

## **USING GIS TO ASSESS THE SYMMETRY OF TROPICAL CYCLONE RAIN SHIELDS**

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### **1. INTRODUCTION**

Tropical cyclones (TCs) that produce heavy rainfall pose a great hazard to populations, as fresh water floods were responsible for nearly 60 percent of U.S. TC-related deaths between 1970-1999 (Rappaport, 2000). Freshwater floods can affect regions that are hundreds of kilometers inland from the point of landfall, exposing more people to this hazard than to high winds and storm surge, which are of major concern only near the coastline. Therefore, it is important to determine where heavy rainfall might occur within a given TC so the public may be warned in advance of the event.

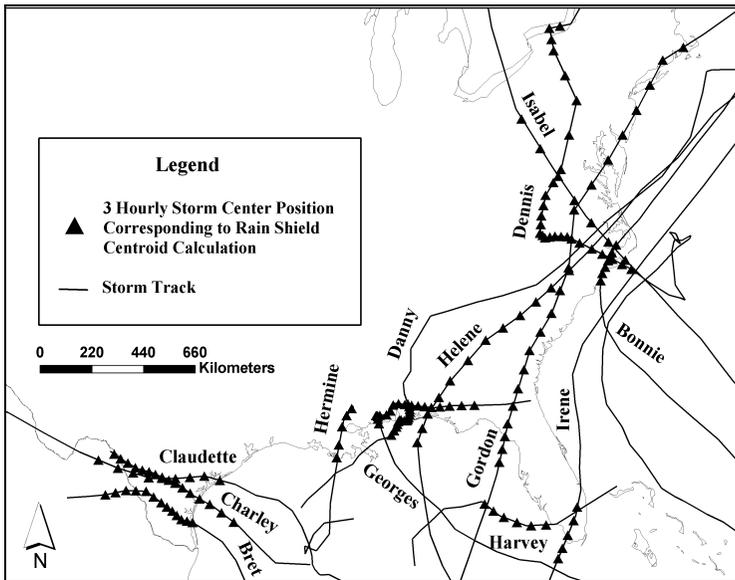
DeMaria and Tuleya (2001) developed the first TC rainfall climatology and persistence model (R-CLIPER). They calculated gauge-estimated rainfall rates for 46 TCs within sets of annular rings placed in 50 10-km increments outward from the storm center. After landfall, a linear decay function determined the rainfall rates. Marks *et al.* (2002) improved R-CLIPER by utilizing satellite data to acquire rainfall rates from 482 TCs. However, inland portions of the rainfall forecast are based on the assumption that rainfall amounts decrease in a symmetrical pattern away from the storm center along the track after landfall, and that the maximum rainfall rates occur at the time of landfall and decrease thereafter. This remains the largest drawback of the R-CLIPER model.

Through observations and modeling studies, previous researchers have demonstrated that TC interactions with the land surface and atmosphere can increase and/or decrease rainfall in different areas of the storm (e.g., Tuleya and Kurihara, 1978; Rogers and Davis, 1993; Chan and Liang, 2003). If TC rain shields are often displaced asymmetrically about the storm's circulation after landfall, improvements to the R-CLIPER model should include a measure of rain shield displacement relative to the storm center. This study develops a method to measure the asymmetrical displacement of TC rain shields. A geographic information system (GIS) is utilized to define the spatial extent of landfalling TC rain shields from base reflectivity radar returns. The geographical center of the rain shield is calculated, and its position is determined relative to the storm center. Examining the distance and bearing of the rain shield from the storm center in hourly increments for 13 TCs reveals how frictional convergence of onshore winds, interaction with steep terrain, strong vertical wind shear, and extratropical transitions can displace the rain shield from a symmetrical distribution about the storm center.

## 2. DATA AND METHODS

This study examines the rainfall patterns of thirteen TCs making landfall in the U.S. from 1997 to 2003 (Figure 1). Base reflectivity returns acquired from the Pennsylvania State University Department of Meteorology were used to define the spatial extent of the TC rain shields. These data have a high spatial and temporal resolution, making them ideal for spatial analysis. Before they are entered into a GIS, radar returns from each station within 500 km of the storm center at the top of each hour are georeferenced and converted into shapefiles (Shipley et al., 2000).

