12A.3 ANALYSIS OF HURRICANE EYE SLOPE USING REFLECTIVITY DATA FROM AIRBORNE DOPPLER RADAR: COMPOSITES AND CASE STUDIES

Andrew T. Hazelton* and Robert E. Hart
The Florida State University, Tallahassee, FL

1. INTRODUCTION

The slope of the hurricane eye/eyewall has been documented observationally since the late 1950s (e.g. Malkus 1958), and the Sawyer-Eliassen model for tropical cyclone structure describes theoretical reasons why the eyewall must slope. However, determining the relationship (if any) between eye slope and intensity has proven to be difficult. An early study by Shea and Gray (1973) suggested that there was a relationship between the slope of the radius of maximum wind (RMW) and intensity, but a more comprehensive recent study by Stern and Nolan (2009) showed that the slope of the RMW has little to no relationship with the intensity of a tropical cyclone (TC), even over the life of a single storm. However, the radius of maximum wind is not necessarily the same as the actual edge of the eye, and may be determined by different processes or timescales than those that determine the extent of the eye. This study uses airborne Doppler radar reflectivity data from NOAA-P3 flights and field campaigns to determine the edge of the eye, calculate the slope, explore the relationship between slope and intensity, and investigate some of the physical processes that affect the slope of the eye. Case studies highlight some of the different mechanisms responsible for changes in slope, and illustrate the details of the slope-intensity relationship and complex connections between various aspects of the hurricane core.

2. DATA/METHODOLOGY

Although it is not possible to exactly pinpoint the cloud edge in the eye, radar reflectivity can be used to estimate the location of this boundary. This is the approach used in this study, which is similar to the methodology employed in previous studies using reflectivity to determine slope (e.g. Corbisiero et al. 2005). However, our dataset has a greatly expanded set of cases. Our methodology is also unique in that it uses cross-sections of 3-dimensional Doppler radar data, rather than composites. Starting from the center of the storm, the algorithm goes radially outward in each of the two directions at each vertical level until it reaches a threshold value of reflectivity (15 dBZ was used for most of the cases). After performing this calculation, the algorithm produces a set of points identifying the horizontal and vertical dimensions of the edge of the eye along the cross section. Next, the algorithm uses linear regression to determine the slope of the "best-fit" line passing through those two sets of points (one for each side of the eye cross section). The algorithm calculates the actual slope ($\Delta z/\Delta x$), but for analyses here the inverse slope ($\Delta x/\Delta z$) is utilized so that near-upright eyes do not approach infinite slope and render composites unusable.

This study uses radar data from several different sources. Radar data for Hurricane Earl came from the NASA Genesis and Rapid Intensification Project (GRIP). The data from this campaign was collected using the Second Generation Advanced Precipitation Radar (APR-2), which is a dual-frequency (13 GHz and 35 GHz) Doppler radar system (Sadowy et al. 2003). Radar data for Hurricane Erin came from NASA's Fourth Convection and Moisture Experiment (CAMEX-4). The other cases use the radar data from research flights by the NOAA Hurricane Research Division (HRD). This data is taken by the tail radar of the NOAA-P3 aircraft, which is a 9.3 GHz Doppler radar, and has been processed by HRD into 3-d composites (available online at: http://www.aoml.noaa.gov/hrd/data_sub/radar.html). Meridional and zonal cross-sections of the data were performed for each flight time available. For the two field experiments, the cross-sections were in the along-flight direction. Combined, the data contains 100 different flight legs into 17 different hurricanes from 2001-2011.

**Corresponding Author Address*: Andrew T. Hazelton, Department of Earth, Ocean, and Atmospheric Science, the Florida State University, Tallahassee, Florida 32306-4520
Email: ath09c@my.fsu.edu

3. RESULTS

a. Distribution of Slopes

A histogram showing the distribution of inverse slopes (Δx/Δz) for the cases examined (Figure 1) has a large tail of higher values (less upright eyes), indicating cases where the eye, especially the upper part, tilted sharply outward. A possible explanation for this is a lack of deep convection in the eyewall. This could be caused by a number of factors, including cooling sea surface temperatures under the TCs or eyewall replacement cycles cutting off the energy flow to the inner eyewall. Some of the factors influencing slope changes in individual storms are discussed later. Despite the large tail, the peak of the distribution (between 1 and 1.5) indicates that the 1-to-1 slope is indeed a preferred structure in TCs.

