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SMALL-SCALE FEATURES OBSERVED IN THE BOUNDARY LAYER OF HURRICANES ISABEL (2003) AND FRANCES (2004)

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1. INTRODUCTION

Studies have shown that hurricanes contain several scales of motion. The most commonly studied and documented structures are the eye, eyewall and rainbands. However, other smaller scaled features have been identified and are believed to also influence hurricane intensity. Small-scale bands with wavelengths ranging between 4 to 10 km have been observed in past hurricanes (Gall *et al.* 1998) but their influence is unclear. Several studies have focused on the hurricane boundary layer (HBL) and identified even smaller scale features. An early observational study using high-resolution Doppler on wheels (DOW) radar data documented sub-kilometer HBL rolls (Wurman and Winslow 1998). Another recent study (Morrison *et al.* 2005) using WSR-88D data identified HBL rolls with larger wavelengths. A simulation study (Nolan 2005) identified instabilities in the HBL with wavelengths ranging from 3 to 5 km.

In an attempt to better understand the HBL and more specifically the small-scale features that are embedded in them, the Texas Tech University Hurricane Intercept Team (TTUHIT) collected high resolution radar data during the landfall of Hurricanes Isabel (2003) and Frances (2004) using the SMART radars (Biggerstaff *et al.* 2005). The primary goal of the experiments was to acquire high spatial and temporal resolution data of the HBL to clearly document the HBL small-scale features in a more precise manner. The SMART radars, using a gate spacing of 66.7 m, were deployed near the path of Hurricanes Isabel and Frances. Various scanning strategies were designed (Lorsolo and Schroeder 2005) and employed to specifically document the HBL and its embedded coherent features in both hurricanes. The object of this paper is to present the preliminary results of the study.

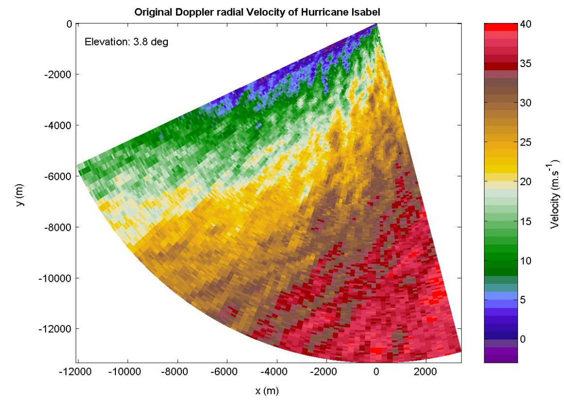

Figure 1: Original Doppler radial velocity data from Hurricane Isabel collected by SMART radar 2 (SR2).

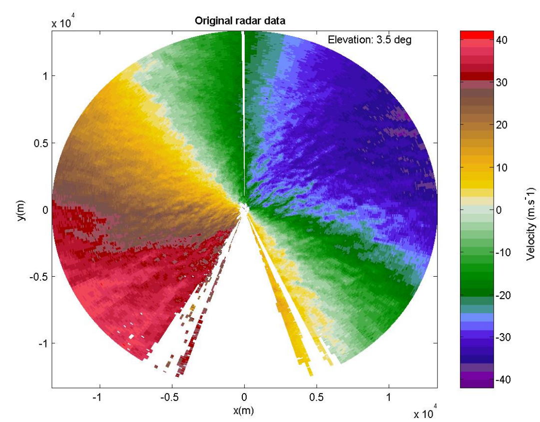

Figure 2: Same as Figure 1, but for Hurricane Frances and collected by SR1.

2. DATA PROCESSING AND RESULTS

2.1. VAD ANALYSIS

Given the relatively high spatial resolution data acquired with the SMART radars, the small-scale features embedded in the HBL were easily identified in the Doppler radial velocity images. Figures 1 and 2 are examples of the original Doppler velocity data collected from Hurricane Isabel and Frances, respectively. The small-scale features appear as fine linear striations superimposed on the hurricane's overall mean wind field.

