3D.5 AIR-SEA COUPLING-INDUCED ASYMMETRIC IN HURRICANE BOUNDARY LAYER AND SURFACE FLUXES

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1. INTRODUCTION

Hurricane is one of the most impressive air-sea interaction features in the world. Heat transferred from the ocean through the turbulent processes in hurricane boundary layer (HBL) is its main energy source (Emanuel 1986). However, ocean also plays a role on reducing storm's intensity, that is, the storm induced sea surface temperature cooling, so called ocean's negative feedback. Most of previous observational and numerical researches address the variation of the hurricane intensity when storm passing the open ocean (Schade and Emanuel 1999, Bender and Ginis 2000). An interesting problem remained is that whether the storm structure responses to its induced asymmetric ocean cooling pattern (Price 1981). Since HBL is the first atmospheric layer which directly “feels” the ocean. Out focus is first put on the response of HBL structure to the asymmetric ocean pattern.

The vertical extent of the HBL is important because it is not only the height at which turbulent flux vanishes, but the layer that “feels” the influence of the surface heat flux. From the planetary boundary layer (PBL) aspect, PBL is shallower with lower low-level thermal instability and deeper with stronger low-level thermal instability. Thus, we can take PBL height as a heat container of hurricane. However, hurricane is a rapidly rotation vortex, and HBL may have different property to PBL. Thus, the first step to investigate HBL structure is to define HBL height. The current definitions of the HBL are 1) almost well mixing layer, this is the height when the virtual potential temperature is 0.5 k larger than that at surface (Anthes and Chang, 1978); 2) inflow layer, at which the radial wind velocity is equal to zero (Smith 1968); 3) the scaling depth, the square root of the ration of 2K over I, where K is the eddy viscosity and I is the inertial instability parameter (Kepert 2001).

Observation result (Kepert 2006) shows that the inflow layer in hurricane may reach to 2 or 3 km, which is much deeper than what we though as the PBL. Previous numerical research usually assume that constant HBL with one or two of this definitions. One interesting problem comes out: does each definition behave similar in the real hurricane. So the objective in this study is first to show the discrepancy of each definition in the hurricane, and what variables relate to it. Then, we will compare the height of HBL in different numerical simulation in the full-coupled mesoscale model to discuss the effects of air-sea coupling and wave-coupling processes on it.

Model description and experiment design are in section 2 while the results are discussed in section 3. The last two part are the conclusion

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and ongoing work.

2. EXPERIMENT DESIGN and MODEL DESCRIPTION

The coupled model is consist of the 5th generation Penn State/National Center for Atmospheric Research mesoscale model (MM5), WAVEWATCH III (WW3), and the 3D Price-Weller-Pinkel (3DPWP) upper ocean model. Experiments include an uncoupled MM5 ctrl (CTRL), atmosphere-ocean coupled (AO), and atmosphere-wave-ocean (AWO) simulations (Table. 1). Comparison between CTRL and AO can account of the influence of the storm induced ocean cooling, while the comparison of AWO and AO can accent on the impact of drag coefficient. The cases chosen here are the Hurricane Frances (2004) and Katrina (2005). There is one more experiences for Frances, which including the effect of sea spray. Both of these two storms reach category five hurricane during their life time, but the ocean condition of Katrina is much more complicate. Our discussion here will be based on Frances, and use Katrina to double check our idea.

	Frances	**Katrina**
UA (MM5)	●	●
AO (MM5 PWP)	●	●
AWO (MM5 PWP WWIII)	●	●
Spray (MM5 PWP WWIII spray)	●	

Table 1: Experiment design

3. RESULTS and DISCUSSIONS

3.1 Intensity and Structure Change

The uncoupled MM5 with a constant sea surface temperature (unlimited heat supply) over-intensify the storm, whereas the AO give us a reasonable minimum sea level pressure. However, the maximum wind speed is still underestimated. By using the full-coupled-model, the simulated maximum wind speed in AWO is much better than others. The inclusion of surface waves seems to produce a better wind-pressure relationship (Fig. 2b). This is due to the reduced stress in high winds using the wind-wave coupling described in Chen et al. (2007) (Figure 1). Figure 2 is the model simulated rain rate field of Frances in CTRL and AO at 1800 UTC 31 August, 2004. The strength of rain rate in CTRL is only a little stronger than that in AO. But rain band is much wider, and more symmetric in CTRL.

