Evaluation and Improvement of HWRF PBL Physics using Aircraft Observations

Jun Zhang

NOAA/AOML/HRD with University of Miami/CIMAS

HFIP Regional Modeling Team Workshop, 09/18/2012

Many thanks to my collaborators:

- Zhang, J. A., **F. D. Marks, Jr., M.T. Montgomery, and S. Lorsolo**, 2011a: An estimation of turbulent characteristics in the low-level region of intense Hurricanes Allen (1980) and Hugo (1989). *Mon. Wea. Rev*., 139, 1447-1462.

- Zhang, J. A., **R. F. Rogers, D. S. Nolan**, and F. D. Marks, 2011b: On the characteristic height scales of the hurricane boundary layer. *Mon. Wea. Rev.*, 139, 2523-2535.

- **Gopalakrishnan, S. G.**, F. D. Marks, Jr, J. A. Zhang, **X. Zhang, J. Bao and V. Tallapragada,** 2012: A Study of the Impacts of Vertical Diffusion on the Structure and Intensity of the Tropical Cyclones Using the High Resolution HWRF system. *J. Atmos. Sci.,* in press.

Acknowledge HRD and EMC HWRF modeling team members (in particular Thiago Quirino, Young Kwon and Weiguo Wang)

Acknowledge scientists from HRD and AOC crews who helped with collecting the data used in this work

Acknowledge the support from HFIP

Outline

- Objectives
- A brief summary of our previous work

  a) How was the problem identified?

  b) Which kind of observations are used in model evaluation?

  c) How was the new physics of turbulent mixing developed and implemented in HWRF?

  d) What is the impact of the modified physics on the simulated structure as seen in idealized simulations?

- On-going work: model diagnostics using simulations of Hurricane Earl (2010)

  a) Is the impact of the modified physics in real-case simulations consistent with that found in idealized simulations?

  b) Is the intensity forecast a physics problem or initialization problem?

- Summary and future work

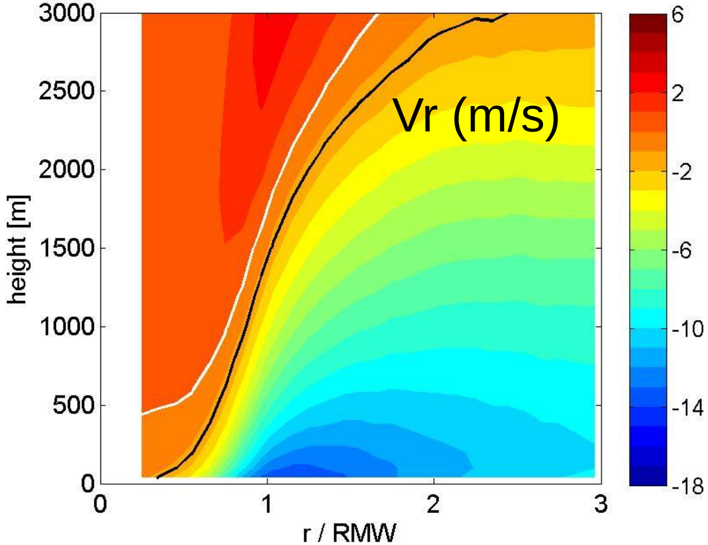
Following HFIP Objectives

- Increase usefulness of observations in high resolution (e.g. regional) hurricane modeling systems.

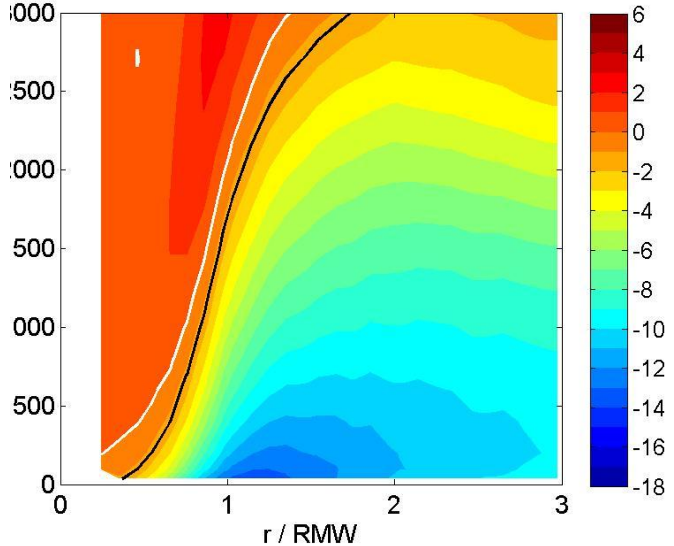
- Develop advanced model diagnostic techniques to support model improvements and identification and analyses of sources of model errors.

How was the PBL problem identified?

HWRFx 9-3 km res



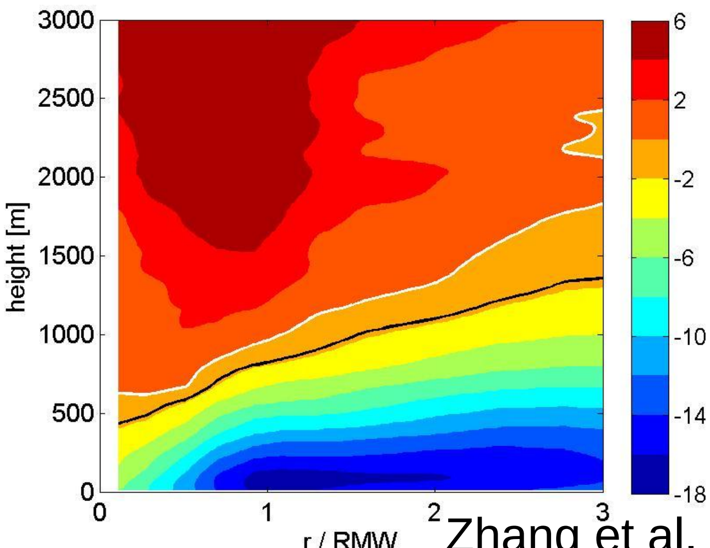
HWRFx 27-9 km res



Zhang, Rogers, and Cangiolosi, 2010, 2011

Dropsonde composite

The black line is the Inflow layer depth



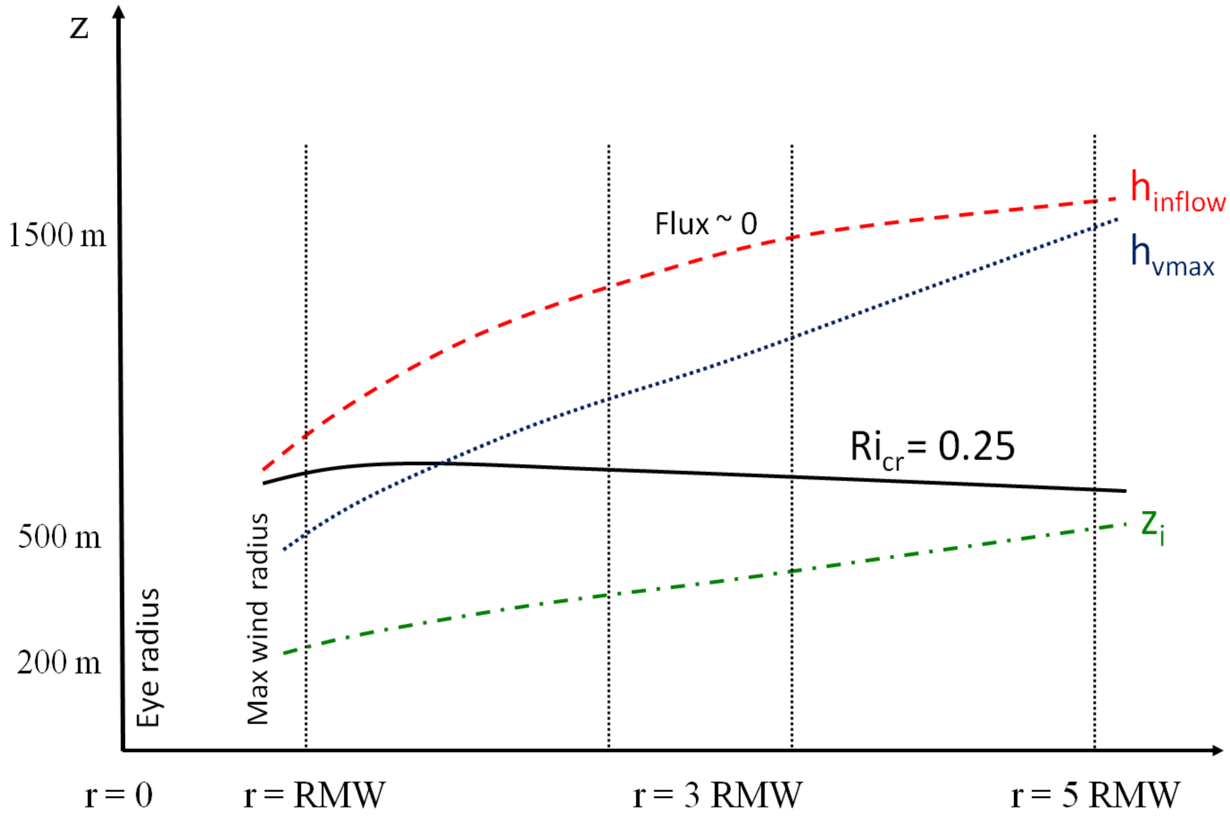
Model diagnostics using the HFIP HRH 69 runs with the experimental version HWRF

The simulated boundary layer height is much higher than observations.

Zhang et al. 2011 MWR

Defining PBL height in hurricanes

(Jun Zhang, Rogers, Nolan, and Marks, 2011 MWR)



h $_{inflow}$ – inflow depth

h_{vmax}- height of the maximum tangential wind speed (Vt)

Z_i - mixed layer depth from the virtual potential temperature profile

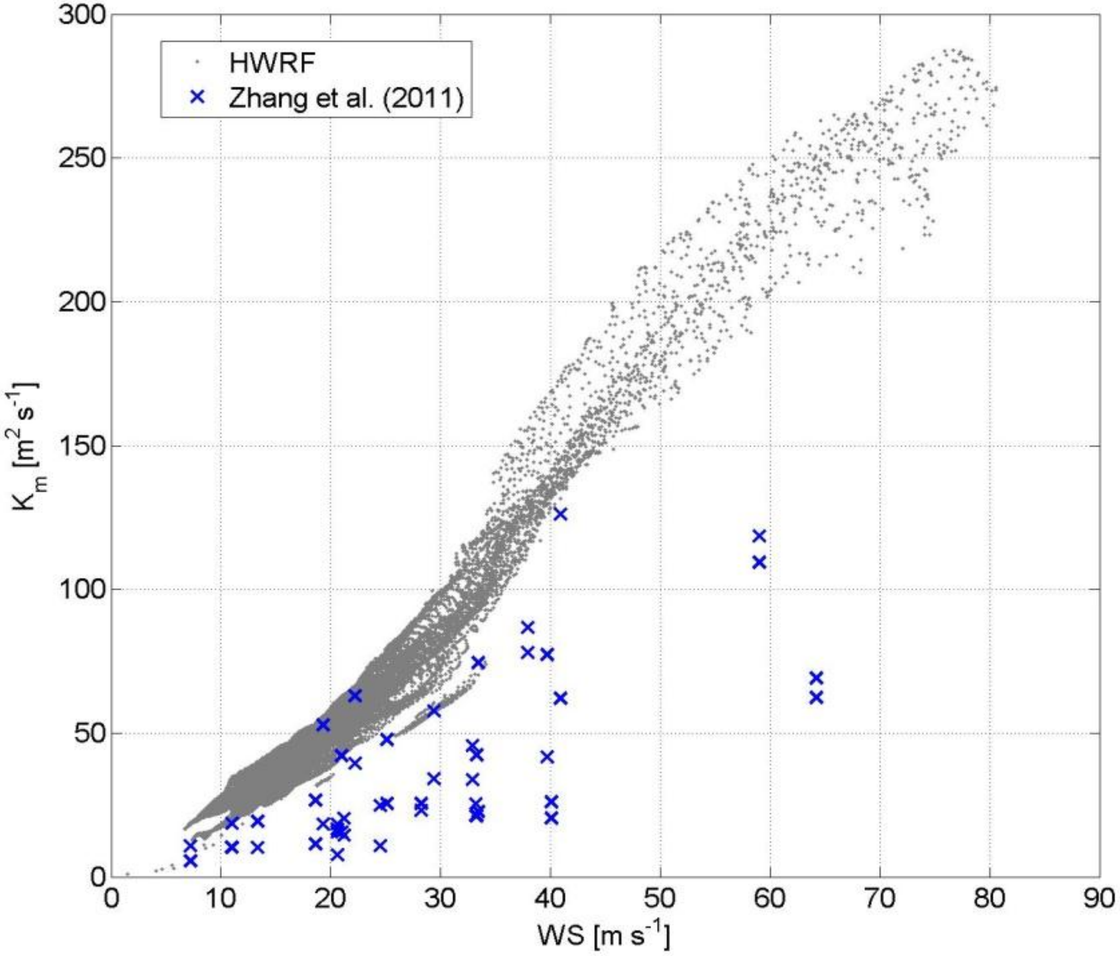
Ri_{cr}-critical Richardson number defined as buoyancy to shear forcing

Flux – momentum flux from CBLAST-hurricane exp

Max Vt in storm rel coordinates occurs well within the inflow layer and within the frictional boundary layer associated with strong inflow that arises in part because of the departure from gradient wind balance.

