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Geographic Analysis of Tornadogenesis from Landfalling and Nearby Tropical Cyclones in the State of Florida

Geographic analysis of tornadogenesis from landfalling and nearby tropical cyclones in the state of Florida

By

Charles Eugene Roop

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Geographic analysis of tornadogenesis from landfalling and nearby tropical cyclones in the state of Florida

By

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Tropical cyclone (TC)-spawned tornadoes in Florida were analyzed to determine patterns of occurrence based on storm and geographic features. Tornadoes were determined to be associated with a landfalling or nearby TC if a tornado occurred within 800 km of the TC's center of circulation. TC-tornadoes were analyzed for patterns based on distance and angle from TC's center, topographic influences, population biases, and influence based on time of landfall. Most TC-Tornadoes tend to occur more often before landfall than after. It was discovered that tornadoes have occurred in different areas with respect to the bearing from the center depending on the landfall location and time of landfall. It was also discovered that land use type, and elevation had little to do with TC-Tornado occurrence. The results do suggest some population bias. The findings will be a guide for operational meteorologists to aid in forecasting likely tornadogenesis from TCs.

DEDICATION

I dedicate this thesis in memory of Erin Elaine Pelton (1985-2009), for she helped me by giving me the drive to pursue this dream.

ACKNOWLEDGEMENTS

I would like to thank Dr. Jamie Dyer for his support and patience through this research. I also give thanks to Dr. Andrew Mercer and Dr. Bill Cooke for being on my committee and sharing ideas. Kate Grala has also been a big help with guidance through the GIS analysis, and I thank her.

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TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Tropical Cyclones (TCs) can cause damage and bodily harm on a massive scale through damaging winds and deadly flooding (Barnes, 2007). After making landfall, the associated hazards for inland populations include coastal and inland flooding through storm surge and heavy precipitation, wind damage, and tornadoes. It's expected that TC-tornadoes can further enhance the effects of a TC by causing additional damage through enhanced local-scale wind magnitude. For instance, TC-tornadoes are believed to have caused $100 million in damage in the United States in 2005 (Schultz and Cecil, 2009).

The State of Florida is no exception to the TC and associated tornado threat. Since the state is a peninsula that has two water bodies that surround it – the Atlantic Ocean and the Gulf of Mexico - Florida is highly vulnerable to TCs. Florida's relatively flat terrain and its 1,300-mile long coastline are other physical reasons for its vulnerability (Barnes, 2007). The dense population of the state – especially along the coast - and its fragile tourist-reliant economy are other important reasons to explore TC-tornado relationships further.

Research in confirmed tornado events associated with landfalling TCs have yielded some answers into how and why tornadoes occur (Malkin and Gallaway, 1974; Hill, et al., 1966; Novlan and Gray, 1974). Hill et al. (1966) found that the incidence of tornadoes is related to the TC's direction of movement and the wind speed of the TC, such that tornadoes tend to occur in TCs originating from the Gulf of Mexico with a north-northeast track. Hill et al (1966) also find that tornadoes usually occur in the northeastern quadrant of the TC, relative to the central low pressure, and at a specific distance from the TC's center of circulation when the TCs are not in the decaying extratropical phase. The tornadoes were found in both inner and outer rain bands as well as convective cells around the TC. Vertical wind shear and helicity were determined to be the greatest on the right-front quadrant of the TC and were attributed to the presence of background environmental shear across the TC's track (McCaul, 1991; Baker et al, 2008). McCaul (1991) determined that Convective Available Potential Energy (CAPE) was the highest far to the right of the TC's track with the tornado outbreaks generally 200-400 km from the center of circulation, and generally higher in the rear of the TC than the front. McCaul (1991) also found that severe weather parameters that correlate best with TC-Tornado outbreak severity are helicity parameters and bulk Richardson number (BRN) shear.

Schultz and Cecil (2009) found that outer-region tornadoes had a stronger diurnal signal than inner, with the highest signal in the afternoon. This is believed to be caused by enhanced diurnal heating, which helps trigger thunderstorm activity. Inner region TC-tornadoes usually occur within 12 hours of TC landfall with no strong preference for the time of day, but can be four to five days out for slow-moving, quasi-stationary TCs.

Past literature (Malkis and Galaway 1953; Hill et al. 1966; Novlan and Gray 1974; Baker et al. 2008) notes that upper-tropospheric temperature and wind profiles associated with mid-latitude system tornadoes and tornadoes caused by TCs are different in terms of wind shear and available instability. Malkin and Galaway (1953) analyzed a

TC-spawned tornado from Hurricane Able in 1952, finding that the upper-air temperature and moisture profiles varied between baroclinic and barotropic environments. It was found that Able lacked a low-level temperature inversion, steep moisture gradient, and excessive instability since, for instance, the Showalter stability index only had a reading of zero for the area analyzed. Later research indicated that a key factor of TC-tornadogenesis would include dry air entrainment aloft (Hill et al. 1966; Novlan and Gray; Baker et al. 2008). Hill et al. (1966) noted that convective instability is a consequence of the dry air entrainment.

McCaul (1991) composed a composite sounding from TC-tornadoes within two hours and 40 km of a sounding launch site, finding that temperature profiles were conditionally unstable below roughly 650 hPa and surrounded by an absolutely stable layer. McCaul (1991) also found that relative humidity was high throughout the vertical profile with dewpoint depressions usually less than 6 °C. Curtis (2004) later found that the majority of TC-tornado outbreak cases in the study had dry air intrusion at the mid-levels with a pronounced relative humidity gradient. The dry air intrusion could either come from 1) a mass of dry air impinged on the northern or northwestern section of the TC's outer circulation, or 2) entrainment from an area of mid-level dry air usually located on the eastern section of the TC (Curtis 2004).

An example of a TC-tornado outbreak with distinct dry air intrusion characteristics is Hurricane George, which crossed over Puerto Rico, Hispaniola, and Cuba before making landfall near Gulfport, Mississippi on 28 September 1998 (Curtis 2004). Soundings from the impact area demonstrated not only a steep relative humidity gradient, but also dewpoint depressions of 8 - 10 °C at 700 hPa (Curtis 2004), which differed from McCaul's (1991) average dewpoint depressions of less than 6 °C.

Previous literature has given various kinematic properties where TC-tornadoes could occur (Hill et al.1966; Spratt et al, 1997; Novlan and Gray 1974; Schultz and Cecil, 2009). It has been suggested that strong vertical shear has played a greater role in tornadogenesis within TCs while instability played a minor role (Spratt et al, 1997; Novlan and Gray 1974). A vertical wind shear speed of about 40 knots is the average for tornadoes, but the frequency of tornadoes is less when the vertical shear is lower (Novlan and Gray 1974). Hodograph patterns indicate that winds do not change direction with height in TC-tornado environments as much as the average setup with Great Plains tornadoes (Novlan and Gray 1974). Sounding parameters were consistent with an increased tornado threat in the right-front quadrant where increased veering of vertical wind shear and increased helicity were evident (McCaul 1991; Schultz and Cecil, 2009).

TC-spawned tornadoes usually occur when the TCs initially move over land and undergo rapid filling (Novlan and Gray 1974). As a TC moves inland, the storm loses its contact with the ocean as a main fuel source. When the cooler air fills the TC, it allows for lower-level positive vertical wind shear to exist for a short time. The large magnitude wind shear can initiate tornadoes by enhancing horizontal vorticity, which could be lifted by a thunderstorm updraft and help initiate tornadoes. Novlan and Gray (1974) note that most tornado-TCs have substantially more vertical shear 1-2 km above ground level than with non-tornadic environments. Favorable deep layer shear is important in TC-tornado development (McCaul 1991) since shear aids in the dynamics needed to form a tornado. Baroclinic boundaries enhance localized lift, which accompanies low-level vertical wind shear and storm relative helicity (SRH), and indicate transitions in stability (Baker et al. 2008; Markowski et al. 1998a,b; Rao et al. 2005).

Coastal influences can enhance tornadogenesis, as found by Rao et al. (2005) and Baker et al. (2008). Rao et al. (2005) found a mesocirculation over the Gulf of Mexico from Tropical Storm Frances in 1998, which made landfall near Victoria, Texas on 11 September. The small-scale mesocyclone existed over the Gulf of Mexico until it struck the coastline and spawned a tornado soon afterwards. Research into a tornado outbreak spawned by Hurricane Ivan's landfall near Gulf Shores, Alabama in 2004 (Baker et al. 2008) found that thunderstorm cells intensified and produced tornadoes soon after arriving onshore. Not only was the shallow and deep vertical wind shear helpful, but increased CAPE was likely a factor due to the dry air intrusion (Baker et al., 2008). Baker et al. (2008) noted that many of the tornado events occurred in the Florida panhandle with close proximity to the coastline. Research into the state's TC-tornado impact is relevant because of Florida's extensive coastline. The water-to-land transition can increase frictional effects, which decrease the wind at the surface and increases vertical wind shear to aid in the development of meso-scale rotation (Novlan and Gray, 1974; Gentry 1983; Schultz and Cecil, 2009).

Anthropogenic impacts along the coastline could also affect TC tornadogenesis. Coleman and Knupp (2009) stated that it's possible the Panama City, Florida tornado that was associated with Hurricane Ivan could have been initiated or enhanced by "positive ambient vorticity" associated with abundant high-rise buildings nearby. Coleman and Knupp (2009) believed it was possible that friction slowed the winds, which caused an area of positive vorticity that enhanced the mesocyclone and aided in the development of the tornado.

Despite the findings highlighted in previous papers, very little research related to TC-tornadoes with a geographic focus on the state of Florida has been conducted. Articles found on tornadogenesis from landfalling TCs have been either geographically broad or TC specific (e.g., Malkin and Gallaway, 1974; Hill, et al., 1966; Novlan and Gray 1974; Baker et al. 2008; Rao et al. 2005). Florida's unique land surface pattern and geography, relatively flat terrain, and its 1,300-mile long coastline (Barnes, 1998) are some of the physical reasons for investigating the phenomenon of TC-spawned tornadoes. The dense population of the state – especially along the coast - and its fragile tourist-reliant economy are other important reasons to explore TC-tornado relationships further. Patterns of TC-spawned tornado touchdowns could help in creating a forecasting methodology for approaching TCs. Forecast products could highlight enhanced risks of tornadoes in a particular storm, allowing the public to take appropriate precautions.

The objective of this research is to study the geographic patterns of tornado touchdowns in TC environments over Florida to identify possible surface features associated with TC tornadogenesis. There will be a need to investigate a) when they occur relative to landfall, b) the location of the tornadoes relative to the TC's center of lowest pressure, and c) their relationship with land features and population centers. The goal of the research is to be able to assist in forecasting tornado probabilities when TCs threaten landfall in Florida based on any geographic patterns discovered. The high population density of Florida, the socio-economical threat and impacts, and the large coastline gives this research heightened importance.

CHAPTER II

DATA AND METHODOLOGY

The data for this project include TC-tornadoes recorded in the United States from 1950–2011. To create the research data set, confirmed tornado reports from 1950–2011 were gathered from the National Climatic Data Center (NCDC) archive (National Climatic Data Center, 2012) and compared to the National Hurricane Center (NHC) tropical cyclone tracks archive, HURDAT (Hurricane Research Division, 2012). The data were reduced to tornado reports that occurred between the time of TC impact and the time that the TC was no longer tracked by the NHC. The time of impact is when a TC-Tornado occurred within 800 km from the center of circulation; therefore, the TC had to be within 800 km of any location in Florida. The hurricane positions from HURDAT, recorded every six hours, were linearly interpolated to hourly track positions and were matched with the sub-hourly tornado positions and times occurrence. For example, if a TC-Tornado occurred at 0012 UTC, it was associated with the TC location at 0000 UTC, while a TC-Tornado occurring at 0040 UTC would be associated the TC location at 0100 UTC. The distance and angle of the TC-Tornadoes from the center of circulation were calculated using Euclidian distance. The data also include TCs that did not make landfall in Florida since McCaul (1991) showed the furthest TC-spawned tornado to be just below 800 km from the TC's center. An example would be Hurricane Ivan, which made landfall on 16 September 2004 in Gulf Shores, Alabama (Baker et al. 2008).

Recent research by Agee and Hendricks (2011) has given reason to decrease the study period to TCs and tornadoes spawned between 1996 and 2011. Agee and Hendricks (2011) indicated a bias in reported tornado occurrences before the implementation of the National Weather Service (NWS) Doppler radar systems and after implementation of the systems. For instance, it was found that pre-Doppler years had a TC-tornado occurrence mean of 1.92 while the post-Doppler era had a mean of 3.85 TC-tornado occurrences. To eliminate the risk of negatively affecting the project results by incorporating a dataset with a known bias, it was decided to remove all TC-tornado events prior to 1996 and focus on occurrences from 1996 - 2011. Once the data were sorted, a total of 248 TC-Tornadoes were counted and plotted (Figure 1).

The analysis for this paper consists of three main pillars based on the stated objectives: Temporal analysis of TC-Tornadoes, spatial relation of tornadoes with TC centers of circulation, and the relationship of TC-Tornadoes with respect to geographic features. The analysis of the relationship with geographic features includes kernel density analysis to determine TC-Tornado “hot spots”, population, land features, and elevation.

