Impact of Boundary Layer Parameterization on HWRF Forecasts of Hurricane Rapid Intensification

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INTRODUCTION

- **One of the most challenging and important aspects of tropical cyclone prediction is rapid intensification (RI). Our recent work has examined the impact of planetary boundary layer (PBL) parameterization on HWRF forecasts of hurricane track, intensity, and structure. We found that lowering vertical eddy diffusivity (Km) in agreement with observations led to substantial improvements in track and intensity forecasts (Zhang et al. 2015). We found also that the storm structure is improved with improved PBL physics compared to observations. A conceptual model that summarizes the axisymmetric structural differences of the two sets of HWRF forecasts before and after physics improvements (Fig. 1).**

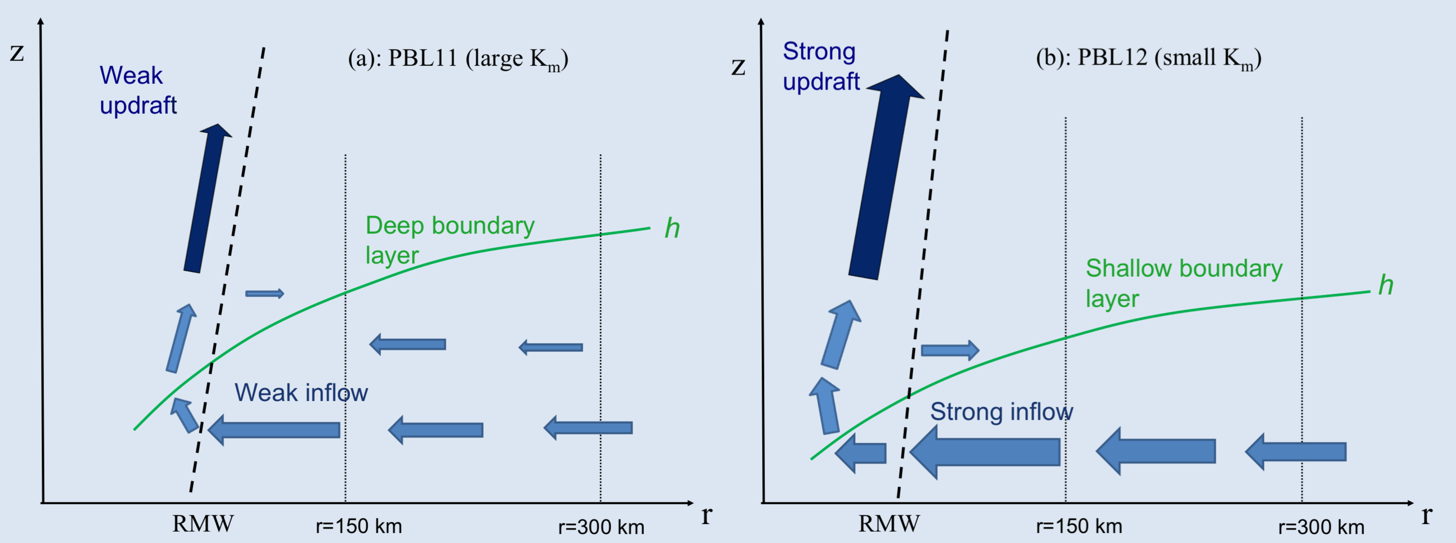

Figure 1. A schematic diagram summarizing the different structures in the PBL11 (a) and PBL12 (b) composites. The thickness and length of the arrow is correlated with the strength of inflow, outflow or updraft. The boundary layer height (h) is represented by the green line.

- **Further analyses of the HWRF forecasts of two RI storms (Tables 1 and 2) indicated that improved PBL physics also improved the overall performance of HWRF's ability for RI prediction (Fig. 2, Zhang et al. 2017). Composite analyses of axisymmetric structure at the RI onset are shown in Fig. 3 and Fig. 4. This result is consistent with previous observational and theoretical studies emphasizing the important role of the efficiency of diabatic heating from deep convection in hurricane intensification (e.g., Hack and Schubert 1986; Nolan et al. 2007; Vigh and Schubert 2009; Rogers et al. 2013; 2015; 2016).**
- **To further evaluate the role of Km on RI processes, a case study approach is used to investigate the asymmetric vortex-scale, convective-scale and boundary-layer structures and their interaction with the environmental shear. The evolution of vortex tilt and the boundary layer thermal structure is compared to theoretical study of Riemer et al. (2010). To compare with the hurricane spin-up theory of Smith et al. (2009) and Montgomery and Smith (2014), angular momentum budget is conducted.**
- **Lessons learned from this study will be fed back to HWRF developers for improvement of other aspects of the model.**

COMPOSITE STUDY

RI Verification

Table 1: Summary of storm information and HWRF forecasts.