Identification of Problem in physics Scheme

pre-2012 HWRF

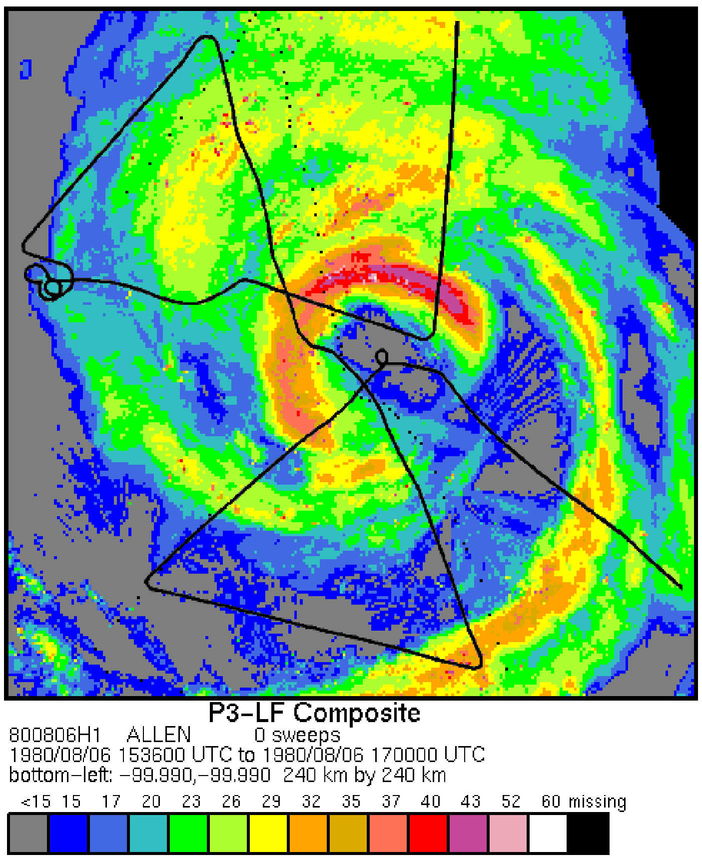


The boundary layer is too diffusive compared to observations!

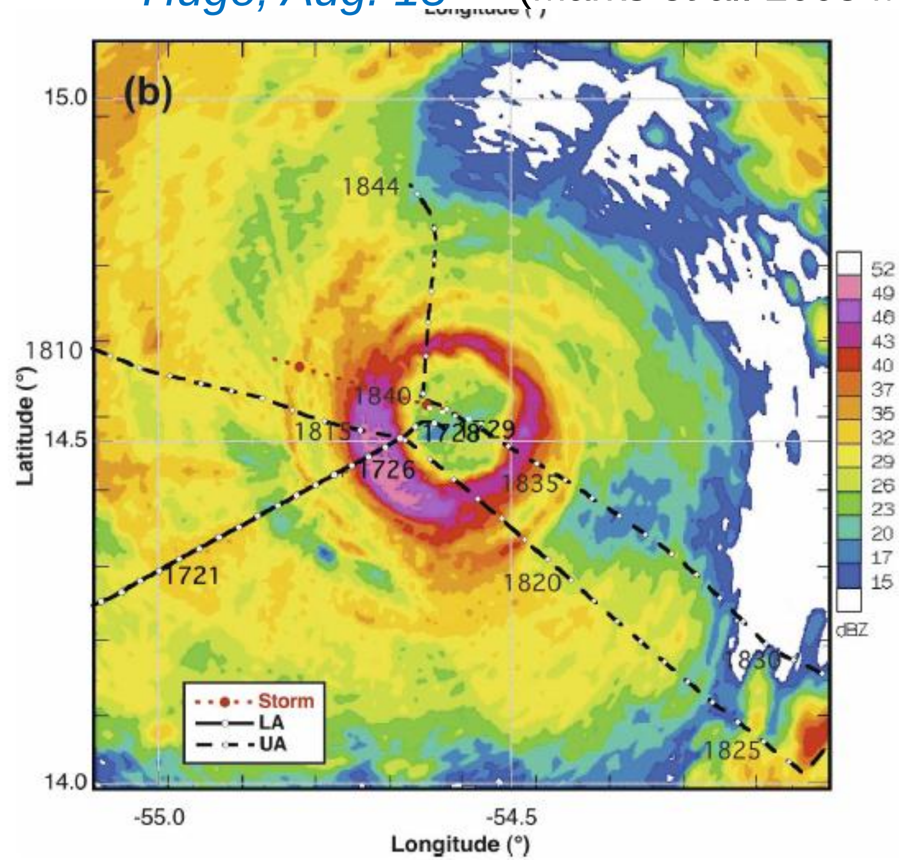
Low-level (~500 m) eyewall penetrations into very intense Hurricanes Allen (1980) and Hugo (1989)

(Jun Zhang, Marks, Montgomery and Lorsolo 2011 MWR)

Allen, Aug. 6 (Marks 1985 MRW)



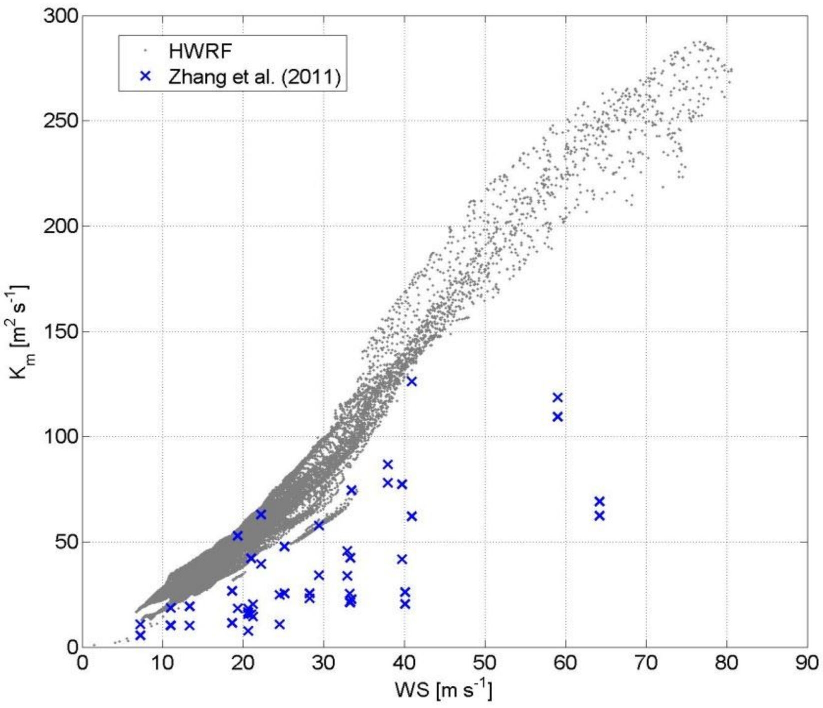
Hugo, Aug. 15 (Marks et al. 2008 MWR)



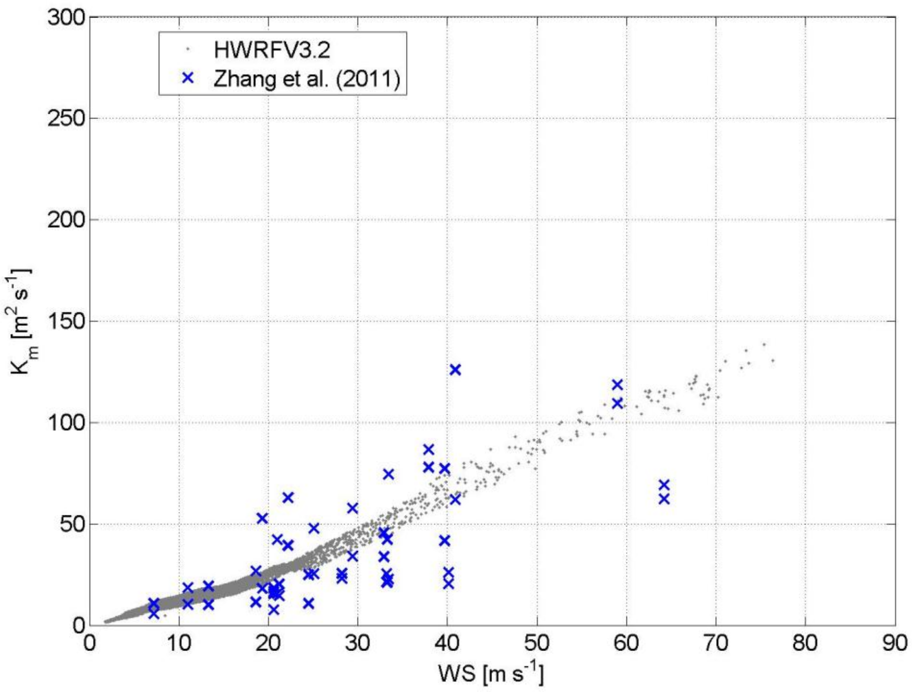
$$\hat{\tau} = \rho(-\overline{w'v_t'}\,\hat{i} - \overline{w'v_r'}\,\hat{j}) \qquad K_m = |\hat{\tau}|\left(\frac{\partial V}{\partial z}\right)^{-1}$$

Use observations to calibrate PBL physics in operational hurricane models

Before modification (pre-2012 HWRF)



After modification (HWRF 2012)

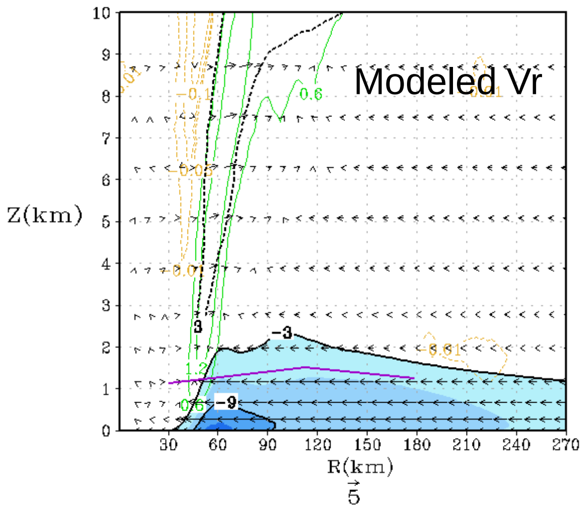


$$K_m = k\,(U_*/\Phi_m)\,Z\,\{\alpha(1 - Z/h)^2\}$$

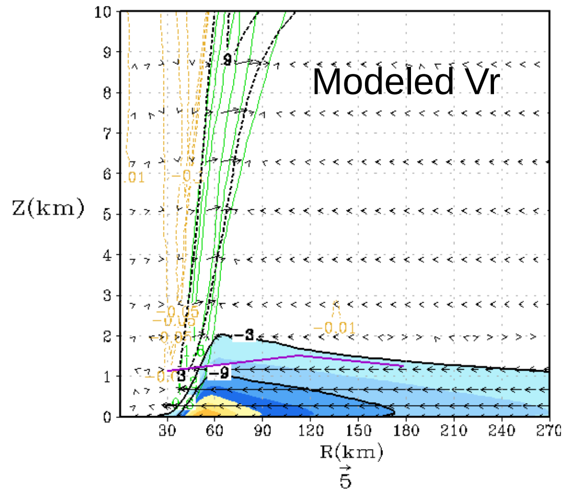
Effects of Vertical Eddy Diffusivity in Idealized HWRF Simulations

(Gopalakrishnan et al. 2012 JAS, in press)