Temporal analysis looks into all TC-Tornado events to determine when tornadoes occur relative to the TCs that make landfall. This indicates when tornadoes are likely to develop as a TC approaches the coast or after the TC makes landfall. To calculate the time of landfall, the time and date of landfall in the United States were used from the Tropical Cyclone Reports from the National Hurricane Center (NHC). Many of the TCs made only one landfall in or near Florida, but there are a few storms that have multiple landfalls or other characteristics that require additional consideration. The methods of determining landfall of some of these TCs can be found in Appendix A.

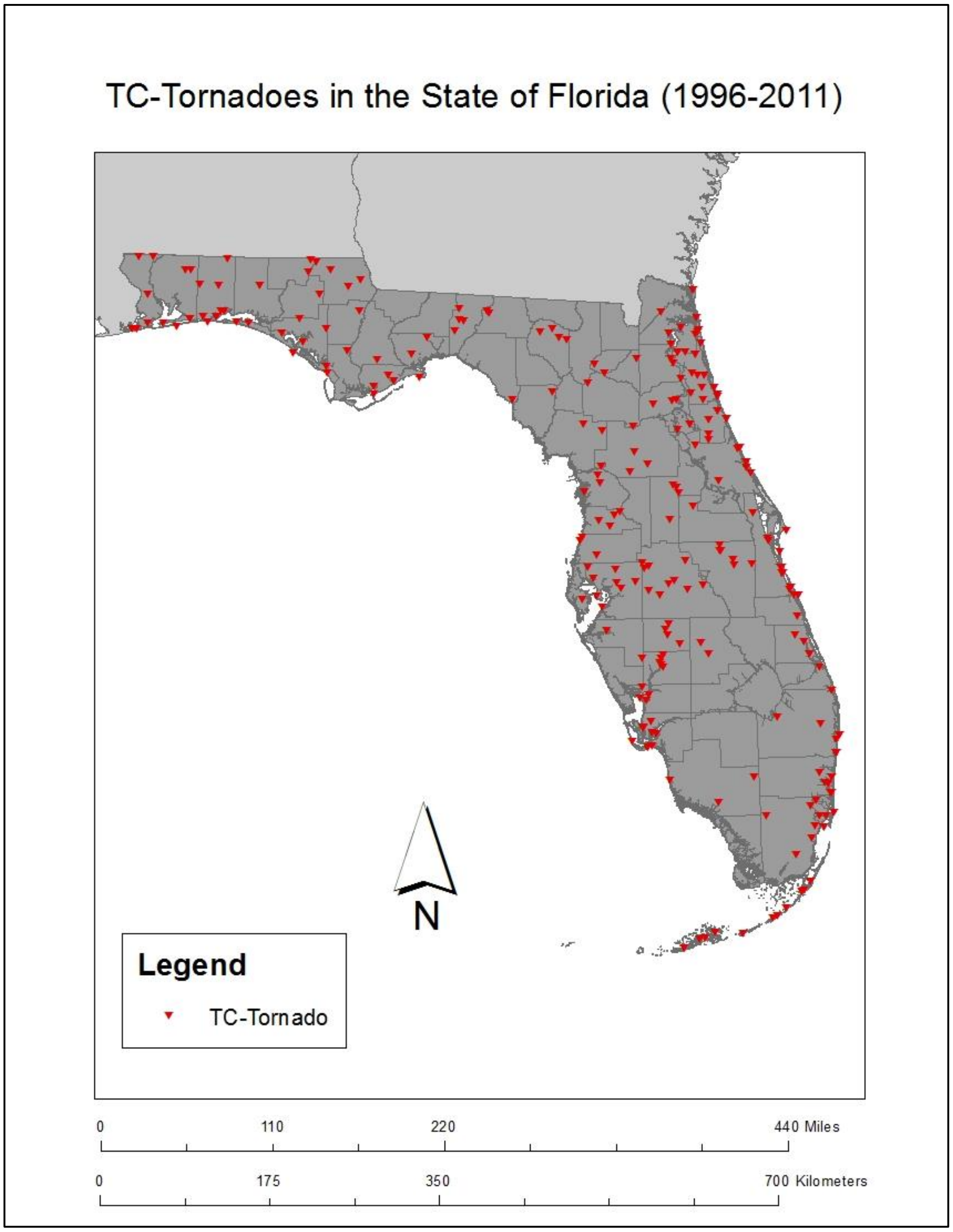

Figure 1 TC-Tornadoes in the State of Florida (1996-2011).

The spatial relationship of tornadoes relative to a TC's center of circulation indicates the relative location of possible tornado development within a TC. To do this, the calculated distance and bearing of each TC-Tornado from the TC's center of circulation was calculated. The temporal analysis already sorted which TC-Tornadoes occurred before or after landfall. These data points were then tallied and split into four categories: Western TCs before landfall, western TCs at or after landfall, eastern TCs before landfall, and eastern TCs at or after landfall. With these four categories, patterns of tornado occurrence – distance from the TC and bearing – were determined. Also, a ratio d/D, the distance of the tornado from the center divided by the radius of the outer-closed isobar (ROCI), was calculated for each TC-Tornado to determine whether the TC-Tornado occurred within the ROCI or outside the ROCI. A ratio of less than 1 indicates that the TC-Tornado occurs within the ROCI, and greater than 1 if outside the ROCI. Some TC-Tornadoes have incomplete d/D ratios because of missing ROCI data.

For geographic relationships, Moran's I is used to determine the best search distance for performing kernel density analysis. Moran's I is a spatial statistical method of determining spatial autocorrelation between different locations (Li et al, 2007; Moran 1950). Spatial autocorrelation can be briefly described as a realization of the First Law of Geography: Values at nearby locations are more correlated than values at locations further away (Tobler 1979; Malczewski 1999). To determine what distance to use for each of the kernel density analyses, Moran's I was run on all TC-Tornado events, eastern landfall events, and western landfall events separately. The highest Z-score associated with a search radius tested was used for each respective analysis. For instance, for all TC-Tornado events, the highest Z-score (5.30) was associated with 95 km; therefore, a 95-km search radius was used for the kernel analysis. The kernel density analysis determines locations of high-density TC-Tornado events in Florida.

The elevation of the state was taken into account to determine any relationships with TC-Tornado occurrence. The topography of the state is relatively flat compared to other states in the United States. The highest point in Florida is at Britton Hill in Walton County where it’s 105 meters (345 feet) above ground level (AGL) (United States Geological Survey, 2005). A digital elevation model (DEM) for the state from the United States Geological Survey (USGS) was used with the original resolution of 30 meters (Figure 2). Both the DEM and kernel density were resampled to 15 km since the DEM was too fine of a resolution for the geographic coordinates given for the TC-Tornado events. After resampling the DEM at 1 km, 15 km, and 25 km, it was decided to chose the 15 km to not only decrease the resolution sufficient enough for the geographic coordinates given, but to eliminate the risk of noise in the data to better determine any relationships with elevation and TC-Tornado occurrences.

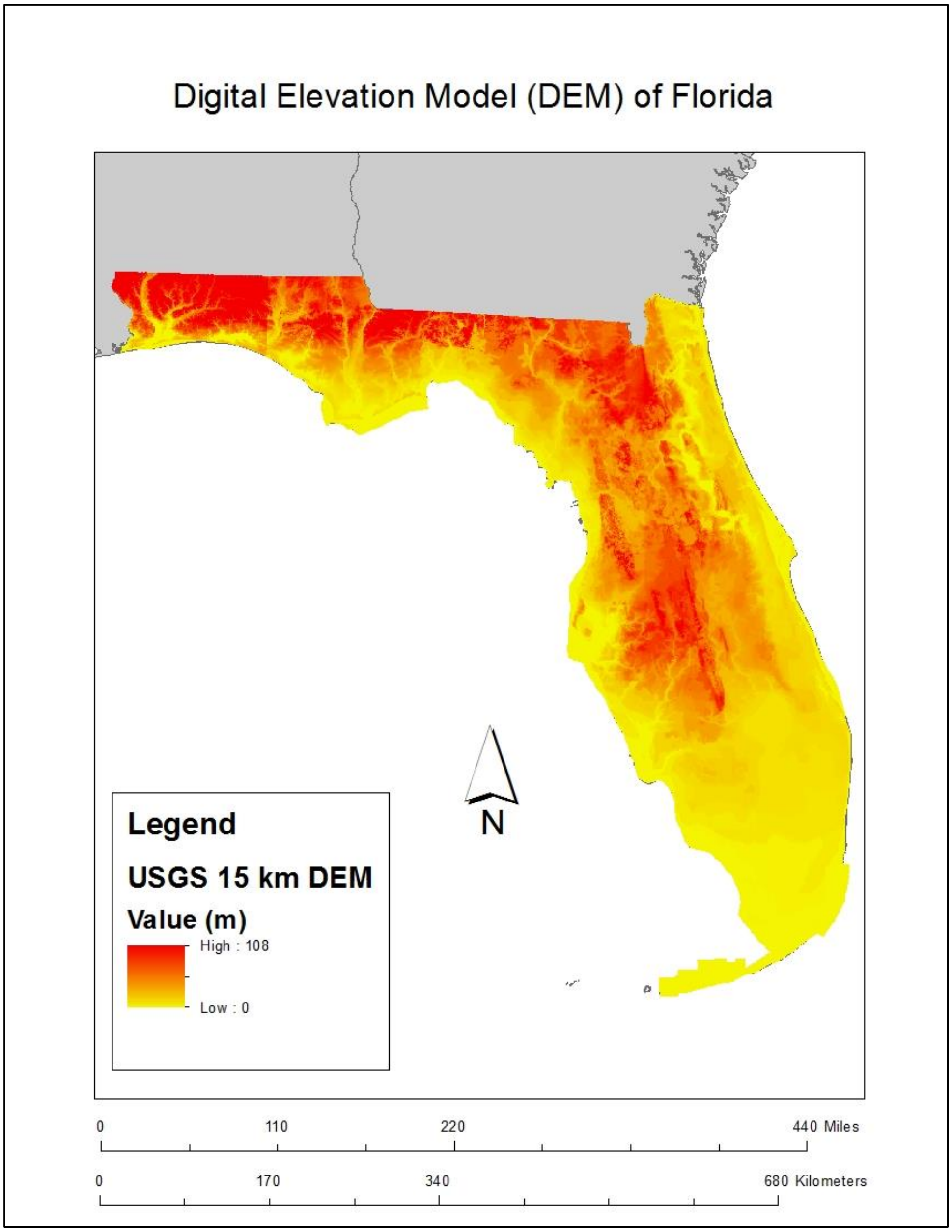

Figure 2 Digital Elevation Model (DEM) of Florida. The data are from the United States Geological Survey.

The land use and vegetation types were analyzed to determine any patterns of TC-Tornado occurrence. Land use data were compiled by the Florida Fish and Wildlife Conservation Commission and contained 43 detailed land class types (Table 1). These were condensed into 10 groups (Table 2) based on shared characteristics to decrease the number of categories in the analysis: Coastal, Scrub, Pines, Swamp/Marsh, Open Water, Shrub/Grassland, Agriculture, Exotic, Urban, and Extractive. The data were normalized by taking the percentage of all TC-Tornadoes in their respective land type location and dividing it by the percent of the land cover pixels in the state, which were 30-meter blocks. All but one of the 248 TC-Tornadoes were assigned land use classifications since a tornado associated with TC Ivan in 2004 occurred in an area with missing land use data.

To determine TC-tornado relationships with population density, population data from 2009 on a county level from the United States Census Bureau were retrieved. TC-Tornado events were counted for each of Florida's 67 counties. This data were used to determine both population and TC-Tornado densities for each county. The TC-Tornado densities were normalized with population densities for each county.

Table 1 Land use types across Florida complied by the Florida Fish and Wildlife Conservation Commission.

VALUE	CELL COUNT	PERCENT OF LAND	LAND CLASS
1	65,802	0.035917	Coastal Strand
2	143,173	0.078149	Sand/Beach
3	640,054	0.349366	Xeric Oak Scrub
4	849,882	0.463898	Sand Pine Scrub
5	3,353,948	1.830711	Sandhill
6	5,302,572	2.894344	Dry Prairie
7	3,910,166	2.134316	Mixed Pine-Hardwood Forest
8	4,301,223	2.347770	Hardwood Hammocks and Forest
9	28,764,646	15.700829	Pinelands
10	42,269	0.023072	Cabbage Palm-Live Oak Hammock
11	65,086	0.035526	Tropical Hardwood Hammock
12	9,498,657	5.184725	Freshwater Marsh and Wet Prairie
13	2,975,605	1.624197	Sawgrass Marsh
14	279,150	0.152371	Cattail Marsh
15	4,711,530	2.571731	Shrub Swamp
16	902,087	0.492393	Bay Swamp
17	6,788,981	3.705682	Cypress Swamp
18	198,290	0.108234	Cypress/Pine/Cabbage Palm
19	6,402,210	3.494568	Mixed Wetland Forest
20	8,007,589	4.370844	Hardwood Swamp
21	156,558	0.085455	Hydric Hammock
22	377,250	0.205917	Bottomland Hardwood Forest
23	1,942,232	1.060143	Salt Marsh
24	2,500,504	1.364869	Mangrove Swamp
25	27,429	0.014972	Scrub Mangrove
26	65,183	0.035579	Tidal Flat
27	32,966,178	17.994184	Open Water
28	7,278,091	3.972657	Shrub and Brushland
29	347,079	0.189449	Grassland
30	4,804,822	2.622653	Bare Soil/Clearcut
31	12,869,229	7.024511	Improved Pasture
32	615,350	0.335881	Unimproved Pasture
33	2,237,919	1.221541	Sugar cane
34	4,103,099	2.239626	Citrus
35	6,159,587	3.362135	Row/Field Crops
36	974,794	0.532079	Other Agriculture
37	228,881	0.124932	Exotic Plants
38	557	0.000304	Australian Pine
39	288	0.000157	Melaleuca
40	2,979	0.001626	Brazilian Pepper
41	13,503,861	7.370917	High Impact Urban
42	4,285,979	2.339449	Low Impact Urban
43	553,864	0.302320	Extractive

Table 2 Reclassified land use types across Florida with the TC-Tornado counts for each land class, TC-Tornado percentage, the percent of land use cover in the state, and the normalized result.

