The Spatial Distribution of Meteorological Impacts Associated with Inland-Moving Tropical Cyclones

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ABSTRACT

Margaret Mae Kovach: The Spatial Distribution of Meteorological Impacts Associated with
Inland-Moving Tropical Cyclones
(Under the direction of Charles E. Konrad II)

The southeastern United States is routinely hit by tropical cyclones. As tropical

cyclones track inland and dissipate, their inland impacts can be substantial. Typically, these

impacts occur due to any combination of the tropical cyclones heavy precipitation, high

winds, or tornadoes. This study will examine the meteorological impacts of 31 inland-

moving tropical cyclones from 1985 to 2008. The spatial distribution of meteorological

impacts is plotted relative to the track (e.g. left vs. right quadrant) and location (forward vs.

rear quadrant) of the cyclone center. Various tropical cyclone attributes, including size,

strength, and speed of movement are related to the occurrence of different impacts and their

location relative to the cyclone track. Results indicate a distinct variation in the spatial

patterns of tornado, high wind and flash flood impacts, particularly when comparing tropical

cyclones of different sizes.

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LIST OF ABBREVIATIONS

TC…………………………………………………………………Tropical Cyclone

TCs………………………………………………………...…………………..Tropical Cyclones

TFCS…………………………………………………..…Track Following Coordinate System

Chapter 1:

Introduction

A tropical cyclone (TC) is an organized low pressure system of convective thunderstorms that originates over tropical water. Most TCs that make landfall in the southeastern U.S. begin as easterly waves, which migrate westward off the Cape Verde islands of Africa. However, a few TCs may form in the subtropics from a stationary front or an upper level low.   For cyclongenesis to occur, TCs require not only an area of low level convergence (i.e. easterly wave, stationary front, upper level low), but high sea surface temperatures. High levels of evaporation provide much latent energy in the form of moist air that rises and condenses adding sensible energy and buoyancy to the updrafts.   TC formation also requires some Coriolis forcing and minimal broad scale wind shear. TC intensity is assessed using the wind-based Saffir Simpson Scale (Table 1.1).

Table 1.1: Classifications of Saffir Simpson Scale(http://www.nhc.noaa.gov/sshws.shtml)

Categories	Sustained Winds	Potential Damage
Tropical Depression	0-38 mph	--
Tropical Storm	39-73 mph	--
Category One Hurricane	74-95 mph	Very dangerous winds will produce some damage
Category Two Hurricane	96-110 mph	Extremely dangerous winds will cause extensive damage
Category Three Hurricane	111-130 mph	Devastating damage will occur
Category Four Hurricane	131-155 mph	Catastrophic damage will occur
Category Five Hurricane	Greater than 155 mph	Catastrophic damage will occur

The vast majority of TCs form during hurricane season, which runs from June 1st to November 30th.   The TC season is most active from August through October (Figure 1.1). During this time, 96% of category 3, 4, and 5 hurricane days occur, along with 87% of Category 1 and 2 and 78% of tropical storm days. Overall, the climatological peak of the TC season occurs on September 10th (Landsea 1993).
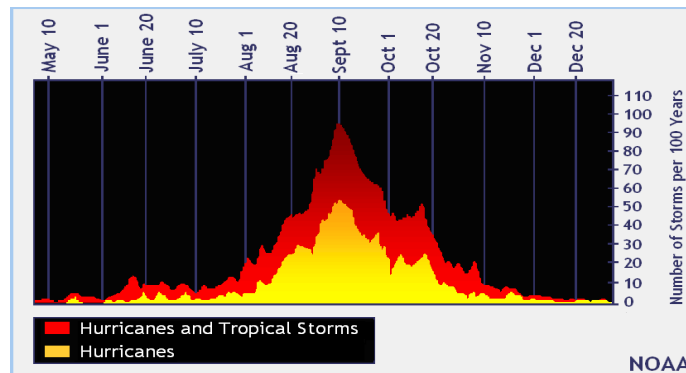
Figure 1.1: Atlantic Basin TC Frequency (http://hurricanes.noaa.gov/prepare/season.htm)

Within the southeastern US, there are three highly active geographic areas of TC activity the Northern Gulf Coast, the South Florida coast, and the North Carolina Outer Banks (Figure 1.2).   The return intervals in these areas are as low as every 2 years along the Outer Banks of North Carolina and every 3 years along the Northern Gulf Coast and the Southern Florida coasts (Keim *et al*. 2007).   The majority of cyclone research has focused on the coastline region despite the fact that the vast majority of the US population who experience these TCs reside in inland areas (Senkbeil and Sheridan 2006). Due to hurricane education, mandatory evacuation, and stricter building codes, most deaths from TCs have shifted from coastal communities to inland communities. In 1972 the American Meteorological Society found that 90% of hurricane-related deaths were due to storm surge along the coastline (AMS 1973, Rappaport 2000). In a more recent study, 63 % of deaths

from 1970 to 1999 occurred within inland counties (Rappaport 2000). Czajkowski and

Kennedy (2010) also found that 80% of hurricane deaths between 2000 and 2007 occurred

within inland counties (excluding any deaths associated with Hurricane Katrina 2005). This

shift indicates the need for a climatology of inland-moving TCs. The following study will

address this need by exploring how the strength, size, and speed of movement of TCs

influence the character and spatial pattern of meteorological and societal impacts.
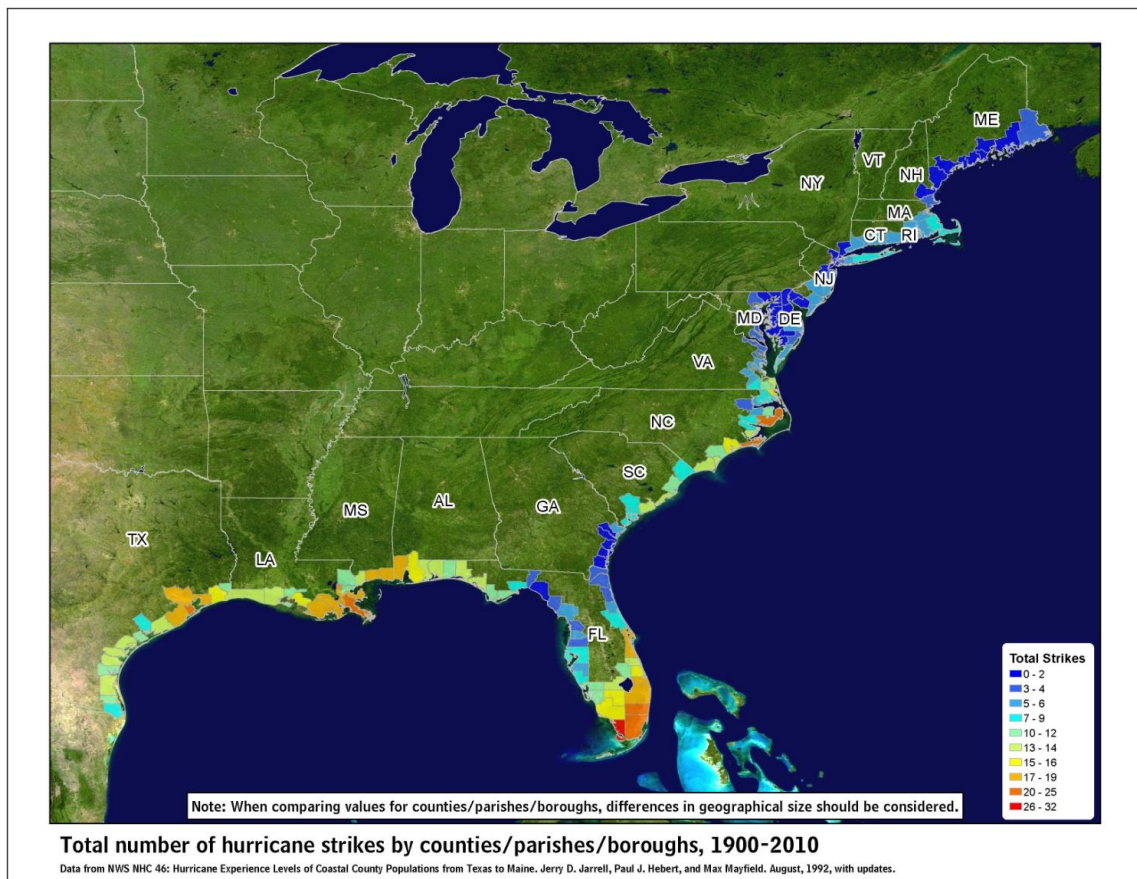
Figure 1.2: Total number of hurricane strike, 1900 through 2009 (
http://www.nhc.noaa.gov/gifs/strikes_us.jpg)

1.2 Tropical Cyclone (TC) Tornadoes

One of the major threats of inland TCs is tornadoes. Tornadoes cause significant

infrastructure damage and 5% of all TC-related deaths (Rappaport 2000). These tornadoes

are found mainly in the right-forward quadrant (e.g. northeast quadrant in a northward

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moving cyclone) relative to a TCs motion (Smith 1965, Gentry 1983, McCaul 1991 Schultz and Cecil 2009).   Of the most recent climatologies, Schultz and Cecil (2009) showed that 80% (1,440 out of 1800) of TC tornadoes occur in the right-forward quadrant (Figure 1.3). Similarly, Novlan and Gray (1974) found that the centroid of 373 hurricane tornadoes from 1948-1972 was located in the right-forward quadrant, while McCaul (1991) and Gentry (1983) found similar maximums in the right-forward quadrant for hurricane tornadoes that occurred from 1948-1986 and 1970-1983, respectively.   Tornadogenesis is much more prevalent in the right-forward versus left-forward quadrant because wind shear and instability is typically greater there (McCaul 1991, Bogner *et al.* 2000).
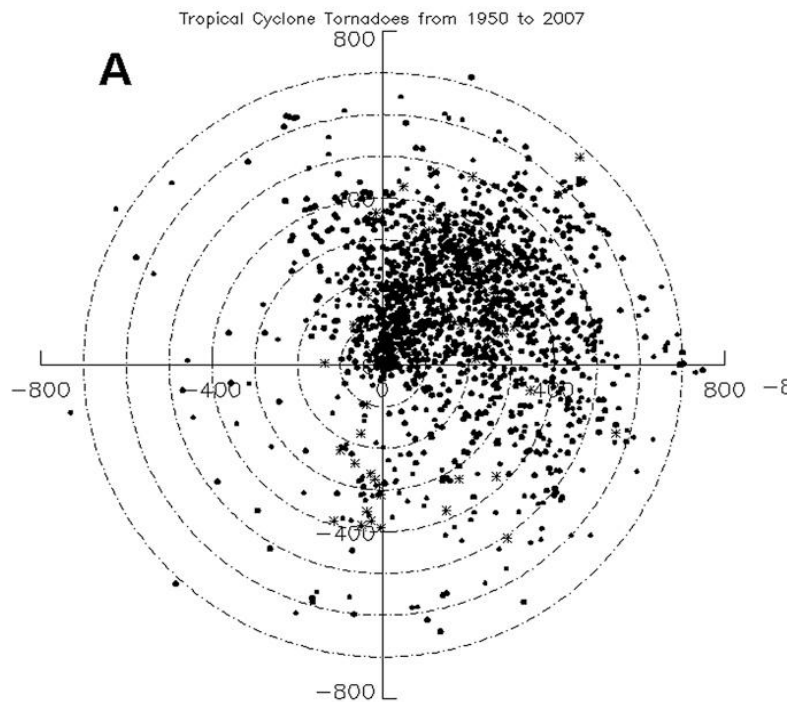
Figure 1.3: Tornado Locations Relative to TC motion (Schultz and Cecil 2009).

TC tornadoes also display preferred locations with respect to the distance from the center of the TC. There are typically two distinct peaks occurring in the right-forward quadrant, one near the core of the storm and another in the outer spiral bands (Gentry 1983, McCaul 1991, Schultz and Cecil 2009).   However, the distances within the right-forward

quadrant vary across different studies.   In a comprehensive climatology, Schultz and Cecil (2009) found a bimodal distribution, with a large maximum between 250 km and 500 km from the TC center, and a smaller secondary maximum (less than a quarter of overall TC counts) within 200 km.

In the outer radii or outer spiral bands (approximately 250 km and 500 km), a lack of cloud cover coupled with vertical wind shear allows enough instability for tornado formation. Schultz and Cecil (2009) found that the outer radii region experiences the greatest proportion of stronger tornadoes (F1 or higher), peaking for 12-24 and 12-36 hours after landfall for F1 and F2 tornadoes, respectively.   Near the cyclone center, cloud cover often inhibits solar insolation and therefore cuts off the instability needed for tornadogenesis.   Tornadoes that occur within the inner core of a TC are less numerous and typically occur close to landfall within strong, well-organized TCs (McCaul 1991, Schultz and Cecil 2009).

In storms with a significant number of tornadoes (20 or more), tornado genesis occurs when the right-forward quadrant displays a pronounced gradient of relative humidity in the middle troposphere (700-500 hPa), with much drier air on the periphery of the cyclone (Curtis 2004).   Other case studies support this tornadogenesis trigger, including the National Weather Service's (NWS) case study of Tropical Storm Beryl. This system produced 37 tornadoes as dry air was entrained in a deep layer above the surface, resulting in steeper lapse rates and enhanced instability (Vescio *et al.* 1996).   These mid-level dry intrusions allow mid-level evaporative cooling in antecedent convective clouds, which increases the environmental lapse rate. Dry air intrusions can also increase instability through solar heating, that is, a lack of cloud cover increases surface based destabilization (Schneider and Sharp 2006).

Numerous studies (e.g. Novalan and Gray 1974, Gentry 1983, Schultz and Cecil 2009) indicate that the majority of tornadoes occur close to the coastline. Schultz and Cecil (2009) demonstrated that 94% of TC tornadoes occurred within 400 km of the coast and 44% within 50 km of the coast. Gentry (1983) hypothesized that TC landfalls are accompanied by a strong increase in surface friction thus slowing the surface winds. In contrast, winds in the middle to upper troposphere remain strong, which results in strong low-level vertical shear. Most tornadoes near the cyclone's center occur within 100 km of the coast due to the greater shear magnitudes at landfall. They decrease in frequency further inland as core TC winds are more similar in speed to those observed in the outer regions of the TC (Schultz and Cecil 2009).   However, there are notable exceptions, including Ivan in 2004, which spurred over 119 tornadoes, many in far inland locations from Florida through Maryland.   McCaul (1991) is one of the few who explained tornado formation away from the coastline. He hypothesized that some hurricanes can maintain a strong circulation aloft several days after landfall, despite decreases in wind speeds within the bottom 1 km of the atmosphere.

When comparing characteristics of individual TCs and their ability to form tornadoes, hurricanes with large sizes and higher intensity typically are the most prolific tornado producers (McCaul 1991).   Low intensity TCs that produce outbreaks have a larger radius then similar non-tornado forming TCs (McCaul 1991). Smith (1965) found that the frequency of tornadoes is inversely proportional to the speed of the hurricane at sea and directly proportional to the speed of the hurricane over land. Fast-moving hurricanes experience an enhancement of wind shear aloft, due to their entrainment into the westerlies (McCaul 1991). At sea TCs are often in a tropical environment with little influence from the

westerlies. Conversely, Novlan and Gray (1974), found no relationship between a TC's speed of movement and number of tornadoes.

1.3 High Wind

The strong winds associated with TCs often weaken rapidly upon landfall due to both friction from the land and the loss of the latent heat energy beneath the storm. This reduction in temperature is due to the loss of sensible and latent heat fluxes from the ocean (Kaplan and De Maria 1995). Sustained winds decrease significantly as TCs migrate inland; however, maximum gust speeds can remain above hurricane force several hundred kilometers inland (Powell *et al.* 1991). The gusts are stronger because turbulence increases and brings faster winds down to the surface in short bursts. In fact, strong, fast-moving cyclones, such as Hurricane Hugo, have produced 98 mile per hour (mph) wind gusts over 100 miles inland from landfall and 87 mph wind gusts almost 200 miles inland from landfall. TCs with a fast speed of motion or high intensity at landfall tend to produce the strongest wind gusts well inland (Kaplan and DeMaria 1995).