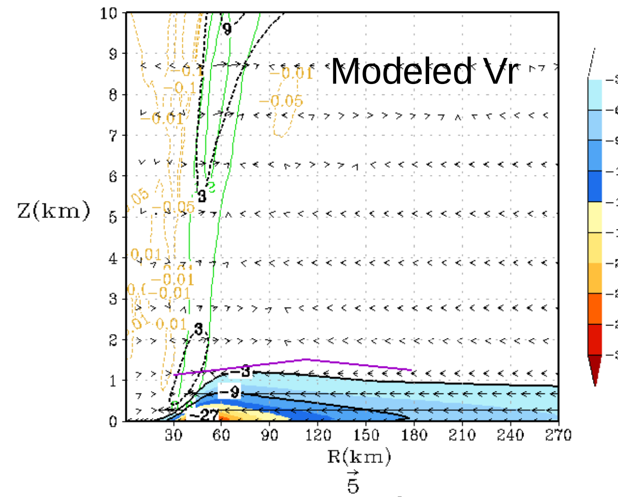
Original Km in HWRF



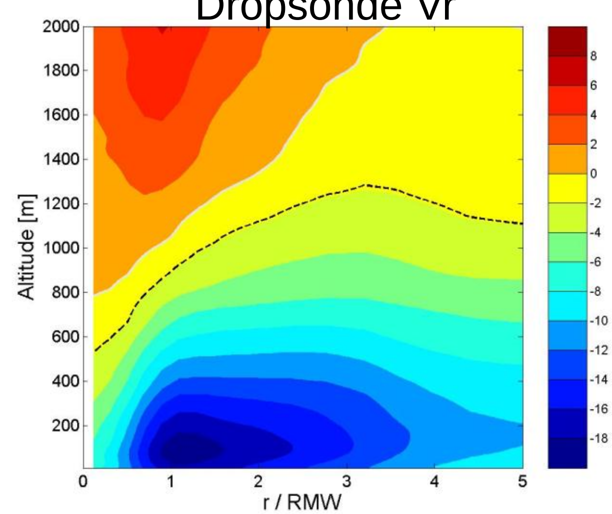
Km / 2



Km / 4

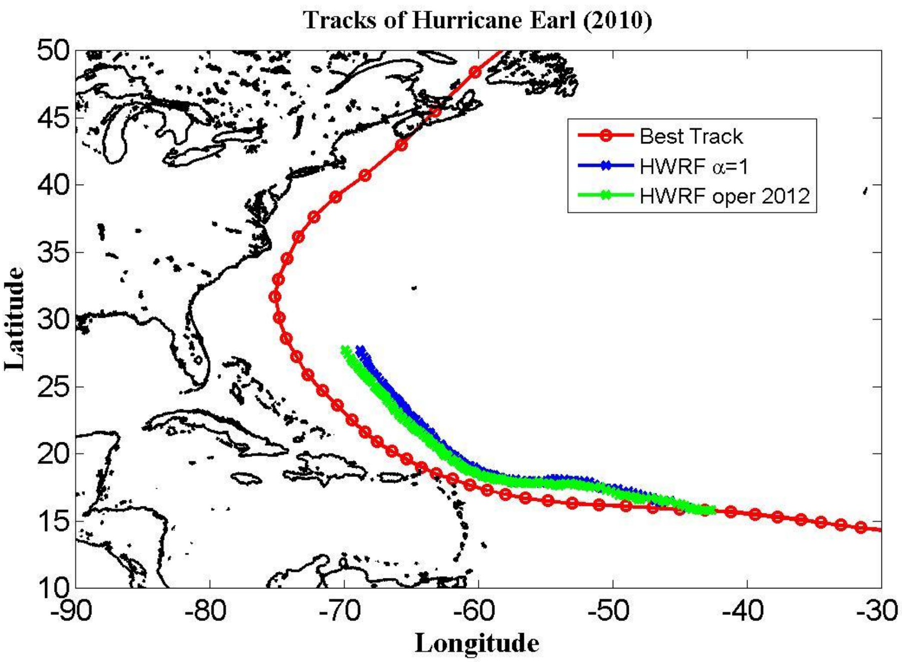


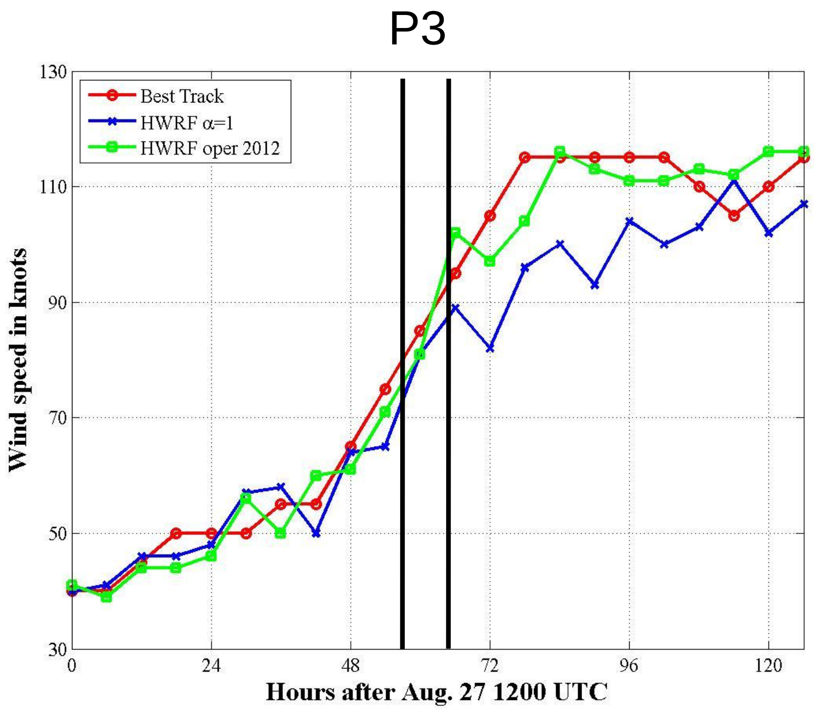
- depth of inflow layer more consistent with dropsonde composites
- peak radial inflow stronger with more accurate Km
- more prevalent role of BL dynamics in spin up process



The purple line is the inflow layer depth from the composite analysis using hundreds of dropsonde data (Jun Zhang et al. 2011b MWR, on the characteristic height scales of the hurricane boundary layer).

Further investigate the impact of vertical eddy diffusivity using HWRF simulations of Hurricane Earl (2010)



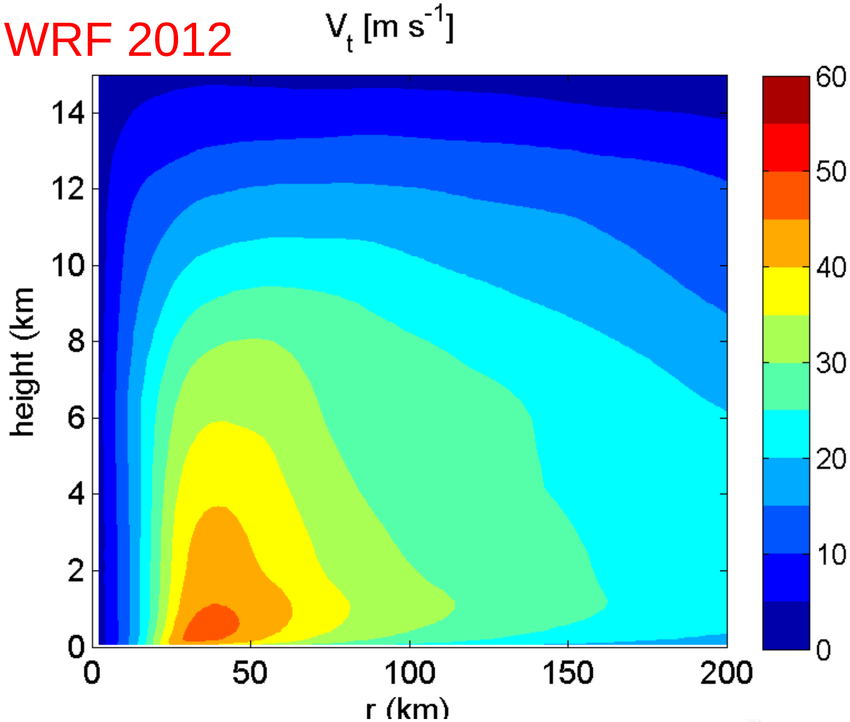


Two simulations with small K_m (α=0.5) vs large K_m (α=1)

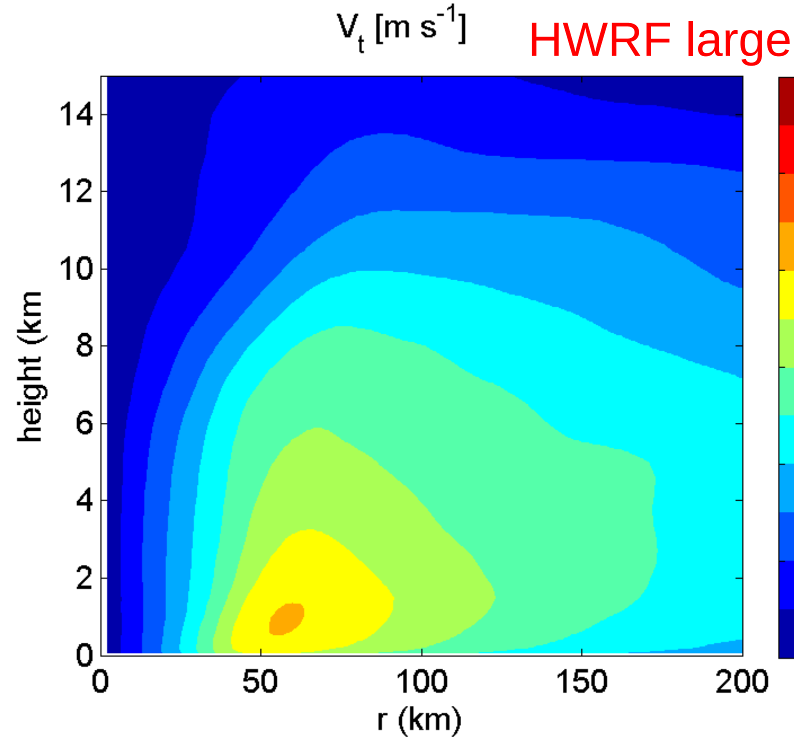
Vertical eddy diffusivity: $K_m = k\,(U_*/\Phi_m)\,Z\,\{\alpha(1 - Z/h)^2\}$

Is the impact of modified physics in real-case simulations consistent with that found in idealized simulations?

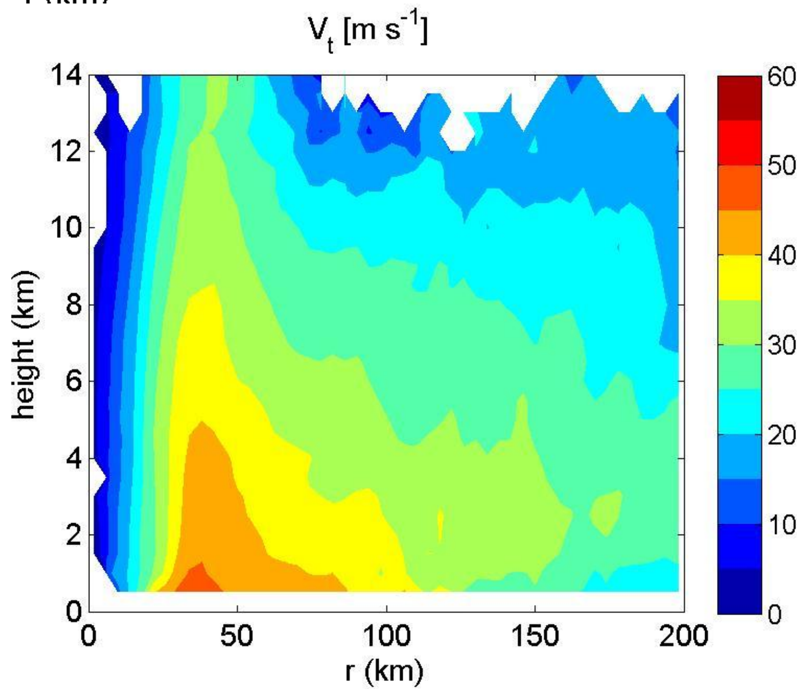
HWRF 2012



HWRF large Km



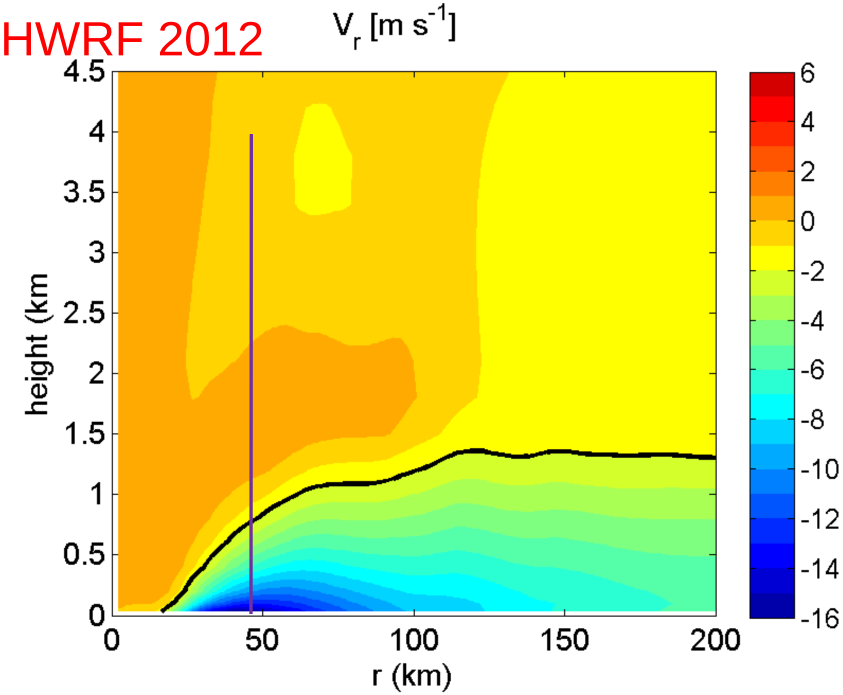
Doppler radar observation



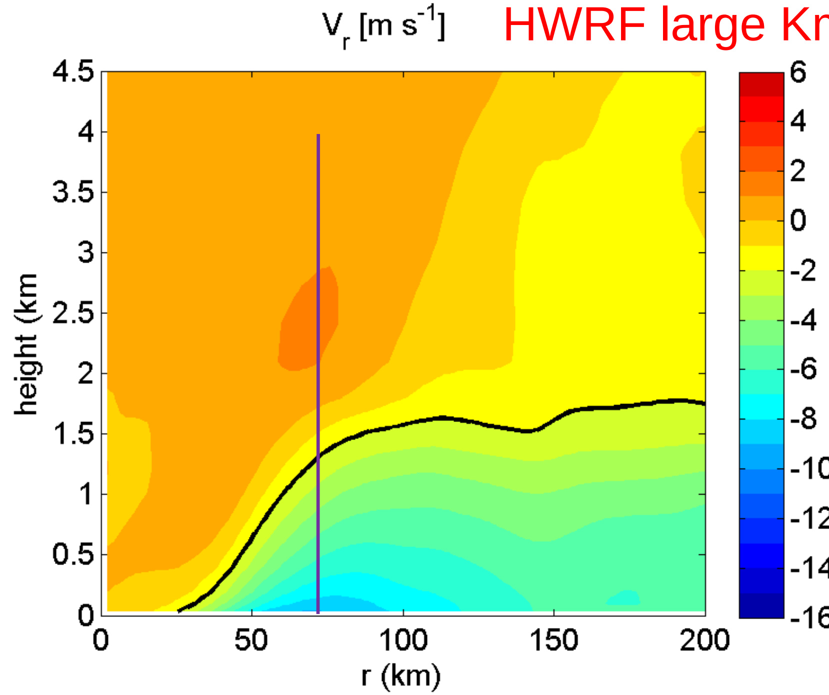
Smaller Km leads to a stronger, deeper and smaller vortex which is more consistent with observations.

