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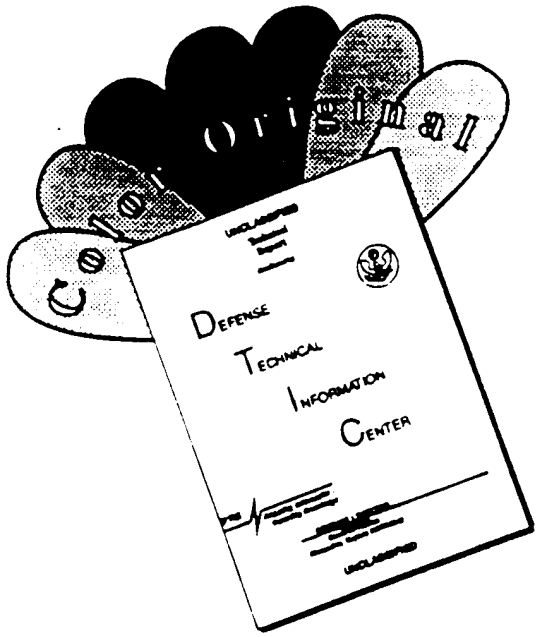

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ANALYSIS OF CLOUD-TO-GROUND LIGHTNING IN HURRICANE ANDREW

A Thesis

by

WILLIAM RANDEL GEORGE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 1995

Major Subject: Meteorology

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May 1995

Major Subject: Meteorology

ABSTRACT

Analysis of Cloud-to-Ground Lightning
in Hurricane Andrew. (May 1995)
William Randel George, B.S., University of Oklahoma
Chair of Advisory Committee: Dr. Richard E. Orville

In August of 1992, Andrew joined a long list of tropical storms that have caused considerable damage and loss of life as they made landfall near a populated area. However, Andrew was unique in the sense that no previous landfalling tropical storm in the United States has provided such an excellent opportunity to study the cloud-to-ground (CG) lightning associated with this type of storm. While numerous thunderstorm systems, particularly the severe storms of the Great Plains, have been studied for lightning characteristics, the ability to conduct similar studies on hurricanes has been limited due to the small number which have occurred since the relatively new National Lightning Detection Network has been operational.

17,036 CG strikes over a 77 hour period were attributed to either the eyewall region or the primary spiral rainbands of Andrew. The overall distribution by polarity of the lightning was found to be 2.1% positive and 97.9% negative. As the storm was dissipating over land in Mississippi all lightning observed near the pressure center was positive. Throughout the lifetime of the storm, the negative first stroke peak current decreased while the positive first stroke

peak current increased.

The mean multiplicity of the negative flashes was 2.6, while the positive lightning had a mean value of 1.2. High-multiplicity flashes (negative CG flashes with 10 strokes or greater) tended to occur in four distinct groups and in time intervals of 19 to 23 hours apart in an area corresponding to the right-forward quadrant to right flank of the storm structure.

Comparison of radar data to the lightning data shows that the deep convective regions of the outer rainbands were the areas with the most lightning. A lack of significant lightning observed in the eyewall region is consistent with previous research suggesting microphysical processes in this part of the storm are not favorable for charge separation.

ACKNOWLEDGEMENTS

Many thanks go to fellow students at Texas A&M University who helped me in various ways. Mr. Mike Nelson was instrumental in the retrieval of the radar reflectivity data from the tapes and getting it into a readable computer display. My office mate, Ms. Svetla Veleva helped me countless times with Unix commands and always had a pleasant smile on her face. Fellow officers, Major Patrick M. Hayes, USAF, and Lieutenant Commander Don T. Conlee, USN, shared a tremendous amount of small computer expertise that was invaluable to graduate school survival. Special thanks are also in order to Mr. Christopher Samsury and Mr. Peter Dodge of the Hurricane Research Division of the National Oceanic and Atmospheric Administration for helping me obtain the radar data tapes of Andrew. Thanks also to my committee chair, Dr. Richard Orville for guiding this research, and to the United States Air Force for the continuing educational opportunities they have provided. Finally, thanks to my family for their constant support in my career and personal endeavors.

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

1. Overview

Andrew was the first Atlantic Ocean tropical storm of the 1992 season. It began as Tropical Depression Three on 16 August 1992 near 11 degrees north latitude and 38 degrees west longitude, approximately 1500 miles east of the Lesser Antilles islands. Andrew became a hurricane on 22 August 1992 and moved across the northwestern Bahamas as a category 4 storm on the Saffir-Simpson scale (Simpson 1974). When it struck southeastern Florida near Miami on the morning of 24 August 1992, Andrew had maximum sustained winds estimated at 145 mph with gusts in excess of 175 mph. Its minimum central pressure of 922 mb was the third lowest this century for a hurricane making landfall in the United States. Andrew continued across the northeastern Gulf of Mexico to strike the Louisiana coast at Point Chevreuil as a category 3 storm with 120 mph winds and a central pressure of 956 mb. Hurricane Andrew was responsible for numerous deaths and over $20 billion in damages which made it the costliest natural disaster in United States history (Mayfield et al. 1994).

Andrew was unique in the sense that no previous landfalling tropical storm in the U.S. has provided such an

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The style is that of *Monthly Weather Review*.

excellent opportunity to study the cloud-to-ground (CG) lightning associated with this type of storm. Previously, the study of lightning in organized storm systems was mainly limited to convective mesoscale and submesoscale phenomena, particularly the severe thunderstorms common to the Great Plains. The ability to observe and record lightning location, strength, frequency, areal extent, etc. has only recently been made possible by a network of lightning detection sensors across the country.

While many studies using lightning data exist for mesoscale convective systems (MCSs), it appears that the lack of landfalling tropical storms since the National Lightning Detection Network (NLDN) has been operational has limited the potential for the study of lightning in hurricanes. The fact that some hurricanes are observed to have significantly more lightning than others might suggest that different cloud microphysical processes could be occurring. Hence, the general goal of this paper is to understand the conditions and environment that produced and inhibited the production of lightning in this particular storm.

2. Lightning

A few introductory remarks are in order concerning the general characteristics of lightning and the terminology associated with it. Lightning is defined by Uman (1969) as

> ...a transient, high-current electric discharge whose path length is generally measured in

> kilometers. Lightning occurs when some region of the atmosphere attains an electric charge sufficiently large that the electric fields associated with the charge cause electrical breakdown of the air. The most common producer of lightning is the thundercloud (cumulonimbus).

We generally speak of two basic categories of lightning: cloud-to-ground, frequently denoted as CG, and cloud discharges. Within the cloud-to-ground category, further distinctions are made between negative flashes (in which negative charge is lowered to ground) and positive flashes (in which positive charge is lowered to ground). Typically only about 4% of cloud-to-ground lightning is positive (Orville 1994). Cloud discharges can be further categorized into intracloud, intercloud, and cloud-to-air flashes, yet little experimental data exists to further distinguish the characteristics of these cloud discharges (Uman 1987).

The total lightning discharge is known as a *flash* and lasts about one-half second. A flash is made up of one or more high-current pulses called *strokes*. The term *multiplicity* is used to denote the number of strokes per flash. A representative cloud-to-ground lightning flash will lower 20 to 30 coulombs of charge to ground and have a first-stroke peak current of 20 to 50 kiloamperes (Orville et al. 1987). Cloud-to-ground lightning is of interest because it is more easily observed, detected, recorded and studied than cloud discharges with existing technology and equipment. Furthermore, cloud-to-ground lightning is responsible for

over 100 deaths annually in the United States (Uman 1986).

3. Previous studies

a. Hurricanes

Johnson and Goodman (1984) studied electrical activity in hurricane Alicia (1983). They found the most electrical activity on the southern side of the storm vortex and intensification of the electrical activity associated with forward movement.

Black and Hallet (1986) looked at the type and distribution of particles above the freezing level in three Atlantic hurricanes: Ella (1979), Allen (1980), and Irene (1981). Supercooled water drops, graupel, columns and aggregated snowflakes were observed during instrumented aircraft penetrations. Although this research contained no direct measurement of cloud-to-ground lightning activity within the observed hurricanes, the cloud physics experiments produced evidence to suggest that remote measurements of lightning might be useful in locating regions in the hurricane containing supercooled liquid water. Their study showed that in mature hurricanes there can be extensive regions of ice with only sparse supercooled water in the eyewall and principal rainbands. This would be consistent with the sparsity of lightning observations in these particular storms. (Commonly accepted theories on charge separation in thunderstorms, e.g., Illingworth 1985, involve

collisions between different forms of ice or between ice and supercooled water, therefore the presence of supercooled water is considered a prerequisite for lightning).

However, Black et al. (1986) found, in their study of Diana (1984), considerable lightning and stated, " . . . the ice phase in active convection is evolving in the presence of supercooled water, leading to lightning discharges." This suggests that the presence of lightning in Diana indicates vigorous convection and the needed conditions (graupel, ice crystals, and supercooled liquid water interacting) for charge separation to occur (Jayaratne et al. 1983).

Venne et al. (1989) investigated cloud-to-ground lightning activity associated with bursts of deep convection near the center of tropical storms that often presages storm intensification within the subsequent 12 to 24 hours. These bursts have a resemblance to mid-latitude mesoscale convective complexes, and indeed, similar behavior has been observed in severe thunderstorms where cloud-to-ground lightning flash rates reach a maximum coincident with peak cyclonic shear and tornado formation (MacGorman and Nielsen 1991). The exact role that these deep convection events play in tropical storm intensification and what triggers them are still unknown. However, it appears that monitoring of the cloud-to-ground lightning activity could be a potential forecasting tool.

Samsury and Orville (1994) tabulated data from the NLDN

for the 1989 Atlantic hurricanes Hugo and Jerry. Noteworthy differences were found in terms of their cloud-to-ground lightning characteristics.

Hurricane Hugo was a category 3 storm when it made landfall and its lightning characteristics were studied for an 18-hour period that included both pre- and post-landfall positions. During this time, only 33 CG lightning discharges were recorded, despite radar reflectivities in excess of 50 dBZ in the eyewall and 40 dBZ in the outer rainbands.

Hurricane Jerry was a considerably weaker storm (category 1) than Hugo. However, during the 18-hour period of study on this storm 691 CG lightning discharges were observed to be associated with it. Jerry, too, had high reflectivity values in the eyewall and rainbands.

Samsury and Orville (1994) concluded that differences exist between hurricanes which aren't fully understood, and that further research into cloud physical properties and dynamics, coupled with lightning data, should provide a better understanding of the electrical nature of hurricanes.

Molinari et al. (1994) have also studied the cloud-to-ground lightning in hurricane Andrew. This research studied the spatial characteristics of the lightning based on radial relationship to the storm center and superimposed the data on infrared satellite imagery. Additional analysis was done on temporal variations and flash characteristics.

Molinari et al. (1994) found a weak maximum of lightning

activity in the eye wall region and a large maximum in the outer rainbands. The eye wall lightning tended to be episodic and, like events studied by Venne et al. (1989), related to storm intensification. They found the general flash characteristics of Andrew to be similar to background data from the same area, with mean peak current values around 45 kA, mean multiplicities around 2.7, and positive lightning accounting for 2-3% of the overall total.

b. Mesoscale convective systems

Numerous studies of cloud-to-ground lightning have been conducted over the past several years to analyze mid-latitude mesoscale convective weather systems (MCS). These include mesoscale convective complexes (MCC), squall lines, tornadic supercells, multicellular storms, and rainbands. It is beneficial to review these works because the techniques and procedures developed in these frequently studied systems provide a basis for future research in less often observed phenomena such as hurricanes.

Goodman and MacGorman (1986) looked at a number of MCCs from 1981 to 1983 that passed within detection range of the NSSL lightning network in central and western Oklahoma. In their work, an analysis of CG lightning related to the life cycle of the MCC, they hoped to further the understanding of the relationships between the physics and life cycle of these storms to their environment. They found that in most cases

flash rates increased exponentially to a peak 1 to 2 hours before the maximum extent of the MCC's cloud shield, then decreased exponentially as the convective activity dissipated and was replaced by a stratiform precipitation region. In general, lightning occurred in the region beneath the coldest cloud tops as depicted on infrared satellite imagery.

The total number of CG discharges observed by Goodman and MacGorman (1986) during the MCC life cycle ranged from 12,000 to 33,000 with a mean value of 22,316 cloud-to-ground lightning discharges per MCC. A single MCC can account for one-fourth of the mean annual lightning strikes to ground for any site it passes over during its most intense phase, making it one of the most prolific lightning producing weather systems in the United States. When analyzed for peak hourly flash rates, the average MCC has almost 2700 CG discharges per hour at its peak and can sustain a rate of 1000 per hour for more than 9 consecutive hours. Another interesting finding was that the most active electrical periods are also characterized by the greatest number of discharges containing multiple strokes (multiplicities > 1), while the first hour of MCC storm development contains a greater fraction of single stroke discharges (multiplicity = 1).

Data from the Oklahoma-Kansas PRE-STORM Project was analyzed by Rutledge and MacGorman (1988) to take a further look at the electrification of mesoscale convective systems. One of the broad goals of the PRE-STORM Project was to

evaluate new sensing systems. One such platform was the NSSL network now expanded into Kansas and capable of polarity as well as location determination.

While previous studies of lightning polarity (Rust et al. 1981) had focused on +CG flashes in the mature stage of severe storms on the Great Plains, Rutledge and MacGorman (1988) sought to examine the presence of +CG lightning in a large stratiform precipitation region trailing a squall line. Lightning data were analyzed in conjunction with WSR-57 radar reflectivity data from Wichita, Kansas. Good correlations were found between peak convective rainfall and peak -CG flash rate as well as between peak stratiform rainfall and the peak +CG rate. Time lags of 2 hours were observed between the peak convective rainfall and the peak stratiform rainfall, which was also the approximate time lag between maximum negative cloud-to-ground lightning activity and maximum positive cloud-to-ground lightning activity. The conclusion was that strong rearward storm-relative flow facilitates a horizontal advection of positive charge from the upper levels of the squall line rearward into the stratiform region. The presence of an abundance of positive charge without the normal underlying negative charge then resulted more readily in +CG flashes.

Rutledge et al. (1990) did further work on the PRE-STORM data in order to present further observational data of +CG lightning in MCSs and to examine the characteristics of

charge generation in stratiform regions associated with MCSs.

