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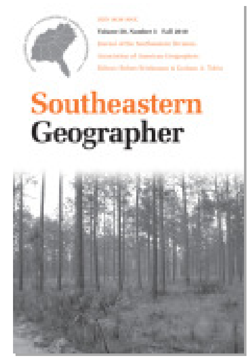

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Comparing the Rainfall Patterns Produced by Hurricanes Frances (2004) and Jeanne (2004) over Florida

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During 2004, Hurricanes Frances and Jeanne produced heavy rainfall across Florida. Although making landfall at the same location and moving along similar tracks, these storms produced different rainfall patterns. We employ a GIS to analyze rain gauge and radar-estimated rainfall data spatially, and we determine which physical mechanisms caused the asymmetrical rain swaths produced by each storm. We find that due to a moist environment and weakening vertical wind shear, the rain fields of Frances covered a large area. Strong convection in several outer rainbands and slow forward velocity yielded high rainfall totals. Although Jeanne contained more convective rainfall than Frances, vertical wind shear, a faster forward velocity, and existence within a relatively dry environment caused rainfall totals to be lower. The techniques employed in this study could be applied to a larger number of landfalling tropical cyclones to better understand where high rain totals occur under different combinations of environmental conditions.

KEY WORDS: tropical cyclone, rainfall, Florida, landfall, Geographic Information System

INTRODUCTION

More tropical cyclones (TCs) have made landfall in Florida than in any other U.S. state (Elsner and Kara 1999). The 2004 Atlantic Basin hurricane season was no exception as four hurricanes (Charley, Frances, Ivan, and Jeanne) and one tropical storm (Bonnie) made landfall in the state. This focus of TC activity prompted forecasters at the National Hurricane Center (NHC) to nickname Florida "the Plywood State" (Franklin et al. 2006). It is well known that when a TC makes landfall, damage and loss of life can result from fast winds, storm surges, tornadoes, and freshwater flooding from heavy rainfall (Rappaport 2000). During the 2004 season, most damage in Florida caused by Hurricane Charley was due to its high wind speeds, and Tropical Storm Bonnie and Hurricane Ivan produced dozens of tornadoes, while Ivan also produced a 4.5 m storm surge. Heavy rainfall produced by Hurricanes Frances and Jeanne caused flooding and damage over much of the northern and central parts of the state.

It can be argued that of these hazards, fresh water flooding poses a significant threat in terms of loss of life and spatial coverage of damage because heavy rainfall can occur both near the point of landfall and many kilometers inland for days after landfall (Elsberry 2002). Thus, a larger portion of the population is vulnerable to flooding caused by landfalling TCs than to wind or storm surge events. For example, half of the deaths caused by Hurricane Camille (1969) occurred in Virginia as heavy rainfall exceeding 508 mm caused flash flooding several days after landfall in Mississippi (Schwarz 1970). Researchers are developing techniques to improve rainfall predictions for TCs (Kidder et al. 2005; Lonfat et al. 2007; Marchok et al. 2007). To improve these forecasts, the mechanisms that cause asymmetries in rain fields and enhance rain rates such as vertical wind shear and storm motion require further observational and modeling studies (Marks and Shay 1998; AMS 2000; Elsberry 2002; AMS 2007). Advanced knowledge of the spatial distribution of rainfall accumulations ("rainfall swath") produced by a TC could allow people to be evacuated from flood-prone regions before the storm's arrival. Therefore, it is important to examine the rainfall patterns produced by these storms and to determine how the interactions of the atmosphere, ocean and land surface, and the TC influence the spatial distribution of rainfall.

This study identifies where deep convection develops within the rain fields of Hurricanes Frances and Jeanne during landfall and identifies the physical mechanisms likely responsible for the spatial patterns of rainfall created by each storm. Many recent observational studies of TC rain fields analyze these storms while they are over water (Cerveny and Newman 2000; Lonfat et al. 2004; Chen et al. 2006; Cecil 2007). When a TC encounters land, the change in latent and sensible heat fluxes as it moves from the ocean onto land and the increase in friction act to alter its wind and rain fields (Miller 1964). Differences in surface wetness (Shen et al. 2002) and roughness (Tuleya et al. 1984), the angle at which a TC crosses the coastline (Powell 1987) and the shape of the coastline (Rogers and Davis 1993), the size of the TC (Kimball and Mulekar 2004), and the time of day that landfall occurs (Konrad 2001) all affect where rainfall develops within a TC. Because Hurricanes Frances and Jeanne made landfall three weeks apart in September 2004 at the same location in Florida (Hutchinson Island near Stuart) with minimum central pressures of 960 mb (Frances) and 950 mb (Jeanne), crossed the coastline at similar angles (280°) at the same time of day (0400 UTC), and were of similar size as measured by the radius of gale-force (17 ms^{-1}) winds and the radius of the outermost closed isobar, they provide a control for the influences of these conditions on the development of heavy rainfall. However, even with these similarities, the official storm total rainfall amounts available from the NHC (Franklin et al. 2006) show that the two storms produced different amounts of rainfall in some of the same locations (Table 1).

This study contributes important observations to better understand the rainfall patterns produced by TCs and employs geographic analysis tools to accomplish its objectives. A modeling study would normally be required to isolate the effects of the atmosphere on rainfall development. However, the similarities between Hurricanes Frances and Jeanne allow many variables that affect the development of rainfall during landfall to be filtered out, allowing this observational study to focus on how atmospheric mechanisms affect the rainfall development during landfall. This study also employs a Geographic In-

Table 1. Ten highest Florida rainfall totals from 2004 Hurricanes Frances and Jeanne according to the National Hurricane Center. Bolded locations are from the same rain gauge.

Frances		Jeanne	
Total Rainfall (mm)	Location	Total Rainfall (mm)	Location
344	**West Palm Beach**	231	**West Palm Beach**
296	Putnam Hall	177	**Ocala**
275	**Gainesville**	153	Melbourne
275	**Ocala**	140	Cross City
253	Daytona Beach	137	Orlando
234	**Jacksonville**	129	Vero Beach
230	Pierson	124	**Gainesville**
227	Ocklawaha	118	**Jacksonville**
225	Umatilla	111	Sanford
212	Hastings	80	St. Augustine

formation System (GIS) to examine the spatial patterns of the rain fields of these storms as derived from radar data. Utilizing a GIS to analyze radar data is a technique that is becoming more popular (Shipley 2005; Vieux and Vieux 2005; Matyas 2009) as hydrologic models are also being developed using GIS. After obtaining data from rain gauges to determine the total rainfall produced by each storm and radar-estimated rainfall to confirm the locations of deep convection, we map the swath of rainfall produced by each storm using a GIS, and measure the symmetry of the swath on each side of the storm track. We also calculate rain rates for different parts of the storm, and determine where rain rates are highest. We then examine data pertaining to storm motion, the magnitude and direction of vertical wind shear, and the relative humidity of the lower, middle, and upper troposphere to determine the combinations of variables that are most responsible for the rainfall distribution produced by each storm.

ENVIRONMENTAL INFLUENCES ON RAINFALL INTENSITY AND SYMMETRY

Hurricanes Frances and Jeanne have similarities in several key geophysical mechanisms that act to control the rain fields of TCs at landfall, particularly with respect to the coastline that they crossed and the land surface over which they traveled. However, additional mechanisms are important to controlling the rain fields of TCs, whether over the ocean or a land surface. This section details how the direction and magnitude of vertical wind shear, storm motion, and tropospheric moisture can shape the rain fields and control where the highest rain rates occur within the storm. We also briefly describe the changes that occur within a TC at the time of landfall.

