Retrieval of hurricane turbulence parameters using airborne Doppler radar measurements

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1. INTRODUCTION

One of the main challenges of hurricane research is to better understand the processes that influence hurricane intensity change, which could ultimately lead to improved intensity forecasts. Among the various parameters believed to impact hurricane intensity change are air-sea interaction and turbulent energy transport within the hurricane boundary layer (HBL) (Malkus and Reihl 1960; Emanuel 1986, 1995). An accurate estimate of hurricane turbulent energy is crucial to identify the role of turbulent processes in the energy transport within a storm in general and in the hurricane boundary layer (HBL), in particular. A better characterization of hurricane turbulence, especially in high wind regimes where observational data are sorely lacking, could provide tremendous insights on the mechanisms involved in hurricane intensity change. More and more hurricane modeling studies are including TKE schemes based on the formulation of Mellor and Yamada (1982), where TKE and dissipation rate are prognostic variables, increasing the necessity of an accurate estimation of these turbulent parameters. To remedy the BL parameterization problem and better understand the turbulent processes at play, observations are needed.

Doppler radar measurements have been increasingly used to study hurricane structure as they generally provide data over large portion of the storms. For over 25 years airborne radars have collected valuable data in the outskirts as well as inner-core of tropical storms (e.g. Jorgensen et al. 1983; Marks 2003). The implementations of the fore and aft scanning (FAST) strategy (Gamache et al. 1995, Jorgensen et al. 1996) and new variational (Gamache 1997; Reasor et al. 2009) and automatic[1] retrieval methods have enabled the retrieval of very accurate high-resolution wind data throughout hurricanes. Extending the use of airborne Doppler measurements to estimate hurricane turbulent parameters could provide a unique opportunity to map turbulence throughout tropical cyclones.

The present study will describe a method of estimation of turbulent kinetic energy (TKE) in a hurricane using NOAA tail Doppler radar data and mapping of the TKE distribution will be provided. Moreover, the measured spectral width data will be used to estimate dissipation in the HBL.

2. TKE ESTIMATION

a) Method

Estimation of turbulent energy in a hurricane has usually been conducted using point measurements, which does not allow for a global assessment of the distribution and the structure of turbulence throughout the storm. Moreover, in-situ measurements in the lowest parts of the HBL have been particularly difficult to acquire and data remain quite limited. Because Doppler radars can provide data over a large spatial coverage as well as low-level data in the inner-core, the use of airborne Doppler measurements offers a unique opportunity to estimate the distribution of turbulent energy throughout a hurricane.

All the data utilized here were collected using the fore and aft scanning (FAST) strategy (Gamache et al. 1995, Jorgensen et al. 1996). After removing the aircraft motion, the Doppler radial velocities (V_r) are a combination of all three components of the wind. Given that Reynolds

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[1] http://www.nhc.noaa.gov/jht/2003-2005reports/DOPLRgamache_JHTfinalreport.pdf

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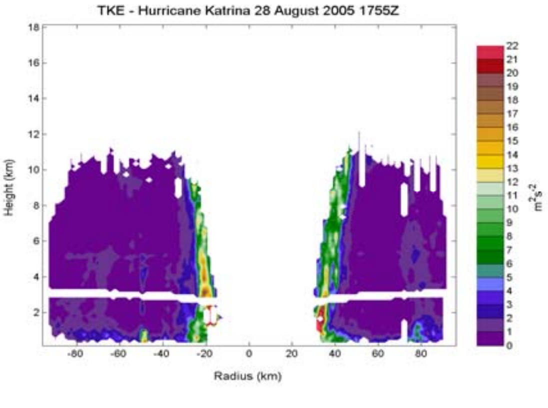
averaging (Stull 1988) allows each component of the wind to be expressed as the sum of a mean and turbulent part. Since the mean TKE is defined as TKE = 0.5 ($\overline{u'^2}$ + $\overline{v'^2}$ + $\overline{w'^2}$) and the turbulent part of the Doppler radial velocity (V_r') is a combination of the turbulent components of the wind, it is hypothesized that the mean squared perturbation $\overline{v_r'^2}$ over a grid cell containing various Doppler measurements is a good approximation of the TKE. The TKE can then be estimated as the variance (σ^2_{Vr}) about the mean of all the V_r within the grid cell:

$$\sigma^2_{V_R} = \frac{1}{N}\sum_{\substack{Overgrid \\ cell}} (V_R - \overline{V}_R)^2 = \frac{1}{N}\sum_{\substack{Overgrid \\ cell}} V_R'^2 \qquad (1)$$