In general, the strongest winds are located in the right quadrant of an inland-moving storm. Winds are maximized in this quadrant because the motion of the cyclone contributes to the counterclockwise circulation (Figure 1. 4).
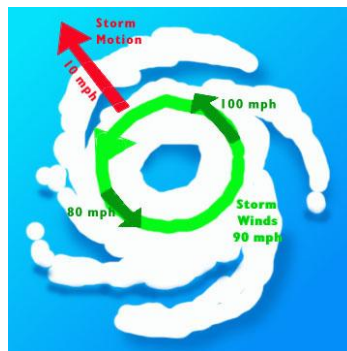
Figure 1.4: Winds in the right quadrant are strongest influenced by the storm's motion (red) and the counter-clockwise circulation (green)
(http://www.aoml.noaa.gov/hrd/tcfaq/D6.html)

Kruk *et al* (2010) found that most states located in the southeastern and northeastern US have experienced high wind events associated with TCs (Figure 1.5). The most favored for tropical storm force winds (i.e. approximately 30 mile per hour) are the Gulf of Mexico states and the Carolinas northeastward through Virginia and into New England. In these locations, return intervals for tropical storm winds are every 2 to 5 years (Figure 1.5A). Hurricane force winds have longer return intervals in the southeastern US, ranging from 6 to 108 years (Figure 1.5B).

To construct these frequency maps, Kruk *et al.* (2010) utilized NHC historical track data in conjunction with reports of the extent of the maximum sustained wind thresholds for different intensities of TCs. The results were overlaid on a grid to determine return intervals throughout the eastern US. While these results demonstrated the occurrence of tropical cyclone winds well inland from the coastline, they fail to incorporate actual wind observations and the uniqueness of each TC's wind field. Further investigation is needed to understand how inland TC winds interact with an area's topography, large scale synoptic environment, and the influence of daytime convection.
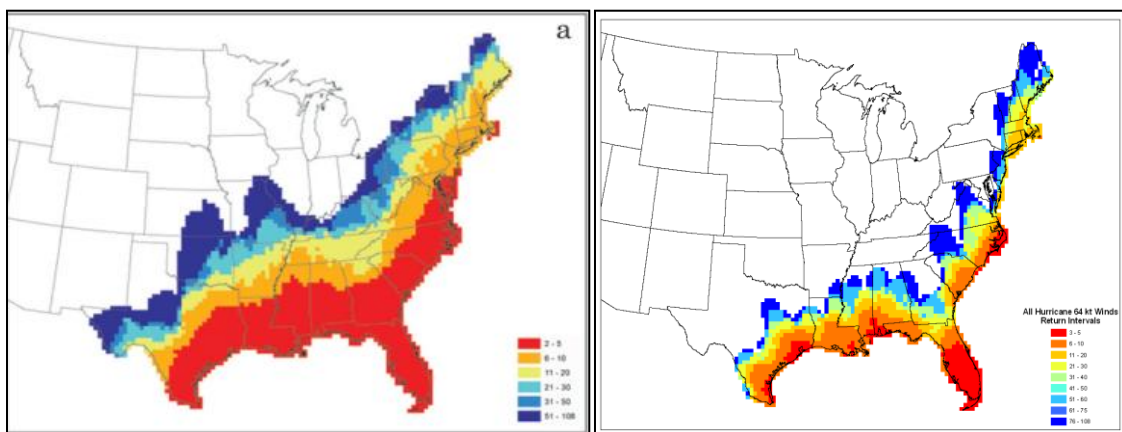
Figure 1.5: (A) (Kruk 2010) Return Intervals for Tropical Storm force winds (B) Return intervals for Hurricane force winds

1.4 Flash Flood

Heavy rain-induced flash flooding is a significant threat of TCs; it accounts for an astonishing 300 deaths from 1970 to 1999, which is over 50% of all TC-related deaths (Rappaport 2000). The spatial distribution of heavy precipitation depends, among other things, on the TC's strength, speed of movement, and presence of vertical wind shear. Larger systems tend to have a larger spatial extent of heavy precipitation, which often causes precipitation to occur a farther distance from the center (Matyas 2007). Konrad *et al.* (2002) also found that TC size is correlated with heaviest precipitation over a broad scale, with 80% of the heaviest large scale (i.e. 300,000 km^2) precipitation events occurring with TCs whose size is in the 61st percentile (in a sample of 101 TCs from 1950 to 1993). However, this relationship was difficult to distinguish from the influences of frontal interactions, which are also present in 70% of large-scale heavy precipitation events (Konrad *et al.* 2002). Similar results were found in Konrad and Perry (2010) with TC size displaying a positive relationship with precipitation totals in the Carolina region. Konrad *et al.* (2002) also found a significant positive correlation between large scale precipitation and TC intensity.

The speed of movement of a TC shows a relationship with the precipitation totals over the smallest spatial scales as slow-moving cyclones produce the heaviest precipitation totals (Konrad *et al.* 2002). Furthermore, as cyclones track away from the coastline, precipitation patterns become more elongated and not necessarily symmetrically-distributed around the TC, which is often the case for precipitation near the coastline (Matyas 2007). Similarly, when TCs move farther inland and weaken, reduction in available moisture may cause rainfall to occur on the right side of the cyclone track (Matyas 2007).

Asymmetric patterns of precipitation around the TC often occur due to the presence of strong vertical wind shear. TCs typically encounter increasing wind shear as they move into the mid-latitudes. In this environment, nearly half (46%) of TCs from the Atlantic basin undergo extratropical transition (Harts and Evans 2001). The transition of the TC to extratropical often occurs in conjunction with the strengthening of a middle tropospheric trough-ridge couplet, an increasing jet streak, and the formation of a downstream front (Atallah and Bosart 1999). In this scenario, precipitation rates and totals can increase dramatically in the left-forward quadrant of the TC as tropical moisture is advected across a stationary front and directed upwards into the right rear quadrant of a developing jet streak.

As noted in the aforementioned studies, a large amount of research has addressed the causes of these TC meteorological impacts (e.g. tornadoes, high winds, and flash floods); however, few studies have identified where these impacts occur in inland environments. In this study, the spatial distribution of the meteorological effects and resultant societal impacts from tornadoes, high winds and flash flooding are examined. This task will be accomplished by plotting the meteorological impacts relative to the TC track (e.g. left vs. right quadrant) and location (e.g. forward vs. rear quadrant) of the cyclone center. Various tropical cyclones attributes, including size, strength, and speed of movement, will be related to the occurrence of different impacts and their location relative to the cyclone track.

Chapter 2:

Data and Methods

2.1 Study Area

The study area is comprised of nine states within the southeastern United States (Figure 2.1). These areas are frequently impacted by tropical cyclones (TCs) from either the Atlantic Ocean or Gulf of Mexico (Keim *et al.* 2010). Topologically, this area contains the Appalachian mountain range, which runs southwestward from western Virginia to northeastern Alabama (Figure 2.1). The area contains several large cities with metropolitan populations exceeding one million, including Atlanta GA, Charlotte NC, Birmingham AL, Richmond VA and Raleigh-Durham NC. Because of Florida's close proximity to Gulf of Mexico and Atlantic Ocean, it was excluded from the study area because of this study's focus on inland environments.
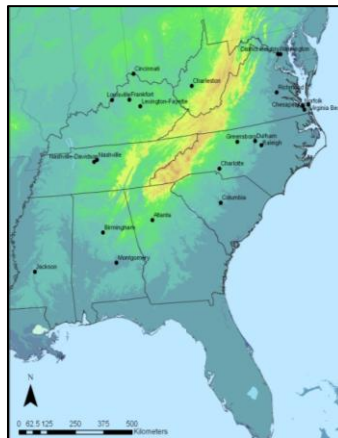
Figure 2.1: States of Study Area

2.2 Methods

Thirty-one TCs were selected from the time period 1985 to 2008 (Table 1). These cyclones are identified because they tracked at least 100 kilometers inland within the southeastern U.S. study area (Figure 2.2). These TCs vary substantially with respect to size, intensity, and synoptic setting.
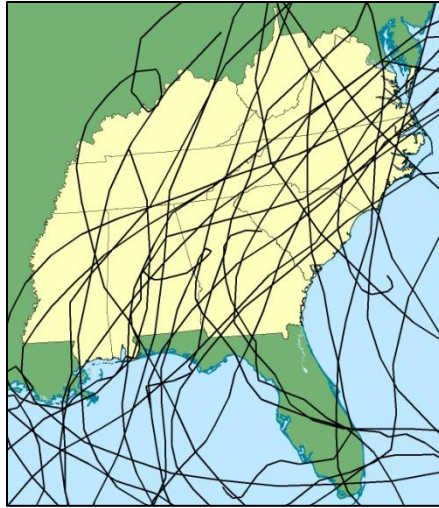
Figure 2.2: All tropical cyclones and tracks used in this study

Table 1: Tropical cyclones used in study

Alberto 1994	Cindy 2005	Ernesto 2006	Helene 2000	Jerry 1995
Alberto 2006	Danny 1985	Floyd 1999	Hugo 1989	Juan 1985
Andrew 1992	Danny 1997	Fran 1996	Isabel 2003	Kate 1985
Beryl 1994	Dennis 2005	Frances 2004	Isidore 2002	Katrina 2005
Bill 2003	Earl 1998	Gaston 2004	Ivan 2004	Opal 1995
Bob 1985	Erin 1995	Georges 1998	Jeanne 2004	

Flash flooding, high wind, and tornado reports were collected for each TC along with a wide range of social impacts information, including deaths, injuries, power outages and infrastructural, environmental, and agricultural damage. These reports were gathered from two main sources: the National Oceanic and Atmospheric Administration's (NOAA) Storm Event's database (http://www4.ncdc.noaa.gov/cgi_wind/wwcgi.dll?wwwEvent~Storms) and Newsbank, a database of America's archived newspapers. (http://www.newsbank.com).

NOAA's storm events database contains an estimate of damage for weather events affecting the United States (Ashley and Ashley 2008). Storm events information is provided by the National Weather Service and other sources, including news media, law enforcement agencies and citizen's reports. Various studies (e.g. Curran et al. 2000 and Changnon 1999) have identified biases in this database, including an underreporting of damages and casualties from "smaller impact" events such as lightning or hail (Ashley and Ashley 2008). Additionally, Storm Events does not include deaths or injuries indirectly related to the storm (Ashley and Mote 2005). Therefore to supplement this database, newspapers were examined to identify additional societal impacts. Newspapers sources are identified throughout the study area using Newsbank, a digital database of American newspapers. A total of 162 newspapers are examined to obtain relevant TC meteorological impact information (Table 2.2). Impact data from newspapers are particularly important for TCs earlier in the period when Storm Events data are less numerous. For TCs prior to 1990, approximately 88% of meteorological impacts were identified through newspaper articles. The remaining 12% of impacts were identified through Storm Events information. For TCs from 1990 to 2000, newspaper data accounts for approximately 57% of the meteorological impacts. In more recent TCs (after 2000) newspaper data accounts for approximately 31% of TC related meteorological impacts.

Table 2.2: Number of newspaper analyzed for study in each state

State	Number of Newspapers
Alabama	18
Georgia	11
Kentucky	12
Mississippi	7
North Carolina	45
South Carolina	26
Tennessee	8
Virginia	24
West Virginia	11

These data have several limitations. They are skewed toward urban locations. With continued increases in population throughout the southeast US, there are secular increases in the number of societal impacts for individual TCs across the study period. To address this problem, flash flood impacts and high wind impacts were aggregated to the county level for analysis. Additionally, confirmed tornadoes (i.e. listed in storm events) were used in the analysis rather than impact data from tornadoes. Lastly, newspaper data lacks geographic coordinates; therefore, information provided (e.g. city, towns, or streets) in the newspaper story was geo-coded to the county level to determine locations.

The classification of meteorological impacts also has several limitations, particularly for high wind impacts, which can be very localized, (e.g. scattered power outages and tree damage) or regional (e.g. power outages and substantial losses in tree and infrastructure) in scale. The assessment of high wind impacts is further complicated by the influence of wet soils, which can compromise a tree's root structure increasing the likelihood of damage by high winds.

Geographic Information Systems (GIS) was applied in this study to provide a spatial perspective of the meteorological fields of the hurricane and location of societal impacts relative to the cyclone center and track (Figure 3). GIS calculates the distances between the

cyclone center/track and the location of each impact.   From these distances, a track-following coordinate system (TFCS) was constructed to depict the distribution of societal impacts around a TCs center (Figure 3b).   The center of the coordinate system represents the center of the TC during the time in which each impact is observed. The X-Axis (i.e. cross track axis) identifies the distance of the impact from the TC track (e.g. negative and positive values indicate impacts that are left and right of track, respectively). The Y-Axis (along-track axis) denotes the distance of the impact down track (positive value) or up –track (negative value) of the cyclone. To illustrate, a map of the impacts of TC Frances (2004) are provided (Figure 3a) and transformed into the TFCS (Figure 3b). Many of the impacts in TC Frances occurred in the right-forward quadrant. Highlighted are a small number of wind impacts in northeast Georgia, which are found within 100 km to the right of the track and nearly 300 km down track of the cyclone (i.e. these impacts occurred well before the cyclone center made its closest passage).
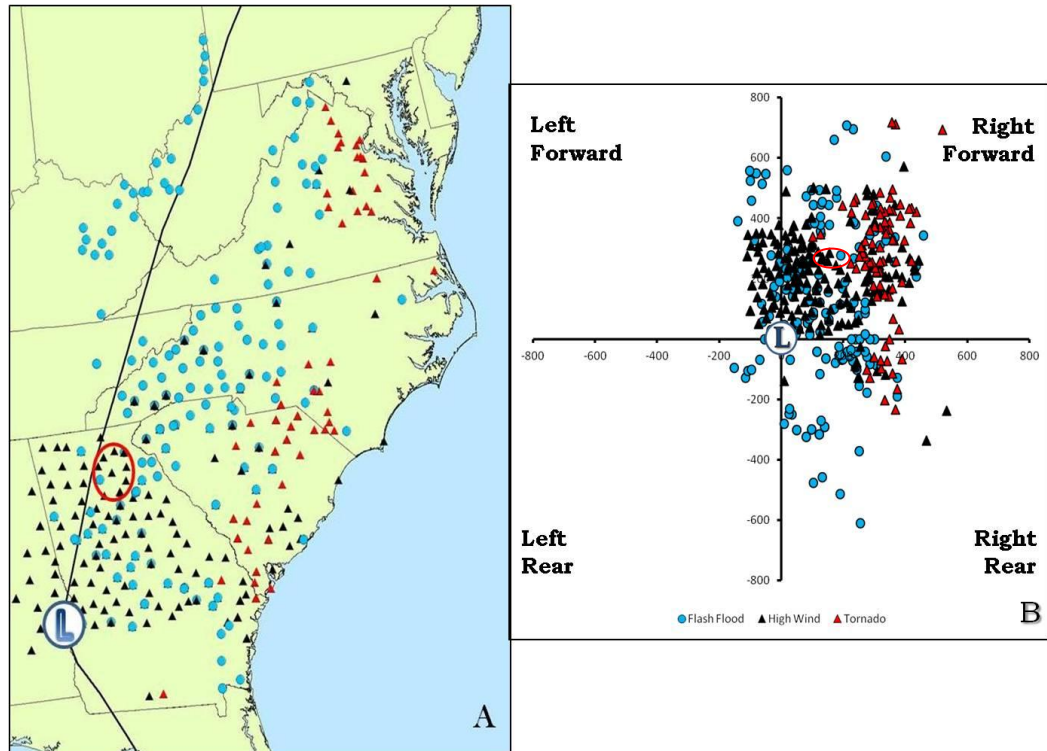
Figure 2.3a: Map of TC Frances 2004 Impacts. The location of high wind and tornado reports are denoted by black and red triangles, respectively, and flash flood reports are denoted by blue circles. Figure 2.3b: The Track-Following Coordinate System of Frances (2004)

In order to identify the location of each impact in the TFCS, two distance measures were required: 1) the distance from the cyclone center to the location of the impact. This distance is measured at the approximate time in which the impact was observed. 2) The minimum distance between the cyclone track and the location of the impact.

In many cases, times and locations must be estimated in order to generate the distance measures. First, the cyclone track information is only given in 6-hour increments from the National Hurricane Center's HURDAT database. These 6 hour increments are linearly interpolated into one hour position estimates. Secondly, the times of the TC impacts had to be estimated in some cases.   Storm Events data typically provided a date and hourly time along with a location, identified by a latitude and longitude. In a few cases, a time range for the impact was reported in which case a midpoint time of occurrence was estimated.

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Newspaper data rarely reported times for an identified impact. Therefore, the closest weather station with hourly data was used to estimate a time impact. For reports that involved high winds, hourly peak wind observations were examined at the nearest weather station. In the case of flash flooding, the midpoint of the 6 hour period of heaviest precipitation was used to estimate the impact time. A six-hour time period was chosen as it provided sufficient time, in most instances, for heavy precipitation to result in flash flooding. Flooding events that occurred more than ten hours after a TC passage were not recorded. For storms earlier in the time period (e.g. 1980-1995), weather stations and data were less numerous. In these cases, wind data and precipitation totals were supplemented with the National Hurricane Center's TC reports and the National Climatic Data Center's hourly precipitation data.