	Tor Count	Tor Percent	Percent of Land	% LC / % LC Type
Coast	0	0.00	0.110	0.00
Scrub	5	2.02	5.540	0.36
Pines	48	19.40	20.210	0.96
Swamp/Marsh	39	15.80	24.510	0.64
Open Water	54	21.90	17.990	1.22
Shrub/Grassland	15	6.07	4.160	1.46
Agriculture	21	8.50	17.300	0.49
Exotic	2	0.81	0.127	6.38
Urban	63	25.50	9.710	2.63
Extractive	0	0.00	0.300	0.00

CHAPTER III

RESULTS AND DISCUSSION

Temporal Analysis of TC-Tornado Occurrence Relative to TC Landfall

The results for all TC-tornadoes show that the maximum time from landfall where a tornado occurred was 96 hours after landfall while the minimum time was 95 hours before landfall. The average time of occurrence was around 9 hours before landfall with a median of 6 hours before landfall. The 25th percentile of TC-tornado occurrences was 15 hours before landfall while the 75th percentile was 2 hours after landfall. The histogram shows a spike in activity before zero hour and a drop in frequency after landfall (Figure 3).

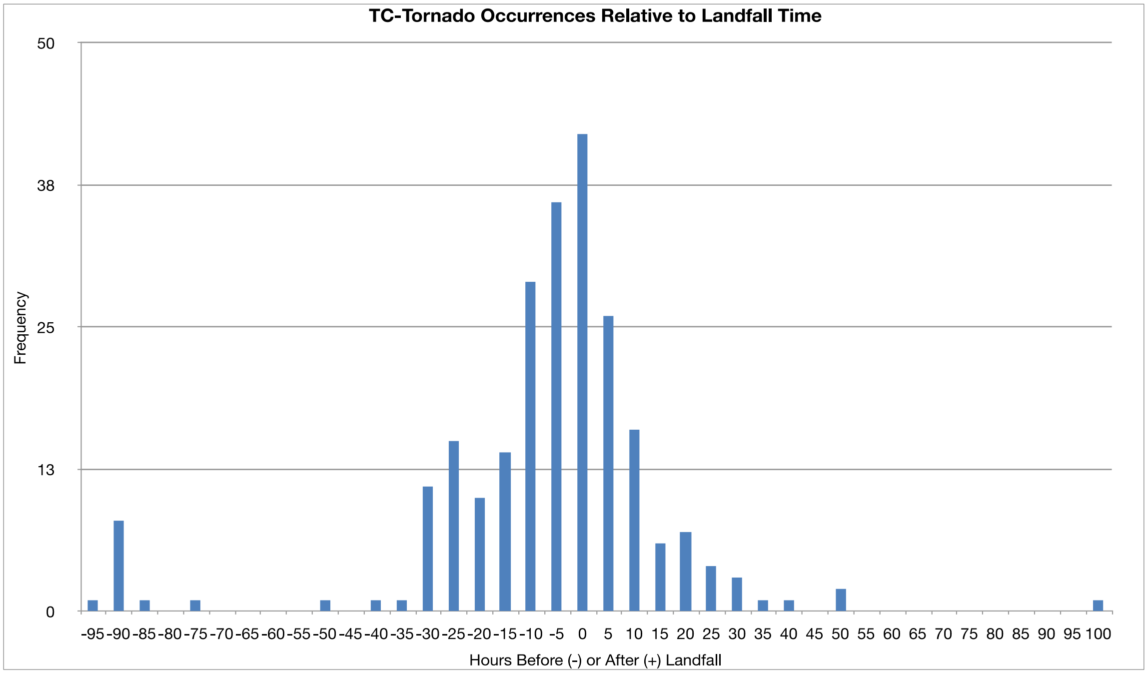

Figure 3 TC-Tornado Occurrences Relative to Landfall Time.

The findings for all landfall locations indicate that about 53% of TC-tornadoes occur within roughly 24 hours before landfall. Possible reasons into the results could be that a) the outer rain bands approach the shore before the center of the TC's circulation, and b) if the TC is approaching from the west, the best shear will be approaching before landfall. The outer bands can allow for thunderstorm development, and if thunderstorms develop with adequate updrafts in zones of sufficient shear, there is a higher potential to have tornadoes develop. The outer rain bands also have the best opportunity for breaks in cloud cover, which would allow for the best instability in that given area due to increased surface heating

The data were also split between eastern and western landfalls. The western landfalling TCs had a maximum time after landfall of 96 hours, with the minimum at 86 hours before landfall (Figure 4). The average time of TC-Spawned tornadoes was around six hours before landfall, with the median at zero hour. The 25th percentile of TC-tornado occurrences was 13 hours before landfall while the 75th percentile was at zero hour.

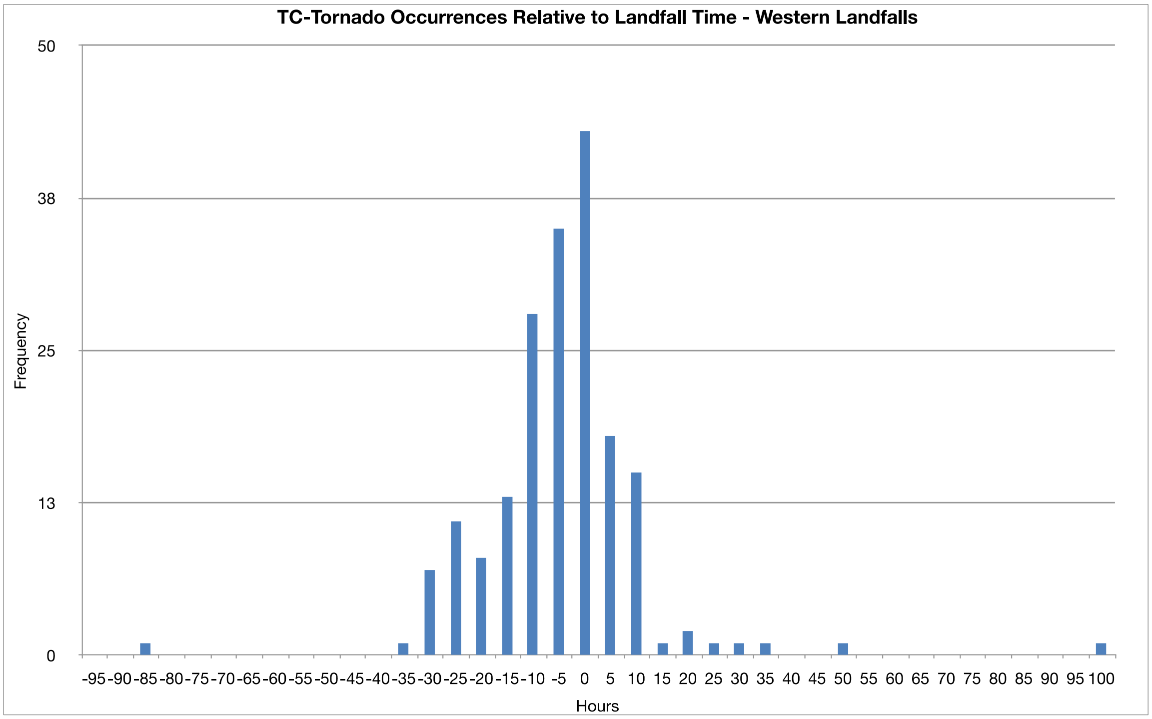

Figure 4 TC-Tornado Occurrences Relative to Western Landfall Time.

The eastern landfalling TCs had a maximum time of 47 hours after landfall, with the minimum at 95 hours before landfall (Figure 5). The average landfall time was 15 hours before landfall. The 25th percentile of eastern TC-tornado occurrences was 30.5 hours before landfall while the 75th percentile was 14 hours after landfall, with a median at zero hour. It’s important to note that the incident count for eastern-landfalling TCs is far less (60) than the western (187)

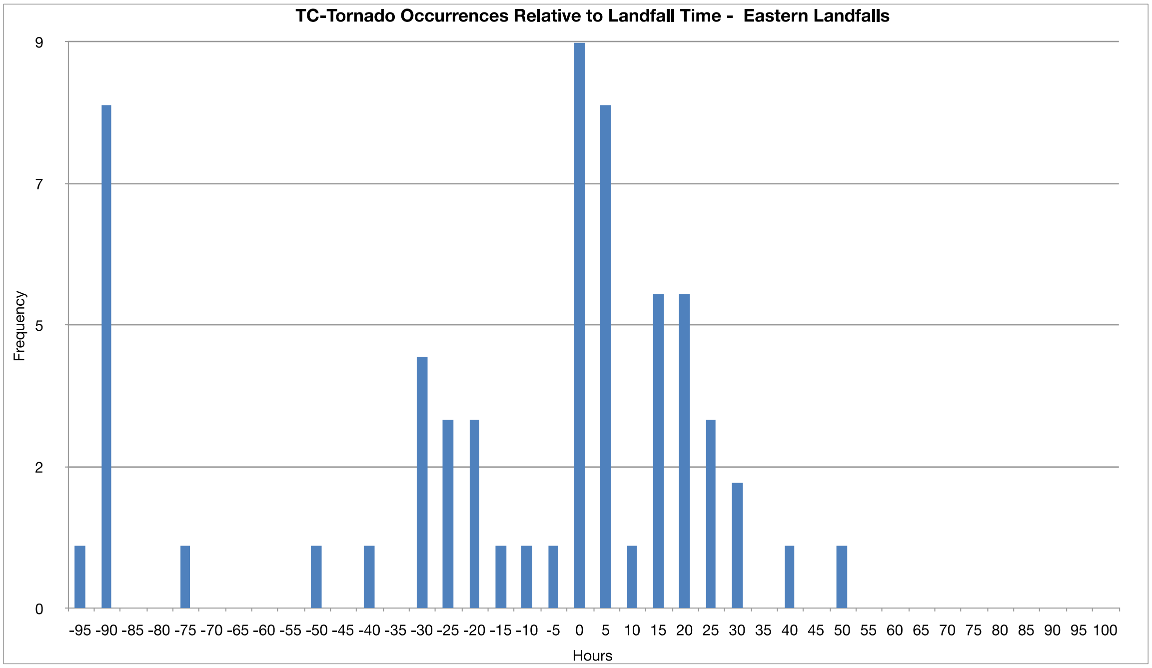

Figure 5 TC-Tornado Occurrences Relative to Eastern Landfall Time.

When divided into eastern and western landfall, some different patterns are discovered. There is a quick drop off - from 15 events 6 to 10 hours after landfall to 1 event 11-15 hours after landfall - of TC-tornado incidents after zero hour in western landfalling incidents. Eastern events show a gradual drop-off of events compared to western events (Figure 5).

The later eastern landfall TC-tornado incident times have one possible explanation. After TCs make landfall on the eastern side of the state and continue westward across Florida, tornadoes can develop on the southeastern quadrant of the TC well after landfall. The TC-tornadoes are likely possible because of the deep southerly flow on the eastern side, advecting moisture. Also, the best shear is on the eastern side of the TC. If there are breaks in the clouds on the eastern side after TC landfall, this allows for sufficient diurnal heating to help initiate thunderstorms

Storm-Centric Analysis of TC-Tornadoes

All TC-Tornadoes

TC-Tornadoes generally occur on the eastern and northeastern side of the TC. Nearly 40% (100 incidents) of all the TC-Tornadoes took place between 45 and 90 degrees, or the east-northeast portion of the TC (Figure 6). The second and third most common locations of TC-Tornadoes were in the north-northeast and east-southeast portions, respectively. The mean direction was 63°. The resultant vector is 168.77 while the circular variance is 0.328. Compared to TC-Tornadoes that occur before western landfall (circular variance of 0.124) and after eastern landfall (0.492), the clustering for all TC-Tornadoes is somewhat weak.

