A Developmental Framework for Improving Hurricane Model Physics using Aircraft Observations

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Acknowledgement

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HRD HWRF modeling team, especially

Gopal, Xuejin Zhang

EMC HWRF modeling team, especially

Vijay Tallapradada, Zhan Zhang, Weiguo Wang, Sergio Abarca, Lin Zhu

Other collaborators and coauthors:

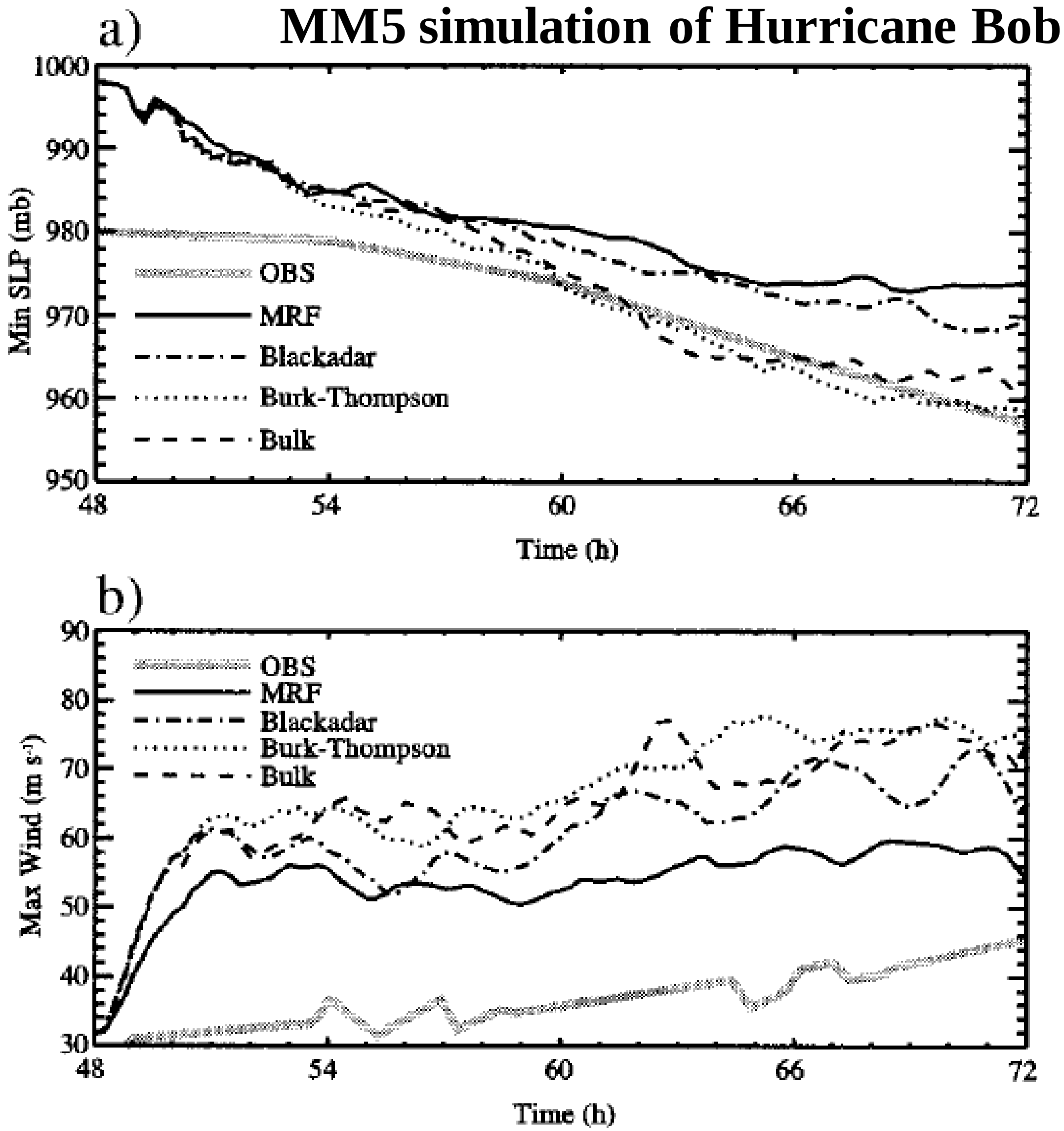
Frank Marks, Robert Rogers, Jason Sippel, David Nolan, Michael Montgomery, Ping Zhu, Bryce Tyner, George Bryan

Outline

- Background and Objectives
- Previous work on improving HWRF physics (Ck, Km) using aircraft observations (R2O)
- Recent and ongoing research on the impact of other aspects of model physics in HWRF on TC forecasts
- Summary and future work

Why is model physics important for hurricane prediction?

MM5 simulation of Hurricane Bob (1991)



(Braun and Tao, 2000)

Sensitivity to boundary-layer parameterization

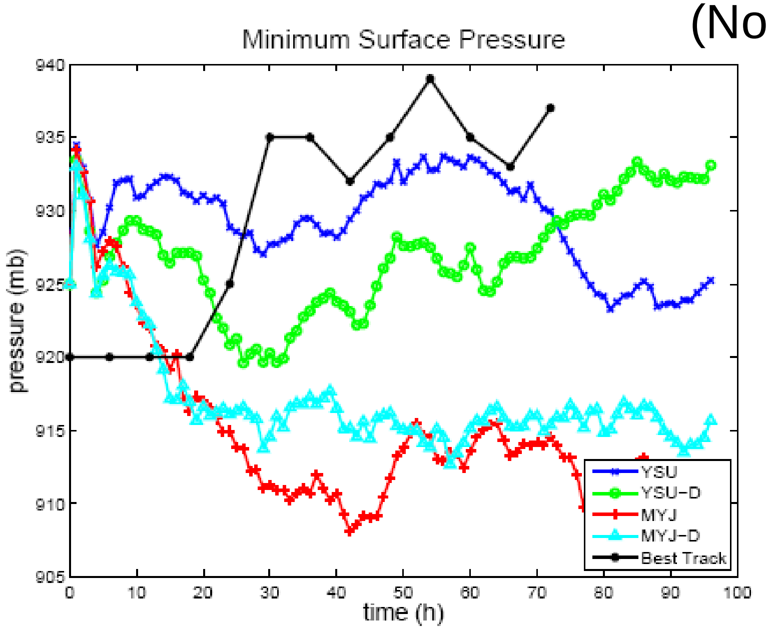
➔ **Skillful prediction of intensity change requires an accurate representation of the boundary layer and parameterization of surface fluxes.**