After constructing the TFCS, the spatial pattern of impacts for each storm was inspected to ascertain impacts that might not be connected with the TC (e.g. those occurring a large distance from the center of circulation). Synoptic surface maps, archived radar, and satellite images were used to confirm if the impacts were in fact associated with the TC. If impacts were outside the TC's large scale circulation they were removed from the TFCS.

Prior TC research has not employed a TFCS. However, Businger et al. (1990) used a storm- following climatology for winter storms to examine the greatest precipitation rates and totals with respect to the storm center and track. From this climatology, storm tracks and precipitation values were composited into three main tracks and precipitation patterns. The TFCS within this study is different in that distinguishes the spatial distribution of individual meteorological impacts around the TC centers. This TFCS is employed climatologically across a sample of TCs to assess the overall spatial pattern of meteorological

impacts and identify those TCs that have impacts whose location relative to the track and TC center is atypical (i.e. an outlier).

GIS was also utilized to measure the size, strength, and speed of movement of the cyclone, which were then related to the spatial distribution of the impacts. The size of the cyclone was estimated by measuring the area inside the outermost closed isobar using NOAA's daily weather maps at the time closest to the TC landfall (Figure 4). These measurements were taken at the point of landfall. Konrad *et al.* (2002) employed this same methodology, calculating the area by manually measuring cardinal distances from the cyclone's center to the outermost closed isobar. The cyclone's speed of movement was estimated from position information given in the NHC's HURDAT database. The speed was calculated by measuring the distance traveled in the first 24 hours after landfall. Lastly, the strength (i.e. maximum wind speed) of the TC was determined at the 6-hour time nearest landfall, classified by the maximum sustained wind speeds.
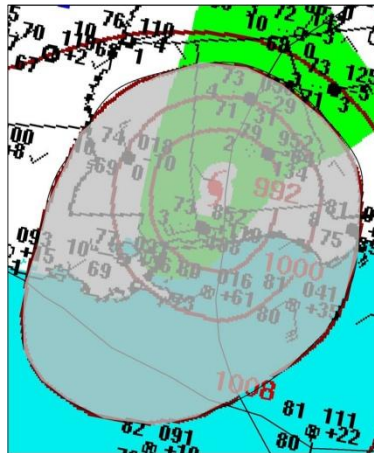
Figure 2.4: TC Ivan (2004) at landfall with GIS used to estimate the area of the shaded region.

Chapter 3:

Results

The purpose of this Thesis is to provide a detailed climatological perspective on where meteorological impacts (e.g. tornadoes, high winds, and flash floods) occur relative to the TC center. In order to address this objective, each meteorological impact is evaluated with respect to the following three main objectives 1) To identify the overall spatial pattern of the meteorological impacts relative to the TC center of circulation 2) To examine why particular TCs have meteorological impacts that depart from what is typical (e.g. the outliers); and 3) To ascertain how TC attributes (e.g. size, strength, and speed of movement) affect the spatial distribution of tornado, high wind or flash flood impacts.

Table 3.1 displays the 31 TCs utilized in this study. The TC sample displays much variability in terms of strength, size, and speed of movement. Roughly 74 and 26% of the TCs made landfall along the Gulf and Atlantic Coasts, respectively. There are 12 tropical storms, 11 weak hurricanes, and 8 major hurricanes in the sample.

Name	Tornado Counts	Tornado Impacts	Flash Food Impacts	High Wind Impacts	Intensity
Hugo 1989	2	4	26	140	Category 4
Andrew 1992	35	41	2	33	Category 3
Dennis 2005	7	7	98	215	Category 3
Fran 1996	1	2	101	236	Category 3
Ivan 2004	93	170	213	368	Category 3
Jeanne 2004	35	40	97	120	Category 3
Katrina 2005	47	88	103	91	Category 3
Opal 1995	13	13	52	203	Category 3
Floyd 1999	17	25	141	169	Category 2
Georges 1998	45	45	55	82	Category 2
Isabel 2003	---	---	87	303	Category 2
Bob 1985	5	5	6	10	Category 1
Danny 1985	37	52	16	20	Category 1
Danny 1997	13	23	75	54	Category 1
Earl 1998	9	19	134	71	Category 1
Erin 1995	---	---	34	70	Category 1
Gaston 2004	20	35	53	23	Category 1
Juan 1985	5	5	1	10	Category 1
Kate 1985	---	1	7	41	Category 1
Alberto 1994	---	---	147	13	Tropical Storm
Alberto 2006	8	24	96	91	Tropical Storm
Allison 1995	3	5	19	31	Tropical Storm
Beryl 1994	38	51	64	28	Tropical Storm
Bill 2003	24	25	112	74	Tropical Storm
Cindy 2005	41	68	136	94	Tropical Storm
Ernesto 2006	3	3	51	55	Tropical Storm
Fay 2008	45	49	118	72	Tropical Storm
Frances 2004	87	135	189	202	Tropical Storm
Helene 2000	6	9	26	7	Tropical Storm
Isidore 2002	---	---	131	141	Tropical Storm
Jerry 1995	---	---	54	1	Tropical Storm

*Table 3.1: The number of societal impacts from TC related tornadoes, flash floods, and high winds. Tornado counts denote confirmed tornadoes rather than impact damage caused by tornadoes.   Tornado counts were used in the tornado results.*

3.1 Tornadoes

There is much variability in the number of tornadoes associated with each TC; most

notably, there were six TCs that were not associated with any tornadoes. Five of the top

tornado-producing TCs were responsible for approximately half of the tornadoes in the study and only nine tornadoes occurred in the lower ten tornado-producing TCs. The intensity and size of the TCs did not show a relationship to tornado counts. However, the TC's speed of movement was negatively correlated with tornado counts (r=-0.398, p-value <0.05). This relationship suggests that TCs with a slower speed of movement spend more time over the region and hence allow more time for tornadogenesis.

Nearly 63 percent of tornadoes in this study occurred in the right-forward quadrant, reinforcing the results of previous studies (McCaul 1991, Schultz and Cecil 2009). The average tornado occurred 131 km upstream and 135 km to the right of the tropical cyclone track (Figure 3.1). In total, 20 of the 25 systems with tornadoes had centroids in the right-forward quadrant (Figure 3.1). All of the TCs with tornado centroids in the left-quadrant either made landfall along the Atlantic Ocean or tracked outside the study area, where tornado reports were not collected. Other systems, like Hurricane Dennis [2005], whose centroid was located 336 km downstream and 663 km to the right of TC's center of circulation, had relatively few tornadoes for a large system. In this TC, two of the seven total tornadoes occurred as the remnants of TC Dennis interacted with a weak, southward-moving cold front along the eastern fringes of the large circulation. The instability along the front coupled with sufficient directional shear contributed to the development of several EF0 tornadoes.
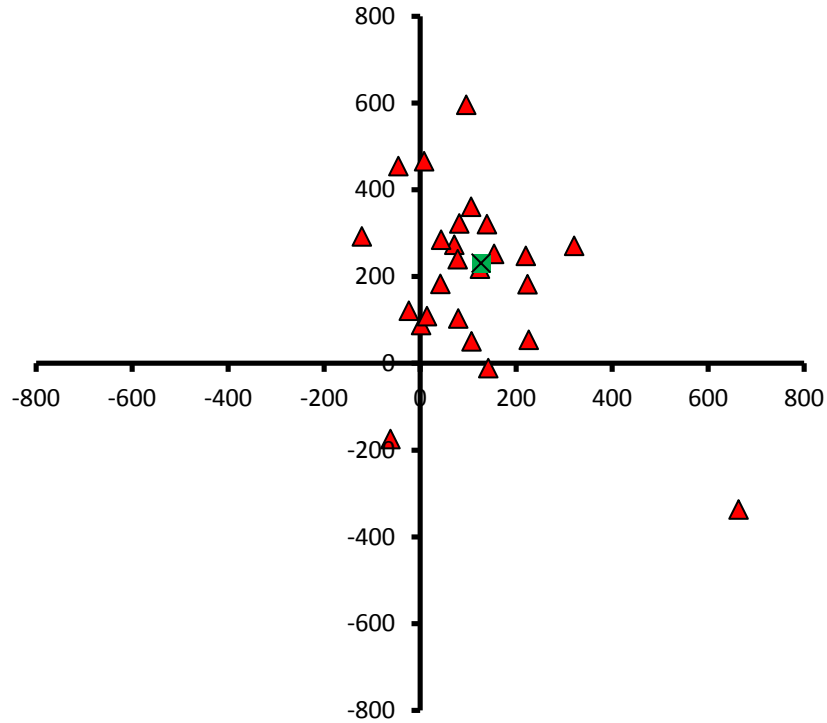
Figure 3.1: Tornado centroids (red triangles) for each TC and the grand centroid (green square) for the entire study sample weighted by the number of tornadoes associated with each TC.

Other TCs produced more significant numbers of tornadoes outside the right-forward quadrant.   These TCs were examined further to identify what environmental features or TC attributes may have played a role in an unusual spatial distribution of tornadoes.   In a few cases, the anomaly can be related to the study area boundaries. For instance, Hurricane Georges [1998] (Figure 3.2) spawned 30 tornadoes in the left-forward quadrant; however, 17 tornadoes occurred in the right-forward quadrant in Florida, which was outside the study area. TC Georges displayed an unusual easterly track across the Northern Panhandle of Florida (Figure 2), and the southerly winds advected warm, moist air in the lower troposphere into the left-forward track region. The warm, moist air coupled with a dry air intrusion in the mid-levels contributed to the tornadogenesis in southwest Alabama and southeastern Georgia. Like the majority of left-forward quadrant tornadoes in our sample,

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TC Georges's tornadoes were close to the cyclone's track (less than 100km). Similar results were found for hurricanes, such as Ivan [2004], Frances [2004], Gaston [2004] and Allison [1995], which all had a large number of tornadoes in the left-forward quadrants.
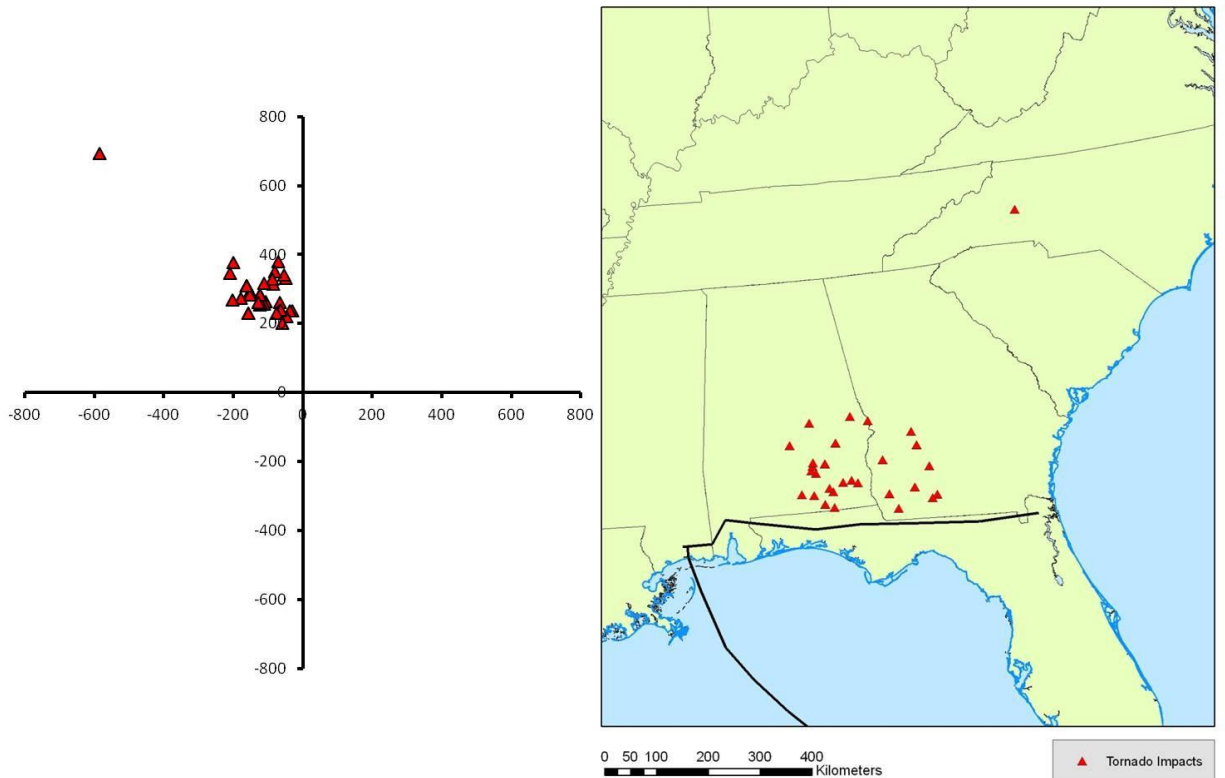
Figure 3.2: Map of Hurricane Georges's [1998] tornado counts (red triangles) and corresponding TFCS; In the TFCS the Y Axis corresponds to the TC track; the X axis of the TFCS corresponds to the cross track axis.

Tropical Storm Bill [2003] provides a noteworthy example of a TC in which a majority of tornadoes occurred in the right rear quadrant (Figure 3.3). As TC Bill migrated northeastward across the southern US, low-level warm and moisture advection occurred ahead of a cold front that was moving southeastward into the Carolinas. This unstable environment coupled with high values of vertical wind shear provided a favorable environment for tornadogenesis. Moreover, the strong westerly winds aloft were connected with a dry air intrusion that further destabilized the atmospheric column.
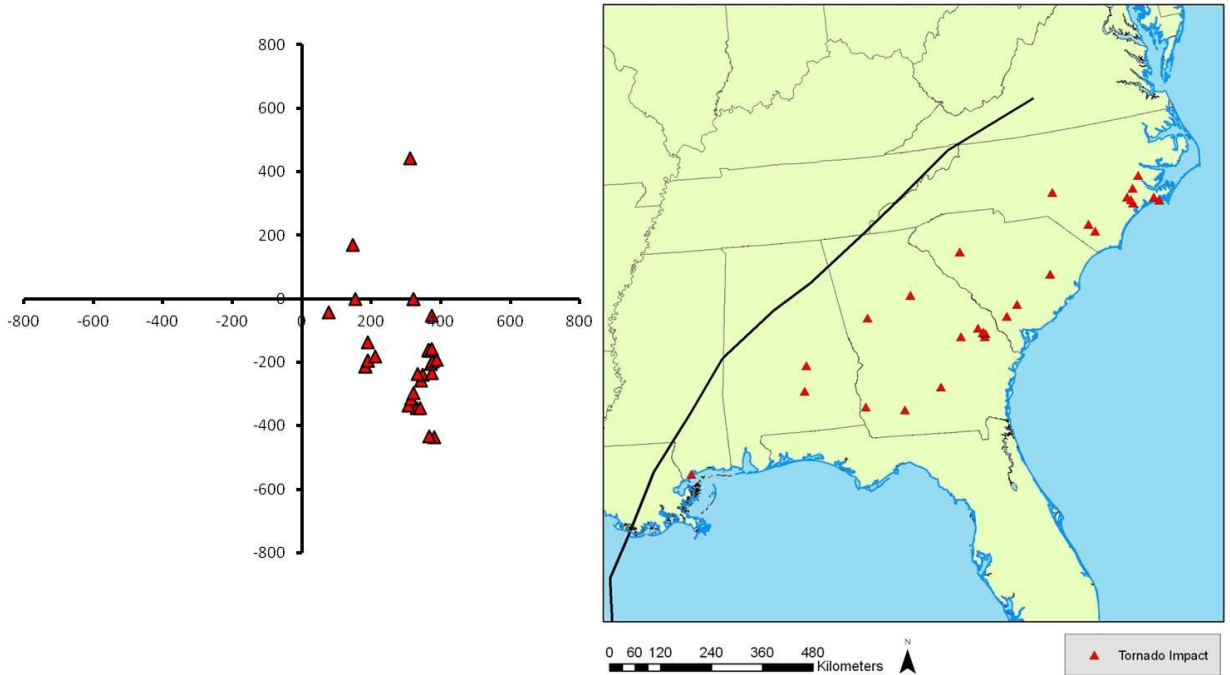
Figure 3.3: Map of Tropical Storm Bill's [2003] tornado counts (red triangles) and corresponding TFCS

