
200
300
>400
0
50
100
150
200
300
400


(a) Emily Polarity
(b) Emily Ipk
(c) Emily iMq
(d) Katrina Polarity
(e) Katrina Ipk
(f) Katrina iMq
(g) Rita Polarity
(h) Rita Ipk
(i) Rita iMq
100
50
0
−50
−100
−100 −50 0 50 100
Distance N−S (km)
Distance E−W (km)