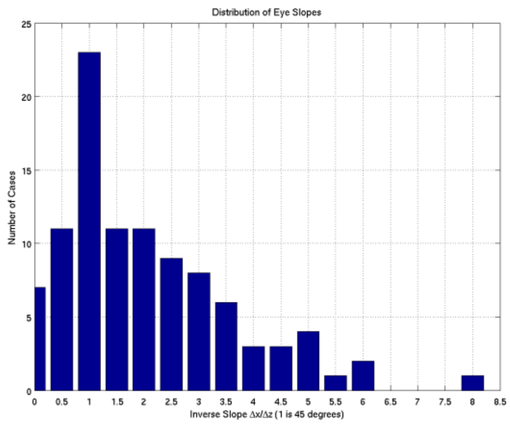

Figure 1: Distribution of inverse eye slopes (Δx/Δz).

b. Overall Relationship Between Slope and Intensity

As discussed earlier, the relationship between the slope of the eye and the intensity of a storm has been a topic of significant debate. There have been conflicting results regarding the relationship of the slope of the radius of maximum wind with intensity, with the most recent and detailed work (Stern and Nolan 2009) suggesting little to no relationship. Previous studies utilizing radar reflectivity have hinted at a correlation between slope and intensity, but our study is the first to determine the slope of the edge of the eye for a significant number of cases, and compare the results with the strength of the storms analyzed. In order to get reliable measurements of the intensity of the storm for each of the different cases, the study used the closest (in time) vortex message from the NOAA Hurricane Hunter Flights into the storms of interest. Figure 2 shows the statistically significant relationship ($r = 0.38$, $p < 0.01$) between minimum central pressure and eye slope for all of the cases analyzed.

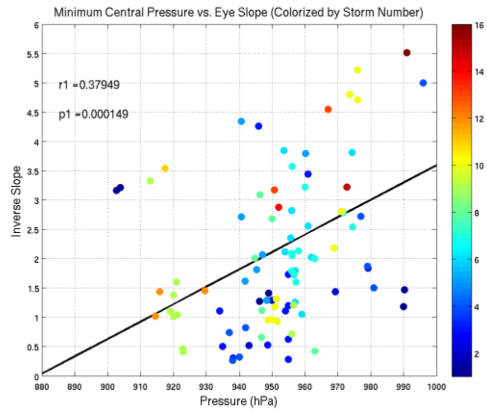

Figure 2: Scatter plot of eye slope (Δx/Δz) vs minimum central pressure

c. Relationships between slope and intensity in the lifecycle of individual storms

While the relationship between slope and intensity is statistically significant overall, it is even more significant for certain individual storms. Table 1 lists the correlations between slope and intensity for all of the storms analyzed that had more than two cases. This "cutoff" was somewhat arbitrary, but was necessary to ensure that there were enough points for comparison. The table also shows the statistically significant (at 95% confidence) correlation, based on the number of cases for each storm. Some of the storms had so few points that any apparent relationship must be interpreted carefully, as is shown in the high significant r values. It is seen from this table that the pressure-slope relationship varies widely between storms. Several of the hurricanes have statistically significant correlations, some as high as 0.9. However, other storms show little to no relationship between pressure and eye slope. It is possible that the factors that determine these differences between individual storm relationships are similar to those that cause differences in the pressure-wind relationship for tropical cyclones, such as storm size (Zehr and Knaff 2007). Smaller-scale inner-core changes may also be responsible for reducing the strength of the pressure-slope relationship, as discussed later in the case study of Ivan.

Storm	r	Sig. r
Frances	0.17	0.75
Ivan	-0.33	0.58
Dennis	0.90	0.95
Helene	0.27	0.71
Felix	0.86	0.71
Gustav	0.67	0.60
Ike	-0.2	0.75
Paloma	0.92	0.63
Earl	0.61	0.58
Katrina	-0.87	0.81
Irene	0.7	0.88

Table 1: Individual storm correlations between slope and intensity, with significant r also shown

d. Case Studies

1) Hurricane Felix (2007)

Hurricane Felix had a statistically significant relationship between slope and intensity ($r = 0.86$, $p < 0.01$). Figure 3 shows two radar cross sections of Felix (with slope calculations) at the beginning and end of a 24-hour intensification period, 2125 UTC on September 1 and 2254 UTC on September 2. During this 24-hour period, Felix rapidly strengthened from a tropical storm with 60-kt winds to a Category 5 hurricane 145-kt winds. The figure illustrates how the eyewall became more upright and vertically established as the inner-core developed and the storm strengthened. At 2125 UTC September 1, $\Delta x/\Delta z$ was 5 and the strong convection in the eyewall only extended up to about 5 to 6 km. By 2254 UTC September 2, $\Delta x/\Delta z$ had decreased to 0.68, and the strong convection in the eyewall extended well above 10 km. Figure 4 shows time series of normalized inverse slope vs. minimum central pressure, eye temperature anomaly, and eye dewpoint depression (from vortex messages from recon flights into Felix), and shows how $\Delta x/\Delta z$ steadily decreased as the storm strengthened.