Further observational analysis of the PRE-STORM data did bear out the hypothesis that positive charge was advected from the convective region of the squall line rearward in the trailing stratiform region. This finding is consistent with research done by Orville et al. (1988) who identified bipolar patterns of negative and positive lightning downwind of negative lightning in mesoscale precipitation regions. These bipoles were aligned with the geostrophic wind and thus appeared to have been positive charges advected downwind from the negative charge area. Orville et al. also believe that a local charge separation process is present producing the enhanced electric fields that would be required to initiate the observed positive cloud-to-ground lightning. Schuur et al. (1991) confirmed the bipolar patterns in their study of a June 1987 Oklahoma squall line also believe that an in situ microphysical charging mechanism is at work in the stratiform region.

Rutledge et al. (1990) suggest this additional class of positive cloud-to-ground lightning activity is associated with the generation of charge through microphysical processes within the stratiform precipitation region, specifically related to ice crystal interactions in regions of low supercooled liquid water contents. Further research into the role of IC lightning influences on stratiform precipitation regions is suggested.

Reap and MacGorman (1989) put together a study of nearly 2 million lightning flashes recorded during the 1985-86 warm seasons by the NSSL network in order to determine some of the climatological characteristics of cloud-to-ground lightning. Their primary objective was to find relationships that could be applied in making operational forecasts of convective weather. While their work produced abundant information on temporal and spatial variation of lightning, it is desired to focus on their comparisons of lightning and radar data. These correlations were obtained by comparing the NSSL network lightning data to manually digitized radar reflectivity (MDR) values from the NWS WSR-57 radar in Oklahoma City. The results of MDR encoding provide the user with the maximum VIP level (Video Integrated Processor) observed within grid blocks identical to those used to archive the lightning data. Table 1 shows the relationship between VIP levels and the more quantitative values commonly used, i.e. reflectivity in dBZ units.

Table 1. VIP Levels - Reflectivity relationships.

VIP Level	Reflectivity threshold (dBZ)
1	29.5
2	35.9
3	40.7
4	47.0
5	51.9
6	55.1

Reap and MacGorman's (1989) results showed a pronounced decrease in lightning activity below VIP 3, the threshold

level used by many to delineate thunderstorm activity using radar data (Reap and Foster 1979). However, 22% of the grid blocks with VIP 2 still have at least two ground strikes. Two possible explanations offered are: 1) growing storms with small reflectivity cores may produce lightning before high reflectivity levels are observed on radar, and 2) due to beam spreading and earth curvature, distant storms may be missed by most of the beam, thus the observation may record a lower VIP level than actually exists.

At the other end of the VIP spectrum in Reap and MacGorman (1989), some grid blocks with high levels have no ground strike activity at all. Again there are two possible explanations: 1) Storms that have little or no lightning activity during their decaying stages when downdrafts predominate the storm structure, and 2) storms that have mostly intra-cloud lightning which is not recorded by the lightning detectors.

Additionally, in Reap and MacGorman (1989) a high correlation was found between severe local storms and high flash rates of +CG lightning, especially for storms producing hail. This makes a strong case for hailstorms being producers of positive cloud-to-ground lightning.

As mentioned previously, one of the early works on the role of positive CG lightning is by Rust et al. (1981). They looked at the origin of 31 positive discharges within mature severe thunderstorms and found that no +CG lightning was

associated with heavy precipitation cores of the storms; the +CG lightning was, however, observed to originate from several other regions of the storms, specifically from the downshear anvil, high on the back of the main convective tower, and through the wall cloud.

MacGorman and Nielsen (1991) have done extensive research into the lightning activity associated with the Edmond, Oklahoma F3 tornado of 8 May 1986. While their primary goal was to compare it to the Binger, Oklahoma F4 tornado of 22 May 1981 which had extensive intracloud lightning, they were unable to make comparisons of total flash rates because the IC data were unavailable for the Edmond tornado.

While the comparisons between the two tornadic storms is beyond the scope of this review, it is useful to extract the information obtained on the characteristics of positive lightning within the tornadic storm. During the Edmond storm, +CG discharges were recorded just prior to the first tornado. Positive flash rates reached their peak during the tornadic phase of the storm. Positive strikes were also observed to occur outside or along the periphery of the negative strike region. Several positive strikes occurred near or inside the mesocyclone itself. The authors suggest that the positive strikes well outside the mesocyclone occurred due to a mechanism similar to that described previously for positive lightning in trailing stratiform

regions of MCSs (Rutledge et al. 1988, 1990). Positive strikes in or near the mesocyclone may have been caused by a region of positive charge underneath the main negative charge of the storm structure, or perhaps by a tilted charge structure within the mesocyclone region.

In contrast to MacGorman and Nielsen's findings, Curran and Rust (1992) found positive cloud-to-ground lightning rates dropped to nearly zero while negative CG rates greatly increased with the tornadic supercell they studied. However, they were studying a specific class of supercell known as low-precipitation (LP) storms as defined by Bluestein and Parks (1983). It's interesting to note that during the splitting and merging phase of this LP storm the majority (84%) of the flashes to ground were positive. It was in its transition to a supercell that the positive ground flashes were virtually non-existent with only 1 of 136 flashes recorded as positive.

Clearly, positive cloud-to-ground lightning discharges have a significant role within mesoscale convective systems, but the exact nature of that role is not fully understood.

Keighton et al. (1991) studied CG lightning location relative to storm structure during a supercell event in Oklahoma in May 1981. They found a strong correlation between CG flash rate and reflectivity cores at midlevels. Furthermore they suggest that the strength of the updraft is related to the CG flash rate in the convective region and

that the overall wind structure in the storm affects the location of the lightning.

4. Charge separation process

Since it has been observed that not all hurricanes share similar lightning characteristics, it could be argued that this indicates that different ingredients are involved in various storms. Many charge separation theories (Fleagle and Businger 1980) have been offered in the past to explain the processes responsible for electrification within thunderstorms, yet there seems to be no general agreement.

Illingworth (1985) surveyed the many possible processes going on within thunderstorms that could act to separate electric charge. He concluded that the mechanism responsible for a charge separation large enough to cause lightning consists of "...charge transfer occurring when ice crystals collide with and separate from a riming hailstone...". (A riming hailstone is one which is growing in the presence of supercooled liquid water.)

Similar findings by Jayaratne et al. (1983) point to the interaction of soft hail, ice crystals, and supercooled liquid water as necessary for thunderstorm electrification.

To summarize the generally accepted basic precipitation charging mechanisms: Heavy, falling precipitation particles interact with lighter particles carried in updrafts. This interaction process serves to charge the heavy particles

negatively and the light particles positively, after which gravity and updrafts separate the opposite charges to form a positive cloud dipole (a cumulonimbus cloud with negative charge at its base and positive charge at the top). The presence of supercooled water seems to be key to the electrification process. As mentioned previously, Black and Hallet (1986) showed there can be extensive regions of ice with sparse supercooled water in the eyewall and principal rainbands in mature hurricanes. Therefore, using lightning detection to look for lightning in these regions of a mature hurricane can serve as a remote sensing tool for qualitative determination of the existence of supercooled water and the other required ingredients for charge separation.

CHAPTER II

DATA, METHODS, AND ANALYSIS TECHNIQUES

1. National Lightning Detection Network and data

a. The National Lightning Detection Network

The National Lightning Detection Network (NLDN), a relatively new observational tool, was established in the summer of 1987. It grew from three independent regional networks: the Bureau of Land Management (BLM) network covering the western states, which was designed to facilitate early detection of lightning-caused fires (Krider et al. 1980); the National Severe Storms Laboratory (NSSL) network, that grew from research efforts of the NSSL in Oklahoma and Kansas (Mach et al. 1986); and a network operated in the eastern United States by the State University of New York at Albany (SUNYA) as described by Orville et al. (1983). It currently consists of 133 sensors linked together by modern telecommunications systems providing coverage of the continental United States (Figure 1).

Although the NLDN is relatively new, the principles of radio direction-finding are not. The basic principles were developed in the 1920's by Watson-Watt and Herd working for the U.S. Navy. Weil (1937) describes their equipment, early principles of direction-finding, gives an account of radio static associated with a hurricane over Florida in 1928 and details a procedure for using direction finding equipment to

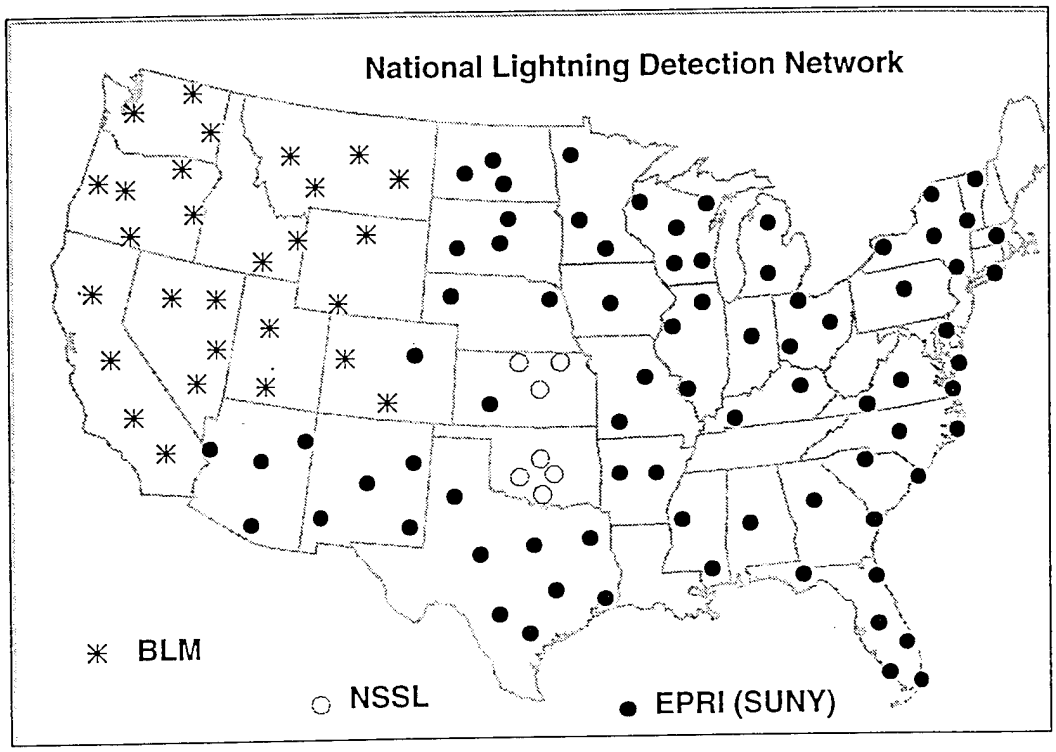

Figure 1. National Lightning Detection Network. The locations of the direction finders comprising the network are shown with the symbols showing the organizations that own and installed the sites. These are the Bureau of Land Management (BLM), the National Severe Storms Laboratory (NSSL), and the Electric Power Research Institute (EPRI) through the State University of New York (SUNYA).

observe hurricanes.

A typical lightning discharge produces several large current surges in the radio frequency spectrum with distinctive radiation field signatures as shown in Figure 2a through 2c. Krider et al. (1976) developed a gated, wideband magnetic direction finder (DF) with sufficient range and angular accuracy to make a realtime network feasible.

So far, intracloud lightning (IC) has not been discussed. The radiation field signature of IC lightning (Figure 2a) is quite different from CG lightning (Figure 2b and 2c). Close inspection of the sample radiation field signatures presented will show the that the IC signature lacks the pulses caused by the step leader process (Krider et al. 1980) and it contains what is known as a "bipolar overshoot" where the polarity reverses very fast. The signal processing electronics of the DF are designed to ignore this signature and only record the CG strikes. This design was necessary to optimize accuracy and eliminate background noise. The DF electronics, therefore, look for specific rise time, width, and subsidiary peak structure characteristics which are unique to the CG flash.

b. Data gathering, processing and dissemination

The equipment installed at each DF site consists of an orthogonal-loop antenna, a flat-plate antenna, and the associated electronics needed to process, record, timekeep,

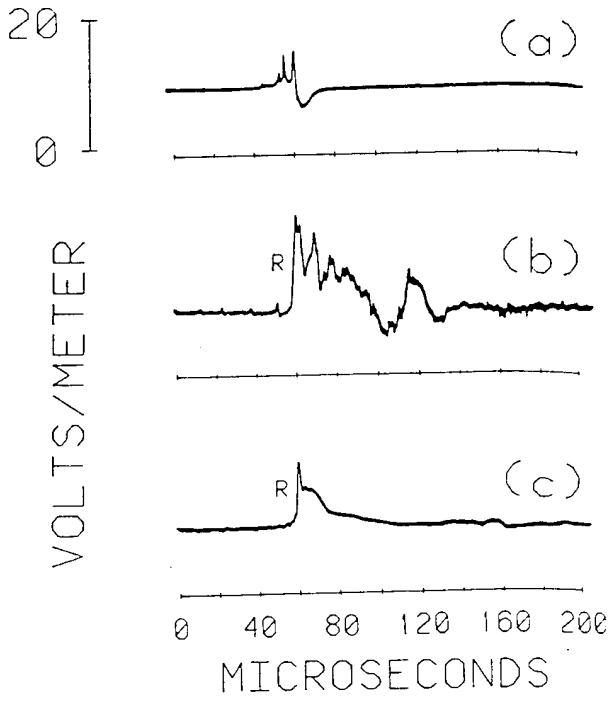

Figure 2. Electromagnetic signatures of lightning. The top trace (a) shows a cloud discharge while the bottom traces (b) and (c) are cloud-to-ground strokes. After Krider et al. (1980).

and disseminate the data.

The orthogonal-loop antenna, which is connected to a wide-band analog receiver (approximately 1 to 400 MHz), senses the voltage induced by the magnetic field, which is proportional to the cosine of the angle between the plane of the loop and the direction of propagation of the incoming field. The direction of the lightning discharge can be determined from the ratio of the signals on the two orthogonal loops, but it has a 180° ambiguity due to the fact that the same readings can be obtained from opposite directions with differing polarities of CG discharges. This ambiguity is removed by the use of the flat-plate antenna to sense the polarity of the electric field associated with the lightning discharge.

The signal recorded by the analog unit is then processed in the direction finder controller (DFC) digital node (essentially a desktop computer) where a time is added to the record through a GOES satellite synchronized clock, and finally is transmitted through a Contel C251 earth station to the Galaxy III telecommunications satellite.

This data is received from Galaxy III through a Contel system at Palo Alto, California and relayed to Tucson, Arizona using land lines where it is processed before being returned along the same lines of communication to the satellite for rebroadcast to users. It is at the processing center in Tucson that the azimuth information from individual

DFCs is compiled into actual lightning locations using the high-precision times to match up multiple detections of the same flash.