Storm name	Number of cycles of simulations	Starting time of the first cycle	Starting time of the last cycle
Earl	40	2010/08/25/18Z	2010/09/04/12Z
Karl	15	2010/09/14/18Z	2010/09/18/06Z

		Observed	
		Yes	No
lowKm	Yes	Hit 16	False Alarm 8
	No	Miss 2	---

		Observed	
		Yes	No
highKm	Yes	Hit 4	False Alarm 0
	No	Miss 14	---

Table 2. Contingency table of RI forecasts for lowKm and highKm.

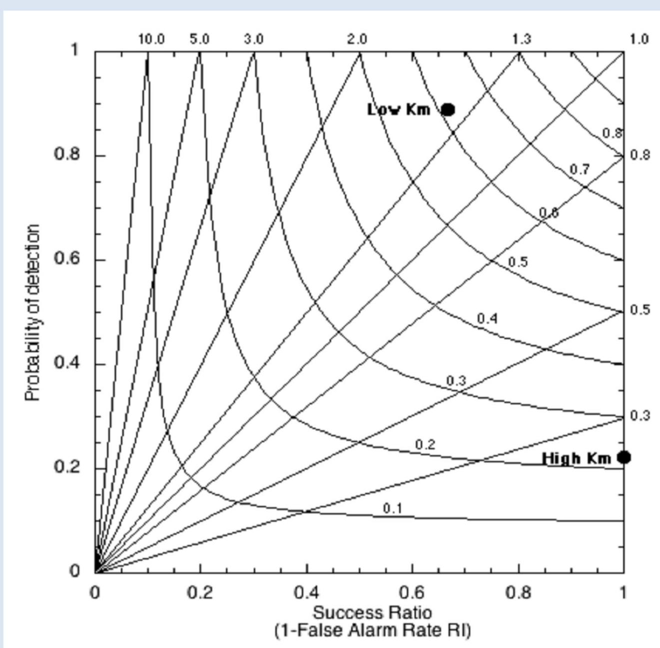

Figure 2: RI verification using the categorical performance diagram for the lowKm and highKm groups. Note that a perfect forecast lies in the upper right of the diagram when the probability of detection (POD) and success ratio (SR) approach unity.

Inner-core Composites

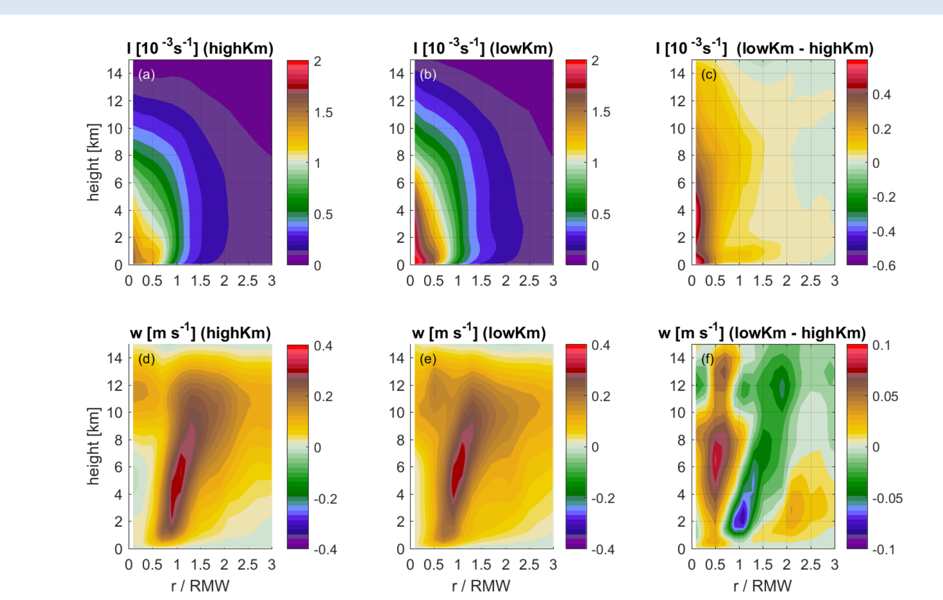

Figure 3: Plots of azimuthally averaged inertial stability (I, upper panels) and vertical velocity (w, bottom panels) as a function of r/RMW and height. The left panels are for highKm, and the middle panels are for lowKm. The right panels show the difference between the highKm and lowKm composites.

