
Brad J. Reinhart
UNDERSTANDING THE RELATIONSHIPS BETWEEN LIGHTNING, CLOUD MICROPHYSICS, AND AIRBORNE RADAR-DERIVED STORM STRUCTURE DURING HURRICANE KARL (2010)

By

BRAD J. REINHART

A Thesis submitted to the Department of Earth, Ocean, and Atmospheric Science in partial fulfillment of the requirements for the degree of Master of Science

Degree Awarded: Summer Semester, 2012
Brad Reinhart defended this thesis on July 2, 2012.

The members of the supervisory committee were:

Henry Fuelberg  
Professor Directing Thesis

Robert Hart  
Committee Member

Guosheng Liu  
Committee Member

The Graduate School has verified and approved the above-named committee members, and certifies that the thesis has been approved in accordance with university requirements.
I dedicate this work to my family, who has always been incredibly supportive as I pursued my childhood dream of becoming a meteorologist.
ACKNOWLEDGEMENTS

First, I thank my parents and my family for their constant support and encouragement. They always emphasized the importance of a quality education and provided me with every opportunity to succeed in life. I am thankful for all the sacrifices they have made and everything they have done for me. I also appreciate the support of my friends and former professors who encouraged me to continue pursuing my goals in graduate school.

I must thank my major professor, Dr. Henry Fuelberg, for all his help and guidance over the past two years. He has been an excellent advisor, mentor, and friend to me. I believe that what distinguishes Dr. Fuelberg from others is his great concern for his student’s well being. He always asked how I was doing before he asked about the work I was doing. I never just felt like an employee, but rather like a member of the Fuelberg Lab family. It was a pleasure working with Dr. Fuelberg, and I thank him for making this process such a rewarding experience. I also thank all the Fuelberg Lab members for their friendship over the past couple years. I really enjoyed the camaraderie of our lab and everyone’s willingness to help each other.

This study would not have been possible without the assistance and support of our GRIP collaborators. I especially thank Andy Heymsfield and Aaron Bansemer (NCAR), Doug Mach and Rich Blakeslee (NASA/MSFC), Steve Durden and Simone Tanelli (NASA/JPL), and Gerry Heymsfield and Steve Guimond (NASA/GSFC). I really appreciate their willingness to answer questions and provide insight about their instruments and datasets. Their time and input have been crucial to the success of this work.

Finally, I thank NASA (Grant NNX09AC43G) and Northrop Grumman (AMS Graduate Fellowship) for funding my research.
# TABLE OF CONTENTS

List of Tables ........................................................................................................................................ vi
List of Figures ......................................................................................................................................... vii
Abstract .................................................................................................................................................. x

1. INTRODUCTION ........................................................................................................................... 1

2. DATA AND METHODS ................................................................................................................... 4
   2.1 GRIP Datasets .......................................................................................................................... 4
   2.2 Additional Lightning Datasets ............................................................................................... 6
   2.3 Flight Leg Lightning Analysis ............................................................................................... 7
   2.4 Electrified/Non-Electrified Classification ............................................................................ 9

3. RESULTS ...................................................................................................................................... 12
   3.1 Characteristics of Electrified and Non-Electrified Regions .................................................. 12
       3.1.1 Vertical Velocity ............................................................................................................. 12
       3.1.2 Cloud Microphysics .................................................................................................... 14
       3.1.3 Radar Reflectivity ........................................................................................................ 17
   3.2 Flight Leg Case Studies .......................................................................................................... 18
       3.2.1 Electrified Leg 2 (1940-2000 UTC) ........................................................................... 18
       3.2.2 Electrified Leg 4 (2110-2130 UTC) ............................................................................ 28

4. SUMMARY AND CONCLUSIONS ............................................................................................... 34

5. REFERENCES ................................................................................................................................. 37

6. BIOGRAPHICAL SKETCH .......................................................................................................... 41
**LIST OF TABLES**

1. GRIP datasets used in this study. .................................................................6
2. Flight legs defined for GRIP flights into Hurricane Karl on 16 September 2010............7
3. Classification of electrified/non-electrified flight legs through Karl’s inner core. ............9
LIST OF FIGURES

1 Flight tracks of the DC-8 (blue) and Global Hawk (green) between 1900-2300 UTC 16 September 2010 overlaid on GOES infrared satellite imagery of Hurricane Karl. ..................4

2 Minimum central pressure and maximum sustained winds of Karl during its rapid intensification on 16-17 September 2010. Sampling periods of the DC-8 and GH are superimposed. ..........................................................5

3 Frequency of WWLLN and GLD360 inner core flashes along flight tracks of the DC-8 (left) and GH (right). These flashes occurred within 10 km of the DC-8/GH flight path and within ± 5 min of DC-8/GH passage. ..........................................................8

4 Electrified leg 2 (left) and non-electrified leg 5 (right) through Karl. The blue and green lines indicate the tracks of the DC-8 and GH. The light blue region highlights those lightning flashes within 10 km of the GH. Note the numerous flashes near the aircraft on leg 2 and the lack of lightning near the aircraft on leg 5. ..............................................10

5 Box and whisker plots of DC-8 flight level, inner core vertical velocities measured by the MMS. The x-axis indicates the flight leg number and the location relative to Karl’s eye. Note that the measurements taken during legs 1-2 were at an average altitude of 10.3 km, while legs 3-5 were sampled at an average altitude of 11.3 km. The interquartile range (25\textsuperscript{th} to 75\textsuperscript{th} percentile) of the data is marked by the edges of the blue boxes, while the red line within each box denotes the median...............................................13

6 Maximum updrafts (blue) and downdrafts (red) based on APR-2 Doppler velocity data for each leg. The electrified legs (2-4) all contain peak updrafts that exceed 10 m s\textsuperscript{-1}, while the peak updrafts for non-electrified legs (1 and 5) do not exceed 5 m s\textsuperscript{-1}. ................................14

7 Conceptual illustration of recently frozen, homogeneously nucleated ice particles (circled) being lofted above the -40°C level by a strong thunderstorm updraft. These recently frozen ice particles suggest that supercooled water may exist below -40°C. .................................15

8 Plot of CDP number concentration (cm\textsuperscript{-3}) as a function of updraft speed (m s\textsuperscript{-1}). The dotted red line represents the linear best fit for the data (r = 0.69). This good correlation suggests that increased small particle concentrations tend to be associated with stronger upward motions. .................................................................................................16

9 CDP concentration (cm\textsuperscript{-3}) plotted versus temperature (°C) between 1900-2300 UTC. The color coded symbols represent the corresponding vertical velocity for each observation. Greater CDP concentrations generally are associated with moderate to strong updrafts. ...............................16

10 Vertical profiles of APR-2 Ku-band reflectivity (dBZ) in the inner core regions of each leg. Note the differences in average reflectivity between the electrified (2-4) and non-electrified legs (1 and 5) above the freezing level in the mixed phase region (5-7 km). .......................18
11 GRIP aircraft tracks and WWLLN/GLD360 lightning flashes between 1940-2000 UTC overlaid on the 1945 UTC GOES infrared (IR) image of Karl. The gold stars designate the location of the GH when LIP detected lightning flashes. A 10 km buffer (light blue) is placed along the GH flight track to highlight WWLLN and GLD360 flashes near the aircraft.................................19

12 $T_B$ differences between the 50.30 and 113.25 GHz channels of HAMSR between 1945-1955 UTC. Large $T_B$ differences (red) in the southeast eyewall indicate regions where greater ice scattering, and thus deep convection, are occurring. WWLLN (*) and GLD360 (+) flashes between 1945-1955 UTC are overlaid for reference.................................19

13 LIP electric field measurements between 1945-1955 UTC. a) 2-D electric field vectors (blue) along the GH flight track. The vectors point away from the positive charge center of the storm that is located northeast of the GH around 1948 UTC. Colors along the flight path indicate the strength of the vertical electric field (color bar). b) Vertical and east/west components of the electric field (green vectors). c) Vertical and north/south components of the electric field (green vectors). Green stars denote WWLLN lightning flashes (1945-1955 UTC)............................................................................................................20

14 a) APR-2 scan geometry depicting the cross track scans performed by the downward pointing antenna (after Sadowy et al. 2003). b) HIWRAP scan geometry showing the conical scan strategy used to sample the storm (after Heymsfield et al. 2006b).................................21

