THE RELATIONSHIP BETWEEN THE RADIUS OF GALE-FORCE WINDS AND THE RAIN SHIELD OF UNITED STATES LANDFALLING TROPICAL CYCLONES.

By

ERIN LEIGH BUNTING

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

2009

To all who provided support and a shoulder to lean on

ACKNOWLEDGMENTS

When entering graduate school everyone tells of the importance of picking the right committee. No wiser words were spoken and from experience I can say a committee is a sounding board, a shoulder to lean on, and an invaluable source of knowledge. For their guidance and support I thank Dr . Corene Matyas, Dr. Jane Southworth, and Dr. Peter Waylen. To Dr. Matyas, I enjoyed the fact that we grew and learned about this process together. I know I am the first of many successful graduate students to come. To my family, one could not ask for a greater support system. We laugh together and grow together, I love every moment of it. Finally, to my fellow graduate students I thank you from the bottom of my heart. I came into this a shy, obsessive compulsive student and you taught me that it is alright to let your hair down and have fun. Thank you for taking me out of my comfort zone; I am a better person because of you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

DIR	Storm Heading
EBT	Extended Best Track
EYED	Eye Diameter
GIS	Geographic Information System
HURDAT	Hurricanes Database
MCP	Minimum Central Pressure
NCDC	National Climatic Data Center
NHC	National Hurricane Center
NWS	National Weather Service
POCI	Pressure of the Outermost Closed Isobar
R17	Radius of Gale-Force Winds
R26	Radius of Damaging-Force Winds
R33	Radius of Hurricane-Force Winds
R-CLIPER	Rainfall Climatology and Persistence Model
ROCI	Radius of the Outermost Closed Isobar
RVMAX	Radius of Maximum Winds
SHIPS	Statistical Hurricane Intensity Prediction Scheme
SPEED	Storm Speed
TC	Tropical Cyclone
TRaP	Tropical Rainfall Potential Model
TS	Tropical Storm
WSR-88D	Weather Surveillance Radar 1988 Doppler

Abstract of Thesis Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Masters of Science

THE RELATIONSHIP BETWEEN THE RADIUS OF GALE-FORCE WINDS AND THE RAIN SHIELD OF UNITED STATES LANDFALLING TROPICAL CYCLONES.

By

Erin Leigh Bunting

August 2009

Chair: Corene Matyas
Major: Geography

While TC-related deaths can be attributed to strong winds, storm surge, or tornadoes; Rappaport (2000) found that the majority of TC-related deaths in the U.S from 1970-1999 resulted from coastal and freshwater flooding caused by heavy rainfall. Significant improvements have been made in forecasts of TC wind field and tracks, yet there is much less known on rain shield dynamics. Currently, the National Hurricane Center (NHC) solely takes gale-force wind extent into consideration when placing watches and warnings along the U.S. coast; meaning that the extent of the rain fall, one of the most deadly and destructive aspects of the TC, is not even included in storm advisory reports. This study analyzes the relationship between TC wind fields and the rain shield within the NHC operational forecasting procedures, in order to understand how the rainfall extent aligns with the storm size variables calculated at the NHC. Specifically, the research question asks: does the extent of the rain shield align with the radius of gale-force winds (R17) during the time at which gale-force winds made landfall? Review of the literature and the NHC forecasting policies lead to the hypothesis that increased environmental forcings will lead to more asymmetrical storms and therefore a higher percentage of the rain shield occurring outside of R17. Forty-two U.S. landfalling TCs from 1995-2006 were analyzed. Within the GIS an overlay of the average R17 and composite reflectivity radar

images was performed, resulting in area calculations of rainfall within and outside R17. In tropical storms and weak hurricanes, typically less than 20% of the rain falls within the R17 boundary. Strong hurricanes generally contain more than 70% of the rain shield within the R17 boundary, because the strong pressure gradient causes the tangential winds to increase in speed, therefore there is a tight wrapping of winds around the center of circulation and an axisymmetrical shape to the rain shield. Analysis of the composition of the rainfall occurring outside of R17 shows the majority (85-95%) of intense rainfall produced by TCs, occurs within the radius of gale-force winds for all storm strengths. In other words, heavy rainfall that may lead to flooding will not occur before the onset of gale-force winds for most TCs.

CHAPTER 1
TROPICAL CYCLONE WIND AND RAINFALL PATTERNS

Due to their substantial size and intensity, tropical cyclones (TCs) are the most destructive and costliest of atmospheric systems (Elsner and Kara 1999). A TC is the generic term used to describe a non-frontal synoptic-scale low-pressure system with organized convection and cyclonic surface wind circulation. These warm-core systems are uniquely composed, and thus, there is a dynamic wind and precipitation pattern across the system. At the core there is an eye that ranges in diameter from 5-50 km, where warm and calm winds are sinking to the ground (Frank 1977). Within the eye there is little deep convection; but surrounding the eye is the eyewall, which is the most intense aspect of a TC. Due to the conservation of angular momentum the strongest winds and heaviest rainfall occur within the eyewall, and are associated with vertically-developed cumulonimbus clouds (Elsner and Kara 1999; Frank 1977). The other key components to the structure of a TC are the spiral rainbands, areas with localized strong winds and precipitation that wrap around the eye but extend hundreds of kilometers outward. The outer rain bands are composed of vertically-developed thunderstorms that trail away from the eye in a spiral fashion (Willoughby 1988). Due mainly to the unique environmentally-dependent composition of TCs, there are a wide variety of related hazards. In this study two of the most severe TC-related hazards are studied, the winds and the precipitation, to determine if the two make landfall in conjunction with one another or if there is a significant time lag between wind field landfall time and rainfall arrival time.

Tropical cyclone winds and precipitation are responsible for the vast majority of TC-related fatalities (Rappaport 2000). Deaths and damage associated with rainfall can be attributed to inland and coastal flooding; whereas wind-related destruction can result from microbursts, tornadoes, or intense sustained winds that are naturally associated with TCs. TC rain and wind climatologies are common in the literature. Rodgers (1981) study produced a TC rainfall climatology that looked at the characteristics and patterns of precipitation derived from satellite imagery. In their rainfall climatology Burpee and Black (1989) looked at the spatial extent of rainfall located near the center of circulation of two U.S. landfalling TCs. Examples of wind field climatologies vary in the literature due to the different temporal and spatial scales analyzed. For example, Kimball and Mulekar (2004) examined the pattern of the outer wind radii in storms that originated in the North Atlantic Basin. The wind field variables utilized in Kimball and Mulekar's study are commonly used size parameters in NHC operational forecasts. In this study I am utilizing principles of TC rain and wind climatologies to examine how the TC wind fields and rainfall extent aligned just as the leading edge of the wind field makes landfall. Specifically the research question asks: Does the extent of the rain shield coincide with the radius of gale-force winds (R17) during the time at which gale-force winds start to make landfall?

The National Hurricane Center (NHC) is responsible for forecasting TC activity in the North Atlantic and East Pacific ocean basins. Part of the operational forecasting procedure at the NHC involves warning the public about potential TC landfalls and giving the public a timeframe for TC arrival as to prepare their homes or evacuate. Coastal watches and warnings are issued 24-36 hours prior to TC landfall. A TC watch is issued by the NHC when TC conditions are possible in a specific area within the next 36-48 hours (Elsner and Kara 1999). TC warnings, on the other hand, indicate that severe TC-related weather conditions are expected within 24 hours (Elsner and Kara 1999). The NHC must consider three factors when issuing watches and warnings (Sheets 1990). First, sufficient lead time must be provided for protection of life and to prevent property damage. Second, the extent of the warnings must be taken into careful consideration as to avoid large government expenditures and to avoid complacency among residents in the path of the storm. The final step in the warning process is to communicate the warning to the possibly effected communities in a manner designed to generate a timely response.

As part of the forecasting parameters the NHC issues advisory reports that address the position, bearing, and other TC-related hazards information. Climate research that utilizes the NHC data is common within the literature due to its reporting of numerous TC hazards variables. For example, Kaplan et al. (2007) utilized the advisory's wind parameters to test the decay model of TCs, and Franklin et al (2007) investigated the error associated with the advisory's positional data. Included in the storm advisory report are several variables of storm speed, motion, and directionality. As seen in the excerpt below from Hurricane Katrina, direction and storm speed are two position variables reported in the advisory reports. In the case of Katrina, the storm was moving at 10 mph in a west-northwest direction. In terms of information of TC-related hazards there is a wide variety of information available in the advisory reports, including: maximum sustained wind speeds, minimum central pressure, tornado potential, estimated storm surge, and estimated rainfall amounts. From the advisory report below we can see that Hurricane Katrina had a minimum central pressure of 935 mb and maximum sustained winds of 145 mph. The advisory report also gives general insight into the spatial extent of TC-related winds. In terms of Hurricane Katrina, see below, the hurricane force winds extended 85 miles from the center of circulation whereas the tropical storm force winds extend 185 miles from the center. There is no note of the gale-force wind / rain shield alignment within the NHC advisory reports. Total rainfall estimates are seen in the advisory reports and there is some regional definition to the rainfall maximum, Hurricane Katrina had an estimated rainfall total of 5-10 inches and the advisory report mentions how the rainfall was projected to fall along the Gulf Coast, but the size of the rain shield and vulnerability of coastal regions are not addressed within the storm advisories.

> *"KATRINA IS MOVING TOWARD THE WEST-NORTHWEST NEAR 10 MPH. A GRADUAL TURN TOWARD THE NORTHWEST IS EXPECTED LATER TODAY.*
>
> *MAXIMUM SUSTAINED WINDS ARE NEAR 145 MPH WITH HIGHER GUSTS. KATRINA IS A CATEGORY FOUR HURRICANE ON THE SAFFIR-SIMPSON SCALE. SOME STRENGTHENING IS FORECAST DURING THE NEXT 24 HOURS.*
>
> *HURRICANE FORCE WINDS EXTEND OUTWARD UP TO 85 MILES FROM THE CENTER...AND TROPICAL STORM FORCE WINDS EXTEND OUTWARD UP TO 185 MILES.*
>
> *COASTAL STORM SURGE FLOODING OF 15 TO 20 FEET ABOVE NORMAL TIDE LEVELS...LOCALLY AS HIGH AS 25 FEET ALONG WITH LARGE AND DANGEROUS BATTERING WAVES...CAN BE EXPECTED NEAR AND TO THE EAST OF WHERE THE CENTER MAKES LANDFALL.*
>
> *RAINFALL TOTALS OF 5 TO 10 INCHES...WITH ISOLATED MAXIMUM AMOUNTS OF 15 INCHES...ARE POSSIBLE ALONG THE PATH OF KATRINA ACROSS THE GULF COAST AND THE SOUTHEASTERN UNITED STATES. THE HURRICANE IS STILL EXPECTED TO PRODUCE ADDITIONAL RAINFALL AMOUNTS OF 2 TO 4 INCHES OVER EXTREME WESTERN CUBA...AND 1 TO 3 INCHES OF RAINFALL IS EXPECTED OVER THE YUCATAN PENINSULA.*
>
> *ISOLATED TORNADOES WILL BE POSSIBLE BEGINNING SUNDAY EVENING OVER SOUTHERN PORTIONS OF LOUISIANA...MISSISSIPPI...AND ALABAMA...AND OVER THE FLORIDA PANHANDLE.*
>
> *REPEATING THE 4 AM CDT POSITION...25.4 N... 87.4 W. MOVEMENT TOWARD...WEST-NORTHWEST NEAR 10 MPH. MAXIMUM SUSTAINED WINDS...145 MPH. MINIMUM CENTRAL PRESSURE... 935 MB."*

The spatial extent of TC winds and the uncertainty associated (Sheets 1990) with TC operational forecasts have led to watches and warnings being placed along broad sweeping portions of the coastline. The radius of gale-force winds (R17), the radius of damaging-force winds (R26), and the radius of hurricane-force winds (R33) are TC size parameters that illustrate the spatial distribution of strong TC winds and are collectively referred to as the outer-wind radii (Kimball and Mulekar 2004). Each of these wind field variables is used in a different manner to understand the dynamics of the storm. In particular, the R17 radius is used to place watches and warnings along coastal areas. R17 is a measure of the spatial extent of 17.5 m/s winds (Kimball and Mulekar 2004). Even though the R17 wind speeds are barely tropical storm strength, they are ideal for watches and warnings placement because it is one of the larger size variables and therefore covers a large proportion of the storm.