In order to isolate these features, the VAD technique (Browning and Wexler 1968) was applied on the original radial velocity data. Figures 3 and 4 show the resulting field of velocity residuals after the mean wind field was removed from the original data. On both images, the small-scale phenomena appear as coherent linear features that are approximately aligned with the mean wind vector. A comparison between the two storms suggests that the features seem finer and more coherent for Hurricane Frances than Hurricane Isabel. In Hurricane Isabel the features seem to take on a more cellular appearance while in Hurricane Frances they appear more linear. In both cases the magnitude of the residuals are similar, ranging from -6 ms^{-1} to +6 ms^{-1}. However, the difference between adjacent positive and negative residuals seems stronger in Hurricane Isabel. Analysis of Plan Position Indicators (PPIs) at different elevation angles indicates that the vertical extent of the features is limited to the HBL

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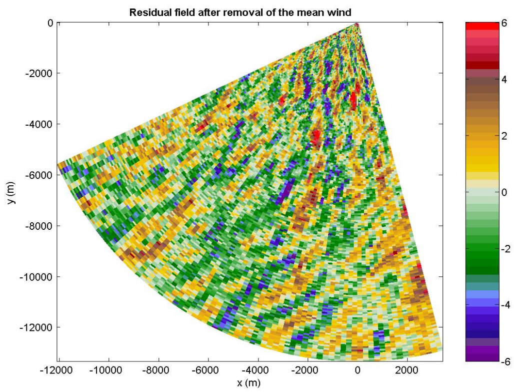

Figure 3: Radar velocity residuals after removing the mean wind filed using the VAD technique for Hurricane Isabel.

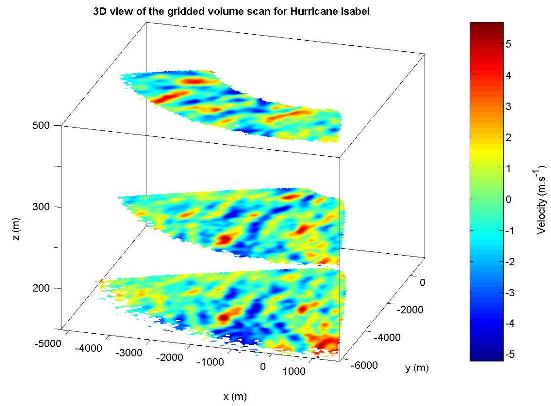

Figure 5: Three-dimensional view of the gridded radial velocity residual data from Hurricane Isabel. The plans are at 200 m, 300 m and 500 m AGL.

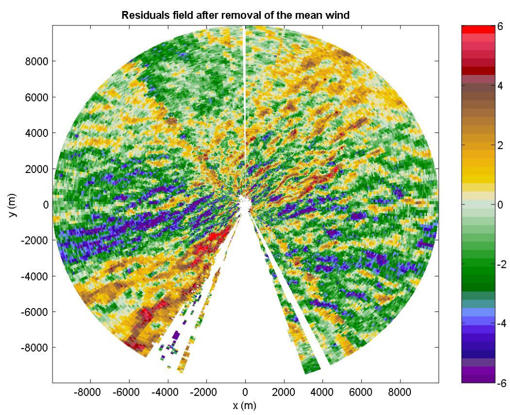

Figure 4: Same as Figure 3, but for Hurricane Frances.

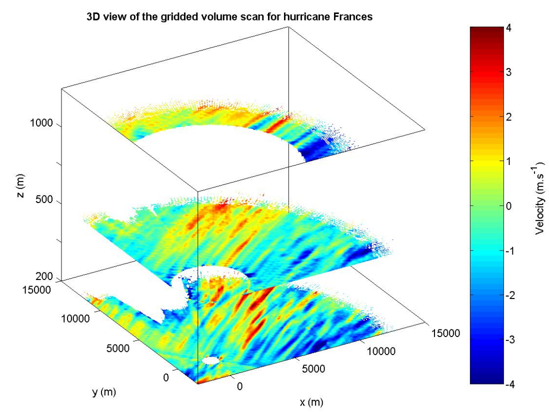

Figure 6: Same as Figure 5, but for Hurricane Frances.

depth.