15 APR-2 data from a southeast to northwest pass through Karl between 1944:00 – 1954:47 UTC. a) Ku-band reflectivity. b) Doppler velocity, with negative values representing upward vertical motion. c) APR-2 experimental microphysics classification product (courtesy of Simone Tanelli, JPL). The black boxes in each panel highlight the electrified convective region of interest. .................................................................................................................................23

16 Ku-band HIWRAP reflectivity data between 1942:59 – 1955:56 UTC. The black box denotes the electrified convective region of interest. Recall that the tilted appearance of the reflectivity is due to the scan geometry of HIWRAP.................................................................24

17 WWLLN-derived inner core flashes between 1940-2000 UTC color coded by time of occurrence. Tracks of the DC-8 (blue) and GH (green) are overlaid. The solid black circle represents the estimated location and size of Karl’s eye based on National Hurricane Center (NHC) data. Because the location of some flashes are not consistent with the NHC center location, the dashed circle shows the location of Karl’s eye inferred from satellite, HAMSR, and lightning data. The location differences could be attributed to WWLLN position errors (see section 2.2) and/or NHC location errors. The shaded region highlights a cluster of flashes (a deep convective burst) rotating counterclockwise around Karl’s eye in the southeast eyewall.................................................................25
GOES 10.7 µm IR satellite images of Hurricane Karl on 16 September: a) 1932 UTC, b) 1940 UTC, c) 1945 UTC, d) 1955 UTC, and e) 2003 UTC. The pink color corresponds to IR cloud top brightness temperatures colder than -80 °C. The white arrows in each panel indicate the deep convective burst moving counterclockwise around the eyewall at approximately 20 m s$^{-1}$. 

Time series of CDP concentration (cm$^{-3}$, top), CAS concentration (cm$^{-3}$, middle), and vertical velocity (m s$^{-1}$, bottom) between 1947 – 1951 UTC. The sudden increase in small ice particle concentrations matches the time of the 20 m s$^{-1}$ updraft.

PIP particle images from the southeast eyewall of Karl: a) 1948:07 UTC, b) 1949:05 UTC, c) 1949:14 UTC, and d) 1950:09 UTC. The black stars on top of the radar scan indicate the approximate location where each particle image was taken. Red circles identify graupel particles in the convective region.

GRIP aircraft tracks and WWLLN/GLD360 lightning flashes between 2110-2130 UTC overlaid on 2115 UTC GOES IR satellite imagery. The gold stars designate locations of the GH when LIP detected lightning flashes. A 10 km buffer (light blue) is placed along the GH flight track to highlight WWLLN and GLD flashes near the aircraft.

LIP electric field measurements between 2115-2130 UTC. a) 2-D electric field vectors (blue) along the GH flight track. The vectors point away from the positive charge center of the storm, which is east of the GH track around 2122 UTC. Colors along the flight path indicate the strength of the vertical electric field (see color bar). b) Vertical and east/west components of the electric field (green vectors). c) Vertical and north/south components of the electric field (green vectors). Green stars denote WWLLN lightning flashes.

APR-2 data from a north to south pass through Karl between 2117:40 – 2126:16 UTC. a) Ku-band reflectivity. b) Doppler velocity, with negative values representing upward vertical motion. c) APR-2 experimental microphysics classification product (courtesy of Simone Tanelli, JPL). The black boxes in each panel denote the electrified convective region of interest.

Ku-band HIWRAP reflectivity data between 2112:03 – 2126:11 UTC. The black box denotes the electrified convective region of interest. Recall that the tilted appearance of the reflectivity is due to the scan geometry of HIWRAP.

Time series of CDP concentration (cm$^{-3}$, top), CAS concentration (cm$^{-3}$, middle), and vertical velocity (m s$^{-1}$, bottom) between 2122 – 2125 UTC. Numerous updrafts exceeding 10 m s$^{-1}$ between 2123-2124 UTC are associated with a broad region of very small ice particles.

PIP particle images from Karl’s southern eyewall: a) 2122:47 UTC, b) 2123:51 UTC, c) 2123:52 UTC, and d) 2125:03 UTC. The black stars on top of the radar scan indicate the approximate locations where each particle image was taken. Red circles identify graupel particles in the convective region.
ABSTRACT

The sporadic nature of lightning in tropical cyclones (TCs) is a topic of great interest to researchers and forecasters. This study explores relationships between lightning, cloud microphysics, and TC storm structure in rapidly intensifying Hurricane Karl (16 September 2010) using data collected by the NASA DC-8 and Global Hawk (GH) aircraft during NASA’s Genesis and Rapid Intensification Processes (GRIP) experiment.

The study capitalizes on the unique opportunity provided by GRIP to synthesize multiple datasets from the two aircraft and analyze the physical properties of an electrified TC. The Lightning Instrument Package (LIP, GH) measured electric fields and provided in situ information about both cloud-to-ground and intracloud lightning. The LIP-derived lightning data were supplemented by information from two ground-based lightning networks--the World Wide Lightning Location Network (WWLLN) and the Vaisala Global Lightning Dataset (GLD360). Microphysics probes on the DC-8 provided particle concentrations and 2-D images of hydrometeors ranging from 0.35 to 6200 µm. Ku-band reflectivities from the Airborne Precipitation Radar (APR-2, DC-8) and High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP, GH) were used with brightness temperatures from the High-Altitude Monolithic Microwave Integrated Circuit (MMIC) Sounding Radiometer (HAMSR, GH) to assess Karl’s convective structure. Flight level vertical velocities from the Meteorological Measurement System (MMS, DC-8) and Doppler velocities from APR-2 provided information about Karl’s convective updrafts.

We analyze five coordinated flight legs through Karl by the DC-8 and GH, focusing on the inner core region (within 50 km of storm center) where most of the lightning was concentrated and the aircraft were well coordinated. The non-inductive charging mechanism that is believed to produce storm electrification requires ice and graupel collisions in the presence of supercooled water. The GRIP data are used to compare properties of electrified and non-electrified inner core regions that are related to this charging mechanism.

MMS and APR-2 reveal that although the majority of inner core updrafts were weak (96.6% < 5 m s⁻¹), the electrified regions typically contained peak updrafts exceeding 10 m s⁻¹. Conversely, the non-electrified regions generally were associated with weaker updrafts that peaked around 5-6 m s⁻¹. Microphysical measurements indicate that enhanced concentrations of small ice particles often were associated with the stronger inner core updrafts. These large
concentrations likely corresponded to regions of recently frozen, homogeneously nucleated ice particles. Thus, the presence of supercooled water below the aircraft was inferred from the microphysical data collected at flight level. Reflectivities from APR-2 and HIWRAP show that the electrified regions of flight legs contained enhanced reflectivities in the mixed phase region, thereby indicating that supercooled water and/or large ice particles were carried aloft by strong updrafts. A deep mixed phase region is known to be crucial for charge separation and storm electrification.

Case studies of two electrified legs are presented to further analyze the convective environments that produced lightning in Karl’s inner core. The GRIP aircraft sampled a deep convective burst and a broad convective region during these two legs. Despite the structural differences between the convection sampled on these legs, we identified three common characteristics of Karl’s electrified regions: 1) strong updrafts of 10-20 m s\(^{-1}\), 2) deep mixed phase layers indicated by reflectivities > 30 dBZ extending several km above the freezing level, and 3) microphysical environments consisting of graupel, very small ice particles, and the inferred presence of supercooled water. These characteristics describe an environment where non-inductive charging and TC electrification are expected. We conclude that the electrified regions in Karl’s inner core were attributable to a microphysical environment that was conducive to electrification due to occasional, unusually strong convective updrafts in the eyewall.
CHAPTER ONE

INTRODUCTION

The sporadic nature of lightning in tropical cyclones (TCs) remains a topic of great interest to researchers and forecasters. Because TCs frequently develop over distant tropical oceans, the availability of continuous data about these storms often is limited. While satellites have greatly improved our ability to monitor TC evolution in real-time, inner core and other TC structural changes are not always evident from satellite imagery alone. Today, lightning detection networks provide real-time, continuous information about electrical activity within TCs around the world. However, there is still uncertainty as to what the lightning data tell us about TCs and how this real-time information can be used operationally.