In this study, the R17 variable is used to define the extent of the TC-related winds because of its use in the NHC operational forecasting procedures. If a relationship exists between the wind field and rain shield, it may be possible to forecast the time of rainfall arrival within the scope of operational forecasting watches and warnings.

Rainfall forecasts are not as precise as those of winds, thus, the NHC does not incorporate them into the operational forecasting procedure; but with TCs contributing 10-17% of global precipitation (Roth 2008), there is a need to better understand the distribution of rainfall associated with TCs. Currently, the NHC employs the Hydrometeorological Prediction Center (HPC) model for TC-related precipitation forecasting. The HPC gridded rainfall models provide estimates of the amount of precipitation that will occur as a result of a TC landfall, and the generalized region over which this rainfall is expected to occur. Instead of incorporating modeled rainfall estimates into the watches and warnings the NHC issues storm advisories with estimated rainfall amounts. These modeled rainfall estimates have no spatial or temporal relationship with the NHC operational forecasting framework; therefore gaining a sense of the relationship between the landfall time of rainfall and winds is difficult in the scope of TC watches and warnings. In this study, we are not looking to improve upon rainfall models such as the baseline Rainfall Climatology and Persistence Model (R-CLIPER). Instead we are looking to define the rain shield within the spatial parameters of operational forecasting variables, specifically R17.

Rappaport (2000) found that 82% of TC-related deaths in the U.S. from 1970-1999 were attributed to water. This figure can be broken down further to show that rainfall and associated flooding caused 59% of TC-related deaths; whereas, storm surge caused 23% of TC-related deaths. There is the potential for flood inducing rainfall across all parts of TCs. But the core, and particularly the eyewall, is associated with the heaviest rainfall within a TC (Willoughby 1988). TCs can produce heavy rainfall throughout the storm, it is therefore important to classify the spatial extent of rainfall to improve rainfall forecasts and climatologies.

The rain shield, or nearly continuous area of rain that typically become heavier as one approaches the eye (Senn and Hiser 1959), is used to define the extent of the precipitation in this study. The size of the rain shield is highly variable due to a variety of environmental factors including: upper-level wind shear, interaction with land, relative humidity, and the intensity of the TC. The rain shield is composed of both stratiform and convective precipitation, which leads to different levels of cloud development and rainfall rates.

The outer edge of the rain shield is defined, in this study, through the use of radar reflectivity returns which are commonly used in forecasting to illustrate the spatial extent of incoming precipitation (Matyas 2007; Matyas 2008). The radar sensor detects precipitation by measuring the strength of the electromagnetic signal reflected back to it after passing through the low or middle levels of a storm. Radar reflectivity measures are converted to rainfall rates through the use of the Z-R algorithm. Researchers employ the climatological Z-R relationship to convert reflectivity values (unit decibels Z) to rainfall rates (R) (Marshall et al. 1948; Jorgensen and Willis 1982). Storms of tropical nature generally have higher rainfall rates compared to non-tropical storms (Rosenfield 1993). Rosenfield (1993) updated the Z-R relationship to include a separate scale for storms of tropical origin. The updated algorithm ($Z=250R^{1.2}$) is used by the National Weather Service (NWS) and the NHC (Rosenfield 1993). The tropical Z-R relationship illustrates that exponentially more precipitation falls from tropical systems than other storms. For example, at 55 dB*Z* the climatological Z-R estimates rainfall rates at 0.144mmh^{-1} (5.68 in/hr) whereas the tropical Z-R estimates rainfall at 0.385mmh^{-1} (15.14 in/hr)

In this study, the rain shield is defined as regions with returning radar reflectivity values greater than 20 dB*Z* (decibels). Values under 20 dB*Z* are generally considered “no data”, ground noise, or light non-accumulating precipitation whereas values at or greater than 20 dB*Z* mark the initial level of accumulating rainfall. Other climatologists have employed this threshold to define the edge of the rain shield (Jorgensen 1984)

A gap in the literature and the need for a rainfall climatology that can be included in the NHC operational forecasts led to the following research question. Does the extent of the rain shield align with the radius of gale-force winds (R17) during the time at which gale-force winds make landfall? To form a hypothesis for this research question, I drew from four different areas of TC research: the NHC watches and warnings policies, literature on rain shields, storm dynamics, and wind fields, it is hypothesized that increased environmental forcings lead to more asymmetrical storms and therefore a higher percentage of the rain shield outside of R17. If there is a correlation between the rain shield and the R17 wind field, then the watches and warnings put in place by the NHC are sufficient to forecast TC precipitation arrival.

CHAPTER 2
THE SPATIAL DISTRIBUTION OF THE TROPICAL CYCLONE RAIN SHIELD IN RELATION TO THE RADIUS OF GALE-FORCE WINDS

Introduction

Due to their substantial size and intensity, tropical cyclones (TCs) are the most destructive and costliest of the atmospheric systems (Elsner and Kara 1999). While TC-related deaths can be attributed to strong winds, storm surge, or tornadoes; Rappaport (2000) found that the majority of TC-related deaths in the U.S from 1970-1999 resulted from coastal and freshwater flooding caused by heavy rainfall. This is exemplified in Tropical Storm (TS) Amelia (1978), which produced 1220 mm (48 inches) of rainfall and caused the deaths of 30 people in southeast Texas (Lawrence 1979); and Hurricane Floyd (1999), which produced 610mm (24 inches) of rainfall and caused 57 deaths across Florida and the Carolinas (Atallah and Bosart 2003). While significant improvements have been made in forecasts of TC wind field and tracks (Franklin et al. 2003; Aberson 2001), much less is known about rain shield dynamics. Currently, the National Hurricane Center (NHC) solely considers gale-force wind extent when placing watches and warnings along the U.S. coast; meaning that the extent of the rain fall, one of the most deadly and destructive aspects of the TC, is not considered when forecasting TC landfall location and conditions. This study analyzes the relationship between the TC wind fields and the rain shield within the framework of the NHC operational forecasting procedures, in order to understand how the rainfall extent aligns with the storm size variables calculated at the NHC.

Currently, the NHC does not include localized rainfall maxima into the operational forecasts. Storm advisories are issued every six hours with generalized precipitation totals, but they do not include information specific to when rainfall will commence in a given region. As storm summaries do not define the spatial extent of the leading edge of the precipitation, residents of coastal areas cannot gauge the arrival time of precipitation when looking at the TC watch and warning maps. The generalized precipitation totals, from the storm summaries, are based on gridded model estimates of rainfall (Marchok et al 2006). Baseline gridded estimates are produced using the Rainfall Climatology and Persistence model (R-CLIPER) (Marks 2002) or the Tropical Rainfall Potential model (TRaP) (Kidder et al. 2005). These rainfall models are not compatible with forecasts of storm size due to their use of standardized grids, therefore the modeled measurements of TC rainfall do not overlay with TC watches and warnings. When forecasting the track and intensity of TCs the NHC consults with national and state government agencies (Sheets 1990) and takes into consideration atmospheric dynamic and storm size variables derived from both objective and subjective climate / meteorological models. Based on the models the NHC issues watches and warnings along the U.S. coastline, based on the extent of gale-force winds.

The operational wind forecast procedure at the NHC involves estimation of six TC size parameters: eye diameter (EYED), radius of maximum winds (RVMAX), radius of gale-force winds (17 m/s) (R17), radius of damaging-force winds (26 m/s) (R26), radius of hurricane-force winds (33 m/s) (R33) and mean radius of the outer most closed isobar (ROCI) (Table 2-1)(Kimball and Mulekar, 2004; Pennington et al., 2000). Variables R17, R26, and R33 are TC size variables that illustrate the spatial distribution of strong winds and are collectively referred to as the outer-wind radii (Kimball and Mulekar, 2004). The outer wind radii are distance measurements from the center of circulation to the edge of 17 ms^{-1}, 26 ms^{-1}, and 33 ms^{-1} wind. Figure 2-1 depicts the relationship between the outer wind radii for Hurricane Charley (2004). Hurricane Charley (2004) had a R17 value of 125.5 km. TC size is typically measured by forecasters as the extent of R17 or ROCI (Merill 1984). To protect coastal residents, TC watches are put in place 36 hours prior to landfall; TC warnings are issued 24 hours prior to TC landfall when the forecast of the storm is more precise (Sheets 1990). The NHC places the watches and warnings based on the extent of gale-force winds (R17) in order to forewarn as many residents within the largest wind swath associated with the storm (Merrill, 1984; Kimball and Mulekar, 2004).

Rainfall forecasts are not as precise as those of wind and surge, because of the complex environmental forcings that can influence them; but with TCs contributing 10-17% of global rainfall, there is a need to understand the distribution of rainfall associated with a TC (Roth 2008). In this study the spatial extent of the precipitation, or rain shield, is defined using radar reflectivity data. The rain shield, or nearly continuous area of rain that typically becomes heavier as one approaches the eye, is composed of both stratiform and convective precipitation and is therefore associated with varying rainfall rates (Senn and Hiser 1959). A multitude of atmospheric variables affect the shape and elongation of the rain shield including shear, relative humidity, trough interaction, and sea surface temperatures. Upper level vertical wind shear (850-200 mb) weakens the TC by interfering with the organized deep convection that occurs around the core and outer bands of the storm (Corboserio and Molinari 2003). Storm intensity also affects the extent of the rain shield. As a TC intensifies the minimum central pressure decreases leading to a steep pressure gradient from the ROCI to the eye (Thorpe 1985; 1986). A steep pressure gradient generates rapid, inward spiraling banding features and therefore a tighter wrapping of winds around the eye (Thorpe 1985; 1986; Willoughby et al 1984). This spatial pattern was seen in the secondary landfall of Hurricane Katrina (2005); the category three storm had a pressure difference from the outermost closed isobar (POCI) to the minimum central pressure (MCP) of 103mb and a rain shield that was axisymmetrical. Relative humidity, a measure of cloud saturation, can also influence the rain shield by gauging if entrainment of dry air into the system is occuring. Frank (1977) found that strong convective regions of TCs have much higher mean relative humidity values than the surrounding tropical atmosphere. Higher relative humidity values imply that entrainment does not hamper deep convection (Frank 1977). This means that rain shields expand with increase relative humidity, and decrease with low relative humidity value because dry air entrainment inhibits the growth of the storm.

This study looks at the relationship between the leading edge of a TC rain shield (as defined by radar reflectivity data) and the edge of R17. Specifically the research question asks: To what degree does the rain shield align with the radius of gale-force winds (R17) during the time at which gale-force winds made landfall? If the two coincide then the lead time for wind conditions can also be used as the lead time for precipitation. Previous research determined the spatial extent of TC precipitation by overlaying various sized grids on rainfall data and determining the quantity within each cell (Rao and MacArthur 1994; Rodger et al. 1994). In this study takes a different approach in that rainfall quantities are not calculated. Instead, the percentages of rainfall within and outside of R17 are calculated in order to understand how the edge of R17 relates to the edge of the rain shield. Although rainfall climatologies have analyzed the pattern and type of precipitation within TCs (Frank 1977; Dvorak 1975; Corobosiero and Molinari 2002), and case studies of individual TCs have determined the impacts of TC-related precipitation across the southeast U.S (Knight and Davis 2007), none of these have specifically addressed the differential pattern of the wind fields and rain shield. Specifically, quantifying how well the wind field (R17) contains the rain shield in U.S. landfalling TCs. Literature and the NHC forecasting policies suggest that increased environmental forcings (i.e. strong upper level wind shear, trough interaction, low relative humidity, or any other atmospheric variables that can influence storm dynamics) lead to more asymmetrical storms and therefore a higher percentage of the rain shield occurring outside of R17.

Study Area

From 1995 to 2006, fifty-four TCs made landfall in the US. Of the 54 TCs, 30 were tropical storms with maximum sustained wind speeds less than 33 m/s and 24 were hurricanes with maximum sustained wind speeds greater than 33 m/s. This study analyzes 42 of the 54 landfalling TC's, 21 of which were tropical storms and 21 were hurricanes (Table 2-2). As seen in figure 2-2 these systems made landfall across various parts of the southeast U.S, and were of varying degrees in strength. To be included, storms must have: 1) made landfall in the US, 2) gale-force winds data for all four quadrants at the time R17 made landfall, and 3) long range composite reflectivity imagery available from the National Climate Data Center (NCDC). Storms that made multiple landfalls in the U.S. were taken into special consideration. In order to include multiple landfalls into the study the TC needed to have sufficient time over warm ocean waters to reintensify. Arbitrarily, a minimum of six hours had to elapse between the first and second landfalls to be included in the study. The addition of multiple TCs landfall brought the number of storms analyzed up to 42.