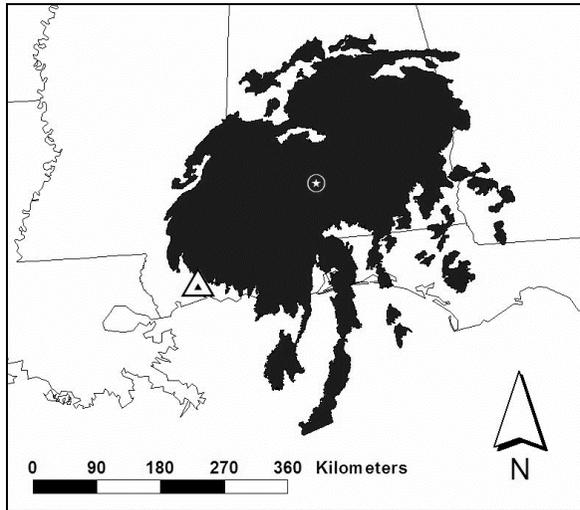
FIGURE 1  
TRACKS OF 13 TCS EXAMINED IN THIS STUDY  
(MARKERS INDICATE STORM CIRCULATION CENTERS  
CORRESPONDING TO RAIN SHIELD CENTROID POSITIONS INDICATED  
IN FIGURES 3-6)



The coordinates of the TC circulation centers are obtained from the National Hurricane Center's best track dataset. As these data are only available in six-hour increments, hourly positions of the storm centers are calculated through a linear interpolation (Corbosiero and Molinari, 2002). The interpolated dataset is then imported into the GIS (Figure 1).

Within the GIS, the radar shapefiles for all stations at the top of the hour are merged into one layer. These data are interpolated using inverse distance weighting, and the isopleths representing the 20 dBZ reflectivity level are converted into polygon shapes. Due to the high spatial resolution of the radar data, other interpolation methods produced similar polygon shapes. After the removal of polygons with perimeters less than 100 km, a script calculates the latitude and longitude of the geographical center, or centroid, of all remaining polygons in the layer (Figure 2). This process was performed on 486 observations for the 13 TCs.

FIGURE 2  
RAIN SHIELD OF GEORGES (1998) TWELVE HOURS POST-LANDFALL  
(TRIANGLE IS STORM CIRCULATION CENTER; CIRCLED STAR MARKS  
RAIN SHIELD CENTROID)



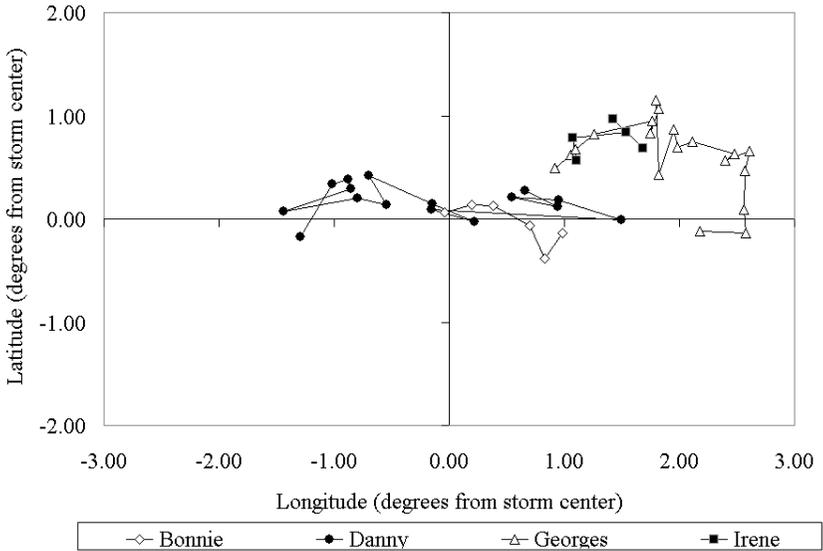
To determine whether the TC rain shields are symmetrically distributed about the storm, a link is established between the rain shield centroid (Figure 2) and storm circulation center (Figure 1) by calculating the distance and bearing of the centroid with respect to the storm center. Smaller (larger) distance values indicate a rain shield that is more symmetrically (asymmetrically) distributed about the storm's circulation. The centroid bearings provide insight into the physical forcing mechanisms responsible for altering the symmetry of the rain shield. For example, frictional convergence of onshore winds occurs as a TC crosses the coastline. This convergence enhances uplift, allowing more moisture to enter the storm's circulation, which increases rainfall. As a result, a TC tracking north may experience an increase in rain shield coverage on its east side, which would increase the easterly component of the rain shield centroid's bearing.

