THE MORPHOLOGY OF EYEWALL CLOUD TO GROUND LIGHTNING IN TWO CATEGORY FIVE HURRICANES

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI'I IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

METEOROLOGY

DECEMBER 2006

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ACKNOWLEDGEMENTS

I would like to thank Dr. Steven Businger for providing me with the chance to conduct this research, and for all his help throughout the scientific and editorial processes. I would also like to thank Drs. Gary Barnes and Tom Schroeder for the help they provided during the editing process. Thanks also go to the NOAA/AOML/Hurricane Research Division and NOAA/NWS/National Hurricane Center for their efforts in the collection of the data used in this study. I would especially like to thank John Gamache and Neal Dorst of HRD for their assistance in making the aircraft radar and 1-second data available to us. I am grateful to Antti Pessi for his technical assistance with the satellite image processing, and to Nancy Hulbirt for her graphics expertise. TRMM satellite data have been provided by the TRMM Science Data and Information System at the Goddard Space Flight Center, Greenbelt, Maryland. This work was supported by the Office of Naval Research under grant number N000140510551.
ABSTRACT

Data from the Long-Range Lightning Detection Network (LLDN), the Tropical Rainfall Measuring Mission (TRMM) satellite, and reconnaissance aircraft are used to analyze the frequency and location of cloud to ground lightning outbreaks in the eyewalls of Hurricanes Rita and Katrina. Each hurricane produced eyewall lightning outbreaks during the period of most rapid intensification, during eyewall replacement cycles, and during the period that encompassed the maximum intensity for each storm.

The strike density (number of strikes per \((100 \text{ km})^2\)) ratio between the eyewall region \((0 - 50 \text{ km})\) and the outer rainband region \((175 - 300 \text{ km})\) was 6:1 for Hurricane Rita, and 1:1 for Hurricane Katrina. This result is in contrast to those of previous remote lightning studies, which found that outer rainbands dominated the lightning distribution. The differences are shown to be at least in part the result of the more limited range of the National Lightning Detection Network (NLDN) data.

Within the effective range of the aircraft radar, maxima in eyewall strike density were collocated with maxima in radar reflectivity. High lightning strike rates were also reliably associated with TRMM low brightness temperatures and large Precipitation Ice Concentration (PIC) product. The differences in storm structure and lightning strike morphology between Hurricanes Rita and Katrina are documented. The implications of the results for the use of LLDN lightning data to remotely examine changes in hurricane intensity and structural evolution are discussed.
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CHAPTER 1. INTRODUCTION

It has been shown that the convective structure of the eyewall of a mature hurricane can provide valuable information about changes in storm intensity (Jorgensen 1984; Black et al. 1986, 1994; Marks 1985; Heymsfield et al. 2001). Marks (1985) showed that intensification of a hurricane could be represented by a contraction of the eyewall, as well as by an increase in the strength of the convection within the eyewall. Black et al. (1994) also witness a strengthening and deepening of the convection contained with in the eyewall of Hurricane Emily (1987) as the hurricane intensified. Heymsfield et al. (2001) also showed that the development of mesoscale regions of intense convection within the eyewall of a mature hurricane could cause significant intensity changes. Thus, it has become of interest to hurricane forecasters and researchers alike, to develop various methods that would allow the continuous examination of the structural evolution of the eyewall within hurricanes.

The lightning flash rates produced by a convective system are positively correlated with the convective strength of that system (Orville and Vonnegut 1974; Orville et al. 1983; Williams et al. 1992). The earlier study by Orville and Vonnegut (1974) examined scanned photographs of lightning flashes provided by Defense Meteorological Satellite Program (DMSP) in order to derive the lightning flash frequencies of specific convective systems. The more recent studies by Orville et al. (1983) and Williams et al. (1992) both used a network of direction finding sensors that were able to detect the cloud to ground lightning strikes produced by convective systems. Williams et al. (1992) also analyzed the individual convective systems using vertical reflectivity profiles provided by a ground based radar; concluding that as convective systems become more vigorous, their cloud to
ground strike rates increase. These findings have been further supported by various other studies and therefore it has been suggested that it is possible to examine the development and evolution of a convective system by examining its lightning strike morphology (Orville et al. 1983; Williams et al. 1992). Thus the examination of eyewall convection with the use of remote lightning data would be possible.

Molinari et al. (1994, 1999) examined the convective structure of hurricanes through the use of remote lightning detection. The study also looked for links between eyewall structure, inferred from the remote lightning data, and changes in storm intensity. Molinari et al. (1999) used lightning data provided by the National Lightning Detection Network (NLDN) to examine the hourly cloud to ground lightning evolution in nine Atlantic hurricanes, three of which were previously studied by Lyons and Keen (1994). He concluded that mature TCs could be divided into three regions with respect to lightning strike density (defined as the number of measured cloud to ground strikes per unit area per time). The greatest strike density was contained within the outer rainband region, beginning ~140 km from storm center and continuing outward. The eyewall region, 0 - 60 km from storm center, contained a secondary maximum in strike density, which was approximately 3 to 6 times less than that of the outer rainband region. The minimum in strike density was found in the inner rainband region, this region was defined as 60 - 140 km outward from storm center. These three regions defined by lightning strike density in Molinari et al. (1999) are comparable with the three convective regions of a mature TC described by Jorgensen (1984); in particular, (i) the eyewall region, an area of outward-sloped convection that surrounds the eye and contains moderate vertical velocities (~ 4 - 6 m s⁻¹), (ii) the stratiform region, which is located just
outward of the eyewall and contains little active convection and weak vertical velocities, and (iii) the rainband region, which is characterized by the variable nature of the reflectivity and vertical velocity profiles.

Molinari et al. (1999) also concluded that moderate and intense hurricanes (maximum sustained winds > 41 m s\(^{-1}\)) contained less cloud to ground eyewall lightning when compared to weak hurricanes (maximum sustained winds 32 – 35 m s\(^{-1}\)). Moderate and strong hurricanes contained < 30 strikes day\(^{-1}\) within 60 km of storm center, with eyewall lightning only occurring in 7% of hourly periods and never occurring for longer than a 5-h period. Molinari et al. (1999) also showed that eyewall lightning outbreaks frequently accompany eyewall replacement cycles, as well as periods of intensification.

Cecil et al. (1999) conducted a study of three TCs using lightning data provided by the Optical Transient Detector (OTD) aboard the polar orbiting satellite Pegasus. Cecil et al. (2002a, b) used the TRMM mounted Lightning Imaging Sensor (LIS) to study 261 TRMM satellite overpasses of 45 TC’s. The OTD and LIS instruments were able to detect the total number of lightning flashes (defined as both intra-cloud lightning flashes and cloud to ground strikes), and operated with a detection efficiency of 60% and 90% respectively. Cecil et al. (1999, 2002a, b) found a radial distribution similar to Molinari et al. (1999), in which there were lightning flash density (defined as, the total number of lightning flashes per area per time) maxima in the eyewall region and outer rainband region, with a distinct flash density minima located within the inner rainband region. However, Cecil et al. (1999, 2002a,b) found that the ratio of flash densities between the eyewall region and outer rainband region was closer to 1:1, not 1:3-6 as found by Molinari et al. (1999).
The detection efficiency of the NLDN is very sensitive to the distance of a lightning strike from the network sensors; as the distance increases the detection efficiency decreases. As a result previous researchers using NLDN data limited their analysis of lightning data to times when TCs centers were within 400 km of at least two direction-finding (DF) sensors (e.g., Molinari et al. 1994, 1999; Samsury and Orville 1994). This limitation made it impossible to examine any lightning data while the TCs of interest were located over the open ocean, and may have resulted in inaccurate conclusions about the spatial evolution of cloud to ground lightning strikes produced by TCs.

In this study, data from the Long-Range Lightning Detection Network (LLDN) are compared with convective precipitation and precipitable ice derived from aircraft radar and TRMM data in the eyewall regions of two category five hurricanes. The overarching goal of this work is to determine the utility of continuous LLDN data to remotely infer the evolution of the convective structure of hurricane eyewalls.
CHAPTER 2. BACKGROUND

2.1 Charge Separation

The theories regarding the various methods of charge separation within the atmosphere are still very exploratory. While different methods of charge separation are known to occur, their order of importance for inducing cloud electrification is not well understood. There are two main methods of charge separation; inductive (IC) and non-inductive charge separation (NIC).

2.1.1 Inductive Charge Transfer

IC can only occur when there is a background electric field within the region of cloud in which the transferring particles are located. There are two main methods of IC transfer, drop breakup and particle rebound. The Earth’s natural electric field causes a dominant initial electric field within the cloud that is usually positive above negative at all altitudes above the freezing mark. This electric field causes the bottom of a droplet to become positive and the top of the droplet to become negative. Drop breakup IC occurs when the environmentally induced charge separation within a droplet is redistributed when the droplet breaks up. The cause of the droplet breakup is usually due to the collision and coalescence process occurring within clouds.

Particle rebound takes place when a smaller particle collides with the bottom of a larger particle due to differential fall velocities. A portion of the positive charge on the bottom of the large droplet will be lost and transferred to the smaller droplet. For both drop breakup and particle rebound the charge separation within the cloud comes as a result of the redistribution of the differing charged particles via gravitational separation
(Beard 1986). The smaller particles have slower fall velocities, and as a result are carried higher into the cloud. This causes the top of the cloud to become positively charged while the larger, negatively charged particles collect at the bottom of the cloud causing it to become negatively charged.