Data and Methods

Geographic Information Systems (GIS) enables spatial analysis and statistics to be performed on TC wind fields and rain shield. Composite radar reflectivity imagery from the National Climatic Data Center (NCDC) and quadrant averaged R17 wind field data from the Extended Best Track (EBT) dataset are used to define the spatial extent of the TC-related winds and precipitation within a GIS. Whereas the Statistical Hurricane Intensity Prediction Scheme (SHIPS) dataset is used to draw conclusions as to why the rain shield shape is highly variable. These datasets are derived from multiple sources including: surface observations, aircraft reconnaissance data, and satellite images (Moyer et al. 2007). Analysis of climatological TC datasets within a GIS allows for the spatial relationship of two of the most destructive TC related hazards to be analyzed and quantified.

Data

Radar reflectivity data (from WSR-88D stations) were obtained from the National Climatic Data Center (NCDC) for the site closest to the R17 landfall location (Klazura and Imy 1993), and the Java NEXRAD tool were used to convert the data into a format utilized with a GIS (Ansari and Del Greco 2005). Level III long range composite reflectivity data were utilized to represent the rain shield as their spatial extent of 460 km is sufficient to depict the rain shield. Composite reflectivity depicts the maximum reflectivity found on any constant elevation angle (Klazura and Imy 1993). The radar reflectivity data depicts the amount of energy returned to the radar's sensor in decibels of Z (dB*Z*), with a range of values from 5 dB*Z* to 75 dB*Z* (Klazura and Imy 1993). This range of values represents light to heavy rainfall. Values below 20 dB*Z* generally represent ground clutter or a false radar signal. Because the portion of the atmosphere being sensed at the 460km distance is 16.8 km above the ground, only the tops of clouds at this distance from the radar site can be detected. This means that the deep convection present at 2-4 km from the ground will not be sensed at long distances away from the radar's site.

Rosenfield's (1993) tropical Z-R relationship is used to convert observed radar reflectivity factors into rainfall rates for storms of tropical nature; Marshal's (1948) Z-R relationship is used to convert radar reflectivity date to rainfall rates for non tropical systems. Radar values of 20 dB*Z* correspond with 0.51 mmh^{-1} rainfall, the minimum rainfall detectable, from radar reflectivity returns (Marshall et al1947; 1948; Rosenfield 1993). Therefore, this study defines the rain shield as areas with radar reflectivity returns greater than or equal to 20 dB*Z*.

The EBT dataset is an extension of the best track dataset (Neumann et al. 1999); compiled from various publications and represents a detailed post-season analysis of North Atlantic basin originating TC intensities and tracks at six hourly intervals (Moyer et al. 2007). The newer version of the best track dataset includes TC size parameters (Kimball and Mulekar 2004). The EBT dataset of Pennington et al. (2000) was compiled from advisories issued by the NHC from 1988 to present (Moyer and Powell 2006).

The NHC maintains position and intensity data for all Atlantic tropical cyclones since 1851; this dataset is referred to as HURDAT (Neumann et al. 1999). Storm heading (DIR) and storm speed (SPEED) were extracted from this dataset to assist with the interpolation of R17 data. When variables DIR or SPEED were not available in the HURDAT dataset, they were calculated by extracting the positional data from the NHC storm advisories and then calculating the storm speed and bearing using the Laake (2003) Excel function.

The SHIPS dataset, which is comprised of TC environmental data from 1982-2006 (DeMaria et al 2005), is used to determine why certain tropical cyclones have a high percentage of rainfall outside of R17. Included in this dataset are climatological, atmospheric environment, ocean, and storm properties variables. From this dataset 4 variables were extracted: storm category (a measure of intensity), generalized 850-200 mb shear (SHRG), 700-500 mb relative humidity, and the climatological sea surface temperature (CSST). While many environmental and atmospheric variables can impact the rain shield shape these four are commonly employed (Corbosiero and Molinari 2002).

Methods

The EBT and SHIPS data must be interpolated to R17 landfall time: (1) to avoid land surface interaction issues, (2) to fall in line with NHC watches and warning policies, and (3) to gauge whether the winds and rain make landfall at the same time. To do this, first we must determine the time of R17 landfall. The 6 hourly position data were interpolated to hourly positions beginning 24 hours prior to the landfall of the center of circulation. At each hour, the distance between the circulation center and landfall location was calculated. The quadrant averaged R17 radius was then subtracted from the distance calculation, and the time when the value was nearest 0 is utilized as R17 landfall time. Table 2-3, illustrates the analysis time for each storm compared with the center of circulation landfall time. Note that R17 landfall occurred for most storm 12-18 hours prior to the center of circulation landfall.

To quantify the spatial extent of the rain shield and compare it to the extent of R17, the radar reflectivity data and R17 data were entered into a GIS. After the radar reflectivity data were converted into GIS format, the rain shield must be defined. All radar reflectivity values less than 20 dB*Z* were exported out of the composite reflectivity image; leaving radar returns with the greatest potential to produce accumulating rainfall, and thus the rain shield is defined as radar reflectivity regions greater than or equal to 20dB*Z*. The center of circulation was then identified within the rain shield using the HURDAT location data; this was done in order to produce the wind field buffer from the eye outward. Next, within the GIS the R17 wind field extent with modeled and overlaid atop the rain shield using a buffer. Using the X-Tools Pro 5.1 extension of GIS several area calculations were completed, including: the total area of the rain shield, the area of the rain shield occurring within the R17 wind field, and the area of the rain shield occurring outside of the R17 extent. The total area of the rain shield was calculated for two reasons: (1) to gauge the total storm rain shield extent and (2) so that the portion of the rainfall within and outside of R17 can later be calculated.

Rain shield sizes varied greatly, thus simple area totals are insufficient to understand the wind/rain relationship in every storm. To convert the rain shield area totals to percentages, the attribute tables of each storm were exported to excel. The percentage of rainfall within and outside of R17 was then calculated. By using the percentage area calculations, issues of storm size are alleviated. With a spatial extent of 460 km, the radar reflectivity data do not always cover the back two quadrants of the storm. Due to the lack of complete spatial coverage of the radar images the percentage of rainfall outside of R17 is used for the analysis, as we are mostly concerned with the rain that is making landfall prior to the gale-force wind landfall. The percentage of the rain shield outside R17 is justifiable for analysis because research has shown that the majority of rainfall occurs in the leading edge of the storm (Elsberry 2002). Since we are concerned with the arrival time of the precipitation and not the duration, the percentage of the rain shield area outside of R17 is a tenable calculation.

Lastly, the type of precipitation occurring outside of R17 is defined. This was done in order to determine whether those areas where the rain shield and wind field did not align were composed of light or heavy precipitation. This is important because the leading edge of precipitation is often heavy, and if it does not align with the R17 wind field which is used to place coastal watches and warnings, than coastal residents may not be prepared for potentially flooding precipitation. The precipitation was classified based on the radar reflectivity value. Radar reflectivity values ranging from 20-35 dB*Z* were extracted from the GIS layer and classified as light precipitation. The light precipitation layer consists of accumulating rainfall with rainfall rates ranging from 0.51 mmh^{-1} to 8.38 mmh^{-1}. The heavy precipitation layer consists of all radar polygons greater than 35 dB*Z*; these radar reflectivity values are associated with intense rainfall rates. The area and percentage area of light and heavy rainfall areas was then calculated, in order to understand the composition of the rainfall occurring outside of R17.

Results

The distribution of R17 is skewed to the right and has a large spread from the smallest to the largest R17 wind field radius. The mean R17 is 199.5 km with a standard deviation of 88.57 km. Kimball and Mulekar (2004) calculated mean R17 figure of 222.3 km and a standard deviation of 104.3 km respectively. The differences are largely due to the different number of years analyzed between the two studies.

Overall, the 42 TCs in this study had a range of R17 wind radii of 308.98 km. Table 2-3 lists the statistical properties of the R17 size parameter for all TCs analyzed. The smallest R17 wind field occurred during tropical storm Bonnie (2004). This TC had a R17 radius of 71.77 km, which was caused largely by strong southwesterly shear that weakened the storm 24-36 hours prior to landfall (Avila 2005). Tropical storm Isidore (2003) had the largest R17 radius of 380.74 km, Isidore's R17 wind field is roughly one third the size of the largest and most intense TC on record, Supertyphoon Tip (1100 km) (Kimball and Mulekar 2004).

All TCs have some portion of their rain shield located outside of R17 (Table 2-4). The average TC had 57% of the rain field located outside of R17. This figure gives the general connotation that the wind field and rain shield do not coincide very well; but upon closer examination there are many TCs with rain shields well contained within the R17 wind field. There are several extreme cases on both ends of the spectrum of note. Firstly, TC Helene (2000) had more than 99% of its rain shield outside of R17. This system became a tropical storm in the southeast Gulf of Mexico under marginal environmental conditions, but the vertical wind shear increased causing the system to become asymmetrical with most of its deep convection, winds, and heavy rainfall displaced to the east of the storm's eye (Franklin et al. 2001). TC Helene (2000) also had a relatively small gale-force wind field of only 84 km, which can be attributed to the vast majority of the precipitation occurring outside of R17. On the other end of the spectrum is Hurricane Wilma (2005) which had only 2.3% of the rain shield outside of R17 due largely to the intensity, the steep pressure gradient, and the large R17 wind field of 324.7km (Pasch et al. 2005). Hurricane Wilma (2005) had one of the largest R17 wind fields of the storms in this study.

Several environmental forcings were examined (Table 2-5); vertical wind shear, relative humidity, sea surface temperature, and intensity, play a large part in the composition of the wind and rain shield and therefore are most likely to cause rain shield asymmetries. Table 2-5 reports these environmental variables by natural breaks in the data based on the percentage of the rain shield occurring outside of R17. The generalized wind shear value, extracted from the SHIPS dataset, indicates that TCs in the lower (25%) quartile had relatively low wind shear values that range from 6.98 – 16.91 ms^{-1}. Whereas in the upper quartile vertical wind shear appears to have affected the shape of the TCs, these TCs (Tropical Storm Cindy 2005; Tropical Storm Bill 2003; Tropical Storm Gabrielle 2001; the first landfall of Tropical Storm Ernest 2006; Tropical Storm Bonnie 2004; Tropical Storm Helene 2000) had generalized vertical wind shear values ranging from 18.60-22.07 ms^{-1}; within the upper quartile there appears to be one outlier, in terms of the shear values, Tropical Storm Barry (2001) had a low vertical wind shear value of 5.88ms^{-1} but 82.13% of the rain shield was outside of the R17 wind field. In terms of relative humidity and sea surface temperature there did not appear to be a direct link with the percentage of the rain shield outside of R17. In the upper quartile, several of the storms (Tropical Storm Cindy 2005; Tropical Storm Barry; Tropical Storm Bill 2003) had high relative humidity percentage but a consistent trend across all of the 42 storms was not observed.

The final variable extracted from the SHIPS dataset is intensity. As seen in table 2-5 all of the storms in the upper two quartiles were weak TCs, Saffir Simpson category 1 or tropical storms. Figure 2-4, which depicts the mean percentage of the rain shield outside of R17 by Saffir Simpson category, and indicates a possible relationship between the percentage of the rain shield outside of R17 and storm intensity. Tropical storms and weak hurricanes (category 1) on average had 73.13% and 66% of the rainfall outside of R17 (Figure 2-4). This corresponds to the hypothesis that increased environmental forcings will cause more of the rain shield to be outside of R17 because weaker TCs are weak due to various environmental conditions. TSs, in this study, varied greatly in the percentage of the rain shield falling outside of R17; with TS Erin (1995) having only 15.44% of the rain shield outside of R17 to TS Helene (2000) which had 99.2% of the rain shield outside of R17. The mean percentage value associated with TS was 77.6%. Storms on or around the mean include: TS Josephine (1996) with 77.31%, the first landfall of Irene (1999) at 77.66%, and Charley (1998) with 77.95% of the rainfall outside of the wind measure. The five category 1 storms in this study had a range of percentage from 60.04% to 72.21%. Examples of Category 1 storms in this study include: Bertha (1996) with a percentage value of 61.35%, Earl (1998) with 64.11%, and Gordon (2000) with 71.75% of the rainfall outside of R17.

