Florida Tropical Cyclone Rainfall Totals as Related to Storm Location and Intensity

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Introduction

As recently witnessed during the 2004 and 2005 Atlantic Basin hurricane seasons, Florida is highly susceptible to the effects of tropical cyclones (TCs). Its elongated shape and location within the subtropics means that TCs forming in the Gulf of Mexico, Caribbean Sea, and the Atlantic Ocean can affect Florida (Vega and Binkley 1993). According to the National Hurricane Center's best track data, 475 named TCs have formed during the past 48 Atlantic Basin hurricane seasons. Forty percent of the 164 TCs that have made a U.S. landfall have come ashore over Florida, which is more than any other state. When calculating return periods for hurricane landfalls in all U.S. coastal counties, Elsner and Kara (1999) found that Monroe County, Florida, experiences the highest frequency of hurricane landfalls, with a return period of four years. Dade and Broward counties have return periods of five years. These facts suggest that Florida is more subject to a direct hurricane strike than any other state along the U.S. Gulf of Mexico or East Coast.

TCs can cause damage through fast winds, storm surge, tornadoes, and heavy rainfall. Although fast winds and storm surge are of concern during a direct hurricane strike, Rappaport (2000) found that nearly 60% of U.S. TC-related deaths during 1970-1999 were due to fresh water flooding. Depending upon the forward speed of the storm (Corbosiero and Molinari 2003), moisture availability (Chan et al. 2004), and interactions with the atmosphere and land surface (Gilbert and LaSeur 1957), heavy rainfall from TCs can commence prior to the circulation center's landfall, continue for days after the storm has

Table 1: Top Ten Rainfall Amounts Produced within the U.S. by Named Atlantic Basin Tropical Cyclones during 1980-2005

Rank	Highest Rainfall (mm)	Tropical Cyclone (Year)	State of Landfall	State Receiving Highest Rainfall	Florida Storm Track [a]	Maximum Florida Rainfall (mm)
1	1034	Allison (2001)	TX, LA	TX	N	257
2	978	Georges (1998)	MS	FL	Y	978
3	932	Danny (1997)	LA, AL	AL	Y	178
4	711	Alberto (1994)	FL	GA	Y	508
5	653	Allison (1989)	TX	LA	N	127
6	650	Dennis (1981)	FL, NC	FL	Y	650
7	612	Floyd (1999)	NC	NC	N	76
8	599	Frances (2004)	FL, FL	NC	Y	381
9	569	Frances (1998)	TX	LA	N	0
10	546	Bob (1985)	FL, SC	FL	Y	546

[a] Y (N) indicates that the TC's circulation center did (not) pass over Florida
Data complied from the Hydrometeorological Prediction Center

tracked inland, and can even occur when a TC does not make landfall. Thus, the effects of TC rainfall can be more widespread than those from fast winds and storm surge. A ranking of the top ten TC rainfall totals for Atlantic Basin storms in the U.S. since 1980 shows that Florida experienced three of these ten high rainfall totals (Table 1). Three additional TCs on this list tracked through Florida even though they produced their highest rainfall total in other states. Thus, in addition to a high risk of a direct hurricane strike, Florida is also vulnerable to high rainfall amounts produced by TCs that may or may not make landfall within the state.

This study examines TC rainfall totals produced in Florida during the 1980-2005 Atlantic Basin hurricane seasons, and their relationship to the position of the storm. Distances between the location of maximum Florida rainfall (LMFR) for each TC and the landfall of each TC are discussed to demonstrate that TCs do not have to make landfall in Florida to produce heavy rainfall within the state, and to determine the distance over which a TC can travel from landfall and

still produce rainfall within Florida. To examine the spatial distribution of heavy rainfall amounts around the storm's track, the distance between the LMFR and the location along the storm's track that is closest to the LMFR is measured to determine whether locations close to the storm track receive the highest rainfall totals. Several physical forcing mechanisms that affect TC rainfall production are discussed to explain variations in TC rainfall patterns over Florida.