Most TCs produced tornadoes across a relative small region; however, Hurricane Ivan [2004] was a major exception; it produced the highest number of tornadoes in the sample and these tornadoes occurred over a 3-day period. In fact, a tornado was observed in every state within the study area with the exception of Kentucky (Figure 3.4). A multitude of factors were responsible for TC Ivan's tornadoes. First, the TC moved slowly thereby providing an extended period of time for tornadoes to form. Second, strong vertical wind shear was present throughout this period, as the mid-level circulation associated with TC Ivan remained strong. Third, a series of dry air intrusions were present at different times in the mid to upper levels, and these intrusions increased the potential instability.
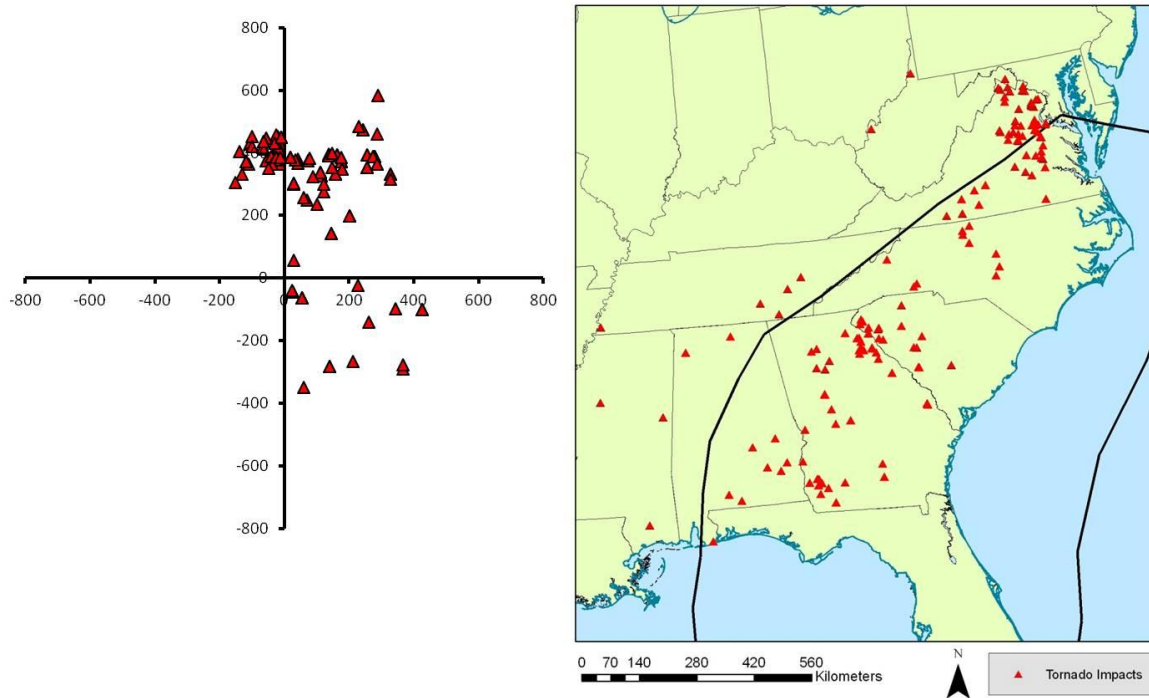
Figure 3.4: Map of Hurricane Ivan's [2004] tornado counts (red triangles) and corresponding TFCS

The three TC attributes of speed of movement, size, and intensity were also related to the spatial distribution of the tornadoes. In order to carry this out, the centroids of the tornado locations for each TC were plotted in the TFCS and segregated into terciles with respect to each TC attribute (Figure 3.5, 3.6, and 3.7). Additionally, the spatial dispersion of the tornado distribution was assessed for the TCs in each tercile through the calculation of standard distance.

As expected, the tornado centroid for the largest TCs plotted the greatest distance from center of circulation (Figure 3.5), with a centroid occurring nearly 300 km upstream and 200 km to the right of the TC center. The tornadoes for the medium and smallest sized TCs occurred closer to the TC center. The smallest TCs display a markedly lower spatial dispersion of tornadoes (SD=197 km) as compared to the medium and large sized TCs (SD = 259 and 264 km, respectively).
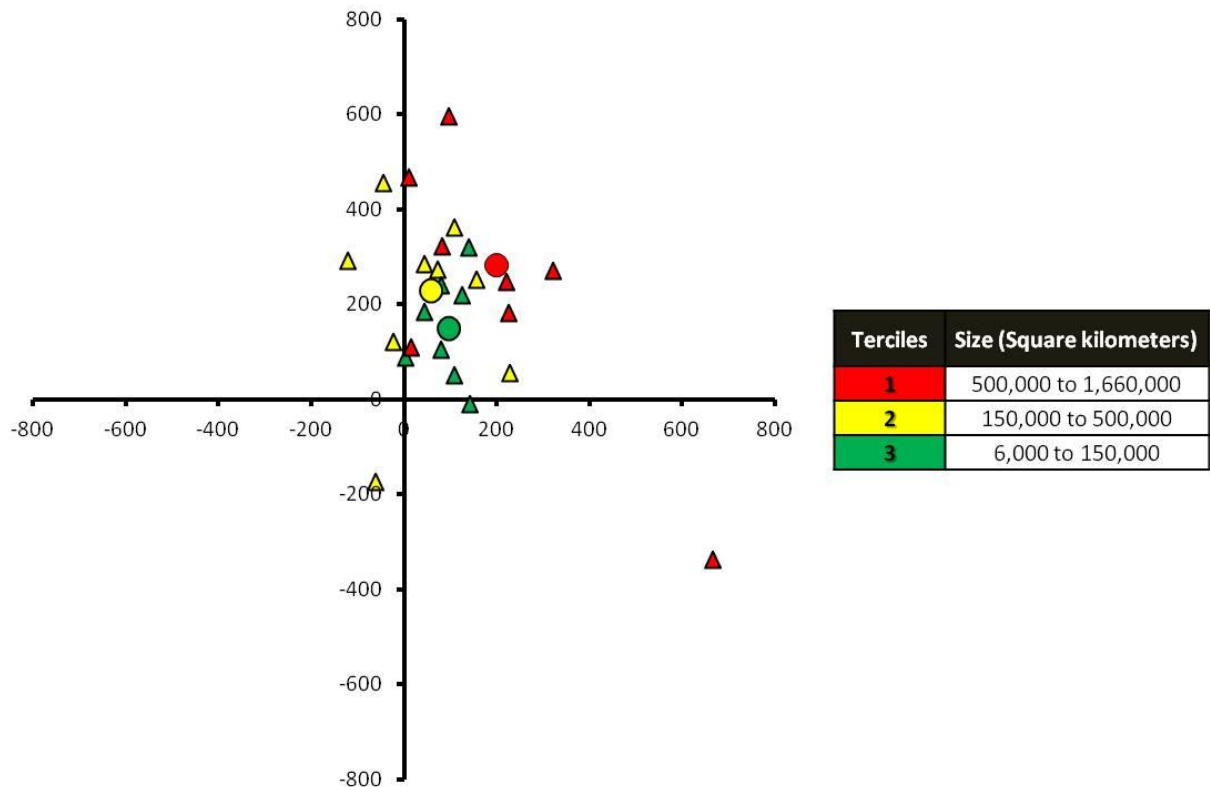
Figure 3.5: TC tercile classes by size; Locations of individual TC tornado centroids are denoted by triangles. The grand centroids for each size class are represented by large circles. Note that the grand centroids are weighted by the number of tornadoes associated with each TC.

The tropical storm-induced tornadoes showed the lowest spatial dispersion (SD=243km), and were farthest to the right of the TC track (Figure 3.6). Tropical storms Frances [2004] and Fay [2008] produced over half of tropical storm tornadoes over 200 km from the TC track. Tornadoes in Category 3 and 4 TCs (SD=245 km) occurred over a smaller area than Category 1 and 2 (SD=379km) TCs. The inverse relationship between the TC strength and spatial dispersion can be tied to the fact that weaker TCs are not as well organized and hence show more variability in the positioning of the thunderstorms that produce tornadoes. Moreover, weaker TCs are more often present in a large-scale environment that contains mid-latitude weather features (e.g. fronts and dry air intrusions) that can shift the positioning

of tornadoes relative to the TC center (e.g. tornadoes not situated in the right-forward quadrant).

Figure 3.6: TC tercile classes by intensity; Locations of individual TC tornado centroids are denoted by triangles. The grand centroids for each intensity class are represented by large circles.

There was little relationship identified between the positioning of the tornadoes and the TC speed of movement as revealed by the closer positioning of the centroids (Figure 3.7). The centroid for the slowest-moving TCs was situated farther from the TC track (168km) as compared to the faster-moving TCs (88km). The slow-moving TCs occurred over a much smaller area (SD= 229 km) as compared to the fastest moving TCs and medium moving TCs (SD=324 km and 301 km, respectively).
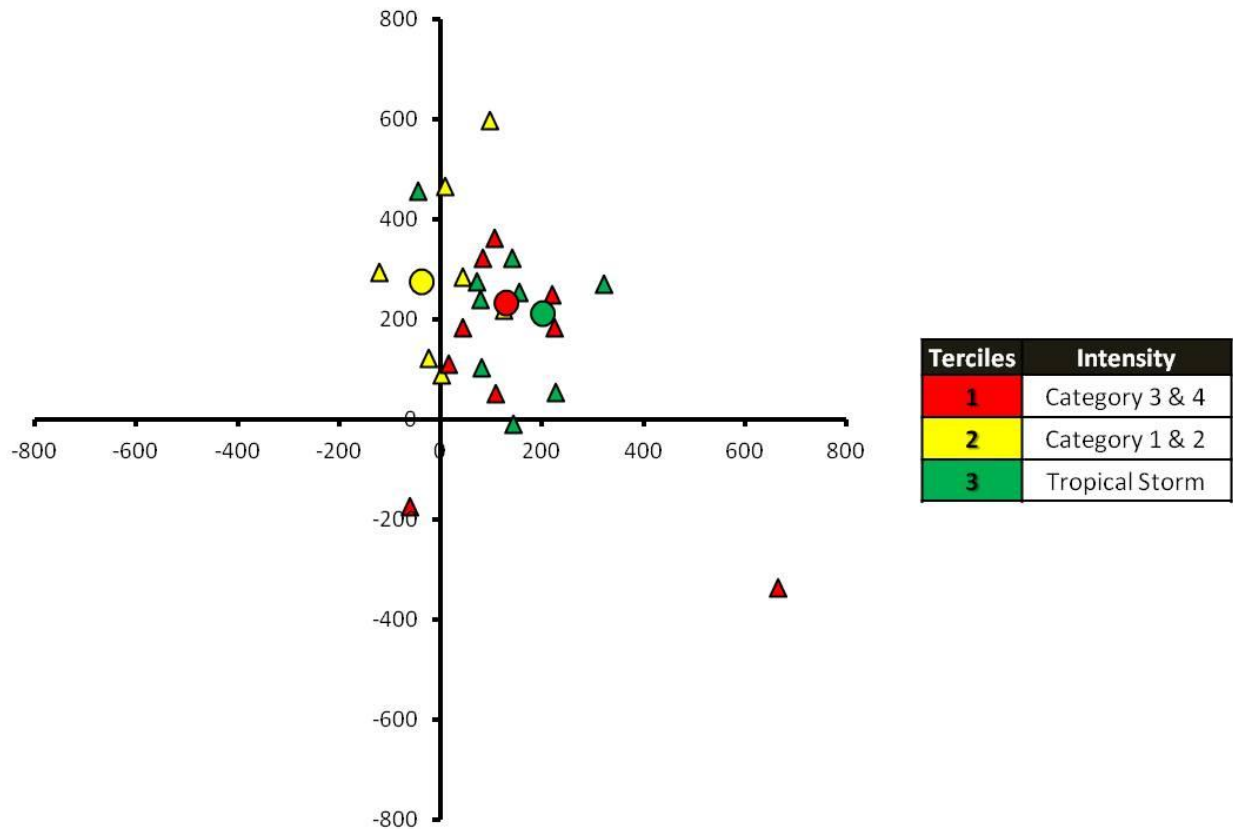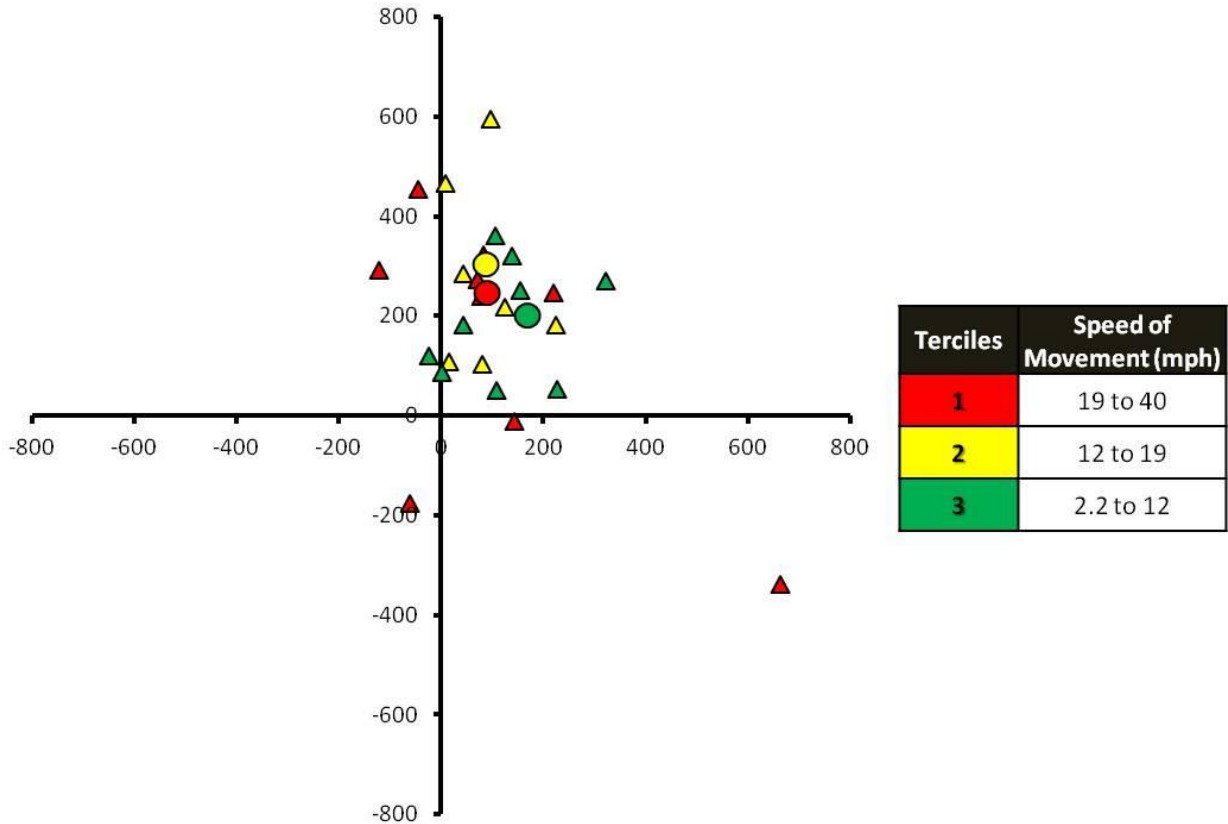
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Figure 3.7: TC tercile classes by speed of movement; Locations of individual TC tornado centroids are denoted by triangles. The grand centroids for each speed of movement class are represented by large circles.

3.2 High Wind

All of the TCs in the sample were associated with high wind impacts. Similar to tornadoes, the sample displayed much variability with five TCs responsible for roughly half of all high wind impacts (Table 1). Four out of the five of the TCs with the highest number of high wind reports were category 3 and 4 hurricanes at landfall. TC intensity and size displayed the strongest correlations with the number of high wind impacts (r= .563 and .410, respectively, and p-values < 0.01). TC speed of movement was not significantly correlated with high wind impacts.