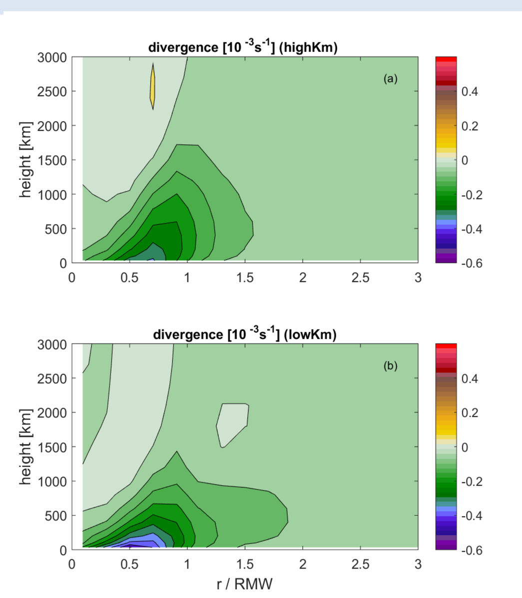

Figure 4 Plots of azimuthally averaged divergence as a function of r/RMW and height for the highKm (a) and lowKm (b) composites.

CASE STUDY

HWRF Forecasts of Hurricane Earl (2010)

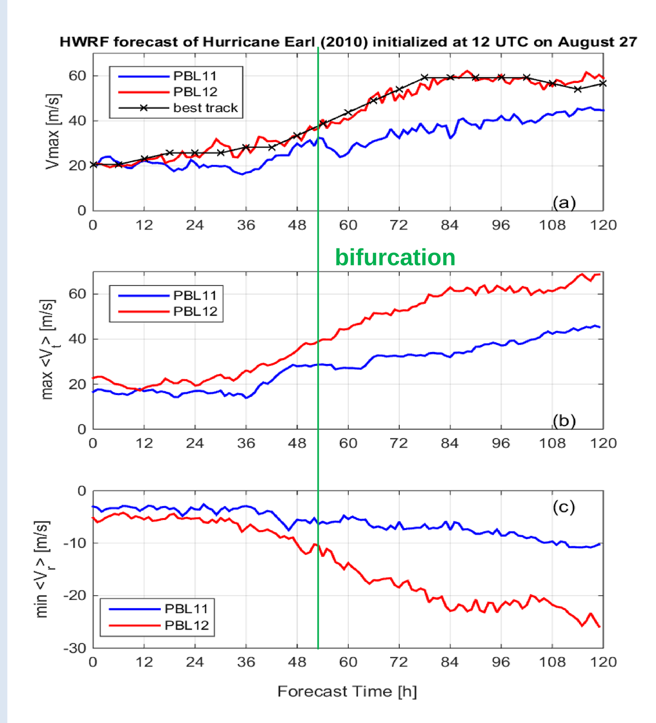

Figure 5: Time series of (a) the storm intensity in terms of the maximum surface wind speed, (b) maximum azimuthally averaged tangential wind speed (Vt), and (c) minimum azimuthally averaged radial wind speed, from two HWRF forecasts of Hurricane Earl (2010) initialized at 12 Z on August 27, 2010 with highKm and lowKm boundary layer physics.

