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CHARACTERIZATION OF HURRICANE TURBULENCE USING AIRBORNE DOPPLER MEASUREMENTS

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1. Introduction

Air-sea interaction and flux transport within the hurricane boundary layer (HBL) have been intensively studied to improve the understanding of the mechanisms responsible for intensity change. Secondary circulations in the HBL are believed to have an influence on vertical fluxes (Morrison et al, 2005, Foster, 2005). Thus, it is crucial to be able to assess the turbulent energy associated with these processes in order to estimate their importance in the overall energy transport. Estimation of turbulent energy in a hurricane have usually been conducted using point measurements (dropsondes, gust probes, ...), which does not allow for a more global assessment of the distribution of the turbulence throughout the storm. Because Doppler radars generally provide data over a large spatial coverage, the use of Doppler measurements seems to be more appropriate to estimate the distribution of turbulence in a hurricane.

The goal of this study is to characterize the distribution of turbulent energy in a hurricane using Doppler measurements from the NOAA P3 airborne tail radar data. The two main objectives are to first evaluate the turbulent energy distribution in and above the HBL in various parts of the storm and at different time periods prior to landfall and identify the possible impact of HBL coherent turbulent features have on this distribution.

2. Method

The NOAA P3 airborne tail radar is the most suitable instrument to conduct this study as it has been used for numerous hurricane missions over the years, providing a large data set. The figure-four pattern commonly used during the NOAA missions allowed the acquisition of data radially sampling the depth of the investigated storm, and throughout all four quadrants. However, the tail radar spatial resolution cannot resolve small-scale features such as those documented in recents studies (Morrison et al, 2005, Lorsolo et al, 2008). Thus, the use of a high spatial and temporal resolution Doppler radar such as the Imaging Wind and Rain Airborne Profiler (IWRAP) is necessary to identify and characterize the properties of coherent secondary circulations of the HBL. The IWRAP is a dual-frequency, vertically scanning airborne Doppler radar flown on the NOAA WP-3D airplane, and was operated during a UMASS and NOAA/NESDIS collaborative effort.

2.1. Turbulent Energy Distribution

Because each Doppler measurement contains information on all three components of the wind, the variance of the Doppler radial velocities (V_R) in a grid cell large enough to contain various look angles, is a good approximation of the turbulence. The analysis is based on the fact that V_R can be expressed as the sum of the mean radial velocity over a grid cell ($\overline{V}_R$) and a turbulent part (V'_R). The turbulent energy can then be estimated as the variance of V_R. over the grid cell. So, to retrieve $\sigma^2_{V_R}$ for a given grid cell, first the three components of the wind have to be obtained. This retrieval is done using a software developed at the Hurricane Research Division of NOAA. The analysis uses a variational method based on Gao et al (1999) method. Vertical cross-sections of the wind components are obtained along the aircraft track. For this case, no boundary condition and no background were used. Each grid cell is a 10 km X 1.5 km X 0.15 km box. The retrieved wind is then projected onto the different directions contains in the grid cell that was initially used to compute the mean wind, providing $\overline{V}_R$ (az) for each azimuthal direction. This $\overline{V}_R$(az) is then substracted from the original Doppler measurement V_R(az) to obtain the fluctuations V'_R(az). The mean (V'^2_R) is a good approximation of the turbulence contained in the grid cell.

2.2. Coherent Turbulent Processes

To evaluate the importance of HBL turbulent processes in the turbulent energy distribution, it is crucial to be able to identify the processes and characterize their properties. HBL coherent processes have been documented over land but little is known for flows over water. It is believed that the IWRAP could help document those features. Because the IWRAP scans

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conically in the vertical direction, analysis of the entire depth of the HBL can be conducted, and the 30-m range gate resolution can provide high-spatial resolution data required to study HBL small-scale features. Thanks to its fast rotation speed (60 RPM) and the simultaneous scanning of two incidence angles for each wavelength (C and Ku), retrieval of high-resolution three-dimensional components of the features might be possible.

3. Preliminary Results

3.1. Turbulence Estimation

The estimation of the turbulence using the Doppler measurements was conducted for an inbound flight of Hurricane Katrina on 28 August 2005 at 1755 UTC. Figures 1, 2 present the radial and vertical velocity fields, respectively. Figure 3 present the standard deviation of V_R. As expected, the strongest turbulence is located in the convective areas, in the eyewall and outer rainbands. Relatively high standard deviation values near the surface are collocated with the inflow layer. This result suggesting that aside from the convective area, the strongest turbulence during the pass was located in the inflow layer. Comparison of the turbulence and the vertical velocity fields suggests some correlation between the two variables. A correlation coefficient of 0.6 was found when correlating the turbulence with the horizontal gradient of vertical velocities, suggesting stronger turbulence in areas of stronger shear of vertical wind.