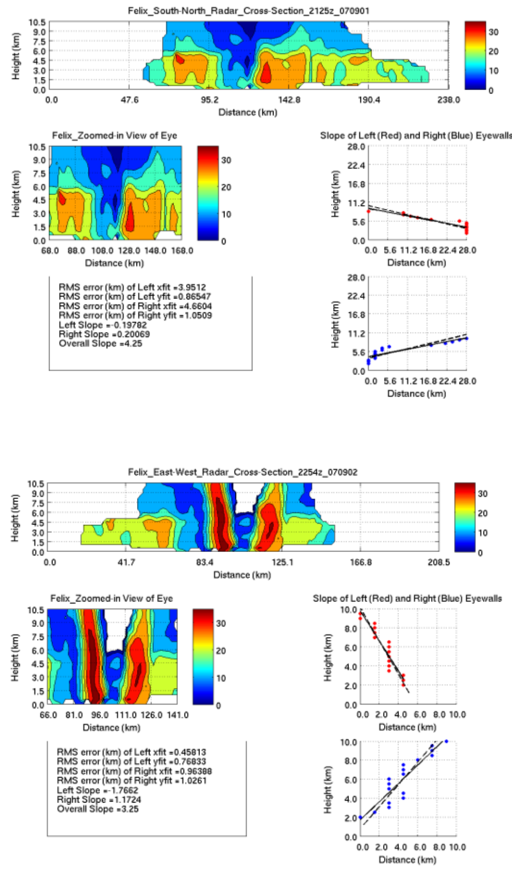

Figure 3: Radar cross-sections and slope measurements of Hurricane Felix at: 2125 UTC Sep. 1 (top) and 2254 UTC Sep. 2 (bottom)

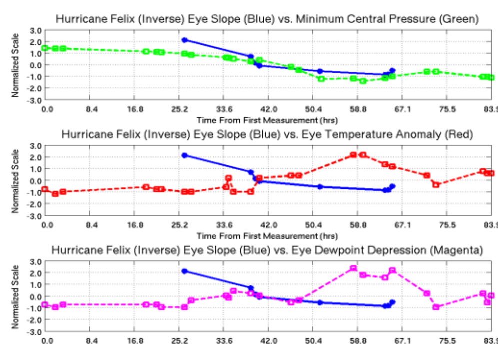

Figure 4: Inverse eye slope vs. minimum central pressure, eye temperature anomaly, and eye dewpoint depression (all variables normalized.)

2) Hurricane Ivan (2008)

What stands out most from the slope

measurements in Ivan is the sharp increase in outward tilt just prior to weakening over the Gulf of Mexico. A radar cross-section of Ivan on 12 September (Figure 5-top) showed a secondary eyewall forming, but the inner eyewall updrafts were still strong, and the slope was upright. By the afternoon of September 13, the inner eyewall had collapsed, leading to a widening of the eye and a significant increase in the slope (Figure 5-bottom). Despite the collapse of the inner eyewall, at the time of the slope measurement on the afternoon of the 13th, the pressure had not yet risen, and was a very low 913 hPa. However, nine hours later the pressure had risen to 924 hPa, and continued to rise on September 14. This point ended up being an apparent outlier in the pressure-slope relationship (both for Hurricane Ivan and overall in the cases analyzed), because the eye slope changed quickly before the pressure had time to respond, suggesting a lag between eye slope and intensity.

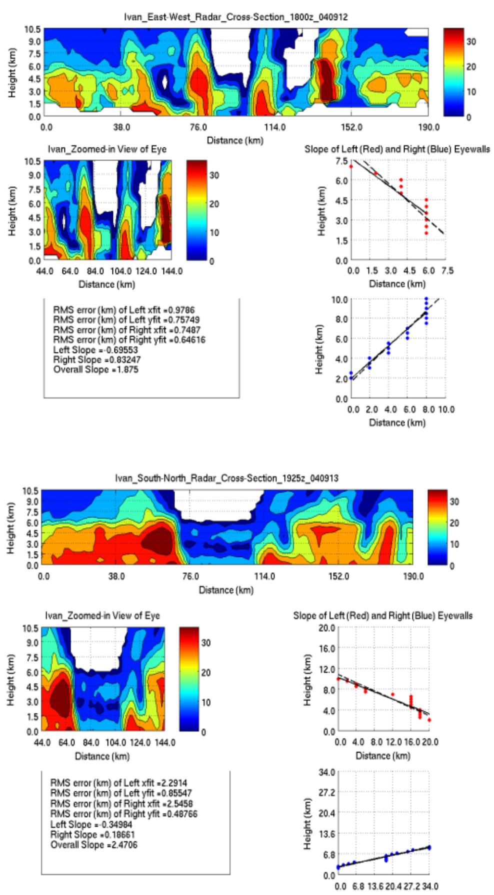

Figure 5: Radar cross-sections and slope measurements of Ivan at 1800 UTC Sep. 12 (top) and 1925 UTC Sep. 13 (bottom)

4. CONCLUSIONS

The results of our study indicate that the slope of the edge of the eye (as determined by reflectivity) is an important aspect of the inner-core structure of TCs. There is indeed a statistically significant relationship between this measure of eye slope and the intensity of tropical cyclones. On an individual storm scale, however, the relationship between slope and intensity is quite variable. The case studies illustrate this point, and show how processes such as eyewall replacement cycles can introduce lag into the relationship between eye slope and intensity. Further analysis of eye slope and how it changes could prove insightful in better understanding and predicting changes in the core structure of TCs.

5. ACKNOWLEDGMENTS

The authors would like to thank those who provided information about the radar data used in this study, including Rob Rogers at the Hurricane Research Division and Stephen Durden at NASA JPL. Partial support for this project was provided by the AMS Industry Graduate Fellowship sponsored by ITT, the Florida State University Legacy Fellowship, and the NASA Genesis and Rapid Intensification Processes (GRIP) Grant #NNX09AC43G.

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