Thanks Sylvie Lorsolo for providing the radar data

HWRF 2012

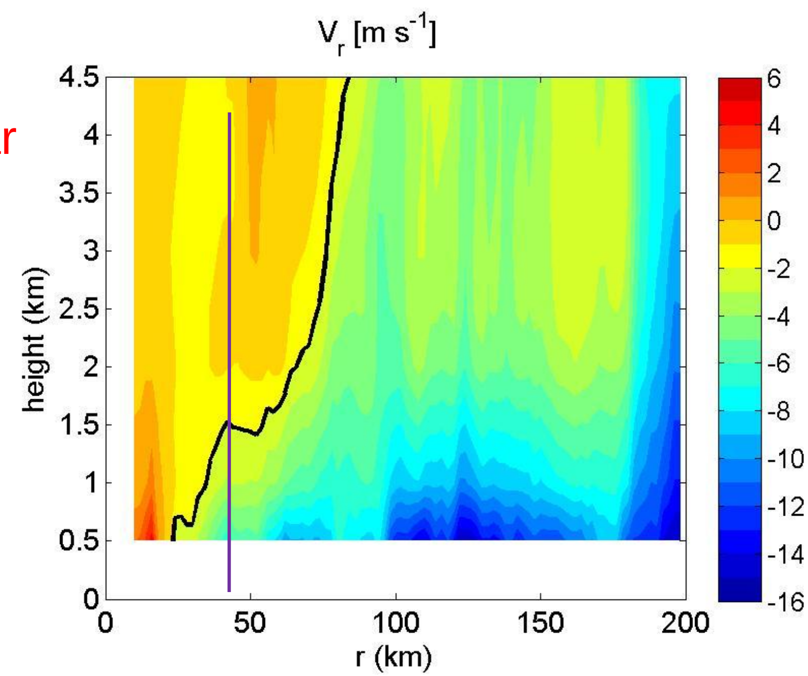


HWRF large Km



Doppler radar observation

Relatively low vertical resolution

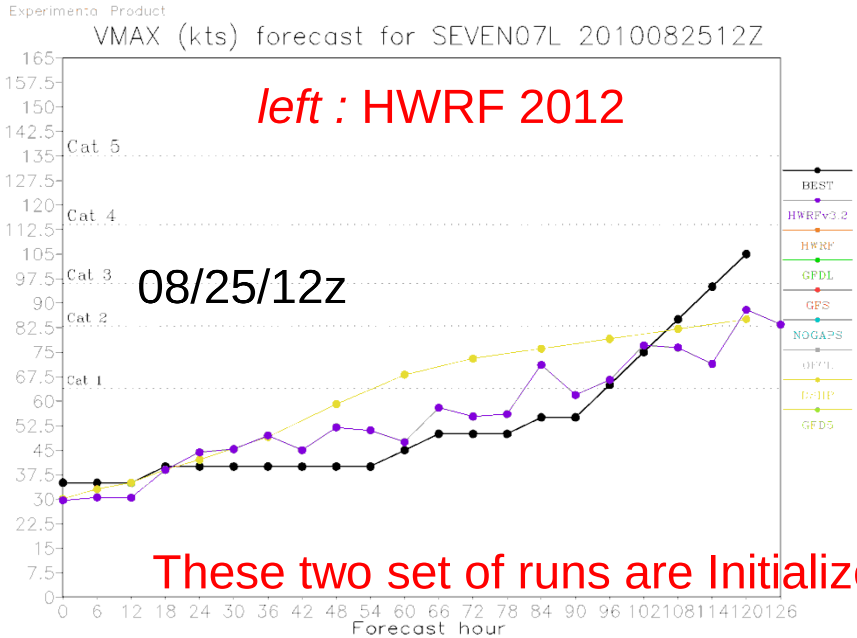


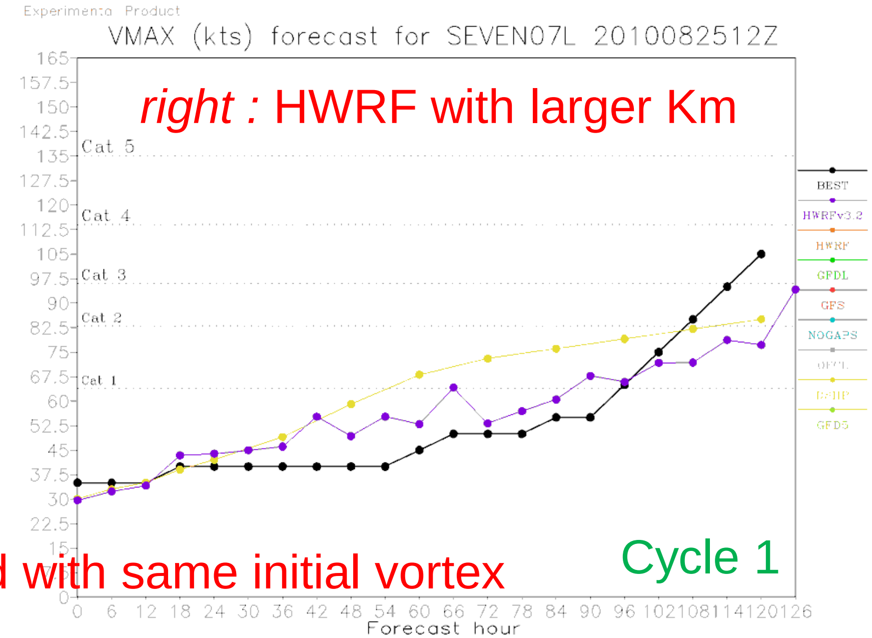
Smaller Km leads to a stronger inflow with shallower inflow layer which is consistent with finding of idealized simulations.
But both simulations failed to match observed structure.

A tough case! Earl went on eyewall replacement cycle on this day.

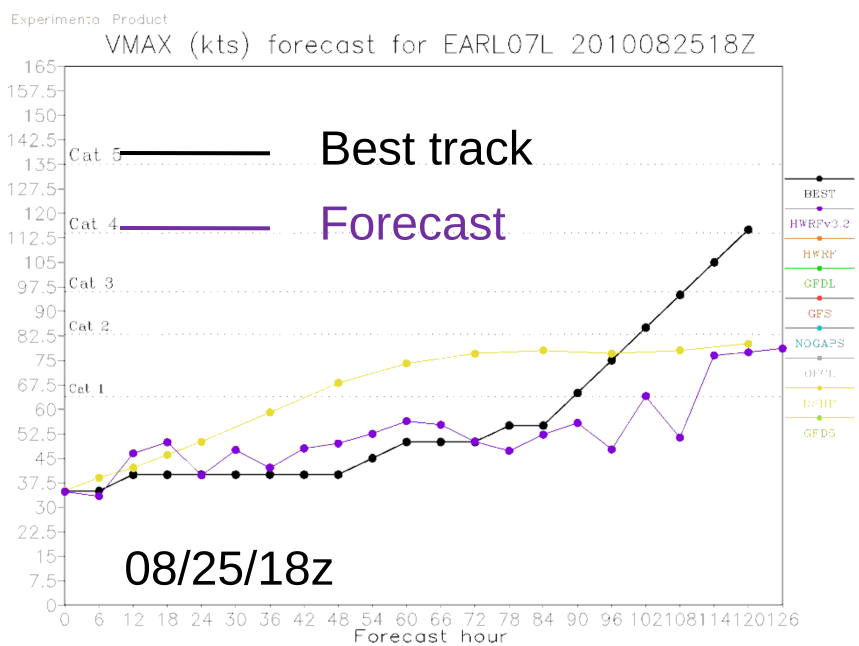
Need to check dropsonde observations to verify Doppler-radar observed structure

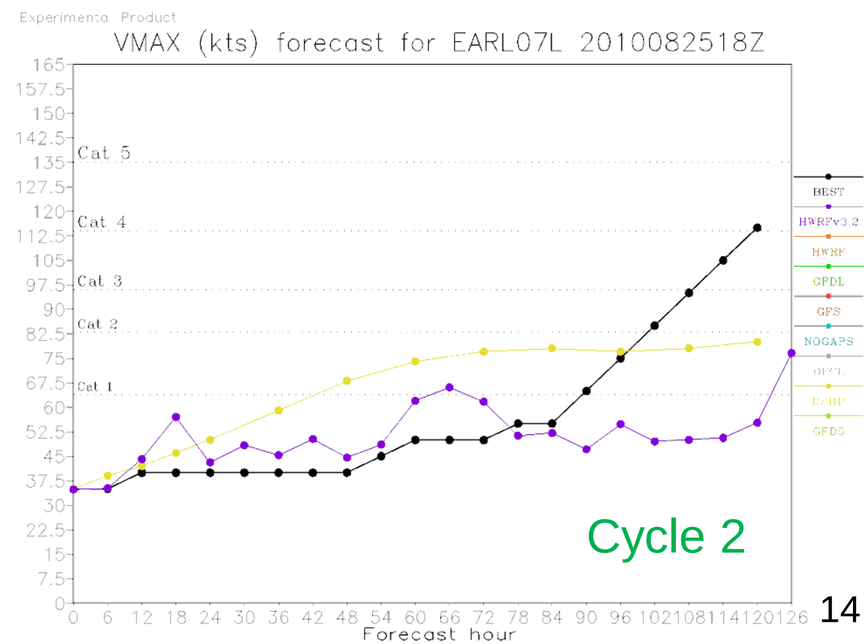
Two sets of cycling simulations of Hurricane Earl with different physics



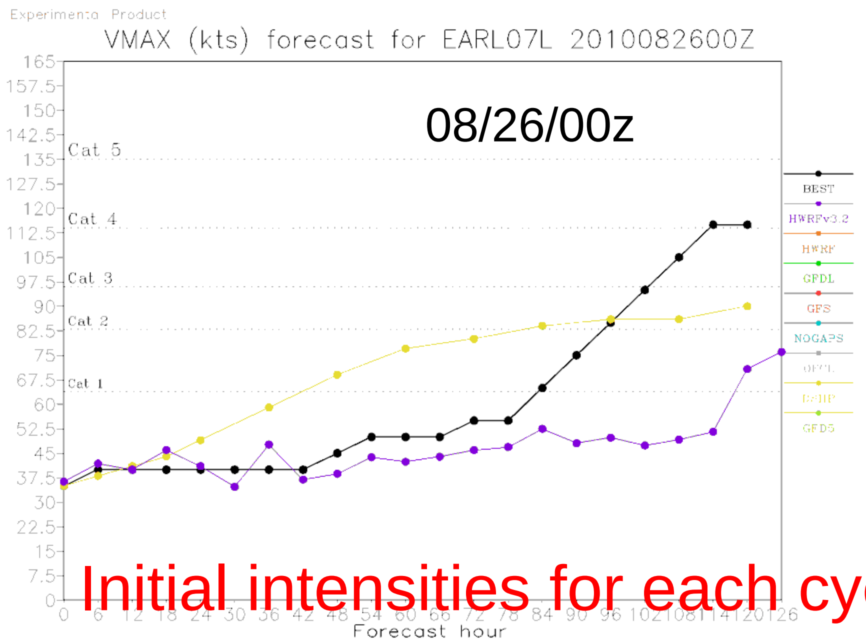


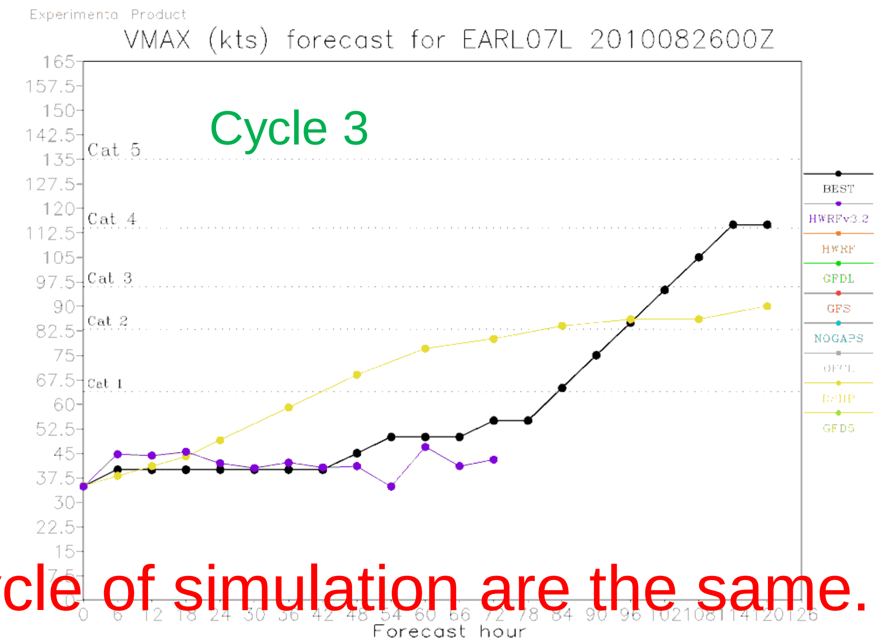
These two set of runs are Initialized with same initial vortex



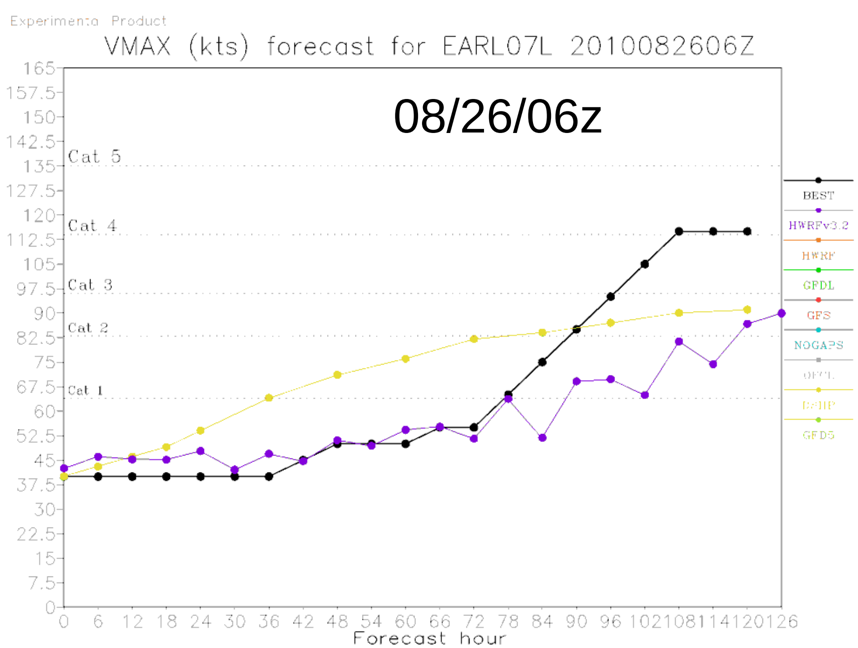


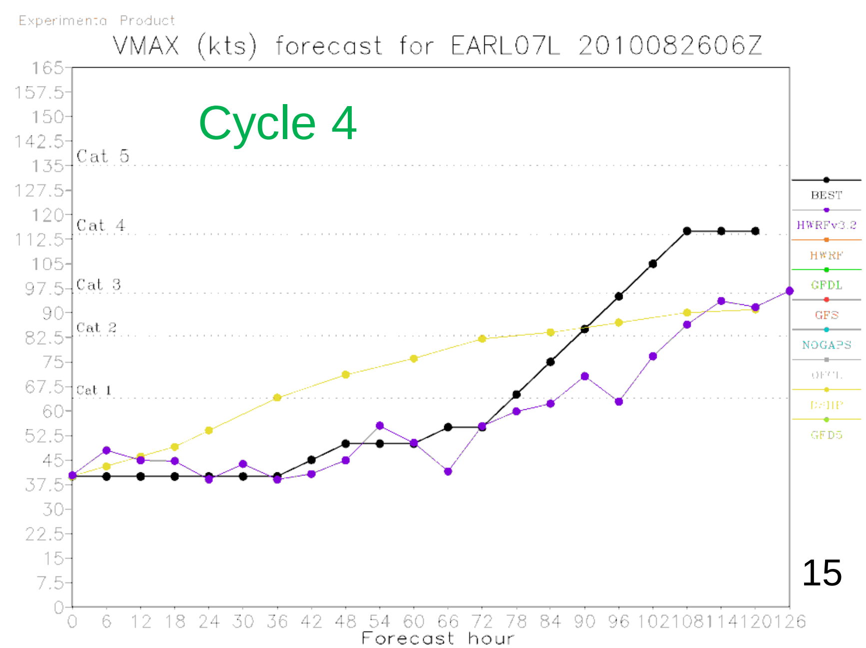
left : HWRF 2012 — *right :* HWRF with larger Km