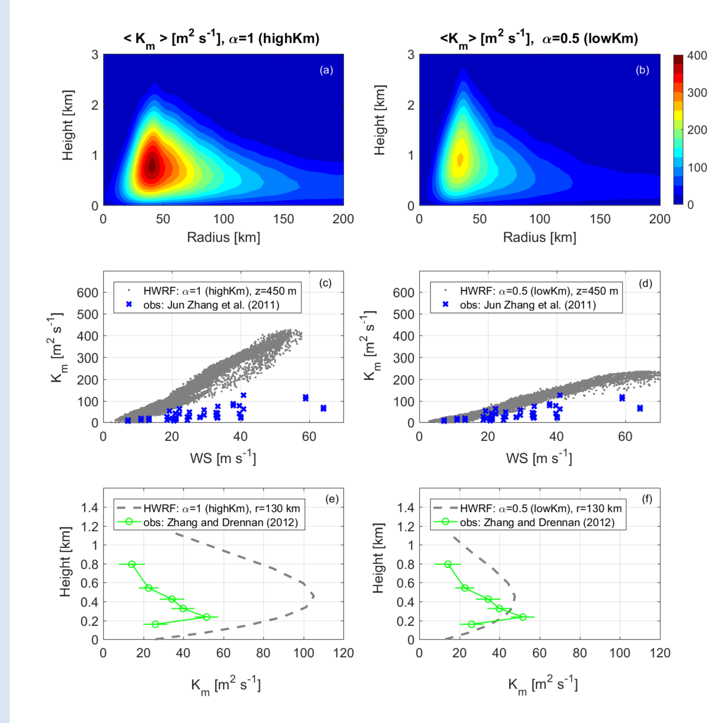

Figure 6: Comparison of vertical eddy diffusivity (K_m) between model simulations and observations. The height-radius plot of azimuthally averaged K_m ($<K_m>$) for the two set of HWRF forecasts are shown in (a) and (b). Observational data are from Zhang et al. (2011) as well as Zhang and Drennan (2012).

Deep Convection

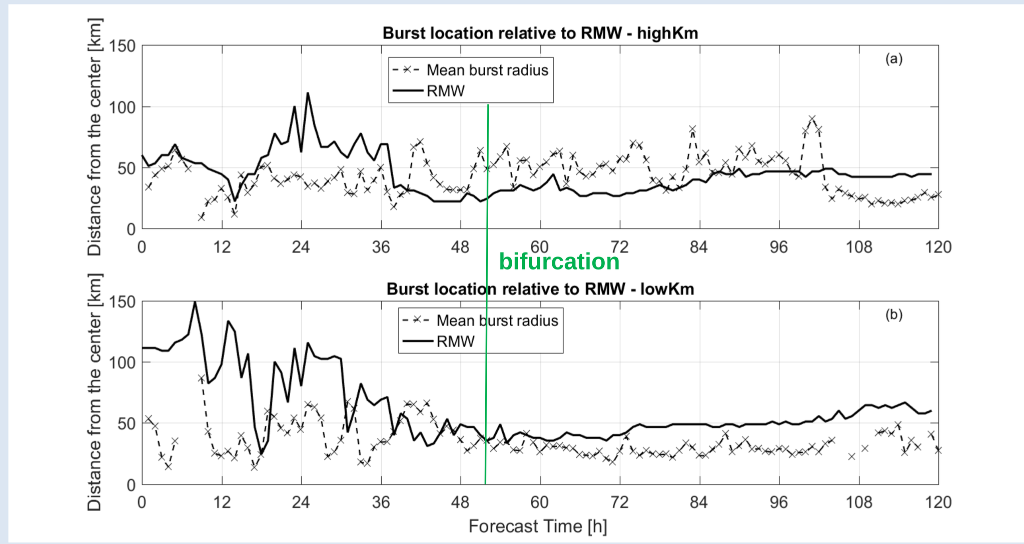

Figure 7: Time evolution of the mean radius of convective bursts and the radius of maximum wind speed (RMW) at 2 km for the highKm (a) and lowKm (b) forecasts of Hurricane Earl (2010).

Convective burst defined as those locations where the maximum vertical velocity > 3 m s[-1].

- The majority of the convective bursts are located within the RMW for the lowKm forecast, while they are outside the RMW for the highKm forecast after the bifurcation point of intensity forecast. This result is consistent with Earl observations reported by Rogers et al. (2015).