Data from two DFC sites are required to locate a lightning discharge using simple radio direction-finding triangulation methods. However, when three or more DFCs record a flash, an optimum location is calculated that takes into account the curvature of the earth's surface (Orville, Jr. 1987).

Operating on high-gain settings, these direction finders have a nominal range of about 400 km, within which approximately 70% of the cloud-to-ground lightning discharges are recorded (Mach et al. 1986). From 400 to 600 km approximately 50% detection efficiency is assumed, as atmospheric attenuation and background noise that exceed the threshold setting on the DF allow only the strongest signals to be recorded. 600 km should be considered the absolute maximum range of the system, as beyond this range not only does the detection efficiency drop well below 50%, but polarities become reversed due to ionospheric reflection of the electric field (Brook et al. 1989). Fortunately, the path of Hurricane Andrew lay entirely within the 600 km range of the NLDN for the period which it affected the U.S. (Figure 3) and it is reasonable to assume that 50 to 70% of the CG strikes in the storm were recorded beginning with the time it initially came within nominal range of the NLDN (around 2200

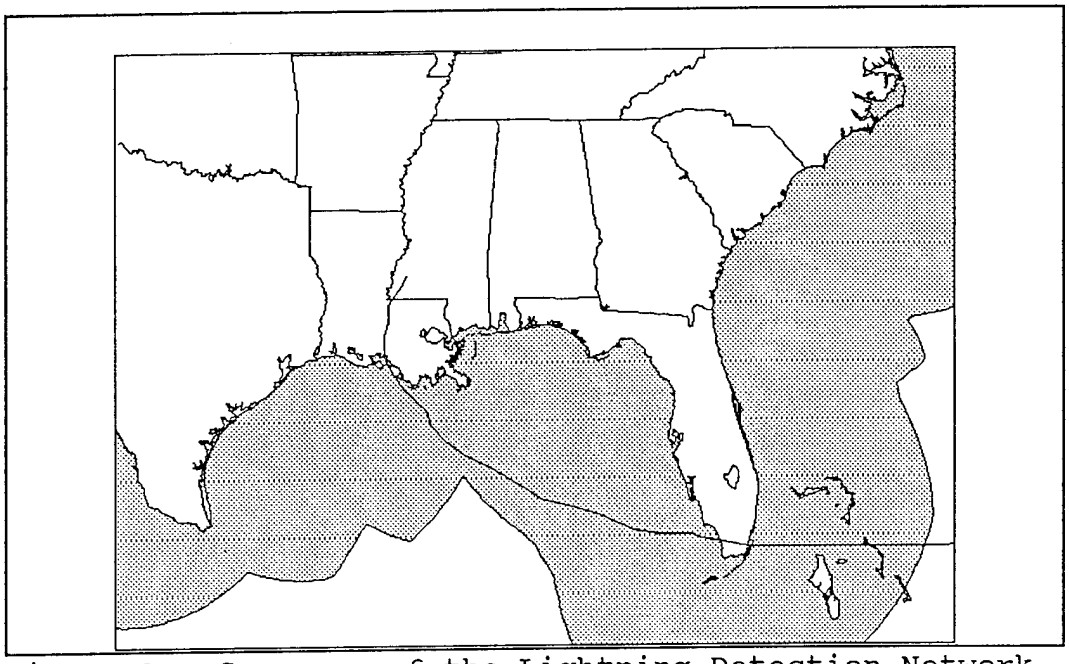

Figure 3. Coverage of the Lightning Detection Network. Shaded area represents nominal coverage by two direction finder sites out to 600 km range. Solid line represents track of Hurricane Andrew.

UTC 23 August 1992).

c. Site errors in the NLDN

Site errors can be broken into two basic categories: systematic and random.

The systematic errors deal with physical characteristics of an installation. Examples are: 1) misalignment of the antenna, which according to Mach et al. (1986) must be kept aligned within 0.5° of true North; 2) resonance effect of the antenna mounting surface, exemplified by mounting the antenna on a metal roof; 3) conductivity of soil/ground in the vicinity of the site; and 4) network geometry which primarily refers to baseline errors that occur when a lightning discharge is in line with two DFCs. In the case of baseline errors, unless there's a third DFC to detect this flash, the crossing angles of the inline sites are too small for accurate location by the basic triangulation. The primary source of random errors is noise in the electronics. This can account for up to a 1° error in azimuth.

Site errors are unavoidable, but once they are known, correction factors can be created for each site and then incorporated into the data processing thus allowing significantly greater accuracy over uncorrected values. In general, most lightning locations are accurate to within 5 to 10 km which is adequate for a mesoscale study such as this.

d. Local data handling and archiving

A subscriber to the NLDN has a terminal built around a desktop computer, typically a 386- or 486-based machine with a large hard disk drive. A small satellite receiver retrieves the processed data from the Galaxy III satellite and it is then ingested into the desktop computer. Proprietary software is then used to display and manipulate the data.

A lightning discharge as recorded and disseminated by the NLDN consists of one line containing 44 bits in ASCII code. This line of data contains date, time, latitude, longitude, signal strength, and multiplicity respectively. The ASCII format is convenient as it lends itself well to manipulating the data on mainframe or desktop computer systems for use in archiving, spreadsheets, plotting, or statistical analysis. A sample line of lightning data is shown:

```
08/25/92 12:45:59 32.178 -100.456  -174.1 02
```

The data is commonly slightly rearranged to facilitate its conversion to binary data which is needed for certain lightning analysis software applications. The rearranged form is shown:

```
08/25/92 12:45:59 32.178 -100.456  2 -34.820000 kA
```

This is a transposition of the last two fields and a multiplication of the signal strength by 0.2 which converts it to range-normalized first-stroke peak current (Orville 1991). The original signal strength value is in LLP (Lightning Location and Protection, Inc. -- the builders of the DFCs) units.

In the Department of Meteorology, Texas A&M University, the data from the entire NLDN are archived by date. The most recent data are available directly from Sun workstations while older records are periodically downloaded and saved on 8mm tape and optical disks. Various commands are available in Unix, Fortran, text editors, or on desktop computers to reduce data sets down to spatial and temporal regions of interest. Many reduced data sets are small enough to be easily kept on floppy disks, and certainly most all data sets can be put onto desktop computer hard drives, especially if kept in a binary format which requires much less storage space than its ASCII counterpart.

The data files for this study were obtained through the following procedure:

1) Dates of interest were identified and the archive tape library was searched to find the proper 8mm data tape.

2) Once the proper tape was located, those files were uploaded again to the departmental Sun.

3) Satellite imagery of Hurricane Andrew and National Weather Service (NWS) radar summaries were analyzed to

determine the areas and times of interest so that the lightning data associated with the hurricane could be isolated. Unix commands were used to sort the data into the desired sets.

4) The reduced data files were transferred via File Transfer Protocol (FTP) to a 486DX-33 desktop computer hosting lightning analysis, mathematics, spreadsheet, and graphics software where the analyses and results were obtained.

2. WSR-57 radar data

So that some correlation of lightning strike locations could be made to radar reflectivities in Hurricane Andrew, radar data from the Miami, Florida and Slidell, Louisiana WSR-57 radars was obtained from the Hurricane Research Division (HRD) of the National Oceanic and Atmospheric Administration (NOAA).

The data furnished by the HRD were 320 x 200 Cartesian arrays of dBZ on 1600 bpi 9 track tapes. The files were read into the meteorology department's Sun computer where a C program was utilized to read data passes to a Fortran subroutine that subsequently put the data into a Gempak grid file. The resulting image files displayed using contour plots of radar plan position indicators (PPI) were saved as bitmap files and exported to a desktop PC for easy display and usage.

The reflectivity contours shown on the PPI images correspond to the commonly used Video Integrated Processor (VIP) scale numbered 1 through 6 for reflectivity threshold values of 29.5, 35.9, 40.7, 47.0, 51.9, and 55.1 dBZ.

CHAPTER III

RESULTS

1. Storm history

Andrew reached hurricane strength on August 22 prior to moving across the northwestern Bahamas as a category 4 storm. This study begins with Andrew passing just north of Nassau coming into range of the NLDN sites in Florida and the Miami NWS radar at 2200 UTC 23 August 1992. This storm remained at hurricane strength for another 67 hours as it moved across Florida, the Gulf of Mexico, and made landfall again in Louisiana. This study of Andrew is continued until it falls below tropical storm strength in southwestern Mississippi at 0300 UTC 27 August 1992.

During this period of 77 hours, 17,036 cloud-to-ground lightning strikes were isolated and attributed to either the eyewall clouds or the primary spiral rainbands of the storm system (Figure 4). While both satellite and radar imagery were used to determine the lightning strikes of interest, some subjectivity was involved in trying to separate out normal summertime airmass thunderstorms from organized convection obviously associated with the tropical cyclone.

2. Lightning characteristics in Andrew

a. Polarity variations

Of the 17,036 CG discharges included in this study, 357

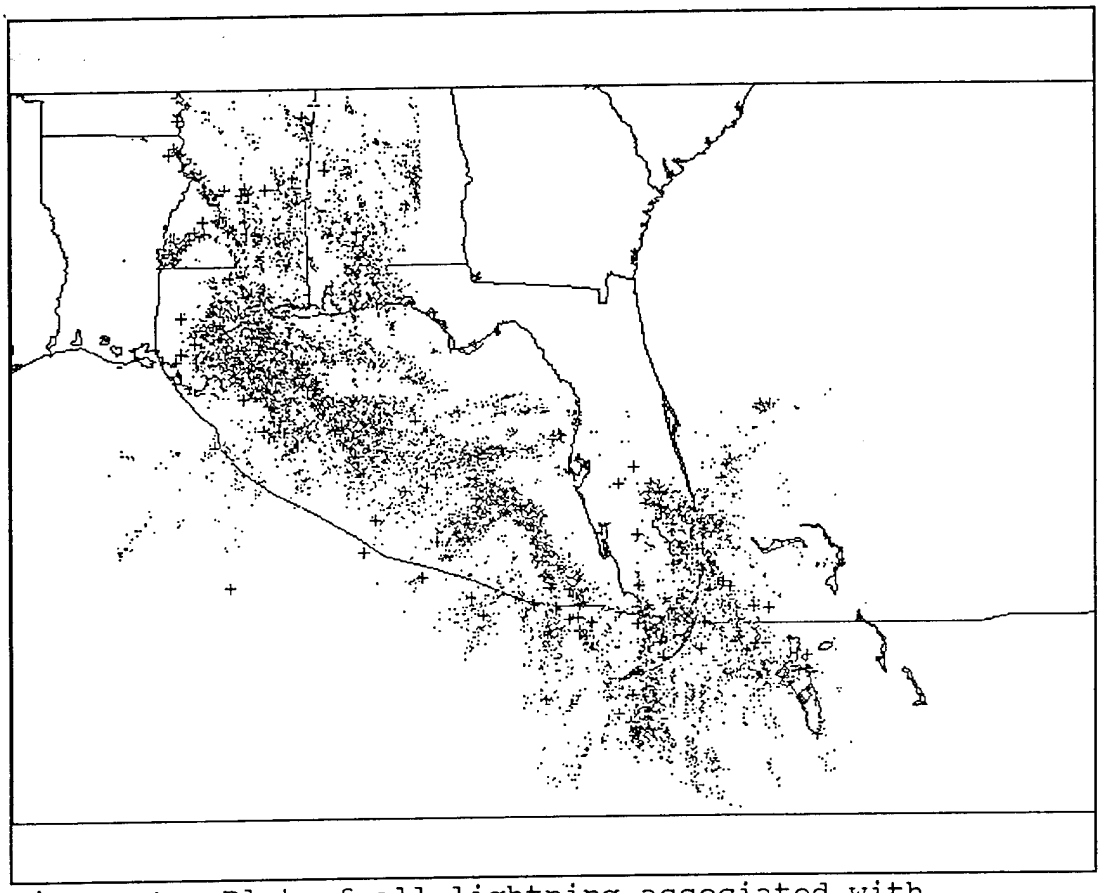

Figure 4. Plot of all lightning associated with hurricane Andrew. The solid line represents the track of Hurricane Andrew. Dots represent negative cloud-to-ground strikes and crosses represent positive strikes.

were identified to be positive discharges, making the overall distribution 2.1% positive and 97.9% negative. It is interesting to note that during the time the storm was diminishing in strength in southwestern Mississippi (1700 UTC 26 August to 0000 UTC 27 August 1992) all lightning observed in the vicinity of the pressure center was positive (Figure 5).

b. First stroke peak current

For comparative purposes in analyzing current and multiplicity characteristics, the lightning data were divided into spatial/temporal segments as well as by polarity. Table 2 gives a complete breakdown of the various categories for the lightning data and the times of interest. Figure 6 shows that during the life of the storm, the negative first stroke peak current decreases while the positive first stroke peak current increases.

c. Multiplicity

Reviewing the multiplicity values yields no startling discoveries. The mean multiplicity of the negative lightning is 2.6. However, it should be noted that the mode is 1 except for the 3000 highest current flashes recorded while the storm was over the Gulf of Mexico. Those data had a mode of 2.

High-multiplicity flashes--here defined as 10 strokes or

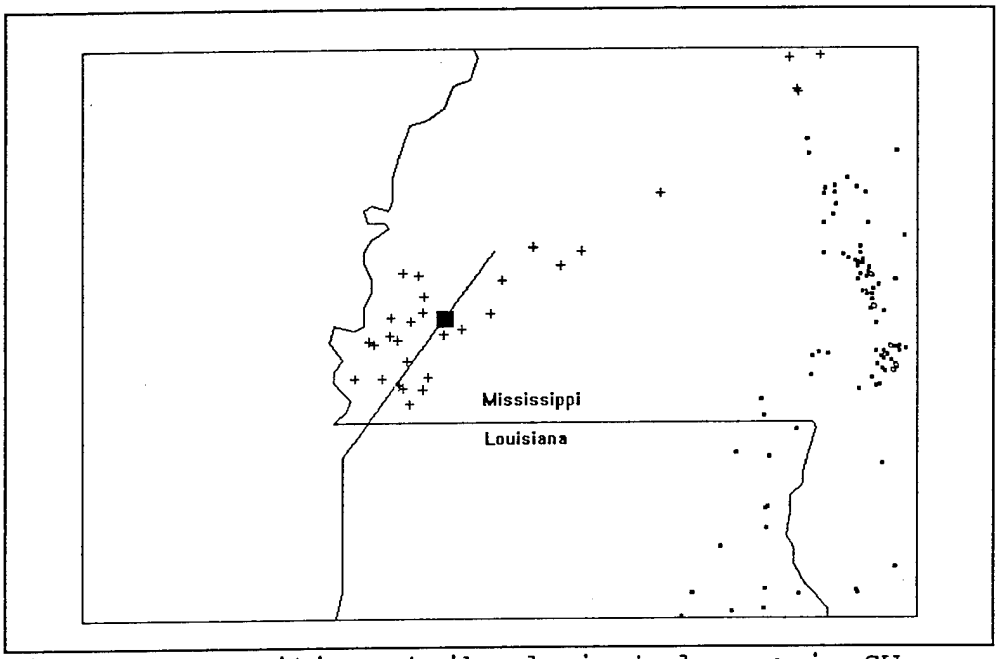

Figure 5. Positive strike dominated area in SW Mississippi. Box shows pressure center of tropical storm Andrew at 0000 UTC 27 August 1992.

