16A.4 **WHAT ARE ANNULAR HURRICANES?**

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1. INTRODUCTION

The appearance of tropical cyclones in IR imagery differs greatly from case to case and over time. This study discusses a category of tropical cyclone, termed "Annular Hurricanes". When annular hurricanes are compared with the greater population of tropical cyclones, as observed in an infrared (IR) data archive of tropical cyclones, they appear distinctly symmetric about their center. Their appearance in IR imagery is characterized by large circular eyes surrounded by a nearly uniform ring of deep convection and a distinct lack of deep convective features (i.e. spiral bands) outside this ring, Figure 1.

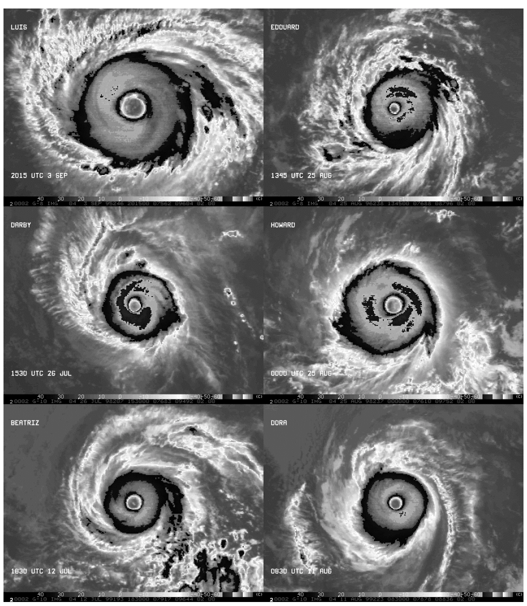

Figure 1: Enhanced IR images of Hurricane Luis at 2015 UTC 3 September (top left), Hurricane Edouard at 1345 UTC 25 August (top right), Hurricane Darby at 1530 UTC 25 July (middle left), Hurricane Howard at 0000 UTC 25 August (middle right), Hurricane Beatriz at 1830 UTC 12 July (bottom left), and Hurricane Dora at 0830 UTC 11 August (bottom right) during the period when they were annular hurricanes. Each image projection is Mercator with a uniform spatial resolution. The resulting spatial scale is 1280 km X 960 km for each panel.

During 1995-1999 six hurricanes (2 Atlantic and 4 Eastern Pacific) were subjectively determined to be "annular hurricanes" (Table 1). It was found that these storms have several features in addition to axisymmetry that separate them from other storms, including systematic formation characteristics, steady intensities, and their existence in only in specific environmental conditions.

Table 1: A list of annular hurricanes, the basin in which they occurred, the times that they exhibited annular hurricane characteristics and the number of hours they exhibited annular hurricane characteristics.

Storm	Basin	Annular Period	Hours
Luis 1995	Atlantic	18 UTC 3 Sept - 04 UTC 4 Sept	10
Edouard 1996	Atlantic	00 UTC 25 Aug – 00 UTC 26 Aug	24
Darby 1998	East Pacific	12 UTC 26 Jul – 18 UTC 27 Jul	30
Howard 1998	East Pacific	18 UTC 24 Aug – 03 UTC 27 Aug	57
Beatriz 1999	East Pacific	18 UTC 12 Jul – 18 UTC 13 July	24
Dora 1999	East Pacific	18 UTC 10 Aug – 03 UTC 12 Aug 03 UTC 15 Aug – 03 UTC 16 Aug	33 24

The evidence to be presented suggests that annular hurricane formation is preceded by a dramatic asymmetric mixing event where meso-vortices mix eyewall air into the eye and visa versa (See Schubert et al. 1999, Kossin and Eastin 2001), culminating in the formation of the axisymmetric storms with large eyes (i.e. annular hurricanes). The thermodynamic structures (as determined from aircraft data) of these storms suggest that a dramatic horizontal mixing event has recently occurred, which is characterized by more uniformly distributed values of θ_e in the eye. At the same time the wind field suggests that some eye-to-eyewall mixing is still occurring, as shown by step-like features in the tangential wind that are associated with local vorticity and angular velocity peaks.

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Once annular hurricanes have formed, they can maintain their annular shape for days if the environmental conditions remain favorable. Annular hurricanes are also very intense, averaging 108 knots in intensity at roughly 85% of their MPI with respect to SST. As a result, annular hurricanes pose an interesting challenge when forecasting intensity change. Unlike typical hurricanes, annular hurricanes tend to experience a long period of nearly steady intensities with a relatively slowly decreasing intensity following their maximum intensity, Fig. 2. As a result of this intensity change characteristic, intensity forecast errors are larger for these storms than for the 1995-2000 mean, with large negative biases, suggesting that the forecasts overestimate the future rate of filling.

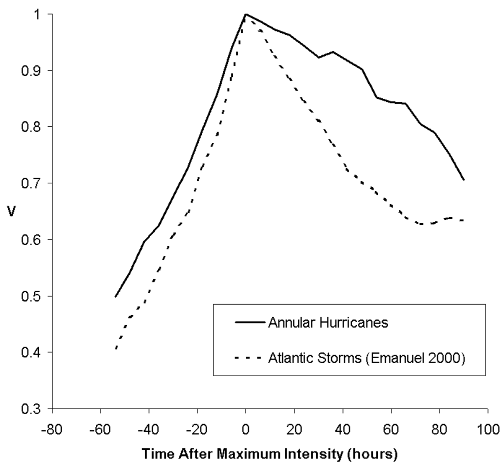

Figure 2: Composite time series of the intensity associated with average Atlantic hurricanes that did not encounter cold water or make landfall (56 cases) as reported by Emanuel (2000) and annular hurricanes (6 cases), normalized by mean maximum intensity. Compositing was done relative to the time of maximum intensity.

Composite analysis will be presented that reveals that typical annular hurricanes exist in a very favorable hurricane environment generally characterized by the combination of 1) weak easterly or southeasterly vertical wind shear, 2) easterly flow and relatively cold temperatures at 200 hPa, 3) a narrow range (25.4 to 28.5 ^{o}C) of SSTs that are nearly constant, and 4) a lack of 200-hPa trough interaction. These individual characteristics are quite commonly observed, but the combination of these factors is quite rare occurring 0.8% and 3.0% of the time in the Atlantic, and Eastern Pacific tropical cyclone basins, respectively.

A secondary topic of this presentation is the objective identification of annular hurricanes. Two approaches will be discussed. The first approach utilizes the digital brightness temperature information contained in the IR imagery. Once azimuthal means of brightness temperature were created they were normalized to a common size and mean brightness temperature and then compared to the mean radial brightness temperature profile of annular hurricanes to form an index. The second approach used the environmental conditions to determine whether an annular hurricane could exist. This required that all the factors associated with annular hurricanes existed. Both techniques seem to work well, suggesting that such information could be examined for possible improvements to intensity forecasts.

2. SUMMARY

Nature sometimes produces a nearly symmetric hurricane. The documentation of these annular hurricanes shows how they are similar and different to the general population of tropical cyclones. Using the documentation of annular hurricanes, particularly the environmental conditions associated with these storms, modeling studies that focus on the formation and evolutionary characteristics of these storms can be designed, and hopefully will lead to even greater physical understanding. It will be shown that the differences between annular hurricanes and the greater population of hurricanes can be used to classify these systems both subjectively and objectively. While the usefulness of such discrimination is beyond the scope of this study, it does suggest a future research topic answering the question; does the identification of annular hurricanes lead to better intensity forecasts?

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