2.1.2 Non-Inductive Charge Transfer

NIC transfer does not need a pre-existing environmental electric field in order to operate. There are three main methods of NIC transfer, thermoelectric effect, contact potential effect, and freezing drop breakup (Pruppacher and Klett 2000).

The thermoelectric effect states that a collision by two particles of different temperatures will cause a temperature gradient across the particles. This temperature gradient causes an ion gradient and a resultant electric field across the particles. Large objects, such as hail will be frozen, while smaller particles may remain in liquid phase (i.e. supercooled water). A collision between the two would tend to cause the colder particle to acquire a negative charge, while the small particle would acquire a positive charge.

Contact potential effect requires the collision of two particles, which have differing electric surface potential. The difference in surface potential of the two particles would then attempt to equalize by transferring charges between particles. Contact potential varies such that it becomes more negative with as temperature decreases, and riming increases. Thus a collision between a rimed ice particle and ice crystal would cause negative charge transfer to the rimed particle and positive charge to the smaller ice crystal (Saunders 1995).
When a droplet begins to freeze the outer ice shell of the droplet is positively charged, while the main inner core is negatively charged. If the droplet fractures during freezing, the main core of the particle will remain negatively charged, and the ice splinters associated with the outer shell will remain positively charged. For all 3 of the NIC mechanisms, separation of the unlike charged particles by gravity and or updrafts and downdrafts, create the electric field within the cloud. The smaller particles tend to acquire a positive charge and the larger particles acquire a negative charge, therefore the bottom of the cloud becomes negatively charged, and the top becomes positively charged.

2.2 Cloud to Ground Lightning

When charge separation occurs within a cloud it creates an electric field. The structure of the electric field can change drastically for various reasons, however the most commonly understood electric field that occurs in most thunderstorms is a vertical dipole. This occurs when charge particles become vertically separated by gravity, updrafts downdrafts, for example, and create a volume of one charge above another volume of opposing charge. It has now been measured that thunderstorms that contain extremely high vertical velocities can have electric fields that are tri- or quad-poles (Black and Hallett 1999). Besides the electric field that is created within the thunderstorm, there is a dipole induced between the lower part of the cloud and the ground. When the strength of the dipole between the cloud and ground reaches a limit, a value known as dielectric breakdown, it is possible for a cloud to ground lightning strike to occur. Uman (1987) showed that each cloud to ground lightning strike requires a charge separation of ~ 10 coulombs per strike, or several strikes and lower tens of coulombs.
2.3 Hurricane Electrification

Charge separation and the resulting dipole orientation depend on many different characteristics of the convective system of interest, such as updraft strength, liquid and ice water concentrations, and temperature. Therefore it is a good idea to discuss the electrification of hurricanes in particular and not just convection in general.

Black and Hallett (1999) examined the electrification and hydrometeor characteristics within Hurricane Claudette (1991) and Hurricane Tina (1992) using an array of field mills mounted on the WP-3D aircraft. As the aircraft penetrated through the TCs, the field mill array was able to measure the strength and the polarity of the electric field at that particular flight level. Detailed measurements of hydrometeor size, concentration, and state (liquid or solid) were also recorded along the flight path using two-dimensional optical array probes, a forward scattering-spectrometer, and a liquid water meter. Radial flight penetrations were completed at various altitudes between 4.5 km and 7 km. All flight levels recorded a positive vertical electric field (no charge or positive charge below the aircraft with negative charge above the airplane) nearly all the time, with negative (negative charge below the aircraft with no charge of positive charge above the airplane) vertical electrical fields recorded only while the plane passed through weak downdrafts around the melting level. The strongest vertical electric fields measured within the eyewall measured \(17 - 24\, \text{kV m}^{-1}\), and were approximately 3-5 times weaker than those measured in continental thunderstorms (Marshall et al. 1995). The peaks in electric field within the eyewall were collocated with strongest updraft velocities and highest super-cooled water concentration. Black and Hallett (1999) concluded that the large amount of ice produced within the eyewall of a mature hurricane
would act to nucleate and freeze much of the liquid water content (LWC) that is present above the 0°C isotherm. This process would result in little super-cooled water droplets within the eyewall, which are needed for charge separation within clouds (Ziv and Levin 1974; Takahashi 1978; Saunders et al 1991). Therefore Black and Hallett (1999) suggest that lightning outbreaks within the eyewall are rare, especially when compared to continental convection.

2.4 Previous Lightning Studies

2.4.1 Lightning Flash Density and Environmental Instability

Lightning strike rates for a particular convective system are closely related to the magnitude of the updrafts and the vertical development of the convective system, as well as the concentration of ice-phase precipitation produced by the convective system (Williams et al. 1992). These three properties of a convective system can be largely dependent on the amount of convective available potential energy (CAPE) within the environment of a convective system. Williams et al. (1992) concluded that higher CAPE values resulted in more intense convection, as denoted by greater radar reflectivity values extending above the melting level, which signify greater concentrations of ice-phase precipitant. These high concentrations of ice-phase precipitant are needed in order to separate enough charge in order to produce lightning within the storm (Ziv and Levin 1974). Thus, intense convection that is formed within high CAPE environments will also produce more lightning strikes per area when compared to weaker convection (Williams et al. 1992).
2.4.2 Lightning Flash Density and Cloud Condensation Nuclei

The concentration of ice-phase precipitant is also dependent on the concentration of cloud condensation nuclei (CCN) present within the environment. CCN aid in the formation of ice-phase precipitant through heterogeneous nucleation processes, therefore atmospheric environments which contain higher concentrations of CCN also usually contain higher concentrations of ice-phase precipitant (Sherwood, 2002). Toracinta and Cecil (2001) determined that continental regions contained the highest concentrations of CCN, with the lowest concentrations found over open ocean regions. This variance in microphysical structure has been shown as one cause for higher concentrations of ice-phase precipitant over continental regions and lower concentrations over open ocean regions (Sherwood 2002). This variance in ice-phase precipitant between continental regions and open ocean regions were also speculated as one of the reasons lightning flash densities are generally higher over continental regions (Cecil et al. 2002a, b).

2.4.3 TRMM Measured Lightning Correlations

Cecil et al. (2002a, b) and Nesbitt et al. (2000) used the Tropical Rainfall Measuring Mission (TRMM)-based microwave imager (TMI) and lightning imaging sensor (LIS) to examine the intensity of convective areas; they found that the greatest lightning flash densities are recorded over continents, consistent with the fact that solar heating of the land produces higher values of CAPE. Convective systems over the open ocean are usually weaker than their continental counterparts because of lower CAPE values (Zipser and LeMone 1980; Jorgensen et al. 1985; Jorgensen and LeMone 1989), and as a result
yield much lower lightning flash rates (Zipser 1994; Cecil and Zipser 1999; Cecil et al. 2002 a and b; Nesbitt et al. 2000).

2.5 In-situ Hurricane Studies

Gray (1965), Jorgensen et al. (1985), and Black et al. (1994) used aircraft-measured vertical velocities to study the size and intensity of convective cores within the eyewall of mature hurricanes. A study of three mature hurricanes concluded that the mean vertical velocity within the eyewall was 4 m s\(^{-1}\) with an average updraft and downdraft diameter of 2.5 km (Gray 1965). Jorgensen et al. (1985) recorded vertical velocities during a total of 115 aircraft penetrations of 4 mature hurricanes, finding the average updraft velocity to be \(~ 4 - 5\) m s\(^{-1}\) at 5 km. Black et al. (1994) found similar results for Hurricane Emily of 1987; however Black et al. (1994) measured strong updrafts (> 20 m s\(^{-1}\)) during a time when Hurricane Emily underwent a period of rapid intensification. Using aircraft Doppler radar to derive vertical velocities in hurricanes, Black et al. (1996) found that 70% of the hurricane eyewall penetrations contained updrafts < 2 m s\(^{-1}\), with \(~ 5\% containing vertical velocities >5 m s\(^{-1}\). The typical vertical velocities found in the eyewalls of a mature hurricanes are therefore relatively weak when compared to continental thunderstorms, which can have updrafts >30 m s\(^{-1}\). These small updraft velocities have been related to the lack of CAPE within the eyewall region of mature hurricanes (Bogner et al. 2000; Emanuel 1986). As a result, lightning outbreaks within the eyewall of mature hurricanes should be a rare event compared to continental convective systems. However, strong convective updrafts, which may occur during rapid...
intensification events, as studied by Black et al. (1994), could contain vertical velocities that are strong enough to produce eyewall lightning outbreaks.
CHAPTER 3. DATA AND METHODS

3.1 LLDN

The lightning data used in this study were obtained from the archives of the long-range National Lightning Detection Network (LLDN) operated by the Vaisala Thunderstorm Group (Cummins et al., 1998, 1999; Cramer and Cummins 1999; Demetriaides and Holle 2005). First implemented in 1996, the LLDN initially comprised all the sensors in the U.S. National Lightning Detection Network (NLDN) (Orville et al. 2002). In 1998, the coverage, detection efficiency, and location accuracy were all improved with the addition of sensor information from the Canadian Lightning Detection Network (CLDN). At the time of the two hurricanes used in this study (2005), the LLDN comprised 187 sensors (Cummins, 2006).