As seen in figure 2-4, the mean percentage of rainfall occurring outside of R17 decreases with an increase in storm intensity. The five category 2 hurricanes included in this study had a mean percentage value of 29.77%. This includes hurricanes such as Frances (2004) with 14.85%, and the 2 landfalls of Georges with 29.38% and 34.47%. There is a marked decline in the mean percentages outside of R17 from category 1 hurricanes to category 2; meaning that more intense category 2 storms contain more rainfall within the R17 boundary. As stated in the hypothesis, TCs that are strongly influenced by various environmental forcings will have more of the rain shield outside of R17. Intense storms are defined as hurricanes of category three or greater

(Simpson 1974). The spatial calculation of intense TCs falls in line with our hypothesis because these systems are either not easily influenced by forcings due to the stage of maturity or are contained within the ideal environmental. With a mean percentage outside of R17 of 25.71%, category 3 storms are even better contained within the wind field. The four category 3 hurricanes in this study: Fran (1996), Bonnie (1998), Jeanne (2004), and Rita (2005) had 49.89%, 10.12%, 19.04%, and 23.78% of their rainfall outside of R17. While the range of percentages appears to be large, the mean of the values illustrates the point that the wind field aligns well with the rain shield in more intense storms. Category 4 hurricanes had on average 36.99% of the rainfall outside of R17. The five category 4 hurricanes in this study include: Opal (1995) at 39.05%, Ivan (2004) at10.55% outside, and the first landfall of Charley (2004) with 46.65% of rainfall outside of R17. Through the percentage outside of R17 is higher for category 4 storms than categories 2 and 3 these storms are still better contained with R17 as compared to category 1 and tropical storms. The higher mean and median values for category 4 hurricanes, as compared with other intense hurricanes, can be explained by further analysis of Hurricane Bret (1999). While Bret made landfall as a strong category 4 hurricane its formation was greatly hindered due to high vertical wind shear caused by an upper-level trough (Lawrence et al. 2001). Even though the trough dissipated and Bret intensified rapidly the asymmetrical shape remained, and thus a larger portion of rainfall was outside of R17 (Lawrence et al. 2001).

The composition of the rain shield falling outside of R17 is also related to storm intensity. Figures 2-5 and 2-6 depict the composition of the rain shield outside of R17 for all storms in this study. From these figures we can see that the vast majority of the precipitation occurring outside of R17 is light precipitation (Equal or less than 35 dB*Z*). In weaker TCs (TS and Category 1), more of the rain shield outside of R17 was comprised of heavy precipitation when compared to more intense TCs, where most of the heavy rainfall was contained within R17. This can be attributed to the fact that more of the TS rain shield falls outside of R17 and the asymmetrical nature of these systems. Figure 2-5 shows the composition of the rain shield outside of R17 for tropical storms. From this figure we can see that the vast majority was light precipitation (90%), whereas only 10% of the rainfall was intense (greater than 35 dB*Z*). Likewise, for category 1 TCs, the average amount of intense precipitation occurring outside of R17 was 13.43%. With a percentage of intense rainfall outside of R17 at 21.7%, the second landfall of Danny (1997) had the greatest amount of intense precipitation outside of R17 of the entire category 1 TCs. This was caused by a wedging of the hurricane between a high pressure system and a mid-troposphere trough that disrupted the TCs winds and rain fields (Rappaport et al. 1999).

The percentages of intense rainfall occurring outside of R17 drops quite substantially from weaker storms to intense storms, as seen in Figure 2-6. The average amount of intense rainfall outside of R17 for category 2 storms was 9.34%. Of these storms Frances (2004) and the first landfall of Georges (1998) had roughly the same percentages of intense rainfall outside of R17, approximately 5%. The other three category 2 TCs had a rain shield that was composed of approximately 12% intense rainfall outside of R17. Five category three storms were analyzed in this study, and these storms had an average of 4.53% of intense rainfall outside of R17. The four category 3 storms in the study, which represent 10% of the overall storms, include: Hurricanes Fran (1996), Bonnie (1998), Jeanne (2004), and Rita (2005).Of these storms, Hurricane Bonnie (1998) had the highest percentage of intense rainfall outside of R17 with 6.5%. This system moved slowly and had ample time to strengthen over the Atlantic Ocean. The weakening of steering currents brought it on shore near Cape Fear, North Carolina; but the compact shape of the rain shield is thought to be caused by the trough interaction just prior to landfall (Pasch et al

2001). Included in the category 4 storms are Hurricane Opal (1995), Hurricane Bret (1999), the first landfall of Hurricane Charley (2004), Hurricane Ivan (2004), and Hurricane Dennis (2005). The lone category 5 storm was one of the deadliest TCs in the Atlantic Basin's history. When Hurricane Katrina (2005) made landfall near the Mississippi / Louisiana border it was an intense category 3 storm, but at the time of R17 landfall, it had yet to weaken and was a category 5 storm. The percentage of intense rainfall occurring outside of R17 for these storms is 9.9%, higher than expected considering the trend seen in category 3 and 4 storms. This deviation from the trend is largely due to the first landfall of Hurricane Charley (2004). Outside of R17 the rain shield of Hurricane Charley (2004) was composed of roughly 23.4% intense rainfall; this is largely to the high sea surface temperatures (29.1°C) and ideal atmospheric conditions (generalized vertical wind shear of 6.55 ms^{-1}) that produced deep convection many kilometers away from the center of circulation (National Hurricane Center; Matyas 2009). Other category 4 TCs fell in line with the trend previously seen; Hurricane Ivan (2004) and Hurricane Dennis (2005) both had a rain shield composition outside of R17 of only 2% intense precipitation.

Discussion

The R17 variable, a wind field of minimal tropical storm strength, is the primary size variable utilized by the NHC when coastal watches and warnings are issued (Kimball and Mulekar 2004; Sheets 1990). Therefore, the greatest winds and storm hazards, including precipitation, might be expected to occur within this area. The fact that 60% of TC-related deaths result from precipitation and the associated inland and coastal flooding, indicates a need to understand how sufficient the wind size variable (R17) is in gauging the extent of other TC-related hazards. This is especially true considering the fact that TC-related flooding has been documented hundreds of kilometers away from the center of circulation, in areas that may not have been in the TC's warning zone, and therefore, not prepared for this hazard.

Various environmental forcings cause the elongation and asymmetry of the rain shield, particularly the pressure gradient (intensity), vertical wind shear, relative humidity, and sea surface temperatures. Preliminarily analysis shows that the rain shield and wind fields are not well aligned for weak TCs (tropical storms and category 1 TCs); meaning that operational forecasts would not be sufficient for forecasting flood inducing precipitation. On the other hand, more intense TCs (category 2 storms or greater) were fairly well contained within the R17 wind field; due largely to the intense pressure gradient that results in a tight wrapping of winds around the eye and a general compactness of the storm. This means that watches and warnings issued by the NHC are sufficient for forecasting the precipitation arrival. Given the destructive aspect of these intense systems, these findings are good news for coastal residents who would have ample time to prepare / evacuate before TC-related winds and heavy rainfall make landfall.

A secondary component of this study looked at the composition of the rainfall occurring outside of R17. Areas classified as light rainfall have little chance of producing intense rainfall and flooding. Heavy precipitation, on the other hand, is capable of producing a rainfall rate of $21.59 mmh^{-1}$ or higher. These heavy precipitation regions have the greatest potential for flooding to occur. The spatial analysis shows that the vast majority of the rainfall occurring outside of R17 is light precipitation; with more intense storms having the lowest percentage of intense precipitation outside of R17 when compared with weaker systems. The radar composition analysis gives great insight into NHC watches and warnings and how well such forecasts are at defining the onset of winds and precipitation. While the rain shield is not well contained within the R17 field, the rainfall typically occurring outside of R17 is light precipitation

Conclusions

In TS and category 1 Hurricanes, a large portion (on average around 70%) of the rain shield is located outside of R17.

Intense storms, which are either mature or contained within an ideal environment, on average have approximately 30% of the rain shield outside R17. This means that the R17 wind field and rain shield for the most part coincide, therefore the NHC operational forecasts of regions likely to experience tropical storm-force winds are also sufficient to forecasts regions likely to experience TC-related rainfall.

Of the rain shield occurring outside of R17, the composition is mostly light precipitation that is not likely to produce flooding

The NHC watches and warnings are sufficient for forecasting the landfall of intense (potentially flood-inducing) precipitation in most landfalling TCs. Exceptions occur when there is a weak asymmetrical TS with an elongated rain shield, or when upper level vertical wind shear values are high and therefore the rain shield is elongated.

Future Research

This project lays the foreground for a larger rainfall climatology project. Future research will examine the radius of the outermost closed isobar (ROCI), the radius of damaging-force winds (R26), and the radius of hurricane-force winds (R33) and the spatial variation / relationship with the rain shield (Table 2.1). This type of research will require a similar methodology as what was used in this study; it will differ in that we will compare the edge of the rain shield to the edge of the other size variables such a ROCI. Other future research goals include: calculating the landfall time of the TC rain shield, which would closely relate to the timing of TC watches and warnings; and correlating the effects of vertical wind shear, storm motion, and other parameters to the rainfall distribution.

Table 2-1. National Hurricane Center Operational Forecast Size Variables

Abbreviation	Meaning	Definition	Wind Measure (ms^{-1})
EYED	Eye Diameter	A measure of the calmest part of the storm. Surrounding the eye is the eye wall, which is the most violent part of a hurricane	NA
RVMAX	Radius of Maximum Winds	A measure of the distance from the center of hurricane circulation to the band of strongest winds	NA
R17	Radius of Gale-Force Winds	A wind field measure slightly above tropical storm force (39.15 mph). Wind measure used as the baseline for TC advisories.	17.5
R26	Radius of Damaging-Force Winds	Tropical Storm force wind measure at or above 57.49mph.	25.7
R33	Radius of Hurricane-Force Winds	A measure of the extent of hurricane winds (74mph)	32.9
ROCI	Radius of the Outermost Isobar	A measure from the center of circulation to the outermost closed isobar.	NA

Source: Kimball and Mulekar 2004

Table 2-2. Tropical Cyclones from 1995-2006 Analyzed in Study.

Name	Year	Category at Eye Landfall	Category at R17 Landfall	Hours from R17 Landfall to Eye Landfall
Erin L1	1995	1	1	7.25
Erin L3	1995	1	Tropical Storm	8
Opal	1995	3	4	9.5
Bertha	1996	2	1	10.75
Fran	1996	3	3	15.25
Josephine	1996	Tropical Storm	Tropical Storm	3.5
Danny L2	1997	1	1	18.75
Bonnie	1998	3	3	21
Charley	1998	Tropical Storm	Tropical Storm	10.75
Earl	1998	1	1	7
Frances	1998	Tropical Storm	Tropical Storm	17
Georges L1	1998	2	2	9.5
Georges L2	1998	2	2	20.75
Mitch	1998	Tropical Storm	Tropical Storm	8
Bret	1999	3	4	10.75
Dennis	1999	Tropical Storm	Tropical Storm	11.5
Floyd	1999	2	2	11
Irene L1	1999	1	Tropical Storm	10.25
Gordon	2000	Tropical Storm	1	15.5
Helene	2000	Tropical Storm	Tropical Storm	14.5
Barry	2001	Tropical Storm	Tropical Storm	7
Gabrielle	2001	Tropical Storm	Tropical Storm	5.5
Eduardo	2002	Tropical Storm	Tropical Storm	7.25
Isidore	2002	Tropical Storm	Tropical Storm	19.25
Bill	2003	Tropical Storm	Tropical Storm	9
Bonnie	2004	Tropical Storm	Tropical Storm	2
Charley L1	2004	4	4	3.75
Charley L3	2004	1	1	2.5
Frances	2004	2	2	15
Gaston	2004	1	Tropical Storm	6.5
Ivan	2004	3	4	19
Jeanne	2004	3	3	11.5
Cindy L1	2005	1	Tropical Storm	8.75
Cindy L2	2005	Tropical Storm	Tropical Storm	5
Dennis	2005	3	4	9.75
Katrina L1	2005	3	4	9
Katrina L3	2005	3	5	19.75
Rita	2005	3	3	16
Wilma	2005	3	2	10
Alberto	2006	Tropical Storm	Tropical Storm	8
Ernesto L1	2006	Tropical Storm	Tropical Storm	5
Ernesto L3	2006	Tropical Storm	Tropical Storm	5