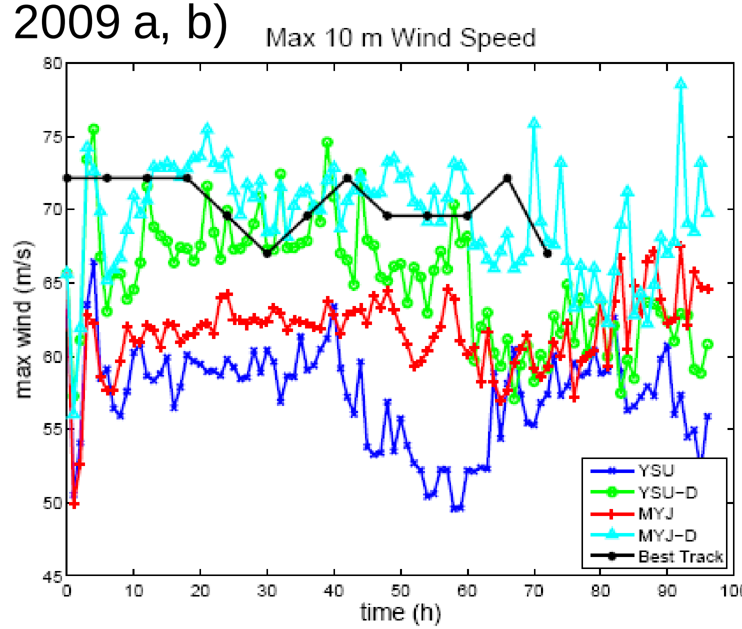
Why is model physics important for hurricane prediction?

- One of the primary goals of this work is the direct comparison of the WRF-simulated bounday layers with in-situ observations at approximately the same time and place

The choice of PBL scheme has a large effect on maximum wind speed and the wind-pressure relationship: WRF simulations of Hurricane Isabel (2003)

(Nolan et al. 2009 a, b)

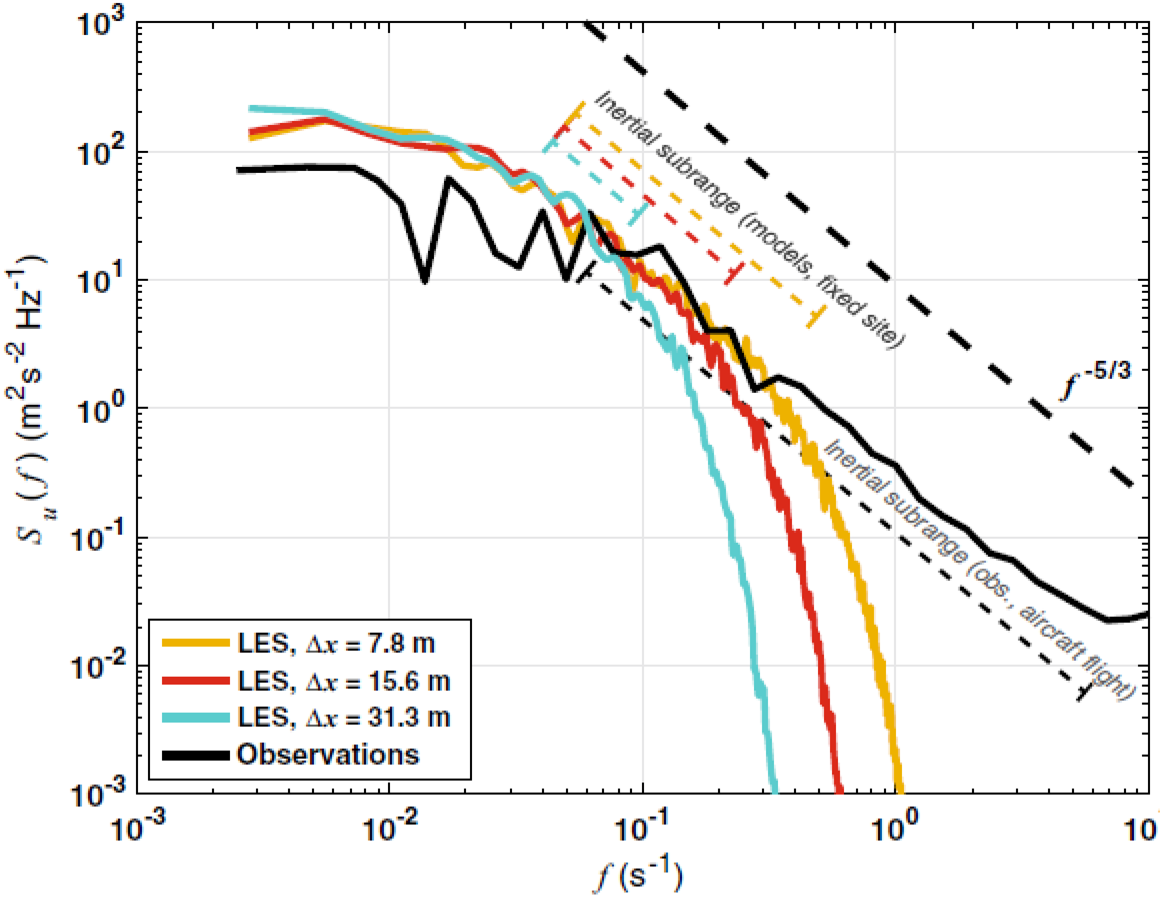




Above, YSU and MYJ refer to the boundary layer parameterizations that come with WRF 2.2. The "-D" appendage refers to codes that have been modified so that the roughness length as a function of wind speed has been changed from the Charnok (1955) formula to one that closely follows the experimental results of Donelan et al. (2004), which stops increasing around 35 m/s. These results and those that follow are for triply nested simulations with 1.33 km resolution in the inner nest.