The LLDN detects very low frequency (VLF) electromagnetic waves reflected from the ionosphere to determine lightning strike locations. The range of the LLDN data used in this study is an order of magnitude greater than that of the NLDN data used in previous hurricane studies (Samsury and Orville 1994; Molinari et al. 1994, 1999), allowing for a more complete documentation of the lightning evolution in Hurricanes Rita and Katrina. As a result of the reversal of the polarity of the signal with each ionospheric reflection, this method of detection makes it impossible to determine the strike polarity. The network also suffers in a small region just north of Cuba, where linear bands of false strikes appear. These linear patterns were also observed in previous lightning studies (Molinari et al. 1994, 1999) and are explained in more detail by Molinari et al. (1999).

The detection efficiency of the network depends on the strike strength, its distance from the network, and time of day (Cummins 2006) (Fig. 1). Strong strikes (greater than
30-kA peak current) and strikes that are close to the network are detected more efficiently. Also, there is a diurnal variation in detection efficiency as a result of the VLF detection method and ionospheric dynamics, with the detection efficiency being greater during nighttime hours. Given the tracks of Hurricanes Rita and Katrina, the detection efficiency values ranged from ~75% to 95% (Fig. 1). This study does not explicitly account for variations in detection efficiency, but in objective applications of lightning data, such as data assimilation into numerical weather prediction models, the variations in detection efficiency need to be taken into account. For this purpose modeled detection efficiency can be used (Cummins, 2006).

Cramer and Cummins (1999) conducted a location accuracy study within the NLDN, using both NLDN and LLDN detection methods. They concluded that median location accuracy of the LLDN detected strikes is ~ 5 km. The vertical sections of lightning bolts provide the strongest signal for the NLDN and LLDN to detect. The location of the lowest couple of kilometers of each strike is often vertical, whereas the higher portions of the lightning bolt may be more horizontal in orientation. Therefore, the lateral displacement of each strike from its cloud origin is not exactly known, but will likely fall within the radius of the median displacement accuracy.

3.2 TRMM

The Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) is a passive radiometer sensor that receives radiation in nine wavelengths. Brightness temperatures from the vertically polarized 85 GHz channel are used in this study (TRMM product 1B11). Also, the hydrometeor profile product is used to estimate the horizontal
and vertical distribution of precipitation-sized ice (for details on algorithm 2A12 see http://disc.sci.gsfc.nasa.gov). The algorithm generates vertical profiles of hydrometeors for 14 levels by combining TMI brightness temperature data with dynamical cloud models. For both the vertically polarized 85 GHz channel and the Hydrometeor Profiler, the scan width is 878 km wide and the ground resolution is 5 km.

### 3.2.1 85 GHz

Passive microwave brightness temperatures at 85 GHz have been used in various studies to determine the vertical development and related strength of convective systems (e.g., Mohr et al. 1999; Cecil and Zipser 1999; Nesbitt et al. 2000; Cecil et al. 2002a, b; Lee et al. 2002). The 85 GHz channel brightness temperature is sensitive to radiation scattering by precipitation sized ice particles. The brightness temperature decreases with deeper vertical distributions, and greater density of these hydrometeors. Nesbitt et al. (2000) and Cecil et al. (2002a, b) also concluded that the frequency of lightning flashes was higher for convective systems in the tropics with lower 85 GHz temperatures.

### 3.2.2 Precipitation Ice

The TMI hydrometeor profile product is able to calculate precipitation-sized ice concentrations (g m$^{-3}$) for various vertical levels. After examining all vertical levels above 5 km, it was determined that level 12 (corresponding to 8 - 10 km elevation) showed the greatest contrast between images taken during times of high strike density and images taken with little or no lightning present. When comparing images from different times and days, as well as comparing different areas within the same image,
stronger convection produces greater precipitation ice concentration (PIC). The greater PIC values are also lifted higher into the atmosphere as a result of the enhanced vertical velocities within the area of active convection; therefore, contrasts were most pronounced at higher levels, which warranted the uses of level 12. Similar contrasts were also seen at level 10 (5 - 6 km) and level 11 (6 - 8 km), however they were less pronounced than those at level 12. A study by Fiorino (2006) examined the accuracy of the TRMM PIC product by comparing TRMM derived PIC values with in-situ aircraft PIC measurements. Finding that with in level 12 the TRMM PIC product tended to slightly underestimate actual values by ~ 20%. When comparing the lower level values of TRMM derived PIC found in Hurricanes Rita and Katrina it is seen that these values are close to the in-situ radar derived values in the hurricane studies by Black (1990) and Gamache et al. (1993).

3.3 Aircraft

The flight level and radar data were collected by the National Oceanic and Atmospheric Administration (NOAA) WP-3D aircraft during numerous flight missions through both TCs. The data used in this study were then obtained from the Hurricane Research Division (HRD).

3.3.1 Radar

Plane Position Indicator (PPI) images were provided by the lower fuselage (LF) radar (5.59 cm wavelength). The radar is a 360° horizontally scanning fan beam radar with a vertical beam width of 4.1°, and a horizontal width of 1.1°. The full scan period of the radar is ~ 30-seconds (The National Oceanic and Atmospheric Administration
Aircraft Operations Center website). The LF radar is affected from both inadequate beam filling as well as attenuation, however during hurricane missions measurement errors as a result of inadequate beam filling are more significant (Marks 1985). Inadequate beam filling occurs when the pulse volume of the radar beam is not filled with homogenous precipitation; when this happens there is a reduction in the strength of the return signal, and a reduction of the actual value of the highest reflectivities contained within the radar pulse volume. The beam width increases as its distance from the radar increases, so the pulse volume becomes larger, increasing the effect inhomogeneous precipitation has on the strength of the return signal. The reduction of return signal as a result of inadequate beam filling during hurricane missions was examined as a function of LF radar altitude and radar distance from target (Marks 1985). At an altitude of 1500m (3000m) at a range of 75 km, mean signal loss was -3 dBZ (~5dBZ). The PPI images used throughout this study are single scans, at various altitudes from 1500 to 2800 m, taken while the P-3 aircraft was within storm center. The analysis within this study focuses on the eyewall regions of both hurricanes, which are always < 70 km from the radar.

Vertical reflectivity profiles (VRP) used in this study are composite images created by the Hurricane Research Division (HRD) from data recorded by the tail mounted Doppler (TA) radar aboard the P-3. The TA radar has a 3.22 cm wavelength, and operates using a 2.07° aft beam width and a 2.04° fore beam width. The radar operates in range height indicator mode (RHI) and the scan period can be adjusted from 0 - 10 revolutions per minute. The TA also suffers from inadequate beam filling, however as a result of the shorter wavelength the effect of attenuation is more of a problem during hurricane missions. Attenuation is a weakening of the radar beam, as the
energy of the beams is lost due to scattering and absorption by hydrometeors. The TA radar experiences a sharp attenuation of the signal just below the radar, while it is pointing downward, which is then poorly interpreted by the composite computer program at the HRD (Gamache, Hurricane Research Division 2006, personal correspondence). The sharp attenuation of the radar is seen in the VRP as the vertical discontinuity of reflectivity values at and below the altitude of the radar. The highest altitude radar flight used in this paper is ~3000 m, thus the altitudes of interest (> 5 km) will not be affected at all by this attenuation problem. The VRPs used in this study are comprised of ~20–30 minutes of TA radar data gathered during radial passes through eyewall by the P-3 aircraft. These data are then processed at the HRD into a single, storm relative, VRP.

3.3.2 In-situ

Vertical and horizontal wind speeds are measured along the aircraft flight path with a sampling rate of 1 Hz. The vertical wind is measured by adding the vertical speed of the aircraft relative to the earth and the vertical wind speed relative to the aircraft. The aircraft vertical speed is calculated using an inertial navigation system, which measures the vertical acceleration of the aircraft (Jorgensen 1984). The vertical wind speed relative to the aircraft is computed using the true air speed of the aircraft as well as the attack, pitch, roll, and sideslip angles of the aircraft. Once these are summed together the vertical wind speeds are resolved with an accuracy of ±0.5 m s⁻¹, within a range of ±20 m s⁻¹ (National Oceanic and Atmospheric Administration’s Aircraft Operations Center website). The environmental horizontal wind speeds are also calculated using the
aircraft true air speed and attack, pitch, roll, and sideslip angles, along with the inertial navigation calculated aircraft track. The horizontal wind speeds are then accurate to \( \pm 1 \text{ m s}^{-1} \), with a range of \( \pm 212 \text{ m s}^{-1} \) (National Oceanic and Atmospheric Administration’s Aircraft Operations Center website). The aircraft position via global positioning system is also included in the 1-second data supplied by HRD, and is used throughout this study to give the aircraft position relative to the hurricanes.

3.4 G.O.E.S.

The GOES-12 satellite area files were obtained from the National Environmental Satellite, Data, and Information Service (NESDIS). The files were processed into standard 4 km resolution infrared images using the Man computer Interactive Data Access System (McIDAS-X) imaging software. Lightning strike data were then overlaid onto the satellite images using the same software.
CHAPTER 4. RESULTS

Hurricanes Rita and Katrina were very similar storms in terms of genesis region, track, and mature lifetime. Hurricanes Rita and Katrina were also two of the most intense hurricanes in the historical record, attaining minimum central pressures of 895 mb and 902 mb respectively (Knabb et al. 2005, 2006).