Data and Methods

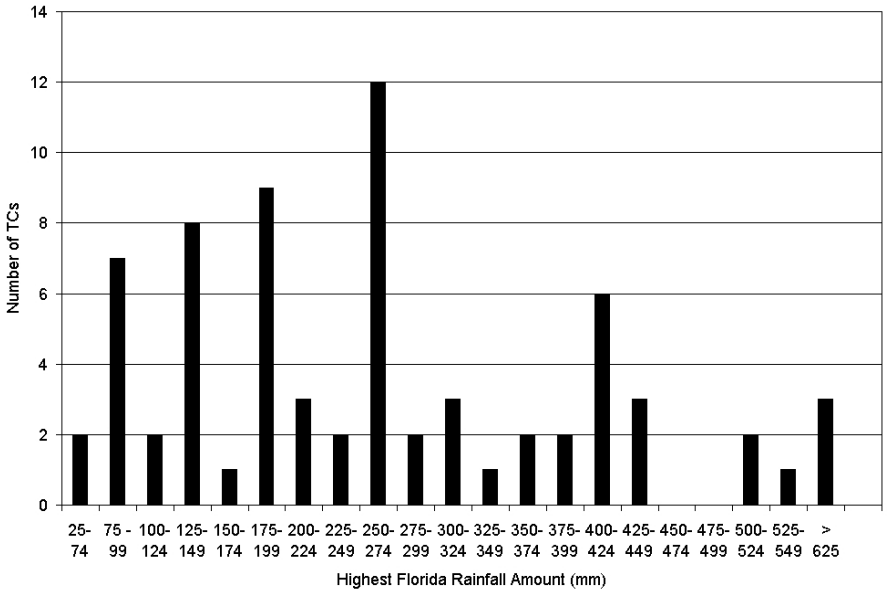
A list of the highest storm total rainfall amount produced by each U.S. landfalling TC and the location receiving this rainfall is available from the Hydrometeorological Prediction Center website (http://www.hpc.ncep.noaa.gov/tropical/rain/tcmaxima.html). This information was utilized to create Table 1 and identify which TCs produced their highest rainfall totals in Florida. Selected rainfall totals reported in the National Hurricane Center (NHC)'s best track dataset, or rainfall totals listed in the storm summary for TCs where individual observations were not listed, were utilized to determine the rainfall amounts received in Florida for all other TCs in the current study. Although these data are the official storm total rainfall amounts recorded by rain gauges at each station, it should be noted that these data may underestimate the actual rainfall amounts that occurred with each storm (Nystuen 1999).

A Geographic Information System (GIS) was utilized to calculate the distance between the LMFR and the landfall location, and between the closest point along the storm track to the LMFR and the LMFR. Storm track coordinates were obtained from the National Oceanic and Atmospheric Administration Coastal Services Division, where storm track data have been converted into a GIS-compatible format (http://hurricane.csc.noaa.gov/hurricanes/download.html). Data utilized to determine the intensity of the storm when the TC was closest to Florida are also contained within this dataset.

Results

Of the 335 TCs that formed within the Atlantic Basin during 1980-2005, 71 (61) produced at least 25.4 mm (125 mm) of rainfall

Figure 1: Maximum Rainfall Amounts Produced by Tropical Cyclones in Florida 1980-2005



within Florida. Forty Atlantic Basin TCs produced their highest rainfall amounts within Florida, nearly twice the amount of Texas, which had the second highest number of TC rainfall maxima during this period. These figures demonstrate that in addition to the effects of fast winds and storm surge associated with a direct landfall, Florida is also susceptible to the effects of TC rainfall, which can occur without a direct landfall.

The average rainfall maximum for the 71 TCs producing 25.4 mm or greater rainfall totals was 270 mm (10.6 in) (Figure 1). Six TCs produced over 500 mm (20 in) of rainfall, and these rainfall amounts occurred within 75 km of the TC's circulation center (Table 2), suggesting that TCs produce their highest rainfall totals close to the storm's center. However, not all of these rainfall totals were produced near the point of landfall. Hurricane Georges (1998) made landfall over 200 km from its LMFR, demonstrating that TCs making landfall in other states can still produce heavy rainfall within Florida.