Recent observational studies have shown that vertical wind shear causes the rain fields of TCs to become asymmetrically-shaped, and may be the primary cause of rain-field asymmetries (Black et al. 2002; Corbosiero and Molinari 2002; Rogers et al. 2003; Chan et al. 2004; Lonfat et al. 2004; Chen et al. 2006; Cecil 2007; Matyas 2008). Wind shear occurs when wind speed and/or direction changes rapidly over a short distance in the atmosphere, and this can displace the warm core of a tropical cyclone from its position above the surface circulation center (Rodgers et al. 1994). As the vortex of a TC tilts in response to the shear, secondary vertical circulations are initiated so that upwards (downwards) motion is enhanced on the side of the vortex that is downstream (upstream) of the shear vector. These updrafts, which add moisture to the storm's circulation, travel cyclonically around the vortex so that the heaviest rainfall occurs to the left of the shear vector (i.e., downshear left) (Corbosiero and Molinari 2002; Rogers et al. 2003). Chen et al. (2006) and Corbosiero and Molinari (2002; 2003) stated that the magnitude of the vertical wind shear must be 5 ms^{-1} or greater between the 200- and 850 hPa levels to induce asymmetries in TC rain fields. Corbosiero and Molinari (2002) found that the influence of the magnitude and direction of wind shear on the rainfall distribution is strong regardless of whether the storm is over water or land. According to Cecil (2007), TCs that experience strong vertical wind shear have rain fields that extend farther away from their circulation centers than storms that experience weak wind shear. Thus, strong vertical wind shear can result in a wide and asymmetrical rainfall swath.

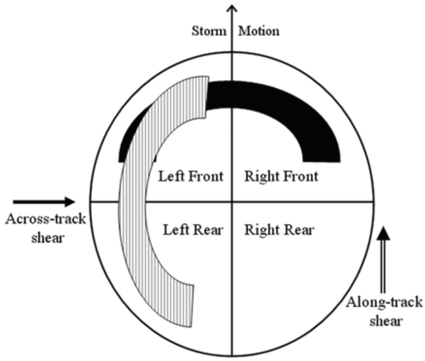

Figure 1. The effects of wind shear on precipitation in tropical cyclones. Along-track shear in the direction of storm motion will produce a rainfall maximum on the left side of the storm track (lined region). An across-track shear vector will produce a symmetrical rainfall distribution to either side of the storm track (black region).

To determine where the highest rain rates will occur within a TC that is experiencing moderate to strong wind shear, the direction of storm motion must be considered along with the direction of wind shear. Rainfall may be asymmetrical relative to the storm track if wind shear is parallel to the storm's motion (Figure 1). A shear vector in the same (opposite) direction as the storm's motion would result in a rainfall maximum falling to the left (right) of the storm's center. However, if the wind shear vector is perpendicular to the storm track, rainfall may be distributed symmetrically on each side of the track (Rogers et al. 2003; Chen et al. 2006). In this case, even though rain rates are asymmetrically-distributed within the storm, the rain will fall on both sides of the track as the storm moves forward to produce a fairly symmetrical rainfall swath on the ground (Figure 1).

Storm motion itself also has an important influence on the location of high rain rates within TCs. When a TC moves at forward velocities of 5 ms^{-1} or less and wind shear is light, rain rates tend to be highest in the forward quadrants of the storm. As Shapiro (1983) and Rodgers et al. (1994) explained, when a TC moves slowly in an environment of low vertical wind shear, the maximum surface radial inflow and convergence is located ahead of the storm. This scenario produces high rain rates ahead of the storm center (Miller 1958), and a rain swath that is fairly symmetrical about the storm's track. When TCs move at faster forward velocities (greater than 7.5 ms^{-1}), rain rates tend to be higher on the right half of the storm (Rodgers et al. 1994), producing a more asymmetrical rain swath.

The moisture content of the environment surrounding a TC influences both the symmetry and the radial extent of its rain fields. Because TCs acquire a large portion of their water vapor from the lower and middle troposphere, not just from the Earth's surface, a moist mid-level environment is required to sustain or increase TC intensity and rainfall (Chan and Liang 2003). The release of latent heat that takes place as condensation occurs within a TC is imperative to its survival. When relatively dry air is drawn into a TC's circulation, it suppresses convection by enhancing evaporatively-driven downdrafts, thereby destroying part of the storm's circulation (Gilbert and LaSeur 1957; Powell 1987; Bluestein and Hazen 1989; Rodgers et al. 1998; Rodgers et al. 2000; Black et al. 2002; Chan et al. 2004; Dunion and Velden 2004). When dry air exists to one side of the storm, rainfall is reduced on that side, yielding an asymmetrical rainfall distribution that extends farther from the circulation center on the side that remains relatively moist. A numerical modeling study performed by Hill and Lackmann (forthcoming) showed that the relative humidity of the environment within which a TC is contained is related to the extent of its rain fields; higher relative humidity values coincided with rain fields than extended farther outwards from the circulation center of the TC than for simulations where relative humidity values were lower.

Several researchers have observed that the heaviest rain rates in TCs occur near the center of the storm, particularly for storms of hurricane intensity (Miller 1958; Rodgers et al. 1994; Cerveny and Newman 2000; Konrad et al. 2002; Lonfat et al. 2004). However, rainbands located more than 100 km from the storm center (Willoughby et al. 1984) can reduce rainfall in the core, or inner 100 km of the storm, by blocking the inflow of warm, moist air. When such downdrafts are present, the greatest convective activity in a TC tends to be located in these outer rainbands (Molinari et al. 1999; Cecil and Zipser 2002; Corbosiero and Molinari 2002; 2003). Hurricanes with strong outer rainbands produce a wide rain swath, and the highest rainfall accumulations may occur more than 200 km away from the storm center.

Near-surface friction increases abruptly when TCs encounter land surfaces (Simpson and Rhiel 1981; Anthes 1982; Tuleya et al. 1984; Powell et al. 1991), which in turn affects where precipitation forms in a landfalling TC. As a TC encounters the coast, the increased friction slows the air moving onshore, while air transitioning from the rougher land-surface back out over the water gains forward velocity (Parrish et al. 1982; Powell 1982; Chen 1995;

Mackey and Krishnamurti 2001). The speed convergence of the tangential onshore winds causes air to travel vertically, radially, or in both directions depending on the rate of spin of the TC's vortex. Provided that ample moisture is available, the increased uplift triggers bursts of deep convection (Jones 1987; Li et al. 1997; Frank and Ritchie 1999; Mackey and Krishnamurti 2001). However, the spatial distribution of the resulting heavy rainfall depends on the tangential wind speed and the location of the radius of maximum winds (Frank and Ritchie 1999; Blackwell 2000). Stronger tangential winds force the precipitation farther downwind of the uplift region. When this occurs in a TC that is traveling at a perpendicular angle to the coastline, heavy rain falls in the left front quadrant of a TC in the northern hemisphere (Jones 1987). Conversely, weaker tangential winds allow a more vertical alignment of the convective clouds so that the right front quadrant experiences the heaviest rain rates.