Table 2. Hurricane Andrew cloud-to-ground lightning characteristics.

TIME (UTC)	Pre-Florida Landfall 23/22 - 24/09	Over Florida 24/09 - 24/12	Gulf of Mexico 24/12 - 26/0830	Over Louisiana (Hurricane) 26/0830 - 26/17	Trop Storm 26/17 - 27/03	Total 23/22 - 27/03
# of Hours	11	3	44.5	8.5	10	77
Total Flashes	756	323	12257	987	2713	17036
Neg Flashes	728	313	12005	971	2662	16679
Pos Flashes	28	10	252	16	51	357
Avg Flashes per Hour	68	108	275	116	271	221
% Positive	3.7	3.1	2.1	1.6	1.9	2.1
Mean Peak Current (kA)						
Total	66.9	65.2	52.5	50.2	41.1	51.4
Negative	67.8	65.6	52.4	50.1	40.2	51.2
Std Deviation	45.4	46.4	32.7	26.9	21.1	31.3
Positive	44.4	52.5	55.5	54.1	85.6	58.8
Std Deviation	25.7	29.6	33.1	28.3	50.7	37
Median Peak Current (kA)						
Negative	52.7	51.8	42.8	42.4	34.5	
Positive	40.5	44.4	48.6	46.4	72.5	
Mean Multiplicity						
Total	2.6	2.4	2.6	2.5	2.5	2.6
Negative	2.7	2.4	2.6	2.5	2.5	2.6
Positive	1	1	1.2	1.3	1.2	1.2
Mode	1	1	*	1	1	1

*Gulf of Mexico mode = 2 for the highest quartile (peak current) of negative flashes. Mode = 1 for remainder.

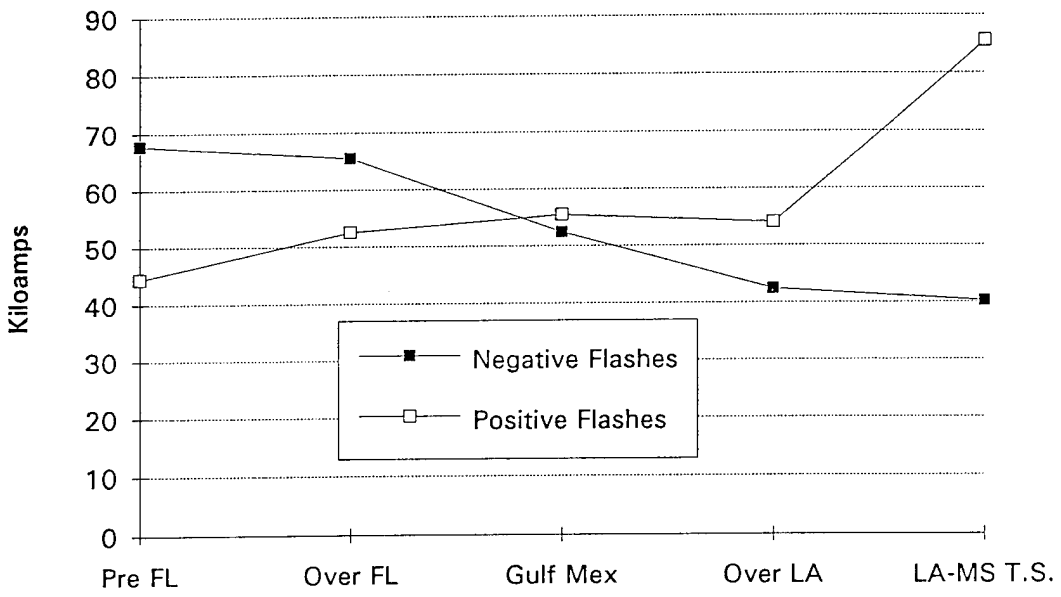

Figure 6. First stroke peak current variations for negative and positive flashes through the life of the storm.

greater--were analyzed separately. 70 CG discharges were identified in this category and an interesting pattern emerged. Over half (36) of these occurred in four distinct groups with each group containing from 5 to 18 separate high-multiplicity discharges. The groups occurred at intervals of 19 to 23 hours apart and each group was tightly concentrated in the same geographical area corresponding to the right-forward to right-middle quadrant of the storm system.

The positive lightning is much more likely to have a multiplicity of 1 as previously shown in Table 2. The highest multiplicity observed in Andrew's positive lightning was 5.

d. Flash rates

As shown in Table 2, the data was categorized into five groups: Pre-Florida, Over Florida, Gulf of Mexico, Louisiana Hurricane, and Tropical Storm. As an overview to the variation in flash rates, it is noted that the most active times for CG activity were over the Gulf of Mexico with an average of 275 flashes per hour, and as a dissipating tropical storm over land where the rate averaged 270 flashes per hour. The least active times were the Pre-Florida landfall phase with 69 flashes per hour, and the Over Florida and Louisiana Hurricane categories with 108 and 116 flashes per hour respectively.

e. Flash density

Flash density patterns were plotted for the negative CG lightning along the storm track (Figure 7). The positive CG lightning density was not plotted due to the small number of positive flashes. With the exception of near southern Florida, the majority of the lightning occurred to the right of the storm track. Highest density concentrations of negative CG lightning were recorded predominately over the Gulf of Mexico and about 100 to 200 km to the right of the storm track. Maximum values were around .06 flashes/km^2.

f. Diurnal pattern

A time-of-day analysis was done on the lightning dataset (Figure 8). Time of maximum lightning was observed to be at approximately 1900 UTC with another maxima at 0000 UTC. Minima occurred at 0400 and 1100 UTC.

3. Radar patterns along the storm track

a. Reflectivity characteristics

As previously mentioned, the radar data used for this study of hurricane Andrew came from the National Weather Service WSR-57 sites at Miami, Florida and Slidell, Louisiana.

The eye of the hurricane first becomes distinctive on the Miami radar around 0000 UTC 24 August 1992. Spiral rainband structure is evident with the strongest reflectivity

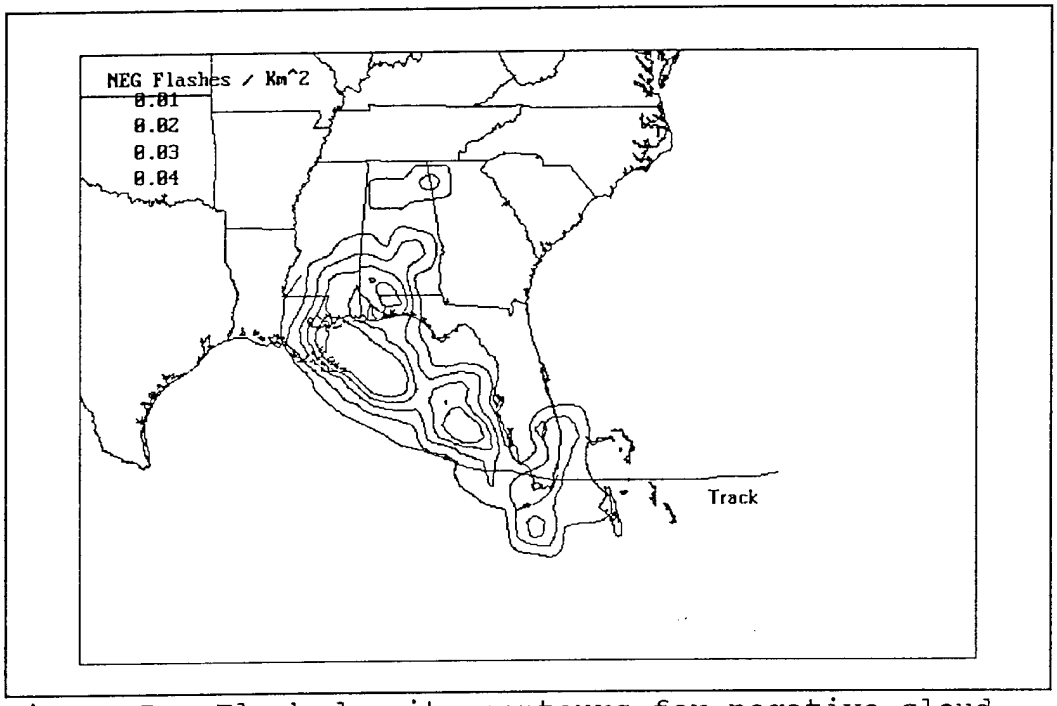

Figure 7. Flash density contours for negative cloud-to-ground lightning associated with hurricane Andrew.

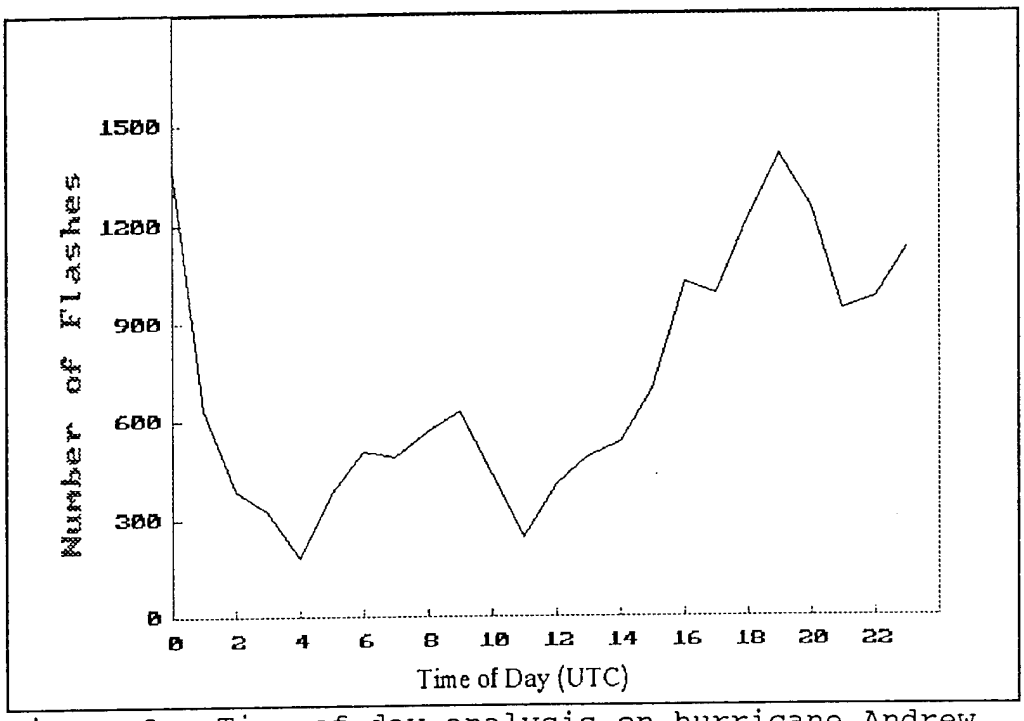

Figure 8. Time-of-day analysis on hurricane Andrew lightning dataset.

within approximately 100 km of the eye in the spiral bands. Some of the outermost rainbands have already moved onshore to the north of Miami. As Andrew makes landfall on Florida, the strongest reflectivities are associated with the eyewall region (EWR) and the trailing rainband. Shortly after making landfall, high winds from Andrew destroyed the Miami NWS radar antenna and no detailed reflectivity data is available after approximately 0835 UTC 24 August 1992 for this region.

The imagery from the Slidell, Louisiana radar begins at 1912 UTC 25 August 1992 with the eye of Andrew approximately 80 miles south of New Orleans. Outer rainbands have already moved onto land. Highest reflectivities are associated with the outer rainband in the right front quadrant of the storm. Additional high reflectivities are found with the inner rainbands. As the eye makes landfall the highest reflectivities are found in the right front quadrant of the EWR, with cells of high reflectivity also evident in the rainbands in the right front quadrant near Lake Pontchartrain. Viewing one of the final images available, the eye is still discernable, however the higher reflectivities are associated with the rainbands on the right flank and right rear of the storm. The Slidell data ends just past 1200 UTC 26 August 1992 as the eye loses much of its definition and the storm is rapidly dissipating in intensity.

b. Comparison of lightning data with Miami radar reflectivities

At the time of the first radar image, 2354 UTC 23 August 1992, most CG lightning is along the Florida coast and is associated with one of the outermost front quadrant rain bands. No lightning was observed near the EWR (Figures 9a and 9b).

At 0254 UTC 24 August 1992 there is no lightning recorded near the EWR. Lightning is disorganized and found around various parts of the storm, but does seem to be most concentrated within the higher reflectivity regions near land (Figures 10a and 10b).

The radar image at 0716 UTC shows considerable cloud-to-ground lightning east of Lake Okeechobee associated with VIP 3 to 4 as well as west of Bermuda in VIP 3 and 4 rainbands in the left rear quadrant of the storm. Some lightning is evident near the EWR (Figures 11a and 11b).

Analysis of one of the final radar images (0835 UTC) available prior to the destruction of the Miami antenna reveals only a little over 100 cloud-to-ground discharges were observed during a two-hour time period from 0700 to 0900 UTC. Lightning was recorded within the EWR as well as the rainbands to the north and to the southeast (Figures 12a and 12b).