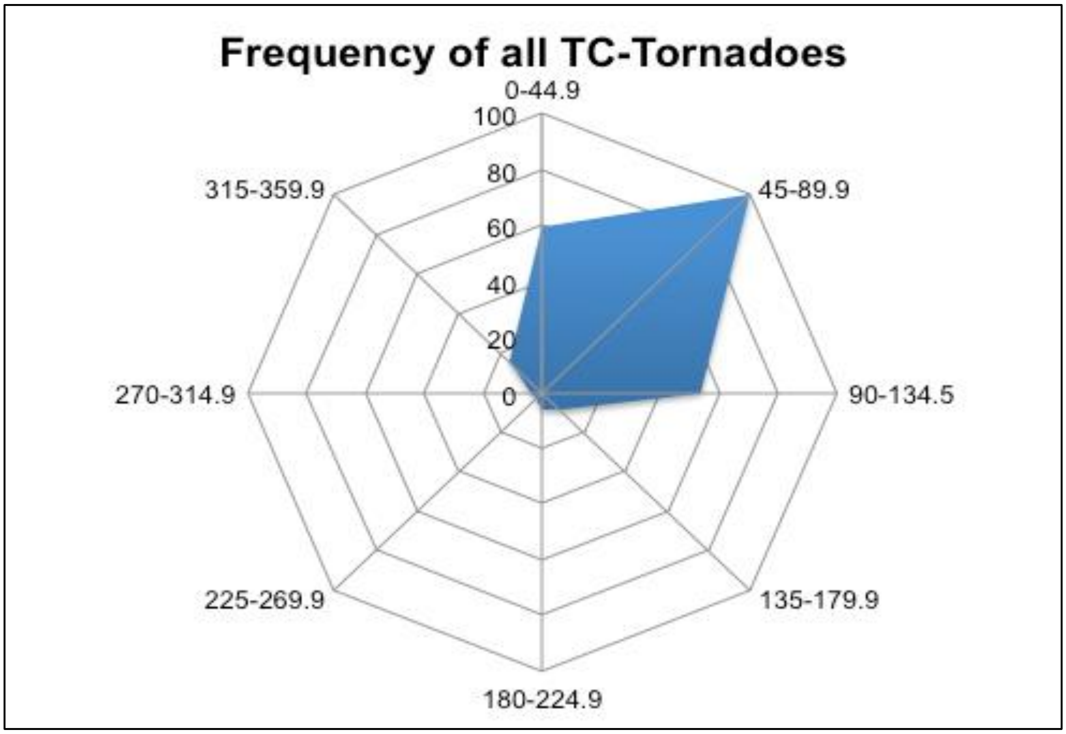

Figure 6 The Frequency of angle (in degrees) from the center of circulation of all TC-Tornadoes.

Based on the results, it appears that grouping of TC-Tornadoes normally prefers the east-northeastern portion of the TC. However, 84% (213 incidents) occurred between 0 and 135 degrees. Considering that the majority of the TC-Tornadoes are from western landfalls (188 incidents), it would appear that the 213 aforementioned incidents are heavily influenced by the western landfalling TCs.

The frequency of TC-Tornadoes with regard to distance from the center of circulation shows that most of the tornadoes occur within 100 to 500 km of the center of circulation (Figure 7). Between 100 and 500 km, a total of 76% (192 count) of the TC-Tornado incidents were recorded. Nearly 22% occur within 200 to 300 km from the center of the TC.

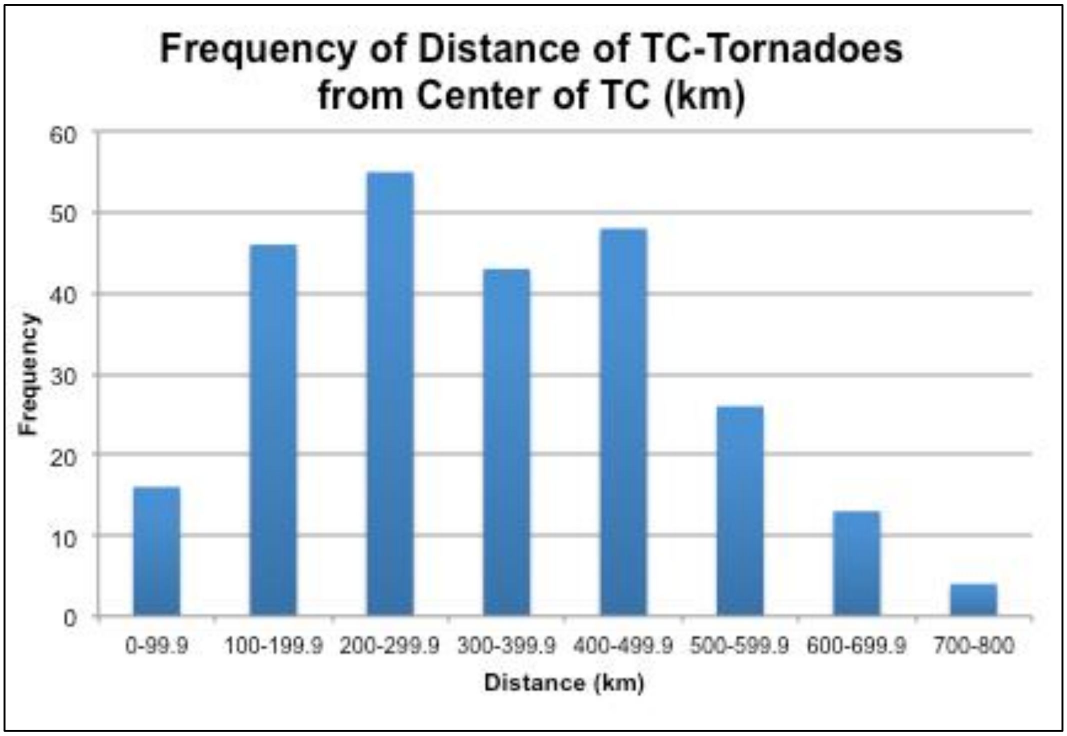

Figure 7 The Frequency of range (in km) from the center of circulation of all TC-Tornadoes.

The frequency gives an impression that very few tornadoes occur less than 100 km from the center of circulation, and greater than 500 km. After 500 km, the tornado frequency decreases through 800 km. Reasons behind these patterns are explained based on their landfall locations and timing.

Western Landfall

Before Landfall

For landfalling TCs approaching Florida from the western side, the majority have occurred in the east-northeast side of the TC (62%, 84 incidents; Figure 8). All have occurred on the eastern side of the TC, with none on the western side. The mean angle is near 65°. The resultant vector was 119.08 and the circular variance was 0.124. The data suggest that there is clustering of the east-northeast location of tornadoes from the center of circulation. A possible reason for the distribution is the location for the tornadoes with respect to the angle from the center of circulation. The best helicity is normally located in the northeastern quadrant of the TC (Schultz an Cecil, 2009).

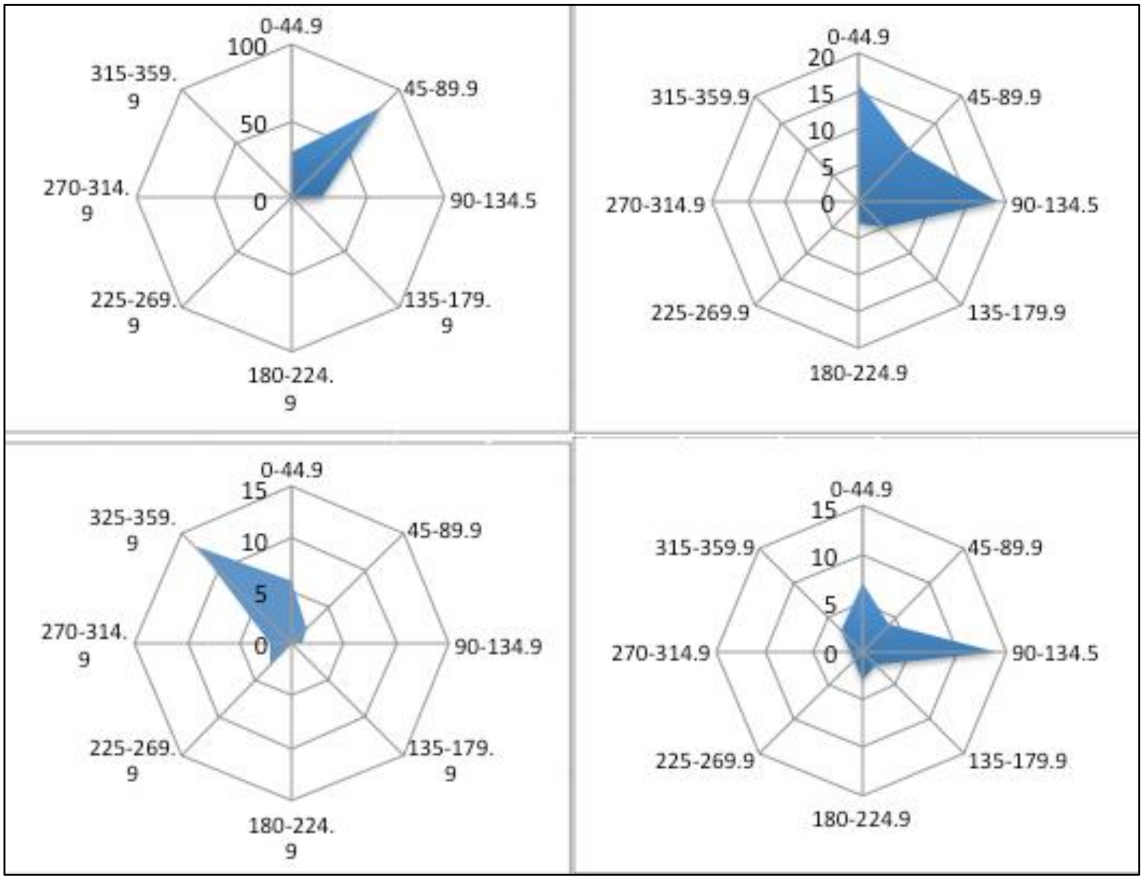

Figure 8 The Frequency of range (in degrees) from the center of circulation of TC-Tornadoes from (clockwise) western landfalls (before), western landfalls (at or after), eastern landfalls (at or after), and eastern landfalls (before).

The frequency of TC-tornado distances from the center of the storm normally distributed, with the maximum frequency of occurrences (24%) between 300 and 400 km from the center of circulation (Figure 9).

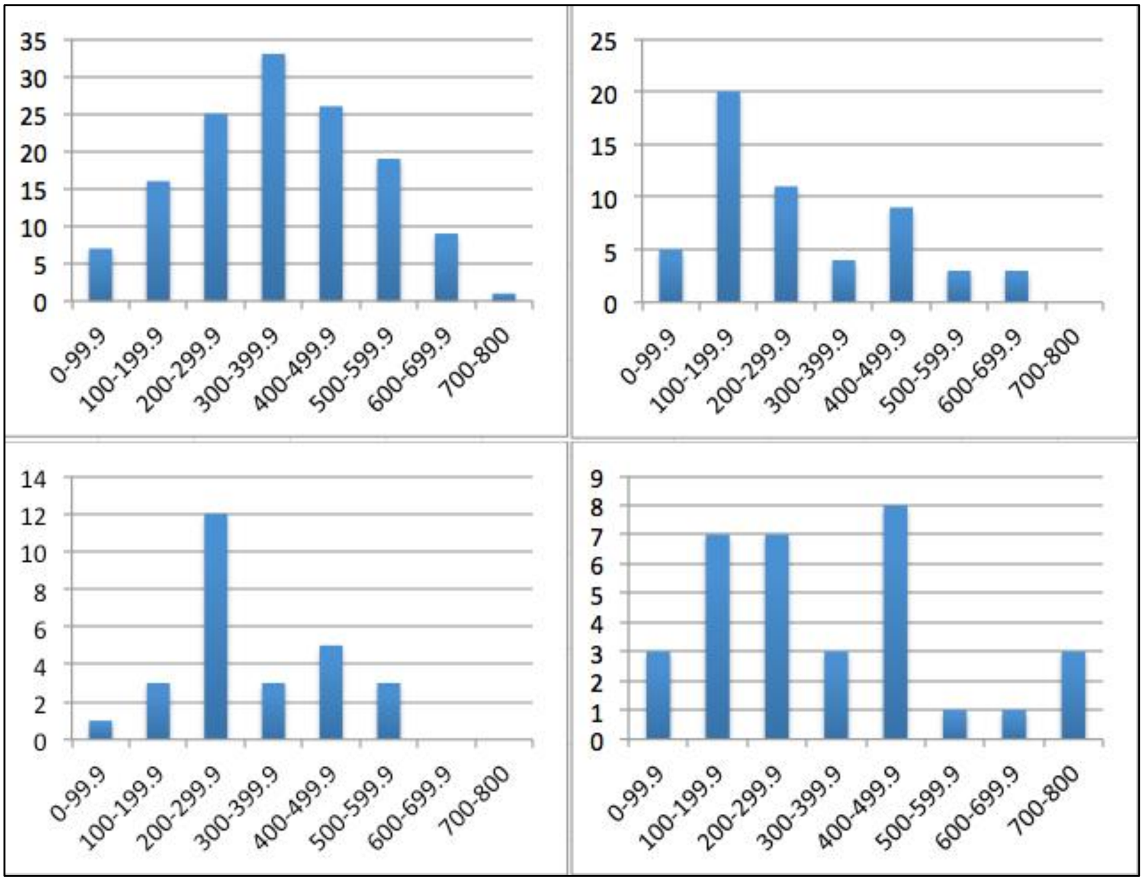

Figure 9 The Frequency of range (in km) from the center of circulation of TC-Tornadoes from (clockwise) western landfalls (before), western landfalls (at or after), eastern landfalls (at or after), and eastern landfalls (before).