### 3. RESULTS AND DISCUSSION

#### 3.1 HURRICANES THAT DID NOT TRACK INLAND AFTER LANDFALL

Four hurricanes either remained within 100 km of the coastline after landfall, or returned to sea after spending less than 24 hours over land (Figure 3). These TCs were examined to determine whether the location of the rain shield centroid corresponds to the region where the effects of frictional convergence should enhance rainfall production. When a TC makes landfall, onshore winds slow upon encountering the rough land surface and promote the upward motion of moist air into the storm's circulation. The tangential wind speed, shape of the coastline, and angle of storm approach to the coastline all affect where the enhanced rainfall occurs in relation to the storm center (Tuleya and Kurihara, 1978; Parrish *et al.*, 1982; Powell, 1987; Rogers and Davis, 1993; Chan *et al.*, 2004). The results of this study show that simply determining the location of the rain shield centroid can account for the displacement of the rain shield away from the storm center caused by these forcing mechanisms.

FIGURE 3  
 THREE-HOURLY POSITIONS OF RAIN SHIELD CENTROIDS RELATIVE TO STORM CENTER FOR HURRICANES THAT DID NOT TRACK INLAND AFTER LANDFALL (STORM CENTER OF CIRCULATION AT EACH TIME STEP IS LOCATED AT THE CENTER OF THE GRAPH (0,0). INTERVALS ON THE GRAPH ARE EQUAL TO ONE DEGREE OF LATITUDE OR LONGITUDE [APPROXIMATELY 111 KM])



Hurricane Georges (1998) made landfall while tracking north, and then moved in an easterly direction parallel to the Florida coastline (Figure 1). The rain shield of Georges remained displaced east of center during all 56 hours of observations (Figure 3). The rain shield centroid also remained 135-170 km from the Florida coastline, indicating that frictional convergence of onshore winds was the primary mechanism responsible for the post-landfall location of the rain shield of Georges. Georges produced over 600 mm of rainfall over areas located 150-250 km east from the point of landfall (Pasch *et al.*, 2001), further confirming the ability of the centroid to indicate the asymmetrical placement of the rain shield relative to the storm track.

The left side of Hurricane Danny's (1997) circulation encountered the coastline several hours prior to the landfall of the eye. As a result, frictional convergence of onshore winds caused the centroid's displacement ahead (east) of the storm center (Figure 3). While making landfall, Danny encountered anomalously warm sea surface temperatures to the left of storm center at the mouth of Mobile Bay (Blackwell, 2000). Rainfall subsequently increased (decreased) to the west (east) of center, causing the rain shield centroid to also shift west of the storm center (Figure 3). In this case, tracking the centroid's position relative to the storm center allows an examination of the effects of both frictional convergence and warm sea surface temperatures on the evolution of the rain shield during and after landfall.

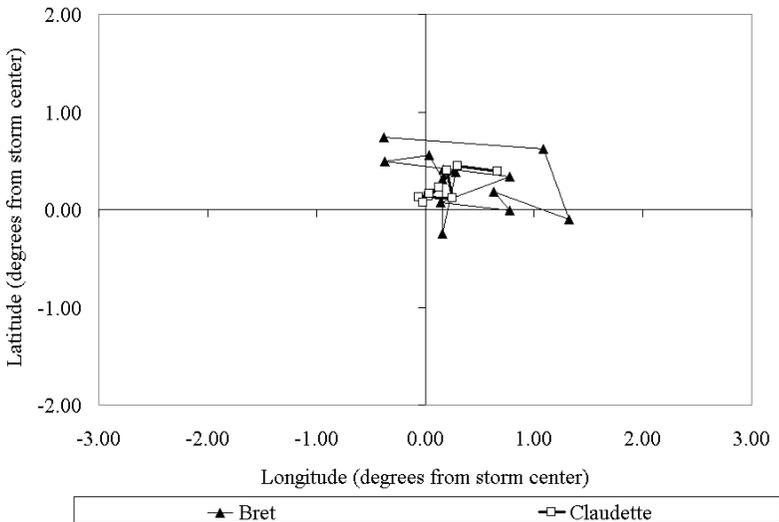
Calculating the rain shield centroid was also successful in tracking the effects of frictional convergence for two TCs that only briefly moved over land. The rain shield of Hurricane Bonnie (1998) was better developed on its right (east) side of center as this side remained over the ocean and continued to advect moisture into its circulation even while the storm center was over land (Figure 3). Hurricane Irene's (1999) rain shield became displaced northeast of center as it passed over the Florida peninsula (Figure 3). Frictional convergence on the east side of Florida enhanced rainfall production even though landfall occurred on the west coast of the

state. Over 25 mm of rainfall occurred along the right side of the storm track, which again demonstrates the need to account for the effects of physical forcing mechanisms such as frictional convergence of winds on the location of the rain shield to improve the spatial accuracy of TC rainfall forecasts. The findings for all four hurricanes described above support the ability of the rain shield centroid calculation to both identify asymmetrically-displaced rain shields, and model the effects of frictional convergence on rain shield development.