The TKE estimates were obtained following the method described in Lorsolo et al. (2010).

b) Results

Data from seven hurricanes from 1997 to 2008 were used and TKE profiles were generated. Figure 1 shows an example of a TKE profile for a single leg for a penetration through Hurricane Katrina 28 August 2005. The TKE profile clearly depicts the highest TKE values in the eyewall region, with magnitudes up to 22 m^2s^{-2}. Aside from the eyewall, strong TKE values are located in the lowest levels in the HBL and in other relatively strong reflectivity areas. Elsewhere, TKE values are < 1 m^2s^{-2}. The analysis of all the cases shows that the correlation of TKE with horizontal and vertical gradients of vertical and radial winds was the highest, with correlation coefficients greater than 0.5, and in numerous instances exceeding 0.7.



The TKE behavior displayed in Fig. 1 is common for all the analyzed legs, with magnitudes of TKE highest in the eyewall region in all cases. Figure 2 represents the R-Z mean profile for all the data included in the analysis. The highest TKE values are located just inside the radius of maximum wind (RMW) and the HBL is well depicted with TKE values above 4 m^2s^{-2} in the lowest levels.

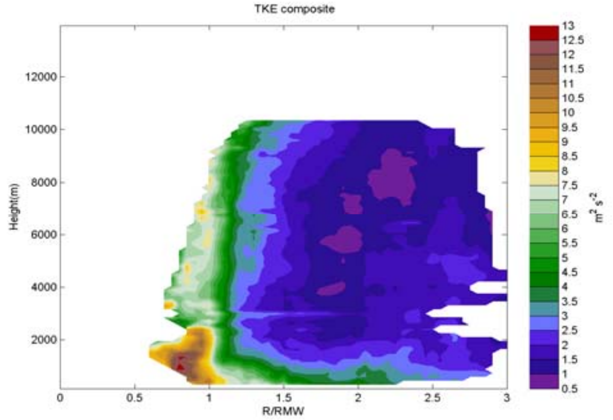


Fig 2: R-Z mean cross-section of TKE for all cases, scaled on RMW

This method of estimating TKE is very effective in identifying localized enhanced turbulence. The TKE field depicts quite well the double eyewall structure that Hurricane Rita was exhibiting on 22 September 2005, with values in the outer eyewall as high as 15 m^2s^{-2} (Lorsolo et al, 2010, Fig. 5). The TKE estimates were able to clearly identify the most turbulent region of the outbound leg and showed that although the inner eyewall on the outbound leg was still stronger in terms of wind speed, the turbulence was not as active as in the new developing eyewall.

3. DISSIPATION RATE ESTIMATION

a) Theory

To obtain a more complete picture of hurricane turbulence, the retrieval of turbulent kinetic energy dissipation rate will be attempted. The difficulty of acquiring observed dissipation rate, especially in the hurricane inner-core has resulted in very little available datasets. Early ground-based Doppler radar studies have described a method to retrieve dissipation rate using the Doppler spectrum width that showed relatively good agreement with other methods of estimation (Frisch and Strauch 1976, Brewster and Zrnić 1986, Chapman and Browning 2001, Meischner et al. 2001). In this study, we will attempt to replicate this method to retrieve the dissipation rate using the airborne Doppler radar.

The relationship between dissipation rate and Doppler spectrum width relies on one fundamental assumption: the turbulence inside the radar volume is assumed to be homogeneous and isotropic. The early work on dissipation using the Doppler spectrum width hypothesizes that the spectral broadening is the sum of the contribution from antenna rotation, shear, the spread of the fallspeed velocity, written as follow:

$$\sigma^2_{Dopp} = \sigma^2_{shear} + \sigma^2_{ant} + \sigma^2_{precip} + \sigma^2_{turb} \qquad (2)$$