Why sub-grid scale physical processes need to be parameterized in hurricane prediction models?

(Bryan et al. 2017 BLM)



Observation from Jun Zhang et al. (2009 JAS)

Projects funded by NOAA's Hurricane Forecast and Improvement Project (HFIP)

Objectives:

•To increase usefulness of observations in improving high-resolution hurricane modeling systems (e.g., HWRF) .

•To develop advanced model diagnostic techniques to support model physics improvements and identification of sources of model errors.

A developmental framework for improving hurricane model physics (Jun Zhang et al. 2012, TCRR)

1. Model diagnostics against observations

2. Development of new physics using observations

3. Observation-based model physics upgrade

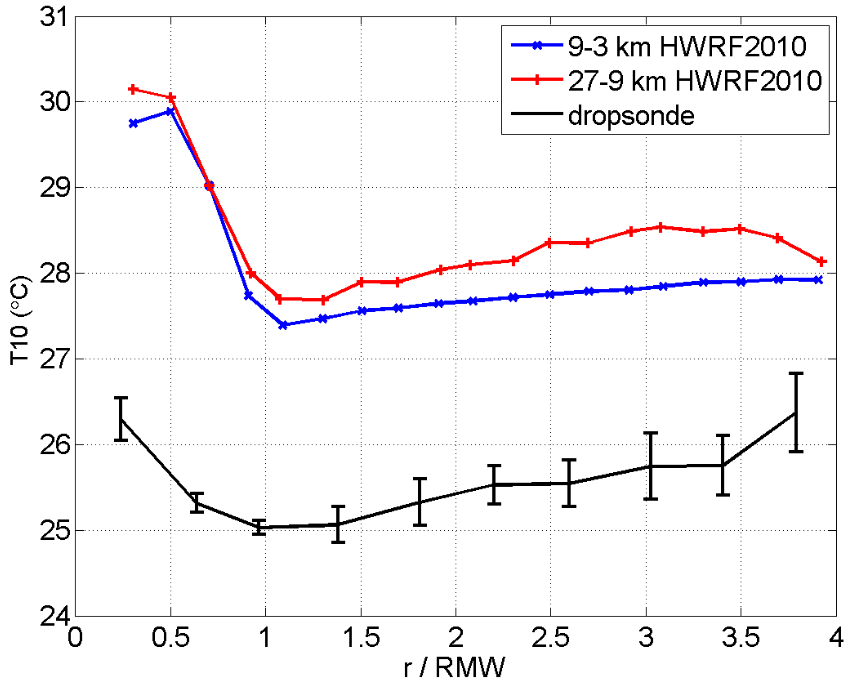
4. Evaluation of the Impact of physics upgrade

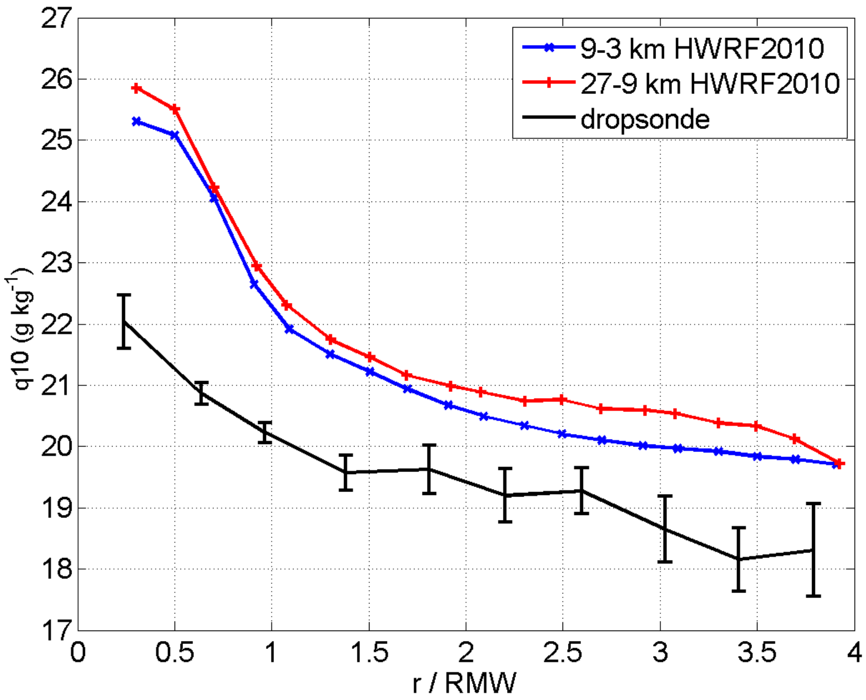
(1) *Develop advanced model diagnostics to identify model deficiency and errors through comparison with observations*

Surface-layer structure diagnostics

Model simulations are from HFIP HRH Test with **2010 version** HWRF (9 storms, 69 runs)

Observational data are from hundreds of GPS dropsondes (Jun Zhang et al. 2011a MWR)