DATA AND METHODS

To compare the rainfall intensity and distribution between Hurricanes Frances and Jeanne, we utilize rainfall data derived from both rain gauges and radar. Although an undercatch 20–40 percent of the rainfall during a high wind event is possible using rain gauges (Larson and Peck 1974), the use of rain gauge data in this study allows results to be compared with earlier gauge-based studies of rainfall produced by TCs making landfall over Florida (Miller 1958; Miller 1964). Radar data also have their limitations as changes in beam height do not allow the low-level precipitation cores of convective clouds, which Barnes et al. (1983) found to be at an altitude of 2 km in TCs, to be sensed at distances farther than 125 km from the radar site. Baeck and Smith (1998) and Matyas (2009) found instances where, despite problems with undercatch, rain gauges have recorded more rainfall during the passage of TCs than is estimated to have fallen after the analysis of radar-derived data. Thus, many studies currently employ both rain gauge and radar-derived data to represent the most accurate rainfall data for a storm event (Llasat et al. 2005; Medlin et al. 2007; Wu et al. 2007).

Daily rainfall totals as recorded by rain gauges are obtained from the National Climatic Data Center (NCDC) for 136 sites located across Florida (Figure 2). Daily rainfall totals are summed to determine the storm-total rainfall at each station over a four-day period (September 4–7 for Frances and September 25–28 for Jeanne). We import these rainfall totals into a GIS, convert them into shapefiles, and employ an inverse distance weighting routine to create isohyets that define the rainfall swath for each storm.

Before the symmetry of the rainfall swath relative to the storm track is calculated, we plot the six-hourly positions of the center of circulation of each storm (Figure 2). We obtain these position data from HURDAT (Jarvinen et al. 1984), which is the official record of TC positions as determined by the NHC. The position of the center of circulation for each TC is recorded at 0000, 0600, 1200, and 1800 UTC, along with its intensity, forward velocity, and heading. At each of these observation times, we measure the distance outwards from the circulation center's position to the 100 mm isohyet on each side of the storm track to quantify the sym-

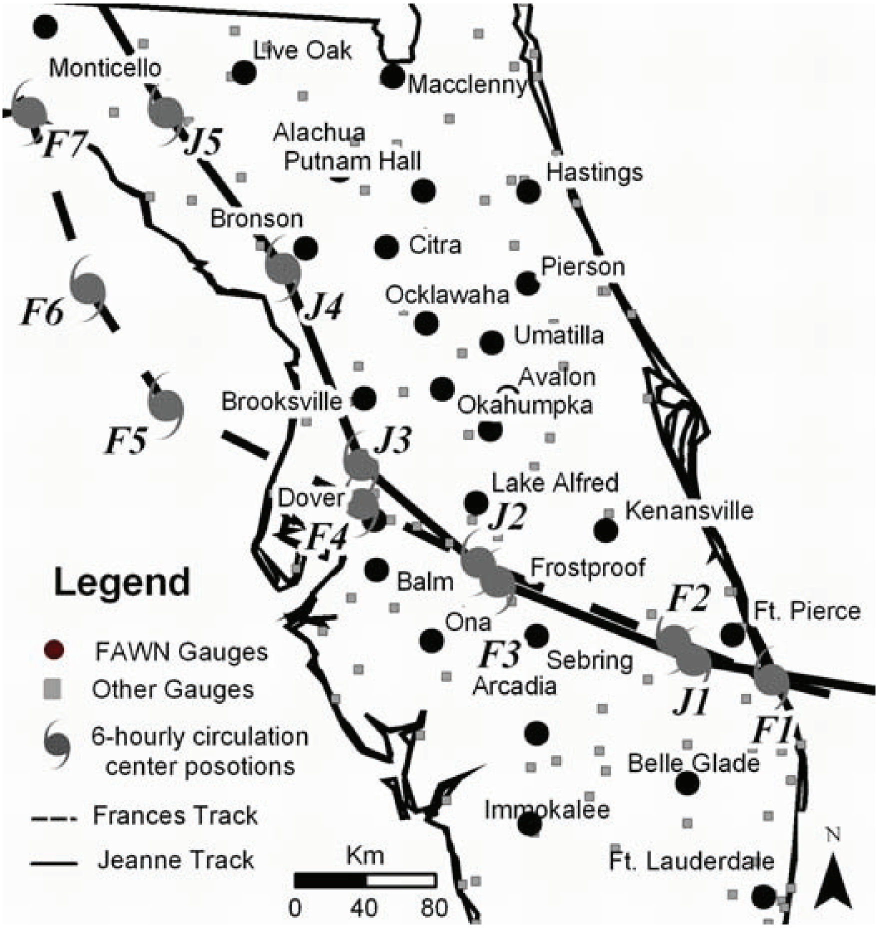

Figure 2. Florida Automated Weather Network (FAWN) rain gauges and other rain gauges utilized in the current study with the tracks and six-hourly positions of Frances (F1–F7) and Jeanne (J1–J5). The map projection has been altered to display more clearly the locations of interest to the study.

metry of the rain swath (Figures 3a, 3b). Measuring the width of the rain swath is not precise as Florida's peninsular shape does not provide a wide strip of land on which rain gauges are located, but it does allow general comparisons of the width of the rain fields to be made between Frances and Jeanne.

To determine where rainfall accumulates from these two storms in locations where rain gauges are not available, radar-derived rainfall data are utilized. Radar reflectivity data are collected at a higher spatial resolution than rain gauge data and their analysis allows rainfall patterns to be analyzed beyond the coastline of Florida. These data are available from the National Climatic Data Center's archive. However,

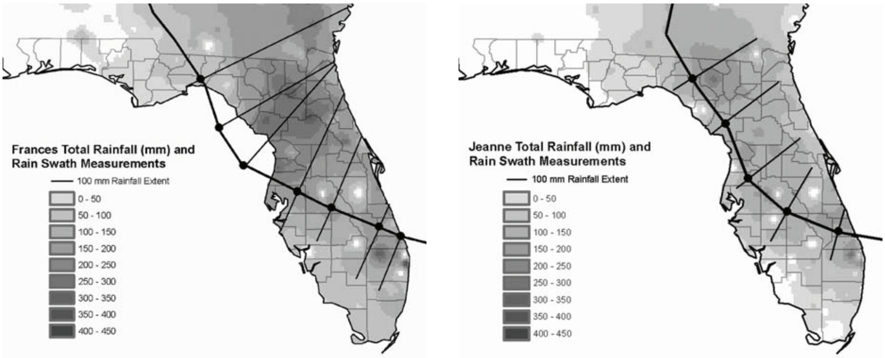

Figure 3. Storm total rainfall amounts produced by a. Frances and b. Jeanne over Florida. The rain swath measured for this analysis extends from the storm track to the edge of the 100 mm isohyet on both sides of the track.

data missing from the Melbourne and Tallahassee stations during the study period do not permit us to calculate storm-total rainfall amounts. Thus, to supplement our rain gauge analysis, we examine radar-derived rainfall estimates when possible to identify the locations of heaviest rain rates. We obtain one-hour precipitation accumulation products (OHPs) (Klazura and Imy 1993; OFCM 2006) for the Weather Surveillance Radar 1988-Doppler receivers at Miami, Melbourne, Tampa, Jacksonville, and Tallahassee. The OHP product utilizes data from multiple base reflectivity scans to estimate the amount of rainfall that occurred during the past hour within a 230 km distance from the radar's location. Rainfall rates (R) are estimated from the reflectivity values sensed by the receiver (Z) by applying a conversion factor. Both the Z and R values depend on the raindrop size and size distribution; R also depends on the fall velocity for a given drop diameter (Marshall and Palmer 1948).