### 3.2 HURRICANES ENCOUNTERING ELEVATED TERRAIN

After making landfall along the Texas coast, Hurricanes Bret (1999) and Claudette (2003) tracked westward, encountering steeply elevated terrain in central Texas. When a TC approaches elevated terrain, uplift is enhanced on the windward side of the storm track, leading to increased rainfall amounts (Bender *et al.*, 1985; Lin *et al.*, 2002). As less rainfall is required to trigger flooding on elevated terrain relative to flat ground, it is critical to determine where rainfall might occur in mountainous regions to facilitate the evacuation of flood-prone areas. The results of this study confirm previous research findings that rainfall is enhanced on the right (windward) side of the storm track. The fact that Bret's track was farther south than that of Claudette (Figure 1), and Bret's rain shield centroid is farther to the north of the storm center than that for Claudette (Figure 4) suggests that the land surface is having an effect on the location of the rain shield. Determining the rain shield centroid position allows the effects of steeply elevated terrain to be modeled for these two hurricanes.

FIGURE 4  
AS IN FIGURE 3, FOR HURRICANES MAKING LANDFALL ALONG THE TEXAS COAST AND TRACKING INLAND ACROSS ELEVATED TERRAIN LOCATED NORTH OF THE STORM CENTER



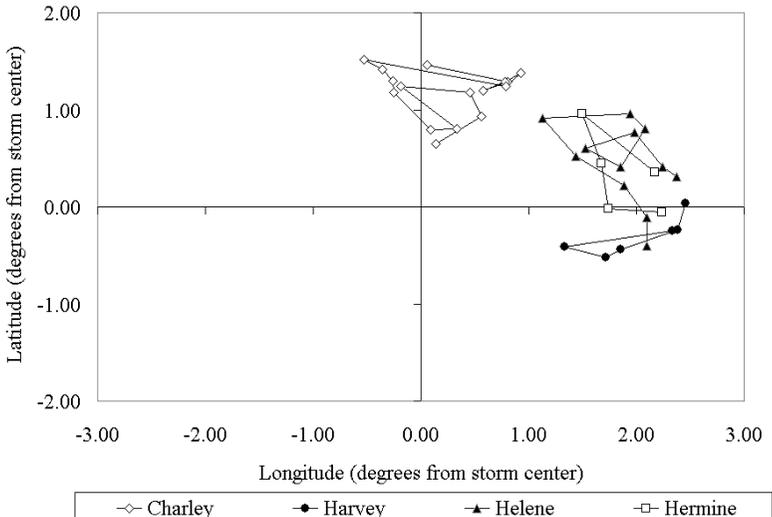
### 3.3 RAIN SHIELD DISPLACEMENT DUE TO STRONG VERTICAL WIND SHEAR

Four tropical storms examined in this study encountered strong westerly wind shear during landfall, causing their rain shields to become asymmetrically distributed about the storm centers (Figure 5). Both observational and modeling studies have found that strong vertical wind shear limits rainfall to the region of the storm that is down shear and/or left of the direction of wind shear (Willoughby *et al.*, 1984; Corbosiero and Molinari, 2002). The strong

westerly winds encountered by Tropical Storm Charley (1998) displaced its rain shield north of the storm center (Pasch *et al.*, 2001). Strong westerly winds caused the rain shield of Tropical Storm Harvey (1999) to be displaced well ahead of the storm center. The only rainfall associated with Tropical Storm Hermine (1998) occurred over 100 km from its center on its right (east side). The rain shield of Tropical Storm Helene (2000) was also displaced ahead of its northeastward track prior to and after landfall due to strong vertical wind shear. These findings demonstrate that tracking the rain shield centroid provides a more accurate depiction of the geographical extent of the rain shield as compared to assuming a symmetrical distribution of the shield about the storm's circulation center when TCs encounter strong vertical wind shear.