2.2. HORIZONTAL STRUCTURE ANALYSIS

To further analyze the linear features, a Cressman scheme was applied to the volume scans, allowing a cartesian display of the data. A qualitative assessment of the features indicated that their wavelength was larger than 150 m and therefore, a radius of influence of 150 m was chosen, as it would not prevent an accurate depiction of the features. To apply the Cressman algorithm, it was assumed that the features' motion was roughly along the mean wind vector, so it could be approximated to be quasi-stationary in a transverse direction during the time of one volume scan. Examination of three-dimensional representations of the gridded data (Figures 5 and 6) shows a clear vertical coherence of the features, which validates the steady state assumption used for the Cressman scheme. Because the scanning strategy used in the Frances case had a better vertical resolution than the one used in Hurricane Isabel, gridded data above 600 m AGL were available for Hurricane Frances, but not for Hurricane Isabel. In the Isabel case, a veering of the features' orientation is apparent between 300 m and 500 m height (Figure 5).

In Hurricane Frances, the veering of the features' orientation is more subtle, but clearly apparent between the lowest and highest cross-sections. In both cases, the features lose definition with height and range. This loss of definition might be attributed to aliasing (due to radar beam spreading) or to the fact that the top of the features has been reached.

Figures 7 and 8 show horizontal cross-sections taken at 300 m AGL from gridded volume scans taken from Hurricane Isabel and Frances, respectively. For Hurricane Frances, the features appear even more defined than on the PPI image. For Hurricane Isabel, the features are also identifiable, but they are more difficult to isolate.

2.3. VERTICAL STRUCTURE ANALYSIS

To fully investigate the structure of the HBL small-scale features, several vertical cross-sections perpendicular to the features were taken, as indicated by the oblique lines on Figures 7 and 8. Figures 9 and 10 show the two cross-sections taken at approximately 2 km from the radar. In the case of Hurricane Frances (Figure 10), the features are again well defined, exhibiting a strong vertical coherence. It seems that in the upper right corner, the features lose

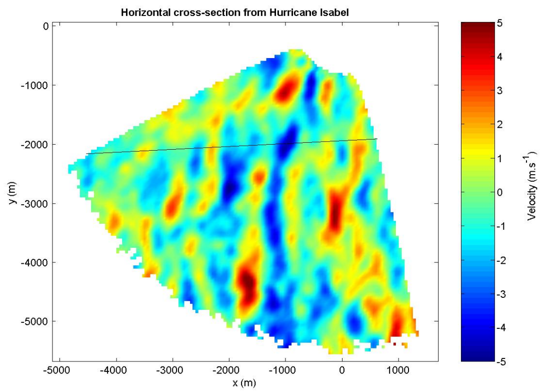

Figure 7: Horizontal cross-section taken at 300 m AGL after cartesian gridding of the volume scan data with a Cressman scheme. A radius of influence of 150 m was used. The solid black line indicates the position of the vertical cross-section shown in figure 9.

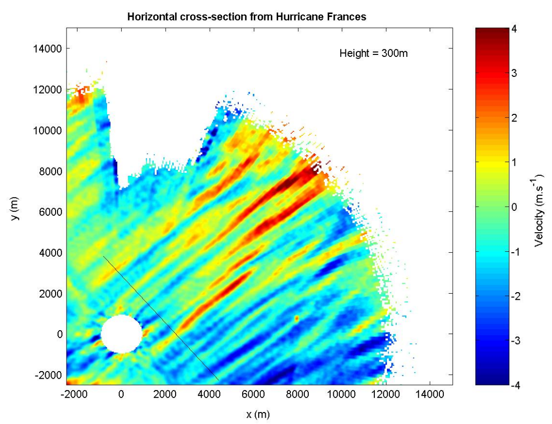

Figure 8: Same as Figure 7, but for Hurricane Frances.