Rainfall data of higher temporal resolution than the daily estimates available at most rain gauges are needed to determine where the highest rain rates occur within each storm. For this reason, we acquire rain gauge data from the Florida Automated Weather Network (FAWN). These data are available in 15-minute increments, and we acquire data from the stations depicted in Figure 2. We identify the FAWN gauge located nearest the circulation center of each storm at each 6-hourly observation time, and determine the average rain rate at this location for three hours before and after the storm passes this location. This provides us with an estimate of rain rates within the core of each TC. We also identify the highest 15-minute rain rate and the station at which this rain rate occurs during the period three hours before and three hours after each observation time. We then calculate the distance between the six-hourly position and rain gauge receiving the highest rain rate to determine whether they occur in the core of the storm, or within the outer rainbands. Many researchers agree (Burpee and Black 1989; Tokay et al. 1999; Ulbrich and Atlas 2002) that a rain rate of 10 mm hr^{-1} signifies convective precipitation. Therefore, we identify instances when the 15-minute rainfall accumulations total 2.5 mm or greater to estimate the percentage of rainfall occurring that is convective in origin, as opposed to lighter rain rates produced by stratiform regions of TCs. When possible, we utilize the radar data to verify the location of the heaviest rain rates.

To identify the variables most likely to have caused the rainfall distributions for each storm, we obtain data that quantify the environment surrounding each storm from the Statistical Hurricane Intensity Prediction Scheme (SHIPS) database (DeMaria et al. 2005). Variables are calculated for an annular region located 200–800 km from the circulation center of the TC, and are available every six hours (0000, 0600, 1200, and 1800 UTC). The environmental vertical wind shear used in this study is defined as the difference between the 200- and 850-hPa winds. Relative humidity data are available for low levels (850-700 hPa), middle levels (700-500 hPa), and high levels (500-300 hPa) of the troposphere.

RESULTS AND DISCUSSION

A. Spatial patterns of rainfall

The official storm total rainfall amounts listed by the NHC (Table 1) show that both storms produce their highest totals at West Palm Beach, located 45 km south of the point of landfall on the left side of the storm track. A maximum rainfall total on the left side of the storm track near the point of landfall can occur when bursts of intense convection are initiated on the right side of the storm and advected cyclonically about the vortex (Parrish et al. 1982). According to the SHIPS dataset, both Frances and Jeanne have eye diameters of approximately 75 km, which means that West Palm Beach is located within the eyewalls of both storms during the time of landfall, making the explanation for a left side rainfall maximum by Parrish et al. (1982) valid for both storms. An inspection of the radar data confirms that West Palm Beach received rainfall from convective cells in the eyewalls of both hurricanes. An examination of the hourly rainfall totals for the rain gauge at West Palm Beach reveals that most of the rain that fell in association with Jeanne occurred prior to the hour of landfall, while the rainfall from Frances occurred both before and after the hour of landfall.

Although the data reported by the National Hurricane Center (Franklin et al. 2006) show that the highest point rainfall total occurs to the left side of the storm track as both hurricanes make landfall, the rain fields for both storms extend farther to the right side of the storm track than the left overall as confirmed by both the rain gauge and radar data (Figures 3a and 3b; Figures 4 and 5; Tables 2 and 3). This finding is contrary to that of Miller (1958) who examined the rain swaths of 16 hurricanes making landfall in Florida and found that rain rates were fairly symmetrical on the right and left sides of the storm track. The rain field of Frances is so broad that at eight and fourteen hours post-landfall, the edge of the 100 mm isohyet on the right side cannot be measured over land. However, as the isohyet extends out to the coastline on the right side of the storm when the center is located at F3 (Figure 3a), this distance is at least two times as far as the 100 mm isohyet on the left side of the track, which is visible in Figure 3a. The radar-estimated rainfall totals confirm that the highest rain rates are

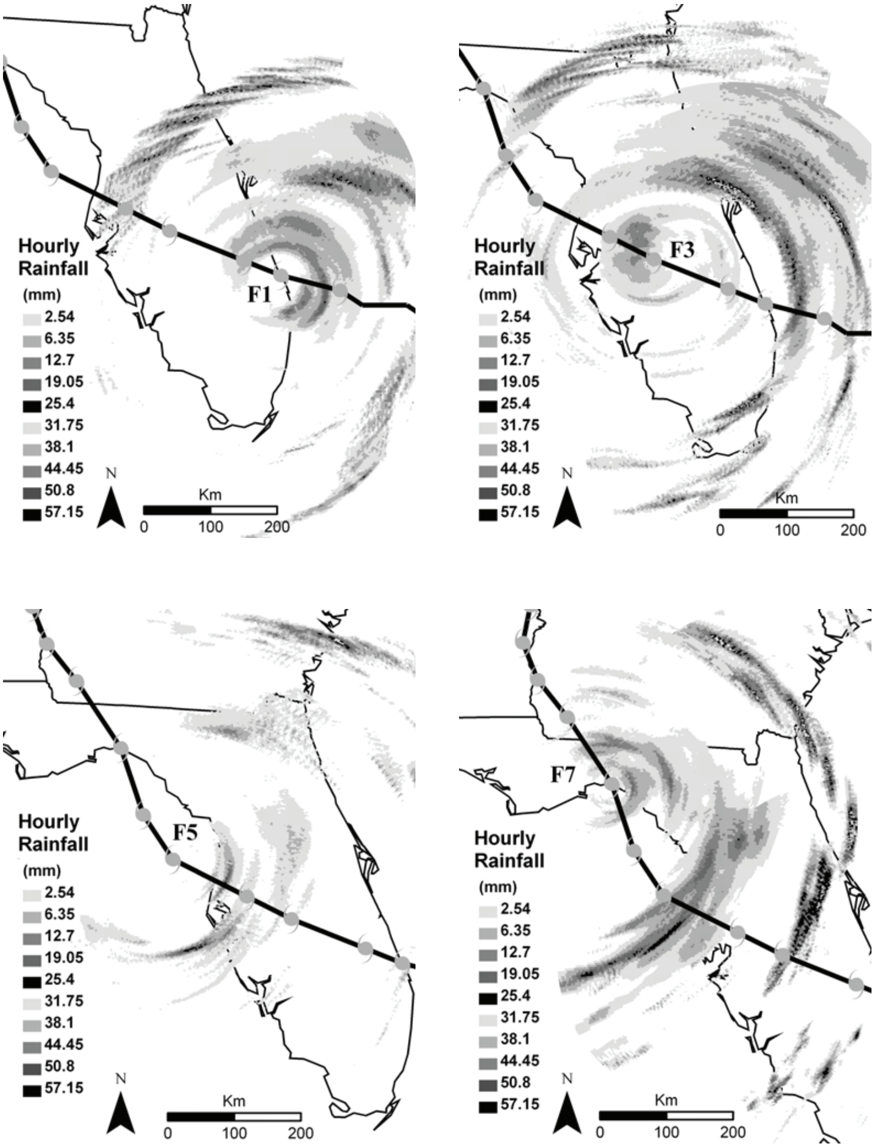

Figure 4. One-hour radar-estimated rainfall accumulations for Frances (2004) at a. 0600 on 5 September, b. 1800 on 5 September, c. 0600 on 6 September, and d. 1800 on 6 September.