Nearly 70% (95 incidents) of the TC-Tornadoes occur with a d/D ratio less than 1. This gives the indication that most of the events are in the inner portion of the TC. One explanation could be that as a TC nears the coast, strong low-level vertical shear can increase as the effects of friction begin (Schultz and Cecil, 2009). The increased friction could increase convergence and, therefore, provide increased vertical uplift and stretching of vorticity (Schultz an Cecil, 2009).

At or After Landfall

The angle of the TC-tornado incidence is multimodal as the majority is occurring in the north-northeast (29%, 16 incidents) and the east-southeast (35%, 19 incidents; Figure 8) sections. The third most frequent direction is from the east-northeast (18%, 10 incidents). Since the data are multimodal, the mean degree calculated, 79°, is not entirely relevant. The resultant vector is 31.88 and the circular variance is 0.42.The majority of the TC-Tornadoes (36%; 20 incidents) occur between 100 and 200 km from the center of circulation (Figure 9). The distribution is skewed to the left as the three top peaks of tornado activity occur between 100 and 300 km, and 400 to 500 km.

The multimodal distribution is likely because of the tornadic thunderstorm development in the northern portion of the storm right at landfall and tornadoes developing in the east-southeastern sub quadrant well after landfall. The average distance from the center of circulation is 274 km with an average distance of the ROCI of 316 km, which suggests that most of the TC-tornadoes are not in the outer fringes of the circulation (9 out of 47 events had a d/D ratio of greater than 1). It is possible that some of the TCs that make landfall deteriorate in strength in response to losing the latent heat energy from the water bodies they originated from, allowing for breaks in the clouds to help initiate instability at the surface and aid in the generation of thunderstorms with adequate updrafts in areas of sufficient SRH to develop tornadoes. It's important to note that TC-Tornadoes in neighboring Alabama and Georgia are not being tracked; therefore, the average TC-Tornado occurrence from the center of circulation may be affected by the omission of events from those neighboring states.

Eastern Landfall

Before Landfall

The eastern landfall TCs give a different set of tornado occurrences relative to the angle from the center of circulation compared to western landfalls (Figure 8). Almost half of the tornadoes (13 incidents) have occurred in the north-northwest side of the TC before landfall. The second top location (22%, 6 incidents) has been the north-northeast side. Tornado occurrences have been absent in the south-southeast and south-southwest portions of the TC. The mean angle of occurrence was 344.4°. The resultant vector is 19.35 and the circular variance is 0.283. The lower resultant vector relative to the western landfall cases is likely due to the lower count of TC-tornado occurrences than the eastern cases.

Nearly 44% of the TC-tornadoes (12 incidents) occurred within 200 and 300 km from the center of circulation (Figure 9). There is a relative peak of activity between 400 and 500 km from the center – nearly 19% of cases (5 incidents), but there were no occurrences beyond 600 km. The average distance from the center was around 317 km with the average ROCI distance of 418 km, indicating that most of the TC-tornadoes occurring within the TC's circulation (only 3 of 25 events) had a d/D ratio greater than 1.

The likely reason for the predominant north-northeast and north locations of events is likely because of the easterly direction of the storm. As a TC approaches the state from the east, it's possible that the elevated low-level shear along the coast along with any thunderstorm bands with sufficient updrafts can help initiate tornadoes. There also appears to be a relationship with the orientation of the eastern Florida coast and the north-northeasterly orientation of events.

At or After Landfall

Most of the TC-tornadoes occurred in the east-southeastern portion of the TC – nearly 42% (14 incidents, Figure 8). This is nearly a compete switch from tornadoes initiated before eastern landfall. 21% have occurred in the north-northeastern portion (7 incidents). No tornadoes were spawned in the west-southwestern and west-northwestern portions of the TC. The mean angle of incidence was 86.9°. The resultant vector was 16.75 while the circular variance was 0.492. Again, the lower resultant vector compared to western landfalls is likely due to the lower data sample size. The circular variance is the highest of the landfall locations and times, indicating greater variability of tornado incident locations.

The occurrence of TC-Tornadoes relative to distance from the center of circulation peaks between 100 to 300 km and 400 to 500 km (Figure 9). The highest amount was between 400 and 500 km from the center – 24% (8 incidents) of all incidents. The average distance of TC-tornadoes is 337 km, while the average ROCI distance is approximately 389 km. Only 4 out of 23 events had a d/D ratio greater than 1.

The shift from the high-frequency north-northwest events before landfall to east-southeast events may have a few causes. After a TC makes landfall along the eastern coast of Florida, coastal and inland areas would be under the influence of the eastern half of the TC, where the best shear is located. Also, the eastern side pulls in additional moisture and instability from the Atlantic. Any breaks in cloud cover on the eastern side along with additional moisture at the surface could enhance instability, generate thunderstorms with sufficient updrafts, and enhance the potential for tornado development.

Geographic Analysis of TC-Tornado Occurrence

Density

All TC-Tornadoes have clusters of high density in northeast Florida within roughly 50 km of the coast (the highest density), in southeast Florida, and a swath from Port Charlotte north to near the Tampa Bay metro area. There are a few localized, high-density clusters near Port Charlotte, east of Pensacola, east of Tampa, and just south of Cape Canaveral (Figure 10).

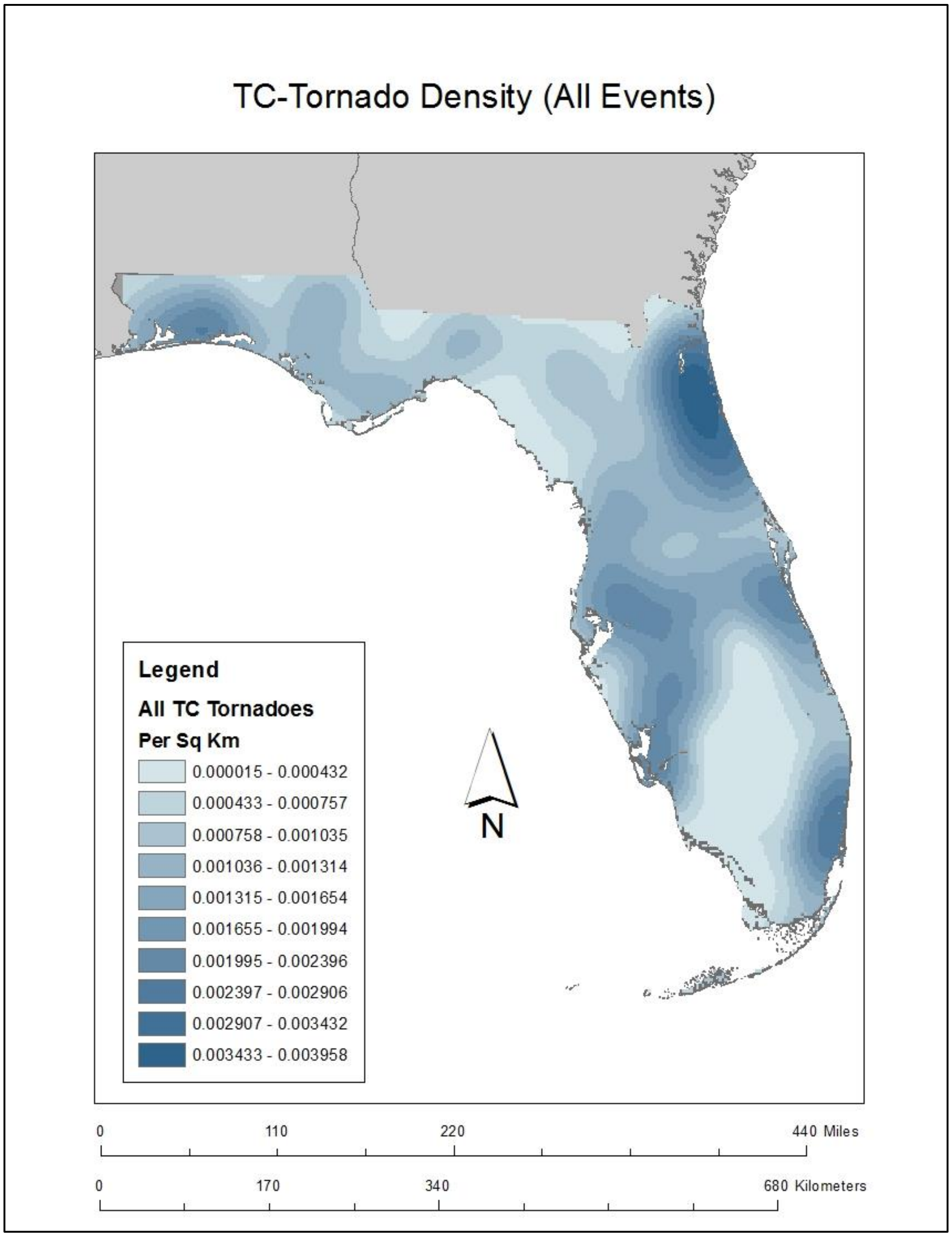

Figure 10 Kernel Density output for all TC-Tornadoes in Florida between 1996-2011, run at a 70 km search radius.

There are some possible reasons for the patterns shown. The high-density cluster in southeast Florida could be at least partially attributed to the highly populated areas including Miami and Fort Lauderdale. If there were more people to observe tornadoes, then the observation count per area could be higher than in low population density areas (e.g. the Everglades). Many of the high TC-tornado densities are relatively close to the coastline. When a TC and associated thunderstorm band approaches the coastline, the surface winds interact with the land and friction increases, therefore slowing down the surface winds. As the surface winds decrease, winds aloft are still relatively faster. The friction interaction increases horizontal speed shear, and, if a thunderstorm with a sufficient updraft is in the vicinity, this can increase the likelihood of tornadogenesis.

TC-Tornadoes from eastern landfalls have similar patterns to all events. There are two high-density hot spots: The Jacksonville - Saint Augustine area, and the Miami-metro area (Figure 11). There is a west-to-east belt of mid-range density of TC-Tornado events from near Spring Hill east to near Vero Beach. Other small clusters exist near Destin, near Live Oak, and the Port Charlotte area.

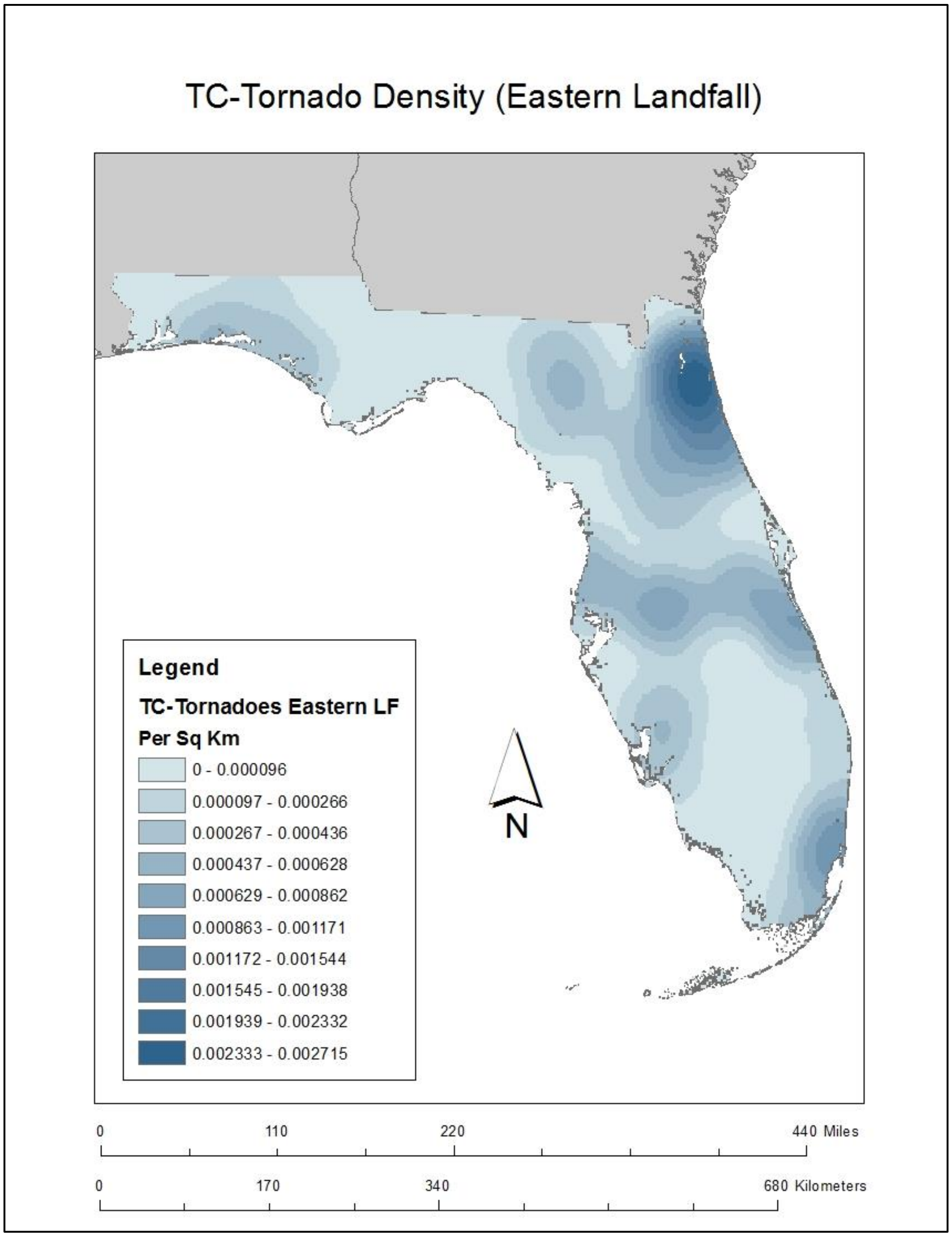

Figure 11 Kernel Density output for TC-Tornadoes in Florida from an eastern landfall between 1996-2011, run at a 65 km search radius.