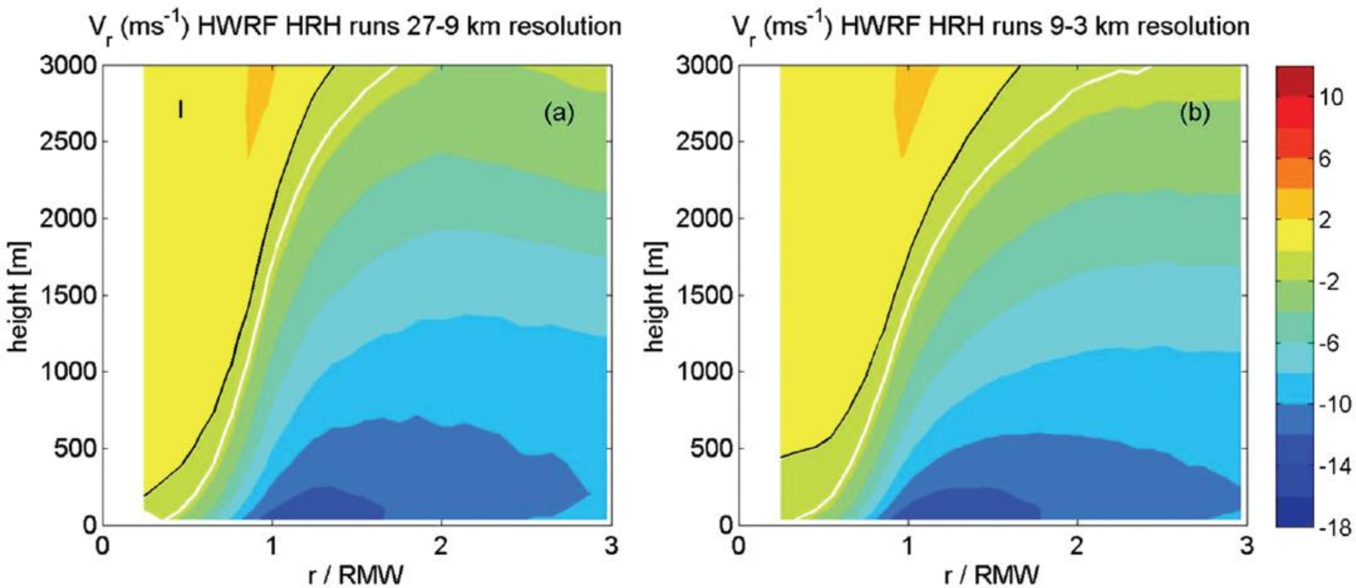


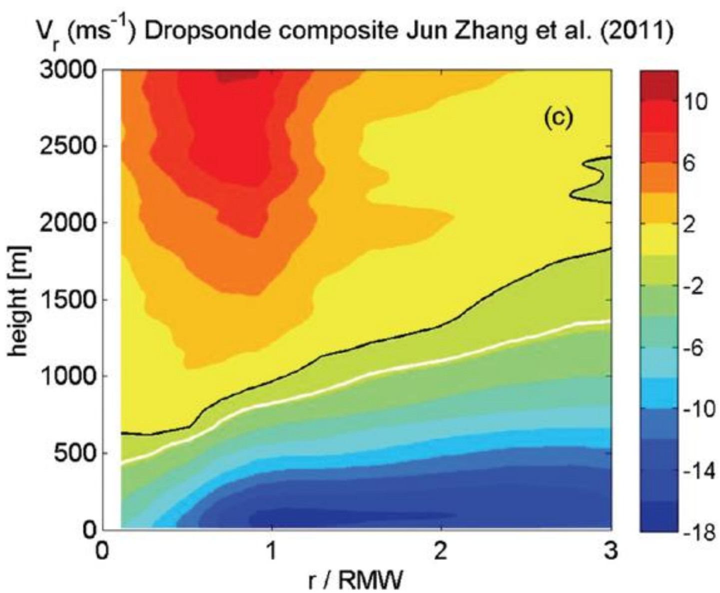


The simulated surface layer is too warm and too moist compared to observations.

Boundary-layer structure diagnostics

Model: 2010 version HWRF





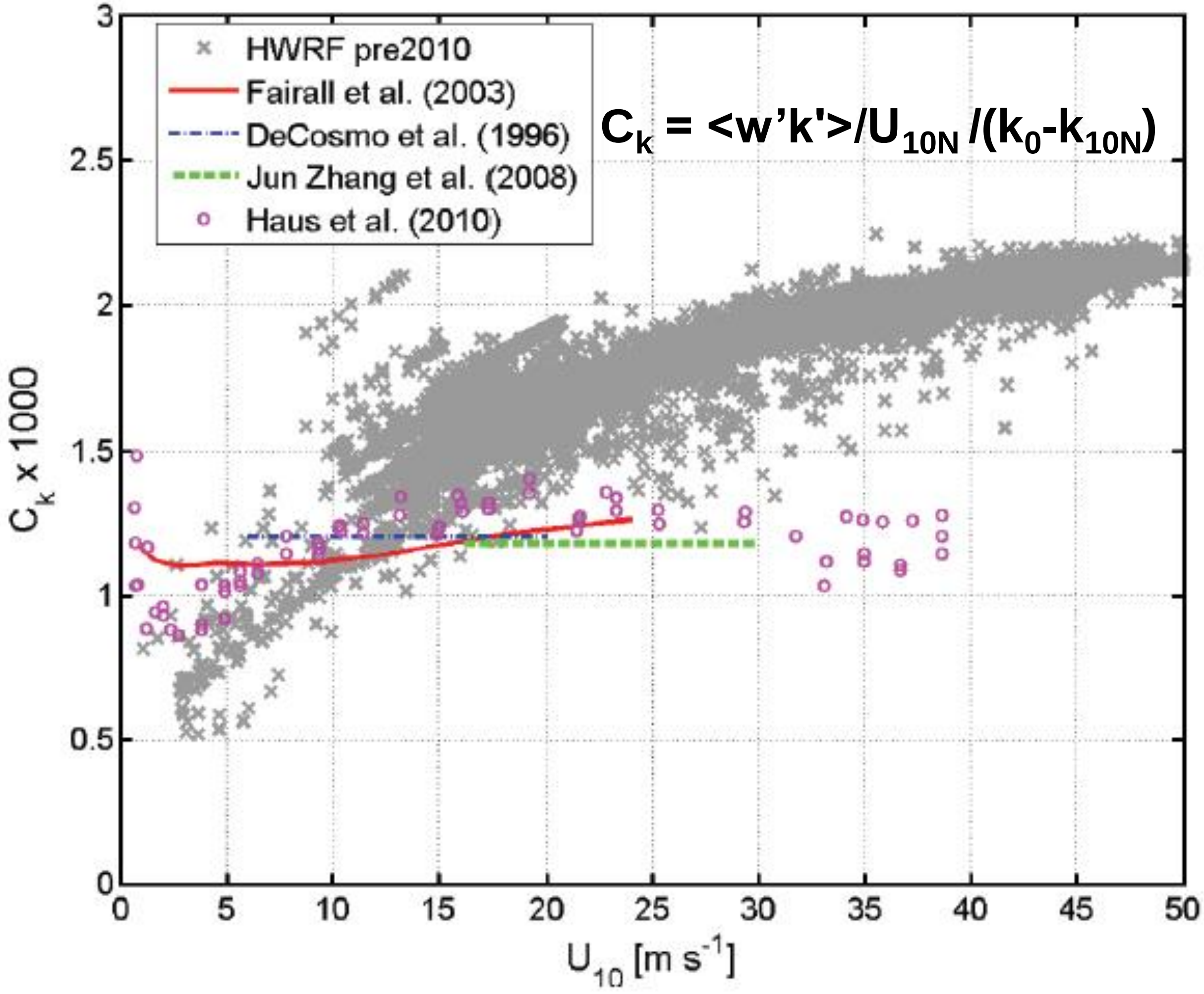
Simulated boundary layer is too deep compared to observations!

