JP1.2 USING GEOGRAPHICAL INFORMATION SYSTEMS FOR THE SPATIAL ANALYSIS OF BASE REFLECTIVITY RADAR DATA AND APPLICATIONS TO THE STUDY OF TROPICAL CYCLONE PRECIPITATION PATTERNS

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1. INTRODUCTION

Tropical cyclones (TC) can produce heavy rainfall, which can cause flooding many kilometers away from the point of landfall. This fresh water flooding now accounts for the majority of the loss of life from these storms (Rappaport 2000). The spatial distribution of TC rainfall is affected by many environmental aspects such as directional wind shear (Corbosiero and Molinari 2002), coastline shape (Rogers and Davis 1993), and topography (Lin et al. 2002). The goal of this research is to model the way in which TC precipitation patterns are altered by both the atmosphere and the land surface as they make landfall. Quantifying the pattern and rate at which TC precipitation changes could assist the development of precipitation forecast models.

I perform a series of spatial analyses on the precipitation patterns of 13 TCs making landfall in the U.S. during 1997-2003 (Table 1). To simplify the spatial analysis, I convert the numerous point data provided by base reflectivity radar returns into polygon shapes by entering the radar data into a Geographical Information System (GIS). I quantify the spatial extent of the derived polygons by overlaying a set of annular rings, dividing the storms into quadrants, and by calculating several geographical measures of shape, such as an area-to-perimeter ratio (MacEachren 1985). I also develop six metrics to characterize the unique changes that the polygon shapes of a TC experience resulting from environmental aspects such as strong directional wind shear or dry air entrainment.

This paper describes how the radar reflectivity data are analyzed within a GIS and discusses two key decisions regarding the spatial and temporal resolution of the data that affects the outcome of the analysis. These are: 1) the minimum reflectivity level to be included in the creation of the polygon shapes; and; 2) the point at which analysis can begin and end due to the spatial limitations of the radar data. These decisions are also important to consider for future work towards modeling changes in TC precipitation patterns.

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2. PROCEDURE

As high resolution data are required to perform the spatial analyses executed in this project, base reflectivity radar returns are utilized as the primary data. I acquired these data from the Department of Meteorology at Pennsylvania State University. Prior to their analysis within a GIS, the data are georeferenced using a Visual Basic script, NEX2SHP, authored by Scott Shipley (1999).

The data are then imported into Arcview GIS and files from all stations containing data for each TC are merged into one file in hourly intervals (Figure 1). In other words, each file contains all reflectivity data for a given storm at the start of an hour, the next file contains the reflectivity data 60 minutes later, etc. To convert the point data into polygon shapes, the reflectivity returns are interpolated using inverse distance weighting (Figure 2). Polygons with a perimeter length less than 100 km are not retained for analysis as they make minimal contributions to the overall area where precipitation occurred. Only polygons located within 400 km of the TC's center of circulation are included in the spatial analyses, as precipitation beyond this distance may be associated with events of non-tropical origin. The centroid of each major polygon in each image is also recorded.

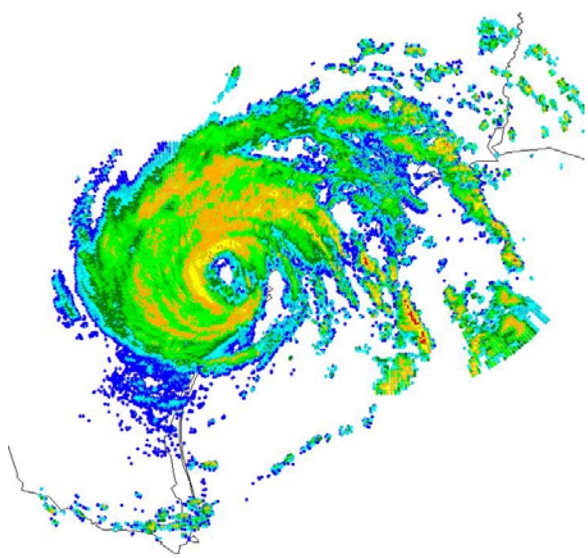

Figure 1. Base reflectivity radar mosaic created for Bret (1999) at the time of landfall along the Texas coast.