A total of 3068 high wind impacts were collected in the sample, and nearly half of these occurred in the right-forward quadrant. The average high wind impact occurred 143 km

upstream and 48 km to the right of the TC track (Figure 3.8).   In total, 17 of the 31 TCs

displayed centroids in the right-forward quadrant. Eleven TC centroids occurred in the left-

forward quadrant, and 8 of these TCs displayed centroids within 80 km of the TC track. The

remaining 3 TCs had centroids over 100km from the TC track. These TCs, however, either

made landfall along the Atlantic Ocean or tracked outside the study area, where high wind

reports were not collected.
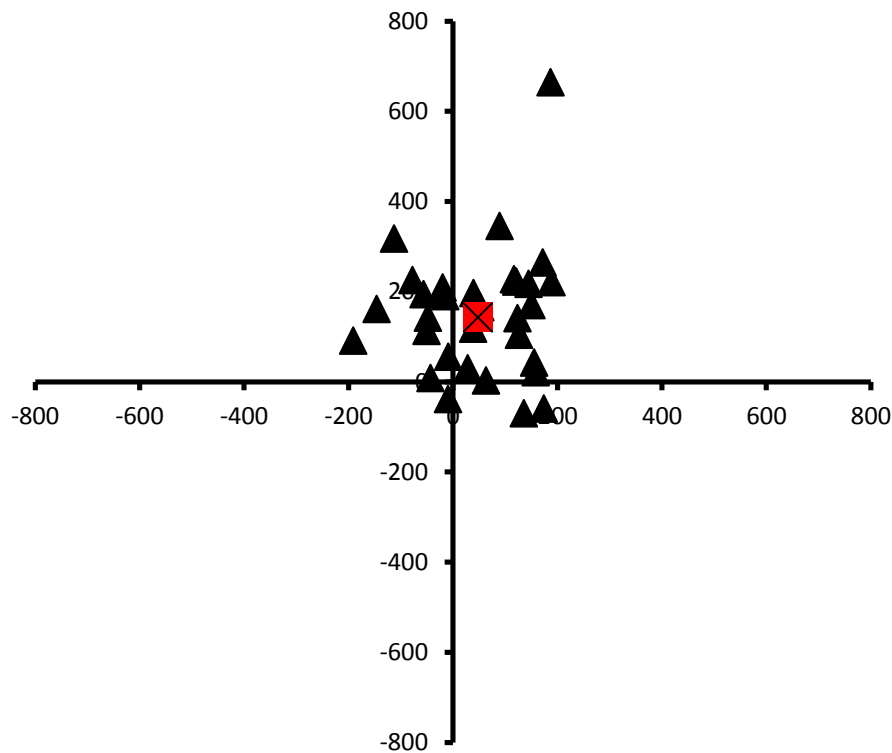
Figure 3.8: *High wind centroids (black triangles) and the grand centroids (red squares)*
for the entire study sample weighted by the number high wind impacts associated with each
TC.

Hurricane Floyd [1999] displayed a centroid farthest removed from the cyclone

center, occurring 91 km upstream and 191 km to the left.   This was partly due to the

presence of a strong high pressure to the west in the Ohio River Valley, which resulted in a

steep pressure gradient and stronger winds farther removed from the TC center. Although a

majority of TC Floyd's high wind impacts occurred near the track, a total of 17 took place

over 300 km to left of the TC track (Fig. 2) in the Appalachian Mountains of western North

Carolina, where many mountain peaks exceed 1,500 meters.   TC Floyd was a large and

strong TC that maintained a strong mid-level circulation. The sharply increasing winds with

altitude coupled with topographic influences resulted in high-elevation wind impacts far

removed from the center of circulation and isolated from wind impacts near the TC track

(Figure 3.9).   A similar situation was observed with Hurricane Hugo [1989], a large intense

TC, whose strong circulation aloft encountered the Appalachian Mountains of Virginia.

Widespread timber losses were reported in the Jefferson National Forest, where reported

wind gusts peaked at 80 mph ("Service Seeks to", A-12).
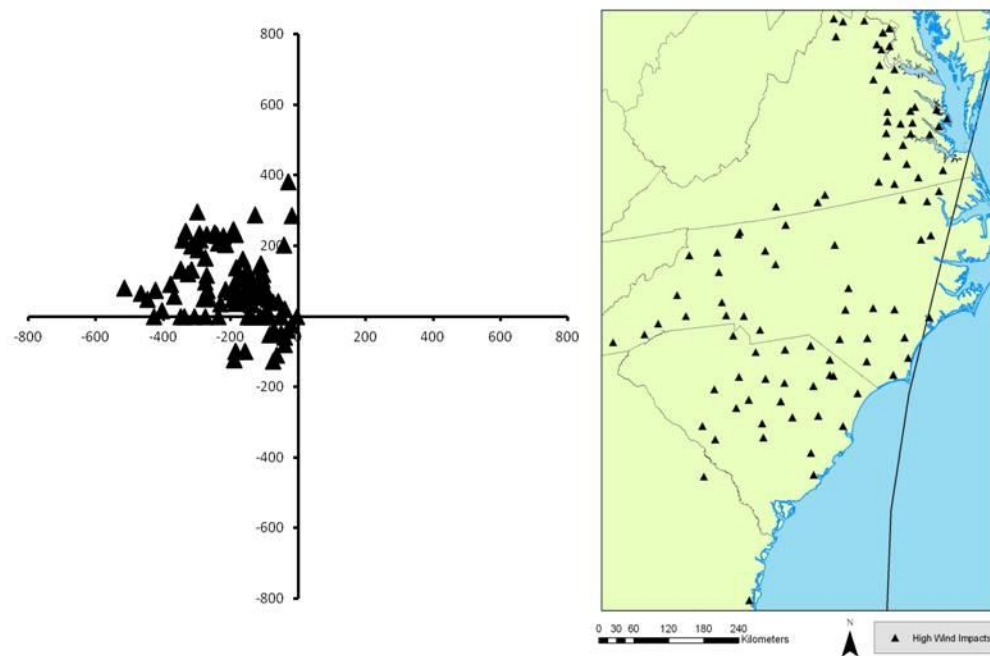
Figure 3.9: Map of Hurricane Floyd's [1999] high wind impacts (black triangles) and corresponding TFCS

Tropical storm Isidore [2002] is a noteworthy example of a TC with a majority of high

wind events occurring in the right-rear quadrant (Figure 3.10). As TC Isidore migrated

north, the cyclonic winds advected dry continental air towards the southeastern US. Near the

leading edge of this dry air, thunderstorms within an outer spiral band developed in the

warm, moist air. This spiral band developed in the far right-rear quadrant of the storm and

migrated northeastward across Georgia, resulting in high wind impacts almost 400 km away

from the TC center. The momentum associated with strong winds aloft was brought down to

the surface in the strong downdrafts resulting in strong outflow winds. A similar scenario

was observed in Hurricane Ivan [2004] when convective outflow winds (79.4mph) from an

outer spiral band caused unexpected damage to roofs, airplanes and several businesses in

Raleigh, NC.
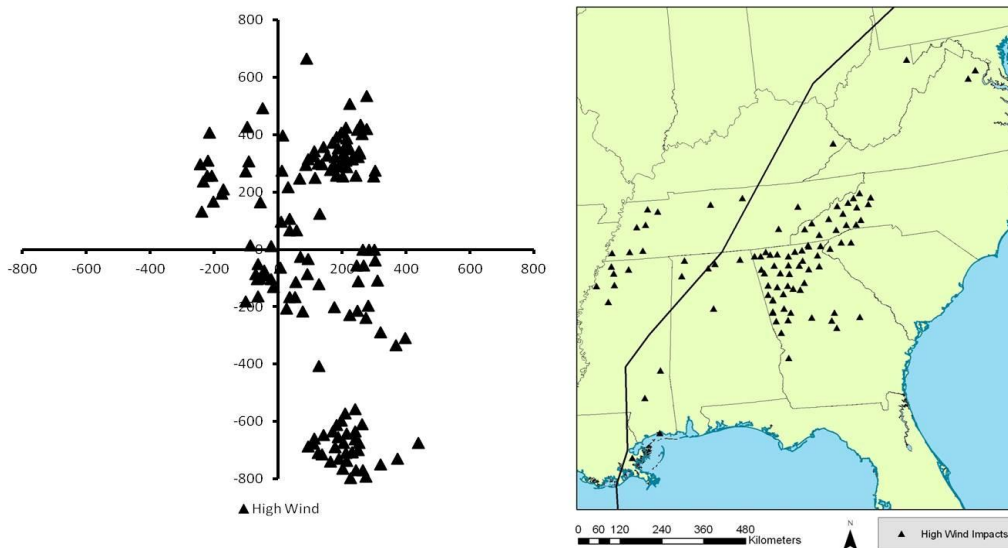
Figure 3.10: *Map of Tropical Storm Isidore's [2003] high wind impacts (black triangles) and corresponding TFCS*

The TC attributes (e.g. size, strength, speed of movement) were also related to the

spatial distribution and spatial dispersion of high wind impacts. For size, the high wind

centroid for the largest TCs was the greatest distance upstream from the center of circulation

(Figure 3.11), with a centroid occurring nearly 161 km upstream and 55 km to the right of the

TC center. The centroids for the medium and smallest sized TCs occur slightly closer to the

TC center. This suggests little difference between the spatial distributions of high wind

events for different-sized TCs. However, the larger TCs displayed a markedly higher spatial

dispersion (SD=198) than both the medium and small sized TCs (SD = 143 and SD = 148,

respectively).

Terciles	Size (Square kilometers)
1	500,000 to 1,660,000
2	150,000 to 500,000
3	6,000 to 150,000

*Figure 3.11: TC tercile classes by size; Locations of individual TC high wind centroids
are denoted by triangles. The grand centroids for each size class are represented by large
circles. Note that the grand centroids are weighted by the number of tornadoes associated
with each TC.*

The category 1 and 2 TCs showed an exceptionally large spatial dispersion (SD=229)

of high wind impacts as compared with the category 3 and 4 TCs and tropical storms

(SD=141 and SD= 137, respectively). Moreover, the centroid of category 1 and 2 impacts

was situated slightly to left of the TC track (-23 km) (Figure 3.12) in contrast to the category

3 and 4 TC centroids, which were situated about 68 km to the right of the track. TCs such as

Hurricane Floyd [1999] and Hurricane Georges [1998] showed high wind centroids well to

the left of the track and hence contributed significantly to the leftward shift of the category 1
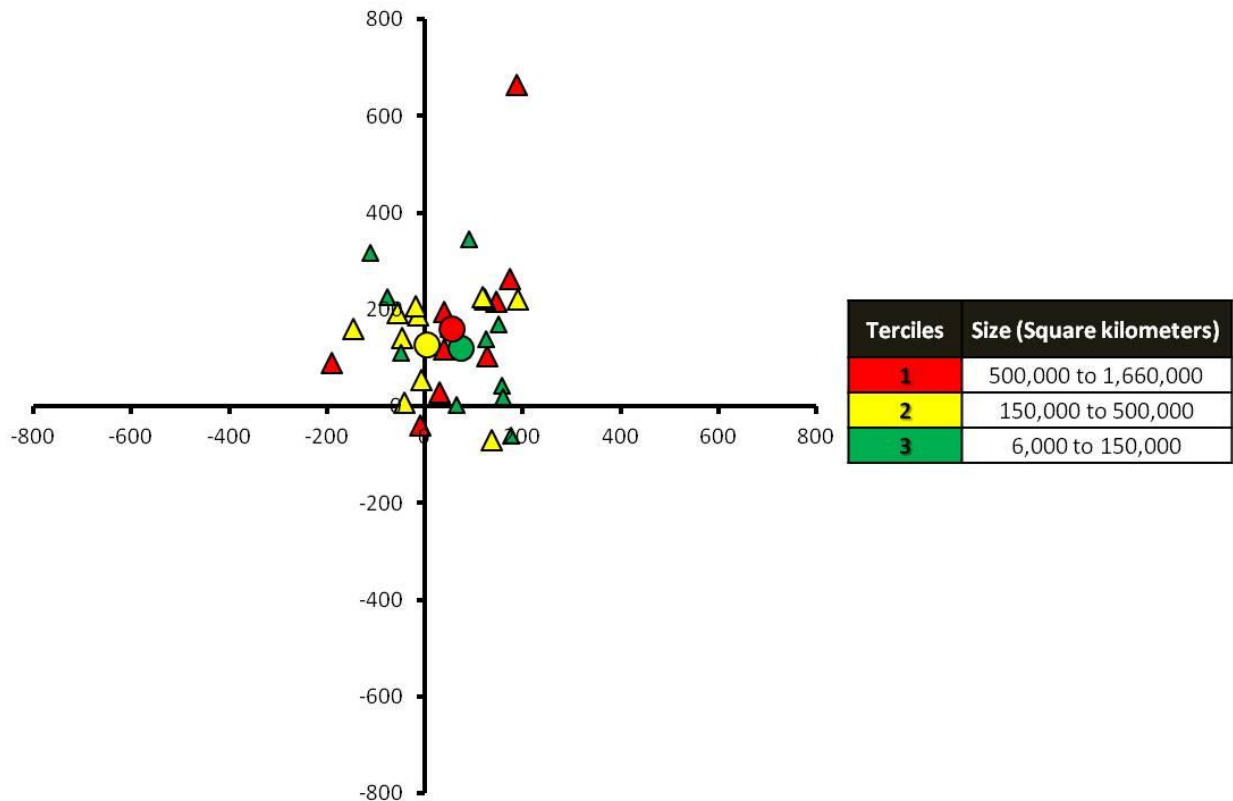
and 2 TCs.
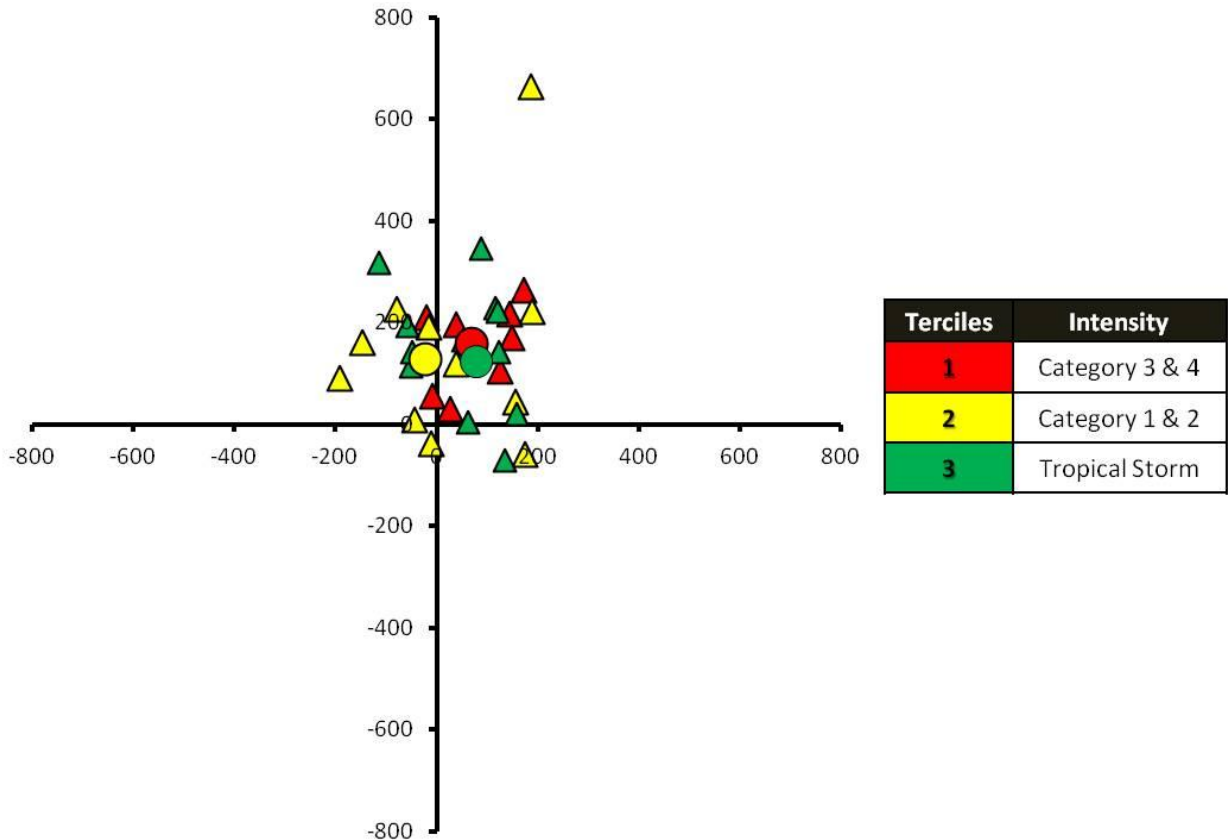
Figure 3.12: TC tercile classes by strength; Locations of individual TC high wind centroids are denoted by triangles. The grand centroids for each strength class are represented by large circles.