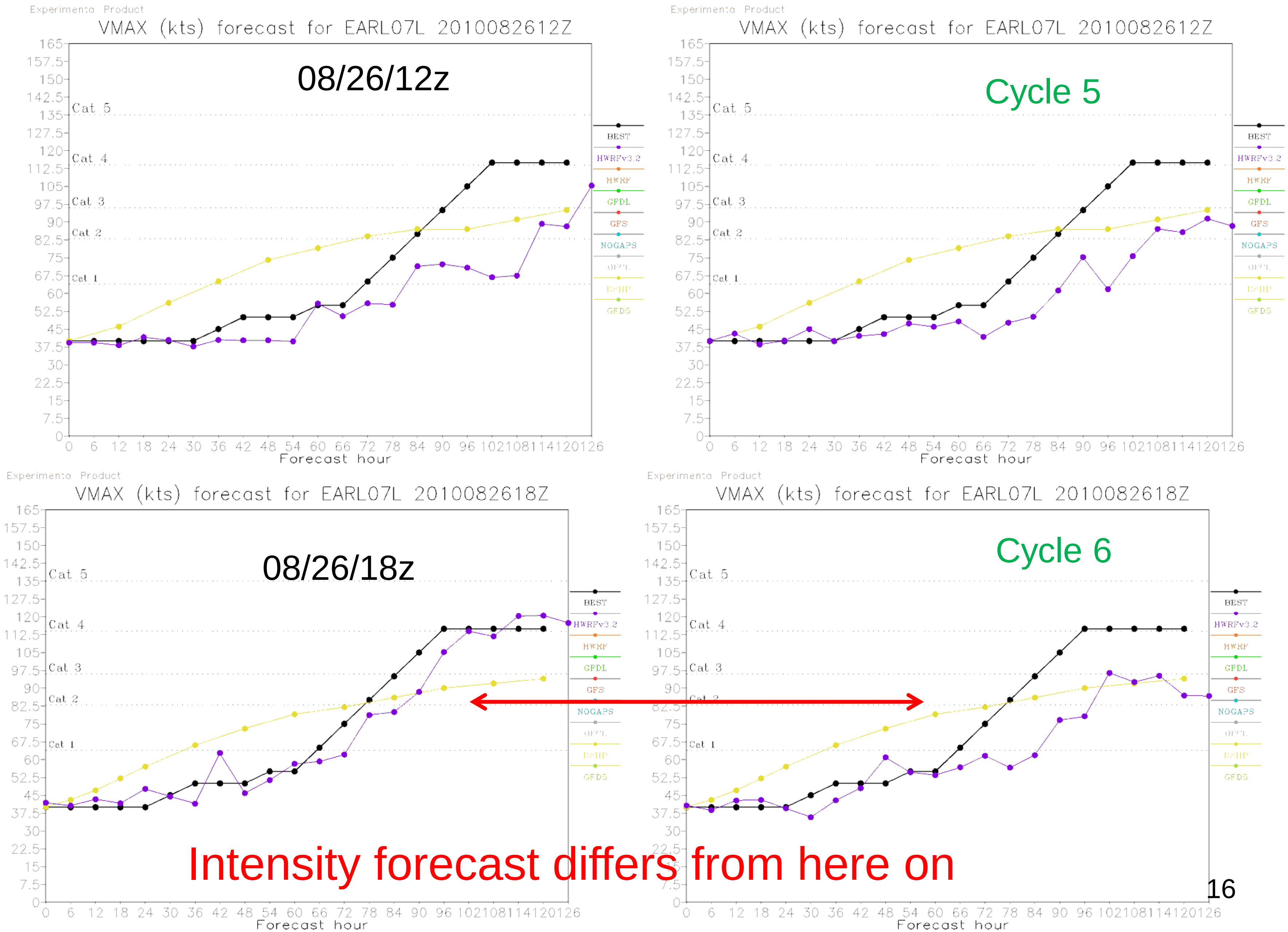


Initial intensities for each cycle of simulation are the same.



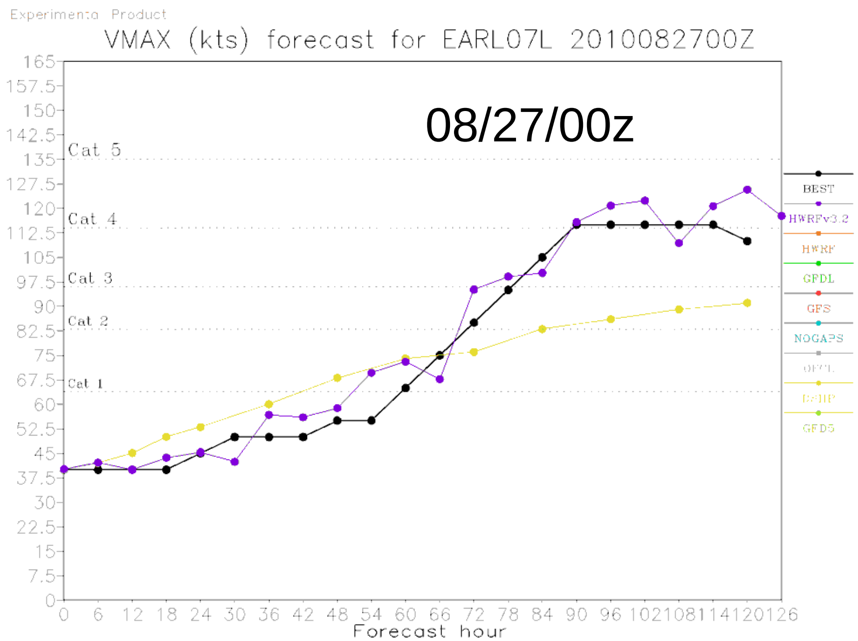


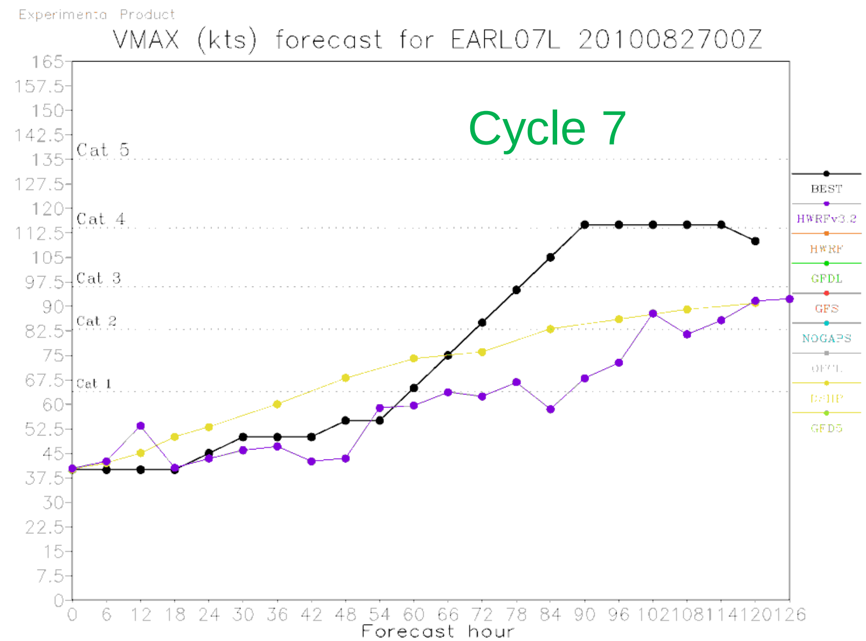
left : HWRF 2012   *right :* HWRF with larger Km