(Jun Zhang et al. 2012, TCRR)

(2) *Identify deficiency of the surface layer and boundary layer schemes*

This is based on development of new model physics using observations.

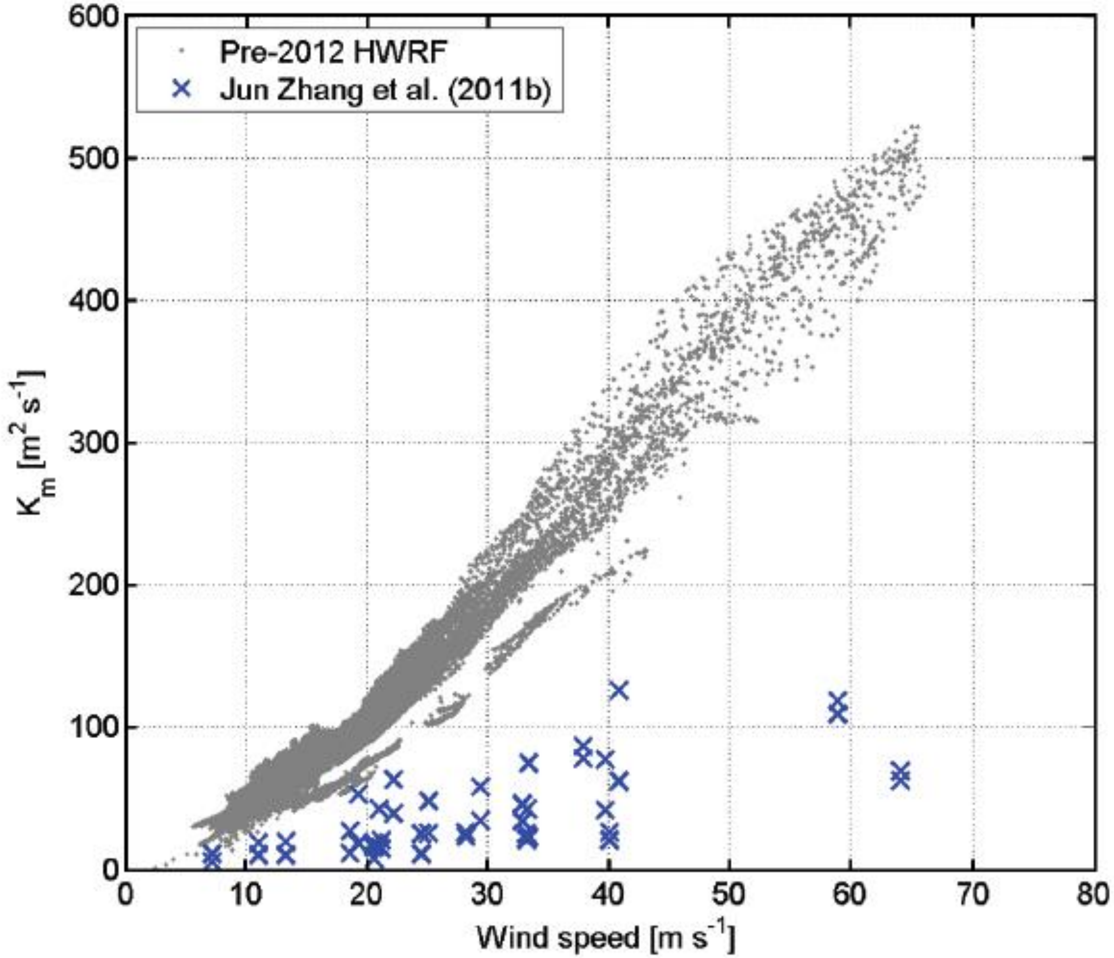
Why is the simulated surface layer too warm and moist?



Surface enthalpy exchange coefficients (C_k) in prior 2011 version HWRF are too large!

Why is the simulated boundary layer so deep?