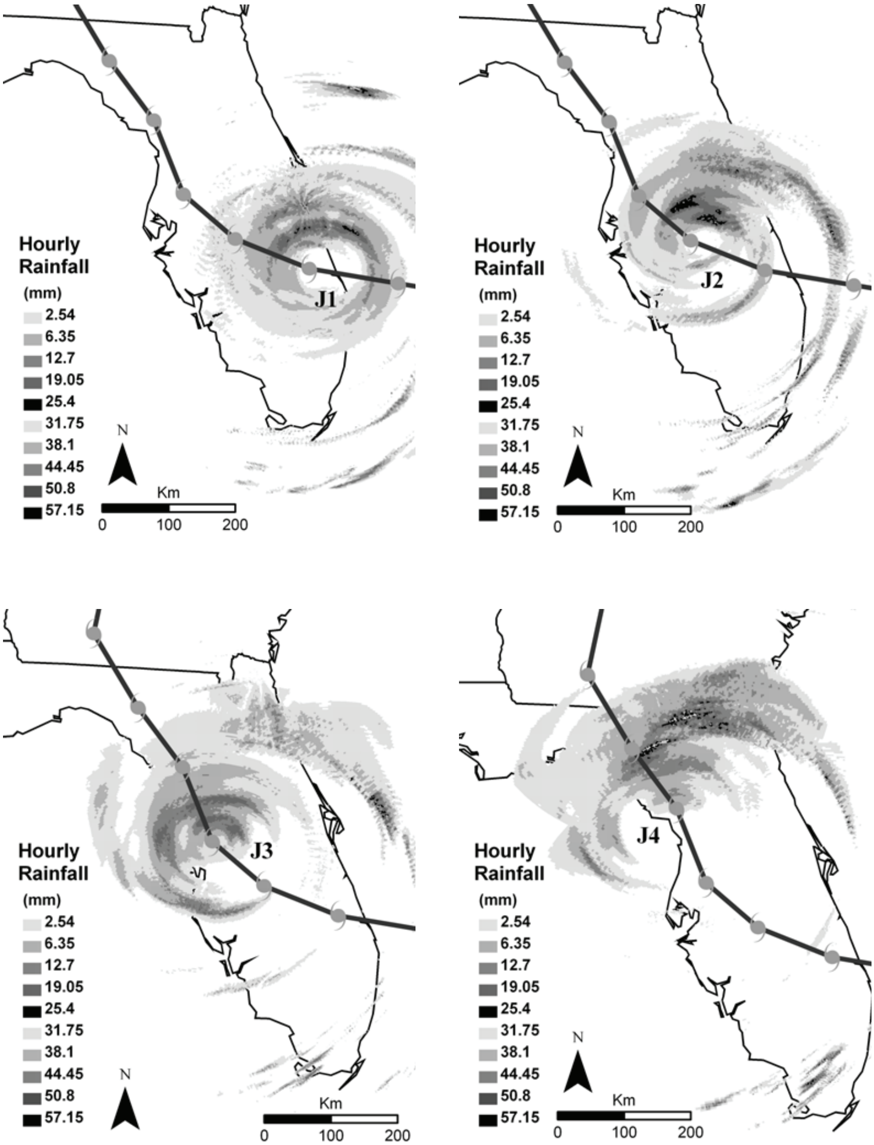

Figure 5. One-hour radar-estimated rainfall accumulations for Jeanne (2004) at a. 0600 on 26 September, b. 1200 on 26 September, c. 1800 on 26 September, and d. 0000 on 27 September.

Table 2. The nearest Florida Automated Weather Network station to the circulation center of Frances for each 6-hour period, the total rainfall measured by that rain gauge, the percent of observations that are convective rain-rates at that station, and the distance from the storm center to the edge of the 100 mm isohyet on each side of the storm track. The storm positions are depicted in Figure 2.

Storm Position	Station	Total Rainfall (mm)	Convective Percentage	Left Width (km)	Right Width (km)
F1	Ft. Pierce	214.38	30	121	N/A
F2	Ft. Pierce	214.38	30	118	63
F3	Lake Alfred	57.40	12	75	151
F4	Dover	132.59	20	99	236
F5	Brooksville	227.89	20	N/A	234
F6	Bronson	309.12	29	N/A	265
F7	Monticello	168.91	21	36	294

located offshore approximately 175 km from the circulation center at time F1 (Figure 4a). The rainband containing this deep convection moves onshore prior to time F2 and remains at approximately 155–175 km from the circulation center over the next 18 hours (Figure 4b and 4c). Little spiral banding occurs on the left side of the storm track during the period F1–F3, helping to limit rainfall totals (Figures 4a and 4b).

The left side of the rain field cannot be measured using rain gauge data while Frances is located over the Gulf of Mexico, but the 100 mm isohyet on the right side of the storm extends outwards to the Atlantic coastline, 260, 350, and 440 km away when the storm is located at F5, F6, and F7, respectively (Table 2). According to the radar data, little rainfall occurs on the left side of the storm track during this period (Figures 4c and 4d). The data from Tallahassee's radar show rainfall rates of 12.7 mm hr^{-1} or less on the left side of the storm. At the same time during periods F5–F7, the radar at Jacksonville estimates rainfall rates on the right side of the storm to be greater than 38.1 mm hr^{-1} in several spiral bands located over Florida as well as over Georgia some 300–350 km from the circulation center of the storm.

Like Frances, the rain swath of Jeanne extends farther to the right side of the storm than to the left. Both the rain gauge and radar data confirm that the highest rain rates within Jeanne are located within the core on the right side of the storm at J1 (Figure 5a) and ahead of the circulation center at J2 (Figure 5b) so that relatively small amounts of rainfall occur on the left side of the storm track. However, one major difference between the two storms is that Jeanne lacks the outer spiral rainbands that surround the core of Frances. For Jeanne, the highest rain rates occur within 90 km of the center of circulation.

During the period J4–J5, the circulation center of Jeanne remains over land. Offshore on the left side of the storm where rain gauge data are not available, radar data from Tampa show that rainfall does occur on the left side of the storm

Table 3. The nearest Florida Automated Weather Network station to the circulation center of Jeanne for each 6-hour period, the total rainfall measured by that rain gauge, the percent of observations that are convective rain-rates at that station, and the distance from the storm center to the edge of the 100 mm isohyet on each side of the storm track. The storm positions are depicted in Figure 2.

Storm Position	Station	Total Rainfall (mm)	Convective Percentage	Left Width (km)	Right Width (km)
J1	Ft. Pierce	142.49	4	65	44
J2	Lake Alfred	103.63	27	75	105
J3	Okahumpka	148.08	52	20	131
J4	Bronson	152.91	29	26	140
J5	Live Oak	182.88	47	40	155

track (Figure 5d). This indicates a fairly symmetrical distribution of rainfall about the circulation center of Jeanne relative to Frances, where very little rainfall occurs in the left front quadrant of the storm. As Jeanne turns towards the north during J4–J5, the rain field develops farther ahead of the circulation center as compared to J3 where rainfall occurs within 100 km of the storm center in all quadrants (Figure 5c). The highest rain rate recorded by a FAWN gauge occurs at Live Oak during J4. Radar data confirm that a band of deep convection develops 90–130 km from the circulation center in the right front quadrant of the storm and produces rainfall accumulations greater than 38.1 $mmhr^{-1}$ (Figure 5d).

An examination of the SHIPS data for each storm (Figure 6) reveals that both the vertical wind-shear magnitude and direction coupled with storm motion causes rain rates to be enhanced on the right sides of both storms, contributing to the asymmetrical rain swaths for each storm.

Observational studies on the effects of vertical wind shear on TCs over the ocean (Corbosiero and Molinari 2003; Chen et al. 2006; Cecil 2007) show that regardless of the strength of the shear, rain rates increase downshear and to the left of the shear vector and are reduced to the right of the shear vector. The forward velocity of the storm causes the highest rain rates to occur ahead of and/or to the right of storm motion. If the wind shear vector is nearly opposite to the direction of storm motion, the downshear left position, where rain rates are enhanced due to wind shear, is located on the right side of the storm track, where motion also enhances rain rates. Thus, both vertical wind shear and storm motion would enhance rainfall on the right side of the storm in this scenario.