4.1 Rita

The density of cloud-to-ground lightning strikes produced within the eyewall of Hurricane Rita was the largest ever detected by the NLDN or LLDN. Molinari et al. (1999) recorded the radial distribution of lightning strikes for 20 km radial bins, in units of number of strikes per 100 km X 100 km per day = (100 km)$^2$ day$^{-1}$. The study first normalized all radial bin totals by (100 km)$^2$; because the total number of hours of lightning data varied for each storm, the totals were then normalized by 24 hours. Molinari et al. (1999) found the highest eyewall region (0 - 40 km) strike count of 225 strikes (100 km)$^2$ day$^{-1}$ in a marginal hurricane (Hurricane Bob of 1985). The most intense hurricane examined was Hurricane Andrew (minimum surface pressure of 922 mb), with the eyewall region (0 - 40 km) only producing 140 strikes (100 km)$^2$ day$^{-1}$. For comparison the eyewall region (0 - 50 km) of Hurricane Rita produced 986 strikes (100 km)$^2$ day$^{-1}$. Although similar data sets are being compared, Molinari et al. (1999, NLDN) and the LLDN used in this study, differences in detection efficiency (DE) must be taken into account. However, these DE differences are not large enough to explain the observed differences in the eyewall flash rates.
Lightning data discussed for Hurricane Rita begins on 21 September at 0000 UTC and ends just prior to landfall on 23 September at 2300 UTC. Lightning data were divided hourly into 25 km annular rings beginning at storm center and continuing outward to 300 km. Following Molinari et al. (1999) the radial bins were grouped into three main regions, the eyewall (0–50 km), inner rainband (75 - 175 km) and outer rainbands (r > 175 km). The strike density maximum for Hurricane Rita was contained within the eyewall region, not in the outer rainband region (Fig. 2). The 0 - 25 km bin of Rita contained a total of 5608 strikes (100 km)$^{-2}$, which is ~7 times larger than any one of the outer rainband bins.

Three eyewall outbreaks occurred during the 71 h period beginning at 0000 UTC on 21 September 2005 (Fig. 3). The first outbreak reached a maximum at 1600 UTC on 21 September, during a period of rapid intensification (as defined by a 15 m s$^{-1}$ increase in maximum sustained winds in 24 hours), where the central pressure of the TC dropped 68 mb in 22.5 h. A second outbreak occurred at the end of the period of rapid intensification, between 2300 UTC on 21 September and 0700 UTC on 22 September during the time Rita reached maximum intensity. A final outbreak at 1800 UTC on 22 September was much smaller than the first two both in intensity and duration.

4.1.1 Rapid Intensification Eyewall Lightning Outbreak

The first eyewall lightning outbreak contained the highest strike rate in this study, producing a maximum hourly strike density of 474 strikes (100 km)$^{-2}$. The outbreak began at 1400 UTC, 10 hours after the TC begun to rapidly intensify, and lasted ~ 5 h.
The eye had begun contracting earlier in the day (Knabb et al. 2005) and now was ~ 40 km in diameter (as measured by PPI radar in Fig. 4).

During the time of this outbreak, aircraft-measured reflectivity shows that the eye was completely enclosed and relatively axisymmetric in structure (Fig. 4). However, reflectivity values varied around the eyewall, with the northwest and southeast containing the highest reflectivity values (> 40 dBZ). During this outbreak lightning strikes were detected in every region of the eyewall. However, strike density maxima is located in the northwestern and southeastern regions of the eyewall coinciding with higher reflectivity values. This asymmetric pattern in strike density lasts for the duration of this outbreak. For all PPI images lightning strike locations are overlaid throughout the entire image to further display the lightning distribution within the two Hurricanes. Because of effects of attenuation and inadequate beam filling previously discussed, each of the aircraft PPI radar images contain a 70 km range ring demarcating the nominal effective range of the LF radar. Therefore the qualitative correlation between aircraft PPI radar reflectivity and lightning strike locations will only be accounted for within the 70 km range ring (Marks 1985). The fact that an overwhelming majority of the strikes were detected within 5 km of maximum eyewall reflectivities in Fig. 4 is consistent with the known relationship between high lightning rates and enhanced convective precipitation, whereas it also acts to verify the location accuracy of the LLDN.

The TA VRP images at various locations around the eyewall show a well-developed outward tilt of the eyewall (Fig. 5). At this time Hurricane Rita displays relatively deep convection for a mature hurricane eyewall region (Figs. 5a,c, d), containing reflectivities of 30 dBZ above the melting level, with a gradual decrease of
reflectivity with height. The attenuation correction problem previously discussed is very
evident in all the images in Fig. 5. The marked discontinuities at flight-level (~ 3000 m),
with decreased values below the aircraft make the use of any data below 3000 m
impossible. However, all the data above the aircraft's flight level are not affected at all by
this severe attenuation problem, and it is within reason to evaluate those data at and
above ~ 4000 m.

Flight-level updraft velocities in the eyewall are substantial, with maximum
velocities measuring > 4.5 m s\(^{-1}\) for each eyewall penetration (Fig. 5). The northern
eyewall pass recorded the strongest eyewall updraft for any radial pass for either storm,
with a peak velocity of 16.5 m s\(^{-1}\). Within this updraft, vertical velocities > 7.5 m s\(^{-1}\)
were observed over a distance of 2 km (Fig. 5a). This radial leg also contained the
greatest number of lightning strikes, with 16 strikes detected in the range of 12 to 28 km
from the center of Rita.

The minimum in strike density within the inner rainbands is a feature Hurricane Rita
shares with previously studied TCs. This region of minimum strike density in Hurricane
Rita was due to the stratiform nature of the cloud development in that region, as seen in
previous studies (Molinari et al., 1994, 1999). All of the VRPs contain a region 50 to 90
km outward of the eyewall characterized by a stratiform reflectivity and a bright-band
signature with almost no vertical development. These bright-band cells outward of the
eyewall are the result of frozen particles falling and melting in the presence of weak
vertical updrafts (Szoke 1986; Yuter and Houze 1995). These bright band cells reside in
the inner rainband region and coincide with the strike density minimum measured in this
study.
The TRMM image shown in Figure 6 was taken just minutes prior to the time of the detected maximum eyewall strike rate. More than 150 cloud-to-ground strikes were detected within the eyewall region from 1520 UTC to 1600 UTC (Fig. 6a). The entire eyewall contained brightness temperatures < 200 K, with most of the eyewall colder than 170 K. According to the study by Cecil et al. (2002a) 85 GHz brightness temperatures <170 K are extremely cold and are rarely found within the eyewall of a hurricane. A frequency study of 261 TRMM overpasses of mature hurricanes concluded that 85 GHz temperature pixels measuring < 170 K are in the 95th percentile of all the mature hurricane eyewalls.

There is a lower strike density in the western region of the eyewall during this time that coincides with warmer brightness temperatures in that area. However, during this outbreak, lightning data do not show an eyewall region void of detected lightning strikes when viewed for periods on the order of ~1 h.

The eye is completely surrounded by PIC > 0.6 g m⁻³ at this level, (Fig 6b). The highest PIC observed, 0.7 g m⁻³, is in the northeastern region of the eyewall, and corresponds to an area of enhanced strike density during the time of the image. PIC reaches a maximum in the eyewall, with values dropping off quickly as you move radially outward (Figs. 5a and 6b). The maximum PIC occurred just outward of aircraft measured maximum radar reflectivity and vertical velocity (Fig. 5a). This 4 – 5 km outward displacement of the PIC maximum from reflectivity maximum can be attributed to advection and the outward tilt of the eyewall with height.
4.1.2 Minimum Central Pressure Eyewall Lightning Outbreak

The second eyewall lightning outbreak was the longest of the three outbreaks, lasting ~8 hours. During this period the eyewall produced a strike density of 1234 strikes (100 km)$^2$, with a maximum hourly density of 169 strikes (100 km)$^2$. This outbreak coincided with NHC estimated maximum intensity reached at 0300 UTC on 22 September, and with a minimum eyewall diameter of ~29 km (Knabb et al. 2006). However, the second outbreak was not as well sampled as the other two, with no aircraft data available and only one TRMM pass toward the end of the period at 0810 UTC.

Eyewall lightning strikes during this time are co-located with the coldest brightness temperatures, located in the north and northwestern part of the eyewall (Fig. 7a). During the time of this image, Hurricane Rita was moving to the west-northwest and had begun to weaken, after reaching maximum intensity ~5 hours earlier. The 40 minutes of lightning data included in the image took place during the end of the eyewall outbreak, and included only 20 eyewall strikes. At this time the 200 K brightness temperature contour is no longer symmetric about the eye. The brightness temperatures within most of the southern quadrant of the eye have risen to ~225 K. However, this TMI recorded a brightness temperature of 139 K, which is the coldest 85 GHz temperature measured throughout these two days.

During this time the PIC that completely surrounded the eye dropped from 0.6 g m$^{-3}$ to ~0.4 g m$^{-3}$ (compare Figs. 6b and 7b). However, Fig. 7b also contains the highest PIC values recorded during the two days, with several values > 0.8 g m$^{-3}$. The low PIC content in the southern portion of the eyewall is most likely associated with the lack of convective updrafts within that region of the eyewall, resulting in the inability to support
a high amount of precipitation-sized ice in 8 – 10 km layer (Fig. 7b). The early developments of the outer eyewall is seen in Fig. 7b, as a large band of relatively high PIC ~75 km west of the center of the TC, and it is shown to become circular and more organized in Fig. 10 (further evolution of the eyewall replacement cycle is shown in Figs. 12 and 13).