Table 2-3. Statistical properties of the distributions of the R17 size parameter

	R17 (km)
Quartiles	
Maximum	380.74
90%	324.75
75%	266.22
Median	172.5
25%	129.64
10%	84.5
Minimum	71.77
Moments	
Mean	199.5
Standard Deviation	88.57
No. of Records	42

Table 2-4. Percentage of Rain Shield Within / Outside of R17

	Name	Year	Category (R17)	Percentage Area Outside
1	Wilma	2005	2	2.27
2	Bonnie	1998	3	10.12
3	Ivan	2004	4	10.55
4	Frances	2004	2	14.85
5	Erin L3	1995	Tropical Storm	15.44
6	Isidore	2002	Tropical Storm	17.42
7	Jeanne	2004	3	19.04
8	Rita	2005	3	23.78
9	Georges L1	1998	2	29.38
10	Katrina L2	2005	5	29.69
11	Georges L2	1998	2	34.47
12	Opal	1995	4	39.05
13	Dennis	2005	4	41.75
14	Charley L1	2004	4	46.65
15	Bret	1999	4	47
16	Fran	1996	3	49.89
17	Frances	1998	Tropical Storm	52.73
18	Erin L1	1995	1	60.04
19	Dennis	1999	Tropical Storm	61.29
20	Bertha	1996	1	61.35
21	Earl	1998	1	64.11
22	Danny L2	1997	1	66.55
23	Floyd	1999	2	67.87
24	Gordon	2000	1	71.75
25	Charley L3	2004	1	72.21
26	Mitch	1998	Tropical Storm	72.52
27	Ernesto L3	2006	Tropical Storm	74.08
28	Josephine	1996	Tropical Storm	75.00
29	Gaston	2004	Tropical Storm	76.69
30	Katrina L1	2005	Tropical Storm	76.89
31	Cindy L2	2005	Tropical Storm	77.03
32	Irene L1	1999	Tropical Storm	77.66
33	Charley	1998	Tropical Storm	77.95
34	Cindy L1	2005	Tropical Storm	78.49
35	Alberto	2006	Tropical Storm	79.07
36	Barry	2001	Tropical Storm	82.13
37	Bill	2003	Tropical Storm	84.22
38	Gabrielle	2001	Tropical Storm	84.35
39	Ernesto L1	2006	Tropical Storm	84.42
40	Edouard	2002	Tropical Storm	91.98
41	Bonnie	2004	Tropical Storm	94.88
42	Helene	2000	Tropical Storm	99.21

Table 2-5. Natural Break Table of Three SHIPS Variables That Commonly Affect Tropical Cyclone Size

Name	Year	Intensity	R17 (km)	Percentage Area Outside	Shear (ms^{-1})	Relative Humidity (%)	CSST (C)
Wilma	2005	2	324.748	2.27	12.18	0.56	27.77
Bonnie	1998	3	282.82	10.12	11.78	0.61	29.5
Ivan	2004	4	367.18	10.55	7.29	0.56	28.6
Frances	2004	2	285.32	14.85	13.28	0.69	28.97
Erin L3	1995	TS	149.7	15.44	6.98	0.57	29.5
Isidore	2002	TS	380.74	17.42	14.87	0.6	28.41
Jeanne	2004	3	246.55	19.04	13.43	0.39	28.4
Rita	2005	3	282.43	23.78	16.91	0.49	28.16
Georges L1	1998	2	208.54	29.38	9.47	0.49	29
Katrina L2	2005	5	320.6	29.69	10.93	0.71	29.1
Georges L2	1998	2	214.72	34.47	9.91	0.47	27.74
Opal	1995	4	349.18	39.05	22.50	0.49	27.56
Dennis	2005	4	274.58	41.75	16.28	0.66	28.83
Charley L1	2004	4	125.498	46.65	19.53	0.48	29.67
Bret	1999	4	143.34	47.00	8.70	0.51	29.3
Fran	1996	3	216.02	49.89	11.71	0.57	~
Frances	1998	TS	337.22	52.73	13.28	0.69	28.97
Erin L1	1995	1	194.46	60.04	7.50	0.52	29.13
Dennis	1999	TS	180.57	61.29	7.69	0.45	27.14
Bertha	1996	1	266.225	61.35	14.14	0.58	27.59
Earl	1998	1	148.55	64.11	23.24	0.44	28.92
Danny L2	1997	1	137.1	66.55	5.25	0.47	30.5
Floyd	1999	2	325.26	67.87	23.55	0.49	28.13
Gordon	2000	1	209.314	71.75	18.29	0.42	28.5
Charley L3	2004	1	118.065	72.21	~	~	28.63
Mitch	1998	TS	263.91	72.52	~	~	26.5
Ernesto L3	2006	TS	144.65	74.08	18.26	0.44	~
Josephine	1996	TS	132.53	75.00	23.15	0.62	27.7
Gaston	2004	TS	84.495	76.69	15.24	0.57	28.3
Katrina L1	2005	TS	98.4	76.89	8.12	0.68	29.13
Cindy L2	2005	TS	129.64	77.03	15.06	0.5	~
Irene L1	1999	TS	153.94	77.66	8.70	0.51	29.3
Charley	1998	TS	223.98	77.95	6.55	0.4	29.1

Table 2-5 Continued.

Name	Year	Intensity	R17 (km)	Percentage Area Outside	Shear (ms^{-1})	Relative Humidity (%)	CSST (C)
Cindy L1	2005	TS	126.35	78.49	19.59	0.61	28.73
Alberto	2006	TS	143.148	79.07		~	28.5
Barry	2001	TS	138.13	82.13	5.88	0.66	28.41
Bill	2003	TS	164.365	84.22	18.60	0.69	28.33
Gabrielle	2001	TS	162.05	84.35	20.42	0.52	28.83
Ernesto L1	2006	TS	94.915	84.42	19.96	~	~
Edouard	2002	TS	72.3	91.98	21.20	0.57	~
Bonnie	2004	TS	71.765	94.88	22.07	0.39	29.5
Helene	2000	TS	83.97	99.21	21.61	~	~

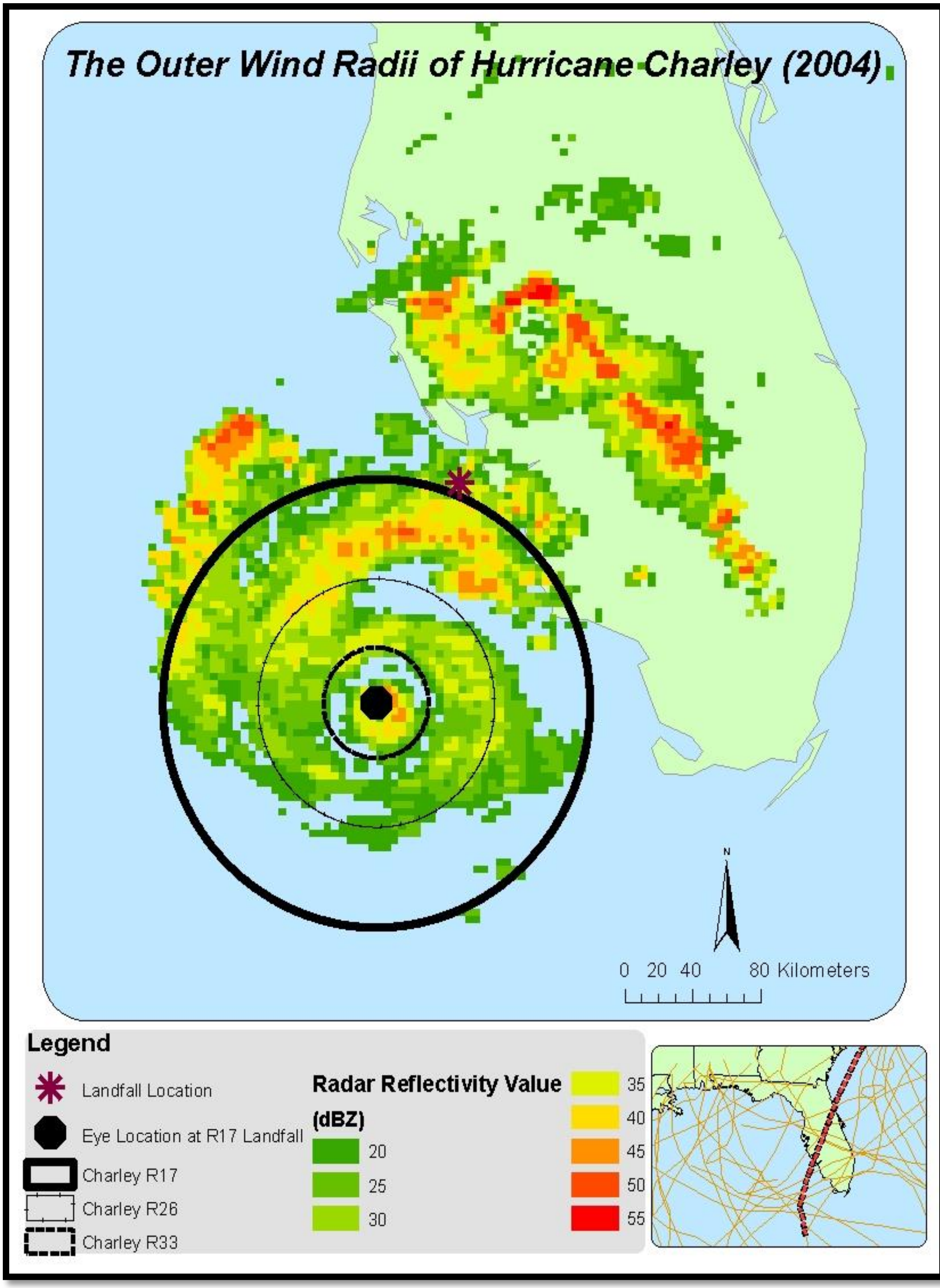

Figure 2-1. An example of the outer wind radii, Hurricane Charley (2004)

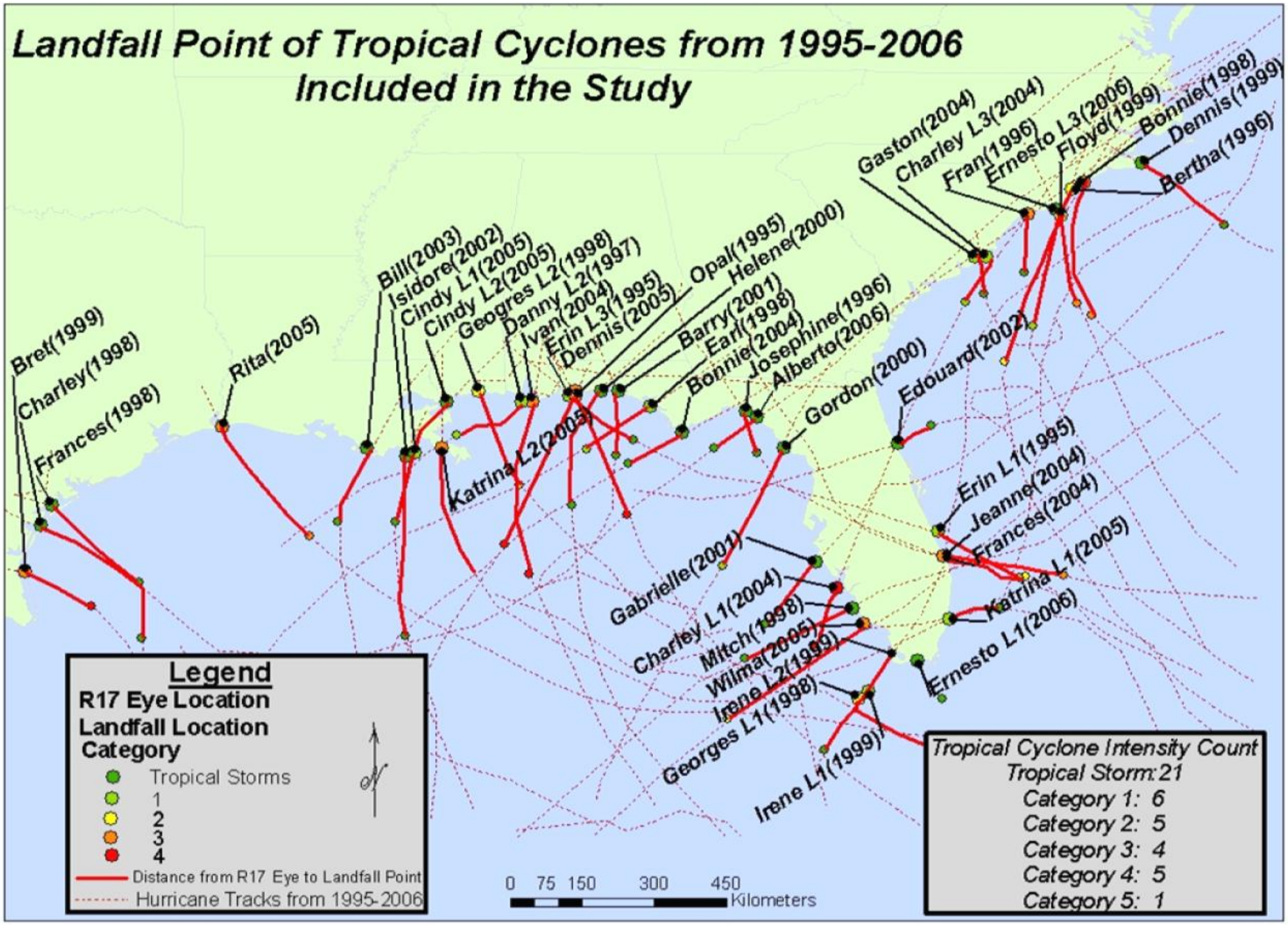

Figure 2-2. Tropical Cyclones Studies from 1995-2006. Including Landfall Point, Track, and Analysis Point