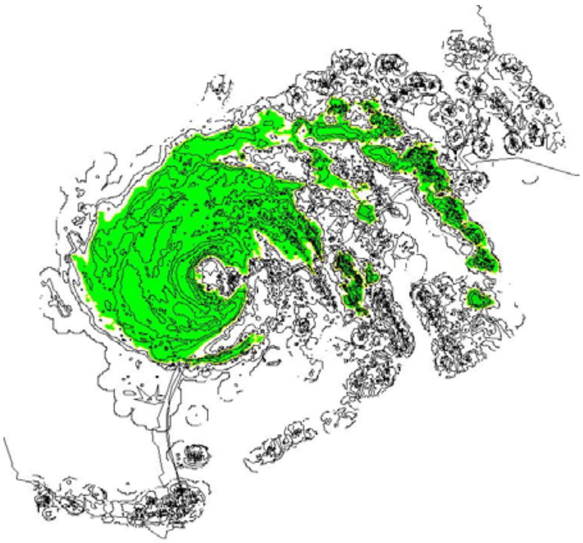

Figure 2. Spatial interpolation of Figure 1. The green areas indicate polygon shapes having a perimeter created from reflectivity returns 20 dBZ and higher. The contour interval is 5 dBZ.

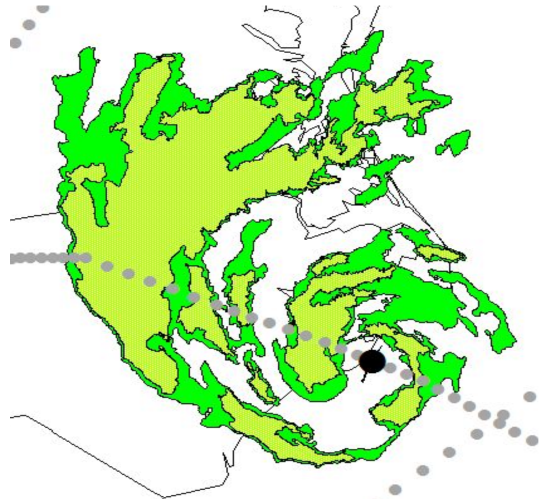

Figure 3. Polygon shapes created from Dennis (1999) at the hour of landfall along the North Carolina coast. Hourly center of circulation positions are indicated by gray dots. Black dot is the current circulation center. Dark green areas are the 20 dBZ polygons; the light green areas are the 25 dBZ polygons.

2.1 Selection of Polygon Shape Perimeter

To convert the interpolated point data into polygon shapes, one contour value must be selected to serve as the perimeter. The extent of a TC's precipitation field can be defined using several of the reflectivity strengths recorded by the radar in dBZ. Jorgensen (1984) used the 20 dBZ perimeter to assess the symmetry of lower level radar reflectivity signatures in four hurricanes. Toracinta (2002) also used the 20 dBZ threshold to analyze rainfall produced by tropical weather systems including TCs. Values less than 20 dBZ are not used as they can result from flocks of birds, swarms of insects, and smoke plumes (Klazura and Imy 1993), which is unsuitable for precipitation analysis. Twenty-five dBZ is the threshold used to differentiate between stratiform and convective precipitation in TC outer rainbands for a few studies (Barnes et al. 1983, Powell 1990, Samsury and Zipser 1995). The polygon shapes resulting from a reflectivity threshold higher than 25 dBZ are likely to be relatively small and fragmented, which would impede the calculation of shape statistics. For this study, I create two sets of polygon shapes for each hourly analysis, one set with a 20 dBZ perimeter and one set with a 25 dBZ perimeter. Separate statistical analyses are performed on each set of shape values to determine which minimum threshold is most appropriate to serve as the polygon perimeter in future research. Figure 3 depicts the difference in the polygon shapes when each interval is analyzed.

2.2 Determination of When Analysis Should Begin and End: Edge Effect

Although this is difficulty to achieve, ideally, analysis should commence at least twelve hours prior to landfall to aid the forecasting of landfall conditions. The edge effect determines the time when the analysis can begin near the hour of landfall and when analysis should cease after landfall. To undergo spatial analysis, the polygon shapes need to be complete, else an artificial edge is required to close off the polygon. Spatial analyses performed on these artificial polygons erroneously indicate that the spatial extent of precipitation is decreasing and its orientation is changing.

Symmetrically-shaped TCs have precipitation in front of and behind the eye. As radar data only spans 230 km from the station (Crum et al. 1993), the storm's entire circulation must be within this distance of the coastline before analysis can commence. Thus, the spatial analysis of TCs that are large, brush the edge of the coastline before returning to sea, or cross the Florida peninsula (Figure 4) are problematic. The edge effect is observed in a rainband on the right-hand side of Figure 2; this image could not be included in the analysis. The point at which analysis begins and the number of hourly observations collected for each TC are examined to determine how far in advance of landfall analysis can commence in most cases.