Many of the tornadoes in the Jacksonville – Saint Augustine area are from hurricanes Frances and Jeanne in 2004. The two TCs made landfall in the same location three weeks apart. Frances and Jeanne account for around 55% of the TC-Tornadoes that occurred from east landfalling TCs. On average, all of the TC-Tornadoes have occurred around 335 km from the center of circulation. Tornadoes within hurricanes Frances and Jeanne have occurred, on average, around 240 km from the hurricane's center before landfall, and around 300 km after landfall. One possible explanation is that as the TCs approach the coastline and eventually make landfall, the increased shear on the northern and northeast side along with the increased friction and thunderstorm bands from the center of circulation helps increase the chances of TC-induced tornadoes. For example, tornadoes initially formed just before and after the first landfall of Hurricane Frances in the north-northwest portion of the storm. As Frances moved northwest then north-northwest, the TC-Tornado occurrences maintained this northerly bearing until the TC's second landfall in Apalachee Bay. After the second landfall, the occurrence bearing switches to the southeastern quadrant, which kept the occurrences in northeast Florida. The northeast Florida region was still under influence of the typical zone of the best shear, and had the best southerly inflow. With enough instability, it's possible to initiate sufficient thunderstorm bands and produce tornadoes. It is important to note that there are only 60 tornadoes from eastern landfalling TCs, so the sample size is relatively small.

Western landfalling TCs have more high-density clusters than the eastern landfalling TCs (188 events compared to 60). The clusters are located in the Pensacola – Fort Walton Beach area, Saint Augustine – Flagler Beach – Daytona Beach area, Sumter County south to Port Charlotte, and the Miami – Fort Lauderdale area (Figure 12). There is also another cluster in a mainly rural portion of the panhandle that stretches from near Apalachicola northwestward to around Chipley.

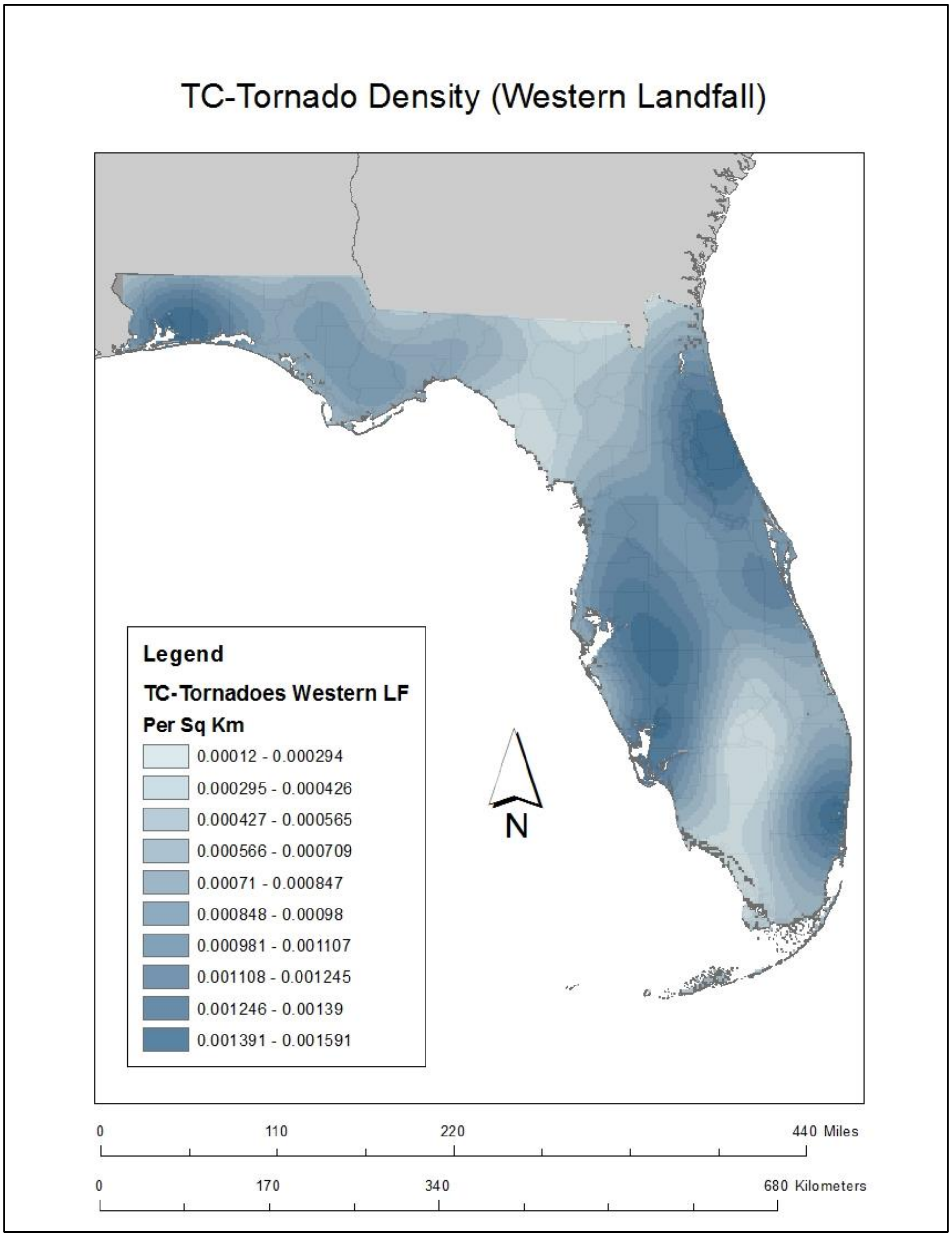

Figure 12 Kernel Density output for TC-Tornadoes in Florida from a western landfall between 1996-2011, run at a 95 km search radius.

The majority of the tornadoes that occurred in the Pensacola – Fort Walton Beach area developed before landfall (around 86%). All tornadoes in the Pensacola region were in the northeastern quadrant at the time of occurrence – within the best zone of shear. The average distance of tornadoes from the center of circulation was 364 km – nearly 30 km further than the average of all TC-Tornadoes. It seems the tornadoes in this region mainly occurred before landfall in the northeastern quadrant with the best shear and likely with sufficient thunderstorms in the rain bands ahead of the TCs.

The lower-density cluster in the central panhandle (28 events) had 57% the events occur before landfall. The average distance of tornadoes from the center of circulation was 314 km – lower than the average with all of the tornadoes initiating within the east-northeastern and east-southeastern areas of the TCs. Before landfall, the locations of tornadoes were all in the east-northeastern sub quadrant while the majority of them are in the east-southeastern sub quadrant afterwards. The changes in directional relationships are likely because of the northerly movement of the TCs.

TC-Tornadoes in the eastern coastal counties from St. Johns south to Brevard have no dominant mode of occurring before or after landfall (50-50 occurrence). The majority of the events occurred in the northeastern quadrant (around 87%) with the remaining occurring in the east-southeastern sub quadrant. 32% of the tornadoes were associated with Tropical Storm Gabrielle in 2001, with most of the tornadoes occurring after landfall. The mean distance of tornadoes from the center of circulation – 287 km – is lower than average of all TC-Tornadoes. It is possible that these TC-Tornadoes occurred from thunderstorm bands on the northeastern quadrant in the best shear. It's also possible that the easterly flow of the TC coming onshore in eastern Florida could have increased the horizontal speed shear, creating an environment of enhanced shear. The onshore flow could also be a transport of additional moisture at the surface, especially if the boundary layer or the profile aloft has been temporarily dried out by breaks in cloud cover away from the center of circulation. The dry breaks could destabilize the local environment and help in the generation of thunderstorms that could produce tornadoes.

The properties of the TC-Tornadoes (18 events) in the metro areas of southeastern Florida vary from the previous region of high density. The average distance of tornadoes occurring from the center of the TC is 430 km – 95 km greater than the average of all TC-Tornadoes. The minimum distance from the center is 97 km with the greatest being 641 km. The bearing from the center ranges from 15 degrees to 286 degrees. It is worth noting that tornadoes before TC landfall have not occurred greater than 111 degrees bearing – meaning the occurrences have been from the north to east-southeast. The bearing after landfall varies greatly. The possible reasoning of the occurrences are the same as the eastern Florida events. With many of the TC-Tornadoes happening before landfall, the same northeastern pattern was noticed.

It's important to note that Hurricane Michelle of 2001, which caused one tornado in coastal Miami-Dade County, did not make landfall in Florida. Instead, the rain bands clipped over South Florida as it traveled from southwest to northeast over western Cuba. This was considered a western "landfalling" storm as it originated from the west.

The cluster of events from Sumter County southward to the vicinity of Port Charlotte has around 44 tornadic events, with all but two occurring before landfall. The average distance of tornadoes from the center of circulation is 339 km – close to the average of all TC-Tornadoes. The distances range between 16 km and 678 km. The bearing ranges from the north to the south-southwest from the center of circulation with the highest frequency of events being east of the center. Unlike the northeast Florida cluster, no TC seems to be the dominant of the West Florida cluster. The majority of the events are occurring on the eastern side of the center of circulation where, once more, the best shear is located. The majority (37 events) of the eastern half TC-Tornadoes before landfall are between 0 and 100 degrees bearing from the center of circulation.

Elevation

Figure 13 indicates a weak relationship of TC-Tornado density and elevation. The density count gets lower with the higher elevation – likely because most of the state is in lower than 40 meters AGL. There is a weak negative relationship with the R-squared at 0.00108 and an adjusted R-squared at -0.0003. The results would suggest that there is a weak relationship with TC-Tornadoes and elevation.

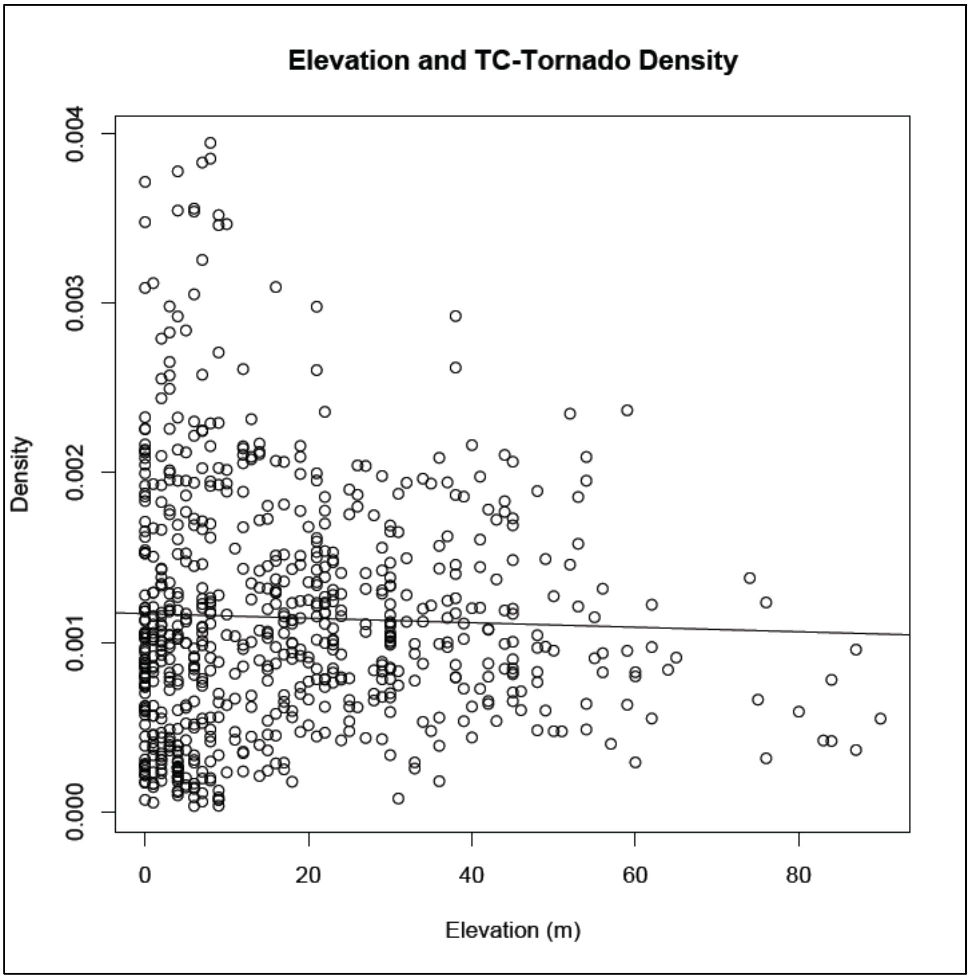

Figure 13 Relationship with TC-Tornado density and elevation (m) with linear equation y = -1.333e-06x +1.664e-03.