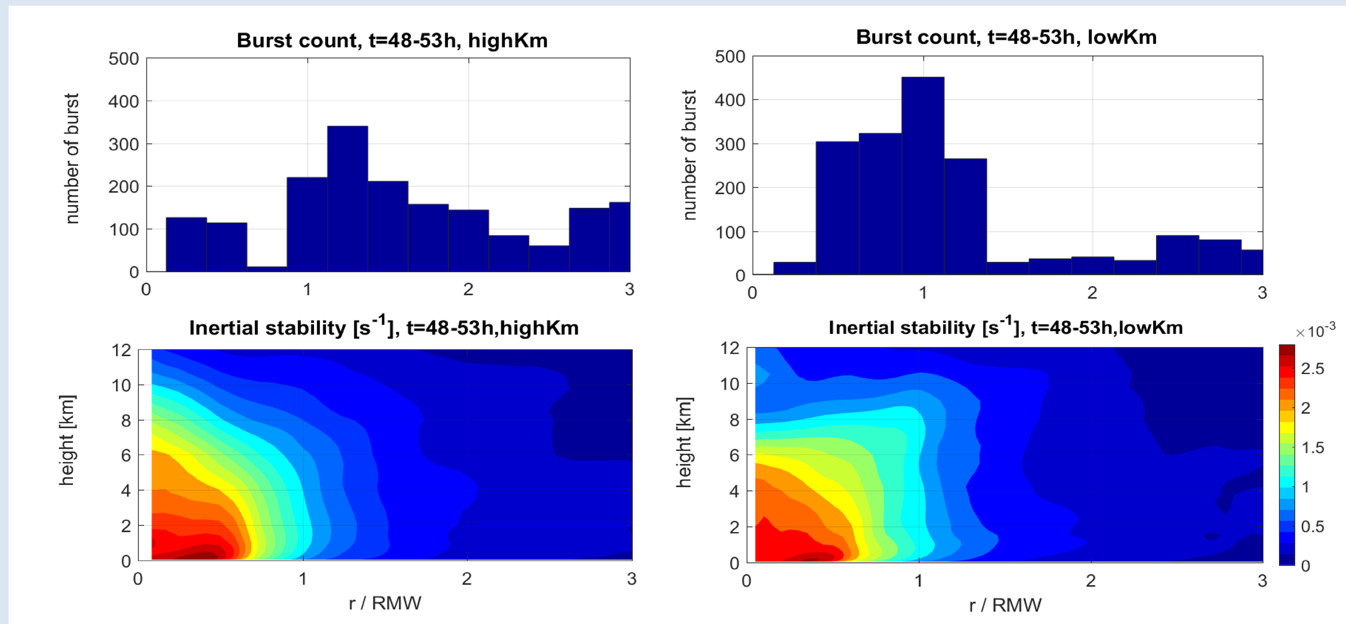

Figure 8: plot of number of convective bursts as a function of radius normalized by RMW at 2 km for highKm (a) and lowKm (b) during the period between 48 and 53 h of forecast time; and azimuthally averaged inertial stability averaged during the period between 48 and 53 h of forecast time as a function of radius normalized by RMW at 2 km for highKm (c) and lowKm (d).

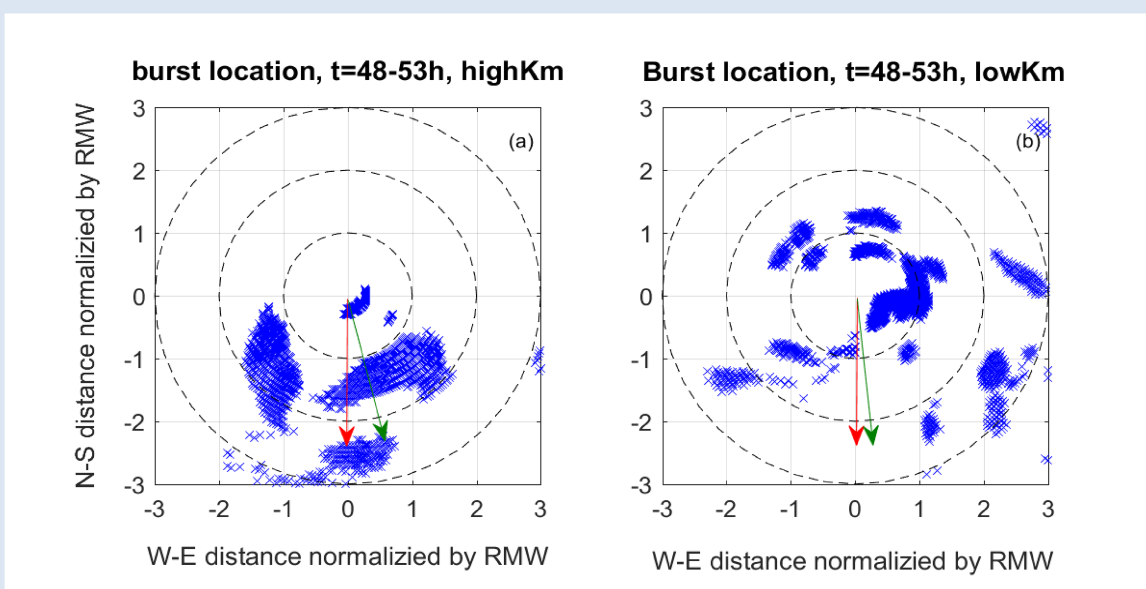

Figure 9: Horizontal view of the burst location during the period between 48 and 53 h of forecast time for highKm (a) and lowKm (b) forecasts. The red arrow indicates the shear direction. The green arrow indicates the tilt direction. The distance to storm center is normalized by the radius of the maximum wind speed at 2 km (RMW).