Simulated results of Katrina shows similar tendency as that of Frances. But AO in this case underestimate the intensity due to the overly strong cooling (negative feedback) which is due to unrealistic ocean initial condition. With the more realistic ocean initial condition, the simulated Katrina intensity in terms of minimum sea-level pressure (MSLP) is improved compared with the observed NHC best track data (not shown here).

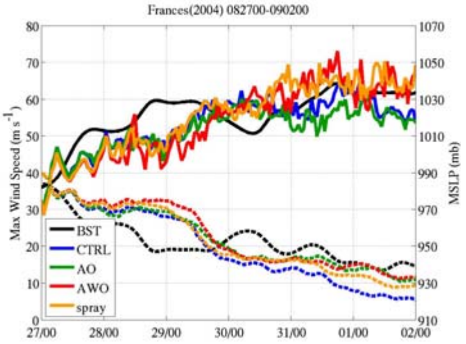

Figure 1: Intensity of simulated Hurricane Frances in terms of minimum sea level pressure (mb, dashed line) and maximum tangential wind speed ($m\ s^{-1}$, solid line). Each color represents experiment UA (blue), AO (green), AWO (red), spray (yellow) and observation (black).

Clearly, experiments with the coupling processes leads to both the hurricane mean state, intensity, and structure change. As mentioned in section 1, investigate HBL structure is the fist step to know the influence of this process on hurricane structure. The rest part of this section will show the results related to HBL based on definition of Anthes and Chang (1978) and Smith (1968).

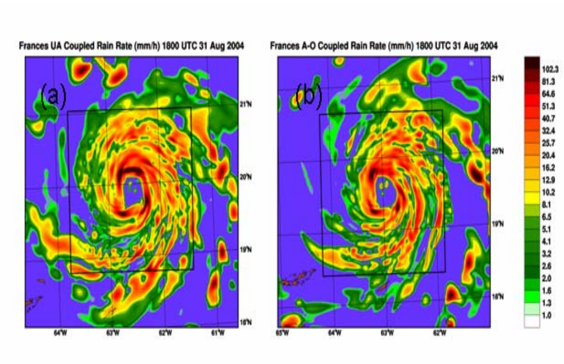

Figure 2: Figure 3: Model simulated rain rate field in (a) CTRL, (b) AO

3.2 THBL and DHBL

The definition of HBL adopted here comes from both thermal and dynamic aspect. The thermal HBL (THBL) is defined as the well-mixing layer (Anthes and Chang, 1978) and the dynamic HBL (DHBL) is defined as the inflow layer where the radius inflow velocity is 2 m s^{-1}. Note that in the real hurricane, there is a deep weak inflow due to the environment flow, storm motion or deep convection, so we use 2 m s^{-1} instead of 0 m s^{-1} here to neglect this weaken inflow.

Figure 3 present the azimuthal average THBL and DHBL with the relative humidity in the AO of Frances. Clearly the height of the DHBL is almost twice than that of THBL. During deviational zone, which is above THBL and below DHBL, the thermal variable should be the function of height. This can also be seen in the virtual potential temperature profile. Besides, these two definitions all show the decrease of the HBL height with the decrease of the distance from storm center. Smith (1986) divides the HBL into three region: outer, transition, and core region. At the outer region, the flow is approximately quasi-geostraphic, thus the HBL height solution is close to the PBL, that is, well-known Ekman solution. Thus the HBL thickness is proportional only to the ratio of $(K/f)^{1/2}$. Based on the Ekman solution, he use the momentum integral method to solve the HBL height. Results from his one-layer axisymmetric hurricane boundary layer also show this tendency. Although there is no advance explanation in that paper, based on the Ekmen solution, we can replace the planetary vorticity to the absolution vorticity, i.e., includ the effect of the hurricane vorticity. Clearly, with the increase of the relative vorticity, the depth of HBL will decrease. Simth (1968) adopt the DHBL definition, but THBL here also shows the same tendency.

The humidity field in the figure 3 indicates that the height of the cloud base is a little shallower than the THBL, which is confirm with the observation.