Land Use

The results show the highest ratio is the exotic plant life (Figure 14, Table 2). However, it is important to know that 0.13% of the land cover in Florida is exotic plant life and there have only been two TC-Tornado events with this class. These exotic plant life TC-Tornado occurrences have been near urban areas. The second, and most likely common, land cover occurrence is urban. The state is 9.7% urban with nearly 25% of TC-Tornado occurrences being over urban areas. The third highest ratio land cover is shrub/grassland, where nearly 6% of the TC-Tornadoes occurred and the state land cover is about 4% shrub/grassland. Open water was the fourth-highest ratio. The TC-Tornadoes have either occurred close to shore, over lakes, rivers, or intercostal waters. The rest of the land classes have ratios less than 1.

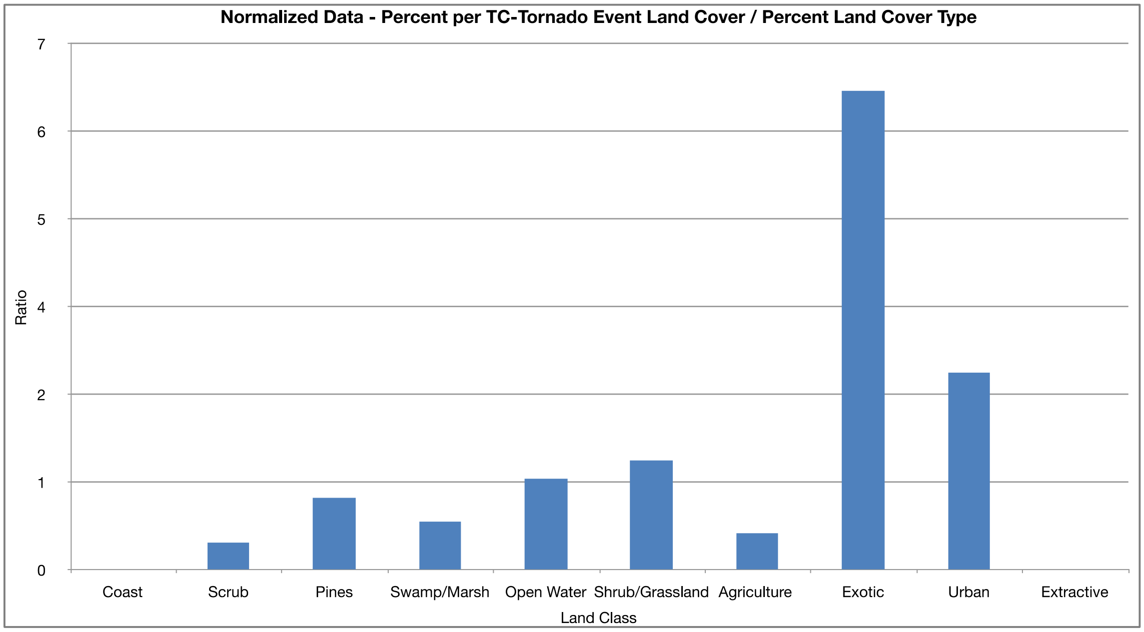

Figure 14 Normalized TC-Tornado events with associated land use.

The results would suggest a population bias since the urban land use type had one of the highest ratios, but definitively determining population bias would require further analysis. The aforementioned analysis will be discussed in the next section.

Population

When all the data were run, there is a weak positive relationship of TC-Tornado density per county and population density per county (Figure 15). The R-squared is at

0.0088 with an adjusted R-squared of -0.0063. The plot and regression results suggest a weak relationship with population and TC-Tornado Occurrence. But when outlier data were removed (Figure 16) – any population densities above 300 people per square kilometer in a county, based on Figure 15 – the R-squared improved to 0.1015 with an adjusted R-squared of 0.086. But the positive slope of the abridged data is not as great as the run with all data. Regardless, this would suggest that there could be a population bias with TC-Tornado events on a county level.

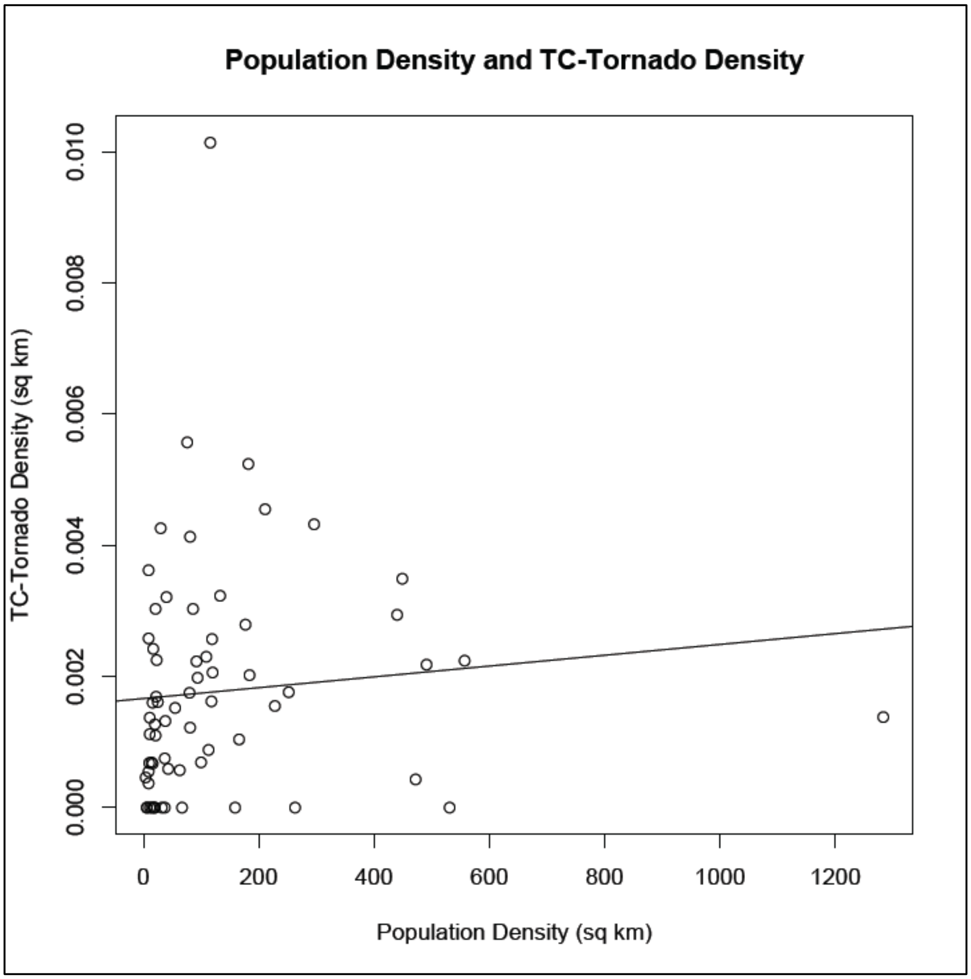

Figure 15 Relationship of county-based population density and TC-Tornado density with the equation of the line y = 8.247e-07x + 1.664e-03.

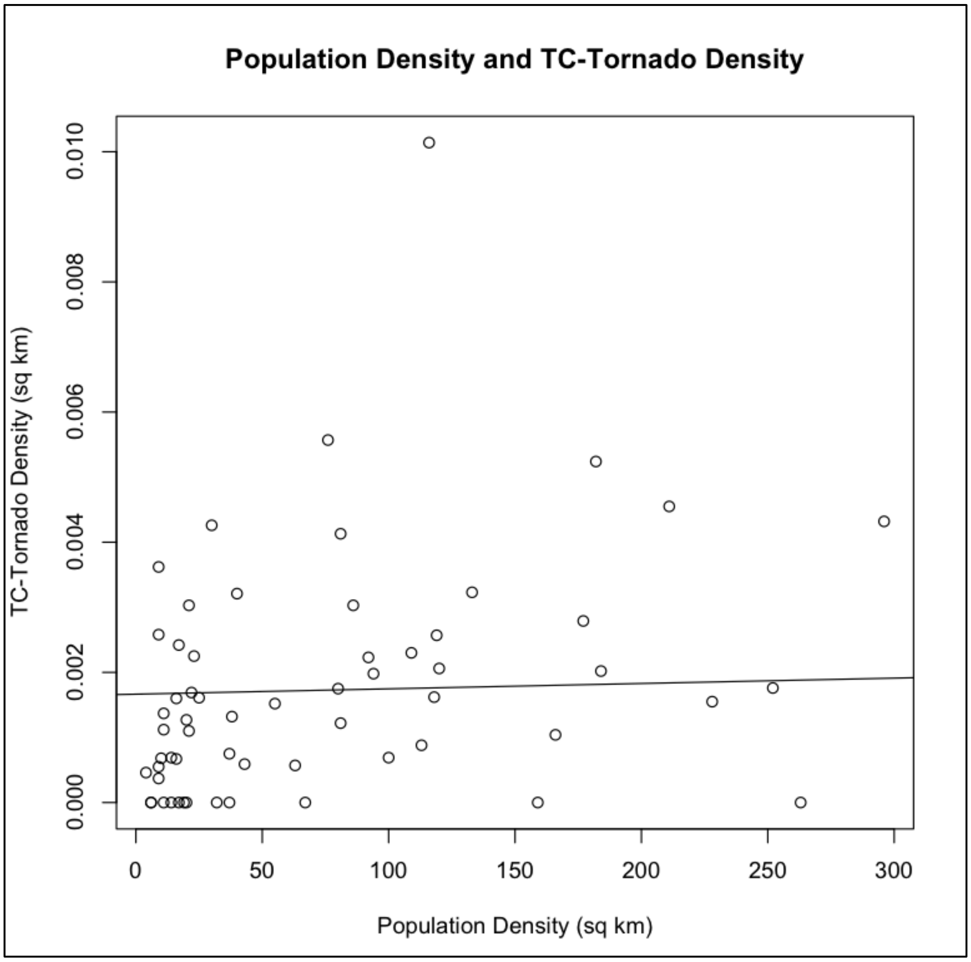

Figure 16 Relationship of county-based population density and TC-Tornado density with outlier data – population density above 300 people per square kilometer – removed, with the equation of the line y = 7.736e-06x + 1.193e-03.

TC-Tornado Density – per square km – on a county level shows the highest densities over the northeastern and east central coasts of Florida, with the highest densities in Saint Johns, Flagler, and Brevard counties (Figure 17). There are high TC-Tornado densities in Monroe County, which include the Florida Keys. Lee County in southwestern Florida also has the highest density in the region with some other relative high densities in west central Florida in Desoto, Hillsborough, and Hernando counties. In the panhandle, highest densities include Escambia and Okaloosa counties with other relatively high-density counties including Bay, Franklin, and Jefferson. In a few areas of high population density, there is a hint of population bias.

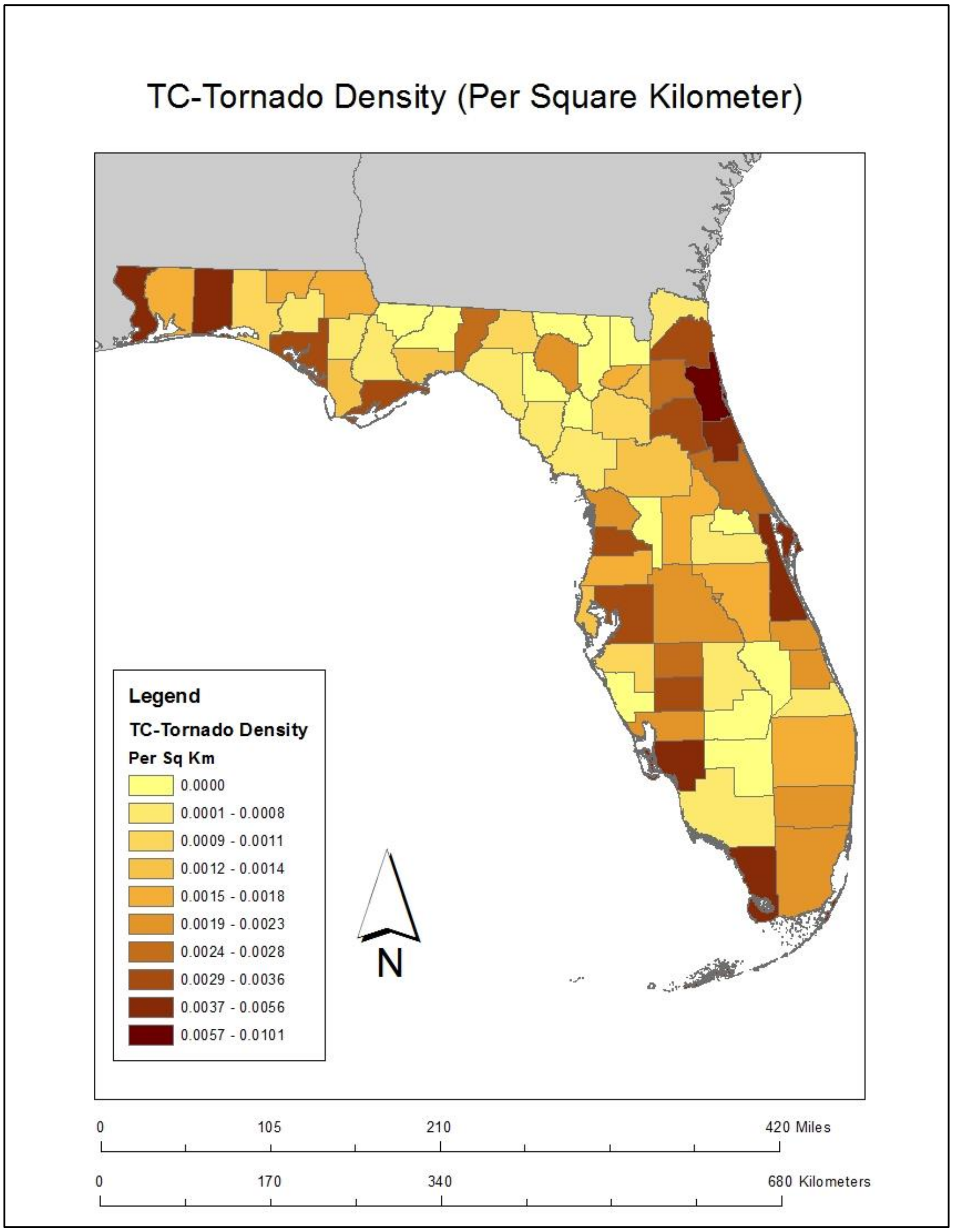

Figure 17 TC-Tornado density per square km in Florida.