- The lager number of bursts are collocated with higher values of inertial stability in the lowKm forecast than in the highKm forecast, consistent with observations (Rogers et al. 2013; 2015).
- The convective burst azimuthal distribution is more symmetric in the lowKm forecast than in the highKm forecast. More bursts are found in the upshear side the lowKm forecast compared with the highKm forecast. This result is consistent with recent observational studies of Hurricanes Earl (Stevenson et al. 2014; Rogers et al. 2015) and Edouard (2014, Rogers et al. 2016) before and during RI, suggesting that the axisymmetrization of deep convection is tied to the hurricane intensification.

CASE STUDY

Vortex Tilt

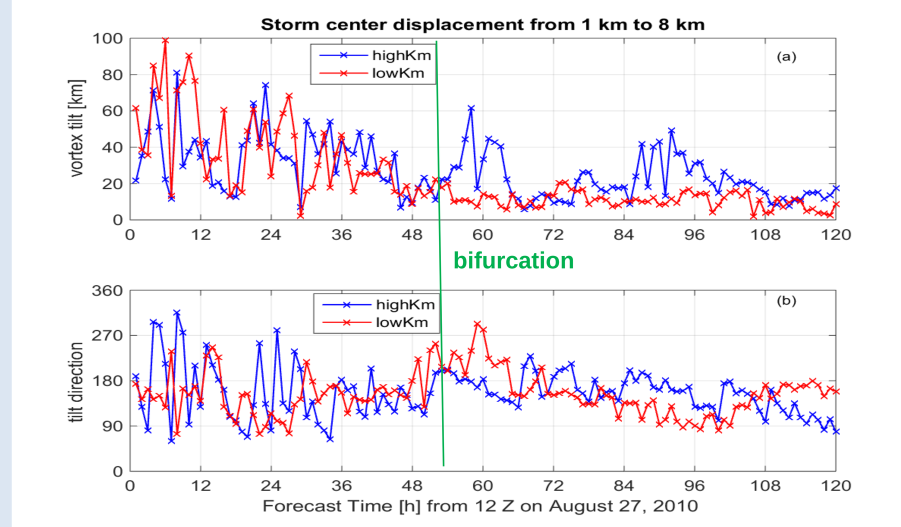

Figure 10: Plot of vortex tilt magnitude (a) and direction (b) as a function of forecast time for highKm and lowKm forecasts of Hurricane Earl (2010). Here the vortex tilt is defined as the storm center displacement form 1km to 8km, and the storm center is defined as the location of the minimum horizontal wind speed.

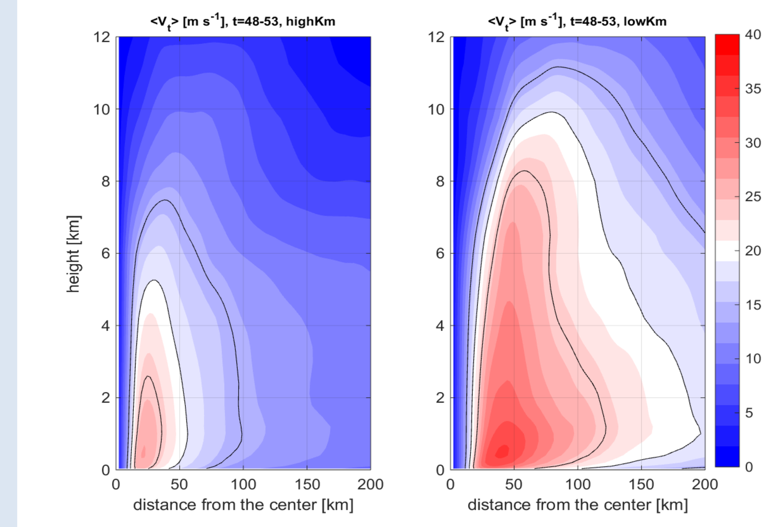

Figure 11: Radius and height plot of the azimuthally averaged tangential wind speed (V_t) averaged during t=48-53 h for highKm (left panels) and lowKm (right panels) forecasts of Hurricane Earl (2010).

