High resolution WRF simulation of landfall hurricane boundary layer winds and turbulent structures

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1. Introduction

Hurricane boundary layer (HBL) turbulent processes not only have a direct socio-economic impact on coastal communities and resources but also play a critical role in developing and maintaining hurricane vortex. But until recently the HBL is relatively poorly characterized compared with the rest of the storm partially due to the difficulty in observation and partially due to the instrumental inability (Kepert 2006). Recent developments and applications, however, have helped minimize the deficiencies and made a breakthrough in HBL observations. For example, Doppler radar observations revealed the existence of intense roll vortices in the HBL and the associated structures (e.g., Wurman and Winslow 1998; Katsaros et al. 2000; Morrison et al. 2005). The airborne, in situ, and remote sensing measurements from the Coupled Boundary Layers Air-Sea Transfer (CBLAST) allowed direct estimates of turbulent fluxes in high hurricane wind conditions (Black et al. 2007 and Drennan et al. 2007). The recent advent of high resolution global positioning system (GPS) dropsondes provided a means to thoroughly document the detailed wind structures in the HBL (Kepert 2006a and 2006b). These observational efforts have helped characterize the HBL wind structures, large turbulent eddy circulations, and turbulent transports.

The broad observational and theoretical consensus that the coherent or organized vortical structures, such as eddies, whorls, or swirling rolls, prevail in the HBL turbulent flow raises an important question: how can we characterize these large turbulent eddies statistically and accurately estimate the transport induced by them? Logically, the large eddy simulation (LES), which explicitly simulates turbulent eddy circulations, will be an attractive approach to elucidate these issues that cannot be solely answered by observations and theoretical analyses. Since the first attempt by Deardorff (1970), LES has achieved great successes in many areas in the atmospheric boundary layer research. However, the classic LESs assume a quasi-steady state of large-scale atmospheric fields. Under this framework, LESs are initialized with idealized vertical profiles and forced with uniform surface conditions and horizontal homogeneous large-scale atmospheric forcings. Such a modeling strategy under quasi-steady assumption cannot be simply applied to the HBL turbulent process study since the hurricane vortex is a moving target and the swirling hurricane winds change continuously.

The distinct feature of the HBL calls for an innovative LES framework so that the turbulent eddy circulations can be realistically resolved under unsteady background flow conditions. With the advanced numerical technique, now obtaining fine scale large turbulent eddy structures in a weather forecasting mode is no longer a numerical vision. It can be realized in a state-of-the-art mesoscale modeling system owing to the multiple two-way nesting techniques. This paper describes a novel multiple scale hindcasting mode LES framework developed from the Weather Research & Forecasting (WRF) model. Using WRF-LES, we investigated the HBL turbulence structures and the associated turbulent transport.

2. Multiple scale LES framework

In this study, we developed an innovative LES framework in a hindcasting mode using a multiple two-way nested WRF to explicitly simulate a spectrum of scales from large-scale background flow, hurricane vortex, mesoscale organization, down to fine scale turbulent eddies in a unified system as il-

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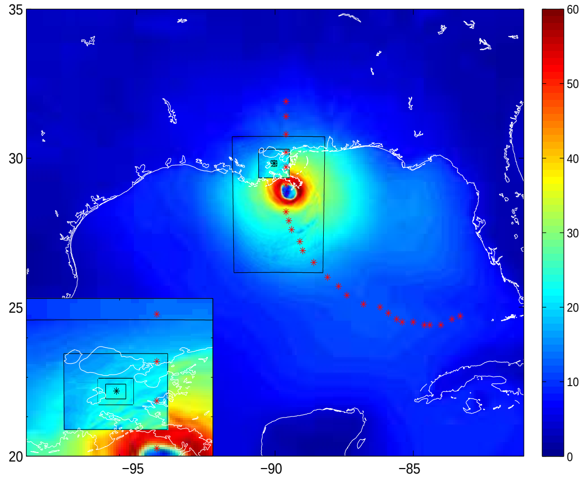