Table 2: Top Ten Maximum Rainfall Amounts Produced by Tropical Cyclones in Florida 1980-2005

Rank	Max. Rain (mm)	Tropical Cyclone (year)	Int. [a]	LMFR [b]	Distance to track (km) [c]	Distance from landfall (km)
1	978	Georges (1998)	TD	Munson	5 R, L	225
2	650	Dennis (1981)	TS	Homestead	65 R	65
3	635	TD # 1 (1992)	TD	Arcadia Tower	75 R	75
4	546	Bob (1985)	TS	Everglades City	40 R	55
5	508	Alberto (1994)	TS	Niceville	15 R, L	10
6	508	Erin (1995)	H	DeFuniak Springs	0	0
7	445	Leslie (2000)	TD	South Miami	255 R	No landfall
8	443	Irene (1999)	H	Boynton Beach	75 R	210
9	427	Jerry (1995)	TS	Golden Gate	140 L	210
10	419	Alberto (1982)	TD	Tavernier	225 R	No landfall

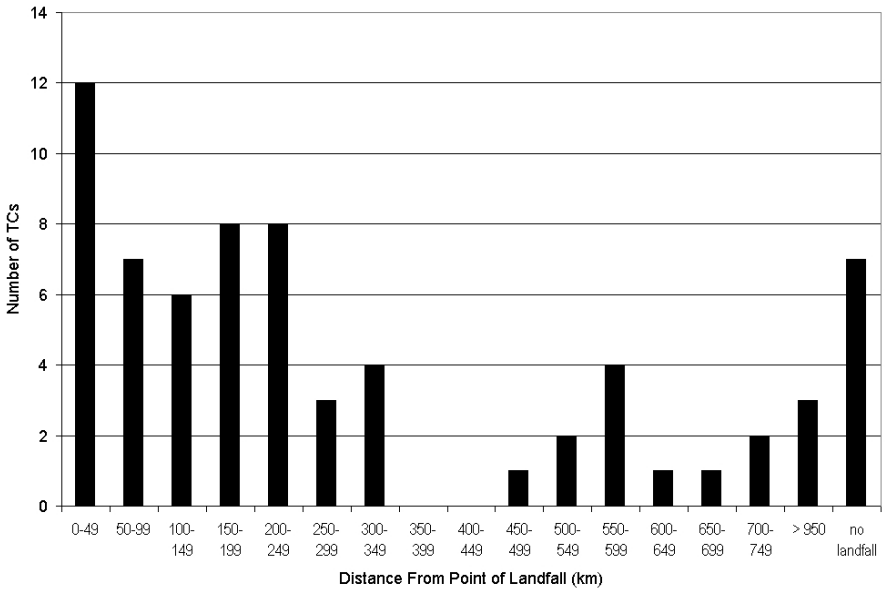
[a] *Int is the intensity of the TC when it affected Florida*
[b] *Location of Maximum Florida Rainfall*
[c] *Distance to track includes whether the gauge was located to the left (L) or right (R) of the storm track*

The following two sections discuss the landfall locations of TCs producing rainfall in Florida, and the distribution of the LMFR about the storm track to ascertain the range of distances over which TC rainfall has affected Florida.

Distance from Landfall Point

It is important to determine the distance over which a TC can travel from its landfall point to produce heavy rainfall within Florida so that people will remain aware of conditions even after landfall has occurred. Most (70% of) TCs tend to produce their highest rainfall amounts in Florida when they make landfall within 50 km (300 km)