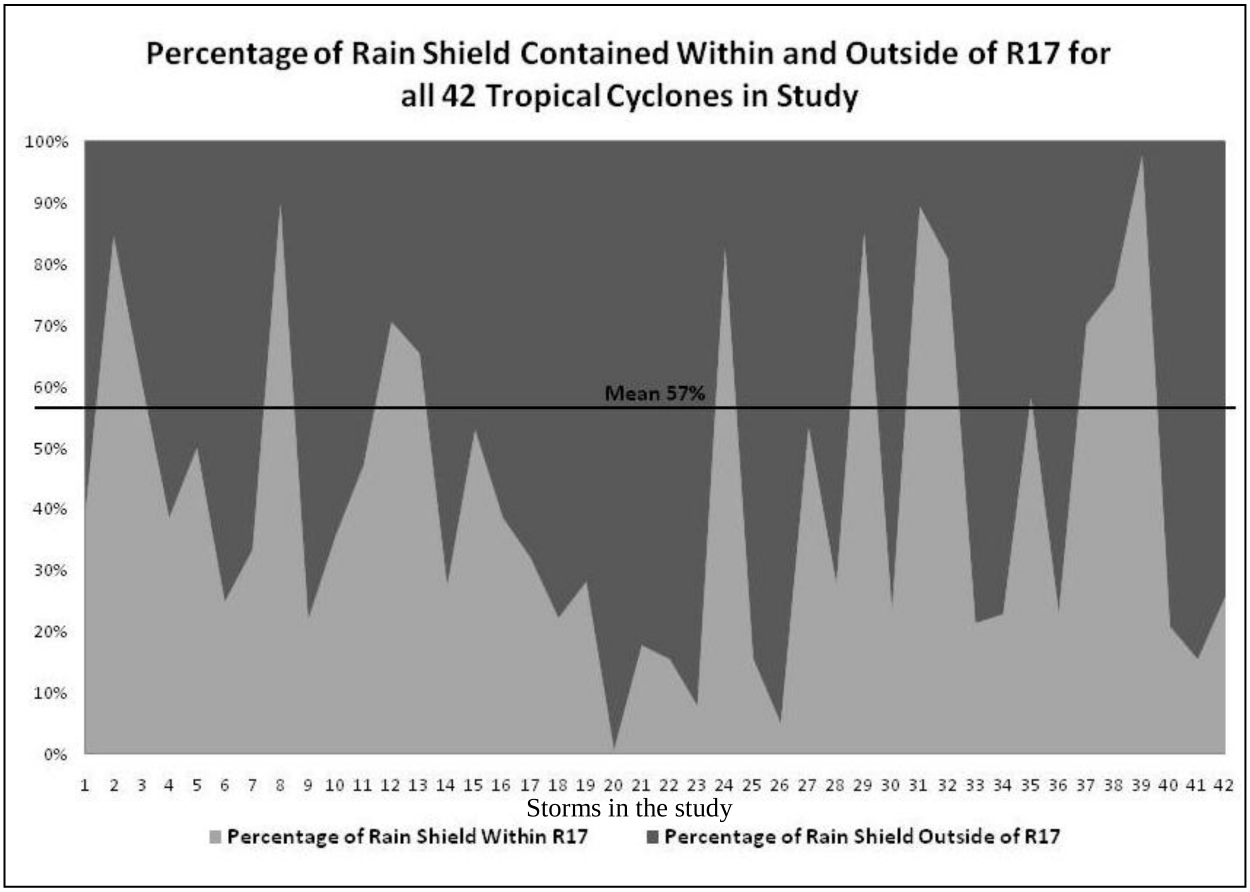

Figure 2-3. Percentage of Rain Shield within and Outside of R17 for All Storms Studied

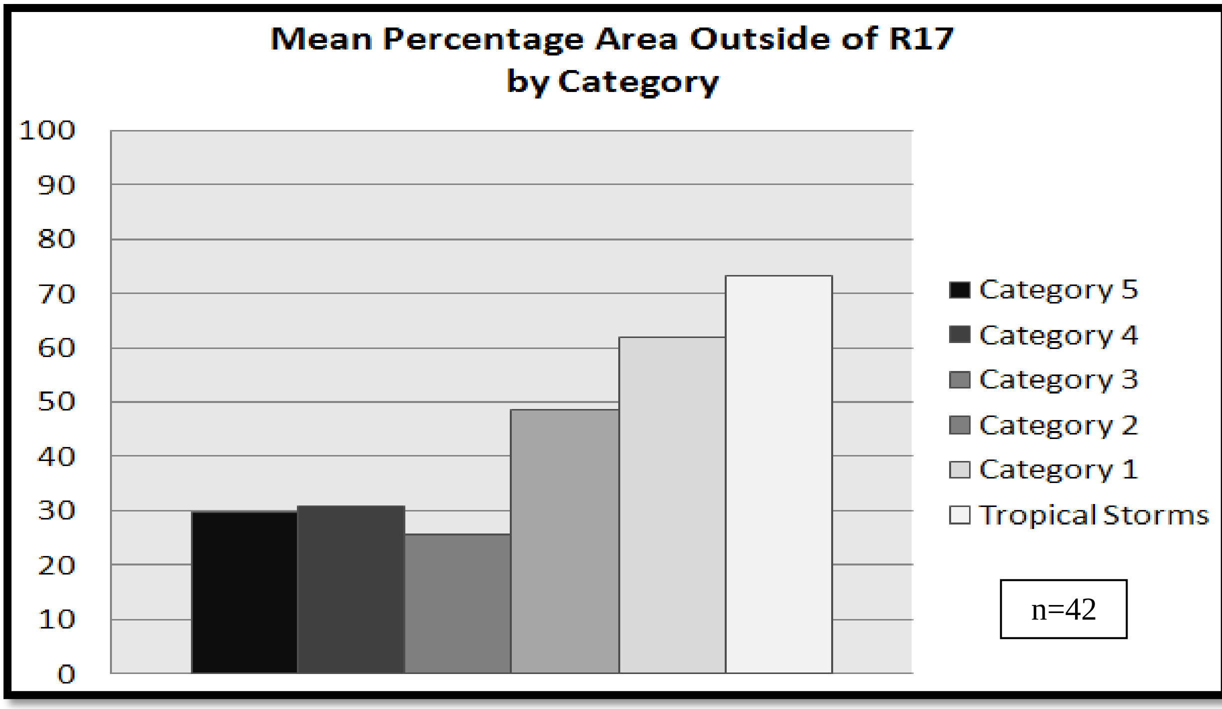

Figure 2-4. Mean Percentage of Rain Shield Occurring Outside of R17 by Category.

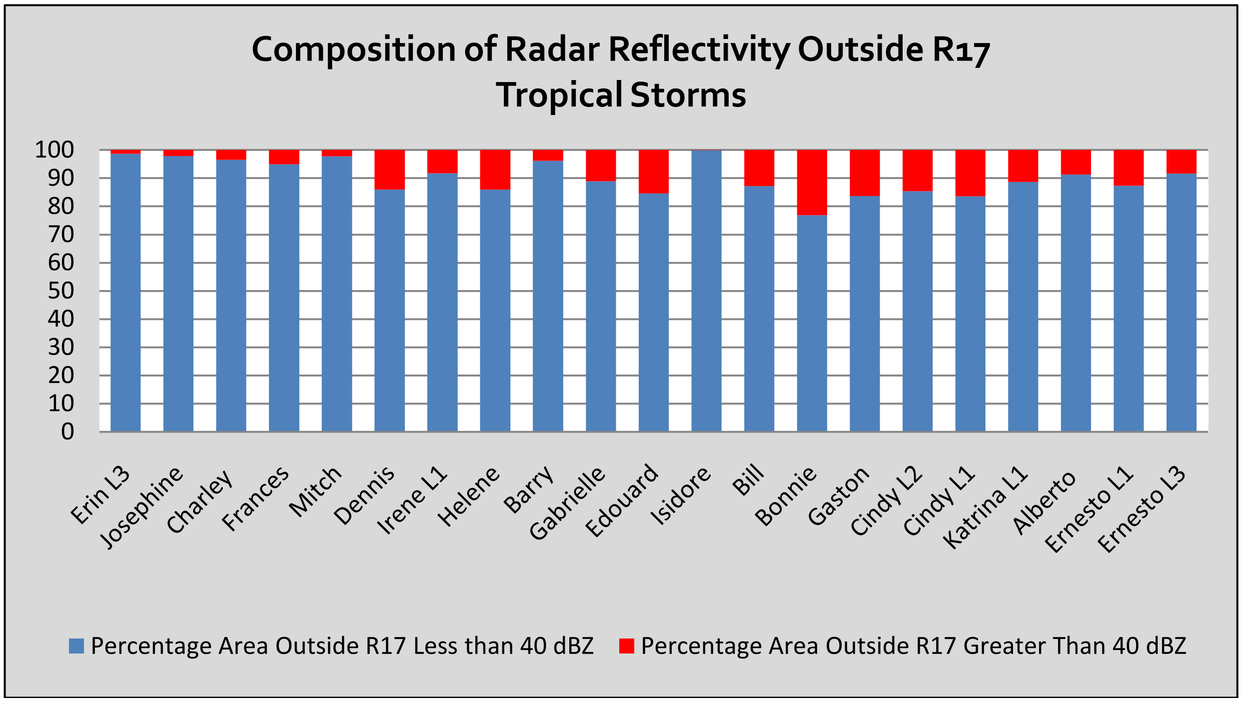

Figure 2-5. Composition of the Rain Shield Occurring Outside of R17: Tropical Storms