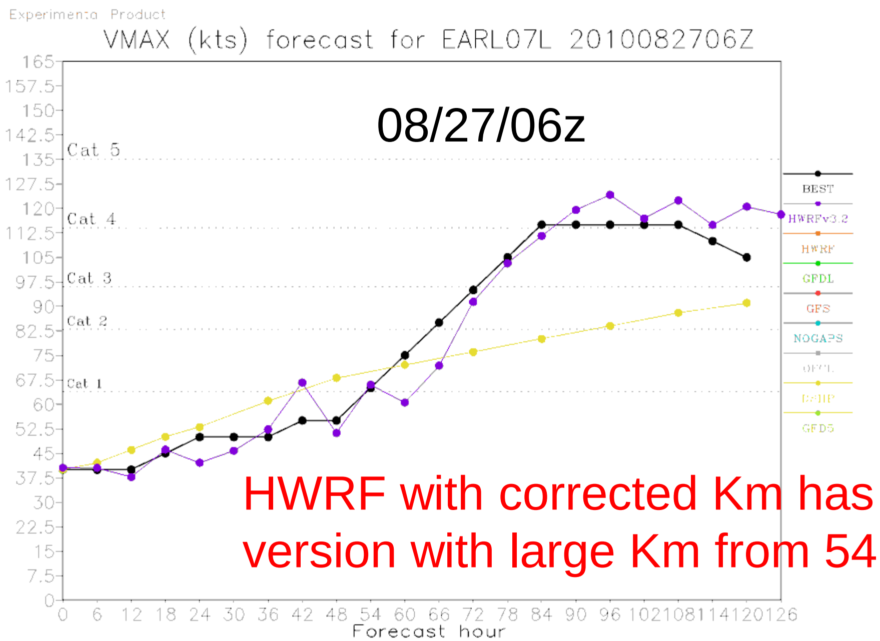


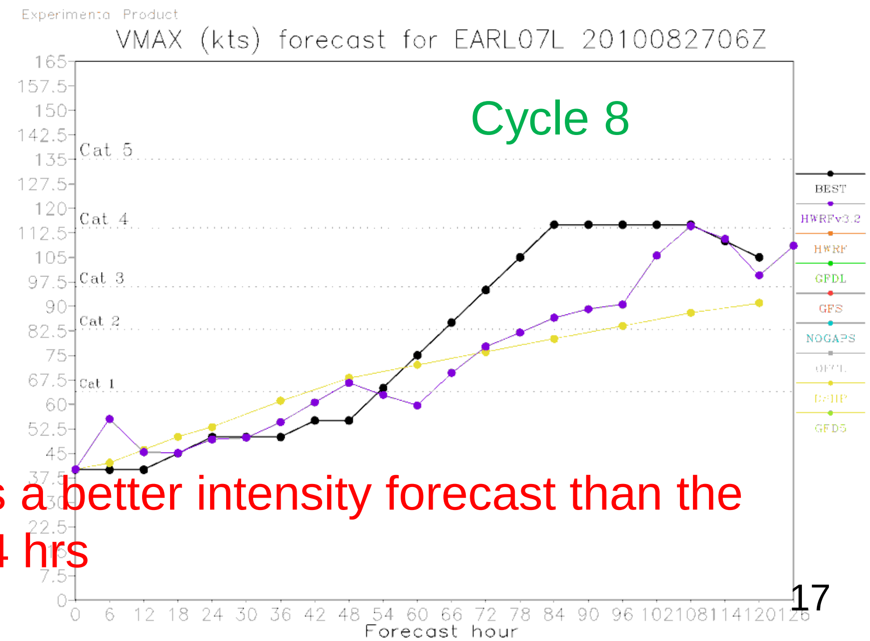
Intensity forecast differs from here on

left : HWRF 2012 — *right :* HWRF with larger Km

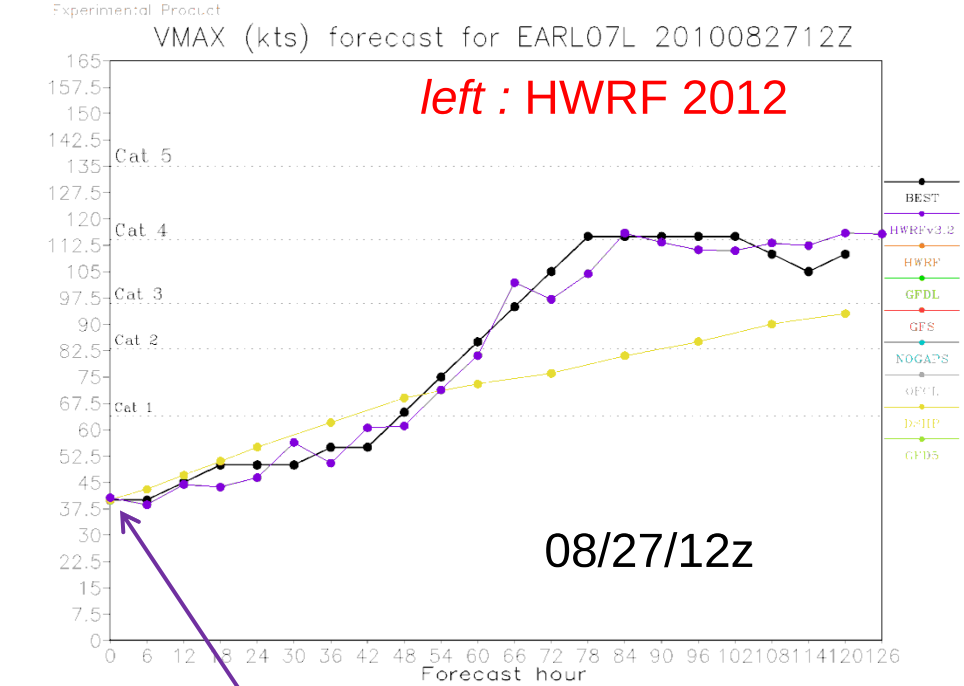


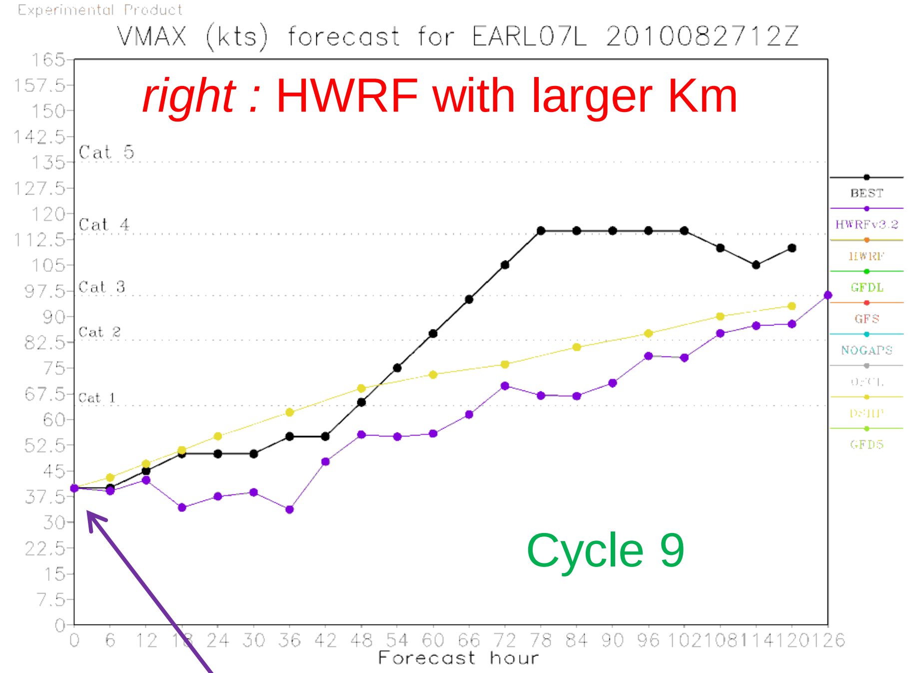




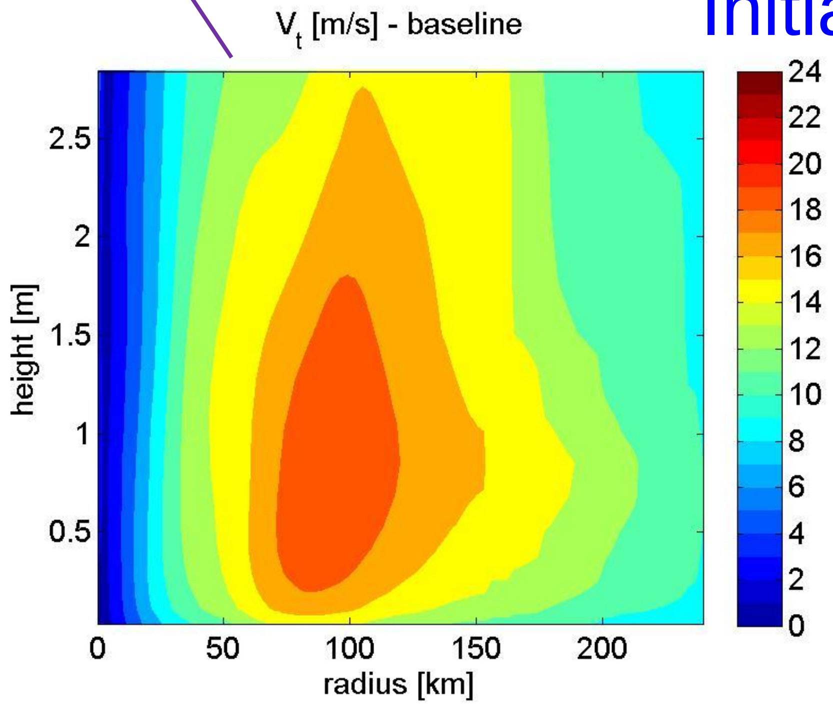


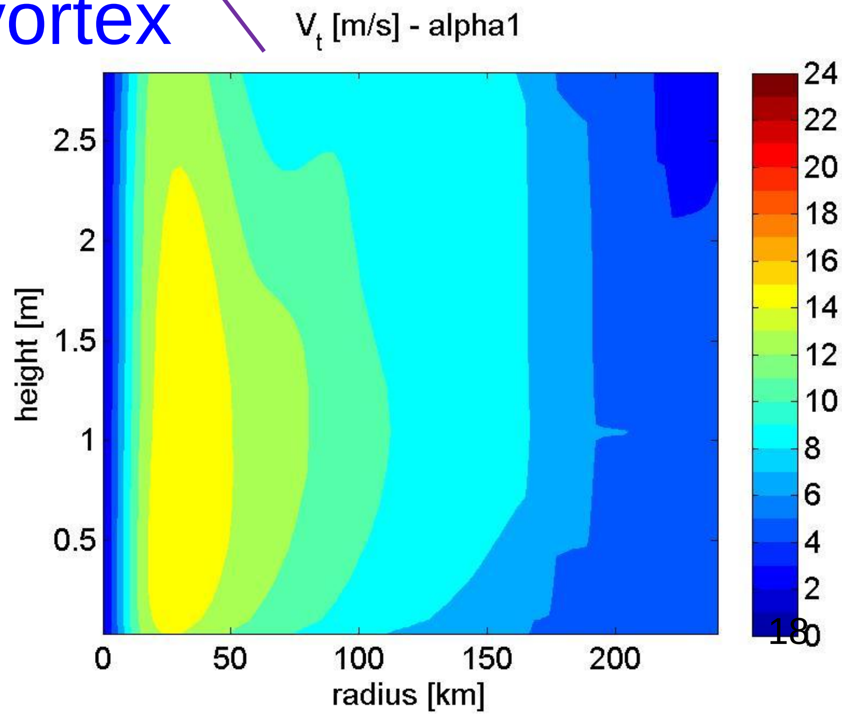
HWRF with corrected Km has a better intensity forecast than the version with large Km from 54 hrs



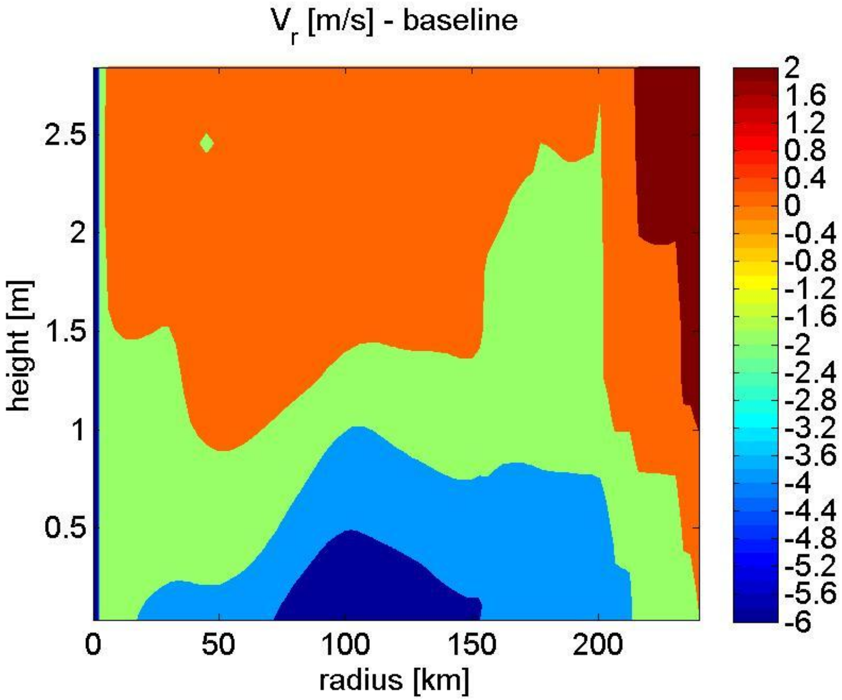


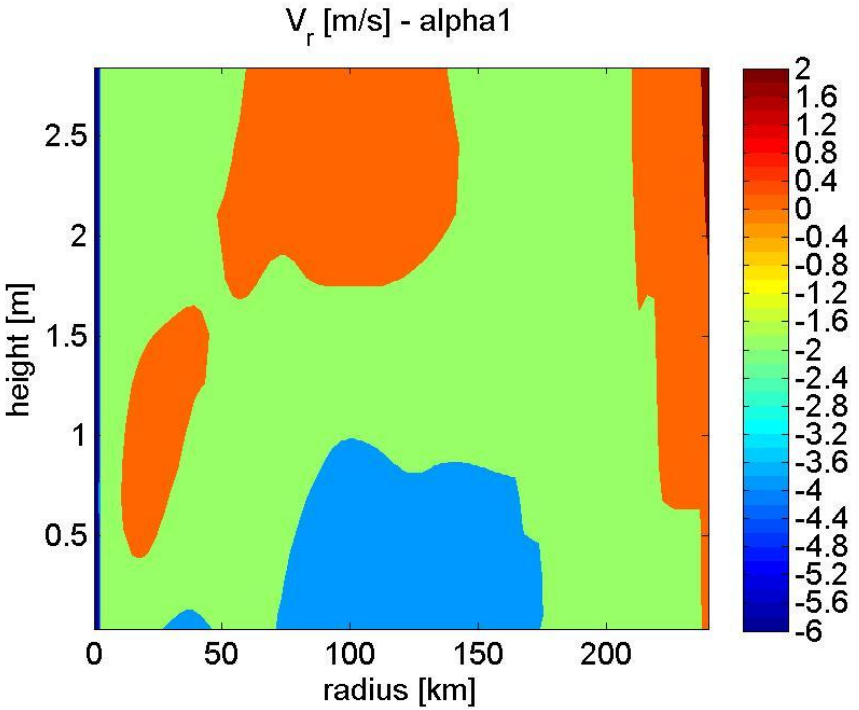
Initial vortex





Initial vortex 2010/08/27/12Z

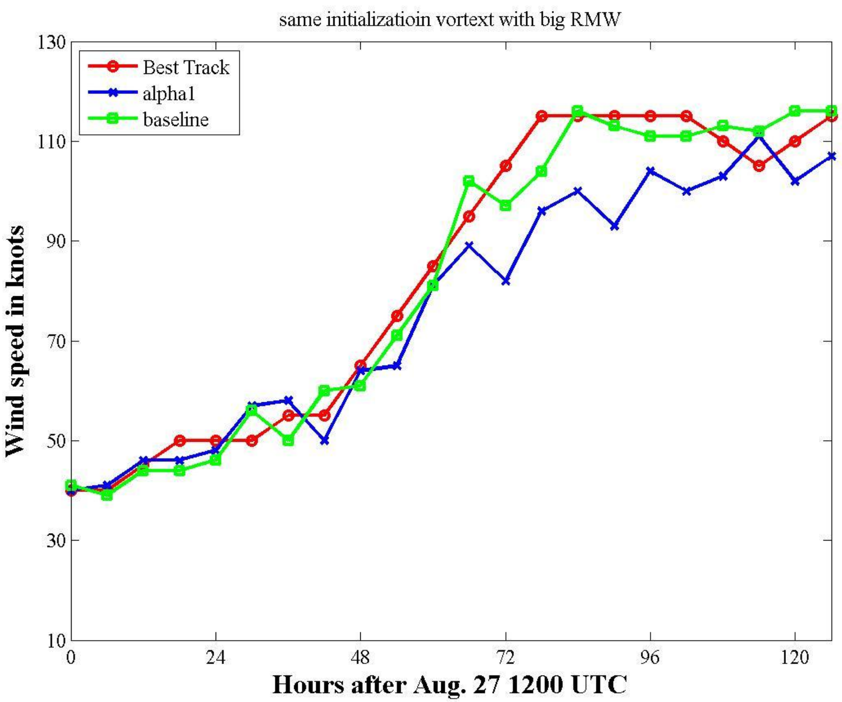


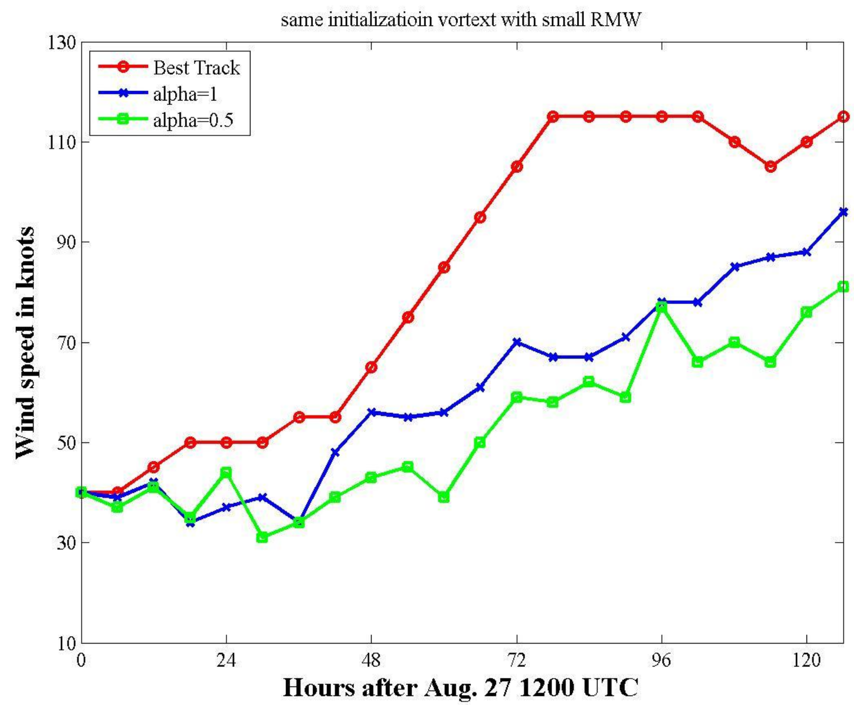


Physics has a strong impact on the initial vortex structure for simulations with cycling;

Although the initial intensities are the same for each cycle, different vortex structures lead to very different intensity forecasts.