definition, which could be due to aliasing. However, because the features seem to change orientation with height (or maybe different features are present at different heights), the cross-section that was perpendicular to the features in the lowest elevations is not normal to the features at the highest elevations. Therefore, the loss of definition could be attributed to the direction of the features relative to the direction of the cross-section. Moreover, the observed flow may change from along-feature to cross-feature along a particular vertical cross-section, which might affect the features' definition in the area of mixed flow. Another factor could be the proximity to the zero-isodop, where the VAD technique was not handled as well.

Figure 9 is a cross-section from Hurricane Isabel. Although the features were difficult to isolate on the horizontal cross-sections, their definition is more striking in the vertical cross-section. In this case, the loss of definition on the edge of the image is not present. This should be due to the fact that the cross-section does not include data close to the zero-isodop and/or that the horizontal and vertical extent of the cross-section is not as large as the cross-section taken for Hurricane Frances. The analysis of the figure

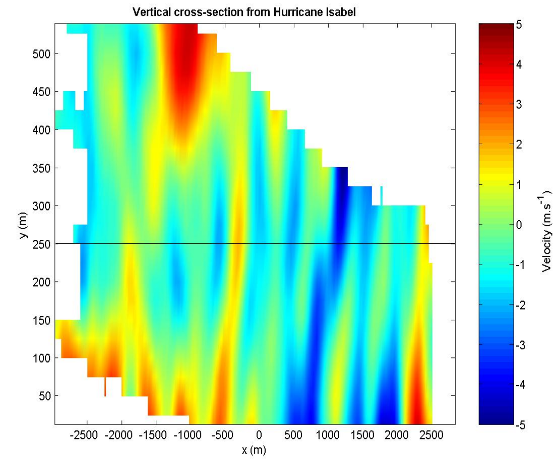

Figure 9: Vertical cross-section of radial velocity residuals taken from the cartesian gridded data. The solid black line indicates the position of the data shown in Figure 11.

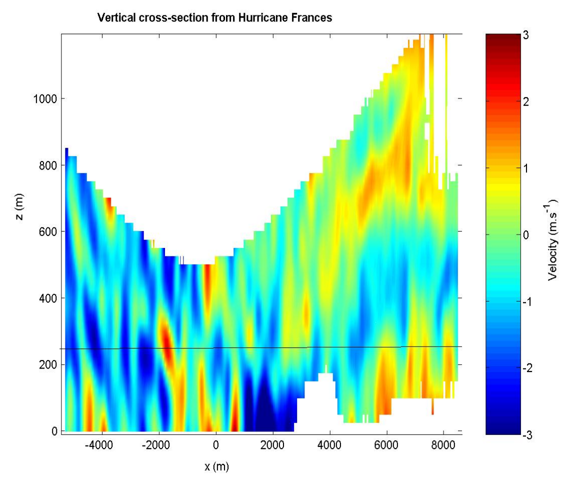

Figure 10: Same as Figure 9, but for Hurricane Frances.

also reveals a slight rightward lean of the features with increasing height. It is uncertain if this lean represents the real behaviour of the features or if it is an artifact of the Cressman analysis steady state assumption.

2.4. WAVELENGTH ANALYSIS

A review of the previous studies focusing on these HBL small-scale features do not show agrement on their scale of motion. A qualitative estimate of the wavelength of the features shows that the scale of motion seems to be the same order of magnitude for both storms. To better estimate and compare the wavelength, data along the cross-sections taken at individual heights were analyzed. Figures 11 and 12 show the residual radial velocity data at 250 m AGL taken from the previous vertical cross-sections (Figures 9 and 10) as indicated by the horizontal black lines. Although