After 0700 UTC 22 September the eyewall strike density steadily decreased until it reached zero at 1200 UTC. Eyewall strike rate remained low for most of the following 24 hours, with 10 or more eyewall lightning strikes occurring in only 2 of those hourly periods. The low eyewall strike density observed during this period is consistent with results found for previous mature or weakening hurricanes (Molinari et al. 1999).

An aircraft eyewall penetration occurred during a time when the strike density was less than 7 eyewall strikes per hour, with only 1 detected eyewall lightning strike during the included 20-minute period (Fig. 8). This lone strike was located in the northwestern region of the eyewall, which contained the highest flight level (~2.4 km) reflectivities at the time. The convective asymmetry in the inner eyewall is clearly seen in Fig. 8, and when contrasting the two VRP images (Fig. 9). Figure 9b contains no reflectivity values > 25 dBZ within the decaying inner eyewall region (10 - 20 km). Note that Figure 9b does not contain PIC data because there was not a corresponding TRMM pass at that time. For both images the inner eyewall region lies in the region 10 – 25 km from the center of the image (Figs. 9a and b). Figure 9a contains higher inner eyewall reflectivities at all levels, with a maximum reflectivity of 35 dBZ well below the melting height. Inner eyewall vertical velocities for figure 9a are double that of 9b, showing 7.5 m s\(^{-1}\) and 3.5 m s\(^{-1}\) respectively.
The reflectivities in the eyewall at this time were weaker than the reflectivities recorded on the previous day (Compare Figs. 9 and 5). Figure 9 shows maximum reflectivity values below the melting level, and reflectivity values falling off rapidly with height above the melting level. This type of vertical reflectivity profile is consistent with weak convection that is associated with little or no cloud to ground lightning (Szoke et al. 1986; Zipser and Lutz 1994).

The 85 GHz image indicates the lack of convective development within the inner eyewall during this time (Fig. 10a). No inner eyewall strikes were detected within 15 minutes from the time of this TRMM TMI image. Approximately 60% of the inner eyewall region contains brightness temperatures warmer than 200 K.

PIC within the inner eyewall region has also decreased since the last TMI pass (compare Figs 10b and 9b). The southern section of the inner eyewall contains PIC values < 0.2 g m\(^{-3}\), with the more convective northern section producing a maximum value of 0.8 g m\(^{-3}\). The western half of the outer eyewall has contracted since the last TRMM pass, however it still contains no PIC values > 0.5 g m\(^{-3}\), and no lightning strikes detected during this time.

4.1.3 Inner Eyewall Lightning Outbreak

The third and final eyewall outbreak took place over 2 hours, occurring prior to the completion of the eyewall replacement cycle. The outer eyewall can be seen in Figs. 11 and 12. The outer eyewall seen in Fig. 11 displayed as an enclosed ring of high reflectivity ~ 50 km from the center of Hurricane Rita. The outer eyewall is also clearly seen in Fig. 12a as the secondary area of high reflectivity (< 40 dBZ) 40 – 50 km from
storm center. During this time the inner eyewall flash density was 72 strikes \((100 \text{ km})^2\), with a maximum hourly strike density of 36 strikes \((100 \text{ km})^2\).

A large majority of detected strikes were within the northern region of the inner eyewall. At this time, the convection within the north and western regions of the inner eyewall was the most intense measured by aircraft radar during the past two days. Both radial passes contain inner eyewall reflectivity values exceeding 30 dBZ above the melting level \((\sim 5 \text{ km})\). The northern eyewall pass shows 35 dBZ reflectivities above 9 km, and a maximum reflectivity value > 40 dBZ around 2 km (Fig. 12a). During the time of the outbreak, this convective area included approximately 30% of the entire inner eyewall, extending continuously around the eye from 195° to 015° azimuth. This area of convection lasted for at least 5 hours, and remained present in the last aircraft eyewall penetration on the 22 September at 2202 UTC. Although this outbreak was collocated with convection that was notably more intense than that sampled during the first outbreak, the one-hour peak strike rate produced by this outbreak was only 8% of that produced by the first outbreak.

Later in the day, ~ 2 h after the images in Figs. 11d and 12a were taken, the WP-3D aircraft penetrated the core of Hurricane Rita it measured a secondary maxima in tangential wind speed associated with the developing outer eyewall (Fig. 13).

4.2 Katrina

Lightning data for Hurricane Katrina include all hours from 0000 UTC 27 August to 0900 UTC 29 August. Data collected prior to 0000 UTC 27 August were not included in this study, because of detection errors associated with the geometry of the LLDN over
Florida. Like Rita, Hurricane Katrina also contained an unusually large amount of
eyewall lightning. The eyewall (0 – 50 km) of Hurricane Katrina produced at total of
1684 strikes (100 km)$^2$ over the examined period, which equates to a strike density of
709 strikes (100 km)$^2$ day$^{-1}$. The total strike density maximum was detected within the
0-25 km radial bin, containing 2973 strikes (100 km)$^2$ during the 57-hour period (Fig.14).
Similar to Rita, a minimum in strike density occurs within the inner rainband region, and
the secondary maximum in the outer rainband region (Fig. 14).

Hurricane Katrina contained 2 major lightning outbreaks in the eyewall during the
two-day period, along with a period of intermittent eyewall lightning (Fig. 15). The first
outbreak reached a maximum at 0300 UTC 27 August and, similar to Hurricane Rita, this
outbreak occurred in the middle of a period of rapid intensification. Also very similarly
to Rita, the second eyewall outbreak occurred during the time when maximum intensity
was reached, between 1300 UTC and 2200 UTC on 28 August. The third and final
period to be examined is a time of intermittent eyewall lightning outbreaks occurring
from 1700 UTC 27 August to 0000 UTC 28 August.

4.2.1 Rapid Intensification Eyewall Lightning Outbreak

Hurricane Katrina’s first lightning outbreak displayed the greatest hourly strike
density, containing 287 strikes (100 km)$^2$. However, this outbreak was short-lived,
lasting $< 2$ h. The outbreak occurred ~ 3 hours prior to the end of the first of two periods
of rapid intensification (RI). At this time Katrina was moving west-southwest at 3.5 m s$^{-1}$,
with maximum sustained surface winds of 45 m s$^{-1}$ located in the southeastern quadrant
(Knabb et al. 2005).
Unlike Hurricane Rita this eyewall lightning outbreak was asymmetric, with the majority of strikes detected in the southeastern quadrant of the eyewall (Fig. 16b). Figure 16a show less than 10 eyewall strikes contained within the TRMM image, catching the tail end of the short-lived outbreak. However, the convective feature and asymmetry of the eyewall are still clearly visible in the 85-GHz image, with the area still containing brightness temperatures < 200 K. PIC, in 8-10 km layer is also shows a maximum in the southeastern quadrant of the eyewall, with TRMM PIC values > 0.62 g m\(^{-3}\) (Fig. 17).

4.2.2 Inner Eyewall Lightning Outbreak

The next time period examined is later in the day on the 27 August, during this time Hurricane Katrina was moving due west at 3 m s\(^{-1}\), with estimated maximum sustained surface winds of 51 m s\(^{-1}\). Between 1635 UTC August 27 and 1705 UTC August 27 the WP-3D aircraft made a southeast to northwest pass through the inner core of the hurricane at ~ 3000m (Fig. 18). The aircraft recorded a double maximum in tangential wind indicating that Hurricane Katrina was undergoing an eyewall replacement cycle. The flight-level peak wind was measured in the southeast pass of the newly forming eyewall at 49 m s\(^{-1}\) at 16:44:40. Lightning within the eyewall during this time became intermittent; with hourly strike rates varying from 0 to 50 strikes (100 km)\(^{-2}\). This period of intermittent eyewall lightning began at ~1700 UTC 27 August in the middle of what appears to have been an eyewall replacement cycle and lasted approximately 10 hours.

The remnants of the inner eyewall are seen as the area of highest reflectivity within the newly formed eyewall (Fig. 19a). The image Fig. 19a was taken in the middle
of a 2-hour period (1730 - 1930 UTC 27 August), during which only two strikes were
detected within the eyewall region. However, between 1630 UTC and 1730 UTC on 27
August 26 eyewall strikes were detected in the southeastern region encompassing the
remnant eyewall rainband. During the entire 10 hours of intermittent eyewall lightning
> 80% of strikes detected were emanating from the region of the remnant inner eyewall
band (Fig. 19c). The near absence of eyewall lightning in Figs. 19a and b reflects the
observation that these smaller eyewall outbreaks were intermittent and short-lived.

All of the detected eyewall strikes for the period of 1930 UTC - 2030 UTC 27
August occurred between 1930 UTC and 1940 UTC 27 August; therefore no lightning
occurred during the time of Fig. 19b. However, the GOES-12 IR image (Fig. 19c) shows
that most of the eyewall strikes occurred in the southwest region of the eyewall. In fact,
during the entire 10 hours of intermittent eyewall lightning over 80% of strikes detected
were in the southeastern quadrant of the storm. The absence of eyewall lightning in these
images also suggests that these smaller eyewall outbreaks were intermittent and short-lived.