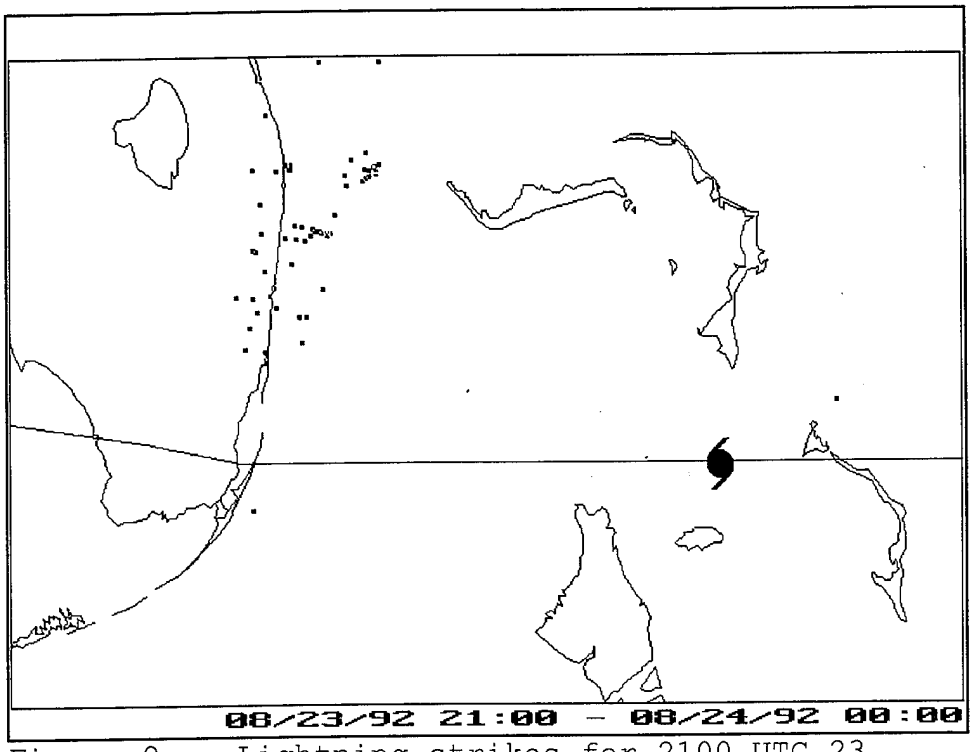

Figure 9a. Lightning strikes for 2100 UTC 23 August to 0000 UTC 24 August 1992.

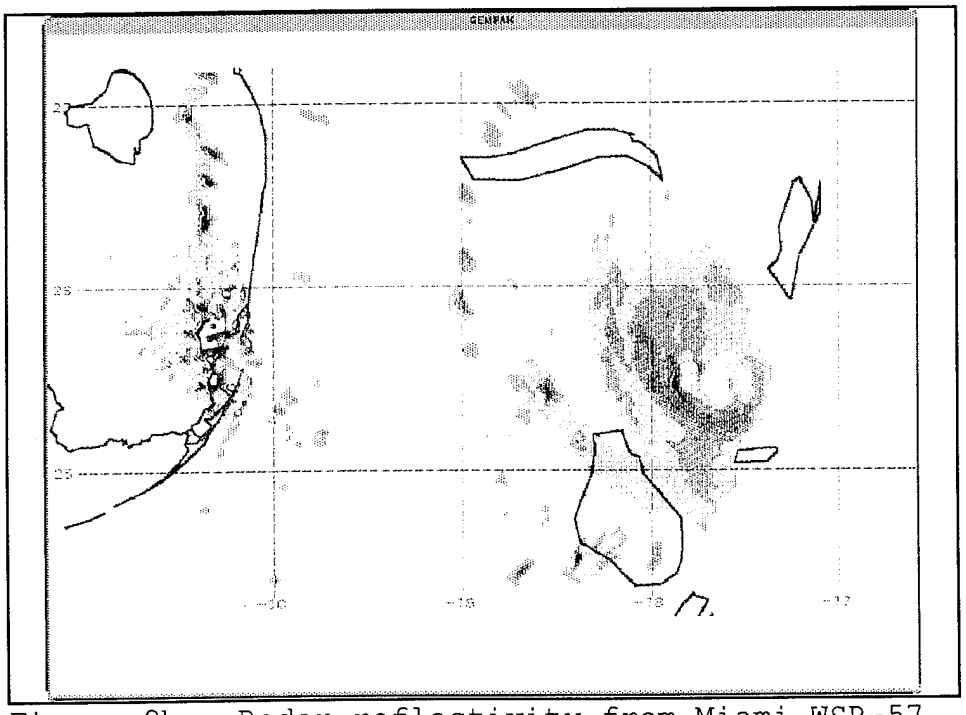

Figure 9b. Radar reflectivity from Miami WSR-57 at 2354 UTC 23 August 1992.

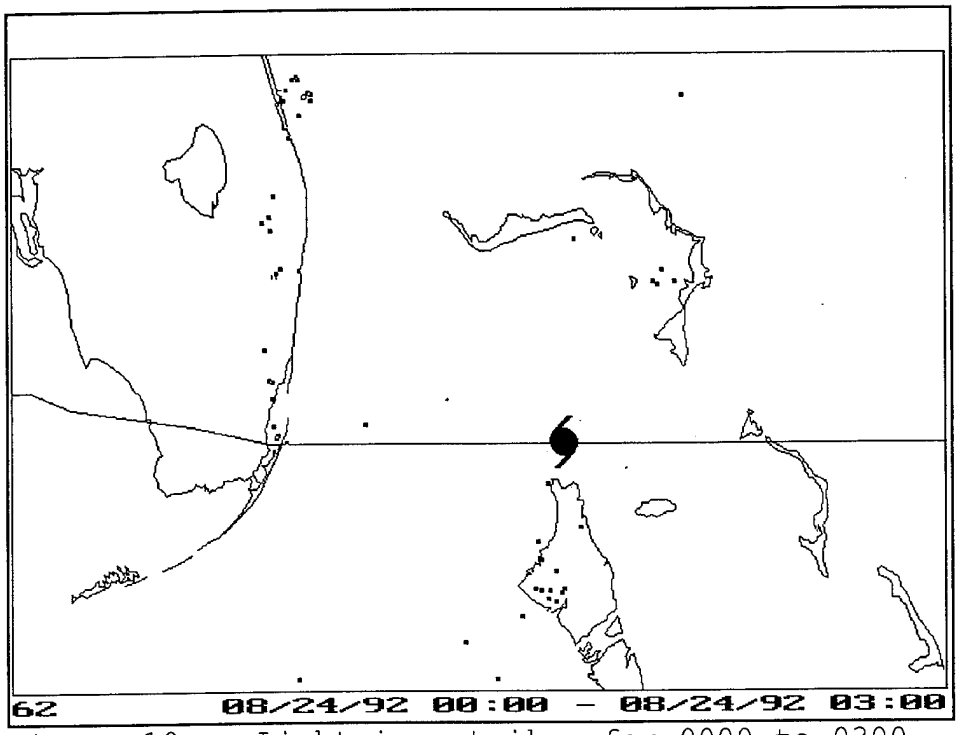

Figure 10a. Lightning strikes for 0000 to 0300 UTC 24 August 1992.

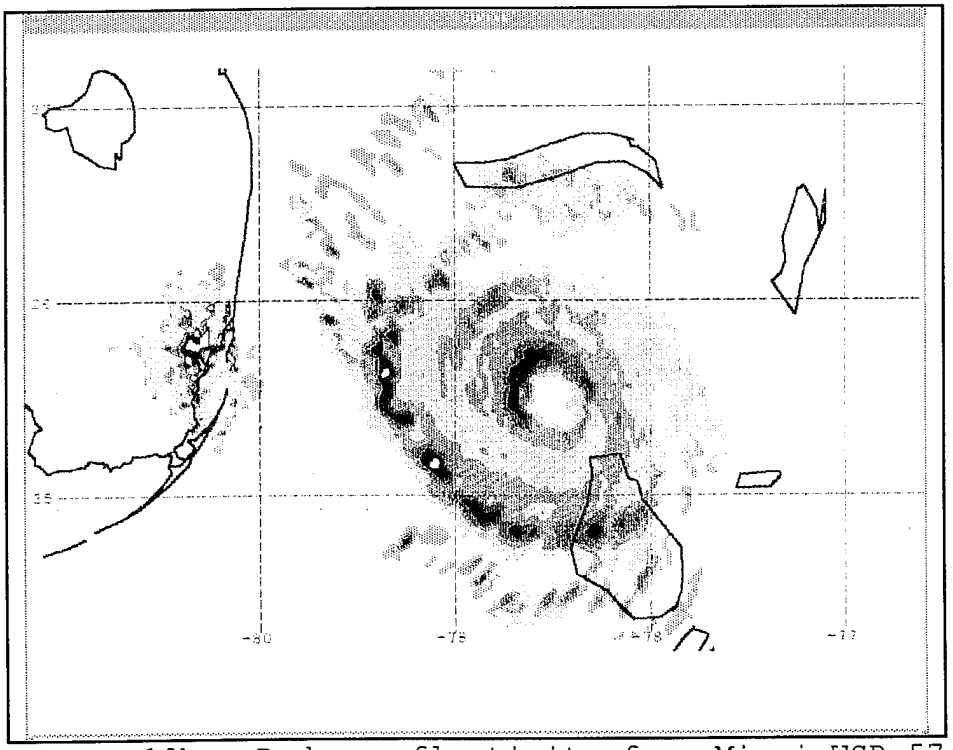

Figure 10b. Radar reflectivity from Miami WSR-57 at 0254 UTC 24 August 1992.

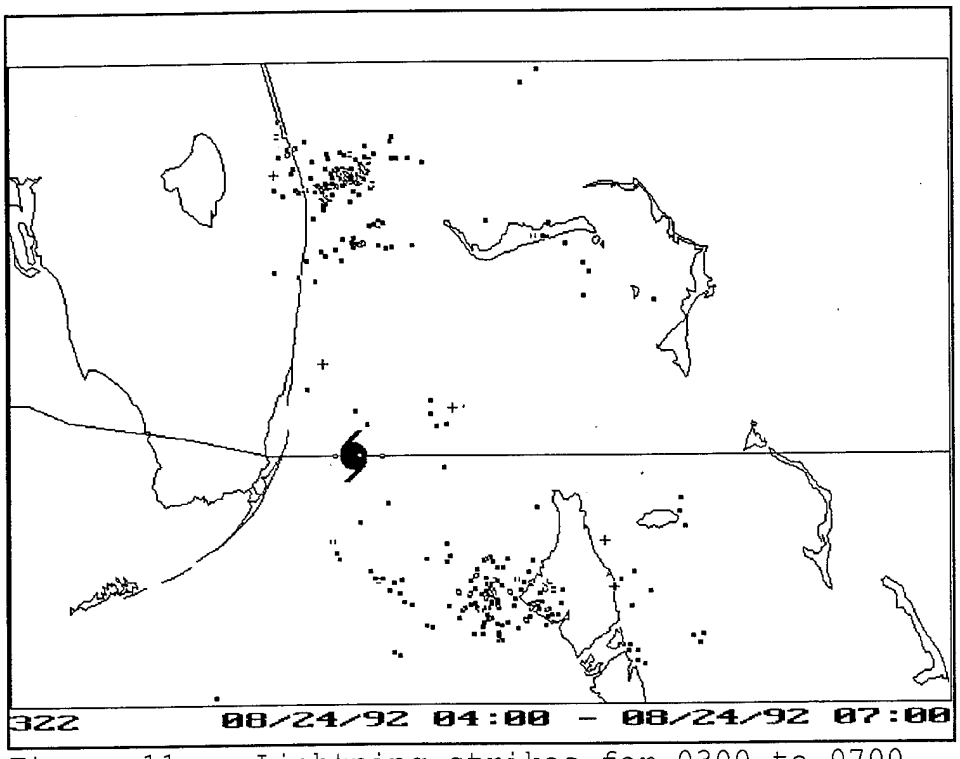

Figure 11a. Lightning strikes for 0300 to 0700 UTC 24 August 1992.

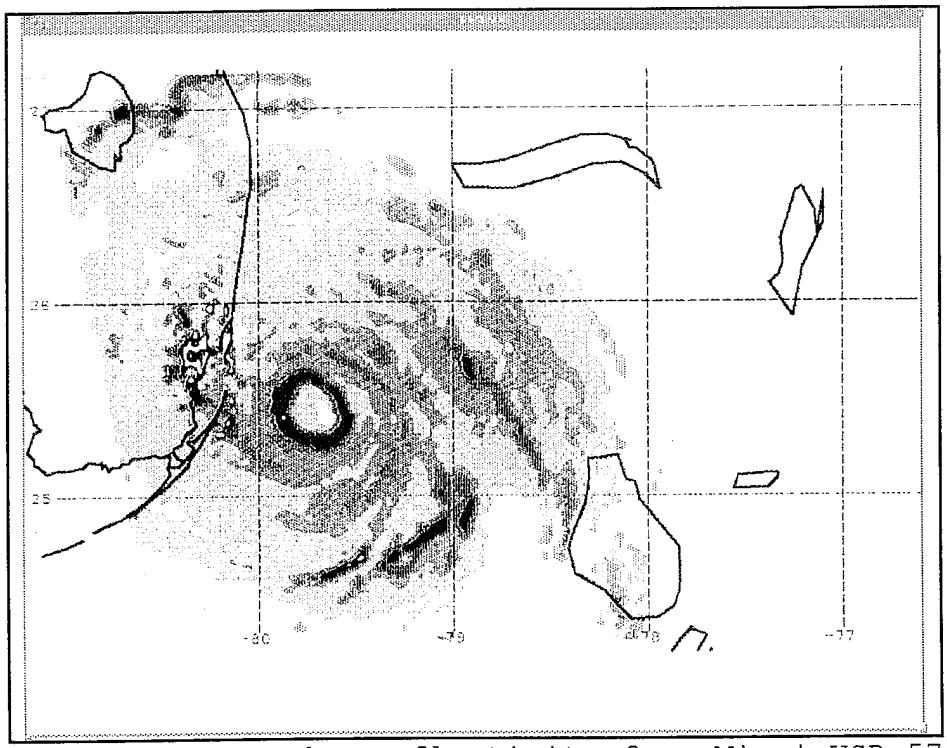

Figure 11b. Radar reflectivity from Miami WSR-57 at 0716 UTC 24 August 1992.