Vertical wind shear out of the west is strong prior to the landfall of Frances (Figure 6a). Thus, upward motion is enhanced on the east side of the storm, causing the maximum rain rates to occur on the north (right) side of the storm, especially offshore. During the time that Frances moves over Florida, shear diminishes to an average of 5 ms^{-1} and the direction shifts to slightly out of the northwest, before shifting to a west origin and increasing slightly at the end of the study period. The motion

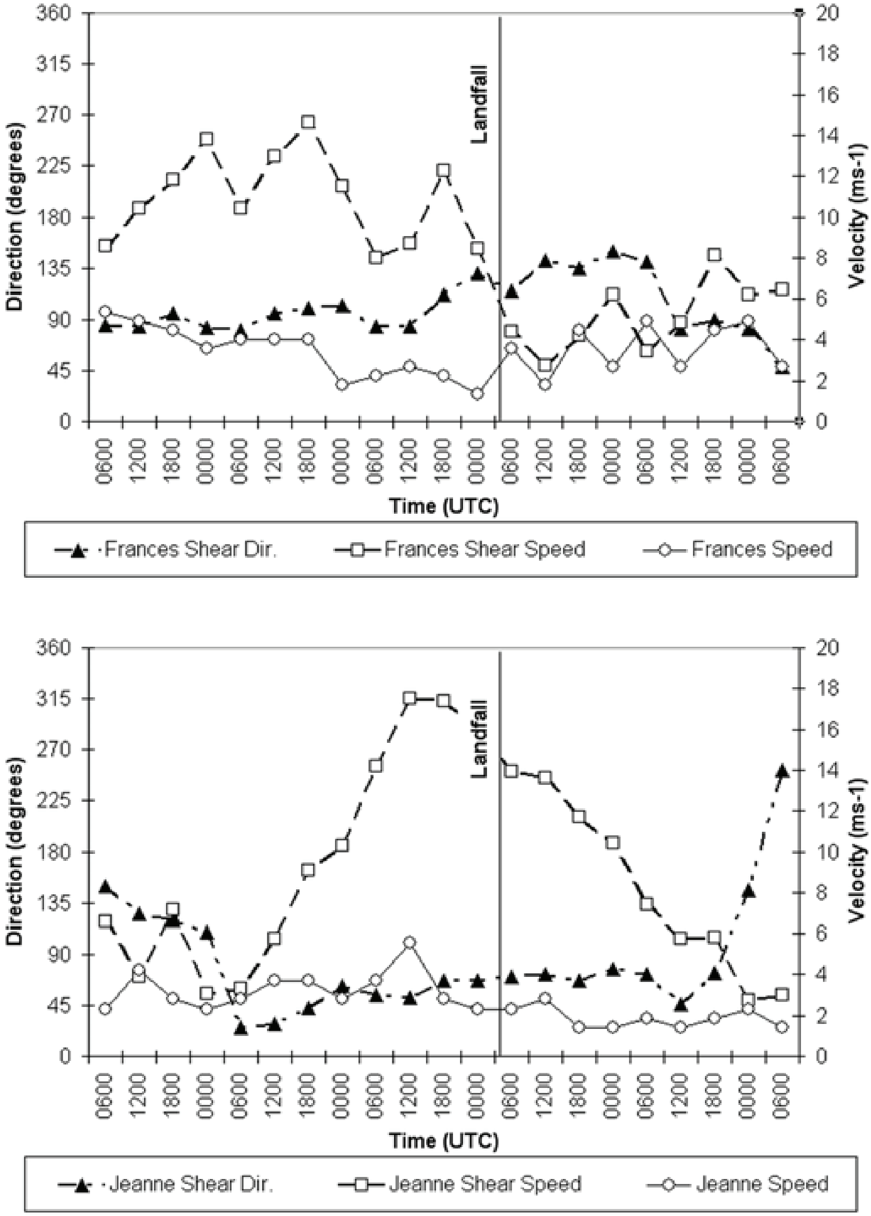

Figure 6. Vertical wind shear direction and magnitude and forward velocity of a. Frances and b. Jeanne every six hours for three days prior to and two days following landfall at Hutchinson Island, Florida.

Table 4. Rainfall data every six hours for Jeanne, including the average rain rate for three hours before and after the circulation center passed the nearest Florida Automated Weather Network rain gauge in the core of the storm, the highest rain rate occurring during that 6-hour time and the rain gauge at which this rain rate occurred, the distance of the gauge measuring the peak rain rate from the storm center, and the percentage of observations at the gauge measuring the peak rain rate that are convective rain-rates. The storm positions are depicted in Figure 2.

Storm Position	Average Core Six-Hour Rain Rate (mm/15min)	Peak Six-Hour Rain Rate (mm/15min)	Location of Peak Rain Rate	Distance from Storm Center (km)	Convective Percentage
J1	3.09	16.76	Kenansville	85	58
J2	3.35	11.43	Kenansville	75	58
J3	3.65	10.67	Brooksville	30	35
J4	3.99	9.65	Live Oak	50	47
J5	2.58	5.08	Monticello	80	15

of Frances prior to and during landfall is toward the west and northwest, turning towards the north once over the Gulf of Mexico. During the first part of landfall, wind shear acts in the opposite direction of storm motion, helping to slow its forward velocity. As most of the rainfall is located on the right side of the storm track, it appears that both vertical wind shear and storm motion exert control on the rainfall according to the results of Corbosiero and Molinari (2003) and Chen et al. (2006). If shear had been the dominant influence throughout F1–F7, the highest rain rates would have occurred behind the storm, creating a more symmetrical rain swath. Convection does develop behind the storm approximately 240 km from the circulation center as the wind shear diminishes, but due to the limited spatial coverage, it does not contribute as strongly to the storm-total rainfall swath as do the spiral bands that produce rain rates exceeding 38.1 mm hr^{-1} on the right side of the storm throughout the study period.

For Jeanne, vertical wind shear is from the west-southwest blowing slightly across the storm track as the storm moves west-northwest to north (Figure 6b). The speed of the shear decreases around the time of landfall and throughout the study period, but remains higher than that experienced by Frances. The forward velocity of Jeanne is 4–5 ms^{-1}, so that storm motion may also affect the position of the rainfall. Similar to the conditions occurring during the landfall of Frances, both vertical wind shear and storm motion combine to enhance rain rates to the right of the circulation center as Jeanne moves towards the west after landfall, and ahead of the storm track as it turns towards the north.

B. Rainfall rates

For rainfall occurring over Florida, the timing of the highest rain rates and their radial position relative to storm center differs between the two storms. Jeanne produces its highest rain rate two hours post-landfall while located at J1 (Table 4). The