Lightning occurs less frequently in TCs than in continental convective systems (Cecil et al. 2002). The non-inductive charging mechanism that is believed to produce storm electrification requires collisions between graupel and ice particles in the presence of supercooled water (Takahashi 1978, Saunders and Peck 1998). A deep mixed phase region provides an environment where collisions between graupel and ice particles produce charge transfer and storm electrification as the charged particles are separated within the storm. Since TC updrafts generally are weaker than those of continental convection (Jorgensen et al. 1985, Jorgensen and LeMone 1989, Black et al. 1996), the smaller frequency of lightning in TCs may be attributed to an insufficient depth of mixed phase hydrometeors.

Charge separation in the eyewall of a TC greatly depends on the relative amounts of supercooled droplets and ice in its updrafts and downdrafts (Black and Hallett 1999). Supercooled water rarely exists in TCs above the -5°C level, primarily due to the downward mixing of ice produced aloft by eyewall convection (Black and Hallett 1986). The efficient radial and azimuthal advection of these ice particles reduces the amount of supercooled water available in TC updrafts (Black and Hallett 1986, Houze et al. 1992). This precludes charge separation from occurring within the inner core of the storm. Therefore, strong updrafts (> 10 m s⁻¹) that can support a deep mixed phase layer containing abundant supercooled water are most conducive to TC electrification (Black and Hallett 1999). TC updrafts of this magnitude, though uncommon, have been observed in intense and rapidly intensifying TCs (Black et al. 1994, Black and Hallett 1999). The precipitation associated with strong TC updrafts cleanses the air of
aerosols that can serve as ice nuclei for ascending droplets in the updraft. This lack of ice nuclei allows supercooled droplets to exist in the strong updrafts at much colder temperatures before the droplets freeze homogeneously (Black et al. 2003). Although rare in TCs, the presence of supercooled water well above the freezing level has been inferred in those TCs where strong vertical motions were sampled (Herman and Heymsfield 2003, Black et al. 2003, Heymsfield et al. 2009).

The characteristics of electrified TCs and oceanic convection have been analyzed using various remote sensing techniques. Vertical profiles of radar reflectivity have been used to assess the microphysical structure and the potential for lightning activity within oceanic convection. Greater reflectivity within the mixed phase region represents an increase in droplet, graupel, and ice particle size and/or concentration. Radar reflectivity in TCs and tropical oceanic convection generally decreases rapidly above the freezing level (Jorgensen et al. 1985, Szoke et al. 1986, Zipser and Lutz 1994, Black et al. 1996). Therefore, lightning probability (Cecil and Zipser 2002) and flash rates (Pessi and Businger 2009) increase with increasing reflectivity throughout the troposphere, especially within the mixed phase region. Microwave ice scattering signatures also have been used to identify regions where precipitation-sized ice is present. Lightning is more likely to occur in regions with decreased 85- and 37-GHz brightness temperatures due to increased ice scattering (Cecil and Zipser 2002).

The spatial and temporal variations of TC lightning have been well documented in recent years. Molinari et al. (1994, 1999) found a distinct radial pattern of lightning in Atlantic hurricanes: A weak maximum in the eyewall, a clear minimum in the region outside the eyewall, and a strong maximum in the outer rainbands. The intermittent nature of eyewall/inner core lightning has led researchers to explore potential forecasting applications. Early case studies (Lyons and Keen 1994, Molinari et al. 1994) showed that inner core lightning bursts preceded the intensification of some TCs. After analyzing lightning from nine hurricanes, Molinari et al. (1999) proposed that inner core lightning bursts may signal the beginning or end of a rapid intensification (RI) period.

Researchers have continued to search for the link between lightning activity and TC intensity change. Inner core lightning outbreaks in Hurricanes Katrina and Rita (2005) were associated with RI periods, eyewall replacement cycles, and the time of maximum intensity (Squires and Businger 2008). Price et al. (2009) found a strong correlation between lightning...
frequency and maximum sustained winds, with lightning activity increasing about one day before the storm reaches maximum intensity. Abarca et al. (2011) proposed that the inner core flash density of TCs in the weaker storm stages can be used to distinguish between intensifying and non-intensifying storms. The TCs studied by Demetriades et al. (2010b) exhibited inner core lightning bursts ranging from fifteen hours before to three hours after maximum intensity. Austin and Fuelberg (2010) found that flash rates are poorly correlated with changes in TC intensity. In fact, they showed that the strongest relationship corresponded with lightning occurring after the greatest decrease in TC central pressure. Clearly, there is still no consensus regarding the utility of lightning data as a predictive tool for TC intensity change.

The tenuous link between lightning frequency and TC intensity led us to focus on the physical properties that contribute to the presence or absence of lightning within a rapidly intensifying hurricane. Although previous studies (Black and Hallett 1999, Cecil et al. 2002, Cecil and Zipser 2002) have analyzed characteristics of electrified TCs, our study synthesizes an unprecedented number of in situ datasets collected during NASA’s Genesis and Rapid Intensification Processes (GRIP) experiment to further investigate this topic. We explore relationships between lightning, cloud microphysics, and TC storm structure using data gathered from research flights into Hurricane Karl on 16 September 2010. GRIP datasets are used to analyze each coordinated flight leg through Karl by the DC-8 and Global Hawk aircraft, assess how well the convective regions were sampled, and classify the legs based on the electrical activity that was observed. We then compare the physical properties of electrified and non-electrified flight legs to understand the lightning variability observed within Karl.
CHAPTER TWO
DATA AND METHODS

2.1 GRIP Datasets

Meteorological data used in this study were collected by the NASA DC-8 aircraft and the Global Hawk Unmanned Airborne System during the 2010 NASA GRIP experiment. The field campaign sought to better understand how TCs form and develop into major hurricanes by sampling storms using multiple research aircraft. On 16 September, the DC-8 and Global Hawk (GH) conducted coordinated flight legs into category one Hurricane Karl from approximately 1900 – 2300 UTC (Fig. 1). This observation period coincided with Karl's RI from a 55 kt tropical storm to a 956 hPa, 110 kt category three hurricane (Fig. 2). During these coordinated flight legs, the DC-8 penetrated Karl at altitudes of 10.3 to 11.3 km, corresponding to flight level temperatures of -32.2°C to -45.4°C. The GH overflew the DC-8 and sampled the storm from altitudes of 17.5 to 18.3 km.

![Figure 1. Flight tracks of the DC-8 (blue) and Global Hawk (green) between 1900-2300 UTC 16 September 2010 overlaid on GOES infrared satellite imagery of Hurricane Karl.](image)
We synthesized several GRIP datasets to analyze the electrification of Karl during this RI period (Table 1). Reflectivity and Doppler velocity data were collected aboard the DC-8 by the dual-frequency Airborne Precipitation Radar (APR-2) (Sadowy et al. 2003). The Meteorological Measurement System (MMS) on the DC-8 provided flight level temperature and wind data (Chan et al. 1998). The various microphysics probes on the DC-8 measured size distributions and concentrations of large and small particles (Baumgardner et al. 2001). Specifically, the Cloud Droplet Probe (CDP) counted particles from 2-50 µm, while the Cloud and Aerosol Spectrometer (CAS) measured particles between 0.35-50 µm. The Precipitation Imaging Probe (PIP) sampled particles in the range 100-6200 µm. The PIP instrument also provided two-dimensional images of the sampled particles for detailed microphysics analysis.

The Lightning Instrument Package (LIP) aboard the GH consisted of electric field mills that sampled the three-dimensional components of the electric field, thereby providing in situ information about total (cloud-to-ground, CG and intracloud, IC) lightning within the storm (Mach et al. 2009). Lightning flashes were inferred from abrupt changes in the electric field near the aircraft. Although LIP has a fairly short range of detection, strong flashes located several tens of kilometers away from the aircraft can be detected (R. Blakeslee and D. Mach, 2012, personal communication). Brightness temperatures from the High-Altitude Monolithic
Microwave Integrated Circuit (MMIC) Sounding Radiometer (HAMSR) (Brown et al. 2011) aboard the GH were used to identify regions of deep convection and assess how well these regions were sampled by the aircraft. Reflectivity data from the High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) (Li et al. 2011) on the GH provided valuable information about Karl’s vertical structure.