Observational data are from Hurricanes Allen (1980) and Hugo (1989)



$$\tau = \rho(-\overline{w'v_t'}\,\hat{i} - \overline{w'v_r'}\,\hat{j})$$

$$K_m = |\tau|\left(\frac{\partial V}{\partial z}\right)^{-1}$$

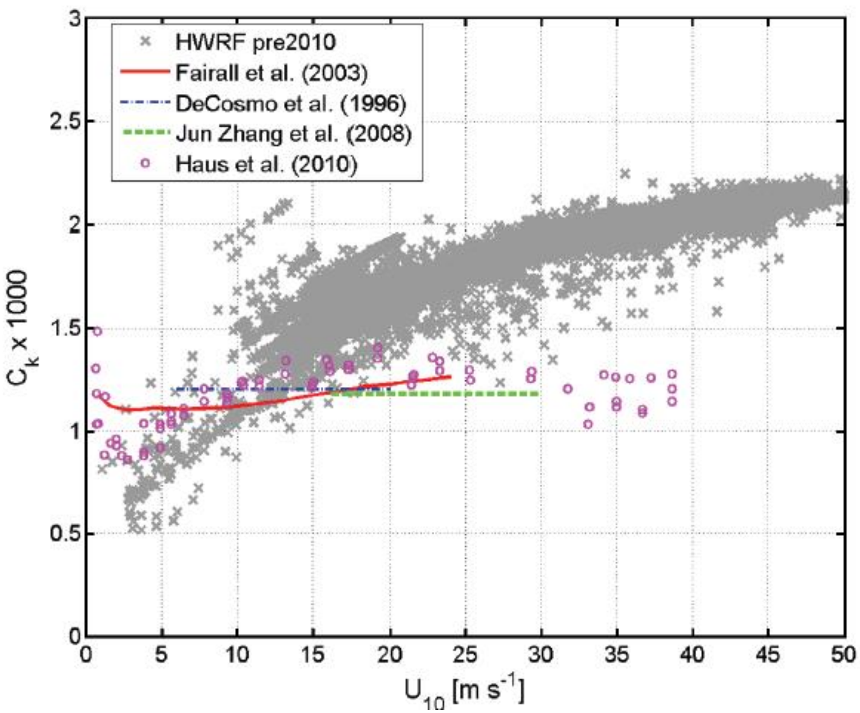
Vertical eddy viscosity or diffusivity

The PBL scheme used in prior 2012 version HWRF is too diffusive!

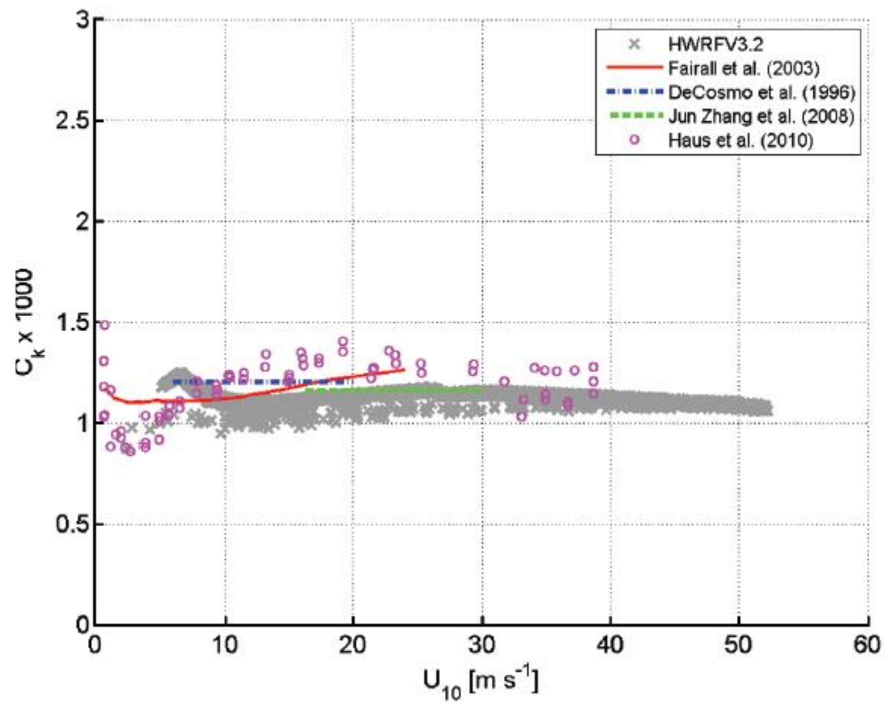
(3) *Work with model developers to improve model physics based on observations*