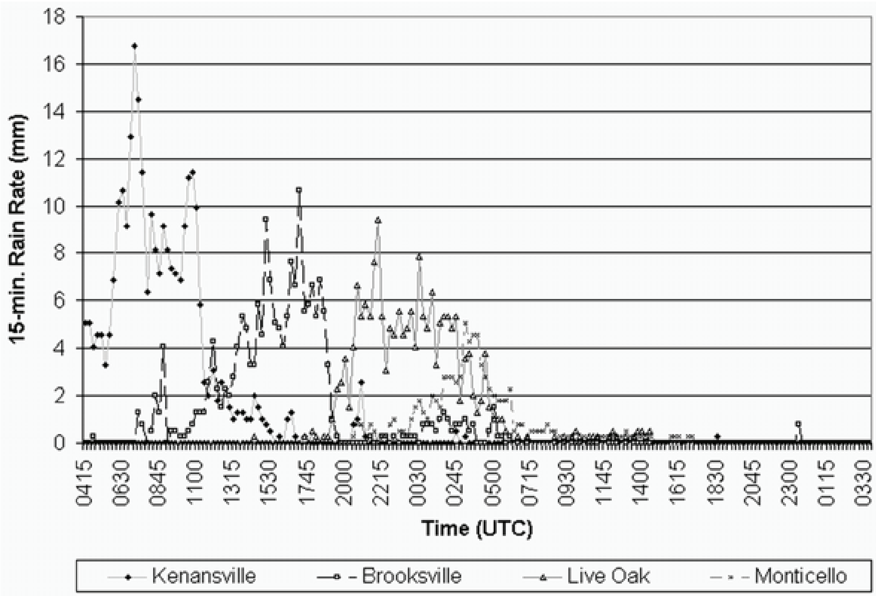

Figure 7. Time series of rain gauge measurements every 15 minutes at the four locations where peak rain rates were measured during the passage of Jeanne that are listed in Table 4.

peak rain rates sampled by the FAWN gauges decrease as the storm crosses the Florida peninsula, with the lowest rain rate occurring at the end of the study period (J5). The gauges measuring the peak rain rates are located 30–85 km from the storm center, indicating that the highest rain rates occur in the core of the storm, rather than in any outer rainbands, and the radar data show similar results (Figure 5). This result is also confirmed when examining a time series of 15-minute rain rates (Figure 7). Rainfall generally spans 12 hours at each of the FAWN gauges, with a maximum of 14 hours near the time of landfall, and minimum of 8 hours at the end of the study period. At most of the gauges analyzed, stratiform precipitation occurs before and after a period of convective precipitation that lasts 6–7 hours. The duration and intensity of convective rainfall diminishes at the end of the study period.

Frances exhibits more variability in its rain rates, in both where they occur relative to the core and outer regions of the storm, and the timing of their occurrence relative to landfall. The peak rain rate sampled by the FAWN gauges occurs eight hours post-landfall when the center is at F2, and then falls and rises several times (Table 5). Moving over the Gulf of Mexico coincides with a rise in rain rates, as well as a slight increase in the maximum sustained wind speeds, although Frances remains a tropical storm. The gauges measuring the peak rain rates are located 35–265 km away from the storm center throughout the study period, indicating that some of the heaviest rain rates occur

Table 5. Rainfall data every six hours for Jeanne, including the average rain rate for three hours before and after the circulation center passed the nearest Florida Automated Weather Network rain gauge in the core of the storm, the highest rain rate occurring during that 6-hour time and the rain gauge at which this rain rate occurred, the distance of the gauge measuring the peak rain rate from the storm center, and the percentage of observations at the gauge measuring the peak rain rate that are convective rain-rates. The storm positions are depicted in Figure 2.

Storm Position	Average Core Six-Hour Rain Rate (mm/15min)	Peak Six-Hour Rain Rate (mm/15min)	Location of Peak Rain Rate	Distance from Storm Center (km)	Convective Percentage
F1	2.16	14.48	Umatilla	235	21
F2	1.80	18.54	Putnam Hall	265	26
F3	1.12	8.89	Ocklawaha	135	19
F4	1.01	12.45	Balm	35	29
F5	1.85	8.38	Brooksville	115	20
F6	1.73	6.86	Monticello	130	21
F7	3.57	13.72	Monticello	45	21

in the outer rainbands of the storm. This observation is also confirmed through an analysis of the radar data (Figure 4). Rainfall spans a longer period at each gauge for Frances (Figure 8) as compared to Jeanne (Figure 7), which also supports the finding that more of Frances' rain is contained in its outer bands rather than in its core, as is the case for Jeanne. Rain falls continuously for more than 48 hours at some locations, and several peaks of convective rainfall occur, indicating that strong rainbands are present both ahead of and behind the circulation center. Once again, radar observations confirm that Frances has several rainbands that extend more than 200 km from its circulation center (Figure 4), while Jeanne does not possess these outer rainbands (Figure 5). Therefore, both the rain gauge data and the radar data show that the rain fields of Frances extend farther from the storm center than the rain fields of Jeanne.

Moisture in the environment surrounding the storms likely accounts for the convective rainfall that occurs over 265 km from the center of Frances, but remains near the core of Jeanne. In the days prior to landfall, tropospheric moisture is higher in the environment surrounding Jeanne than that surrounding Frances (Figure 9). However, a reversal in this trend begins within a day of landfall. By the day of landfall, relative humidity values for Jeanne drop by approximately 15 percent in the middle and upper levels of the troposphere, while relative humidity at these levels increases by 10 percent for Frances. Because Frances exists in a more moist environment and experiences a decrease in vertical wind shear (Figure 6), strong convection is able to develop in the outer rainbands, as is evidenced by the high rain rates observed at Umatilla and Putnam Hall (Table 5). Black (2002) discusses a similar occurrence for Hurricane Dean (1989) prior to its land-

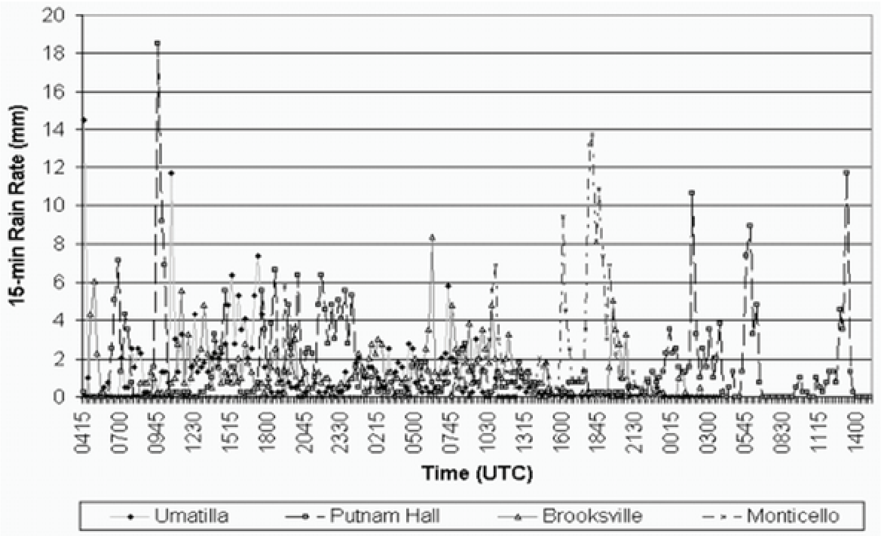

Figure 8. Time series of rain gauge measurements every 15 minutes at the four locations where peak rain rates were measured during the passage of Frances that are listed in Table 5.

fall. The dry environment surrounding Jeanne did not permit outer rainbands to form. In their modeling study, Hill and Lackmann (forthcoming) found that outer rainbands produced high rain rates in an environment with 80 percent relative humidity, whereas outer rainbands did not form when relative humidity was below 60 percent. Thus, even though the storms are of similar size at landfall as measured by the radius of gale-force winds and radius of the outermost closed isobar, the rain fields of Frances extended several kilometers beyond its wind fields, while the rain fields of Jeanne remained within the region of gale-force winds.