At ~2100 UTC Hurricane Rita had a new slowly contracting eyewall and
sustained winds of ~50 m s\(^{-1}\). There were no eyewall strikes within a 40-minute period
centered on the time of the images in Fig. 20. The 85-GHz image shows temperatures <
200 K were located throughout the eastern and northeastern region, with the coldest
eyewall brightness temperatures in the eastern region of the eyewall (Fig. 20a). PIC is
also at a maximum in the eastern region of the eyewall (Fig. 20b). However, the
maximum values of PIC in the eyewall have dropped slightly, with only 3 TRMM values
above 0.6 g m\(^{-3}\) (compare Figs. 20b and 17). After this image was taken, 56 eyewall
strikes were detected from 2200 to 2230 UTC 27 August, with all but 2 of the strikes detected in the southeastern region of the eyewall.

As Katrina begins to undergo the second of its two periods of rapid intensification, further organization of the eyewall is seen, displaying deeper, more symmetrical convection (Fig. 21 and 22). Excluding a small section in the northern region of the eyewall, the entire eyewall contains PIC values > 0.45 g m\(^{-3}\) (Fig. 21b).

The low brightness temperatures (<150 k) and high ice values (> 0.8 g m\(^{-3}\)) in Fig. 21 are upshear from the area of highest strike density on the northeast side of the eyewall. The pixel nearest to the group of lightning strikes shown at 25.2N 86.1W measured the highest value at this vertical level for either storm at 0.9 g m\(^{-3}\).

A sharp gradient in brightness temperatures is located near the concentration of strikes, with a much weaker gradient upwind of the strikes. Examination of a rapid scan loop of GOES-IR images overlaid with lightning data (not shown) during the time of this TRMM image (Fig. 21), shows a localized lightning outbreak moving cyclonically around the eastern region of the eyewall, presumably moving along with a convective tower. It is suggested that ice particles ejected upward from the convective tower would trail upwind of the convection due to decreasing tangential wind speed with height. However, it is difficult to prove this hypothesis in the absence of continuous in-situ aircraft reflectivity and tangential wind data.

4.2.3 Minimum Central Pressure Eyewall Lightning Outbreak

Hurricane Katrina attained maximum intensity at 1800 UTC on 28 September, with estimated minimum central pressure of 902 mb and maximum sustained surface winds of
77 m s\(^{-1}\) (Knabb et al. 2005). The third and final eyewall outbreak started at 1300 UTC on 28 September and continued for approximately 9 hours, reaching a maximum strike density of 128 strikes (100 km\(^2\)) \(h^{-1}\) at 1800 UTC. This outbreak was more symmetrical than the previous two, with strikes detected in every azimuth of the eyewall. During the 9-h period this outbreak produced an average strike density of 64 strikes (100 km\(^2\)).

Figure 22a shows that reflectivity values in the eyewall do not vary greatly throughout different sections of the eyewall. However, slightly higher reflectivities were observed in southeastern and northern region of the eyewall, and these regions also contained higher strike densities. This asymmetric pattern of active convection and the maxima in strike density both remained stationary relative to storm center for the remainder of the outbreak, with the strike density increasing in the south-southeastern region of the eyewall as the outbreak came to an end (Figs. 22b and c).

VRP's show that northeast and southwest regions of the eyewall contained maximum reflectivities below the melting level (~5 km), with 25 dBZ observed above 7 km (Figs. 23a and b). These two azimuths both contain relatively little lightning during the time of the pass, with lightning detected cyclonically downwind of each. The airplane pass through the northwest region of the eyewall recorded reflectivities that decrease rapidly with height above the melting level, which is characteristic of weak convection (Fig. 23c). This radial pass also contains the least amount of lightning when compared to the other passes through the eyewall. Downwind of the northwest eyewall pass, the western and southwestern regions of the eyewall contain the least lightning during the outbreak.
The deepest convection measured within the eyewall during this outbreak period was in the 180° azimuth (Fig. 23d). This radial pass was flown approximately 5 hours after maximum intensity was reached, at the time when Katrina had begun to weaken. Reflectivities of 30-dBZ were measured above 8 km, with 20 dBZ extending to ~ 11 km. The flight level updraft for this part of the eyewall contained positive vertical velocities continuously for 15 km along the flight path. This azimuth also contains the greatest strike density, consistent with the strike distribution seen in Fig. 22c.

The peak values of PIC for both the 315° and 180° are both approximately 0.6 g m⁻³ (Figs. 23c and d). Therefore, in this case there is no obvious correspondence between PIC and strike density and higher reflectivity between these two azimuths, as the 180° section contained a much higher strike density throughout the outbreak. It is suggested that this lack of correspondence is due to the vertical shear of the horizontal wind with respect to the area of active convection. The wind advects the ice concentrations cyclonically around the storm, whereas the area of active convection remains stationary relative to storm center (Figs. 22b, c). The tangential wind speed ~ 25 – 30 km from storm center, at the PIC level 12 (8 – 10 km) are ~ 55 m s⁻¹ (Fig. 25). Taking the value of the diameter of the eyewall at this time to be ~ 90 km, ice particles advected upward to a height of 8-10 km would be displaced 90° cyclonically around the eyewall from the stationary convective source in only 20 minutes. The slightly higher values for the northwestern eyewall region could be because of its position downwind from more intense convection in the northern region of the eyewall.

On very small time and spatial scale there can be discrepancies found in the correlation between lightning strike density and PIC/Brightness temperatures. For
example, it is not apparent from the lightning strike locations in Figs 24a, b that detected lightning strikes coincide well with low brightness temperatures and highest PIC values. This image only contains lightning from 2102 -2142 UTC, during which time there was a brief reduction in eyewall strike density just before a last local maximum was reached at 2300 UTC (shown in Fig. 15). However these two images do correlate well with the spatial distribution of strike density that was present for most of the 9-h outbreak (Figs. 22 and 24c). The lowest 85 GHz brightness temperatures were located in the southeastern and northern regions of the eyewall, with the western eyewall region void of temperatures < 225 K. The PIC values are also highest in the southeastern and northern regions of the eyewall, with both of these eyewall regions containing TRMM pixel values > 0.73 g m⁻³, while the western region contained very little lightning during the 9-h period, values < 0.4 g m⁻³.
CHAPTER 5. SUMMARY AND CONCLUSIONS

Data collected by the National Long-Range Lightning Detection Network (LLDN), along with TRMM and reconnaissance aircraft data have been used to investigate the morphology of lightning outbreaks in the eyewalls of Hurricanes Rita (2005) and Katrina (2005). The LLDN network is one of few observing systems, outside geostationary satellite-based instruments, that provide continuous real-time data throughout a synoptic-scale coverage area over the open ocean. Given the small sample size in the analysis of only two hurricanes presented, some of the conclusions of this research are necessarily of a qualitative rather than a quantitative nature. Nevertheless, the correspondence of the lightning outbreaks with strong reflectivity and high precipitable ice concentrations inferred from aircraft and TRMM data, show that the LLDN data stream holds promise for future applications to assess hurricane convective structure and evolution.

5.1 Comparison between Hurricane Rita and Katrina

Both Hurricanes Rita and Katrina produced their greatest hourly eyewall strike density during their respective periods of rapid intensification. However, the morphology of these two outbreaks and their associated convective structures proved to be very different. Hurricane Rita’s eyewall outbreak lasted ~ 3 hours, and was quasi-symmetric about the eye, with cloud to ground lightning strikes detected in every azimuthal section of the eyewall. In contrast, Hurricane Katrina’s outbreak was asymmetric, with the all the eyewall strikes detected in the southeastern region of the eyewall. The bulk of the eyewall strikes occurred during ~ 20 minutes from 0325 UTC to 0345 UTC 27 August, a period much shorter than that of Hurricane Rita’s outbreak. Rita was a stronger storm
than Katrina at the time of its burst of eyewall lightning, and the symmetric character of the observed convection may have prevented wind shear from dissipating the electric field built-up by the convection, helping to prolong the outbreak.

During the eyewall replacement cycles the eyewall region produced brief periods of cloud to ground lightning. Hurricane Rita produced one outbreak, which lasted less than 2 hours, while Katrina produced multiple sub-hourly eyewall outbreaks. The hourly strike density of these outbreaks for both storms were ~ 50 strikes (100 km)$^2$. Aircraft radar data showed that the lightning outbreaks were produced by the decaying inner eyewall, and not by the developing outer eyewall in both storms.

One of the most intriguing results is that Hurricanes Rita and Katrina both contained a long-lived eyewall outbreak centered on the time when maximum intensity was reached. The eyewall strike densities during these periods of maximum storm strength were comparable, with hourly strike densities between 140 – 175 strikes (100 km)$^2$ for each storm. Hurricane Katrina’s eyewall outbreak reached a maximum within the same hour as minimum central pressure was reached (as estimated by the NHC). While the eyewall of Hurricane Katrina was completely enclosed and circular, eyewall strike density values were not quite symmetric about the eye, showing higher values in the southeast region of the eyewall.