Hurricane Opal [1995] showed the highest values of dispersion in the study sample as its high wind impacts were recorded in every state within the study area (Figure 3.13). This large spatial dispersion can be tied to TC Opal's large size as well as her transition to an extra-tropical storm as she migrated northward towards the Ohio River Valley. During this extra-tropical transitioning stage, the strongest winds occurred far removed from the center of circulation, in areas such as northwestern Virginia. TC Opal's large region of damaging wind gusts may also be tied to her exceptional strength at landfall (Category 3) and her fast speed of movement, which was second fastest in the sample. Several newspaper sources indicated that TC Opal's large region of high winds were responsible for millions of power outages throughout the southeastern US and at least 20 deaths and 14 injuries.

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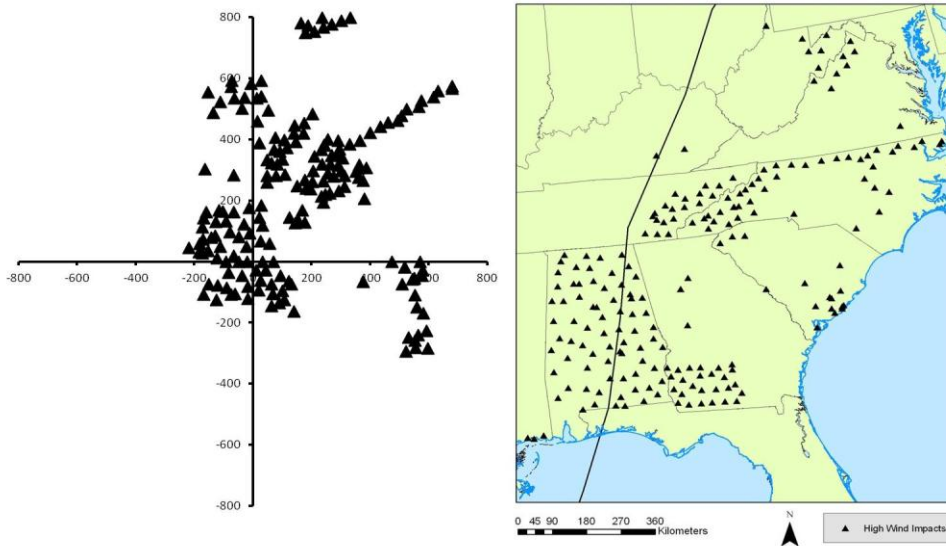
Figure 3.13: Map of Hurricane Opal's [1995] high wind impacts (black triangles) and corresponding TFCS

3.3 Flash Flood

Unlike other TC impacts, flash flood reports were more evenly dispersed across the study sample, with only 34 percent of impacts concentrated in the top five events. Additionally, the intensity, speed of movement, and size of the TCs did not show a relationship with the number of flash flood impacts.

The centroid of the flash flood reports plotted 129 km upstream of the center and 24 km to the right of the TC track (Figure 3.14). Flash flood centroids clustered around the TC track with 55% occurring nearly 50km from the track and 74% occurring less than 100km. In total, 16 TC flash flood centroids occurred in the left-forward quadrant, 13 in the right-forward quadrant and 2 in the right-rear quadrant (Figure 3.14). Most TCs with flash flood centroids in the right-forward quadrant were farther removed from the TC center. Similar to high wind events, those TCs with left-forward quadrant centroids made landfall along the Atlantic or had centroids in close proximity to the TC track.

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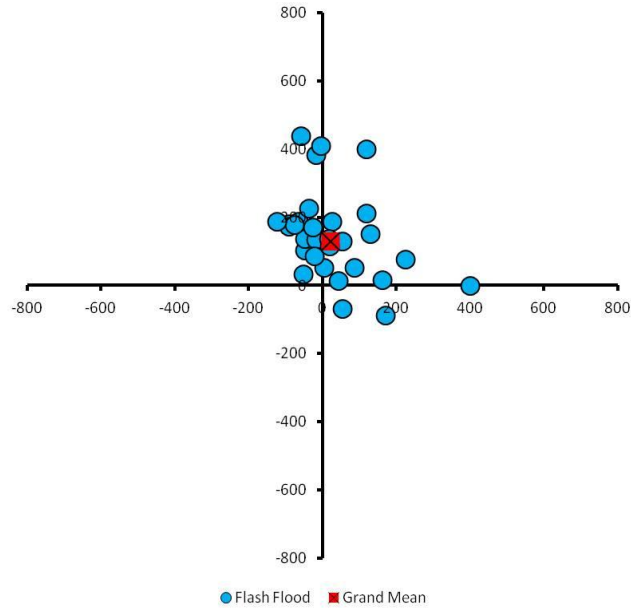Figure 3.14: *Flash flood centroids (blue circle) for each TC and the grand centroids (red square) for the entire study sample weighted by the number of flash flood impacts associated with each TC.*

Hurricane Jeanne [2004] provides a good example of a TC in which a majority of flash flood impacts occurred in the left-forward quadrant (Figure 3.15).   Nearly, 66% of TC Jeanne's flash flood impacts were located left of the TC track. As TC Jeanne migrated northeastward across Virginia, the cyclone began transitioning into an extra-tropical feature near the Delmarva Peninsula.   During this transition, the precipitation shifted to the left of the cyclone track and expanded in coverage.   Figure 3.15 illustrates this shift with precipitation far removed from the cyclone track in Virginia.   The flash flooding centroid associated with Tropical Storm Jerry [1995] occurred the greatest distance to the left of the TC track (121 km) (Figure 3.16). TC Jerry produced heavy rainfall and flooding in Georgia, South Carolina and North Carolina with totals ranging from 10 to 20 inches (Figure 4).   TC Jerry's circulation was ill-defined in the upper levels and may be tied to the scattered coverage of precipitation over a broad area.   Rainfall was also enhanced by Jerry's slow

speed of movement and orographic uplift along the southern slopes of the Blue Ridge
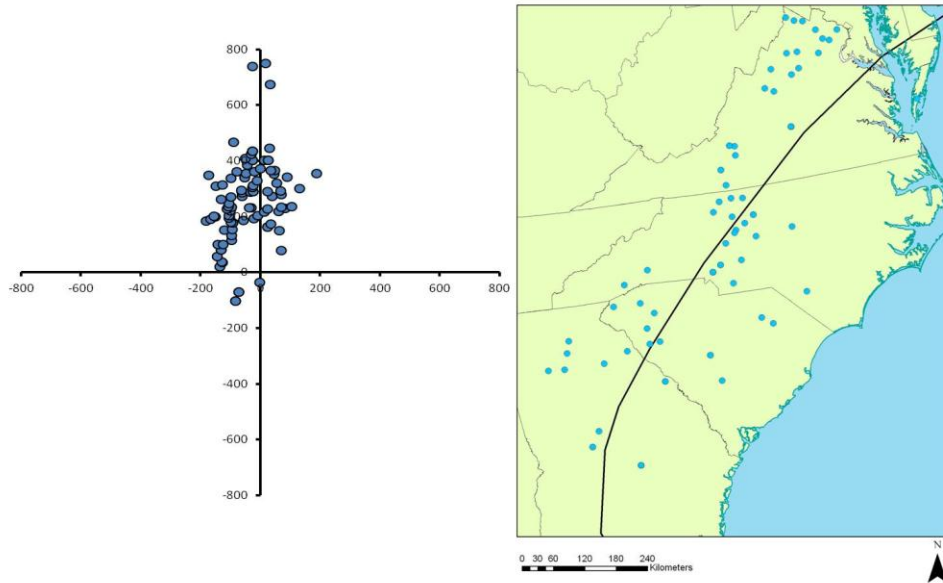
Mountains (Konrad 2001).

Figure 3.15: Map of Hurricane Jeanne's [2004] flash flood impacts (blue circle) and corresponding TFCS
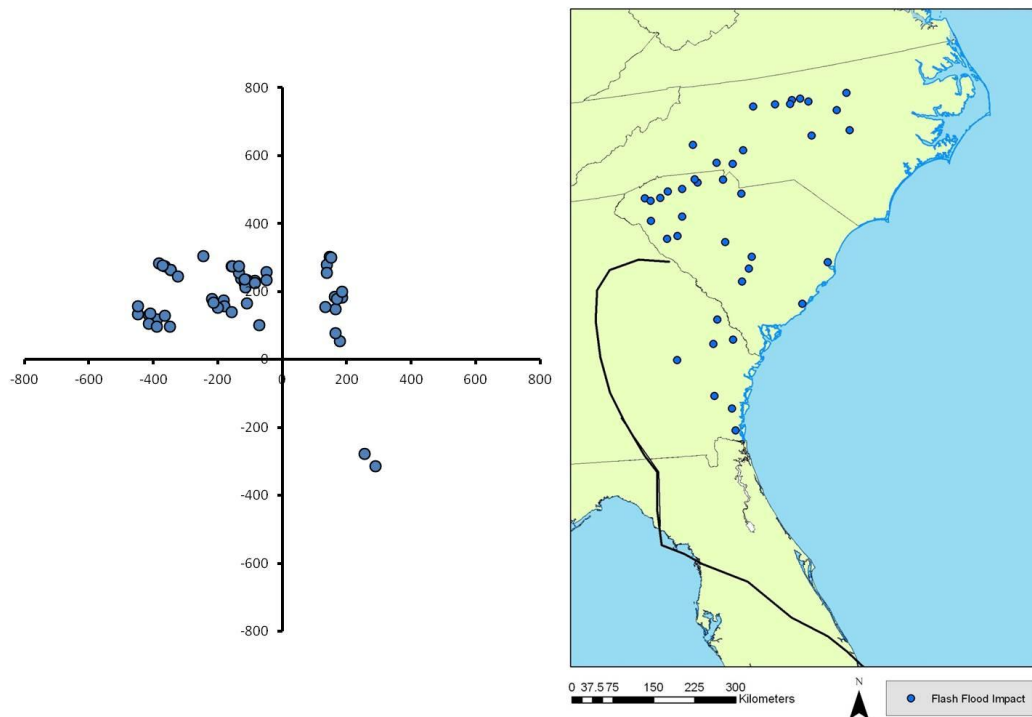
Figure 3.16: Map of Tropical Storm Jerry [1995] flash flood impacts (blue circles) and corresponding TFCS

Hurricane Dennis [2005] is another noteworthy exception in which the majority of flash flood impacts occurred in the right-rear quadrant (Figure 3.17). As TC Dennis migrated northward from the Gulf Coast, the TC weakened into an elongated remnant low in Tennessee. Similar to TC Jerry, this upper level circulation was also weak and may be tied to a dispersed pattern of scattered precipitation. During this time, the main right inflow band produced high precipitation totals across the extreme southern Appalachians as well as the western half of Georgia and southern Alabama, resulting in 47 flash flood impacts in the right-rear quadrant. The other TC with a majority of right-rear flash flood impacts was Tropical Storm Alberto [1994] (Figure 3.18). TC Alberto displayed an unusual quasi-stationary motion across central Georgia, where it looped and began retrograding southwest towards Alabama. During this time, devastating flash floods occurred throughout a large area of southern GA.
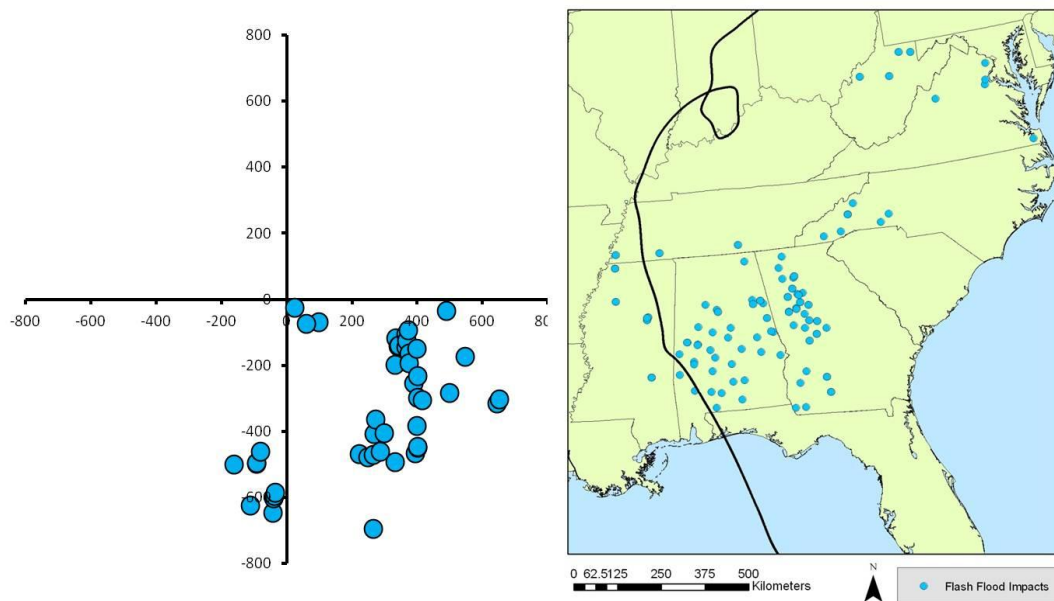
Figure 3.17: Map of Hurricane Dennis's [2005] flash flood impacts (blue circle) and corresponding TFCS
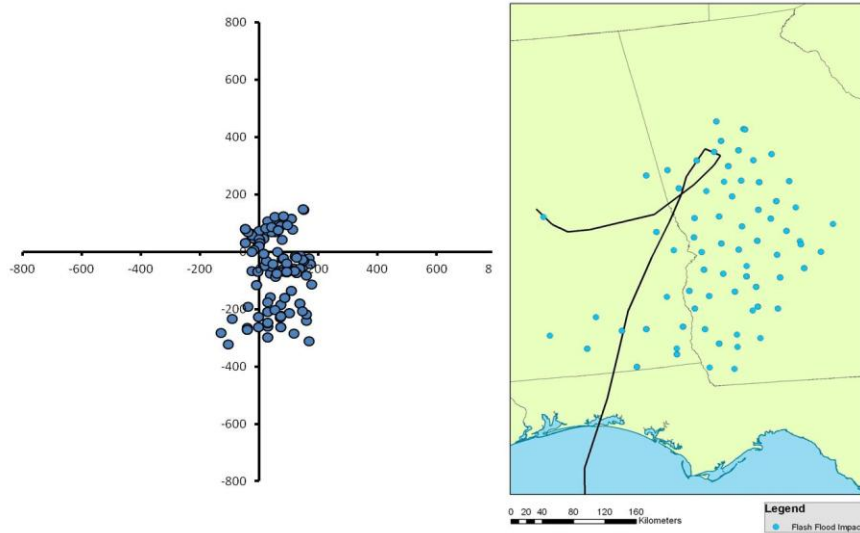
Figure 3.18: Map of Tropical Storm Alberto's [1994] flash flood impacts (blue circles) and corresponding TFCS

Although Hurricane Frances [2004] displayed a flash flood centroid in the right-forward quadrant, the TC was unusual in that it produced flash flood impacts over a large area (Figure 3.19).   TC Frances's large spatial dispersion of flooding impacts can be tied to its large circulation, which interacted with an eastward-moving cold front. This interaction contributed to the production of heavy precipitation that resulted in 15 flash flood impacts over 500 km upstream from TC Frances's center of circulation.   Also, the southeasterly winds in the right-forward quadrant of TC Frances produced orographic lifting over the Appalachian Mountains of North Carolina and southwest Virginia, which increased the rainfall rates and hence contributed to the widespread flash flooding.
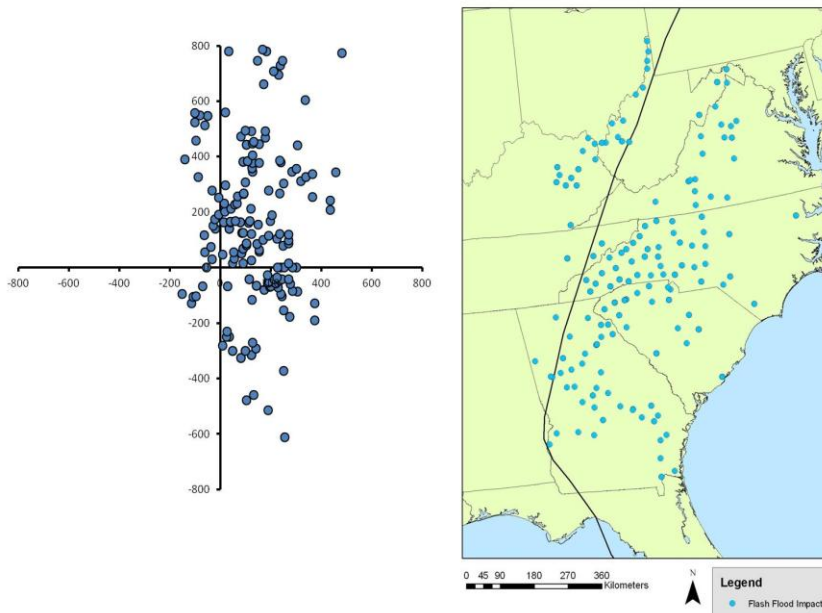
Figure 3.19: Map of Hurricane Frances's [2004] flash flood impacts (blue circles) and corresponding TFCS

The TC attributes (e.g. size, strength, speed of movement) were also related to the spatial distribution of flash flood impacts. Additionally, the spatial pattern of flash flood impacts for TCs with frontal boundaries in the vicinity was compared with those that did not have any fronts.