Implementation of observation-based physics in HWRF

Pre 2010 HWRF



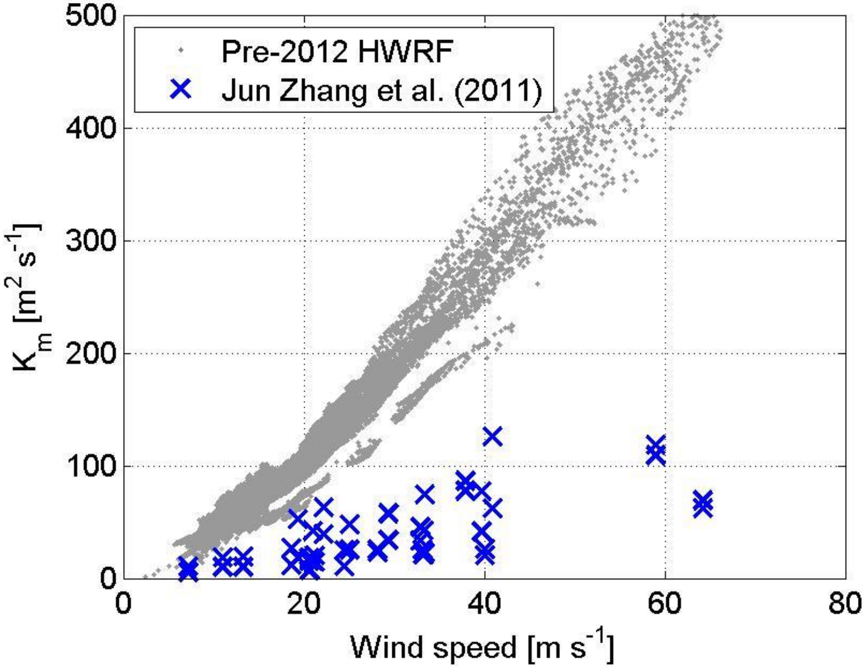
2010 HWRF and thereafter



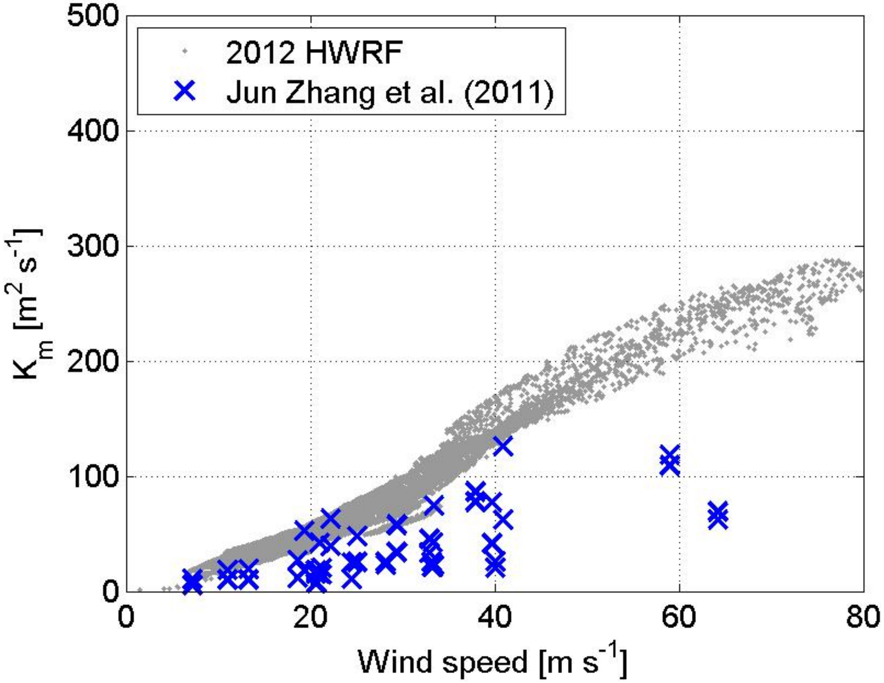
Thanks to Young Kwon and Bob Tuleya who modified the HWRF code!

Use observations to improve PBL physics in the operational hurricane HWRF

(Jun Zhang et al. 2012; Gopal et al. 2013)