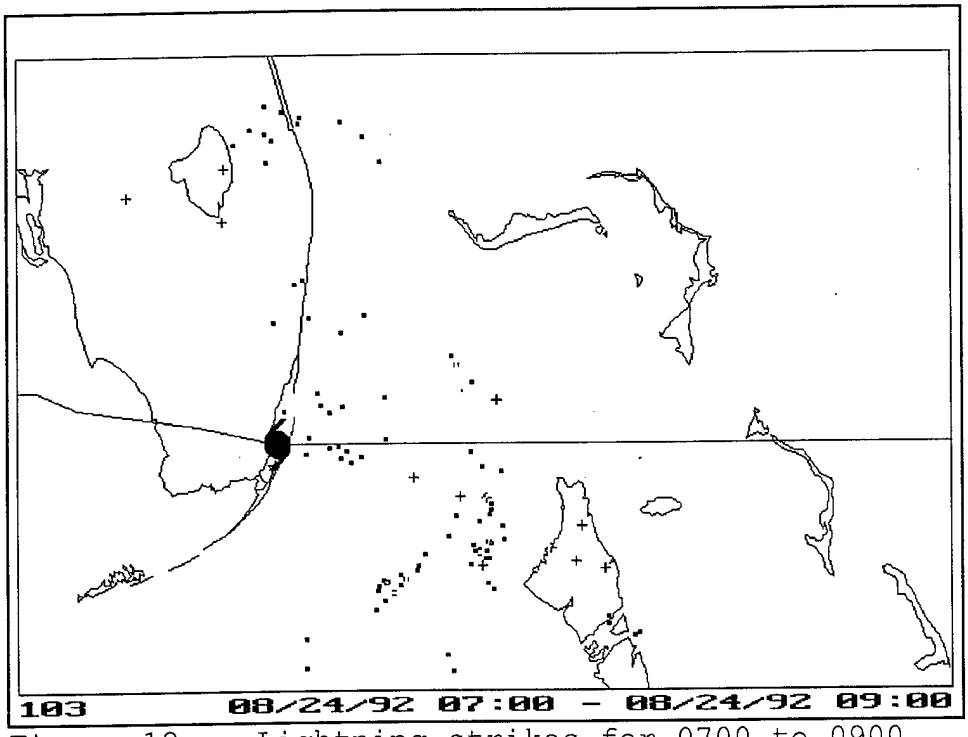

Figure 12a. Lightning strikes for 0700 to 0900 UTC 24 August 1992.

Figure 12b. Radar reflectivity from Miami WSR-57 at 0835 UTC 24 August 1992.

c. Cloud-to-ground lightning in southern Florida and in the Gulf of Mexico

From 0841 UTC 24 August 1992 (when the Miami radar was destroyed) until shortly after 1900 UTC 25 August 1992 (when the Slidell WSR-57 data begins) there is no quantitative radar imagery available for comparison to the lightning data. However, this time period accounts for some 10,000 CG discharges (approximately 60% of the total in this study) averaging over 290 flashes per hour. For thoroughness in this study, the areal characteristics of the CG lightning during this period are briefly discussed.

As the hurricane moved westward across southern Florida and into the open waters of the Gulf of Mexico, much of the lightning was in the rear of the storm, with a noticeable absence of lightning in the EWR while over land once it moved beyond the Miami/Homestead areas where it initially made landfall (Figure 13). Once Andrew was over the waters of the Gulf, very little lightning was observed in the vicinity of the EWR. Most of the lightning occurred in the right front quadrant wrapping around the right side to the right rear of the storm. While other quadrants of the storm were not totally devoid of lightning activity, by far the majority occurred to the right of the storm track (Figures 14, 15, 16, and 17).

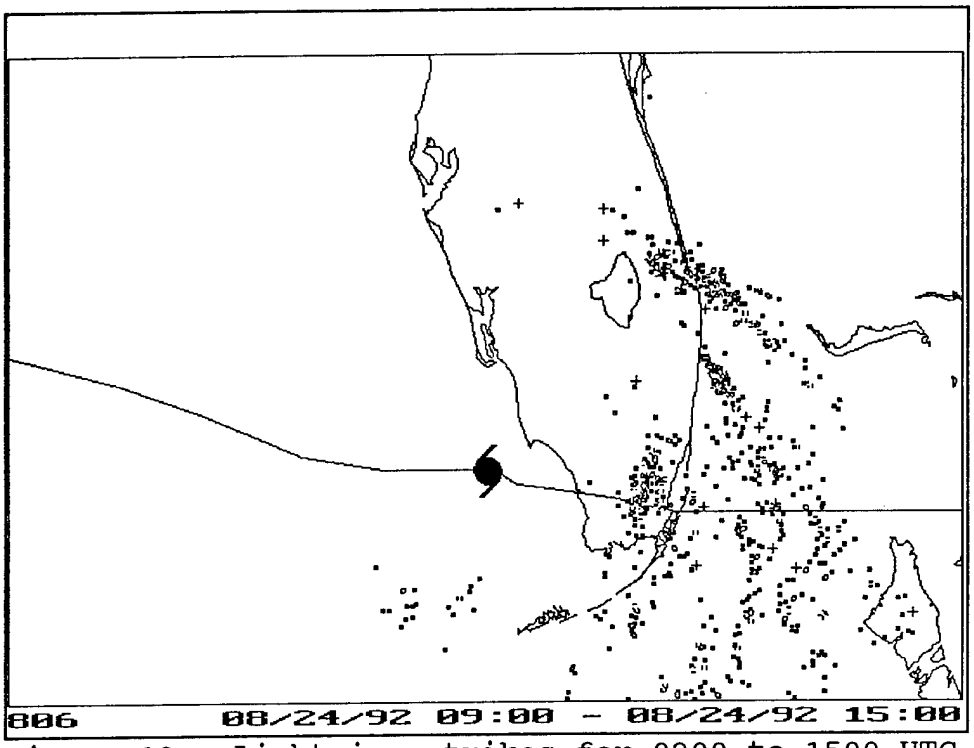

Figure 13. Lightning strikes for 0900 to 1500 UTC 24 August 1992.

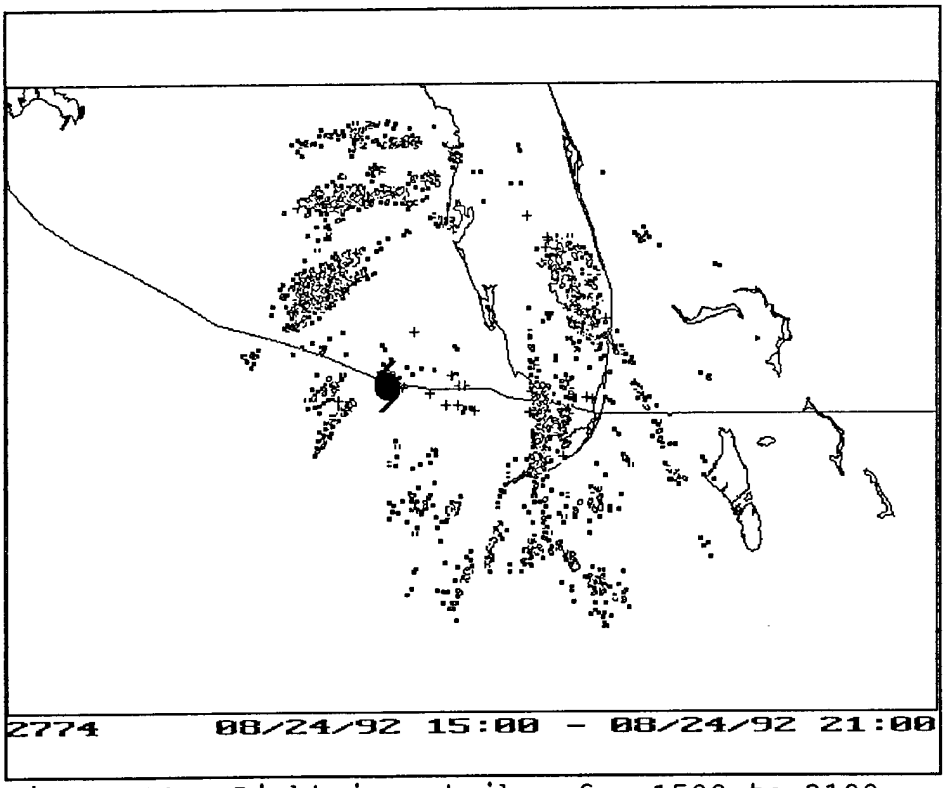

Figure 14. Lightning strikes for 1500 to 2100 UTC 24 August 1992.

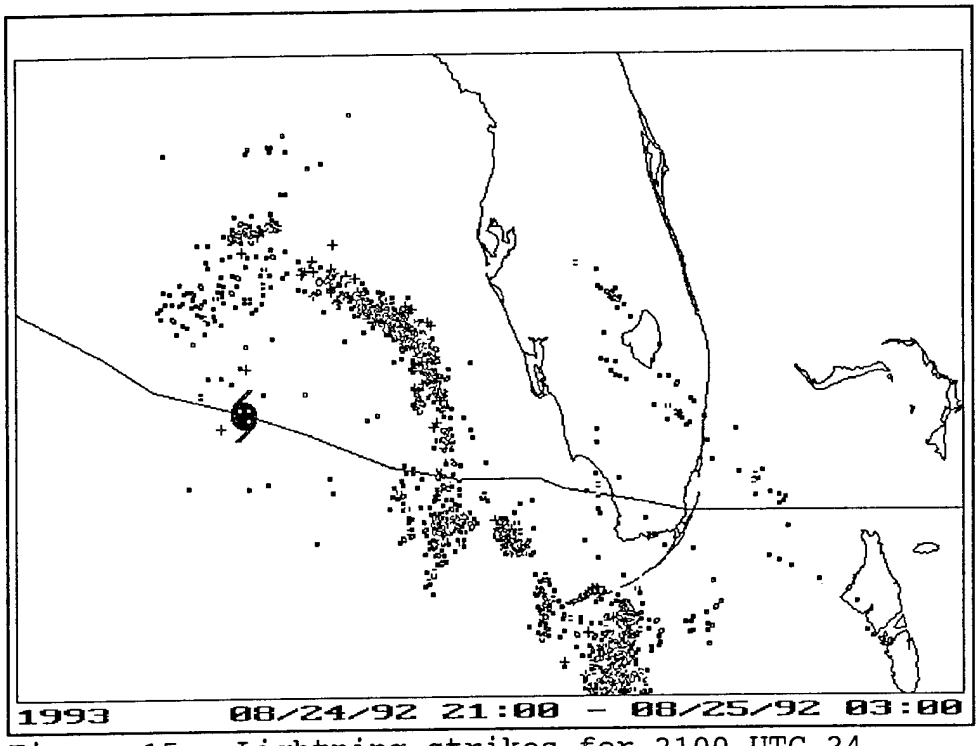

Figure 15. Lightning strikes for 2100 UTC 24 August 1992 to 0300 UTC 25 August 1992.

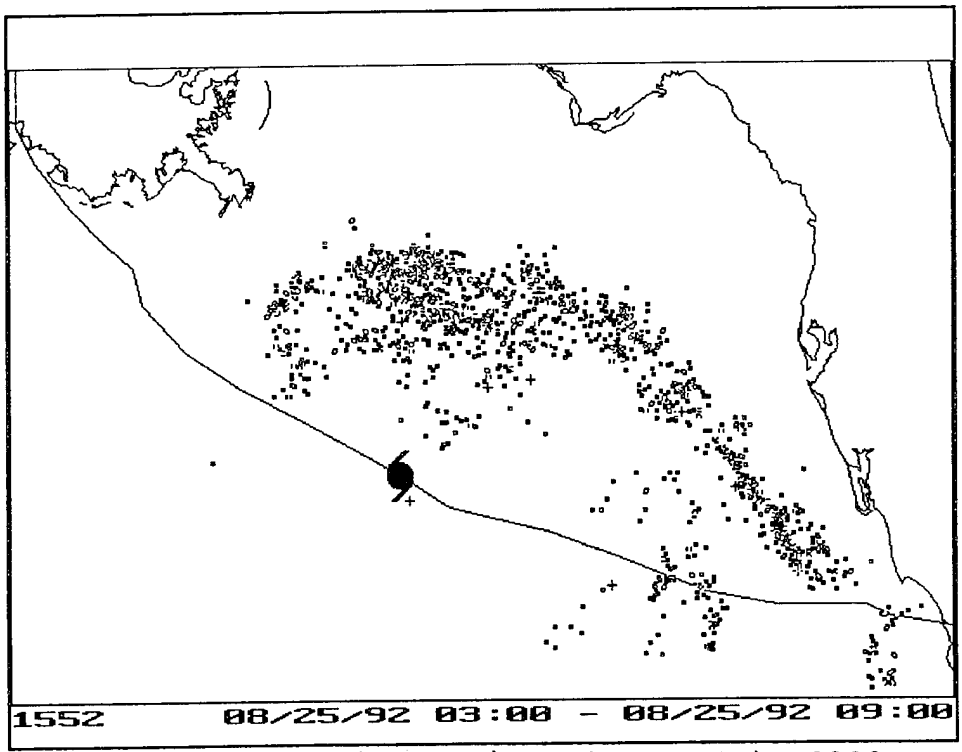

Figure 16. Lightning strikes for 0300 to 0900 UTC 25 August 1992.

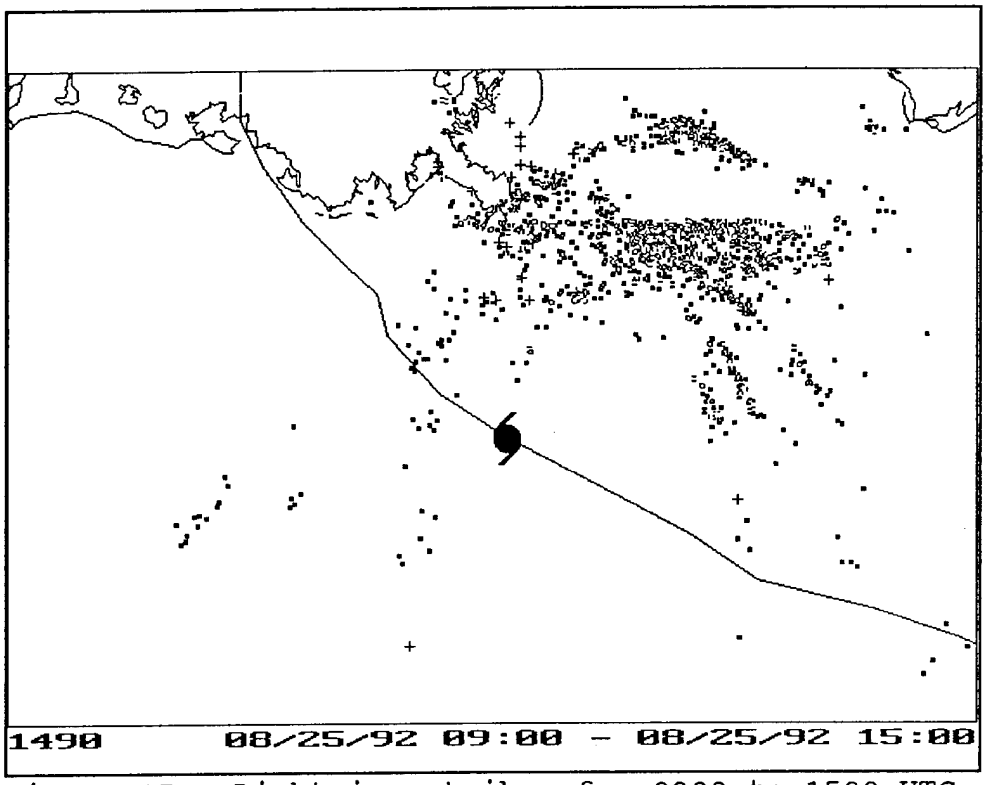

Figure 17. Lightning strikes for 0900 to 1500 UTC 25 August 1992.

d. Comparison of lightning data with Slidell radar reflectivities

At 2100 UTC 25 August 1992 there is slight lightning activity associated with the EWR. There is a substantial amount of lightning activity in the right front quadrant of the storm associated with the inner and outer rainbands from southeastern Louisiana extending into the Gulf of Mexico (Figure 18a and 18b).