The frontal TCs displayed a flash flood centroid significantly farther upstream (161 km) than TCs with no front (49 km) (Figure 3.20). The spatial dispersion for TCs with frontal interactions was also noticeably lower (SD = 165) then TCs with no front in their vicinity (SD = 206). This relationship suggests that fronts provide a focusing mechanism for precipitation, often concentrating heavy precipitation far removed from the TC center. Numerous examples exist within this sample, including hurricanes, such as Frances [2004], Floyd [1999], and Opal [1995], which were described earlier in the chapter.
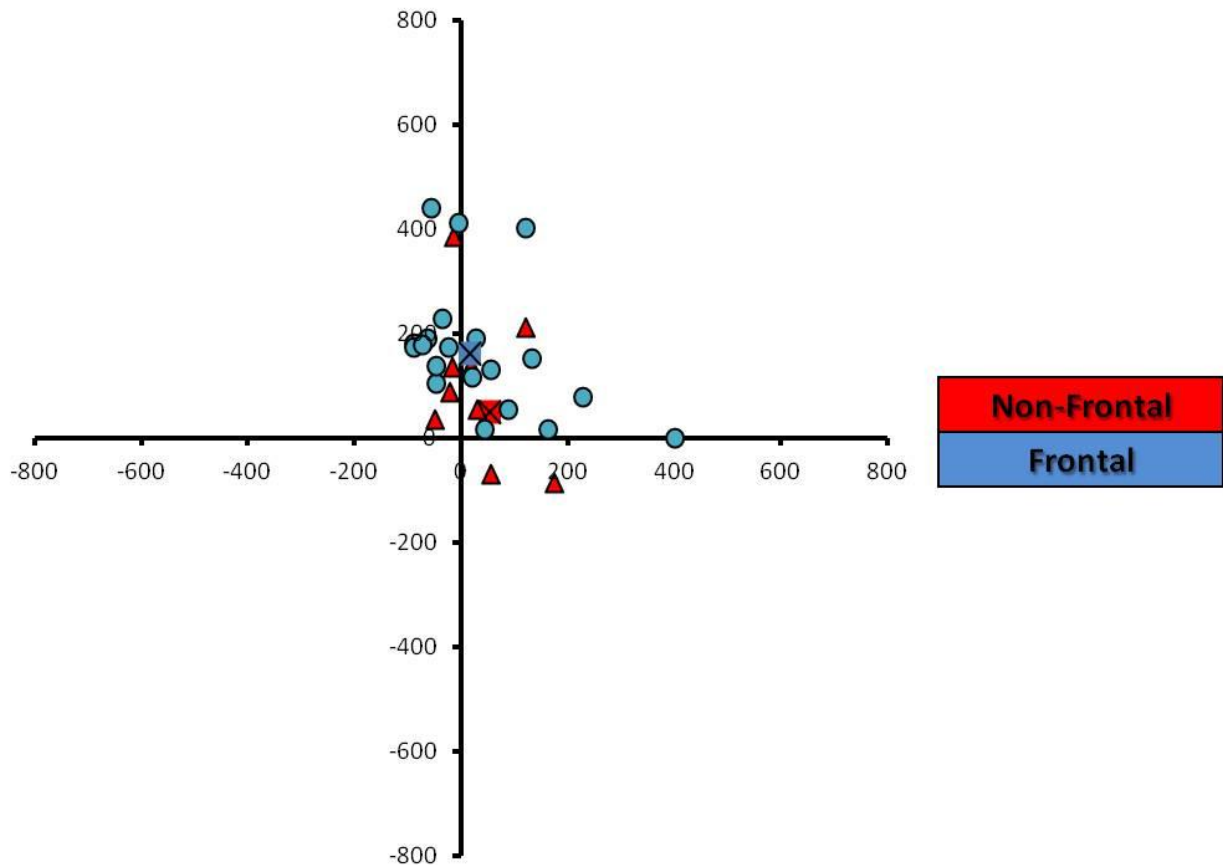
Figure 3.20: TC class by frontal and non-frontal; Locations of individual TC flash flood centorids are denoted with red triangles for frontal and non-frontal for blue circle. Grand centroids for each frontal (blue) and non frontal class (red) are represented by squares.

The flash flood centroid for the largest TCs was the greatest distance from the center of circulation (Figure 3.21), with a centroid located 154 km upstream and 47 km to the right of the TC center. The medium and small TCs centroids occurred slightly closer to the TC center (Figure 3.21). The smaller TCs displayed a markedly higher dispersion (SD=264) as compared to medium and large TCs (SD = 83 and SD = 133, respectively). The lower dispersion in larger TC may be tied to frontal interactions, which were present in six of the 10 large TCs. The outer circulation of larger TCs was more likely to impinge on frontal boundaries, which provide a focusing mechanism for precipitation, and a more localized concentration of flooding reports (i.e. low spatial dispersion values).
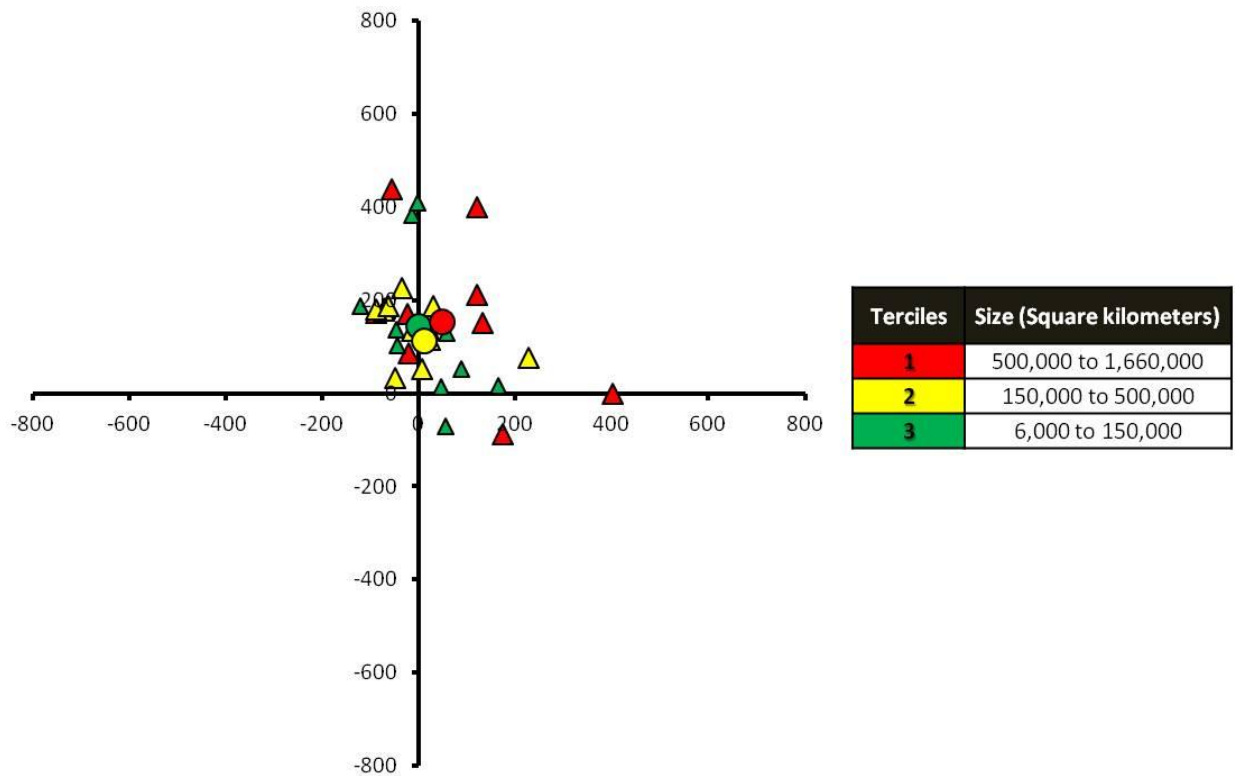
Figure 3.21: TC tercile classes by size; Locations of individual TC flash flood centroids are denoted by triangles. The grand centroids for each size class are represented by large circles. Note that the grand centroids are weighted by the number of flash flood impacts associated with each TC.

The tropical storm-induced flash flood impacts showed the lowest spatial dispersion

(SD = 180 km), and were closest to the TC track (Figure 3.22). Category 3 and 4 TCs and

Category 1 and 2 TCs occur over a much larger area (SD = 238 and SD = 228, respectively).

This inverse relationship suggests that the spatial pattern of precipitation changes little

between weak and strong TCs.

Figure 3.22: TC tercile classes by intensity; Locations of individual TC flash flood centroids are denoted by triangles. The grand centroids for each intensity class are represented by large circles.

The flash flood centroid for the fastest-moving TCs was situated slightly farther upstream from the TC center (164 km) as compared to the slow-moving TCs (106 km) (Figure 3.23). The flash flood centroid for the fast-moving TCs occurred over a smaller area (SD = 158) relative to the slowest-moving and medium-moving TCs (SD = 203 and SD = 201, respectively). Faster-moving (1st tercile) TCs also had fewer flash flood impacts (681) relative to those in the 2nd tercile (951) and 3rd tercile (812). Fast-moving Hurricane Floyd [1999] was a notable exception to this relationship as its heavy rainfall was observed over a large area. In this case, TC Floyd's outer circulation interacted with a deep mid-latitude trough and jet streak resulting in prolific precipitation well downstream of the circulation center over eastern North Carolina (Attalah and Bosart 1999).
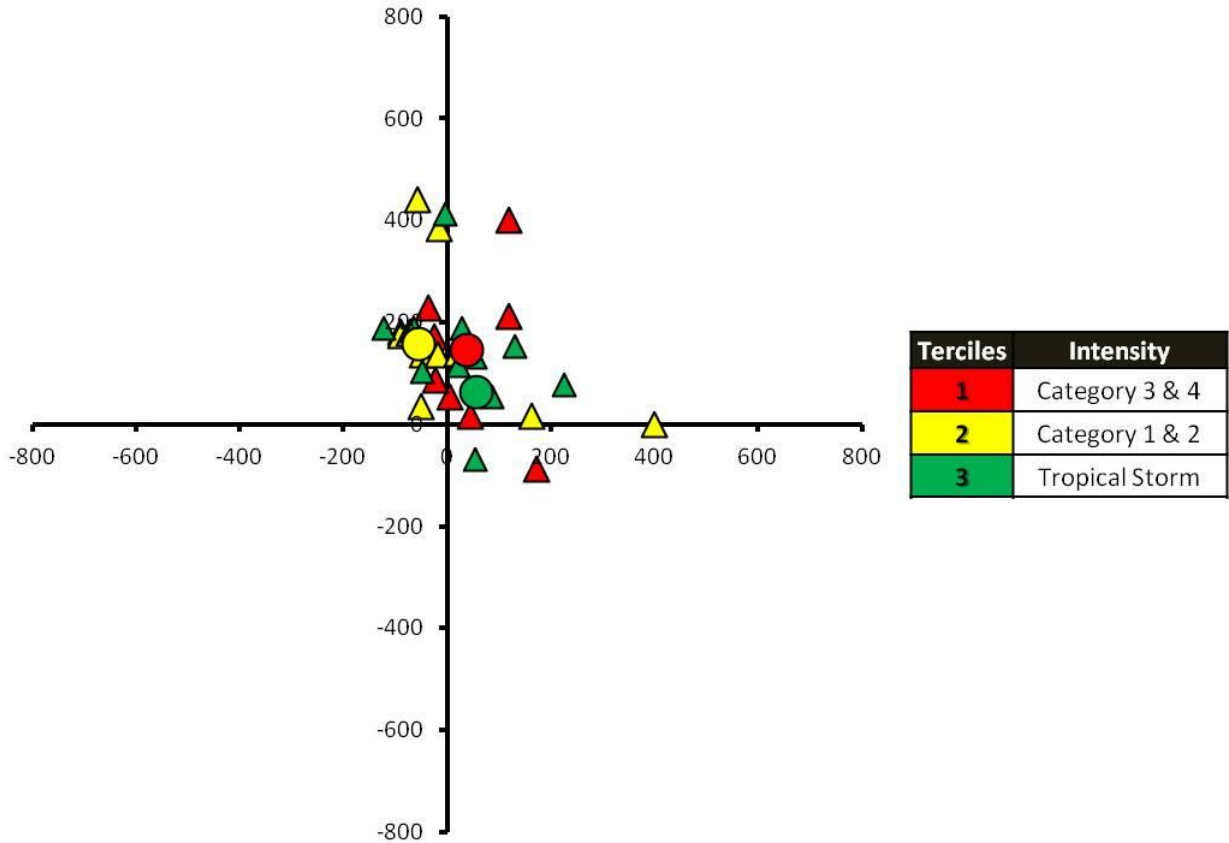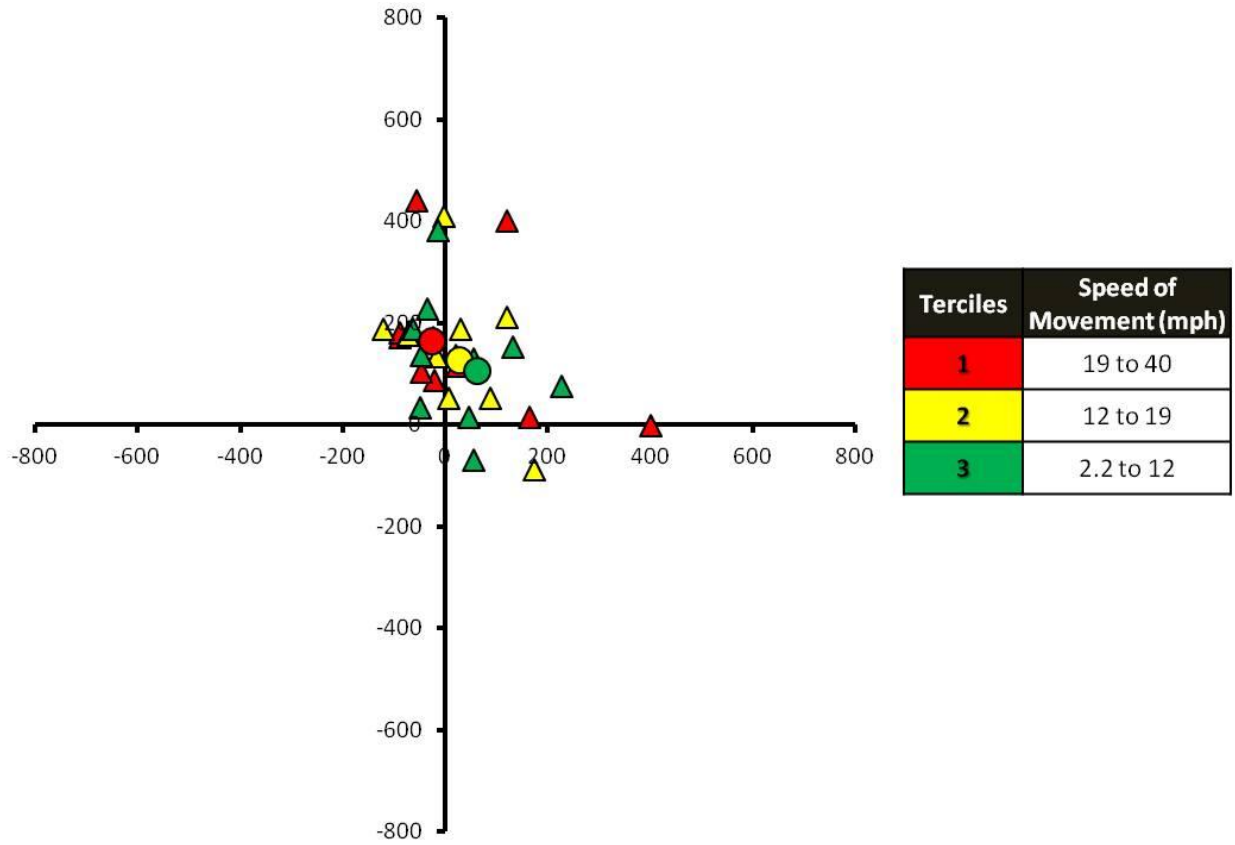
Figure 3.23: TC tercile classes by speed of movement; Locations of individual TC flash flood centroids are denoted by triangles. The grand centroids for each speed of movement class are represented by large circles.