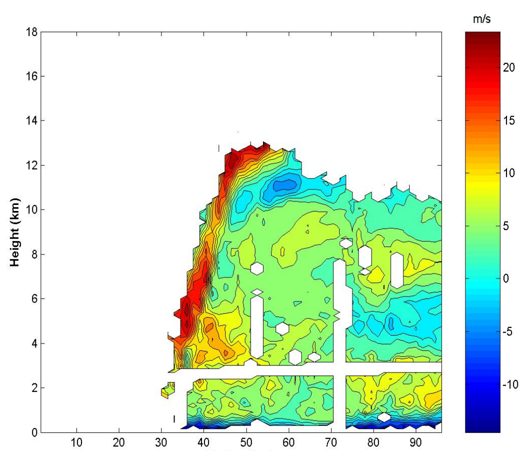

Figure 1: Radial wind speed.

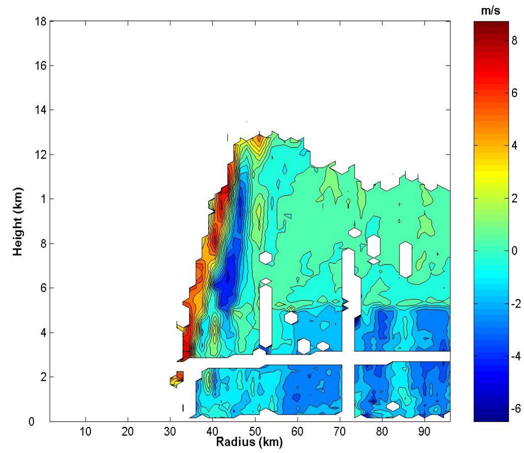

Figure 2: Vertical wind speed.

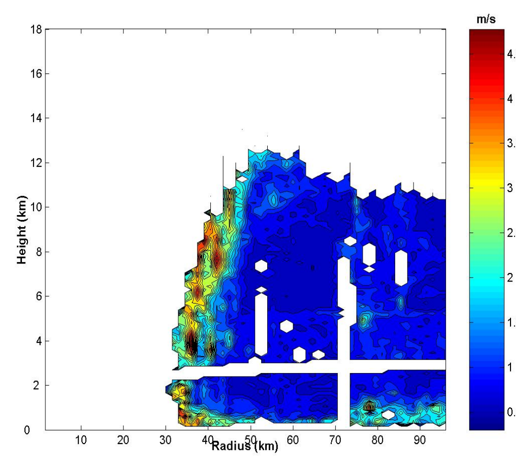

Figure 3: Standard deviation of V_R

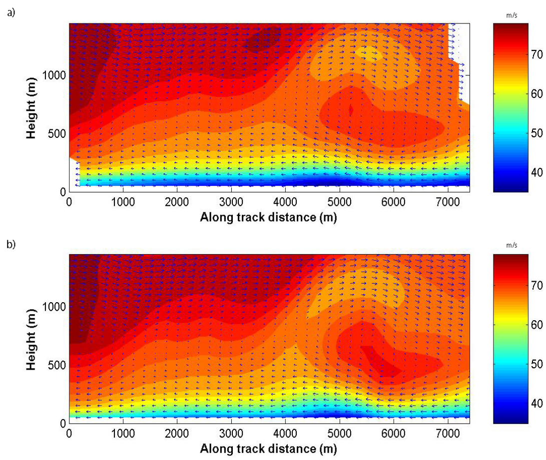

Figure 4: Vertical cross-section of horizontal wind speed with wind vector overlayed for the coarser case. a) represents the wind field from the analysis while b) presents the original wind field.

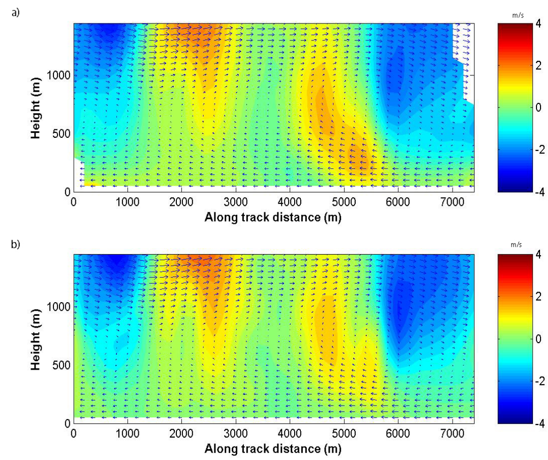

Figure 5: Vertical cross-section of vertical wind speed with wind vector overlayed for the coarser case. a) represents the wind field from the analysis while b) presents the original wind field.