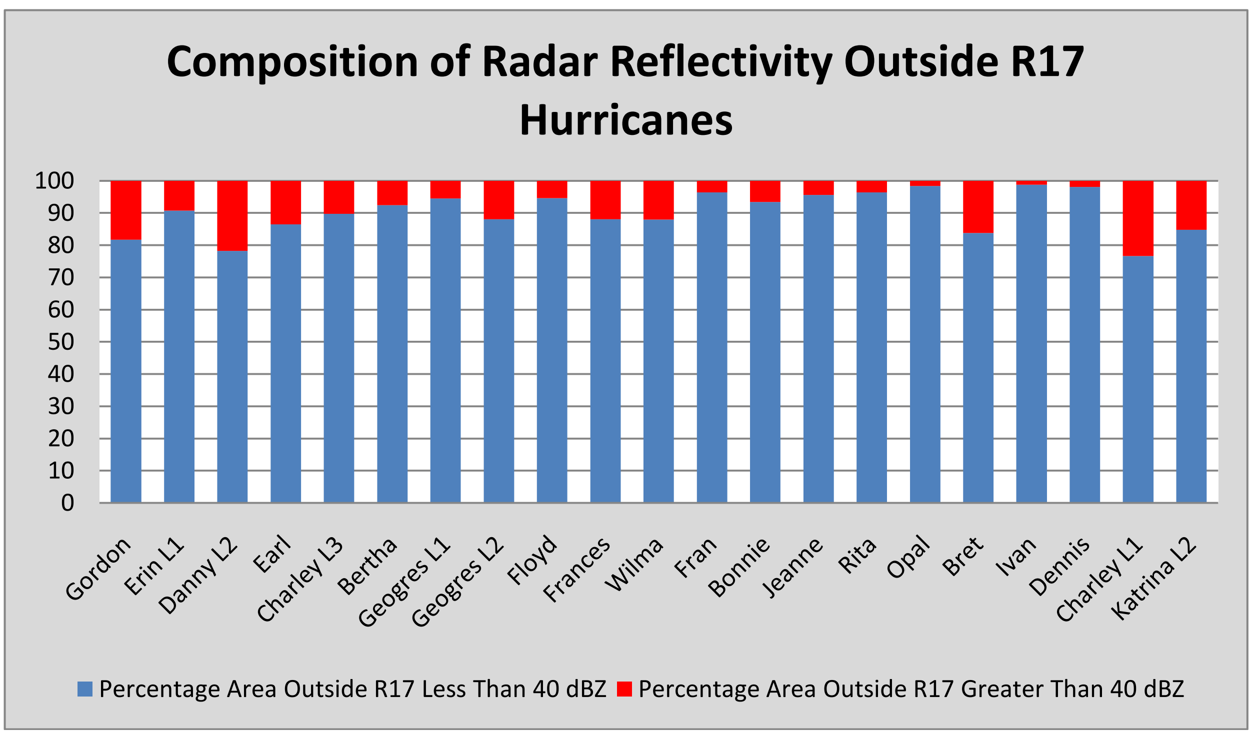

Figure 2-6. Composition of the Rain Shield Occurring Outside of R17: Tropical Cyclone Cat 1-5

CHAPTER 3
THE PLACE OF CLIMATOLOGY IN THE GEOGRAPHIC DISCIPLINE

Spatio-Temporal Principles in the Geographic Discipline

As a spatial discipline, geography seeks to understand patterns on the landscape and the processes which create them from both a human and environmental perspective (Holt-Jensen 1999). The spatial and temporal principles of geography make it unique from other disciplines and allow research to be conducted at various scales and extents (Matthews and Herbert 2004). This chapter focuses on the varying effects of scale on climate research and the impacts of my research on geography and atmospheric sciences. The intent of the first section is to define the role of spatial and temporal theories within climate research, particularly my own research. The intent of the second section of this chapter is to gage what was original about my research, and how such rainfall climatologies contribute to the academic community.

Scale is about size, whether it be relative or absolute. The spatial aspect of geography refers to the distribution and relationship of features across space. Individual geographers tend to emphasize differing aspects of the spatial continuum. For example, physical geographers study the distribution of climatic patterns, vegetation, soils, landforms, and a multitude of other environmental variables (Skaggs 2004). With a geographer's eye, spatial restrictions on research are alleviated and therefore research conducted within the geographic discipline can examine various environmental / human variables are multiple scales (Carleton 1999). This change in spatial scale is exemplified in contemporary climate change research, as regional climate models (RegCM) incorporate multiple environmental, oceanic, and atmospheric boundary layers to model how variously scaled atmospheric events will impact a region. Geography is a discipline of diversity, under whose spatial umbrella we study and analyze processes, systems, behaviors, and countless other phenomena that have a spatial expression. The spatial interests in patterns, distribution, and interactions unite geographers across all subfields.

Within the geographic subfield of climatology, research is conducted at various spatial scales. In my study, synoptic-scale TCs are analyzed to examine the patterns of their associated winds and precipitation. Examples of varying spatial scales in the subfield of climatology are abundant including: global-scale events like the trades winds, synoptic-scale events which include tropical cyclone and middle latitude cyclones, mesoscale events like the tornadoes and thunderstorms, and micro-scale events like microbursts or dust devils. The spatial scale of research for both meteorology and climatology range from the global scale to the micro scale (Thompson and Perry 1997; Barry and Carleton 2001; Carleton 1999). Climatologists approach extreme weather research by looking at the general patterns of multiple storms over multiple years, by studying storms of various size and over a long period of time general conclusions can be reached on the atmospheric physics and dynamics involved on the storms life cycle.

Space and time are inevitably connected. This relationship can be seen simply as a frame of reference within which mechanisms become processes that cause change in differing phenomena (Richards et al 2004). All geographic phenomena vary as a function of time. Consequently, one must consider the rate at which geographic phenomena change. Dependent on the geographic subfield, the temporal scale of research will vary. It is vital to examine and understand the temporal scale of research being undertaken by a geographer, because it can mean the difference between finding correlations between events or not.

Temporal resolution is particularly interesting within the context of aerial photography, satellite imagery, and other remotely sensed data. Most applications within geography do not require an extremely fine temporal resolution. In terms of temporal resolution, meteorologists and climatologists use some of the most fine-scale data available. Through the use of hourly or sub hourly radar or other remotely sensed images, climatologists and meteorologists can examine alterations to the life cycle and dynamics of events such as tropical cyclones or middle latitude cyclones.

Climatology and meteorology have long been associated with one another due to their common studies of atmospheric dynamics. The major difference in the two fields being that meteorology is very fine-scale temporally, and climatology deals with the spatial and temporal generalization of weather so that longer-term trends can be recognized. By examining variously scaled atmospheric events, climatologists can focus on the trends and driving forces associated with weather patterns. Whereas, meteorology focuses on the day-to-day, or event moment-to-moment changes in weather systems or patterns. As studies on the long-term trends of weather have been used to implement forecasting procedures, continued climate research helps fine tune such procedures. While weather extremes exist and can pose a challenge to forecasters (i.e. Hurricane Katrina), the general patterns of weather are better for predictive models as they are the conditions that occur on most days.

New Methodologies Being Employed by Geographical Climatologists

In 2006, the NCDC released software which transforms WSR-88D radar data into GIS shapefile format (Ansari and Del Greco 2005). Radar has assisted weather predictions for over forty years, but its use in research, particularly in the geographic discipline, is much more recent (Krajewski and Smith 2002; Xie et al 2005). Radar data, which are effective at depicting storm size and rainfall, allow for many new and different types of climate research to be conducted. NEXRAD radar products have been used to analyze the statistical characterization of extreme rainfall frequency, for validation of satellite remote sensing data, and to examine the dynamics of rainfall distribution (Krajewski and Smith 2002; Habib and Krajewski 2002; Xie et al. 2005).

The inability of traditionally used climate data, like rain gauges, to adequately depict the spatial distribution of rainfall volume is why climatologists and meteorologists have looked to radar as an alternative tool to obtain spatially accurate rainfall data. The spatial distribution of radar over a large area, in my study 460 km^2, provides continuous data across the radar's swath. Essentially, radar gives researchers a way to see between the rain gauges, and to interpret the type of rainfall (stratiform or convective) occurring in a region.

Since 2006, more atmospheric research is utilizing radar data within a GIS to model the rainfall patterns. What makes my research unique from other studies that used radar and GIS is the integration of NHC operational forecasting size variables. These forecasting procedures helped to define the extent of the wind field, therefore we can examine how the rain shield interacts with previous defined forecasting size variables. Previous studies examining storm size, including Kimball and Mulekar's (2004) study, utilized statistics and grid overlays to understand the relationship between storm size and storm development. In my study the GIS model was built to examine the relationship between the rain shield and wind field just as R17 winds started to make landfall. The research methods developed for this study allow for other size variables, including ROCI and R26, to be studied in a similar way; thus giving us a better understanding of the complex rain / wind relationship.

My research on the rain shield and wind field interaction showed that in weak TCs the vast majority of the rain shield fell outside of R17; whereas in stronger storms (category 3 or greater) the R17 boundary better contained the rain shield. Intense storms are well contained within R17 because the strong pressure gradient causes the tangential winds to increase in speed, therefore there is a tight wrapping of winds around the center of circulation and an axisymmetrical shape to the rain shield. These conclusions were reached by calculating the area of the whole rain shield within and outside of R17. Based on these calculations the current NHC operational wind forecasts are insufficient for forecasting the landfall of TC-related precipitation. But analysis of the composition of the rainfall occurring outside of R17 shows that watches and warnings are not necessarily insufficient for forecasting TC rainfall. The majority of intense rainfall produced by TCs, occurs within the radius of gale-force winds for all storm strengths. In other words, heavy rainfall that may lead to flooding will not occur before the onset of gale-force winds for most TCs. This means that NHC wind forecasts are sufficient for forecasting the arrival time of intense precipitation.

Hewitt (1997) argued that disasters are quintessentially geographic phenomena due to the scope and involvement of multiple environmental factors. Within the geographic discipline one of the largest areas of research involves natural hazards. This area of study looks to understand the climatological, hydrological, and geomorphological trends of naturally occurring extremes (Matthews and Herbert 2004). Research on natural hazards involves but is not limited to: monitoring hazards, developing management practices for both the short and long terms, and understanding how humans are agents of change (Alexander 2004). While extensive research has been done on natural hazards, particularly tropical cyclones, there is still much unknown about these events. This study contributes, in a small manner, to the geographic discipline due to its methodologies, technologies employed, and links to scale.

Within the scope of my research there were multiple datasets employed which are rarely used in the geographic discipline. As stated above, bringing radar images into a GIS is a relatively new process but one that is quickly growing in popularity. Other datasets such as the EBT, HURDAT, and SHIPS are traditionally used for statistical atmospheric research; but in this study these datasets are visualized and studied within a GIS which is a relatively new development to the geographic discipline. The use of the aforementioned datasets and radar reflectivity data were necessary for this study because we wanted to produce a rainfall climatology that aligns with the NHC operational forecasting guidelines. This study contributes to geography a new perspective on datasets, a better understanding of the spatial relationship between TC wind fields and rain shield, and new methodologies for modeling the spatial relationship of TC size variables.

Traditionally, climatological research has involved the use of grids and statistics to quantify the relationship among climate variables. As a result of being associated with geography, climate research methodologies are expanding and coming up-to-date with geographic technologies and spatial statistics. GIS, remote sensing, and other geographic technologies are relatively new to climatology but are potentially very powerful. One of the first publications of GIS application in climate research was provided by Shipley and Graffman (1999); they used GIS to model climate data collected by the Air Force (Shipley et al. 2000). The implications of GIS in climate research vary from new modeling techniques to new analysis methods that involve spatial statistics. Climate data can be displayed in a GIS in a variety of ways; lightning strikes as point vector data, radar reflectivity data as vector or raster layers, and isolines layers of pressure or temperature are common examples. Direct meteorological observations or indirect observations provide different thematic layers of information that can be useful parameters for describing the varying state of the atmosphere. GIS and spatial statistics allow us to build models and calculate the neighborhood statistics, variance, and density on datasets in a manor rarely done before.

There is so much not yet known about tropical cyclones that geographic technologies could shine new light on. This baseline study exemplifies the use of GIS and radar to analyze atmospheric hazards. From this project, multiple new research questions were developed, all of which include radar data and GIS methodologies. Many feel that the integration of radar into a GIS would greatly impact the NHC and NWS forecasting policies (Shipley et al. 2000; Schultz and Reeves 1999), which could lead to more precise forecasting procedures and more time for residents to prepare for severe weather. The use of datasets such as the Hurricane Database (HURDAT; Jarvinen et al 1984), Extended Best Track (EBT; DeMaria et al. 2005), and the Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al 1999) are crucial to climatological studies because they contain an abundance of data on TC size, atmospheric conditions, and environmental variables. By applying these datasets in a geographic framework, new models can be created, comparison of storm variables can be done with more accuracy, and spatial statistics can be applied to the datasets. Future research will examine the radius of the outermost closed isobar (ROCI), the radius of damaging-force winds (R26), and the radius of hurricane-force winds (R33) and their spatial variation / relationship with the rain shield. To take this study one step further, a comparison of the rain shield composition will be done to study the convective and stratiform precipitation pattern within and outside of R17. It is anticipated that this study will lay the framework for a larger research project which will produce a rainfall climatology that examines all the size variables utilized by the NHC when forecasting for synoptic-scale events such as tropical cyclones.