**Table 1.** GRIP datasets used in this study.

<table>
<thead>
<tr>
<th>GRIP Instrument</th>
<th>Aircraft</th>
<th>Data Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airborne Precipitation Radar (APR-2)</td>
<td>DC-8</td>
<td>Ku-band reflectivity, Doppler velocity, and experimental microphysics product</td>
</tr>
<tr>
<td>Cloud microphysics probes (CDP, CAS, CIP, PIP)</td>
<td>DC-8</td>
<td>Size distributions and total concentrations of large and small particles (0.35 to 6200 µm)</td>
</tr>
<tr>
<td>High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP)</td>
<td>GH</td>
<td>Ku-band reflectivity data</td>
</tr>
<tr>
<td>High-Altitude MMIC Sounding Radiometer (HAMSR)</td>
<td>GH</td>
<td>50.30/113.25 GHz brightness temperatures</td>
</tr>
<tr>
<td>Lightning Instrument Package (LIP)</td>
<td>GH</td>
<td>Electric field measurements and total (cloud-to-ground and intracloud) lightning</td>
</tr>
<tr>
<td>Meteorological Measurement System (MMS)</td>
<td>DC-8</td>
<td>Flight level temperature and wind data</td>
</tr>
</tbody>
</table>

### 2.2 Additional Lightning Datasets

The LIP-derived lightning data were supplemented by information from two ground-based lightning networks—the World Wide Lightning Location Network (WWLLN) (Rodger et al. 2006) and the Vaisala Global Lightning Dataset (GLD360) (Demetriades et al. 2010a). WWLLN is a global network consisting of over 50 stations that detect very low frequency (VLF) radiation, or sferics, emitted by lightning discharges. Although WWLLN has a low detection efficiency (DE) (Rodger et al. 2006), recent research has noted improvement (Abarca et al. 2010) and shown that WWLLN sufficiently samples electrical activity in Atlantic TCs for many research purposes (Abarca et al. 2011). Abarca et al. (2010) determined that WWLLN has an average northward location bias of 4.03 km and westward bias of 4.98 km. GLD360 is a relatively new lightning network that detects global CG flashes with an expected DE of 70% and
location accuracy of 5-10 km (Demetriades et al. 2010a). Data from these additional networks were beneficial to our research since they continuously detect lightning over the entire world, whereas LIP only detects electrical activity within a few tens of kilometers of the GH while sampling a storm. However, WWLLN and GLD360 (unlike LIP) do not provide information about total lightning since they primarily detect CG flashes.

2.3 Flight Leg Lightning Analysis

We chose Karl for this study because intermittent periods of frequent inner core lightning were detected by the global networks during the DC-8 and GH coordinated GRIP flights on 16 September. Karl was in the middle of an RI cycle during the GRIP flight period (Fig. 2). Since better understanding rapidly intensifying storms was a key GRIP objective, Karl was an ideal case to analyze. Five individual DC-8 and GH flight legs were subjectively defined as coordinated, straight line passes (approximately 20 min in duration) through Karl (Table 2). These legs were limited to relatively straight passes because some data quality was diminished when the plane turned or rolled. There also was limited coordination between the aircraft when maneuvering in the outer regions of the storm to set up for the next pass.

Table 2. Flight legs defined for GRIP flights into Hurricane Karl on 16 September 2010.

<table>
<thead>
<tr>
<th>Leg</th>
<th>Start Time (UTC)</th>
<th>End Time (UTC)</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19:00</td>
<td>19:20</td>
<td>N – S</td>
</tr>
<tr>
<td>2</td>
<td>19:40</td>
<td>20:00</td>
<td>SE – NW</td>
</tr>
<tr>
<td>3</td>
<td>20:20</td>
<td>20:45</td>
<td>SW – NE</td>
</tr>
<tr>
<td>4</td>
<td>21:10</td>
<td>21:30</td>
<td>N – S</td>
</tr>
<tr>
<td>5</td>
<td>21:45</td>
<td>22:05</td>
<td>SE – NW</td>
</tr>
</tbody>
</table>

We used LIP, WWLLN, and GLD360 lightning data to evaluate the location and frequency of lightning along each flight leg. The shortest distance between each WWLLN and GLD360 flash and each aircraft track was calculated. The flashes that occurred during the flight legs and within 10 km of each aircraft were identified. This 10 km threshold was chosen after several different distances were tested. Based on our combined analyses of GRIP and lightning datasets, we were confident that data collected within 10 km of a lightning flash still represent
the electrified environment that produced the flash. Additionally, 10 km was within the estimated flash detection range of the LIP (R. Blakeslee and D. Mach, 2012, personal communication). The flash time was compared with the time the aircraft was closest to the flash location to determine whether the lightning occurred before, during, or after data were collected in that region of the storm. This information provided a starting point for classifying each leg based on observed electrical activity.

Figure 3 shows the number of WWLLN and GLD360 inner core flashes by leg that occurred within 10 km and ± 5 min of DC-8 (left) and GH (right) passage. The flashes were counted separately for the DC-8 and GH because the spatial and temporal coordination between the aircraft varied for each leg. For the purposes of this study, the inner core was defined as the region within 50 km of Karl’s center. This distinction is consistent with previous studies (Molinari et al. 1994, 1999) that designated eyewall flashes as those occurring within 40 km of storm center. We focused on the inner core because the GRIP aircraft typically were closest to each other as they penetrated Karl’s eye. This coordination enabled us to use datasets from both aircraft to better understand the structure and electrical nature of the storm. Since many recent studies have focused on the potential value of TC inner core lightning (Squires and Businger 2008, Price et al. 2009, Demetriades et al. 2010b, Abarca et al. 2011, Fierro et al. 2011), this region was deemed the most appropriate for study. Figure 3 illustrates the lightning variability observed within the inner core regions of Karl for the five flight legs. One should note again that the global lightning networks primarily detect CG flashes.

[Graph showing the frequency of WWLLN and GLD360 inner core flashes along flight tracks of the DC-8 (left) and GH (right). These flashes occurred within 10 km of the DC-8/GH flight path and within ± 5 min of DC-8/GH passage.]
Although LIP did not provide two-dimensional locations of lightning, electric field vectors were used to determine where electrical activity was occurring relative to the GH. The strength and orientation of the field vectors were plotted to assess the relative distance of charge centers from the GH flight path. Additionally, abrupt electric field changes were analyzed to derive LIP flash counts for each leg. This information was used in conjunction with the global lightning datasets to identify the electrified and non-electrified passes through Karl. LIP flash counts and electric field data will be presented in the results section for two specific legs of interest.

2.4 Electrified/Non-Electrified Classification

The lightning datasets described in the previous section were used to subjectively classify each flight leg as electrified or non-electrified. We superimposed the GRIP flight tracks on microwave and infrared satellite imagery, with WWLLN and GLD360 flashes overlaid. The LIP electric field data provided valuable insight into the location of charge centers and total lightning relative to the GH. These plots allowed us to determine where lightning was present relative to each aircraft. Table 3 classifies each of Karl’s five flight legs. The distinction between electrified/non-electrified flight legs strictly pertains to the presence or absence of lightning along flight tracks within Karl’s inner core. Figure 4 provides examples of an electrified and non-electrified leg.

Table 3. Classification of electrified/non-electrified flight legs through Karl’s inner core.

<table>
<thead>
<tr>
<th>Leg</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Non-Electrified</td>
</tr>
<tr>
<td>2</td>
<td>Electrified</td>
</tr>
<tr>
<td>3</td>
<td>Electrified</td>
</tr>
<tr>
<td>4</td>
<td>Electrified</td>
</tr>
<tr>
<td>5</td>
<td>Non-Electrified</td>
</tr>
</tbody>
</table>
Legs 2 and 4 clearly were electrified since numerous WWLLN and GLD360 flashes occurred within the inner core regions sampled by GRIP aircraft. In addition, the LIP electric field vectors indicated that charged storms were located close to the GH flight track during these legs. Although the global networks did not detect any lightning that met the criteria along leg 3, strong LIP electric field signatures did indicate the presence of electrical activity near the GH. Based on the LIP measurements, leg 3 was classified as electrified. It is possible that the LIP-detected IC lightning during leg 3 was not strong enough for the global networks to detect until the storm began producing CG flashes several minutes later. In addition, one should note that the DC-8 flew this leg approximately 8-10 min before the GH and, thus, may have sampled the storm before electrification commenced. These would explain the absence of WWLLN and GLD360 lightning during this leg (Fig. 3). Case studies of select electrified legs will be presented in the results section.