Figure 1: 10 m high winds at 9:00 UTC, August 29th 2005. Boxes indicate the WRF nested domains. * indicates the location of PWT.

lustrated by Figure 1. This multiple two-way nested WRF features an LES, Domain 5 in this case, which has a resolution both in horizontal and vertical comparable to the typical resolution of LES. WRF-LES distinguishes itself from the classic LES in many ways. First, WRF-LES is nested within WRF mesoscale simulations to ensure robust up-scale and down-scale interactions across a spectrum of scales. This is particularly important for the HBL simulation since the evolution of the HBL winds involves a complicated interplay among the storm-scale flow, deep convections, meso-vortices, and turbulent eddy circulations. Second, in WRF-LES the initial condition and forcings needed to drive a WRF-LES are provided by WRF mesoscale simulations that are initialized from the standard real-time forecast data or re-analyses data, which allows WRF-LES to produce realistic turbulent eddy circulations as the hurricane vortex evolves. This unique hindcasting feature of WRF-LES ensures that the high resolution simulation data is generated in the same dynamic and thermodynamic environment as that in which observations might be collected. This permits a direct comparison between observations and simulations. For example, in this study, we compare the WRF-LES results with the data collected by the Portable Wind Tower (PWT) deployed at the location where the landfalling hurricane passed by.

In this study, using WRF-LES we simulated landfall Hurricane Katrina. As illustrated by Figure 1,

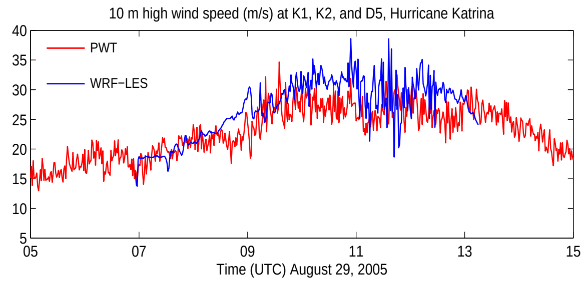

Figure 1: MWR observed liquid water path (mm) at different facilities at the SGP site.

we configured four two-way nested WRF domains with grid meshes of 200x200, 121X190, 121X121, 121X121, and 211X211, respectively. The nesting ratio is 1:3 for all the nested domains. Domain 1 with a horizontal resolution of 8100 m was configured to cover the entire Gulf of Mexico. In order to get a better the hurricane vortex structure, Domain 2 with a horizontal resolution of 2700 m covers the entire hurricane moving track during the simulation. The inner most domain 5 (D5) has a horizontal resolution of 100 m and a vertical resolution varying from 6 to 60 m below 2 km. The location of D5 is chosen since we are focusing on the HBL turbulent processes during hurricane landfall and there is a PWT deployed at the center of D5.

3. Simulation results

Figure 2 compares the 10 m winds between the WRF-LES simulation and the tower observations. Overall, the simulated trend in surface winds matches observations pretty well. Simulation appears to over-estimate 10 m winds slightly. One reason is that the simulated wind is the instantaneous output, while observations are the one-minute average, which would give us slightly low wind speed.

Figure 3 shows the structure of the simulated large turbulent eddies. In the upper panel, the eddy has a relatively large scale, about one and half kilometer in width and depth. The background shows the change in virtual potential temperature and moisture. The updraft of the eddy detrains cool and moist surface air upward, while downdraft entrains warm and dry air aloft downward. In this way, a large turbulent eddy can efficiently transports energy and moisture upward.

Large turbulent eddies are also responsible for generating surface wind gust. The downward leg of

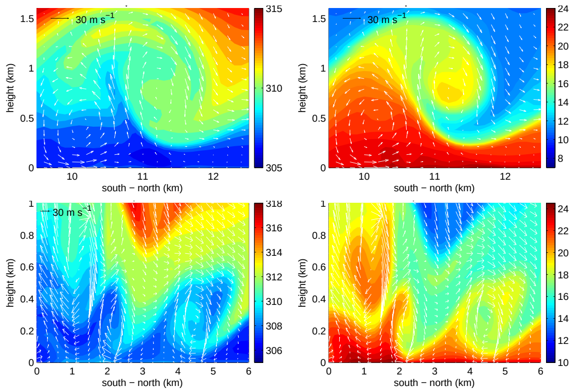

Figure 3: Vertical structure of large eddy circulations simulated by WRF-LES.