Is this a model physics or initialization problem?





Big and strong initial vortex with different physics

Small and weak initial vortex with different physics

$$K_m = k\,(U_*/\Phi_m)\,Z\,\{\alpha(1 - Z/h)^2\}$$

Summary

1. HRD's in-situ aircraft observation data are unique, which provide baseline for physics development and improvement (i.e., vertical diffusivity setup in HWRF), as well as model diagnostics;

2. Is the impact of modified physics in a real-case simulation consistent with that in idealized simulations? Yes.

2. Is the intensity forecast a physics problem or initialization problem? Both.

For a single simulation, initialization may be more important than physics for intensity forecast or vice versa. But improved physics is definitely crucial for intensity forecast with cycling simulations.

Future work

1. More diagnostics

Composite analysis of the model simulations from multi-storms is needed to quantify the impact of modified physics on the simulated structure.

Further investigate how the physics package is connected with the model initialization.

2. Further improve the HWRF PBL scheme, how?

Is the current method for modifying the GFS PBL scheme (MRF scheme) the best one?

$$K_m = k\,(U_*/\Phi_m)\,Z\,\{\alpha(1 - Z/h)^2\}$$

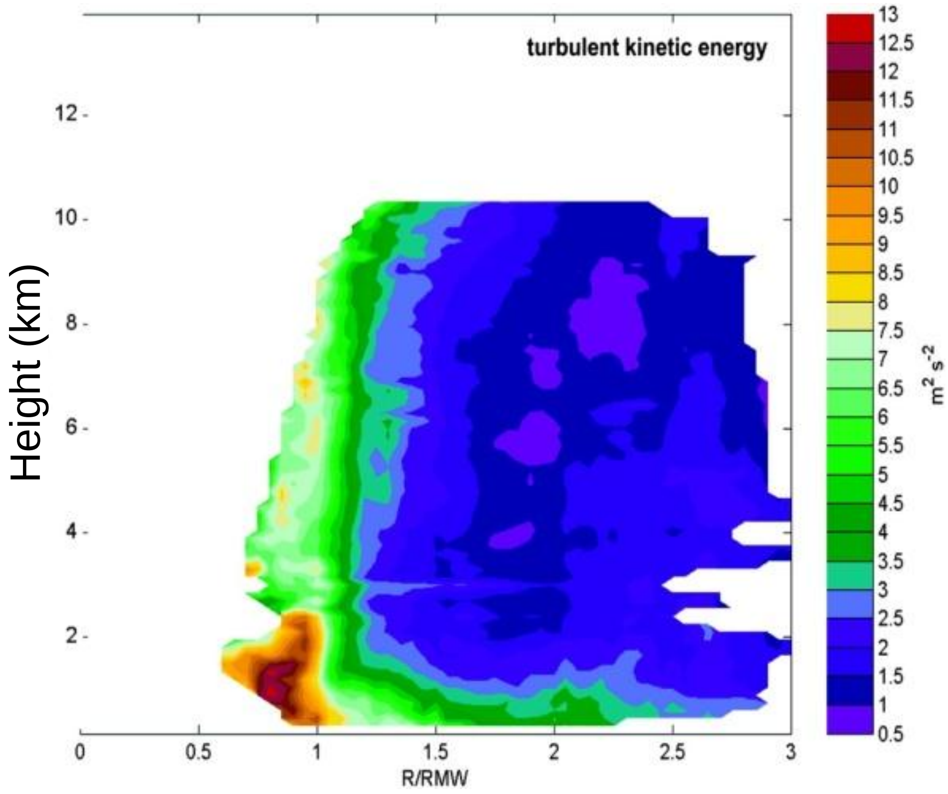
Shall we try a different PBL scheme in HWRF?

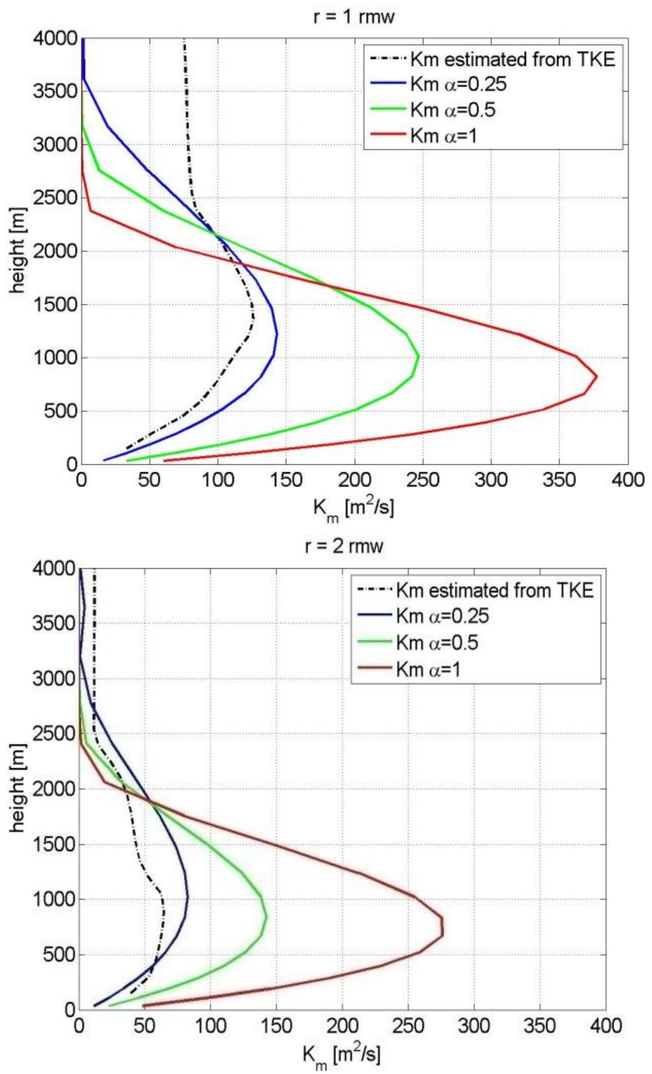
Shall we include parameterization of BL rolls in the GFS scheme?

How about thermodynamic part parameterization of the BL?

Vertical Eddy diffusivity estimated using observed TKE

(Lorsolo, Zhang, Marks, Gamache, 2010)





$$K_m = c\, l\ (TKE)^{1/2}$$

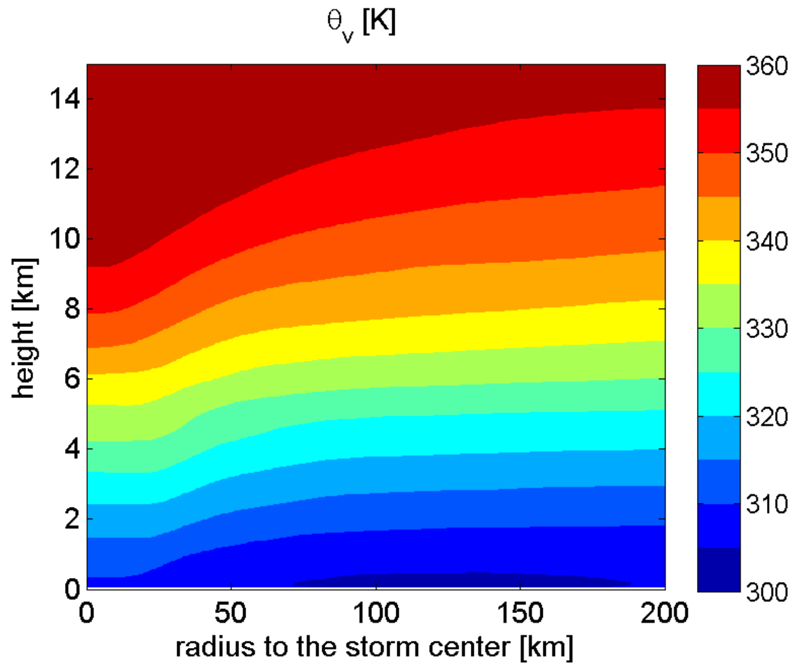
$$c = 0.41$$

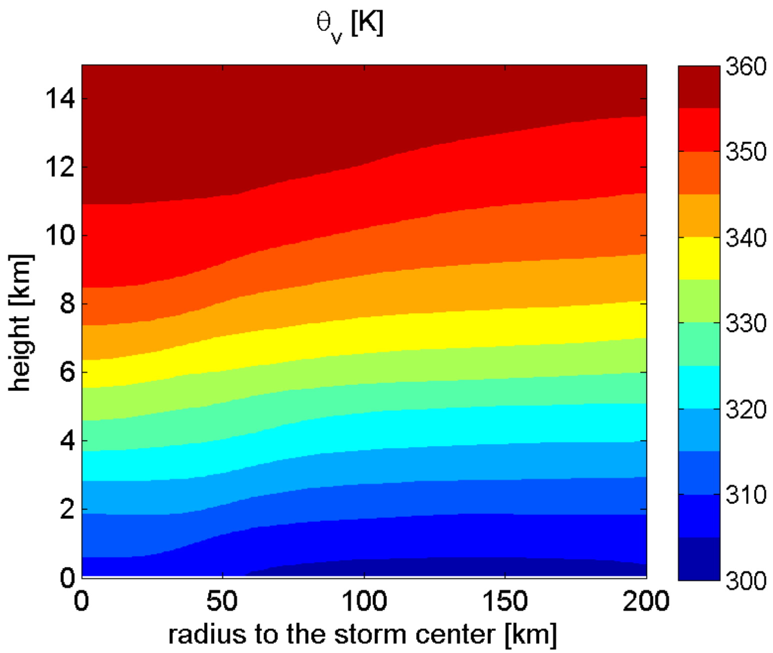
$$\frac{1}{l} = \frac{1}{\kappa z} + \frac{1}{l_\infty}$$

$$l_\infty = 100m$$

Note that this is a rough estimation to be further tested in the future.

Structure comparison

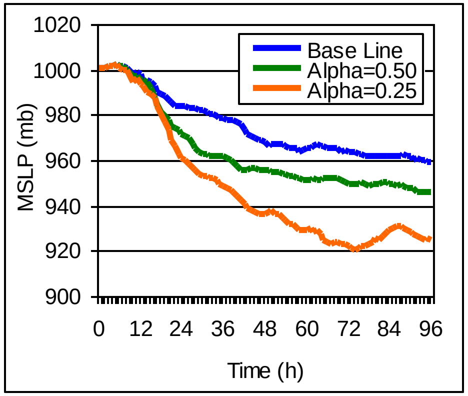


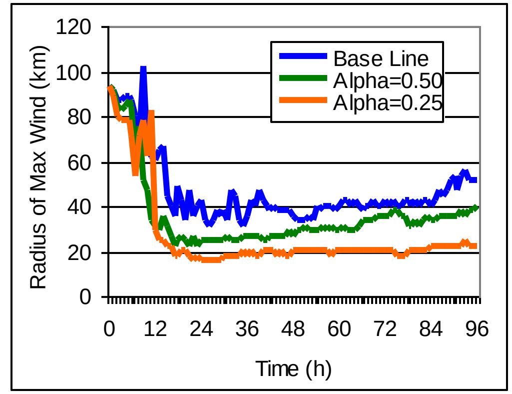


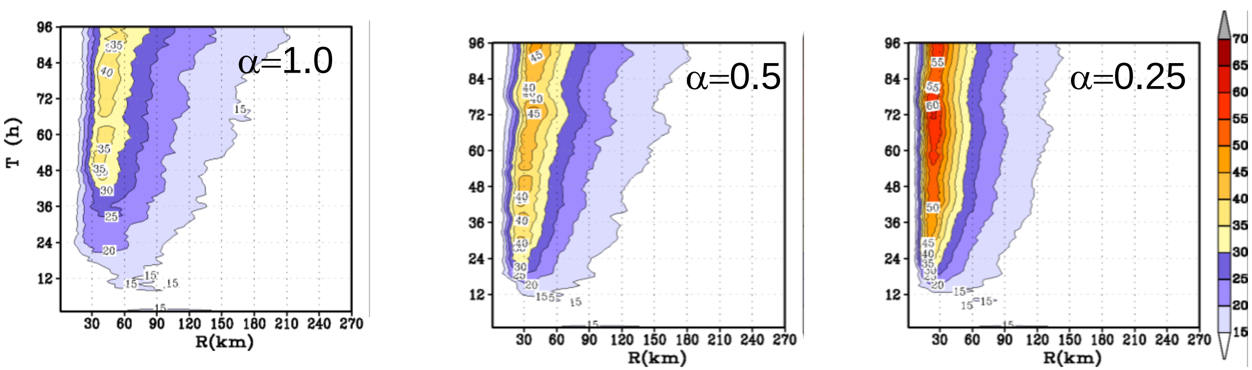
Baseline - operational HWRF
(small vertical eddy diffusivity)

PBL physics using alpha = 1
(large vertical eddy diffusivity)