For the tail Doppler radar, the contribution due to the plane motion should also be added (Jorgensen et al., 1983). More recently Fang and Doviak (2008) showed that, the contributions from antenna rotation and the shear are coupled terms and that each component of equation (2) should be averaged temporally or spatially to decouple the components. Once each component is subtracted from the measured Doppler spectrum width, the dissipation rate can be estimated using Labbit's relationship (1981).

a) Preliminary Results

The first step of this project is to obtain a first order estimate of the mean Doppler spectrum width and each contribution to the spectrum broadening and evaluate some of the implications that could arise from attempting this technique using the airborne TA Doppler radar in a hurricane environment. Figures 3, 4, and 5 present profiles of Doppler spectrum width, antenna and precipitation fall speed contributions, respectively. The Doppler spectrum width profile (Fig. 3) exhibits the highest values in the HBL and the eyewall region, the most turbulent areas as seen in the TKE data. However, values > 20 m^2s^{-2}, closest to the surface and at the edge of reflectivity regions, are due to inhomogeneous beam filing in these areas. The antenna contribution (Fig. 4) shows values similar to those expected for a ground-based radar scanning at low elevation angle but not for a moving platform (Jorgensen et al. 1983). The formulation used to compute the antenna contribution does not account for the aircraft motion and should be adjusted to do so in the future. The variance due to the relative motion of the particles because of the plane speed was also estimated and ranged from 1.3 – 1.9 m^2s^{-2}. Figure 5 only shows contribution of the fall speed variability below the melting level as that is likely the largest contribution to the spectral width. As expected, the contribution due to fall velocity is dependent on the scanning elevation angle. Thus, the closer the scanning is to the vertical direction the larger the contribution will be. Values closer to the flight level (ie. smallest elevation angles) have values similar to what have been estimated in the earlier studies (Frisch and Strauch 1976, Meischner et al. 2001).