Leg 5 was designated non-electrified because no inner core lightning was detected and the LIP electric field vectors were relatively weak. Leg 1 was more difficult to classify because although the ground based networks detected many flashes, the great majority of them occurred 75-100 km away from Karl’s center. One inner core flash was detected near the DC-8 and another near the GH; however, these flashes occurred on opposite sides of the eye. Additionally,
the aircraft were separated by approximately 15 km during the leg and thus may have sampled very different environments. The poor aircraft coordination and lack of a clear electrified inner core region were reasons to classify leg 1 as non-electrified. The choice of this classification ultimately was not significant because the poor spatial coordination prevented us from analyzing leg 1 in detail.
CHAPTER THREE

RESULTS

We first contrast the vertical motions, microphysical properties, and radar reflectivities of Karl’s electrified and non-electrified flight legs to characterize the conditions that support TC electrification. The physical parameters that we examine are related to lightning production via the non-inductive charging mechanism and were sampled by GRIP aircraft. This is followed by detailed examinations of two electrified legs.

3.1 Characteristics of Electrified and Non-Electrified Regions

3.1.1 Vertical Velocity

Non-inductive charging requires strong updrafts that can support a deep mixed phase precipitation region where charge separation can occur (Black and Hallett 1999). We used MMS flight level vertical velocity measurements and APR-2 Doppler velocities from the DC-8 to evaluate vertical motions along each flight leg in Table 2. The DC-8 penetrated Karl at an average altitude of 10.3 km during legs 1-2 and 11.3 km on legs 3-5.

Figure 5 shows the distribution of DC-8 flight level, inner core vertical velocities categorized by leg and inner core quadrant. The majority of vertical velocities are between ± 2 m s\(^{-1}\), consistent with previous research (Jorgensen et al. 1985, Black et al. 1996) showing that TC updrafts tend to be weak, especially when compared to updrafts in continental convection. Although the majority of inner core vertical velocities are weak, the electrified regions of legs 2 and 4 exhibit much stronger peak updrafts (20.2 m s\(^{-1}\) and 12.5 m s\(^{-1}\), respectively). These areas comprise a relatively small portion of the inner core; only 3.4% of the analyzed inner core updrafts exceed 5 m s\(^{-1}\) and less than 1% exceeds 10 m s\(^{-1}\). Conversely, the non-electrified legs almost exclusively contain updrafts less than 6 m s\(^{-1}\), with the southeast quadrant of leg 5 being the only exception. Leg 3 is the only electrified leg that does not exhibit strong upward motion at flight level. However, since the DC-8 sampled this region approximately 8 min before the GH detected significant electric fields, it is not surprising that strong updrafts do not reach flight altitude during the DC-8 sampling period.
**Figure 5.** Box and whisker plots of DC-8 flight level, inner core vertical velocities measured by the MMS. The x-axis indicates the flight leg number and the location relative to Karl’s eye. Note that the measurements taken during legs 1-2 were at an average altitude of 10.3 km, while legs 3-5 were sampled at an average altitude of 11.3 km. The interquartile range (25th to 75th percentile) of the data is marked by the edges of the blue boxes, while the red line within each box denotes the median.

Doppler data from the APR-2 provide vertical motions below DC-8 flight level. Figure 6 displays maximum values of updrafts (blue) and downdrafts (red) for each leg. The maximum updraft along each electrified leg (2-4) exceeds 10 m s\(^{-1}\), with the strongest updraft of 15 m s\(^{-1}\) occurring during leg 4. These maxima all occur at altitudes of 8-9 km, with the exception of leg 4 whose updraft core is near 3.3 km. This lower tropospheric altitude of maximum updrafts suggests that the inner core convection in electrified leg 4 was still maturing as the DC-8 penetrated the eyewall. On the other hand, maximum updrafts along the non-electrified legs (1 and 5) do not exceed 5 m s\(^{-1}\). These results indicate that the strongest vertical motions are located within Karl’s electrified inner core regions. The peak updrafts in these regions meet or exceed the 10-12 m s\(^{-1}\) threshold proposed by Zipser and Lutz (1994) as necessary for rapid storm electrification.
Figure 6. Maximum updrafts (blue) and downdrafts (red) based on APR-2 Doppler velocity data for each leg. The electrified legs (2-4) all contain peak updrafts that exceed 10 m s$^{-1}$, while the peak updrafts for non-electrified legs (1 and 5) do not exceed 5 m s$^{-1}$.

3.1.2 Cloud Microphysics

The non-inductive charging mechanism requires collisions between graupel and ice particles in the presence of supercooled water (Takahashi 1978, Saunders and Peck 1998). Unfortunately, supercooled water was not directly measured at DC-8 flight level as the flight legs were at temperatures of -32°C to -45°C. However, the available cloud microphysics data can be used to characterize hydrometeors within the inner core of Karl and infer the presence of supercooled water below aircraft altitude.

The CDP and CAS instruments aboard the DC-8 measured the concentration of small particles (< 50 µm in diameter) at flight level. Herman and Heymsfield (2003) and Heymsfield et al. (2006a, 2009) found enhanced concentrations of small ice particles (< 50 µm) near the strong updrafts of TCs and oceanic convection. Large concentrations of small particles were strongly correlated with updraft strength in Hurricane Humberto (2001) (Heymsfield et al. 2006a). Since the small ice particle concentrations observed in these regions were deemed too great to have developed solely by heterogeneous nucleation processes, the authors proposed that nucleation occurred via homogeneous freezing (Herman and Heymsfield 2003, Heymsfield et al. 2009). Figure 7 illustrates this process near the -40°C level of a deep convective storm. The
presence of recently frozen, homogeneously nucleated ice particles at flight level implies that supercooled droplets were present below the aircraft in order to be frozen at flight level. This information helps explain the presence/absence of lightning within different regions of Karl.

Figure 7. Conceptual illustration of recently frozen, homogeneously nucleated ice particles (circled) being lofted above the -40°C level by a strong thunderstorm updraft. These recently frozen ice particles suggest that supercooled water may exist below -40°C.

We examined the relationship between small particle concentrations and vertical velocities in Karl on 16 September. Since particle concentrations were sampled at 5 s intervals, they were matched with corresponding 1 s MMS vertical velocities. Figure 8 shows CDP number concentration (cm⁻³) plotted as a function of updraft speed (m s⁻¹) between 1900-2300 UTC. The dashed line represents the linear best fit between the data. CDP concentration and updraft speed exhibit a moderate positive correlation (r = 0.69). A similar analysis (not shown) between CAS concentration and updraft speed yields r = 0.56. This relationship is further explored in Fig. 9, which shows variations between CDP number concentration, temperature, and vertical velocity (color coded). The greater small particle concentrations clearly are associated with moderate to strong updrafts. Although the hydrometeors at flight level all were frozen, these pulses of small ice particles indicate regions where supercooled droplets may exist below aircraft altitude (A. Heymsfield and A. Bansemer, 2012, personal communication). As we will show later, greater small particle concentrations often were observed within electrified regions of Karl.
Figure 8. Plot of CDP number concentration (cm$^{-3}$) as a function of updraft speed (m s$^{-1}$). The dotted red line represents the linear best fit for the data ($r = 0.69$). This good correlation suggests that increased small particle concentrations tend to be associated with stronger upward motions.

Figure 9. CDP concentration (cm$^{-3}$) plotted versus temperature (°C) between 1900-2300 UTC. The color coded symbols represent the corresponding vertical velocity for each observation. Greater CDP concentrations generally are associated with moderate to strong updrafts.
3.1.3 Radar Reflectivity

Previous studies have shown that TC/oceanic convection generally exhibits modest reflectivities that decrease rapidly above the freezing level (Szoke et al. 1986, Zipser and Lutz 1994, Cecil et al. 2002). These findings are consistent with weak TC updrafts and the rapid conversion of liquid particles to ice above the freezing level (Jorgensen et al. 1985). Because water has a greater dielectric constant than ice, liquid droplets produce greater reflectivities than ice particles of similar size. Therefore, enhanced reflectivity in the mixed phase region indicates the presence of supercooled water and/or large ice particles at temperatures less than 0°C. Greater reflectivities in the mixed phase region also result in an increased probability of lightning in TCs and oceanic convection (Cecil and Zipser 2002, Pessi and Businger 2009). We used APR-2 data to study the variability of reflectivity profiles along the electrified and non-electrified legs of Karl.