3.2. Coherent Turbulent Processes

A study to evaluate the IWRAP capability in resolving HBL small-scale features was conducted. The IWRAP data were simulated using a wind field obtained from a WRF-LES simulation of Hurricane Yvan (2004) (Zhu, 2008). On 16 September at a coastal location, the WRF-LES output documented coherent structures exhibiting similar characteristics as the features observed in recent observational studies (Morisson et al., 2005, Lorsolo et al., 2008), although the features display much larger wavelengths. Because the features that are sought to be solved are smaller, the scales of the features obtained with the WRF-LES were artificially reduced (around 1.5 km and 700 m wavelength) to investigate if the IWRAP can resolve these types of scales of motion. The simulated radial velocities were computed by first interpolating the wind data at the bin location, then taking the radial component, no error was added to the data. The wind retrieval uses the HRD software previously mentioned. For these cases, no boundary condition and no background were used.

Figures 4, 5 show results from the analysis and the original data, for a flow exhibiting features with wavelength of about 1.5 km. Both horizontal wind and vertical wind are retrieved accurately. The features are well captured by the analysis. Overturning flow associated with the features' circulation was well retrieved. The magnitude of the horizontal wind appears to match the original data, although it seems that the analysis underestimates the wind speed below 300 m AGL. In Figure 4 the maximum located at 1.3 km AGL, at 3 km range in not present in the original vertical wind field. The magnitude of the vertical wind is also accurately retrieved.

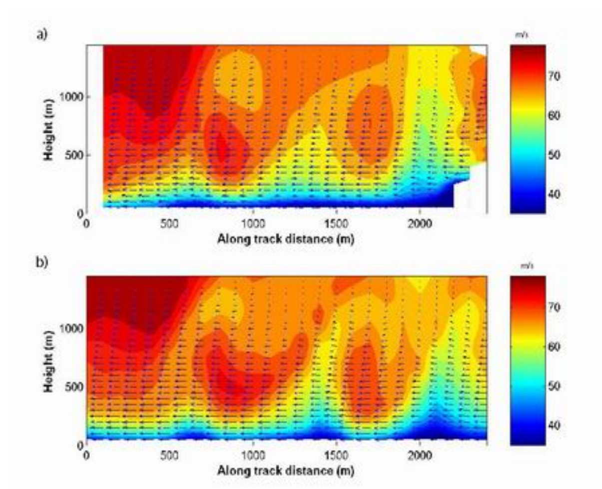

Figure 6: Vertical cross-section of horizontal wind speed with wind vector overlayed for the finer case. a) represents the wind field from the analysis while b) presents the original wind field.

Retrieval for the wind field with smaller wavelength was also conducted and results are presented in Figures 6 and 7. The sub-kilometer features were resolved by the analysis, however in this case, the vertical wind field in particular was not as accurately retrieved as in the previous case, which is confirmed by a higher random mean square error (rms) and lower correlation values. In the lowest 500 m the vertical wind was vastly overestimated, while the horizontal wind was less affected. Retrieval using two incidence angles was used but did not noticeably improve the analysis. When data below 250 m was removed, the correlation coefficient increased of 33% while the rms decreased of 22%.

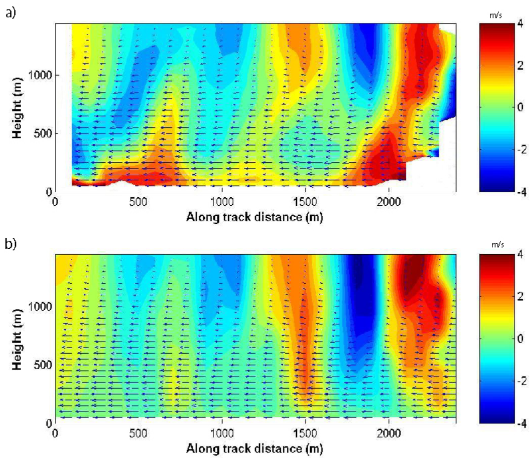

Figure 7: Vertical cross-section of vertical wind speed with wind vector overlayed for the finer case. a) represents the wind field from the analysis while b) presents the original wind field.

4. Conclusion and Future Work

The preliminary results of the estimation of turbulence using Doppler measurements are encouraging. Further work will be conducted for several hurricanes and at different stages of the storms lifetime. Comparison with in-situ turbulence data collected during the CBLAST experiment will also be performed. Identification of the processes responsible for higher turbulence could be performed using IWRAP data. The study simulating IWRAP data in a turbulent flow showed that the IWRAP might be able to identify coherent features of the HBL. More runs to investigate the wind retrieval quality for noisy data will be performed.

An investigation of the factors that could negatively affect the estimation of the turbulence will be conducted. Lothon et al. (2004) found that the correlation between the vertical velocity and the precipitation fall speed can influence the Doppler measurement and therefore the estimation of the turbulence. In environments such as hurricanes where strong vertical velocities exist, it is crucial to understand the effect that the interaction between vertical motion and precipitations has on V_R. Moreover, to accurately retrieve the three dimensional components of the wind, the fall speed should be accurately determined.

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