The next radar image at 0100 UTC 26 August 1992 shows a total absence of lightning in the vicinity of the EWR. All the lightning at this time period is occurring to the right of the storm track in the right front and right side of the storm (Figure 19a and 19b).

At 0600 UTC, although there is VIP 3 and 4 reflectivity within the EWR, no lightning activity is recorded there. The lightning at this time is associated with the rain band in the right front quadrant over Lake Pontchartrain (Figure 20a and 20b).

The 1213 UTC data shows once again no lightning in the vicinity of the EWR and only very little lightning found in the right front quadrant rain band north of Lake Pontchartrain and well to the south of the storm in the trailing bands still over the Gulf of Mexico (Figure 21a and 21b).

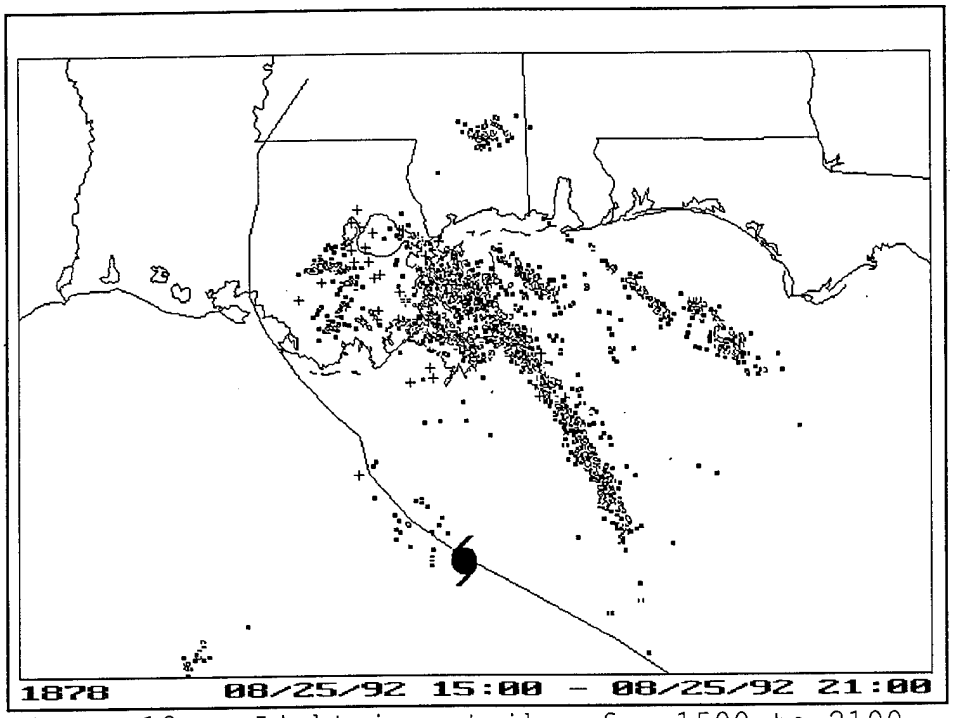

Figure 18a. Lightning strikes for 1500 to 2100 UTC 25 August 1992.

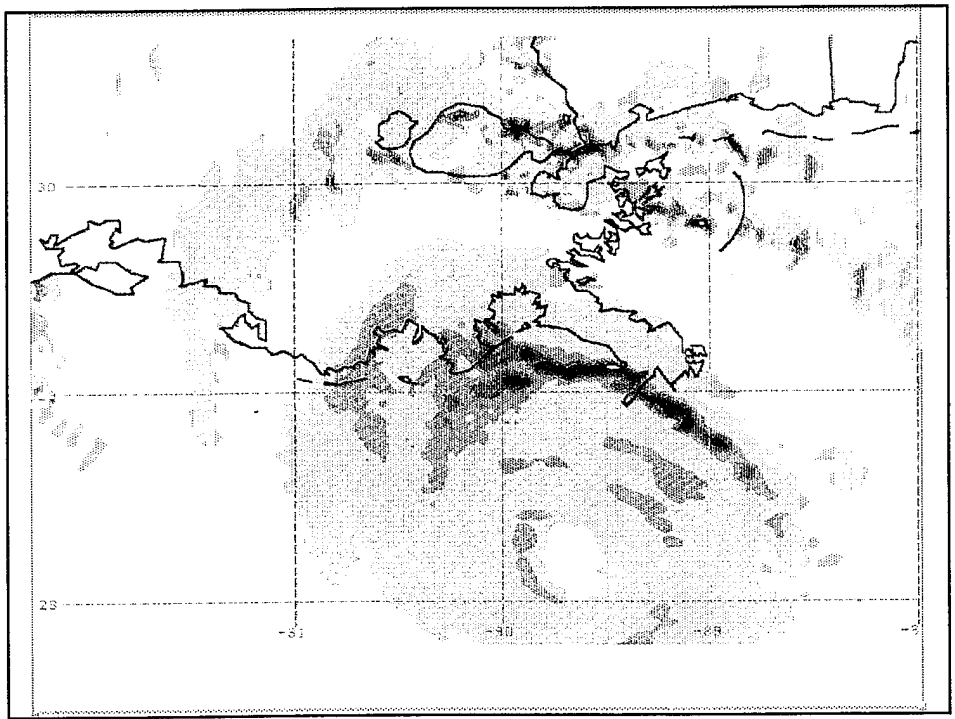

Figure 18b. Radar reflectivity from Slidell WSR-57 at 2100 UTC 25 August 1992.

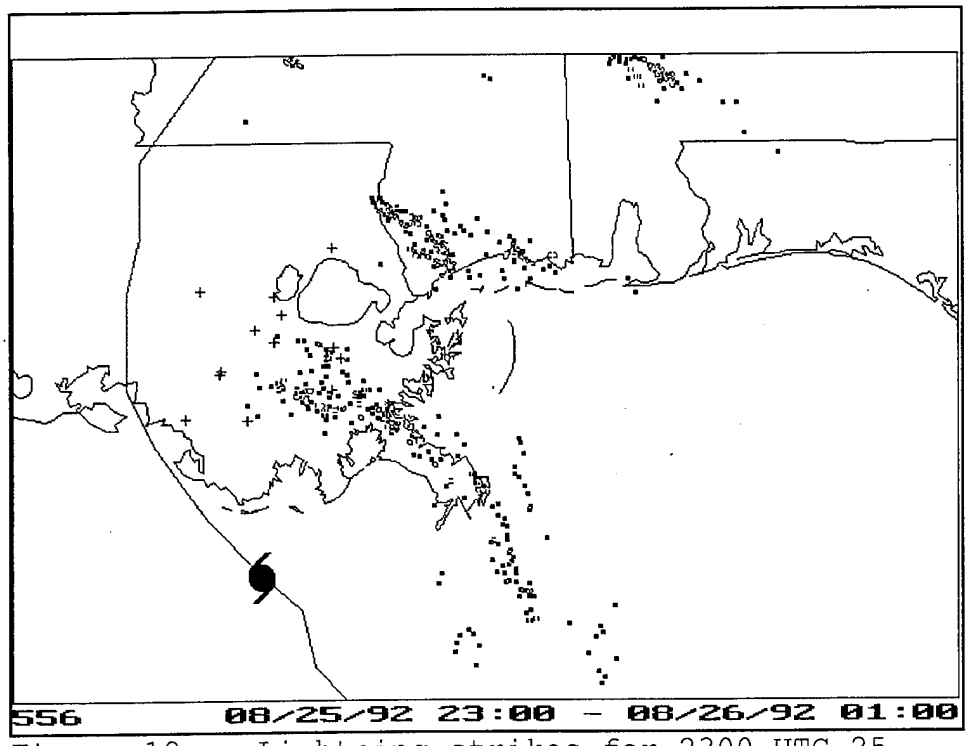

Figure 19a. Lightning strikes for 2300 UTC 25 August 1992 to 0100 UTC 26 August 1992.

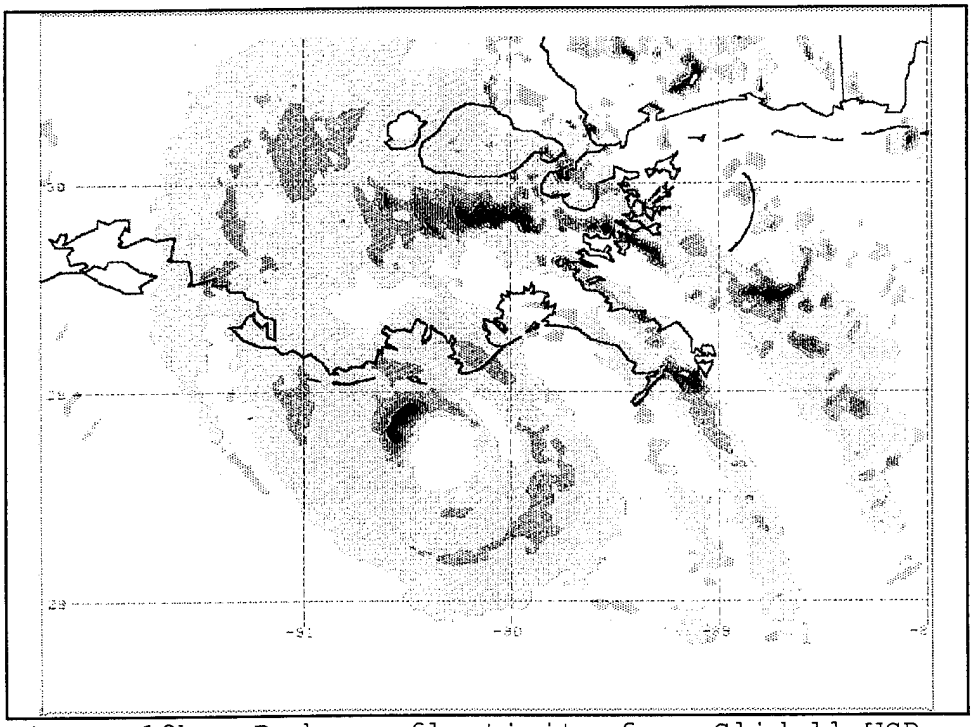

Figure 19b. Radar reflectivity from Slidell WSR-57 at 0102 UTC 26 August 1992.

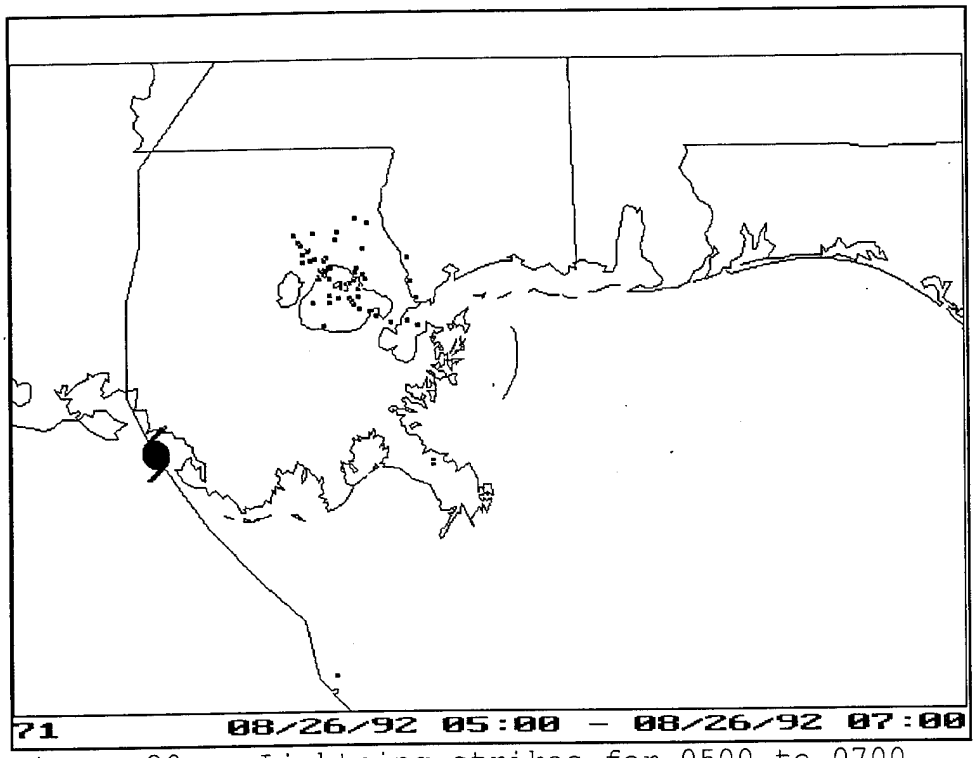

Figure 20a. Lightning strikes for 0500 to 0700 UTC 26 August 1992.