LIST OF REFERENCES

Aberson, S. D. 2001: The Ensemble of Tropical Cyclone Track Forecasting Models in the North Atlantic Basin (1976-2000) *Bull. American Meteorological Society*, **82,** 1895-1904.

Alexander, D. E. 2004: Natural Hazards on an Unquiet Earth. *Unifying Geography: Common Heritage, Shared Future*, by J. A. Matthews and D. T. Herbert, 266-282. New York: Routledge, Taylor, and Francis Group

Ansari, S., and S. Del Greco. 2005: GIS Tools for Visualization and Analysis of NEXRAD Radar (WSR-88D) Archived Data at the National Climatic Data Center. *21st International Conference on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology.*

Atallah, E. H., and L. F. Bosart. 2003: The Extratropical Transition and Precipitation Distribution of Hurricane Floyd (1999). *Monthly Weather Review*, **131**, 1063-1081.

Barry, R. G., and A. M. Carleton. 2001: *Synoptic and Dynamic Climatology.* New York: Routledge.

Burpee, R. W., and M. L. Black. 1989: Temporal and Spatial Variations of Rainfall Near the Centers of Two Tropical Cyclones. *Monthly Weather Review*, **117**, 2204-2218.

Carleton, A. M. 1999: Methodology in Climatology . *Annals of the Association of American Geographers*, **89**, 713-735.

Corbosiero, K. L., and J. Molinari. 2002: The Relationship between Storm Motion, Vertical Wind Shear, and Convective Asymmetries in Tropical Cyclones. *Journal of the Atmospheric Sciences*, **60**, 366-376.

Demaria, K. L., and J. Kaplan. 1999: An Updated Statistical Hurricane Intensity Predication Scheme (SHIPS) for the Atlantic and Eastern North Pacific Basins. *Weather and Forecasting*, **14**, 326-337.

DeMaria, M, M. Mainelli, L. K. Shay, J. A. Knaff, and J. Kaplan. 2005: Further Improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Weather and Forecasting*, **20**, 531-543.

Dvorak, V. F. 1975: Tropical Cyclone Intensity Analysis and Forecasting from Satellite Imagery. *Monthly Weather Review*, **103**, 420-430.

Elsberry, R. L. 2002: Predicting Hurricane Landfall Precipitation: Optimistic and Pessimistic Views from the Symposium on Precipitation Extremes. *Bulletin of the American Meteorlogical Society*, **83**, 1333-1340.

Elsner, J. B., and A. B. Kara. 1999: *Hurricanes of the North Atlatic: Climate and Society.* US: Oxford University Press.

Frank, W. M. 1977: The Structure and Energetics of the Tropical Cyclone I. Storm Structure. *Monthly Weather Review*, **105,** 1119-1135.

Habib, E., and W. F. Krajewski. 2002: Uncertainty Analysis of the TRMM Ground-Validation Radar-Rainfall Products: Applications to the TEFLUN-B Field Campaign. *Journal of Applied Meteorlogy*, **41**, 558-572.

Hewitt, K. 1997: *Regions at Risk: A Geographical Introduction to Disasters.* Longman: Harlow.

Holt-Jensen, A., and B. Fullertor. 1999: *Geography, History and Concepts: A Student's Guide.* New York: SAGE.

Jorgensen, D. P. 1984: Mesoscale and Convective-Scale Characteristics of Mature Hurricanes. Part I: General Observations by Resarch Aircraft. *Journal of Atmospheric Science*, **41**, 1268-1285.

Jorgensen, D.P., P.T. Willis. 1982: A Z-R Relationship for Hurricanes *Journal of Applied Meteorology*, **21**, 356-366.

Kidder, S. Q., S.J. Kusselson, J.A. Knaffm R.R. Ferraro, R.J. Kuligowski, M. Turk. 2005: The Tropical Rainfall Potential (TraP) Technique. Part I: Description and Examples. *Weather and Forecasting*, **20**, 456-464.

Kimball, S. K., and M. S. Mulekar. 2004: A 15-Year Climatology of North Atlantic Tropical Cyclones. Part I: Size Parameters. *Journal of Climate*, **17**, 3555-3575.

Klazura, G. E., and D. A. Imy. 1993: A Description of the Initial Set of Analysis Products Available from the NEXRAD WSR-88D System. *Bulletin of the American Meteorological Society*, **74**, 1293-1311.

Knight, D., and R. Davis. 2007: Climatology of Tropical Cyclone Rainfall in the Southeastern United States. *Phyisical Geography.* **55**, 126-147.

Krajewski, W. F., and J. A. Smith. 2002: Radar Hydrology: Rainfall Estimation. *Advances in Water Resources*, **25**, 1387-1394.

Lawrence, M. B. 1979: Atlantic Hurricane Season of 1978. *Monthly Weather Review*, **107**, 477-491.

Lawrence, M. B., L. A. Avila, J. L. Beven, J. L. Franklin, J. L. Guiney, and R. J. Pasch. 2001: Atlantic Hurricane Season of 1999. *Monthly Weather Review*, **129**, 3057-3084.

Marks, F. D., G. Kappler, and M. DeMaria. 2002: Development of a Tropical Cyclone Rainfall Climatology and Persistence (R-CLIPER) Model. *25th Conference on Hurricanes and Tropical Meteorology.* San Diego, CA: American Meteorological Society, 327-328.

Marshall, J. S., and W. M.K. Palmer. 1948: The Distribution of Raindrops with Size. *Journal of the Atmospheric Sciences*, **101**, 165-166.

Marshall, J. S., R. C. Langille, and W. M.K. Palmer. 1947: Measurement of Rainfall by Radar. *Journal of the Atmospheric Sciences*, **122**, 186-192.

Matthews, J. A., and D. T Herbert. 2004: *Unifying Geography: Common Heritage, Shared Future.* New York: Routledge, Taylor and Francis Group.

Matyas, C. J. 2009: A Spatial Analysis of Radar Reflectivity Regions within Hurricane Charley (2004). *Journal of Applied Meteorology and Climatology*, **48**, 130-142.

Matyas, C. J. 2007: Quantifying the Shapes of U.S. Landfalling Tropical Cyclone Rain Shields. *The Professional Geographer*, **59**, 158-172.

Matyas, C. J. 2008: Shape Measure of Rain Shields as Indictors of Changing Environmental Conditions in a Landfalling Tropical Storm. *Meteorological Applications*, **59**, 259-271.

Merrill, R. T. 1984: A Comparison of Large and Small Tropical Cyclones. *Monthly Weather Review*, **112**, 1408-1418.

Moyer, A. C., J. L. Evans, and M. Powell. 2006: Comparison of Observed Gale Radius Statistics. *Meteorology and Atmospheric Physics*, **97**, 41-55.

Neumann, C. J., B. R. Jarvinen, C. J. McAdie, and G. R. Hammer. 1999: Tropical Cyclones of the North Atlantic Ocean, 1871-1998. *National Oceanic and Atmospheric Administration*, **293**, 206.

Pasch, R. J., E. S. Blake, H. D. Cobb, and D. P. Roberts. 2005: Hurricane Wilma (October 15-26, 2005). Tropical Cyclone Report, Washington D.C. National Oceanic and Atmospheric Association (NOAA), U.S. Department of Commerce.

Pennington, J., M. DeMaria, and K. Williams. 2000: Development of a 10-year Atlantic Basin Tropical Cyclone Wind Structure Climatology. *Dataset available at: http://www.bios.edu/rpi/private/pubs/2000pre/demaria/demaria.html*.

Rao, G. V., and P. D. MacArthur. 1994: The SSM / I Estimated Rainfall Amounts of Tropical Cyclones and Their Potential in Predicting the Cyclone Intensity Changes. *Monthly Weather Review*, **112**, 1568-1574.

Rappaport, E. N. 2000: Loss of Life in the United States Associated with Recent Atlantic Tropical Cyclones. *Bulletin of the American Meteorlogical Society*, **81**, 2065-2073.

Richards, K., M. Bithell, and M. Bravo. 2004: Space, Time, and Science. In *Unifying Geography: Common Hertiage, Shared Future*, by J. A. Matthews and D. T. Herbert, 327-352. New York: Routledge, Taylor, and Francis Group.

Rodgers, E. B., and R. F. Adler. 1981: Tropical Cyclone Rainfall Characteristics as Determined from Satellite Passive Microwave Radiometer. *Monthly Weather Review*, **109**, 506-521.

Rodgers, E. B., S. W. Chang, and H. F. Pierce. 1994: A Satellite Observational and Numerical Study of Precipitation Characteristics in Western North Atlantic Tropical Cyclones. *Journal of Applied Meteorlogy*, **33**, 129-139.

Rosenfield, D., D. B. Wolff, and D. Atlas. 1993: General Probability-Matched Relations between Radar Reflectivity and Rain Rate. *Journal of Applied Meteorology*, **32**, 50-72.

Roth, D. Tropical Cyclone Rainfall. 2008: *NOAA Hydrometeorological Prediction Center.* Camp Springs, MD.

Schultz, J. R., and R. W. Reeves. 1999: GIS @ NWS Forum for the Discussion of Applications and Requirements for Geographic Information Systems (GIS) at the National Weather Service. Silver Springs, MD: 30 Jun- 1 Jul.

Senn, H. V., and H. W. Hiser. 1959: On the Origin of Hurricane Spiral Rain Bands. *Journal of Atmospheric Sciences*, **16**, 419-426.

Sheets, R. C. 1990: The National Hurricane Center -- Past, Present, and Future. *Weather and Forecasting*, **5**, 185-232.

Shipley, S. T., I. A. Graffman, and J. K. Ingram. 2000: GIS Applications in Climate and Meteorology. *ESRI User Conference.* Paper 159.

Simpson, R. H., H.S. Saffir. 1974: The Hurricane Disaster Potential Scale. *Weatherwise*, **27**, 169-186.

Skaggs, R. H. 2004: Climatology in American Geography. *Annals of the Association of American Geographers*, **94**, 446-457.

Thompson, R. D., and A. Perry. 1997: *Applied Climatology.* New York: Routledge.

Thorpe, A. J. 1985: Diagnosis of Balances Vortex Structure Using Potential Vorticity. *Journal of Atmospheric Sciences*, **42**, 397-406.

Thorpe, A. J. 1986: Synoptic Scale Disturbances with Circular Symmetry. *Monthly Weather Review*, **114**, 1384-1389.

Willoughby, H.E. 1988: The Dynamics of the Tropical Cyclone Core. *Aust. Meteorological Magazine*, **36**, 183-191.

Willoughby, H. E., F. D. Marks, and R. J. Feinberg. 1984: Stationary and Moving Convective Bands in Hurricanes. *Journal of the Atmospheric Sciences*, **41**, 3189-3211.

Xie, H., X. Zhou, E. R. Vivoni, J. M.H. Hendricks, and E. E. Small. 2005: GIS-Based NEXRAD Stage III Precipitation Database: Automated Approaches for Data Processing and Vizualization. *Computers and Geosciences*, **31**, 65-76.

BIOGRAPHICAL SKETCH

Erin Leigh Bunting is originally from Gainesville, Florida. After completing a Bachelor of Science from the University of Florida in the Spring of 2006, she applied to the graduate program in the Department of Geography. After several years and assistance from committee members: Corene Matyas, Jane Southworth, and Peter Waylen her Master's thesis was completed. With a Master of Science in geography, Erin applied to the doctoral program at UF. At the doctoral level, she plans to examine land use patterns and the effect of climate change across parts of Florida and Mexico.

THE RELATIONSHIP BETWEEN THE RADIUS OF GALE-FORCE WINDS AND THE RAIN SHIELD OF U.S. LANDFALLING TROPICAL CYCLONES.

Erin Leigh Bunting
352-3920494
Geography Department
Dr. Corene Matyas
Masters of Science
May 2009

Tropical Cyclones are naturally occurring weather phenomena that affect the entire state of Florida. This study focuses on the relationship between the wind fields and rain fields of landfalling tropical cyclones. With a high percentage of tropical cyclone deaths related to inland and coastal flooding it is vital to understand their relationship in conjunction with the wind fields. This is a preliminary study that will hopefully lead to a rainfall climatology that can be utilized in conjunction with the National Hurricane Center's operational Tropical Cyclone forecasts.