The partition of stratiform and convective rain rates within each storm differs. Nearly 60 percent of the rainfall that occurs at Kenansville is convective as Jeanne moves inland, and 50 percent of the rain that falls at Okahumpka is convective as well (Tables 4 and 3). By comparison, only 30 percent or less of the rainfall produced by Frances at all FAWN gauge locations is convective (Tables 5 and 2). The development of deep convection due to movement over warm waters within a moist atmospheric environment prior to landfall (Figure 9) allow high rain rates to persist in the core of Jeanne for one day after landfall. After this time, rain rates decrease sharply as relative humidity levels, which are steady during the day of landfall, begin to decrease (Figure 9). For Frances, the formation of strong outer rainbands prevents high rain rates from occurring within the core of the storm. As explained by Willoughby et al. (1984) and Heymsfield et al. (2001), the outer rainbands take in the warm and moist air from the near-surface environment and produce relatively cool downdrafts which then continue inwards towards the center of

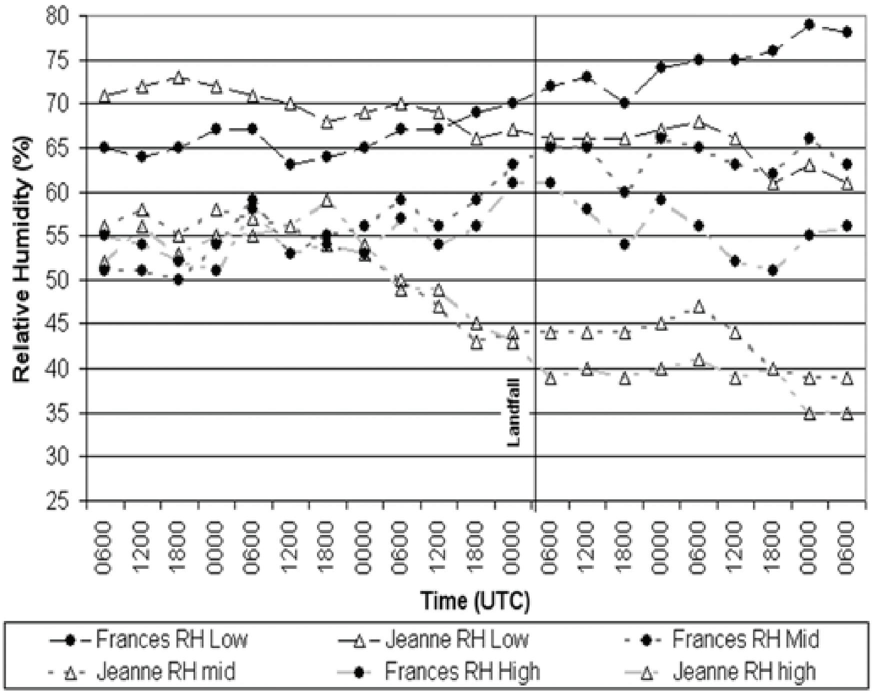

Figure 9. Relative humidity values at 850-700 hPa (low), 700-500 hPa (mid), and 500-300 (high) of Frances and Jeanne every six hours for three days prior to and two days following landfall at Hutchinson Island, Florida.

the storm. Thus, deep convection cannot develop across the core of the storm, and the core, along with the regions between the rainbands, is comprised mostly of stratiform precipitation.

Although Jeanne has a higher percentage of rain rates that are convective rather than stratiform as compared to Frances (Table 4), storm-total rainfall amounts in Florida are higher for Frances than for Jeanne (Tables 1, 2, 3). It is likely that Frances' slower forward velocity and a broader rain field with the heaviest rainfall embedded in outer rainbands both contribute to the higher rainfall accumulations. The variable that likely is most responsible for the high rainfall accumulations from Frances is the storm's relatively slow forward velocity. At times, Jeanne moves twice as fast as Frances while over the Florida peninsula (Figure 6). Thus, even though 70–80 percent of the rain fields of Frances are comprised of stratiform precipitation, this rainfall persists for more than two days due to the slow forward motion of the storm. The presence of strong convection within several outer rainbands both adds to rainfall totals and creates a wide rain field for Frances that adds to the duration of rainfall.

CONCLUSIONS

Hurricanes Frances and Jeanne made landfall at the same location on the east coast of Florida in September 2004 on a similar track at the same time of day, and were of similar size. Despite these similarities, the storms produced different rainfall totals across Florida. To compare the rain fields of these storms, we acquired rainfall data from rain gauges and radar-derived rainfall totals. We used a GIS to map the rain swath of each storm, and measured the width of the rain swath on each side of the storm track every six hours to determine rain-field symmetry. We also calculated the rainfall intensity from 15-minute rain gauge observations to determine whether convective or stratiform precipitation dominated the rain fields of each storm, and calculated the distance of the highest rain rates from the circulation center for each six-hour period. Radar observations were utilized to confirm the locations of convective rainfall. We related these attributes of the rain fields to the environment surrounding each storm and the motion of the storm.

The changing environmental conditions at the time of landfall caused the rain fields of both storms to become distributed asymmetrically about the storm track. For Frances, weakening wind shear and high relative humidity values allowed deep convection to develop in the outer rainbands on the right side of the storm more than 250 km from the circulation center. Storm motion also influenced the location of high rain rates, causing much more rainfall to accumulate on the right side of the storm track than the left side. The strength of the outer rainbands caused rain rates to be lower near the center of circulation, and as a result, only 20–30 percent of the rain field of Frances was comprised of convective precipitation. Despite the lower overall rain rates, the broad rain field that contained high rain rates within the outer rainbands, in combination with a slow forward velocity and increasing atmospheric moisture, produced high rainfall accumulations to the right of the storm track. These mechanisms resulted in more rainfall accumulating on the ground during the passage of Frances than during the passage of Jeanne.

Jeanne transitioned from a moist, low-shear environment to a dry atmospheric environment with increasing vertical wind shear as it crossed the Florida peninsula. The dry environment did not allow outer rainbands with deep convection and high rain rates to form as they did during Frances. The combination of the wind shear's direction across the track of Jeanne with the motion of the storm caused the rain swath to extend farther to the right side of the storm track than to the left side of the storm track. Rain rates were highest in the core of Jeanne, and the rain field overall contained more convection than did Frances, but a faster forward velocity only allowed rainfall to persist for half of a day, compared to the two-day duration of rainfall produced by Frances.

As multiple physical mechanisms affect the development of rainfall within landfalling TCs, modeling studies are normally needed to isolate the role of the atmosphere in shaping the rain fields. As the similarities between Hurricanes Frances and Jeanne allow many variables that affect the development of rainfall during landfall to be filtered out, this observational study demonstrates how the atmosphere affects the spatial distribution and amount of rainfall produced by these two TCs. This work supports the results of modeling studies that investigated how vertical wind shear, storm motion, and relative humidity affect the rain fields of TCs, and is also in agreement with observational studies on the effects of vertical wind shear and storm motion on the rain fields of TCs that are not making landfall.

Future work should employ a GIS-based spatial analysis of the rain fields using radar data and rain gauge data to examine the rain swaths of a larger sample of TCs. Storms should be grouped according to their location of landfall and the environmental conditions present prior to and during landfall to further explore how storm motion, vertical wind shear, atmospheric moisture, land surface conditions, diurnal variations in convection, and other factors affect the symmetry and intensity of rainfall. For storms that exist in environments that change prior to landfall, such as Frances and Jeanne, research should focus on how quickly the changing conditions affect the rain fields of the TCs. A more precise accounting of convective and stratiform portions of TC rain-fields could be undertaken through an in-depth spatial analysis of radar reflectivity data as well. Radar data are available for many locations within the U.S. beginning in 1995. As 63 of U.S. landfalling TCs between 1980 and 2008 have occurred since 1995, an examination of their radar-derived and rain gauge-derived rainfall patterns could yield a greater understanding of the physical mechanisms that lead to different spatial patterns of TC rain fields as they move over land.

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