Influence of Vertical Eddy Diffusivities on Structure and Intensity Predictions



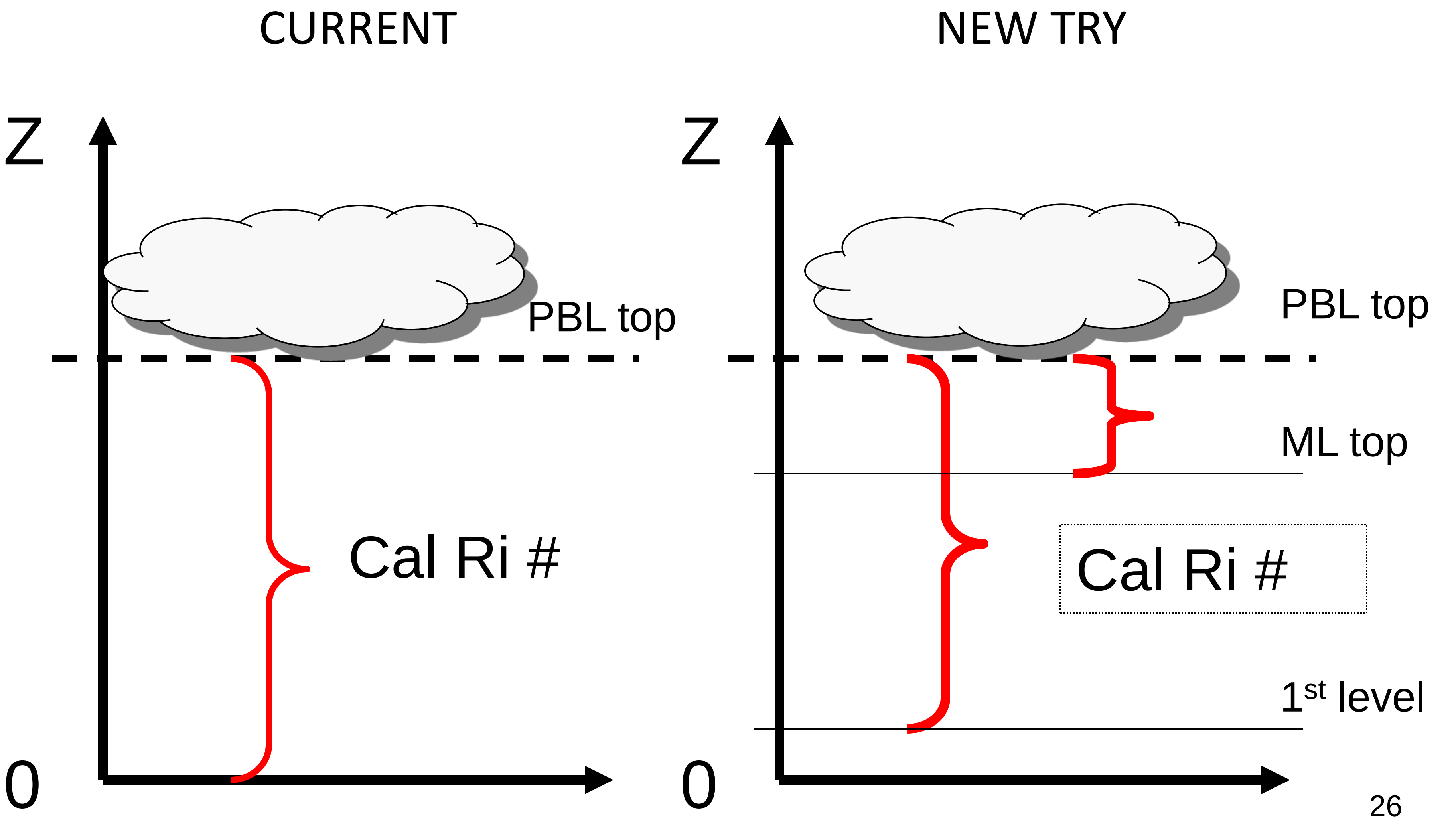




Time history of the intensification process in an idealized storm for the three simulations provided in Table 1: (a) minimum mean sea level pressure in hPa, (b) radius of maximum wind at the first model level; Hovemoller diagram of the axisymmetric mean wind at a height of 10 m for (c) baseline simulation (α=1), (d) Km reduced to half (α=0.50), and (e) Km reduced to a quarter (α=0.25).

Slide Courtesy of Gopal

Try a different way for PBL H

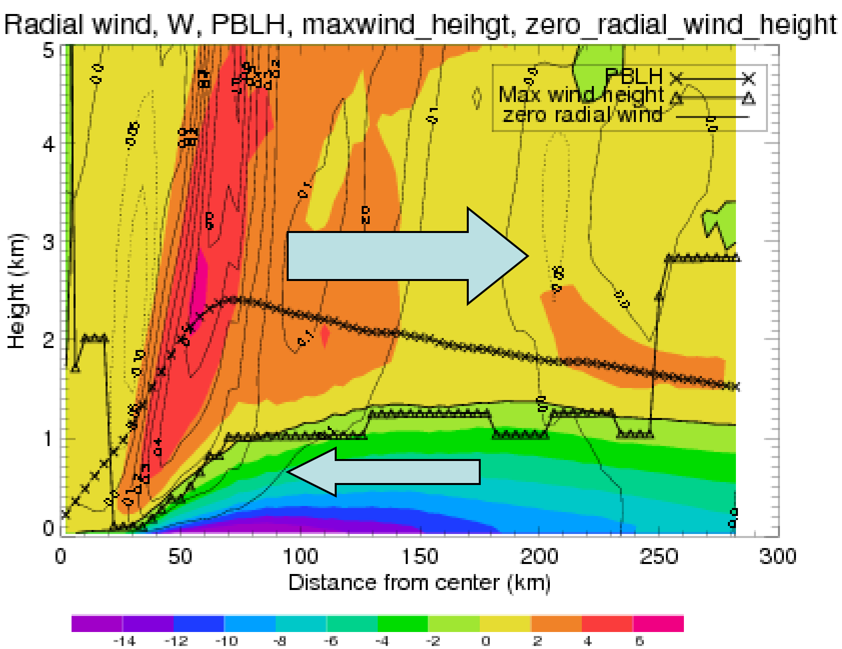


Slide Courtesy of Weiguo Wang and Young Kwon

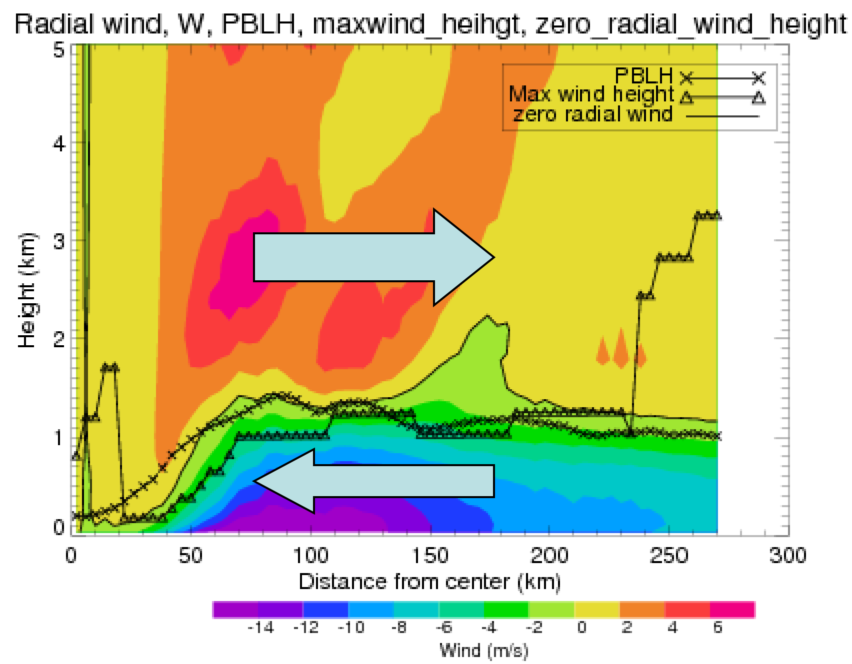
(Secondary circulation)

Radial wind / PBLH / inflow layer / max wind height

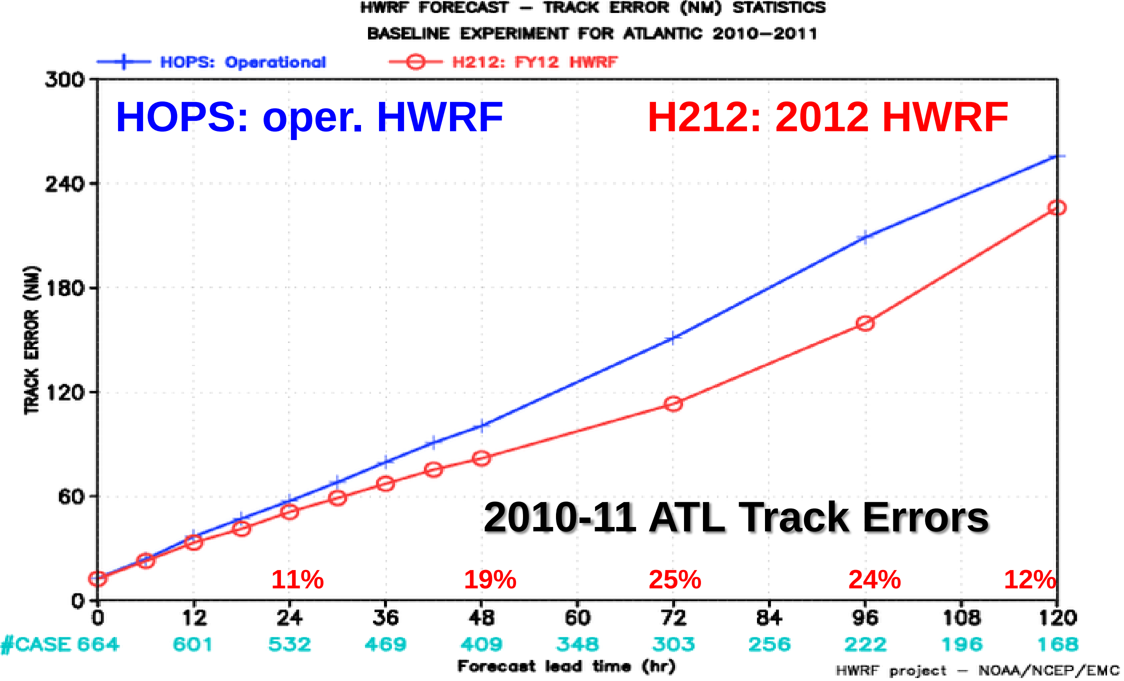
HWRF-OPERATION

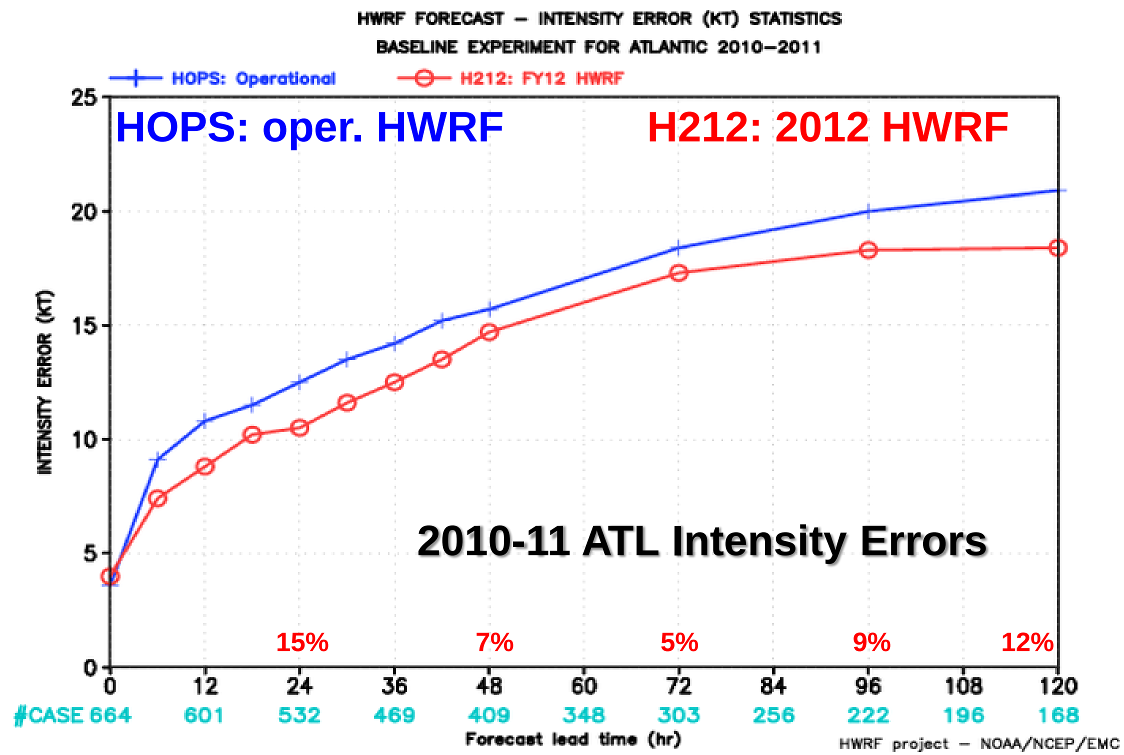


NEW PBL-H



Slide Courtesy of Young Kwon and Weiguo Wang





EMC verification of the 2012 version HWRF model with new surface layer and boundary layer physics and high horizontal resolution (3km)

87% of total retrospective runs from 2010-2011 seasons show 10-25% reduction in track errors and 5-15% reduction in intensity errors

37 Storms

2010: Alex, Two, Bonnie, Colin, Five, Danielle, Earl, Fiona, Gaston, Hermine, Igor, Karl, Matthew, Nicole, Otto, Paul Richard, Shary, Tomas

2011: Arlene, Bret, Cindy, Don, Emily, Franklin, Gert, Harvey, Irene, Ten, Lee, Katia, Maria, Nate, Philippe, Rina, Sean

Slide Courtesy to Vijay Tallapradada (HWRF team leader)