- The vortex tilt becomes much smaller in lowKm forecast than highKm forecast before the intensity bifurcation point.
- The hurricane vortex in the lowKm forecast is much broader and deeper than that in the highKm forecast, making the vortex in the lowKm forecast more resilient to shear.

Boundary-layer Thermal Structure

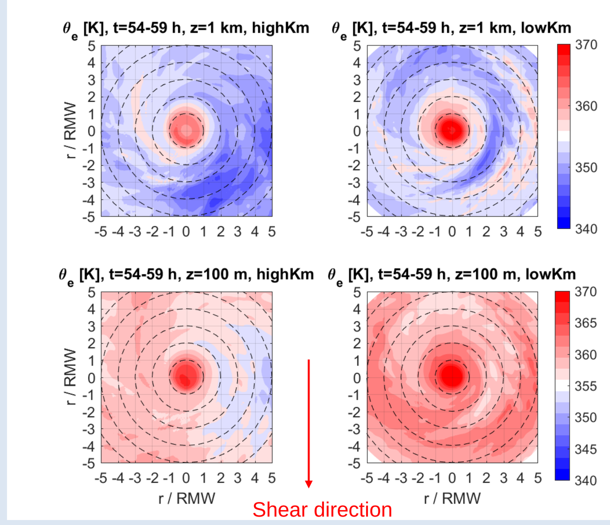

Figure 12: Horizontal view of the equivalent potential temperature (θ_e) at the heights of 1 km (left panels) and 100 m (right panels) averaged during the period from 54 to 59 h from the initial time. The upper and lower panels are from the highKm and lowKm forecasts, respectively

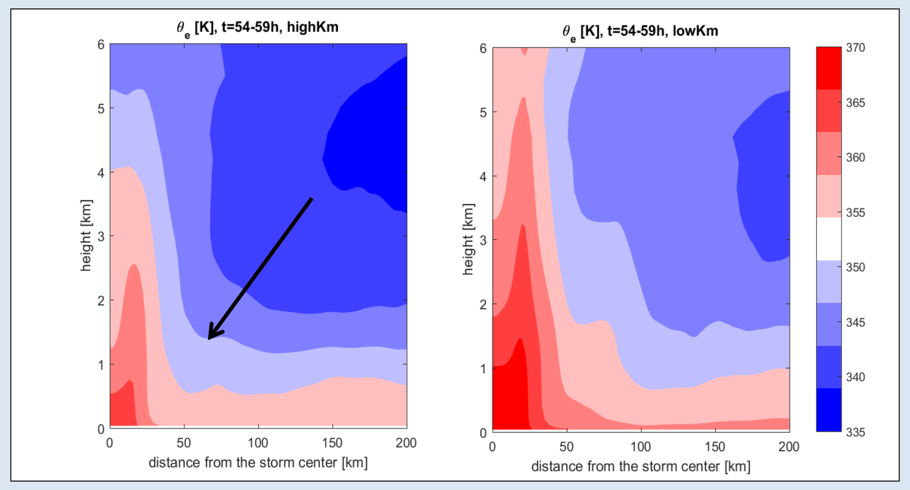

Figure 13: plot of azimuthally averaged equivalent potential temperature (θ_e) averaged during the period from 54 to 59 h from the initial time from the highKm (a) and lowKm f(b) forecasts, respectively.

- The boundary layer entropy (θe) is much smaller in the highKm forecast than in the lowKm forecast.
- The boundary layer thermal structural difference is tied to the difference in the vortex tilt. This is result is consistent with Riemer et al. (2010).