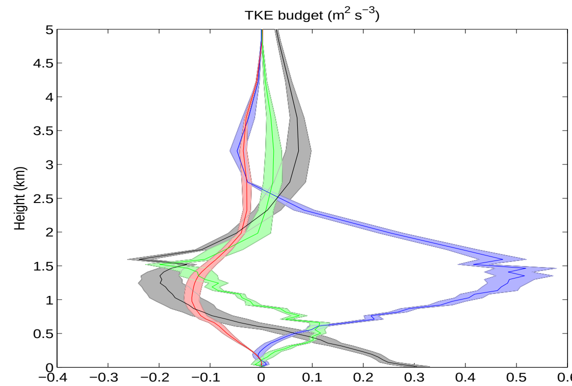

Figure 4: TKE budget, blue: shear production; red: buoyancy production; green: transport; black: pressure correlation.

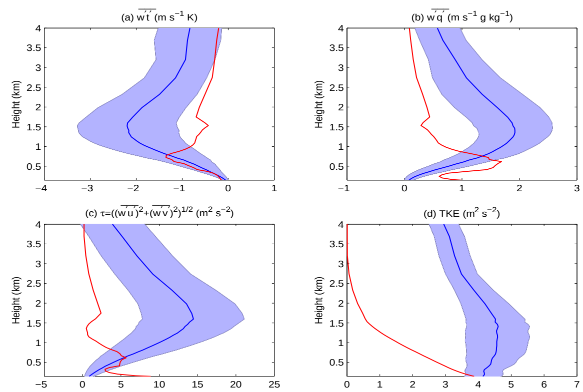

Figure 5: Turbulent fluxes and TKE induced by the resolved large eddies compared with the parameterized fluxes and TKE in domain 2.

the eddy transports momentum from upper layer to the surface to result in local wind maximum, while the upward leg is the momentum sink reflecting the air slowed down by the surface friction. This explains why some times buildings and trees experience major damage in a damage swath less than a kilometer, whereas those outside the swath are only slightly affected. The damage pattern actually reflects the existence of large turbulent eddies. The bottom panel shows two parallel rolls with a smaller scale about 500 meters in depth. The range of roll size is very close to the radar observations.

Figure 4 shows the TKE budget associated with resolved turbulent eddies. As expected, the shear production is the dominating term. The buoyancy production is negative, acting as a sink for TKE. One explanation is that this is a over-land case, the land surface could be cool due to hurricane precipitation. The transport term is negative above 1 kilometer and then changes its sign to positive below this heigh, indicating that there is a net TKE transport from the upper layer to the lower layer. In the normal situation, this would be impossible since turbulence is generated near the surface. For HBL, there are plenty of turbulence aloft associated with convective clouds. In fact, if there are convections, it is difficult to draw a line to define boundary layer height. Thus, this budget analysis reveals the distinct feature of the HBL turbulence.

Figure 5 shows the turbulent fluxes and TKE associated with the resolved turbulent eddies in domain-5 compared with the parameterized fluxes and TKE in domain-2 with a resolution 2700 m. Apparently, the current turbulence parameterization cannot realistically represent the turbulent transport associated with the large eddies induced by strong hurricane winds. Without properly representing the effect of these large eddies and their interaction with larger scale flow, models will have problems to predict right hurricane intensity.

4. Conclusion

The unique WRF-LES focuses on investigating turbulent structures in landfall HBL. The simulations indicate that large turbulent eddies are very efficient in transporting momentum, heat, and moisture within the HBL and between the HBL and the layer above. Current boundary layer scheme cannot appropriately represent the turbulent transport induced by large turbulent eddies.