5.2 Lightning, Radar Reflectivity, and TRMM

Aircraft radar reflectivities showed the best spatial correlation with lightning strikes. When areas of high strike density within the eyewall were detected they were invariably co-located with areas of high reflectivity (i.e. Figs. 4, 8, 11, and 20). The strength and
vertical development of convection was also correlated with high strike density. Areas of eyewall convection that contained 30 dBZ reflectivities at higher altitudes (i.e. > 7 km), along with reflectivity values that decreased slowly with height above the freezing level contained greater lightning strike densities.

The TRMM 85 GHz and PIC product both displayed spatial and temporal correspondence with the eyewall lightning. Low 85 GHz brightness temperatures and high PIC were not always indicative of the presence of eyewall lightning; however, when significant amounts of eyewall lightning were detected, low brightness temperatures and high PIC were always recorded within close proximity of the strikes. Moreover, the differences in location were consistent with advective processes. Two PIC eyewall averages were taken for Hurricane Rita at 3 different levels, one average for a time when there was high eyewall strike density, and the other when there were no detected eyewall strikes (Fig. 26). The period when the eyewall contained lightning strikes, higher PIC values were recorded at all levels when compared to the time of no lightning. The percent difference was greatest at level 12 (8-10 km), the level chosen for presentation throughout this study.

Fitting with the high intensity of these two hurricanes, the 85 GHz brightness temperatures within their eyewalls were also historically low when compared to the previous hurricane study by Cecil et al. (2002a,b). Cecil et al. (2002) found that less than 5% (10%) of eyewall pixels sampled measured values < 150 K (175 K). The eyewalls of Hurricane Rita and Katrina contained more than 20% (75%) of their eyewall pixels < 150 K (175 K).
Maximum vertical velocities observed in flight-level data in the eyewalls of Rita and Katrina varied from 3 m s\(^{-1}\) to 16.5 m s\(^{-1}\). The single highest vertical velocity (16.5 m s\(^{-1}\)) was measured during the time of highest eyewall strike density, however a more general correlation was not found. It is suggested that the lack of correlation is the result of limited sampling in rapidly evolving convection and the healthy tendency for reconnaissance pilots to avoid convective cores.
CHAPTER 6. DISCUSSION

6.1 Impact of a Coastal Proximity Limitation

Using the NLDN data, M99 was forced to limit the analysis of lightning data to times when TCs centers were within 400 km of at least two direction finding (DF) sensors. However, the use of the LLDN in this study allowed continuous monitoring of Hurricanes Rita and Katrina, and did not require the implementation of the coastal proximity limitation (CPL) used in M99. It is of interest to see if the results presented here would differ if the same CPL restriction was applied (Table 1).

In contrast to the results presented in M99, eyewall lightning represented a dominant contribution of the lightning distribution of these two hurricanes. In fact eyewall cloud to ground strikes were detected more often then not during these two Hurricanes. When the CPL is used we see that the percent of hourly observations decreases dramatically for Rita, while it remains nearly unchanged for Katrina.

M99 concluded that intense hurricanes, those of the intensity of Rita and Katrina, would likely contain less eyewall lightning than hurricanes of weaker intensity. Hurricane Andrew (1994), a storm of similar intensity to Hurricanes Rita and Katrina was sampled by M99, and contained an eyewall flash density of 140 strikes (100 km)\(^{-2}\) day\(^{-1}\). If M99 CPL had been used in the study of Hurricane Rita, a very similar 145 strikes (100 km)\(^{-2}\) day\(^{-1}\) would have been recorded. However, the actual lightning data shows that the eyewall strike density for Hurricane Rita is 986 strikes (100 km)\(^{-2}\) day\(^{-1}\), which is nearly an eight-fold difference. Hurricane Katrina also contains much more eyewall lightning than any of the hurricanes studied in M99; however unlike Hurricane Rita, when the CPL is implemented for Hurricane Katrina the eyewall strike density increases. It is possible
for Hurricane Katrina’s strike density to increase with the implementation of the CPL because the eyewall strikes category is not the total number of eyewall lightning strikes recorded during the period; rather it is the total number of eyewall lightning strikes recorded during the period which is then normalized by one day. Therefore, while the total number of eyewall strikes decreased with the implementation of the CPL, the average number of eyewall strikes per day actually increased; representing that a Hurricane Katrina’s eyewall was most lightning active while the storm was within 400 km from the coastline.

The length of lightning outbreaks also change significantly with the implementation of the CPL. The longest continuous eyewall lightning episode (defined as one or more detected lightning strikes in each hourly period) documented by M99 was 5-hours in duration. In contrast, the longest eyewall lightning episodes for Hurricane Rita and Hurricane Katrina lasted for 31 and 22 hours, respectively. Implementing the CPL reduces the longest continuous eyewall outbreak down to 12 hours for Katrina, and Rita’s longest is reduced down to only 4 hours.

The eyewall lightning produced by Hurricane Rita was more impressive than that of Hurricane Katrina, that is to say that Hurricane Rita had greater eyewall strike densities, and the highest single hour strike density (compare Figs. 3 and 14). The eyewall of Hurricane Rita also produced the longest lightning episode, with eyewall lightning lasting continuously for more than 24 h. However, if CPL is implemented, the conclusions would have been reversed, and eyewall lightning in Hurricane Katrina would have appeared to be the more significant of the two. In summary, the differences in the results produced by artificially restricting the data coverage to that of the NLDN

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highlight the value of the LLDN data stream for remotely observing lightning in tropical storms.

6.2 Implications of Lightning Morphology

Hurricanes Rita and Katrina both contained nearly symmetric eyewall lightning outbreaks during the period when maximum intensity was reached. During the time of maximum intensity the eye diameter for both Hurricane Rita and Katrina had reached a minimum, and radar and TRMM data showed evidence of enhanced convection. It is likely that vertical motion associated with the convection was also enhanced, thus promoting elevated rates of charge separation within the eyewall. The resulting strong symmetric electric field would not be prone to dissipation by wind shear effects and mixing prevalent in mature hurricanes (Black and Hallett 1994). The symmetric character of the charge separation process made it possible for the eyewall to sustain strong electric fields for extended periods of time and produce the recorded high strike densities.

In contrast, lower than expected strike densities can accompany very deep eyewall convection, if that convection is asymmetric about the eyewall, as observed in Hurricane Rita (i.e., Figs. 11 and 12). The large vertical shear of the horizontal winds within the eyewall of mature hurricanes can cause locally enhanced charge separation created by intense asymmetric convection to be mixed out. This differential horizontal mixing would cause a rapid reduction in electric field strength and diminish cloud to ground strike density.
6.3 Applications of LLDN Lightning Data to Hurricanes

The possibility of using ground-based lightning detection to forecast intensity and structure change in hurricanes has been proposed in previous studies (Molinari et al. 1994, 1999; Samsury and Orville 1994). The results of this thesis provide additional evidence that changes in eyewall lightning morphology reflect changes in convective structure within the eyewall, and this evolution can be continuously monitored with the LLDN.

The strongest eyewall lightning outbreaks in both storms analyzed here occurred after the intensification period began, and thus provided no warning that the storm would intensify. However, outbreaks, which were centered on the time of maximum intensity, began ~4 – 5 h before maximum intensity was reached, a phenomenon also documented in M99. The specific dynamics associated with these eyewall outbreaks are still not understood, but their occurrence may provide forecasters with additional evidence that the storm is nearing maximum intensity.

Past investigators have capitalized on the correlation between convective rainfall and lightning rates to improve numerical forecasts of storms by assimilating latent heating rates derived from lightning data (Alexander et al. 1999; Chang et al. 2001; Papadopoulos et al. 2004; and Pessi et al. 2004). Similar correlations have been found between lightning rates and precipitable ice, which is less sensitive to the microphysical character of the air mass. Also, this thesis has added further support to the mean location accuracy of 5 km, which was concluded by previous LLDN location accuracy studies. Therefore, there is an opportunity to assimilate the LLDN data stream over data sparse regions to provide an important correction in the core of modeled tropical storms.
An example of how one could use LLDN lightning data to quantitatively examine the evolution of a hurricane's convective structure is illustrated in Fig. 27. By examining a time series of the radial distribution of lightning strike density, it is possible to show the eyewall contraction that took place as Hurricane Rita underwent rapid intensification. From 0300 UTC 21 September to 1200 UTC 21 September it is shown that most eyewall lightning took place in the 25 – 50 km radial bin. At ~ 1300 UTC the eyewall maximum began to switch to the 0 – 25 km eyewall bin, and by 1500 UTC the inner eyewall contained a lightning strike density twice that of the 25 – 50 km bin.