Angular Momentum Budget

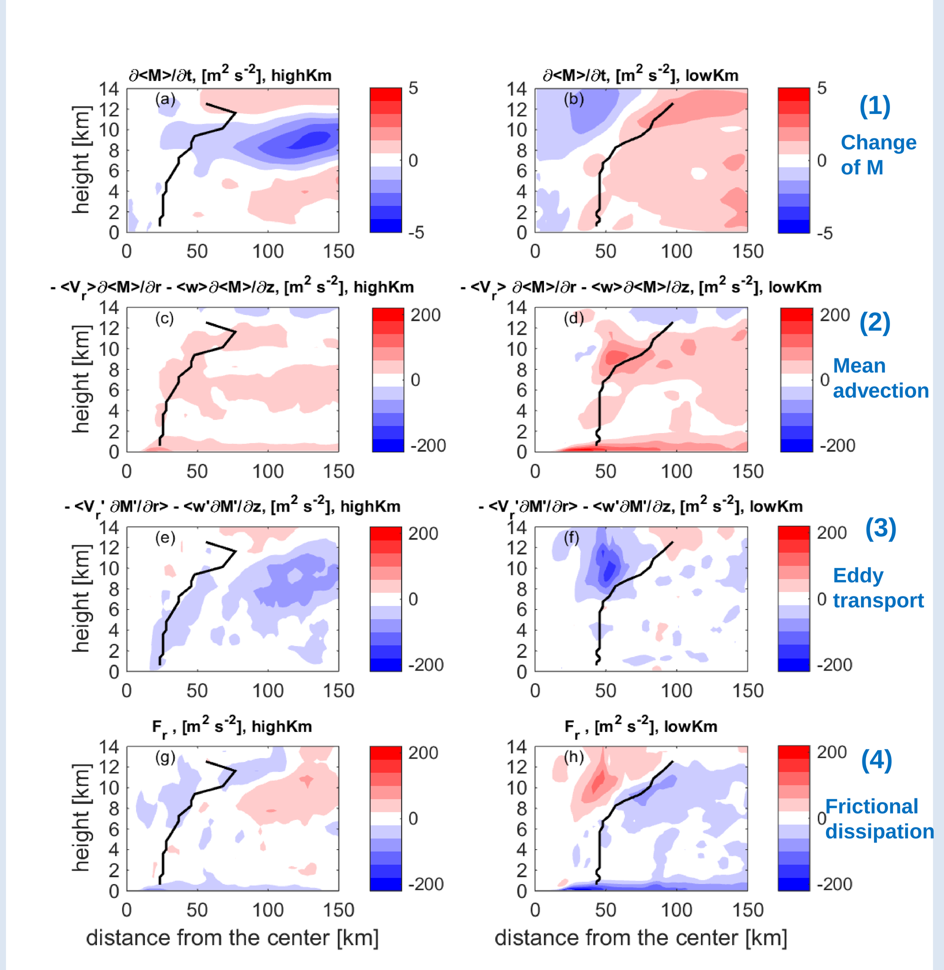

Figure 14: Radius-height plots of the terms in the azimuthally-averaged absolute angular momentum (<M>) budget for simulations with the highKm (left panels) and lowKm forecast (right panels) during a period before the bifurcation point of the intensity forecast (48-53 h). These budget terms include the local rate of change of (<M>) (a and b), the total mean advection (c and d), the sum of the eddy transport of (<M>) (e and f), and the friction term, F_r (g and h). The black line represents the radius of maximum azimuthally-averaged tangential wind speed.

$$\underbrace{\frac{\partial\langle M\rangle}{\partial t}}_{(1)} = \underbrace{-\langle V_r\rangle\frac{\partial\langle M\rangle}{\partial r} - \langle w\rangle\frac{\partial\langle M\rangle}{\partial z}}_{(2)} \underbrace{-\left\langle V_r'\frac{\partial M'}{\partial r}\right\rangle - \left\langle w'\frac{\partial M'}{\partial z}\right\rangle}_{(3)} + \underbrace{F_r}_{(4)}$$

- Convergence of angular momentum (i.e., radial advection of mean *M*) in the boundary layer is much larger in the lowKm forecast than that in the highKm forecast.
- The vertical mean advection of *M* is also larger in the lowKm forecast than that in the highKm forecast.
- The eddy advection of *M* acts to spin down the vortex especially above the boundary layer for both lowKm and highKm forecasts.
- This result is consistent with theoretical and numerical studies on hurricane spin-up (Smith et al. 2009; 2017; Montgomery and Smith 2014; Zhang and Marks 2015; Smith and Montgomery 2016).

SUMMARY AND FUTURE WORK

- This study demonstrates how the observation-based model physics improvement in HWRF model led to improvement in hurricane intensity change forecasts.
- Model diagnostics on the axisymmetric and asymmetric hurricane inner-core structure helps explain why the improved the model physics made better forecasts.
- Our results are consistent with previous observational, theoretical and numerical studies on RI processes, suggesting the recent model physics upgrade in HWRF is encouraging.
- Structural metrics developed in our study will help identify model errors related to other aspects of the model physics in hurricane models.
- Future work will follow a similar approach as in this study to improve other aspects of the operational hurricane models including model initialization, data assimilation and other aspects of the model physics such as horizontal diffusion, microphysics, etc.