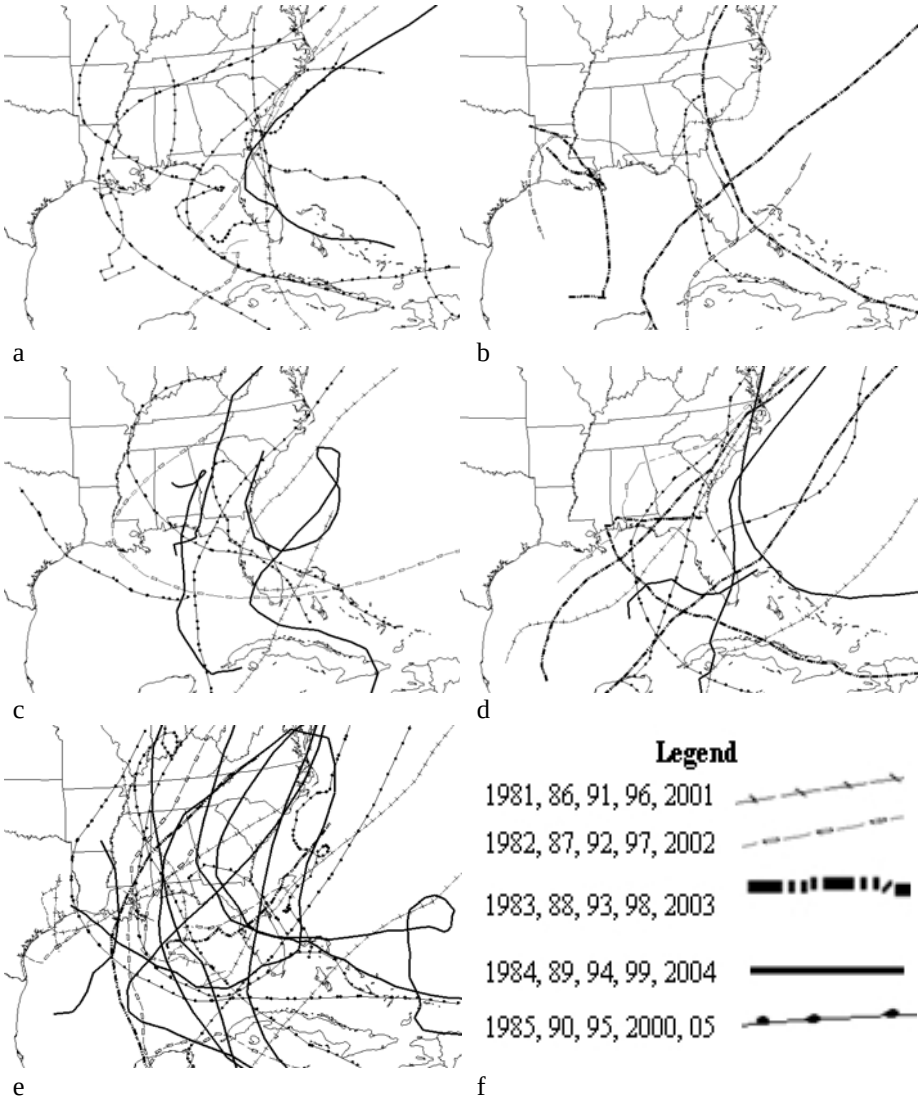
Figure 2: Distance Between the Landfall Location and the Florida City Receiving the Maximum Rainfall Amount



of the LMFR (Figure 2). However, as witnessed during Tropical Storm Allison (2001), heavy rainfall can also occur in Florida up to 1050 km from the point of landfall (Figure 1). Jefferson County, Texas received 1033 mm (40.68 in) of rainfall in total, the highest amount produced by a TC in the U.S. during 1980-2005 (Table 1). Six days after the initial landfall over Freeport, Texas, Allison produced 257 mm of rainfall over Tallahassee, Florida. Subtropical ridges located on either side of Allison were responsible for its slow forward velocity and eventual northeast track. Over half of the 41 deaths caused by Allison were due to fresh water flooding; eight people died in Florida (Beven et al. 2003). This example illustrates that Florida residents need to exercise caution even after a TC has made landfall and even though landfall may occur several states away.

The highest amount of rainfall within Florida during 1980-2005 occurred with Hurricane Georges (1998) (Table 2). Like Allison, Georges did not make landfall within Florida. However, the cir-

Figure 3: Tracks for Tropical Cyclones Producing Over 75 mm of Rainfall in Florida during: a) 1980-1985, b) 1986-1990, c) 1991-1995, d) 1996-2000, e) 2001-2005, f) legend



culation center of Georges did pass through northern Florida the day following its landfall near Biloxi, Mississippi (Pasch, Avila, and Guiney 2001). Munson, Florida, located 225 km east from Biloxi,

received 978 mm (38.46 in) of rainfall from Georges. Several rain gauges approximately 75 km west of Munson and 150 km east from Biloxi, recorded rainfall totals between 635-765 mm, indicating that Georges produced heavy rainfall in multiple locations. Even though Georges made landfall as a Category 2 hurricane on the Saffir-Simpson scale (Simpson and Rhiel 1981), the effects of its heavy rainfall were much more wide-spread than from its fast winds, as hurricane-force winds only extended an average of 51 km outward from its circulation center.

Allison and Georges are two examples of TCs that produced heavy rainfall within the state of Florida, although neither storm made landfall within the state. The second highest total rainfall amount for Florida since 1980 was produced by Tropical Storm Dennis (1981) (Table 2), a storm that did make landfall in Florida (Lawrence and Pelissier 1982). Homestead received 390 mm of rainfall within 24 hours as Dennis made landfall in Monroe County and tracked north, entering the Atlantic Ocean near Daytona Beach. The LMFR for Dennis occurred 65 km from its point of landfall. Lawrence and Pelissier (1982) estimated that over $25 million in damage was caused by the rainfall of Dennis in southern Florida.