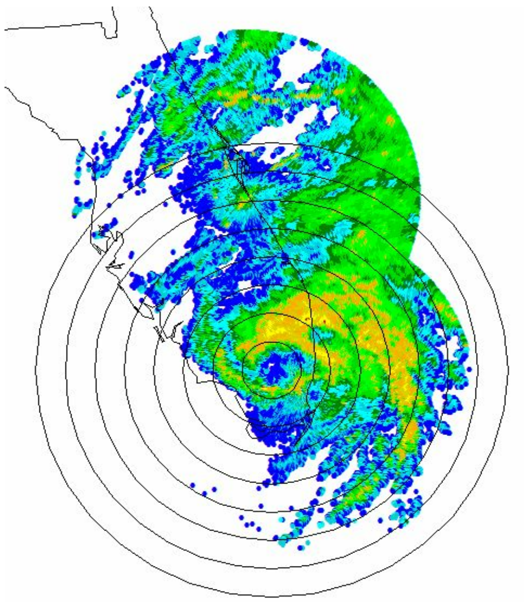

Figure 4. Radar mosaic for Irene (1999). Rings encircle the center of circulation in 50 km increments as they were overlain for analysis in the study. The spatial extent of the radar data limits the analysis of TCs moving across the Florida peninsula.

2.3 Statistical Analysis

To determine which spatial and temporal scales are best-suited to characterize changes in TC precipitation patterns, I perform several stepwise multiple regression analyses. Each model has 28 potential predictors, including the spatial analysis data described previously. Specifically, these predictors are: 1) eight annular ring variables; 2) four quadrant variables; 3) four geographical shape measures; 4) six TC-specific shape measures; and 5) other data relevant to the current state of each TC, such as maximum sustained wind speed, time since landfall, distance from the coastline, and size. The models predict two different aspects of TC precipitation. These aspects are: 1) areal extent of precipitation; and 2) the location of the centroid of each major polygon relative to the circulation center of the storm. The latter requires the development of separate regression models for the east and north bearing of the centroid relative to the circulation center, and the distance of the centroid from the circulation center. Relating the centroid location to the circulation center allows the location of precipitation to be predicted using the National Hurricane Center's six-hourly prediction of the center of circulation. To minimize the effect that intensity differences have in classifying TC polygon shapes, individual analyses are performed utilizing data for TCs at hurricane, tropical storm, and tropical depression intensity.

3. RESULTS

The predictors entering the stepwise multiple regression analyses show the key environmental aspects associated with the spatial extent of precipitation and polygon centroid location to be storm intensity, forward velocity, distance from the coastline, and the presence of strong directional wind shear. The latter two become key predictors when TCs are at tropical storm or tropical depression intensity. The following sections detail how the spatial and temporal dimensions of this study discussed in Sections 2.1 and 2.2 were important in determining these results.

3.1 Polygon Shape Perimeter

A comparison of the statistical results for the data collected from the 20 dBZ and 25 dBZ polygon shapes indicates that the lower reflectivity level (20 dBZ) is the most appropriate perimeter for the polygons analyzed in this study. In many of the regression analyses performed using the 25 dBZ shape data, the results are not statistically significant, particularly for TCs at tropical depression intensity. When both the 20 and 25 dBZ models are statistically significant, the models constructed with the 20 dBZ polygon data typically account for more variance using fewer predictors than did those constructed with the 25 dBZ polygon data. After the TCs move inland, most of the deep convection present prior to landfall dissipates. The 25 dBZ shapes become very fragmented and small in area when compared to the 20 dBZ shapes. This finding suggests that tracking changes in TC precipitation patterns during and subsequent to landfall is best accomplished using a 20 dBZ minimum reflectivity value. Differences in the 20 dBZ and 25 dBZ polygon shapes of Isabel (2003) are shown in Figure 5.

3.2 Availability of Analysis Data Prior to Landfall and Length of Post-Landfall Analysis Period

In total, 479 hourly observations are analyzed. The temporal frame for each TC varies among the 13 storms (Table 1). In six cases, analyses commence six hours or more before landfall. Due to its shallow angle of approach to the coastline, the analysis of Danny (1997) begins ten hours prior to landfall. Eighty hourly observations are analyzed from Dennis (1999) due to its slow forward velocity, including six hours before landfall. However, five storms cannot be analyzed prior to landfall due to radar data spatial limitations.