FIGURE 5

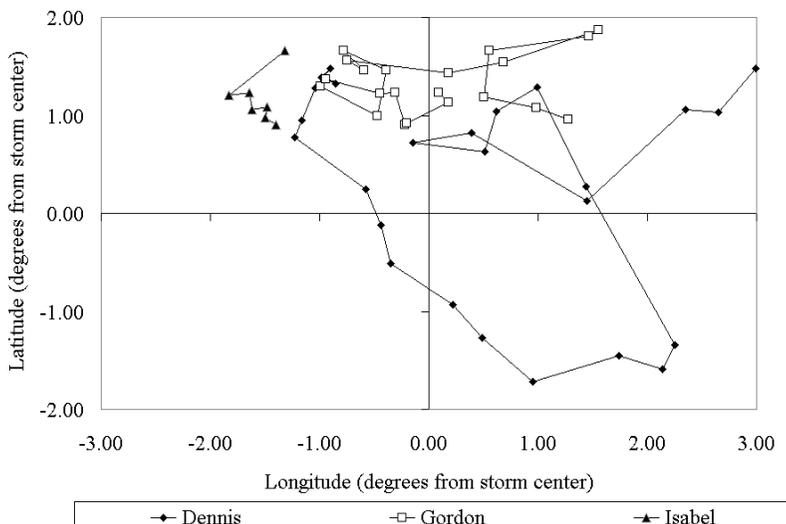
AS IN FIGURE 3, FOR TROPICAL STORMS AFFECTED BY STRONG WESTERLY WIND SHEAR. RAIN SHIELDS ARE DISPLACED DOWNSHEAR (EAST) OR LEFT OF SHEAR (NORTH)



### 3.4 EFFECTS OF EXTRATROPICAL TRANSITION ON RAIN SHIELD DISPLACEMENT

When a TC transitions into an extratropical cyclone, structural changes occur that affect the placement and shape of the rain shield. In a TC that is tracking north, the rain shield is displaced ahead of and to the left (west) of the storm center (Atallah and Bosart, 2003). Gordon (2000), Isabel (2003), and Dennis (1999) undergo an extratropical transition (ET) and are the only TCs whose rain shield centroids were displaced ahead of and to the left the storm center. This consistency in rain shield centroid location (Figure 6) indicates that calculating the centroid is a viable method for tracking rain shield asymmetries due to ET, and could be implemented to determine when an ET begins.

FIGURE 6  
AS IN FIGURE 3, FOR TROPICAL CYCLONES EXPERIENCING AN EXTRATROPICAL  
TRANSITION



Tropical Storm Gordon (2000) is the best example of an ET in this study as the storm is analyzed six hours prior to landfall, through the ET that begins approximately fifteen hours after landfall (Franklin *et al.*, 2001), and for an additional 32 hours after the ET. Figure 6 shows how the rain shield of Gordon shifted from the right (east) to the left (west) side of the track after landfall as the ET occurred. The rain shield of Hurricane Isabel remained ahead of and to the left (west) of the storm track during the entire analysis period (Figure 6) as it developed extratropical characteristics (Lawrence *et al.*, 2005).

Tropical Storm Dennis encountered a variety of physical forcing mechanisms that altered its structure and rainfall production during its lifespan, including wind shear, dry air entrainment, and encountering warm sea surface temperatures just prior to landfall. The complex interactions of these forcing mechanisms, as well as interaction with the Appalachian Mountains after landfall are evident in the relationship between the storm center and rain shield centroid (Figure 6). However, toward the end of the observation period, Dennis began an ET (Lawrence *et al.*, 2001). Evidence of this ET is visible in Figure 6 as the rain shield centroid begins to shift to the left (west) and ahead (north) of the storm center.

#### 4. CONCLUSIONS AND FUTURE RESEARCH

Various atmospheric and land surface forcing mechanisms can affect rainfall development in a landfalling TC, such as frictional convergence from onshore winds and strong wind shear. These forcing mechanisms cause the rain shield to be asymmetrically distributed about the storm's circulation center. As current TC rainfall forecast models depict a rain shield that is symmetrically distributed about the storm center, it is important to develop a method by which to assess the asymmetries that often occur. Analyzing the shape and location of landfalling TC rain shields could help improve rainfall forecasts and allow flood-prone areas to be evacuated prior to the storm's arrival.

This study calculated the geographical center of a TC's rain shield and related its location to the storm center to model asymmetrical rain shield displacement. The centroid locations calculated

in this study correspond to the rainfall patterns noted by previous observational and modeling studies for TCs affected by the frictional convergence of onshore winds during landfall, steeply elevated terrain, strong vertical wind shear, and an extratropical transition. These findings indicate that calculating the rain shield centroid and analyzing its position relative to the storm center could help improve the spatial accuracy of a TC rainfall climatology and persistence model.

Future research will investigate additional methods to classify the asymmetrical shapes of the rain shields themselves, such as the use of shape metrics (e.g., elongation, fragmentation). The shapes of the rain shields as determined from these metrics will be categorized based upon the forcing mechanisms that affect each TC. The examination of TCs in addition to those utilized in the current study will allow the associations between the rain shield shape metrics and forcing mechanisms to be tested with statistical significance. The development of a representative rain shield shape for combinations of forcing mechanisms could allow a more accurate prediction of the spatial extent of heavy TC rainfall, which could reduce the loss of life associated with freshwater floods produced by TCs.

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