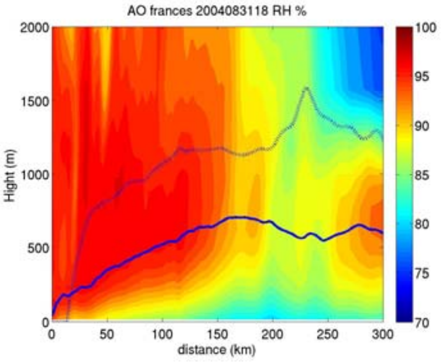

Figure 3: Azimuthal average THBL (solid line), DHBL (dashed line) and relative humidity (shaded) from AO of Frances on 1800 UTC August, 2004.

Figure 4 is the time series (from 0600 UTC 30 to 1800 UTC 31 August, 2005) THBL, DHBL and vorticity at about 400 m in CTRL of Frances. Corresponding time and intensity in terms of minimum sea level pressure is labeled with the color, respectively. The slop of the THBL and DHBL remain in this period. One main reason is that although the storm is intensifying in this period, the degree of amplifying is not significant, only from 940 mb to 926 mb. However in the Katrina simulation (not shown here), the slop of the THBL is a little flat when the storm developing while that of the DHBL maintains. The depth of the HBL in these two definitions and in both Katrina and Frances all decrease with the increase of the intensity. Comparing with the vorticity, the relation between the THBL/DHBL height with vorticity are obviously as we discuss before. So we can say that within a hurricane, the HBL height decrease while the local vorticity increase.

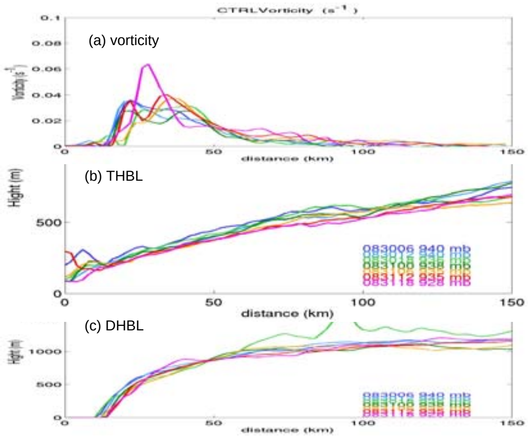

Figure 4: Time series variation of (a) vorticity, s-1; (b) THBL, m; and (c) DHBL, m. Color indicate different from 0600 UTC 30 to 1800 UTC 31 August, 2004. (From dark blue, light blue, light green, dark green, yellow, and red to magenta)

Figrue 5 is a scatter diagram in terms of THBL/DHBL and surface flux. Clearly that within in one simulation, the height of the boundary layer decrease with the increase of the surface flux. However, this statement is only reasonable when we compare the height in different location within the same experiment. While comparing with different storms or the same storm in different experiments, the height of HBL is increase with the increasing surface flux, especially THBL. The difference of the HBL between each experiment is not proportion to the difference of surface flux (figure 6). This suggests that the THBL/DHBL height is obvious controlled by the surface flux, but the accurate connection is still unclear.

So far, we know that both DHBL and THBL depend on the vorticity which also presents the amplitude of the rotation wind speed. The relation between the surface flux and HBL height is stronger in THBL. Figure 7 shows that the HBL height in these two definitions in all experiment at 1800 UTC 31 August, 2004. Compare with fig. 1, THBL reflects the minimum sea level pressure, while the DHBL reflects the maximum wind speed. Comparing the CTRL and AWO experiment, due to lacking of the ocean's negative feedback in the CTRL, the intensity in terms of the minimum sea level pressure is strong, thus the THBL is higher than in AWO. But with the wave model, the wind is modified and is larger than CTRL, than we can see the higher DHBL.

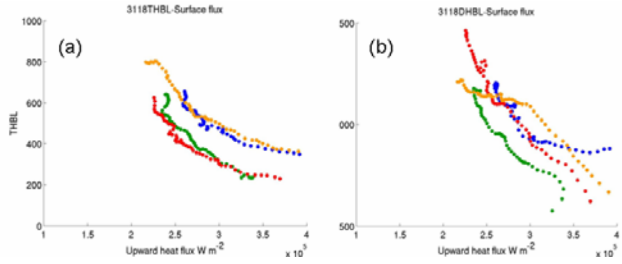

Figure 5: Scatter plot of surface (W m^{-2}) and (a) THBL (m); (b) DHBL(m). The color shows the different experiment for Frances as in Figure 1.