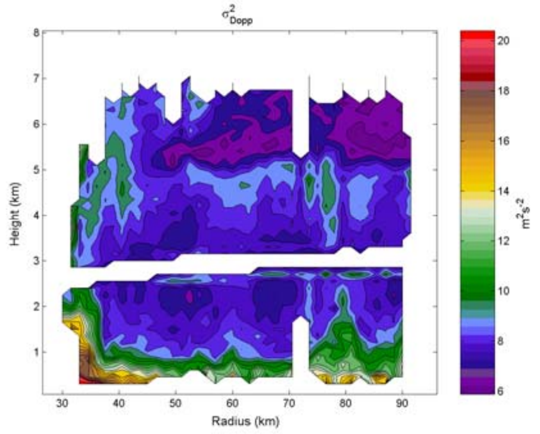


Fig 3: Profile of Doppler spectrum width in m^2s^{-2}

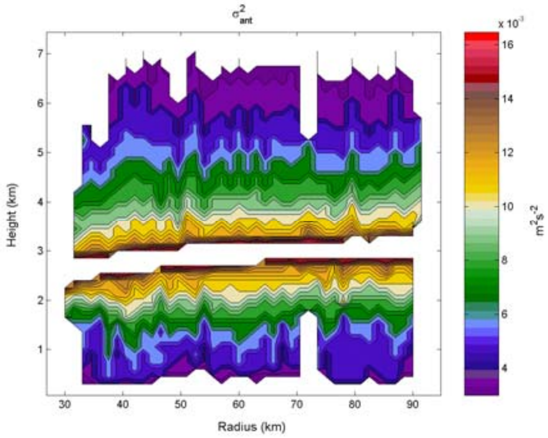


Fig 4: Profile of the antenna contribution in m^2s^{-2}

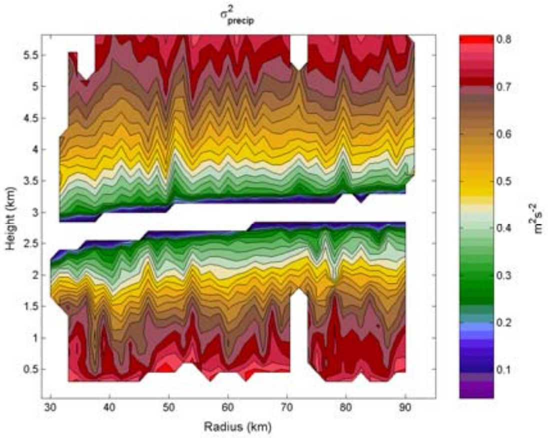


Fig 5: Profile of the precipitation fallspeed in m^{2}s^{-2}

Jorgensen et al. (1983) evaluated the shear contribution to the Doppler spectrum width in a hurricane environment to range from 2.2 to 6.0 m^{2}s^{-2}. Dropsonde data acquired for 13 mature storms allowed for a good estimate of the shear below flight-level. Because the shear levels off at the top of the layer (not shown here), it was assumed to keep the same value up to the top of the Doppler analysis. The shear contribution profile was then retrieved (Fig. 6), exhibiting smaller values that those presented by Jorgensen et al. (1983) except in the lowest levels, where the shear contribution exceed 16 m^{2}s^{-2}.

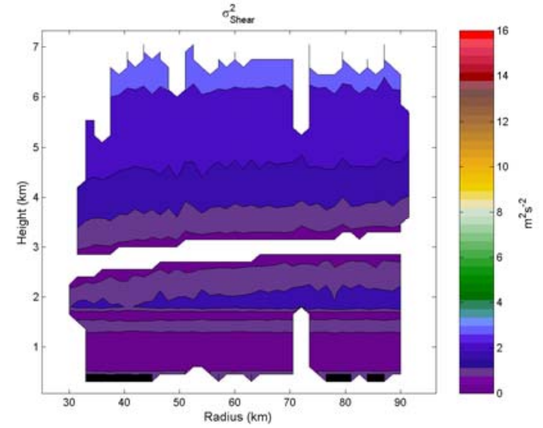


Fig 6: Profile of the shear contribution in m^{2}s^{-2}

Figure 7 is a vertical profile of turbulent energy dissipation rate ε, showing the highest dissipation rate occurring in the lowest portion of the eyewall with values > 0.5 m^{2}s^{-3}, which is likely due to ground return. High values (0.1 - 0.3 m^{2}s^{-3}) can be found in the HBL, then steadily decreasing with height. Overall the dissipation rate estimates appear relatively higher than expected, especially above the HBL. Such high values were retrieved using a similar method in midlaltitude thunderstorm, away from the BL. Istok and Doviak (1986) documented ε with values as high as 0.3 m^{2}s^{-3}, with parts of the storm exhibiting values of 0.7 m^{2}s^{-3}. Similarly, Brewster and Zrnić (1986) found values ~0.2 m^{2}s^{-3}, using two different methods. More recently, Meischner et al. (2001) used this method to investigate thunderstorm anvils and found values as high as 0.05 m^{2}s^{-3}. Very few dissipation estimates exist for hurricanes, especially in hurricane inner-cores. Zhang et al. (2009) estimated ε using the Couple Boundary Layer Air-Sea Transfer (CBLAST) experiment data and found values of ~ 0.06 m^{2}s^{-3} in the lowest levels. However, data from the HBL of hurricane Hugo exhibited values ranging 0.2 – 0.5 m^{2}s^{-3} (Zhang et al., 2010).

A more in depth analysis will be done in the future to evaluate the dissipation estimates using the Doppler spectrum width. The high values of dissipation are likely due to some of factors contributing to the spectrum width broadening being underestimated. However, it should be noted that because turbulence is not isotropic everywhere in a hurricane environment, the dissipation estimate will only have a physical meaning in areas where turbulence is in the inertial subrange.

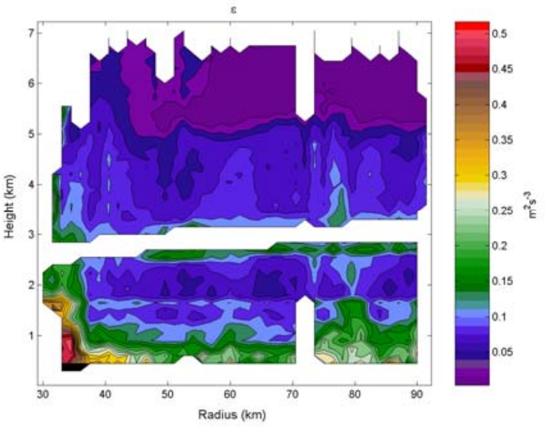


Fig 6: Profile of turbulent dissipation rate in m^{2}s^{-3}

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