Some TCs cannot undergo analysis even though their precipitation fields are quite large and they still possess an eyewall several hours post-landfall. Because of radar coverage limitations along the Florida peninsula (Figure 4), Irene (1999) is analyzed for seven hours before landfall, but only six hours post-landfall. The curvature of Bonnie's (1998) track took its precipitation field out of radar range along the North Carolina coast at 15 hours post-landfall. Fast-moving TCs, such as Isabel (2003) (Figure 5) also experience relatively short analysis periods as their precipitation moves out of radar range. Thus, it is not possible to establish a definitive period of analysis over which each storm can be analyzed using the methods described in this paper. However, even though a 12 hour pre-landfall analysis is not available within the bounds of the current data and methods, some storms in future analyses will likely be available for analysis six or more hours pre-landfall, which is still enough time to provide information about the spatial extent of post-landfall precipitation. The use of other data such as satellite imagery may extend the pre-landfall analysis window.

4. CONCLUSIONS AND DISCUSSION

The results of this study indicate that the procedure detailed here could be implemented on a larger data sample to develop a climatological-scale model of TC precipitation patterns. The 20 dBZ reflectivity data should serve as the perimeter for the polygon shapes, and analysis of some storms during the time before landfall is possible using the current data and analysis techniques. As additional TCs are analyzed, statistical models could be developed that utilize the rate of shape change and location of precipitation polygons to forecast precipitation patterns based on relevant atmospheric and land surface features.

The procedures described above could also be modified and applied at finer spatial and temporal scales. For example, deep convection present in the eyewall could be analyzed using a higher threshold dBZ level to serve as the polygon shape perimeter and analyzed in intervals as small as ten minutes. The reduced size and closer location to the circulation center of these polygons would allow analysis to commence sooner than previously possible and would overcome the current obstacle of needing the storm's entire circulation to be present within the radar's range.

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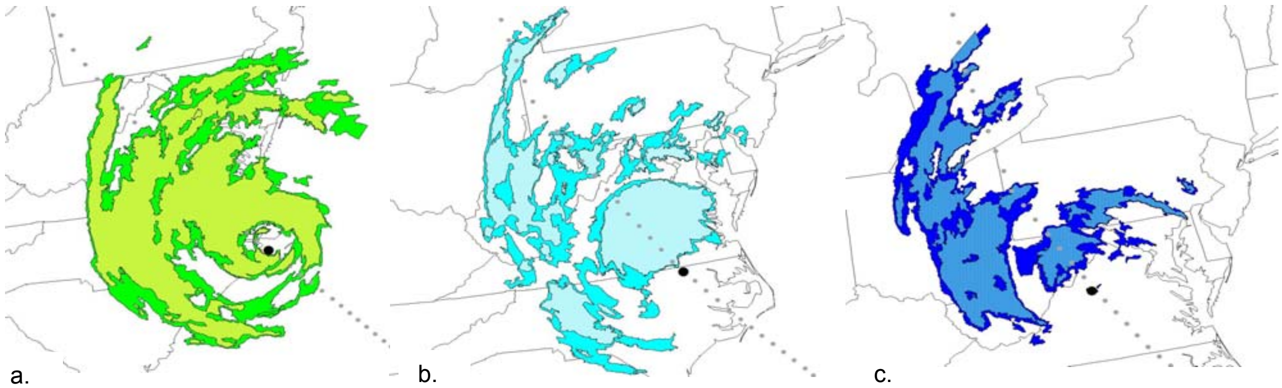

Figure 5. Polygon shapes for Isabel (2003) using both the 20 (darker color) and 25 (lighter color) dBZ reflectivity value thresholds at a). landfall, b). six hours post-landfall, and c). twelve hours post-landfall. Gray dots represent all hourly circulation center positions. The black dot represents the current location of the circulation center.

Table 1. Number of observations for each TC including hour of first and last observation and total number of observations. Hours are relative to landfall; negative is before landfall, positive is after landfall, zero is the hour of landfall.

Tropical Cyclone	Hour of First Observation	Hour of Last Observation	Total Hours
Danny (1997)	-10	+36	47
Bonnie (1998)	0	+15	16
Charley (1998)	-9	+38	48
Georges (1998)	0	+55	56
Hermine (1998)	0	+13	14
Bret (1999)	0	+37	38
Dennis (1999)	-5	+74	80
Harvey (1999)	-16	0	17
Irene (1999)	-7	+6	14
Gordon (2000)	-6	+56	63
Helene (2000)	-8	+29	38
Claudette (2003)	0	+24	25
Isabel (2003)	-2	+20	23