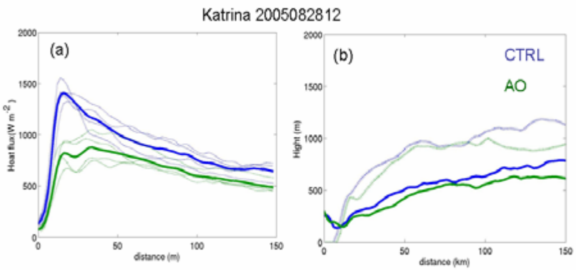

Figure 6: (a) Surface flux in Katrina simulation on 2812 UTC August, 2005 of CTRL (blue) and AO (green). Solid line is the azimuthal average while the dotted line is the mean surface flux in different quadrant. (b) Like (a) but for THBL (solid) and DHBL (dotted). At this point the intensity in CTRL is 910 mb/ 60 m s^{-1} while that in AO is 937 mb/ 51 m s^{-1}.

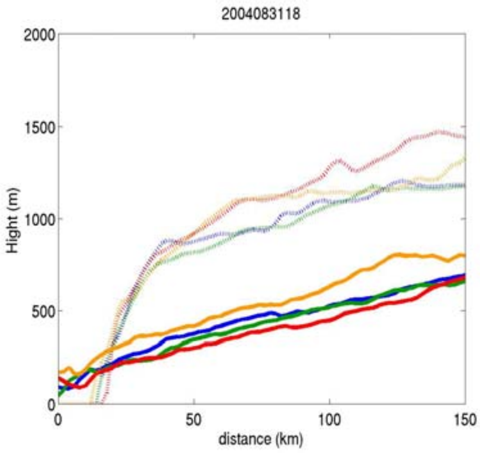

Figure 7: THBL (dotted) and DHBL (solid) in Frances in all simulation on 1800 UTC 31, 2005. Color means the experiments as that in figure 1.

3.3 Quadrant Information

Figure 8 shows the sea surface temperature anomalous field and HBL height with different definitions in AO of Frances. The shallowest THBL is coincidence with the strongest sea surface temperature cooling, and both of them are located in the right-real quadrant. Looking at the different quadrant mean state, the THBL reveals this asymmetric pattern while the DHBL presents the asymmetric but oppose pattern (not shown here). Thus is deeper in the rear pattern while shallower in the front pattern.

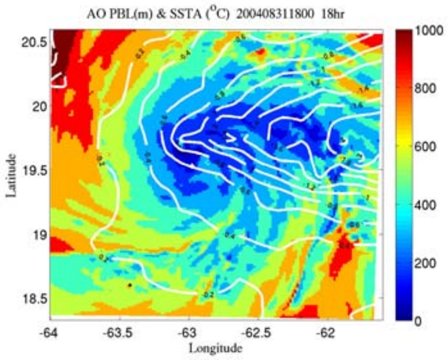

Figure 8: THBL (shaded) and sea surface anomaly (contour) on 1800 UTC 31 August, 2004.

4. CONCLUSIONs

Conclusions here are:

- The definition of the HBL gives us a quite different BL structure.
- With the definition of DHBL, the thermal variable should be function of height, not the constant.
- Both dynamic definition and thermal definition have good relation with the vorticity.
- Thermal definition is more close to the definition of the PBL in terms of the good relation with the surface flux.
- Dynamic definition can reveal the feature of the wind, this is obvious when compare with the CTRL and AWO simulation. This also the reason why the slop of THBL and DHBL is quite different.
- The boundary layer height in the thermal HBL is different in the four quadrants. In the first two quadrants, DHBL is close to THBL, but in the third and forth quadrant, they are much deeper than THBL.

5. Future work

The current work just shows the difference between THBL and DHBL. The behavior of the stability definition (Kepert, 2001) HBL is also interesting. We will use the same method to discuss the stability defined HBL and the turbulent process in the HBL associated this three definition. According to these discussions, we will try to define a HBL which can contain most information and also can contain the turbulent process in it. After that, we will use this mesoscale model to calculate the TKE budget to see the behavior of each term in TKE compare with the observation (Zhang 2007). Furthermore, we will calculate the TKE budget in both coupled and uncoupled run to see the influence of the coupling processes on hurricane boundary layer.

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