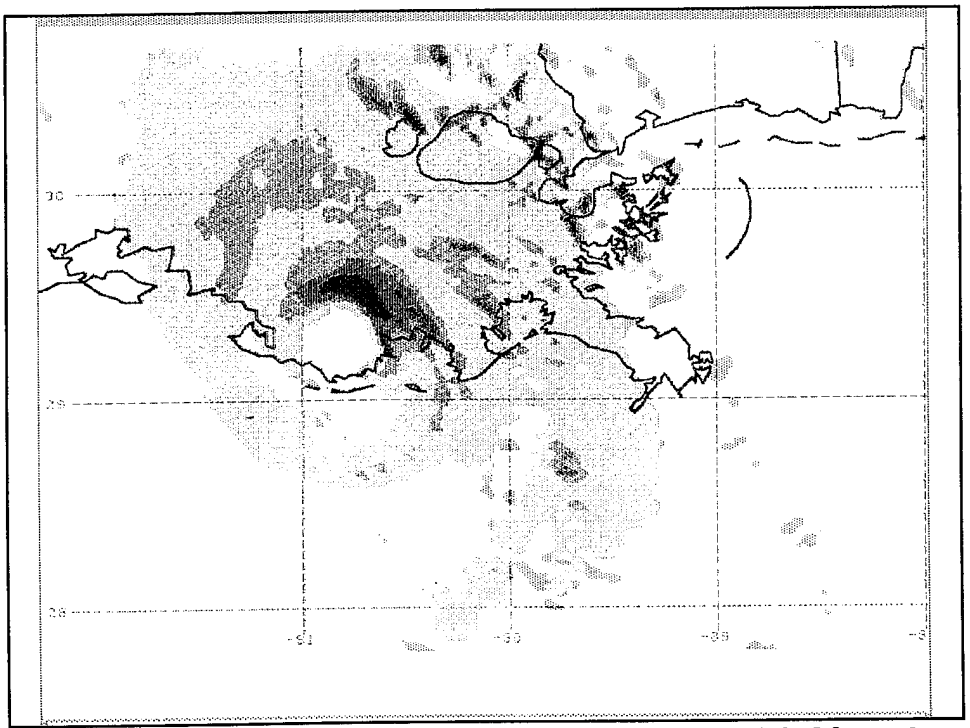

Figure 20b. Radar reflectivity from Slidell WSR-57 at 0600 UTC 26 August 1992.

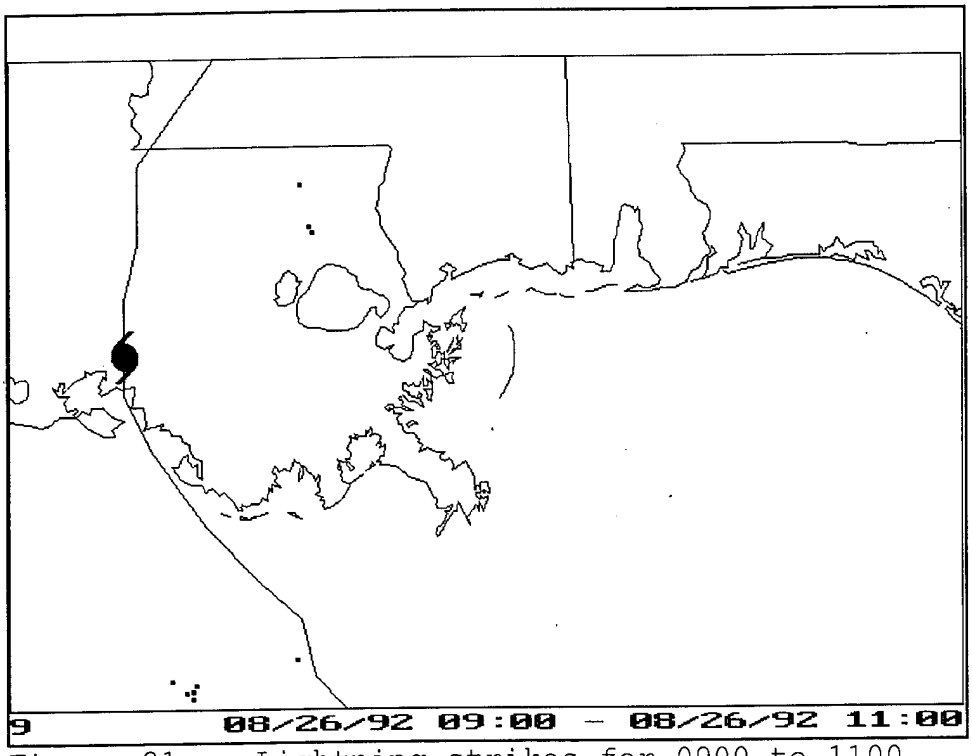

Figure 21a. Lightning strikes for 0900 to 1100 UTC 26 August 1992.

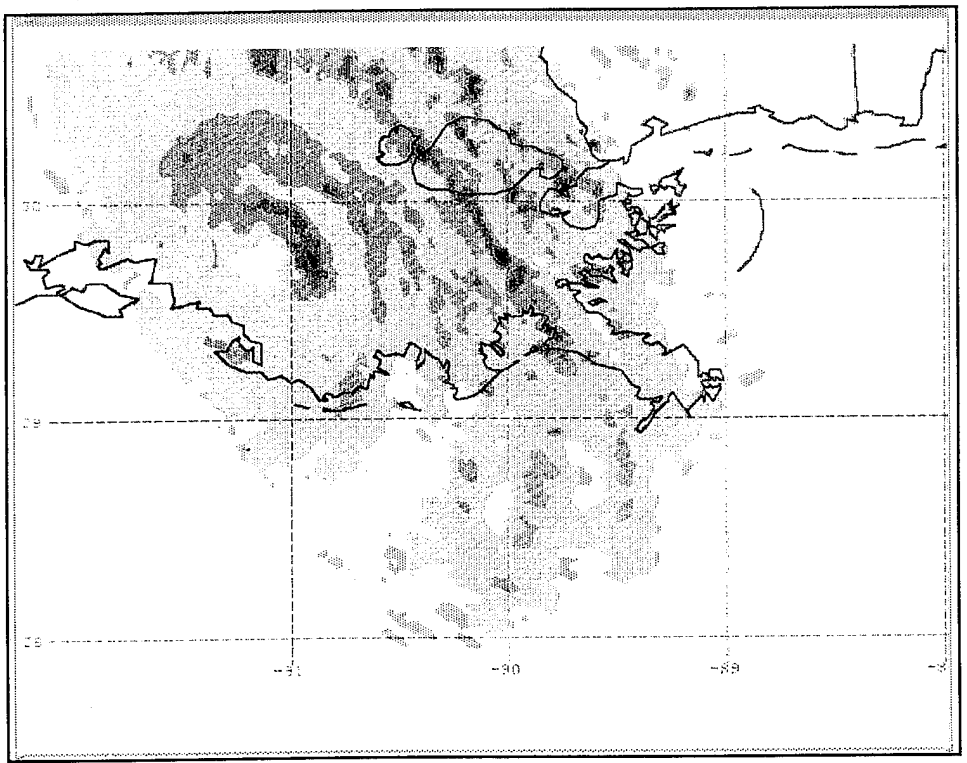

Figure 21b. Radar reflectivity from Slidell WSR-57 at 0902 UTC 26 August 1992.

e. Lightning during dissipation of Andrew

The final time segment of data analyzed has no radar imagery associated with it. As discussed previously, Figure 5 shows 7 hours of lightning strikes ending at 0000 UTC 27 August 1992 as Andrew is a dissipating tropical storm in southwestern Mississippi. In sharp contrast to the previous cases where no lightning was observed in the EWR, numerous CG strikes are seen associated with the EWR and all have positive polarity. Also noted in this data, are numerous strikes in the rain bands on the right front quadrant of the storm.

CHAPTER IV

DISCUSSION

1. Comparison to previous hurricane studies

a. Pre-NLDN studies

Similar to the findings of Johnson and Goodman (1984) most of the cloud-to-ground lightning activity was observed to come from the periphery of the storm with little CG lightning associated with the eyewall region.

Black et al. (1986) found considerable lightning in their study of Hurricane Diana (1984). However, they found frequent lightning in both the eyewall region and the outer rainbands. The eyewall lightning was found to be associated with an intensification of the storm's strength. Hurricane Andrew's strength remained fairly steady throughout most of the time of this study. It had already reached maximum wind speed and minimum central pressure prior to coming within range of NWS radar and the NLDN. It is, therefore, difficult to draw any relationship between intensification and the eyewall lightning observed in Andrew. In comparing diurnal patterns observed in Andrew and Diana, both have morning minima and late afternoon or early evening maxima. However, the lightning in Diana tended to reach its peak later in the day (at 0000 to 0100 UTC compared to 1900 UTC for Andrew).

b. Studies using NLDN data

Samsury and Orville (1994) used NLDN data to quantify the lightning in the 1989 hurricanes Hugo and Jerry. While Jerry had several hundred flashes, Hugo, a much stronger storm (120 knots versus 70) had only 33 CG discharges despite 40 to 50 dBZ radar reflectivities. With over 17,000 flashes attributed to Andrew, it appears an electrical giant by comparison to Hugo and Jerry. Even considering Andrew's longer lifetime and track within the range of radar and NLDN, the amount and hourly rate of lightning associated with Andrew is of almost an order of magnitude larger than that associated with Jerry.

Since Jerry did have several hundred flashes, a comparison of the characteristics between Andrew and Jerry is in order.

Table 3. Comparison of hurricanes Jerry and Andrew.

	Jerry	Andrew
Hourly rate, pre-landfall	33.5	68.7 (FL) 275 (LA)
Hourly rate, post-landfall	32.0	108 (FL) 116 (LA)
% Positive, pre-landfall	6.5	3.7 (FL) 2.1 (LA)
% Positive, post-landfall	25.5	3.1 (FL) 1.6 (LA)
Median neg. peak current (kA)	42.0	51.2
Mean multiplicity	2.3	2.6

From this comparison it can be seen that the flash rates were much higher for Andrew, especially as Andrew moved out of the Gulf of Mexico onto Louisiana. Also it should be noted that Jerry had a considerably higher percentage of positive lightning.

A similarity in the location of the lightning within the

storm structure is noted when Andrew is compared to Jerry and Hugo. In all three storms the most favored region is the right-forward to right-rearward quadrants. One variable to consider with Andrew, however, is that the track of Andrew over the Gulf of Mexico placed the left side of the storm at the limits of the range of the NLDN, so that it would be difficult to say there was less lightning actually in that region versus saying less lightning was recorded from that region.

In the Molinari et al. (1994) study of Andrew, similar findings to those presented in this paper were noted with respect to mean first stroke peak currents, multiplicities, and spatial/temporal relationships. Their comparison to satellite imagery presented a slightly different perspective than did this study using radar reflectivities. Both show that the majority of the lightning in Andrew occurred in the outer rainbands. The Molinari study has the added result of suggesting that the eye wall lightning episodes are related to storm intensification--a relationship not examined in this paper.

2. Comparison to other mesoscale convective systems

Goodman and MacGorman's (1986) study on CG lightning related to the life cycle of MCCs makes an interesting comparison for Hurricane Andrew. In terms of the number of CG discharges associated with the system, Andrew fits nicely

into the range of values of 12,000 to 33,000 per MCC that they studied. However, the MCCs have a much shorter lifetime than did Andrew and the MCC's peak rate of 2700 CG discharges per hour was not matched by Andrew's peak of 763.

As mentioned in the results, in many instances the area of peak CG lightning activity was associated with the areas of highest radar reflectivity. This is consistent with findings by Reap and MacGorman (1989) in their climatological study of nearly 2 million flashes during 1985-6. Their results showed a pronounced decrease in lightning activity below VIP 3 which is borne out in Andrew where lightning seemed most common in rainbands with reflectivities in the VIP 3 to 4 range.

The role of +CG lightning relating to severe storm development was studied by Rust et al. (1981) and MacGorman and Nielsen (1991). While these studies tended to look for an increase in +CG strikes as a presage to severe weather (i.e. tornado or hail), no such correlation was noted in Andrew. During the mature stage of Andrew no distinctive patterns of +CG lightning were noted. However, the area around the decaying eyewall region became positive strike dominated (PSD) as the pressure center moved through southwestern Mississippi between 1700 UTC 26 August and 0000 UTC 27 August 1992. During this time period, approximately 25 +CG discharges were recorded as the storm diminished in intensity reaching tropical depression classification just 3

hours later. It is hypothesized that as the storm dissipated stratiform precipitation became more widespread as convection died out. Perhaps the +CG lightning occurrence was due to a mechanism similar to that described by Rutledge et al. (1988, 1990) where there was horizontal advection of positive charge from upper levels of squall lines rearward into stratiform precipitation regions.

3. Potential charge separation processes in hurricanes

In general, CG lightning observed in Andrew tended to occur in rainbands associated with VIP level 3 or greater. Occasionally some lightning was found in the eyewall region with similar reflectivities, but for the most part there was a noticeable absence of lightning in the eyewall. This might suggest that different microphysical processes are involved in the eyewall regions than in the rainband regions, although both may exhibit similar radar reflectivities. Based on previous research by Black and Hallet (1986) that showed mature hurricanes can have extensive regions of ice with only sparse supercooled water, it could be inferred that this was the case for the EWR of Andrew. The substantial CG in the rainbands suggest favorable conditions existed for charge separation with supercooled water, ice crystals, and graupel combined with vigorous convection as suggested by Jayaratne et al. (1983).

During the final hours of Andrew as a hurricane, there

were extensive rainband regions of high reflectivity over Louisiana for which there was little or no associated CG lightning (Figures 21a and 21b). This is similar to the lack of CG lightning in high reflectivity regions of dissipating convective systems as reported by Reap and MacGorman (1989). This could be related to downdrafts dominating the storm structure as thunderstorms reached their final stages, or perhaps the storms had predominately intracloud lightning which was not detected by the lightning networks.

CHAPTER V

CONCLUSION

1. Review of findings

In general, with some 17,000 flashes attributable to it, Hurricane Andrew was one of the most prolific cloud-to-ground lightning producing hurricanes ever observed. However, since the ability to record and analyze quantitatively this type of lightning activity is a relatively new development, it is too early to tell whether Andrew could be considered an anomaly among tropical systems. There are other examples in literature of hurricanes with little or no lightning as determined by means other than lightning detection equipment.

In comparison to mesoscale convective systems typical of the United States Great Plains, Andrew displayed a quantity and polarity distribution (percent positive/negative) of lightning that would place it in the same category as a summertime mesoscale convective complex. This suggests some similar role in the overall atmospheric electrical balance is played by both mid-latitude and tropical mesoscale systems of convective nature.

The location of lightning with respect to radar reflectivity turned up no unusual discoveries. The deep convection regions of the outer rainbands were the areas with the most lightning. The lack of significant lightning in the eyewall region reinforces previous research indicating

microphysical processes in this part of hurricanes are not favorable for the charge separation necessary for abundant CG lightning. Work was cited evidencing the absence of supercooled liquid water (key to charge separation) in eyewall convection is typical in hurricane structure.

2. Suggested future research

With the now well-established NLDN, future study of hurricanes that make landfall in the contiguous United States will be commonplace. It is suggested that studies similar to this one be conducted upon all future storms and comparisons made in the lightning characteristics of each. New categorizations of tropical storms and hurricanes may be made possible by identifying differing electrical characteristics.

This study did not cover lightning relationships to vertical velocities in hurricanes and this remains an area open to original research.

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