As a TC making landfall over 1000 km west of Florida can still produce heavy rainfall within the state, it is important to determine which features of the atmosphere influence TC tracks. Plotting storm tracks for TCs that have produced rainfall within Florida illustrates several different trajectories taken by these 65 TCs (Figure 3). Large-scale circulation patterns usually determine the track of a particular TC (Wu and Wang 2004). Variations in the storm tracks of North Atlantic Basin TCs can be attributed to the positions of the polar jet stream over North America and the subtropical high in the North Atlantic Ocean (Elsner, Liu, and Kocher 2000).

Both the atmosphere and the land surface can affect a TC's track. When experiencing high wind shear, Ueno (2003) found that the differing wind speeds and directions throughout the vertical column of the troposphere can cause a variety of TC tracks. Modeling work by Dengler (1997) showed that the orientation of the coastline could deflect the track of a landfalling TC. In the absence of these

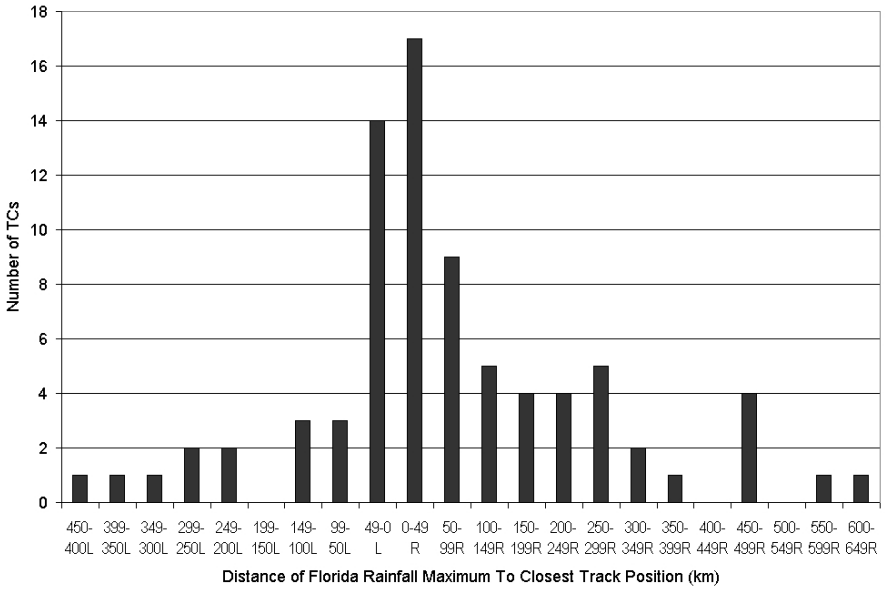
features, the storm's inertia carries it towards the northwest in the northern hemisphere. Given the complex interactions between a TC and its environment, Florida residents must exercise caution throughout the hurricane season, and prepare for the possibility that a storm making landfall in Texas could move eastward and produce heavy rainfall in northern Florida, or that a TC moving through the Florida Straights may not make landfall, but could still produce heavy rainfall in the southern portion of the state.

Position of Maximum Florida Rainfall Relative to the Storm Track

The TCs examined in this study produced their Florida rainfall maxima at distances ranging from the storm's circulation center out to 610 km from the circulation center (Figure 4). More than half (40 percent) of the LMFRs were less than 100 km (50 km) from the storm track, suggesting that locations closer to the storm track are more likely to experience high rainfall totals. The side of the storm track where the LMFR occurred was also examined. The LMFR occurred on the left side of the storm track in 34 percent of the cases examined, while 18 percent of TCs produced rainfall maxima on both sides of the storm track. To better understand how rainfall can be produced ahead of and/or to either side of the storm track at varying distances, it is important to understand the physical forcing mechanisms that control rainfall production with the TC.

The movement of winds from the relatively smooth ocean surface to the rougher land surface can also enhance rainfall production in certain portions of the storm. The onshore winds converge as they slow, which enhances uplift and precipitation generation (Parrish et al. 1982). In a TC making landfall at a perpendicular angle to a straight coastline, this enhanced uplift occurs on the right side of the storm in the northern hemisphere. Rogers and Davis (1993) demonstrated that the shape and orientation of the coastline can affect where this enhanced rainfall is produced within the storm. Faster tangential winds and/or a smaller radius of maximum winds would allow moisture to circulate about the storm before precipitating out (Li et al. 1997), which could produce a rainfall maximum on the left side of the storm. Due to the relatively narrow shape of Florida's peninsula, it is possi-

Figure 4: Distance of Location of Florida Rainfall Maximum from the Closest Approach of the Tropical Cyclone's Circulation Center



ble for onshore winds to occur on the coastline opposite from where the storm center makes landfall. Therefore, a TC making landfall on the west coast of Florida could produce a rainfall maximum on the east coast of Florida on the left side of the storm. This process could also account for increased rainfall amounts to the left of the storm track.