Figure 10 shows vertical profiles of APR-2 Ku-band reflectivity averaged over each of the inner core flight legs, color coded for comparison. Since the APR-2 performs cross track scans, we selected the most nadir of each set of scans for this analysis. The sharp increase in reflectivity just below 5 km indicates the height of the freezing level. Each of the profiles exhibits a sharp decrease in reflectivity above the freezing level. This is consistent with previous results from TCs and tropical oceanic convection (Szoke et al. 1986, Zipser and Lutz 1994, Cecil et al. 2002). However, the electrified legs (2-4) clearly have greater inner core reflectivities than the non-electrified legs (1 and 5) both above and below 0°C. In fact, legs 2 (pink) and 4 (blue) have greater reflectivities than the non-electrified legs throughout most of the troposphere. Enhanced reflectivities in the 5-7 km region indicate that supercooled water and/or large ice particles are being lofted well above the freezing level, thus producing a well-developed mixed phase region. Not surprisingly, legs 2 and 4 also contain the most inner core lightning.
3.2 Flight Leg Case Studies

3.2.1 Electrified Leg 2 (1940-2000 UTC)

Leg 2 was an electrified southeast to northwest flight segment through Karl between 1940-2000 UTC. The DC-8 and GH were well coordinated during this pass, and the global lightning networks detected numerous flashes within Karl’s southeast eyewall during the sampling period (Fig. 11). We used HAMSR brightness temperatures to further assess Karl’s convective structure during this and other flight legs. Since the depression of microwave brightness temperature ($T_B$) due to ice scattering is greater at high frequencies than low frequencies, large differences between high and low frequency $T_B$ indicate where deep convection is occurring (Brown et al. 2007). Figure 12 shows large 50.30/113.25 GHz $T_B$ differences in the southeast eyewall, confirming that the convective region contains deep storms. We will focus on this portion of leg 2 in the following analyses.

**Figure 10.** Vertical profiles of APR-2 Ku-band reflectivity (dBZ) in the inner core regions of each leg. Note the differences in average reflectivity between the electrified (2-4) and non-electrified legs (1 and 5) above the freezing level in the mixed phase region (5-7 km).
Figure 11. GRIP aircraft tracks and WWLLN/GLD360 lightning flashes between 1940–2000 UTC overlaid on the 1945 UTC GOES infrared (IR) image of Karl. The gold stars designate the location of the GH when LIP detected lightning flashes. A 10 km buffer (light blue) is placed along the GH flight track to highlight WWLLN and GLD360 flashes near the aircraft.

Figure 12. $T_B$ differences between the 50.30 and 113.25 GHz channels of HAMSR between 1945-1955 UTC. Large $T_B$ differences (red) in the southeast eyewall indicate regions where greater ice scattering, and thus deep convection, are occurring. WWLLN (*) and GLD360 (+) flashes between 1945-1955 UTC are overlaid for reference.
Figure 13 shows electric field measurements recorded by LIP along leg 2. This image is similar to Fig. 6 of Mach et al. (2009) and Fig. 3 of Mach et al. (2010) who described electrified overflights during previous field campaigns. Electrified convection typically produces positive electric fields above the storm (Williams 2009). The blue lines in Fig. 13a depict the x-y components of the field, with the vectors extending outward from the flight track away from the positive charge aloft. Vector length represents the strength of the electric field at points along the flight path. Figs. 13b and 13c are longitude/altitude and latitude/altitude plots, respectively, that depict the vertical components of the electric field in the east/west and north/south directions. Together, the plots in Fig. 13 comprise a three-dimensional view of the electrical structure measured by LIP. The orientation of the electric field vectors in Fig. 13a reveals that the charged convection around 1948 UTC is located just northeast of the GH. Although WWLLN detected numerous flashes near the GH (Fig. 13, green stars), LIP only detected two flashes along this leg. However, this relatively small flash count may be attributed to the “shower effect”, where a large storm near the sensors masks field changes due to lightning further away from the aircraft (R. Blakeslee and D. Mach, 2012, personal communication).

Figure 13. LIP electric field measurements between 1945-1955 UTC. a) 2-D electric field vectors (blue) along the GH flight track. The vectors point away from the positive charge center of the storm that is located northeast of the GH around 1948 UTC. Colors along the flight path indicate the strength of the vertical electric field (color bar). b) Vertical and east/west components of the electric field (green vectors). c) Vertical and north/south components of the electric field (green vectors). Green stars denote WWLLN lightning flashes (1945-1955 UTC).
The WWLLN lightning flashes (green stars) overlaid on Fig. 13 suggest that lightning was concentrated on the west side of the GH flight path, which seems to conflict with the storm location indicated by the LIP electric fields. There are several possible explanations for this difference in location: (1) There may be flashes on the east side of the flight track that the global networks do not detect, (2) The global networks may not be locating the lightning flashes precisely, or (3) The location of the CG flashes may be displaced from the positive thunderstorm charge aloft detected by the LIP. Regardless, it is clear that the GRIP aircraft penetrated an electrically active region along this leg.

Vertical reflectivity data from APR-2 and HIWRAP help describe the structure of Karl’s inner core convection. Although both radars measure Ku-band reflectivity, they employ different scan strategies (Fig. 14). APR-2 has a downward pointing antenna that scans across the aircraft track (Fig. 14a, Sadowy et al. 2003). Near nadir scans can be identified based on the orientation of the aircraft. On the other hand, HIWRAP has a conical scan configuration, with the inner/outer beams tilted 30° and 40°, respectively, from the vertical (Fig. 14b, Heymsfield et al. 2006b). Therefore, the Ku-band reflectivity data from HIWRAP presented here will be tilted approximately 30° from nadir.

Figure 14. a) APR-2 scan geometry depicting the cross track scans performed by the downward pointing antenna (after Sadowy et al. 2003). b) HIWRAP scan geometry showing the conical scan strategy used to sample the storm (after Heymsfield et al. 2006b).
Reflectivities from both APR-2 (Fig. 15a) and HIWRAP (Fig. 16) show a deep convective cell within Karl’s southeast eyewall. This was the focus of the electrical activity observed along leg 2. APR-2 on the DC-8 shows this cell having enhanced reflectivity aloft with a 35 dBZ region extending several km above the freezing level. HIWRAP on the GH reveals that the eyewall convection extends well above 12 km. Enhanced reflectivity aloft is a good indicator that graupel and supercooled water are being carried far above the freezing level by strong updrafts (Zipser and Lutz 1994). APR-2 Doppler velocities (Fig. 15b) show updrafts of 5-10 m s$^{-1}$ above the freezing level, with strong downdrafts near the surface. The maximum DC-8 flight level updraft exceeds 20 m s$^{-1}$ in this region (Fig. 5), the strongest MMS-derived vertical motion on this day. Fig. 15c contains an experimental microphysics classification product provided by APR-2 scientist Simone Tanelli (JPL). This product uses APR-2 reflectivity, Doppler velocity, and cross-polarization data to classify scattering particles as rain, snow, graupel, or ice (S. Tanelli and S. Durden, 2011, personal communication). Tanelli et al. (2004) provide details on an earlier version of this precipitation classification algorithm. Figure 15c reveals a region of graupel (indicated by the peach color) collocated with the reflectivity core that extends several km above the freezing level, which is located near 5 km. This configuration is expected in electrically active convection. We will analyze the cloud microphysics of this region in greater detail later.
Figure 15. APR-2 data from a southeast to northwest pass through Karl between 1944:00 – 1954:47 UTC. a) Ku-band reflectivity. b) Doppler velocity, with negative values representing upward vertical motion. c) APR-2 experimental microphysics classification product (courtesy of Simone Tanelli, JPL). The black boxes in each panel highlight the electrified convective region of interest.
Figure 16. Ku-band HIWRAP reflectivity data between 1942:59 – 1955:56 UTC. The black box denotes the electrified convective region of interest. Recall that the tilted appearance of the reflectivity is due to the scan geometry of HIWRAP.