Chapter 4:

Summary and Conclusions

This study addressed how the attributes of TCs and their larger scale synoptic environment influence the character and spatial pattern of meteorological impacts. The spatial patterns of the meteorological impacts were examined using a track-following coordinate system (TFCS), which relates the locations of tornado, high wind, and flash flood impacts to the positioning and track of the TC. In total, 31 landfalling TCs observed between 1985 and 2008 were examined with nearly 7,000 resultant impacts identified from newspaper sources and NOAA's Storm Events database.

4.1 Tornadoes

The majority of TC tornadoes occurred in the right-forward quadrant where wind shear and instability are maximized. This is consistent with findings in prior tornado climatologies (Smith 1965, Gentry 1983, McCaul 1991 Schultz and Cecil 2009). Nearly one-third of the tornadoes in the study sample occurred outside the right-forward quadrant. Almost half (47%) of these tornadoes were observed in the left-forward quadrant and the other half occurred in the right-rear quadrant (46%). A small number of TCs (e.g. Bill [2003], Georges [1998], Ivan [2004]) were prolific tornado producers, generating the majority of these right rear and left-forward tornadoes. In these events, TCs moved into an extratropical environment, where mid-latitude weather features (e.g. fronts and dry air

intrusions) interacted with the TC's circulation in ways that favored tornadogenesis outside of the right-forward quadrant.

TC attributes were also related to the spatial distribution and the number of tornadoes. The centroids of the tornado locations of each TC were plotted in the TFCS and segregated into terciles with respect to each TC attribute:

- For TC size, the tornado centroid for the largest TCs was the greatest distance from the TC's center. The largest TCs also had a much higher spatial dispersion of tornadoes as compared to the medium and small-sized TCs. Prior studies have not examined the spatial distribution of tornadoes for different TC sizes, but have found an increase in tornado counts with larger TCs (McCaul 1991). While higher tornado counts were observed in some of the larger TCs (e.g. particularly for TCs such as Ivan [2004] and Frances [2004]), no direct correlation between size and the number of tornadoes was found.

- Tornadoes associated with Category 3 and 4 TCs occurred over a much smaller area than tornadoes associated with tropical storms. The inverse relationship between the TC strength and spatial dispersion can be tied to the fact that weaker TCs are not as well organized (i.e. tornado-producing thunderstorms more dispersed across the region). Also weaker TCs are often present in a large-scale environment that contains mid-latitude features (e.g. fronts and dry air intrusions) that can shift the positioning of the tornado-bearing thunderstorms relative to the TC center.

- The fastest-moving TCs displayed a greater spatial dispersion of tornadoes than the slower-moving TCs. TC speed also correlated with fewer numbers of tornadoes, signifying that faster-moving TCs provide a shorter opportunity for tornadogenesis to

occur. This finding runs contrary to prior studies (Weiss 1987, Smith 1965), which tie faster-moving TCs to an extratropical environment containing faster steering winds aloft, greater wind shear, and hence more tornadoes. This study suggests that the extratropical environment provides a larger region with the proper ingredients (e.g. wind shear and instability) for tornadogenesis; however this does not necessarily translate into a greater number of tornadoes.

4.2 High Winds

High winds displayed the greatest number of impact reports in the study sample, totaling 3068 impacts for all 31 TCs. High wind damage showed a strong preference for the right-forward quadrant, where the motion of the cyclone contributes to the counterclockwise circulation. High wind reports were tightly clustered around the TC track, however 23% occurred more than 200 km from the track. In some instances the high wind reports were recorded exceptionally far from the center or outside the right-forward quadrant. This typically occurred in the outer spiral bands of the TC where momentum from faster winds aloft was brought to the surface in strong thunderstorm downdrafts. Higher elevations can also cause high winds exceptionally far from the TC center through topographic funneling. In this scenario, large TCs with a strong circulation aloft produce more damage in higher elevations than in lower elevations. Powell and Houston (1998) found similar events with more localized damage on exposed hillsides and hilltops for TC such as, Hugo [1989], Iniki [1992] and Merilyn [1995]. Our findings are similar, but demonstrate a TC's ability to produce high wind in higher elevations several hundred kilometers from the TC center.

Similar to tornadoes, the TC attributes were segregated into terciles and related to the spatial distribution of high winds:

- Larger TCs were tied to a high wind centroid farthest removed from the TC center. These TCs also displayed a markedly higher spatial dispersion of wind impacts followed by medium and then small sized TCs. Moreover, TC size exhibited a positive relationship with the number of high wind impacts (r=0.410). The increase in number of impacts and dispersion of high winds with TC size verify the use of the wind's areal extent as a measure of TC size (Merrill 1984).
- Category 3 and 4 TCs have a lower spatial dispersion of high wind events compared to Category 1 and 2 TCs. Higher intensity TCs also exhibit more high wind impacts, suggesting that higher intensity TCs produce a greater number of high wind impacts in a more concentrated area.

4.3 Flash Flood

Flash flood impacts clustered around the TC track with over half occurring within 50 km of the track and nearly 75% occurring less than 100km from the track. The majority of these impacts occurred in the right-forward quadrant; however, nearly 40 percent were in the left-quadrants of the TC. All TCs in this sample moved with a northward component towards an extratropical environment where fronts are more frequent. In cases in which the TC was undergoing extratropical transitioning, the axis of heaviest precipitation often falls to the west of the TC track (Ritchie and Elsberry 2001). Nearly two-thirds of the sampled TCs were associated with fronts. Of these 21 TCs, 11 of them displayed flash flood centroids in the left-quadrant, with large numbers of flash floods impacts occurring to the left of the TC track.

In addition to examining the spatial distribution of flash flood impacts, TCs with frontal interactions were related to TCs with no frontal interactions:

- TCs occurring in the vicinity of fronts displayed a flash flood centroid much farther upstream. These TCs also showed a markedly lower spatial dispersion than non-frontal TCs, suggesting that fronts provide a focusing mechanism for precipitation far removed from the TC center.

- The largest TCs displayed a flash flood centroid farthest removed from the TC center, confirming that larger rain shields occur within larger TCs (Konrad *et al.* 2002, Matyas 2007). However, larger TCs exhibited a markedly lower spatial dispersion of flooding impacts. This lower dispersion may be tied to frontal interactions with the TC (e.g. TC moisture lifted over a quasi-stationary front), which were present in six of the 10 large-sized TCs. Additionally, the outer circulation of large TCs was more likely to impinge on fronts, which provide a boundary for focusing the heavy rainfall.

- Matyas (2007 and 2010) investigated the shape of TC rain shields and concluded that tropical storms have an asymmetric precipitation distribution, with the precipitation concentrated in the right-forward quadrant. Similar results were found in this study, with the tropical storm flash flood impacts displaying a lower spatial dispersion and a centroid closer to the TC track in the right-forward quadrant. Matyas (2007) related this phenomenon to a weaker cyclonic circulation advecting less moisture into the left-quadrant of the cyclone and a pattern of directional wind shear in which strong westerly winds aloft advect the moisture and clouds to the east of the cyclone track.

- Flash flood impacts for faster-moving TCs occurred over a much smaller area than medium and slow-moving TCs. This is consistent with Konrad et al. (2002), who identified a negative correlation between TC speed and precipitation totals, especially over small areas.

This study has provided a climatology of the spatial distribution of tornado, high wind, and flash flood impacts relative to the TC center and track. It reveals that impacts occur periodically in locations far from the TC center and track, where the peripheral circulation interacts with adjacent weather features.   Weather forecasters need to be mindful of this possibility.   More generally, they can use the relationships identified in this study to identify the potential impacts within their forecast region. Emergency managers may also use this study by demonstrating to the public that the threat of tropical cyclones can occur far from the coastline or the TC center.

The research in this study could be extended through the analysis of TCs that occurred earlier in the record. While weather observations and radar data are less numerous, newspaper archives exist. One challenge to a longer period of analysis involves long-term changes in the infrastructure and population across the region as many cities (e.g. Raleigh, Atlanta, and Charlotte) have grown rapidly.

Future work may focus more on the details of the meteorological impacts, for example, the nature and magnitude of the damage. The newspaper articles recorded in this study can provide this information. Moreover, they provide an accounting of a wide range of social impacts, such as power outages, automobile accidents, timber lost, agriculture damage, and injuries from TC clean up. An analysis of these social impacts could provide inland emergency response and local governments with information on the need for stricter building codes, education, or future emergency response plans.

REFERENCES

AMS: Policy statement of the American Meteorological Society on hurricanes. Bull. Amer. Meteor. Soc., 54 (1973), 46–47

Ashley S T., Walker S.A. "Flood Fatalities in the United States." *Journal of applied meteorology and climatology* 47.3 (2008): 805-18. Web.

Ashley W. S, T, Mote. "Derecho Hazards in the United States." *Bulletin of the American Meteorological Society* 86.11 (2005): 1577-92. Web.

Ashley W. S., A. W. Black "Fatalities Associated with Nonconvective High-Wind Events in the United States." *Journal of applied meteorology and climatology* 47.2 (2008): 717-25. Web.

Atallah E. H., L.F. Bosart. "The Extratropical Transition and Precipitation Distribution of Hurricane Floyd (1999)." *Monthly Weather Review* 131.6 (2003): 1063-81. Web.

Bogner P., G. Barnes, and J. Franklin . "Conditional Instability and Shear for Six Hurricanes Over the Atlantic Ocean." *Weather and forecasting* 15.2 (2000): 192-207. Web.

Businger S., Knapp, DI. "Storm Following Climatology of Precipitation Associated with Winter Cyclones Originating Over the Gulf of Mexico"*Weather and Forecasting* (1990): 378 – 403. Web.

Changonon S.A. "Data and approaches for determining hail risk in the contiguous United States" *Journal of Applied Meteorology* 38 (1999): 1730-1739.Web

Curran B., Holle R., and Lopez. R. "Lightning Casualties and Damages in the United States from 1959 to 1994." *Journal of Climate* 13.19 (2000): 3448-64. Web.

Curtis, L. "Midlevel Dry Intrusions as a Factor in Tornado Outbreaks Associated with Landfalling Tropical Cyclones from the Atlantic and Gulf of Mexico." *Weather and forecasting* 19.2 (2004): 411-27. Web.

Czajkowski J E. Kennedy. "An Analysis of Coastal and Inland Fatalities in Landfalling US Hurricanes." *Natural hazards (Dordrecht)* 59.3 (2011): 1513-31. Web.

Emanuel K., T. Jagger. "On Estimating Hurricane Return Periods." *Journal of Applied Meteorology & Climatology* 49.5 (2010): 837-44. Web.

Gentry R. C, "Genesis of Tornadoes Associated with Hurricanes." *Monthly Weather Review* 111 (1983): 1793. Web.

Hart, R., J. Evans. "A Climatology of the Extratropical Transition of Atlantic Tropical Cyclones." *Journal of Climate* 14.4 (2001): 546-64. Web.

Hurricane Research Division; Frequently Asked Question (2011):   Retrieved October 17, 2011, from http://www.aoml.noaa.gov//hrd/tcfaq/tcfaqHED.html. Web.

International, United Press. "Service Seeks to Salvage Wood." *Richmond Times-Dispatch* 9 Oct. 1989, City, Business: A-12. *NewsBank.* Web. 14 Nov. 2011.

Kaplan, J., M. DeMaria. "A Simple Empirical Model for Predicting the Decay of Tropical Cyclone Winds After Landfall." *Journal of applied meteorology* 34.11 (1995): 2499-512. Web.

Keim B D., R. Muller, G W. Stone. "Spatiotemporal Patterns and Return Periods of Tropical Storm and Hurricane Strikes from Texas to Maine". *J. Climate* 20 (2007) 3498–3509. Web.

Konrad C. "The Most Extreme Precipitation Events over the Eastern United States from 1950 to 1996: Considerations of Scale" *Journal of Hydrometeorology* 2.3(2001) 309 – 325.

Konrad C. M.F Meaux, D.A Meaux. "Relationships between Tropical Cyclone Attributes and Precipitation Totals: Considerations of Scale." *International Journal of Climatology* 22.2 (2002): 237-47. Web.

Konrad C., B. Perry. "Relationships between Tropical Cyclones and Heavy Rainfall in the Carolina Region of the USA." *International Journal of Climatology* 30.4 (2009): n,a-n/a. Web.

Kruk M C., E. J. Gibney, D H. Levinson, M. Squires. "A Climatology of Inland Winds from Tropical Cyclones for the Eastern United States." *Journal of Applied Meteorology & Climatology* 49.7 (2010): 1538-47. Web.

Landsea Christopher C. W. "A Climatology of Intense (Or Major) Atlantic Hurricanes." *Monthly Weather Review* 121.6 (1993): 1703-13. Web.

Malmstadt J. C., J. B. Elsner, T. H. Jagger. "Risk of Strong Hurricane Winds to Florida Cities." *Journal of Applied Meteorology & Climatology* 49.10 (2010): 2121-32. Web.

Matyas Corene C. J. "Associations between the Size of Hurricane Rain Fields at Landfall and their Surrounding Environments." *Meteorology and Atmospheric Physics* 106.3-4 (2010): 135-48. Web.

---.. "Quantifying the Shapes of U.S. Landfalling Tropical Cyclone Rain Shields*." *The Professional geographer* 59.2 (2007): 158-72. Web.

Mcclay KS, DeMaria M, VonderHaarTH (2008): Tropical Cyclone Inner Core Kinetic Energy Evolution. Mon Wea Rev: 136: 4882-4898. Web.

Merrill R. T. "A Comparison of Large and Small Tropical Cyclones." *Monthly Weather Review* 112.7 (1984): 1408-18. Web.

Novlan D. J., W. M. Gray. "Hurricane-Spawned Tornadoes." *Monthly Weather Review* 102.7 (1974): 476-88. Web.

Senkbeil J. C., Sheridan C. S, 2006: A Postlandfall Hurricane Classification System for the United States. *Journal of Costal Research* 1025-1034. Web

The Saffir-Simpson Hurricane Wind Scale (2011): Retrieved October 17, 2011, from http://www.nhc.noaa.gov/sshws.shtml. Web.

Tropical Cyclone Climatology (2011): Retrieved October 17, 2011, from http://www.nhc.noaa.gov/climo/. Web.

Powell M. D, P. Dodge and M.L Black. "The Landfall of Hurricane Hugo in the Carolinas: Surface Wind Distribution." *Weather and forecasting* 6 (1991): 379. Web.

Powell, M. D. Vickery, P. J. Reinhold, T. A. "Reduced Drag Coefficient for High Wind Speeds in Tropical Cyclones." *Nature (London)* 422.6929 (2003): 279-83. Web.

Powell M., S. Houston. "Surface Wind Fields of 1995 Hurricanes Erin, Opal, Luis, Marilyn, and Roxanne at Landfall." *Monthly Weather Review* 126.5 (1998): 1259-73. Web.

Rappaport E. "Loss of Life in the United States Associated with Recent Atlantic Tropical Cyclones." *Bulletin of the American Meteorological Society* 81.9 (2000): 2065. Web.

Ritchie Elizabeth E. A and Russell Elsberry . "Simulations of the Transformation Stage of the Extratropical Transition of Tropical Cyclones." *Monthly Weather Review* 129.6 (2001): 1462-80. Web.

Schneider D.,S. Sharp., "Radar Signatures of Tropical Cyclone Tornadoes in Central North Carolina." *Weather and forecasting* 22.2 (2007): 278-86. Web.

Schultz L. A.,D. J. Cecil, "Tropical Cyclone Tornadoes, 1950–2007." *Monthly Weather Review* 137.10 (2009): 3471-84. Web.

Smith John J. S. "The Hurricane-Tornado." *Monthly Weather Review* 93.7 (1965): 453-9. Web.

United States Geological Science Kansas Water Science Center (2011): Retrieved November 12 http://ks.water.usgs.gov/waterwatch/flood/definition.html. Web.

Verbout S. M., D.M Schultz, L.M. Lesile, H.E. Brooks, D. Karoly, K.L, Elmore "Tornado Outbreaks Associated with Landfalling Hurricanes in the North Atlantic Basin: 1954–2004." *Meteorology and atmospheric physics* 97.1-4 (2007): 255-71. Web.

Vescio M. D., S. J. Weiss, and F. P. Ostby, Tornadoes Associated with Tropical Storm Beryl. NWA Dig.,21.2(1996) , 2–10.