The TC-Tornado densities were normalized with population densities for each county. The results show relatively high ratios over the panhandle with the highest over Gulf, Franklin, and Jefferson counties (Figure 18). In the peninsula, the ratios are relatively low except for Hardee, Desoto, and Monroe counties where the ratios are high. The ratios are in the mid to high range over Saint Johns, Putnam, and Flagler counties. Overall, there doesn’t appear to be a noticeable pattern of high TC-Tornado occurrence with high population areas based solely on the normalized data. High population counties such as Miami-Dade, Broward, Hillsborough, Pinellas, and Duval have low ratios.

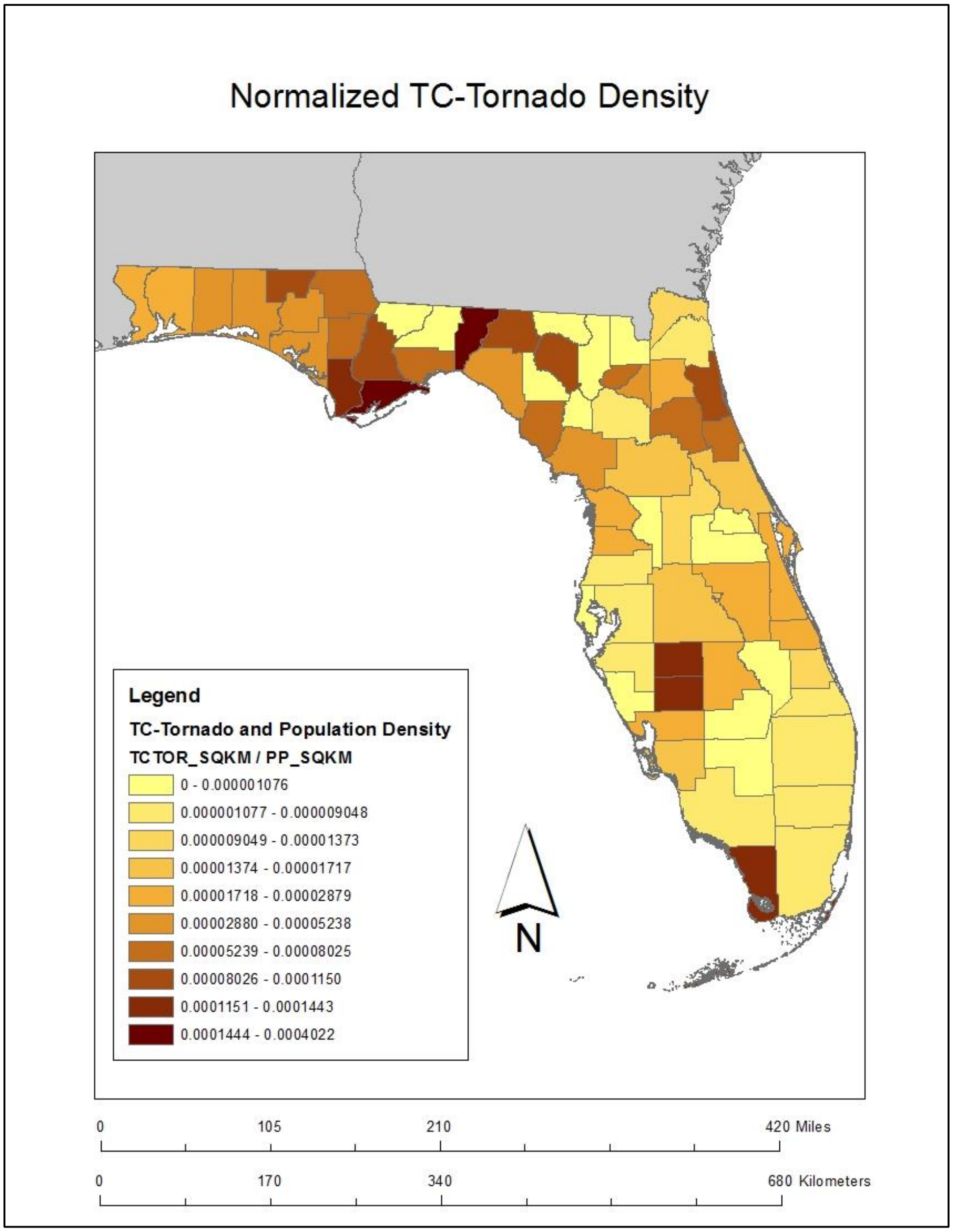

Figure 18 Normalized TC-Tornado density (TC-Tornado density / population density) in Florida.

CHAPTER IV

CONCLUSION AND SUMMARY

Based on the temporal analysis of TC-tornado occurrences before or after TC landfall, location of tornadoes relative to TC center of circulation, and geographic variables, it can be concluded that the occurrences are likely not based on geographic features such as land use type or elevation. Instead, where a TC-Tornado occurs is more dependent on the path and landfall location of the associated TC. The results in the storm centric analysis indicate clear patterns of TC-Tornado occurrence depending on where and when the storm makes landfall. However, there is some evidence of a population bias on a county level based on the improvement in relationships of population density and TC-Tornado density when outlier population densities are removed.

Operational meteorologists should pay attention to certain attributes in predicting where tornado occurrence is possible with landfalling or nearby TCs. With TCs making landfall from the west, attention should be paid to the northeastern quadrant. After western landfall, the northeastern and east-southeastern portion of the TC should be monitored for further tornado development. Forecasters need to monitor the north-northwestern portion of an eastern-landfalling TC and the east-southeastern portion after landfall.

Unlike some previous literature that suggested many of the TC-Tornadoes form after landfall (Novlan and Gray 1974), the numbers given by this project indicate that most have TC-tornadoes occur well before landfall in Florida. Regardless, forecasters should be vigilant of tornado development before and after landfall.

Clusters of TC-Tornado activity have been determined with the highest density of events located in northeastern Florida, urbanized southeast Florida, and the western panhandle. But with such a small sample size of events (n = 248) and lack of confidence that land use, population, and elevation had much to do with these high density locations, it can not be said that these locations are susceptible to TC-tornados due to geographic characteristics. It's likely due to chance that these areas of higher TC-tornado frequency exist where they do. For instance, it's likely that northeast Florida hot spot is likely in response to TCs Frances and Jeanne in 2004 since many of the tornadoes are from those two storms.

The weak relationships determined with population and elevation suggests that these two variables have little to do with TC-Tornado formation. Linking TC-tornado events over certain land-use types hinted at a high occurrence over urbanized areas. But, as stated previously, the population density and TC-Tornado density for all counties has been determined to be a weak relationship. With the remaining land use types, there doesn't appear to be a strong relationship.

There are several caveats with this research that could influence the results, but that cannot be directly taken into account in the analysis. The low sample size and time frame, especially tornadoes per TC, was a major limitation. The low sample size limited analysis by not allowing storm-detailed analysis or any further breakdown by other attributes. Some TCs made more than one landfall due to Florida's unique geography, which, at times, resulted in a few subjective procedures of determining when landfalls took place (see Appendix A). The fact that Florida is a relatively narrow peninsula with two water bodies surrounding the majority of the state, coastlines with varying orientations, and TCs making landfall at different angles from different directions make this a unique study. As more TC-tornado events are reported in the future, this project could be revisited to determine if the results remain consistent. Also, more detailed geographic population data would be helpful to better determine population bias.

The main focus on the research was to determine patterns based on geographic attributes and locations of tornadoes associated with TCs; therefore, more research would be needed to further understand Florida TC-tornado occurrences. Further research into TC-tornadoes in Florida with respect to thermodynamic profiles and severe weather indices could be one idea of future research. Also, modeling landfalling or nearby TCs to determine what type of environment develops tornadoes – or even tornado outbreaks – would also be useful to the meteorological community

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APPENDIX A

EXPLANATION OF LANDFALL TIMES OF COMPLEX LANDFALLS OF TROPICAL CYCLONES

Some of the TCs that initiated tornadoes had multiple landfalls in the United States. Hurricane Georges in 1998 had two landfalls: One at Key West, Florida on 25 September at 1530 UTC, and the other – and final – at Biloxi, Mississippi on 28 September at 1130 UTC. When analyzing the TC-tornado times and dates, a nearly three-day lull in tornado activity was noticed – between 25 September at around 1800 UTC and 28 September at 0300 UTC. The second round of TC-tornado activity occurred around the time of the second landfall; therefore, the finalized dataset used both of the U.S. landfall dates and times, and placed the TC-tornadoes with the respective landfalls.

Hurricane Irene in 1999 had two landfalls around Florida: Key West, Florida on 15 October at 1300 UTC, and the second at Cape Sable, Florida on 15 October at 2000 UTC. Since the landfall times and locations are relatively close, the final landfall was used.

Tropical Storm Allison in 2001 had two landfalls in the U.S.: Freeport, Texas on 5 June at 2100 UTC, and the second at Morgan City, Louisiana on 11 June at 0200 UTC. Since the TC-tornado events coincided with the Morgan City landfall time and location, the second and final landfall time and date was used.

Hurricane Charley in 2004 – which caused 15 TC-induced tornadoes – made four U.S. landfalls. Two were in Florida: Cayo Costa on 13 August at 1945 UTC, and near Punta Gorda one hour later. The final Florida landfall was used since it struck the mainland as Cayo Costa was one of the barrier islands and crossed Pine Island Sound and Charlotte Harbor before making landfall in the peninsula. The remaining two landfalls were in South Carolina and likely did not influence tornadogenesis.

Hurricane Frances in 2004 made landfall twice in Florida: Hutchison Island on 5 September at 0430 UTC, and at the mouth of the Aucilla River on 6 September at 1800 UTC. Since tornadoes occurred in both the panhandle and peninsula, leaving one landfall would skew the results by suggesting tornadoes were initiated hours well after or before landfall in the different regions. But, determining which landfall was related to each tornado would be difficult since no geographic patterns of tornado occurrences were determined with each landfall. The final landfall at the mouth of the Aucilla River was used. This does skew the results as this makes the first TC-tornado 51 hours before landfall where it could have been sooner.

Hurricane Cindy in 2005 made two landfalls: Grand Isle, Louisiana on 6 July at 0300 UTC, and made final landfall three hours later near Ansley, Mississippi. The final landfall was used.

Hurricane Katrina in 2005 made three landfalls: Near the Miami-Dade and Broward County, Florida line on 25 August at 2230 UTC, near Buras, Louisiana on 29 August at 1110 UTC, and made final landfall 29 August at 1445 UTC near the Louisiana and Mississippi border. One TC-induced tornado occurred in south Florida on 26 August while five occurred in the panhandle on 29 August. Two landfalls were used for their respective regions of occurrence.

Ophelia in 2005 technically made landfall based on Beven and Cobb (2006), but in Grand Bahama Island on 6 September at 1600 UTC. Since the TC did not make landfall on a mainland, it’s not likely that hitting the island influenced the two reported tornadoes associated with Ophelia.

Hurricane Ernesto in 2006 made landfall at two locations in Florida: Near Plantation Key on 30 August at 0300 UTC and southwestern Miami-Dade County on 30 August at 0500 UTC. The final landfall was used in the dataset.

Tropical Storm Fay in 2008 was a complicated TC since it had four documented landfalls in Florida. The first took place in Key West on 18 August at 2030 UTC, the second at Cape Romano on 19 August at 0845 UTC, the third at Flagler Beach on 21 August 21 at 1900 UTC, and the final at Carrabelle on 23 August at 0615 UTC. Two landfalls were used to determine tornado time relative to landfall time: 19 August at 0900 UTC and 23 August at 2300 UTC.

Gustav in 2008 never made landfall in the state of Florida, but instead made landfalls in Cuba – two, to be precise – and made final landfall in Texas. Gustav spawned tornadoes in the upper Florida Keys. Since the TC technically make landfall anywhere in or near Florida, it would be difficult to relate the tornado occurrence with a landfall; therefore, this storm was removed from the temporal analysis in chapter III