An analysis of lightning flashes in the eyewall reveals a cluster of WWLLN-derived inner core flashes that rotates in a counterclockwise direction around Karl’s center (Fig. 17). Intense convective bursts, or convective events (CEs), produced similar patterns of lightning in the eyewalls of Hurricanes Katrina and Rita (2005) (Fierro et al. 2011). GOES IR satellite imagery (Fig. 18) shows a small region of intense convection with cloud top $T_{B} < -80^\circ C$ rotating counterclockwise around the eyewall at a speed of approximately 20 m s$^{-1}$. The satellite and lightning data indicate that this convective burst persists for approximately 30 min. Recent observational (Guimond et al. 2010) and modeling (Fierro and Reisner 2011) studies have shown evidence of deep convective bursts preceding the RI of some TCs. The convective bursts in Guimond et al. (2010) contained maximum updrafts of 20 m s$^{-1}$ at altitudes of 12-14 km, with strong downdrafts flanking the updrafts. The simulated CEs of Fierro and Reisner (2011) contained updrafts in excess of 10 m s$^{-1}$ and propagated at speeds approximately 10 m s$^{-1}$ less than the azimuthal flow in the eyewall. The CEs tracked in Fierro et al. (2011) had lifetimes ranging from 12-40 min. These characteristics are very similar to those of Karl’s deep convection during leg 2. Therefore, it appears that the GRIP aircraft did penetrate a deep convective burst embedded within Karl’s eyewall. We note that this convective burst occurred while Karl was rapidly deepening (Fig. 2), which is consistent with the findings of Guimond et al. (2010) and Fierro et al. (2011).
Figure 17. WWLLN-derived inner core flashes between 1940-2000 UTC color coded by time of occurrence. Tracks of the DC-8 (blue) and GH (green) are overlaid. The solid black circle represents the estimated location and size of Karl’s eye based on National Hurricane Center (NHC) data. Because the location of some flashes are not consistent with the NHC center location, the dashed circle shows the location of Karl’s eye inferred from satellite, HAMSR, and lightning data. The location differences could be attributed to WWLLN position errors (see section 2.2) and/or NHC location errors. The shaded region highlights a cluster of flashes (a deep convective burst) rotating counterclockwise around Karl’s eye in the southeast eyewall.

Figure 18. GOES 10.7 µm IR satellite images of Hurricane Karl on 16 September: a) 1932 UTC, b) 1940 UTC, c) 1945 UTC, d) 1955 UTC, and e) 2003 UTC. The pink color corresponds to IR cloud top brightness temperatures colder than -80 °C. The white arrows in each panel indicate the deep convective burst moving counterclockwise around the eyewall at approximately 20 m s⁻¹.
We next use CDP (2-50 µm) and CAS (0.35-50 µm) particle concentration data in conjunction with 2-D images from PIP (100-6200 µm) to analyze the microphysics of the electrified region. Figure 19 is a time series of CDP and CAS concentrations as well as MMS vertical velocity. The sharp increase in CDP and CAS concentrations just after 1949 UTC corresponds to the time of the 20 m s⁻¹ updraft measured during this leg. In fact, the greatest small particle concentrations and vertical velocity sampled during this entire flight occurred here on leg 2. The collocation of very small ice particles and strong updrafts are consistent with the findings of Herman and Heymsfield (2003) and Heymsfield et al. (2006a). Furthermore, the concentrations of these small particles are too great to have occurred solely by heterogeneous nucleation processes (Herman and Heymsfield 2003, Heymsfield et al. 2006a), thus implying that homogeneous freezing is another mechanism for ice production in this region of the eyewall. Since homogeneous nucleation occurs near temperatures of -40°C, the small ice particles measured at DC-8 flight level likely were recently frozen. This supports the notion that supercooled water was located somewhere below the DC-8 as it penetrated the core of the electrified convection.

![Graphs showing time series of CDP concentration, CAS concentration, and vertical velocity between 1947 - 1951 UTC.](image)

**Figure 19.** Time series of CDP concentration (cm⁻³, top), CAS concentration (cm⁻³, middle), and vertical velocity (m s⁻¹, bottom) between 1947 – 1951 UTC. The sudden increase in small ice particle concentrations matches the time of the 20 m s⁻¹ updraft.
Figure 20 contains images of particles sampled by PIP at various locations in the southeast quadrant of Karl. Figures 20a and 20d reveal that small ice particles and aggregates are present on either side of the deep convection; however, there is no indication of graupel. In contrast, Figs. 20b and 20c reveal much greater concentrations of small ice particles collocated with 1-2 mm graupel particles (circled in red). The location of the graupel particles within the convective region is consistent with the microphysics classification product shown in Fig. 15c. Large concentrations of very small, recently frozen ice particles at flight level enable us to infer the presence of supercooled water below the aircraft in this electrified region (Herman and Heymsfield 2003). A convective environment with small ice, large graupel, and supercooled water is certainly conducive to charge separation and TC electrification (Black and Hallett 1999).

![Figure 20](image)

**Figure 20.** PIP particle images from the southeast eyewall of Karl: a) 1948:07 UTC, b) 1949:05 UTC, c) 1949:14 UTC, and d) 1950:09 UTC. The black stars on top of the radar scan indicate the approximate location where each particle image was taken. Red circles identify graupel particles in the convective region.
3.2.2 Electrified Leg 4 (2110-2130 UTC)

It is informative to examine a second electrified flight leg through Karl. Leg 4 was an electrified north to south pass between 2110-2130 UTC. It is an example of a broader electrified region where the two aircraft penetrated slightly different portions of the eyewall. The aircraft were fairly well coordinated, although the GH veered away from the DC-8 in the southern eyewall, presumably trying to avoid some of the stronger convection (Fig. 21). The global lightning networks detect flashes along both aircraft tracks (Fig. 3); however, Fig. 21 shows that the lightning actually is more concentrated near the GH flight path. LIP-derived electric field data (Fig. 22) indicate that the positive charge aloft associated with the electrified convection is located east of the GH flight track. There were 13 LIP-derived flashes detected during this leg, the greatest of any flight leg analyzed in this study.

Figure 21. GRIP aircraft tracks and WWLLN/GLD360 lightning flashes between 2110-2130 UTC overlaid on 2115 UTC GOES IR satellite imagery. The gold stars designate locations of the GH when LIP detected lightning flashes. A 10 km buffer (light blue) is placed along the GH flight track to highlight WWLLN and GLD flashes near the aircraft.
Figure 22. LIP electric field measurements between 2115-2130 UTC. a) 2-D electric field vectors (blue) along the GH flight track. The vectors point away from the positive charge center of the storm, which is east of the GH track around 2122 UTC. Colors along the flight path indicate the strength of the vertical electric field (see color bar). b) Vertical and east/west components of the electric field (green vectors). c) Vertical and north/south components of the electric field (green vectors). Green stars denote WWLLN lightning flashes.

A comparison of APR-2 reflectivities from the DC-8 (Fig. 23a) and HIWRAP reflectivities from the GH (Fig. 24) reveals differences between the regions sampled in the southern eyewall. Fig. 23a shows that the DC-8 sampled a region with multiple convective cells embedded within the inner core. While no cell is as vertically developed as the convection in leg 2 (Fig. 15a), a region of 30 dBZ reflectivity does extend above 9 km. APR-2 Doppler velocity (Fig. 23b) reveals a deep updraft extending from 1.5 km to 9.5 km. The weak echo region near the surface in Fig. 23a confirms that vertical motions in the eyewall are quite strong at this time. The maximum Doppler-derived updraft of 15 m s$^{-1}$ is located just above 3 km. This relatively low altitude suggests that the eyewall convection is still strengthening. The APR-2 microphysics product (Fig. 23c) shows several regions of graupel above the freezing level, the deepest of which extends above 8 km. HIWRAP reflectivity (Fig. 24) suggests that the GH may have flown over deeper convection than the DC-8 during its penetration of the inner core. The innermost convective cell in the southern eyewall extends above 13 km, similar to the convection sampled along leg 2 (Fig. 16). These enhanced reflectivities aloft may help explain why the flash counts in Fig. 3 are greater near the GH than the DC-8.
Figure 23. APR-2 data from a north to south pass through Karl between 2117:40 – 2126:16 UTC. a) Ku-band reflectivity. b) Doppler velocity, with negative values representing upward vertical motion. c) APR-2 experimental microphysics classification product (courtesy of Simone Tanelli, JPL). The black boxes in each panel denote the electrified convective region of interest.
Small particle concentrations and vertical velocities through the electrified southern eyewall of Karl are shown in Fig. 25. Several flight level updrafts exceeding 10 m s\(^{-1}\) are present between 2123-2124 UTC. These updrafts are associated with a broad region of enhanced small ice particle concentrations. The maximum CDP and CAS values during this leg are the second greatest sampled on this day (with the greatest occurring along leg 2). Once again, the enhanced presence of small particles suggests that supercooled water may be present below the aircraft. The multiple updrafts measured along leg 4 (Fig. 25) are weaker than the single, more powerful updraft along leg 2 (Fig. 19). However, the magnitudes of particle concentrations are similar on both legs, and the increase in small ice particles occurs where strong vertical motions are present. These findings agree with the observations of Herman and Heymsfield (2003) and Heymsfield et al. (2006a).
Figure 25. Time series of CDP concentration (cm$^{-3}$, top), CAS concentration (cm$^{-3}$, middle), and vertical velocity (m s$^{-1}$, bottom) between 2122 – 2125 UTC. Numerous updrafts exceeding 10 m s$^{-1}$ between 2123-2124 UTC are associated with a broad region of very small ice particles.