TC interactions with the atmosphere can also cause a TC's rain shield to become displaced from the circulation center of the storm. For example, strong vertical wind shear inhibits rainfall from occurring on the upshear side of the storm (Corbosiero and Molinari 2003). In other words, if the wind shear is from the west, most rainfall will occur on the east side of the storm. If a storm experiencing westerly wind shear is moving towards the east, the rain shield will be displaced ahead of the storm, and locations on either side of the storm track could experience heavy precipitation. Strong wind shear

Table 3: Correlation Values for Maximum Rainfall Amounts and the Distance from the Storm Track at which they Occurred

Type	All Data	Hurricanes	Tropical Storms	Tropical
Correlation	-0.42*	-0.72*	-0.36	-0.34
No. Cases	69	19	29	21

** denotes significance at the 0.01 level*

causing a displaced rain shield could account for the large distances between some LMFRs and the TC circulation centers.

As stated previously, the majority of LMFRs occurred within 100 km of the storm track. Pearson correlation coefficients were calculated to determine if a relationship existed between the rainfall total and the proximity of the storm track for the 69 TCs producing at least 75 mm of rainfall (Table 3). All TCs were analyzed together and then were stratified by intensity. The storm's intensity was defined using its maximum sustained wind speed when first entering or at its nearest position to Florida.

Results suggest that hurricanes produce higher storm total rainfall amounts close to their storm track. Marks et al. (2002) found through an examination of 245 TCs that high rain rates for hurricanes were located closer to the storm center than for tropical storms, which supports the correlation coefficients calculated in the current study. In the Marks et al. (2002) study, peak hurricane rainfall rates exceeded 7 mm/hr at a distance 25 – 50 km away from the storm center. Rainfall rates decreased to 4 mm/hr 125-150 km away from the storm center, and 1 mm/hr 250-300 km away from storm center. This decrease in rain rates away from the storm center would correspond to decreasing rainfall totals away from the storm center.

Conclusions and Future Research

This study examined the location receiving the maximum storm total rainfall amount within Florida for TCs that occurred during 1980-2005. Seventy-one TCs produced an inch or more of rainfall within Florida during this period, with an average maximum rainfall

total of 254 mm (10.6 in). The locations of these Florida rainfall maxima were compared to the landfall location of each TC, and the TC's closest position to the point of rainfall maxima to determine the range of distances over which Florida residents should be on alert for the potential of TC-produced rainfall. TCs making landfall as far away as Texas have tracked eastward to produce rainfall in Florida, and six TCs affected Florida without making a U.S. landfall. This finding suggests that people in Florida should prepare for the possibility of TC-produced rainfall even when a TC is forecast to come ashore in other states.

More than half of the TCs examined produced their Florida maximum rainfall within 100 km of either side of the storm track. Yet, 20 percent of the LMFR were located more than 300 km from the storm track, suggesting that Florida residents need to stay informed about potential rainfall hazards even if the TC is not forecast to track directly through their area. Although intensity does not appear to influence the maximum amount of rainfall received, an inverse relationship was found between hurricane rainfall totals and distance from the storm track. The key factors proposed by this study to enhance rainfall for storms tracking through Florida are interactions with the atmosphere which affect the speed of motion and moisture availability, and frictional convergence along the coastline.

Future research will further investigate the atmospheric and land surface physical forcing mechanisms responsible for TC rainfall production in Florida. TCs whose tracks were influenced by similar atmospheric conditions will be grouped to identify similarities in rainfall patterns resulting from atmospheric physical forcing mechanisms. TCs making landfall along coastlines of similar shape, and TCs of similar intensity and radius of maximum winds will be examined together to determine the effects of enhanced friction and convergence at the coastline. Acquisition of data for all Florida stations receiving rainfall for each TC will facilitate a calculation of the area over each TC produces rainfall, and the amount of TC-produced rainfall received each year.

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