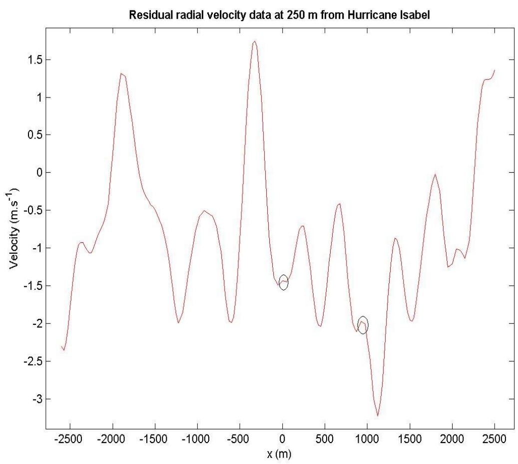

Figure 11: Radial velocity residual data taken approximately perpendicular to the features at 250 m for Hurricane Isabel. The small circles indicate smaller undulations that have not yet been examined.

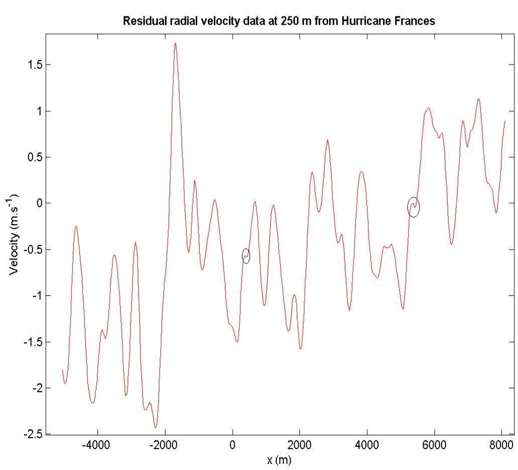

Figure 12: Same as Figure 11, but for Hurricane Frances.

the shape of the signals is strongly sinusoidal, the amplitude of the maxima and the minima is highly variable. In the case of Hurricane Frances (Figure 12) for example, the difference between maxima and minima can vary anywhere from 0.003 ms^{-1} to 4.2 ms^{-1}. In this example, the calculated wavelengths range from 100 m to 1 km with an median value of about 400 m. Similar results were found in the case of Hurricane Isabel. A more comprehensive analysis including data from several volume scans will be done to obtain quantitative wavelength results.

A careful examination of the overall behaviour of Figure 12 indicates that there may be a larger oscillation superimposed on the main smaller oscillations, hinting that a larger scale phenomenon of roughly 6 km is present in the HBL. This phenomenon is not apparent in Hurricane Isabel curve, however the smaller size of the cross-section does not allow to conclude that this phenomenon is not present in Isabel data.

3. CONCLUSIONS AND FUTURE WORK

The preliminary results of the study of the BL of Hurricanes Isabel and Frances revealed abundant presence of sub-kilometer linear features. It seems that the features are better defined in the case of Hurricane Frances; however, the first estimate of the features wavelength indicates that the scale of motion might be similar in both storms. The preliminary estimate of the wavelength was on the order of 350 to 400 m at 250 m AGL. The smallest wavelength previously documented was of approximately 600 m (Wurman and Winslow 1998). A careful examination of Figures 11 and 12 shows very small undulations (as indicated by the small black circles) that might not be the signature of the features that we are trying to isolate. Further analysis will be conducted to find out if the smaller undulations in the signal are from the current features under investigation, even smaller scale features present in the HBL, or the result of noise within the collected data. Then, an analysis including a relatively large amount of data will be conducted in order to obtain the wavelength distribution of the features for both hurricanes.

The analysis of horizontal and vertical cross-sections of radar volume scans showed that these features are horizontally and vertically coherent and seem to have a vertical extent limited to the depth of the boundary layer. To fully address the vertical depth of the features more data will be added to the analysis. The examination of residual radial velocity data perpendicular to the features reveal that several scales of motion are present in Hurricanes Frances signal. PPIs with larger azimuthal extent will be analyzed to find out if Hurricane Isabel exhibits the same characteristics.

ACKNOWLEDGMENTS

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