In summary, although only two storms are documented in this study, the results show promise for the use of continuous LLDN data to remotely infer the temporal evolution of hurricane convective structure. It is the hope of the author that this thesis will spur interest in the application of LLDN data to the challenges presented by tropical cyclones.
Tables

<table>
<thead>
<tr>
<th></th>
<th>Molinari et al. (1999)</th>
<th>Rita</th>
<th>Katrina</th>
<th>Rita (CPL)</th>
<th>Katrina (CPL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent of Eyewall Lightning</td>
<td>7%</td>
<td>70%(52%)</td>
<td>82%(60%)</td>
<td>45%(8%)</td>
<td>81%(10%)</td>
</tr>
<tr>
<td>Eyewall strikes ((10^4 \text{ km}^2 \text{ day}^{-1}))</td>
<td>140 (Andrew 1994)</td>
<td>986(1895)</td>
<td>709(1252)</td>
<td>145(15)</td>
<td>849(2,153)</td>
</tr>
<tr>
<td>Longest Duration of Continuous Eyewall Lightning</td>
<td>5 hours</td>
<td>31 Hours (25 Hours)</td>
<td>22 Hours (14 Hours)</td>
<td>4 Hours (1 Hour)</td>
<td>12 Hours (12 Hours)</td>
</tr>
</tbody>
</table>

Table 1. Comparing the results found by Molinari et al. (1999), with the results found in this study. All of Molinari et al. (1999) eyewall results were calculated using the radial bin 0 – 40 km from storm center. Percent of eyewall lightning is the percent of the total hourly observations which contained at least one single eyewall strike. Longest Duration of Continuous Eyewall Lightning is longest continuous period in which at least one eyewall strike was detected. Eyewall flashes for Molinari et al. (1999) is for the most intense storm sampled out of the nine studied. Percent of eyewall lightning and Longest Duration of Continuous Eyewall Lightning for Molinari et al. (1999) are both taken from the maximum value recorded of all nine storms examined. For Hurricanes Rita and Katrina the eyewall is defined as 0 – 50 km and (0 – 25 km). The middle column represents totals for the entire time period examined within this study, while the right-hand column only included data while the hurricanes were within 400 km from the coastline.
Fig. 1  Model derived detection efficiency contours (%) for the Gulf of Mexico region a) daytime b) nighttime (after Cummins, 2006). Hourly storm tracks for both Hurricane Rita and Katrina are displayed using hourly interpolations of best-track 6-h data obtained from National Hurricane Center. Strom track during times of local day (night) are represented by the black (grey) lines.
Fig. 2  Radial distribution of lightning strike density for Hurricane Rita between 20 September 1800 UTC and 23 September 0900 UTC. Strike totals normalized by the total number of strikes (100 km)$^2$. 
Fig. 3 Time series containing the number of cloud-to-ground strikes within 50 km of the center of Hurricane Rita (blue line), and hourly track of minimum central pressure (red line). Pressure values are linear interpolations of best-track 6 h data obtained from National Hurricane Center. Times when TRMM data (blue line) and aircraft data (green shading) were available are also indicated.
Fig. 4  NOAA P-3 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 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.
Fig. 5  Vertical reflectivity profile (VRP) composites created by the NOAA P-3 aircraft tail radar during radial eyewall cross-sections flown between 1506 UTC and 1617 UTC 21 September, aircraft altitude of 2,600 – 2,800 m. Overlaid onto each cross-section is flight level vertical velocity measured along the corresponding flight path (heavy solid line), along with radial lightning strike locations (red bars) during the time of the radial flight. a) 000°, with radial distribution of level 12 (8 – 10 km) PIC values (dotted line) obtained from the 21 September at 1540 UTC TRMM data. b) 090°, c) 170° and d) 270°.
Fig. 6  TRMM data collected as the satellite passed over the center of Hurricane Rita at 1540 UTC, lightning strike locations (circles) from 21 September 1530 UTC to 1550 UTC. a) 85-GHz TMI image with lightning (red circles).  
b) Level 12 (8-10 km) PIC image with lightning (black circles).

Fig. 7  TRMM data collected as the satellite passed over the center of Hurricane Rita at 0810 UTC, with lightning strike locations (circles) from 22 September 0750 UTC to 0830 UTC. a) 85-GHz TMI image with lightning (red circles).  
b) Level 12 (8-10 km) PIC image with lightning (black circles).
Fig. 8  As in Figure 4, but at an altitude of 2,700 m with a radar reflectivity for 22 September 1452 UTC. Superimposed the image is 20 minutes of lightning data (black circles) centered on the time of the image.
Fig. 9  As in Figure 5, but with data collected between 1435 UTC – 1638 UTC, 22 September. Aircraft altitude varied 2,600 – 2,800 m during each pass. Image a) contains level 12 (8 – 10 km) PIC values (thin line) obtained from the 1442 UTC TRMM pass. a) 225°, b) 135°.
Fig. 10  As in Figure 6, but with TRMM data for 1442 UTC 22 September. a) 85-GHz TMI, b) Level 12 (8-10 km) PIC. Note: no lightning strikes were detected within 30 minutes of the time of the image.
Fig. 11 As in figure 4, but reflectivity for a) 1720 UTC, altitude of 2,100 m b) 1751 UTC, altitude of 2,300 m c) 1806 UTC, altitude of 1,600 m and d) 912 UTC, altitude of 2,300 m.
Fig. 12  VRPs constructed from aircraft data collected from Hurricane Rita between 1702 UTC and 1818 UTC 22 September. Each image contains radial lightning strike locations (red bars) during the time of the corresponding radial flight leg. a) 000°, at an altitude 2,000 – 2,200 m and b) 270°, at an altitude 1,600 – 1,800 m.
Fig. 13  Aircraft Derived Tangential winds as measured at flight level (2,800 – 3,000 m).

Measurements were taken for a 30-minute period beginning at 2033 UTC September 22. The flight entered the northeast core of Hurricane Rita at ~ 30° and exited the eye eastbound at ~ 90°.
Fig. 14 Radial distribution of the total number of detected lightning strikes for Hurricane Katrina between 27 August 1800 UTC and 29 August 0900 UTC. Strike totals normalized by the total number of strikes (100 km)$^2$. 
Fig. 15  Time series containing the number of cloud-to-ground flashes within 50 km of the center of Hurricane Katrina (blue line), and hourly track of minimum central pressure (red line). Pressure values are linear interpolations of best-track 6 h data obtained from National Hurricane Center. Times when TRMM data (blue line) and aircraft data (green shading) were available are also indicated.
Fig. 16  (a) 85-GHz TRMM image taken of Hurricane Katrina at 0420 UTC 27 August, overlaid with lightning strike locations (black circles) from 0400 UTC to 0440 UTC.  (b) GOES-12 infrared satellite image taken at 0345 UTC 27 August, overlaid with lightning strike locations (red dots) from 0300 UTC to 0400 UTC.
Fig. 17  TRMM layer 12 (8 – 10 km) PIC image of Hurricane Katrina for 0420 UTC 27 August, overlaid with lightning data (black circles) from 0400 UTC – 0440 UTC.
Fig. 18 Aircraft measured tangential winds in the Hurricane Katrina for a 30 minute period beginning at 1635 UTC 27 August. The inner core pass entered the eye from the southeast at ~ 135° and exited to the northwest at ~ 315° direction, with flight level 2,900 - 3000 m.
Fig. 19  As in Fig. 4 but with radar reflectivity for Hurricane Katrina for 27 August
a) 1759 UTC b) 2007 UTC. (c) GOES-12 infrared satellite image of Hurricane
Katrina taken at 1945 UTC 27 August, overlaid onto the image are lightning
strike locations (red dots) from 1900 UTC to 2000 UTC. The black circle is a
70 km range ring from storm center (black "x").

Fig. 20  As in Fig. 6, but for Hurricane Katrina 2053 UTC 27 August, with lightning
strike locations (circles) from 2033 UTC to 2113 UTC. a) 85-GHz TMI image
with lightning strike locations (red circles). b) Layer 12 (8 – 10 km) PIC values
with lightning strike locations (black circles).
Fig. 21 As in Fig. 6, but for Hurricane Katrina at 0324 UTC 28 August, with lightning strike locations (circles) from 0302 UTC – 0344 UTC. a) 85-GHz TMI image with lightning strike locations (red circles). b) Layer 12 (8 – 10 km) PIC values with lightning strike locations (black circles).
Fig. 22  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 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.
Fig. 23  As in Fig. 5, but for hurricane Katrina from 1725 UTC – 2400 UTC 28 August. Radial passes were made at an altitude 2,400 -2,600 m. c) and d) contain the radial distribution of precipitation ice concentration values (thin solid line) obtained from the 28 August 2122 UTC TRMM image. a) 045°, b) 225°, c) 315° and d) 180°.
Fig. 24  (a) and (b), As in Fig. 6 but for Hurricane Katrina at 2122 UTC 28 August.

Each image is overlaid with lightning strike locations from 2102 UTC – 2142 UTC.  a) 85-GHz TMI image with lightning strike locations (red circles).  b) Layer 12 (8 – 10 km) precipitation ice content image with lightning strike locations (black circles).  c) GOES-12 Infrared satellite image taken of Hurricane Katrina at 2045 UTC 28 August, overlaid onto the image are lightning strike locations (red dots) from 2000 UTC – 2100 UTC.
Fig. 25 A vertical profile of the tangential wind of a radial pass through the northwest eyewall at ~ 315°. The image is a composite made with data from the aircraft tail radar for ~ 30 minute period beginning at 1900 UTC 28 August.
Fig. 26 Precipitation ice content pixel values for two separate TRMM passes during hurricane Rita. Average pixel values were calculated for 1° x 1° latitude longitude box centered on the eye, for 3 different TRMM determined levels for both days. All TRMM pixels within the eye were omitted from the average.
Fig. 27  Volume plot of the radial distribution of lightning strike density in Hurricane Rita from 0300 UTC – 2100 UTC 21 September.
References


Pessi, A.T., S. Businger, T. Cherubini, K. L. Cummins, and T. Turner, 2005: Toward the assimilation of lightning data over the Pacific Ocean into a mesoscale NWP model. 85th Annual AMS Meeting held in San Diego, CA.


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