Figure 26 contains images of particles sampled by PIP at various locations within the southern eyewall. One should recall that the DC-8 was flying approximately 1 km higher during this leg than on leg 2. The particles on either side of the deep convection (Figs. 26a and 26d) consist of small ice and aggregates. However, within the region of enhanced reflectivity (Figs. 26b and 26c), the PIP data indicate that graupel (circled in red) is being lofted to flight level above 11 km. This high altitude graupel reaches 3 mm in diameter (Fig. 26b). Thus, the graupel signature in Fig. 23c is supported by the in situ microphysical data in Fig. 26. Furthermore, very small ice particles collocated with the graupel suggest that supercooled water is present below the aircraft. The numerous lightning flashes detected by WWLLN, GLD360, and the LIP (Fig. 21) in the southern eyewall give credence to the inference of supercooled water in this region. Despite the structural differences between the eyewall convection of legs 2 and 4, the electrified nature of both regions can be attributed to a microphysical environment that is conducive to electrification due to strong vertical motions in Karl’s inner core.
Figure 26. PIP particle images from Karl’s southern eyewall: a) 2122:47 UTC, b) 2123:51 UTC, c) 2123:52 UTC, and d) 2125:03 UTC. The black stars on top of the radar scan indicate the approximate locations where each particle image was taken. Red circles identify graupel particles in the convective region.
CHAPTER FOUR

SUMMARY AND CONCLUSIONS

The sporadic nature of TC lightning raises questions about what information lightning data convey about a storm. Global lightning networks such as WWLLN and GLD360 provide unprecedented, continuous information about electrical activity in TCs around the world. However, there still is uncertainty as to how this lightning data can be utilized. Various studies have explored potential links between lightning frequency and changes in TC intensity (Molinari et al. 1999, Squires and Businger 2008, Price et al. 2009, Austin and Fuelberg 2010, Demetriades et al. 2010b, Abarca et al. 2011, Fierro et al. 2011), but their results have been inconclusive. Our study has examined the physical properties that contributed to the presence or absence of lightning in rapidly intensifying Hurricane Karl on 16 September 2010. We used numerous datasets (Table 1) collected by the NASA DC-8 and Global Hawk aircraft during the 2010 NASA GRIP experiment to analyze Karl’s vertical motions, cloud microphysics, and radar-derived storm structure. We then examined how these properties varied along five flight legs (Table 2) through electrified and non-electrified inner core regions of the storm, as determined by LIP, WWLLN, and GLD360 lightning data (Table 3).

Flight level vertical velocities from the MMS (Fig. 5) and Doppler-derived vertical velocities from the APR-2 (Fig. 6) revealed that Karl’s electrified inner core regions typically contained peak updrafts exceeding 10 m s\(^{-1}\), with some as strong as 20 m s\(^{-1}\). These findings are consistent with previous studies (Zipser and Lutz 1994, Black and Hallett 1999) that related strong vertical motions to enhanced TC lightning activity. Conversely, the non-electrified regions of Karl’s inner core generally were associated with weaker updrafts that peaked at approximately 5-6 m s\(^{-1}\). Concentrations of small ice particles (< 50 \(\mu\)m in diameter) exhibited a moderate positive correlation with updraft speed (Fig. 8), and the greatest concentrations often were associated with moderate to strong updrafts (Fig. 9). As in previous TC microphysical studies (Herman and Heymsfield 2003, Heymsfield et al. 2006a), the greatest concentrations of small ice were deemed too large to have occurred solely by heterogeneous nucleation. It is likely that some of these ice particles at flight level (10.3-11.3 km) were recently frozen (Herman and Heymsfield 2003), indicating that supercooled water existed below the aircraft. The presence of
supercooled water above the freezing level is critical for TC electrification (Black and Hallett 1999).

Data from the APR-2 (Fig. 10) revealed that the electrified legs contained reflectivities several dB greater than the non-electrified legs throughout most of the troposphere. These enhanced reflectivities in the mixed phase region of the electrified legs indicated that supercooled water and/or large ice particles were being carried aloft by the strong updrafts. Enhanced reflectivity above the freezing level is a good indicator of deep convection whose strong updrafts produce an environment conducive to electrification (Zipser and Lutz 1994, Cecil and Zipser 2002, Pessi and Businger 2009). These radar signatures were consistent with the in situ microphysical data and the inference of supercooled water in the electrified inner core regions.

Case studies of legs 2 and 4 analyzed properties of electrified inner core regions in more detail. During leg 2 (Fig. 11), the GRIP aircraft sampled a deep convective burst that produced lightning in Karl’s southeast eyewall (Figs. 17-18). On leg 4 (Fig. 21), the aircraft penetrated a broader convective region with widespread lightning in the southern eyewall. Despite the structural differences between the convection sampled during these legs, we can identify several common characteristics of Karl’s electrified regions. Our results show that the electrified inner core regions generally were associated with: 1) strong updrafts of 10-20 m s\(^{-1}\) (Figs. 15b and 23b), 2) deep mixed phase layers indicated by reflectivities > 30 dBZ extending several km above the freezing level (Figs. 15a, 16, 23a, 24), and 3) microphysical environments consisting of graupel, very small ice particles, and the inferred presence of supercooled water (Figs. 20 and 26). These characteristics describe an environment where non-inductive charging (Takahashi 1978, Saunders and Peck 1998) and TC electrification (Black and Hallett 1999) are expected. We conclude that the electrified regions in Karl’s inner core were attributable to a microphysical environment that was conducive to electrification due to occasional, unusually strong convective updrafts in Karl’s eyewall.

This study capitalized on the unique opportunity provided by GRIP to synthesize multiple datasets from two aircraft and thereby analyze the physical properties of an electrified TC. The ability to monitor TC lightning globally, continuously, and remotely makes lightning data a potentially valuable resource that demands further investigation. Improvements in lightning
detection and future hurricane field campaigns will provide further insight into TC electrification and lightning variability as it relates to TC evolution.
REFERENCES


BIOGRAPHICAL SKETCH

Brad Reinhart was born in Gulfport, Mississippi on February 22, 1988. He grew up in Diamondhead, Mississippi, where the unpredictable weather of the Gulf Coast fueled his interest in meteorology at a very young age. In particular, he developed an interest in hurricanes due to the constant threat and occasional landfall of hurricanes near his hometown (most notably Hurricane Georges in 1998 and Katrina in 2005). After graduating high school in 2006, Brad chose to attend Texas A&M University to pursue a career in meteorology. At Texas A&M, Brad was active in the student AMS chapter, Texas A&M Weather Broadcasting, and undergraduate research programs. He was introduced to lightning research while working on his NOAA Hollings Scholar project at the National Weather Service Melbourne, Florida during the summer of 2009.

Brad graduated Summa Cum Laude with Foundation Honors from Texas A&M University in May 2010 with a B.S. degree in Meteorology. Brad was awarded an AMS/Northrop Grumman Graduate Fellowship the same year, and he decided to continue his education at Florida State University. Over the past two years, Brad has worked under the guidance of Dr. Henry Fuelberg studying lightning in tropical cyclones. As an FSU graduate student, Brad participated in the 2010 NASA GRIP experiment and was able to fly into Category 3 Hurricane Earl aboard the NASA DC-8. He has presented his research at the AMS Conference on Hurricanes and Tropical Meteorology and multiple NASA GRIP Science Meetings. Brad has also worked for the National Data Buoy Center since June 2010 as part of the Student Career Experience Program (SCEP). He is a member of the FSU chapter of Chi Epsilon Pi.