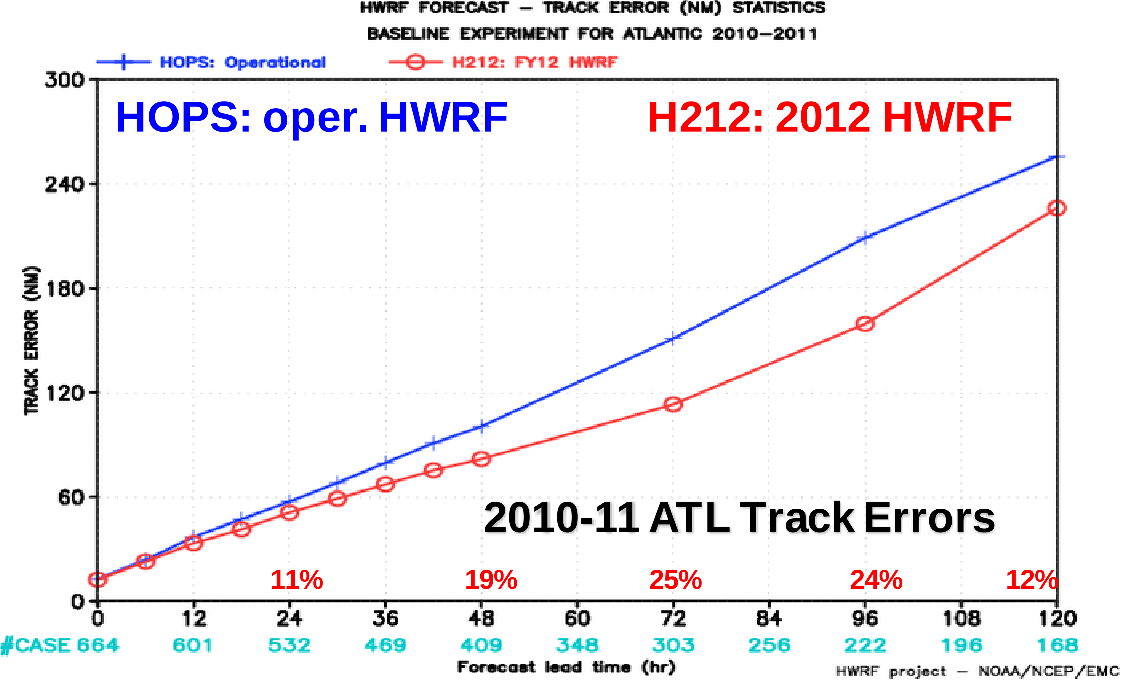
Before modification

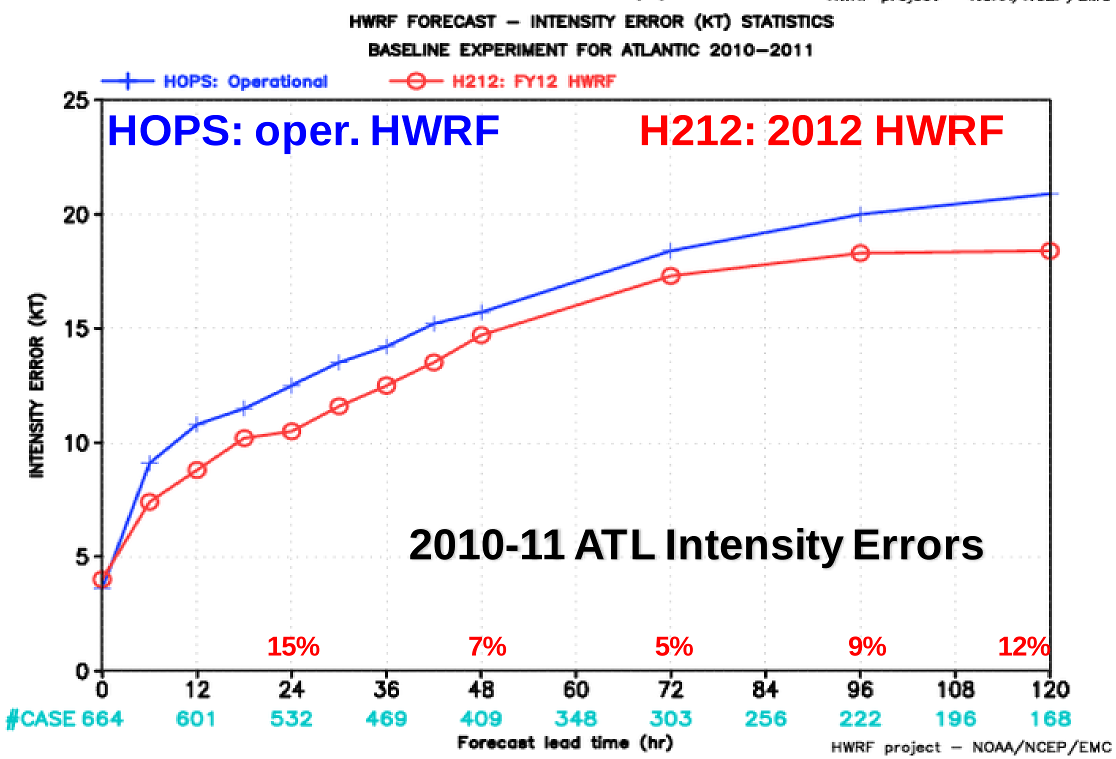


After modification

Thanks to Gopal who modified the HWRF code!

(4) *Evaluation of the impacts of observation-based physics on simulated storm structure and intensity forecast*





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

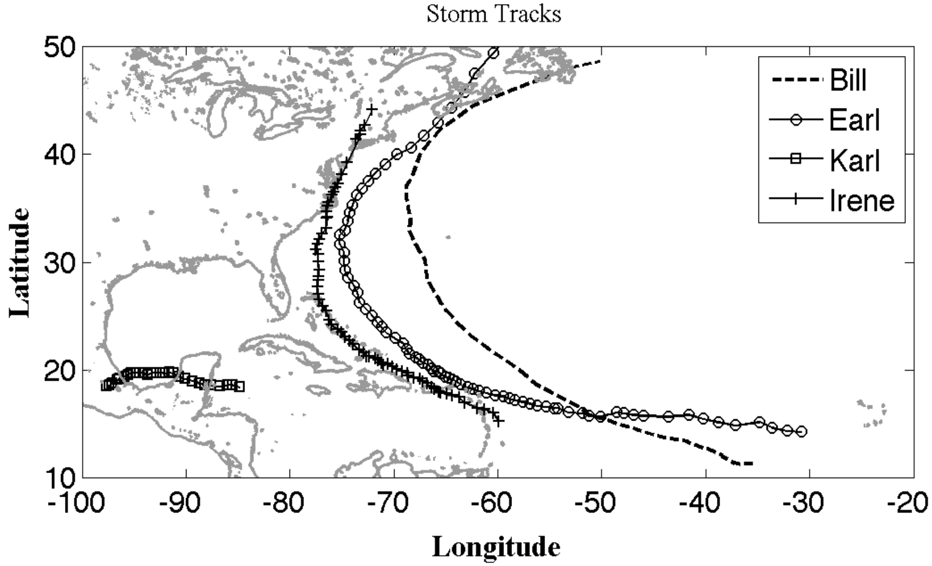
37 Storms

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

(Vijay Tallapradada et al. 2014)

Evaluation of the impact of physics upgrade
A clean experiment



Two sets of HWRF simulations of four hurricanes (PBL11 vs PBL12)

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

$\alpha = 1$ in PBL11

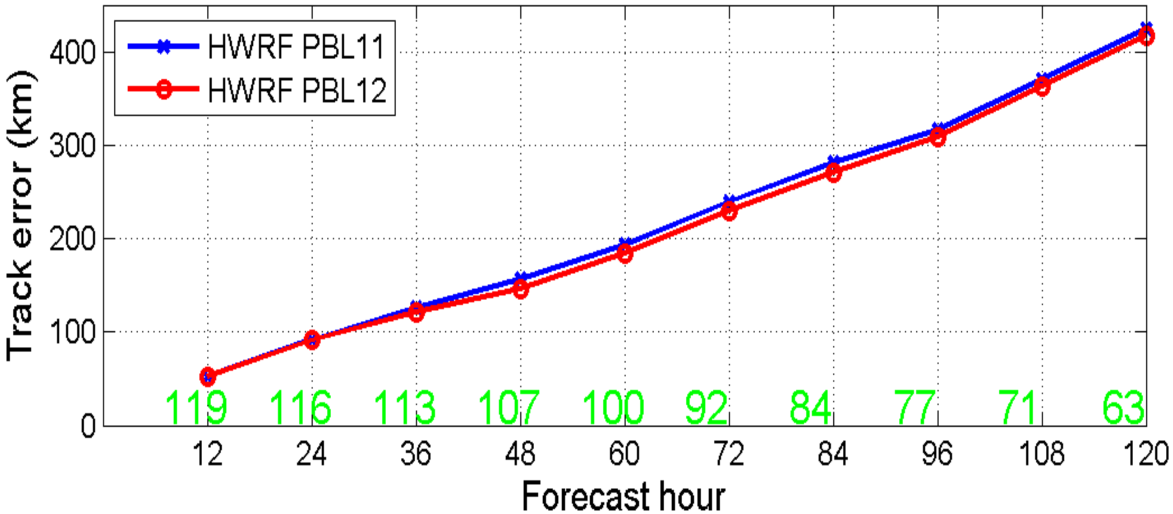
$\alpha = 0.5$ in PBL12

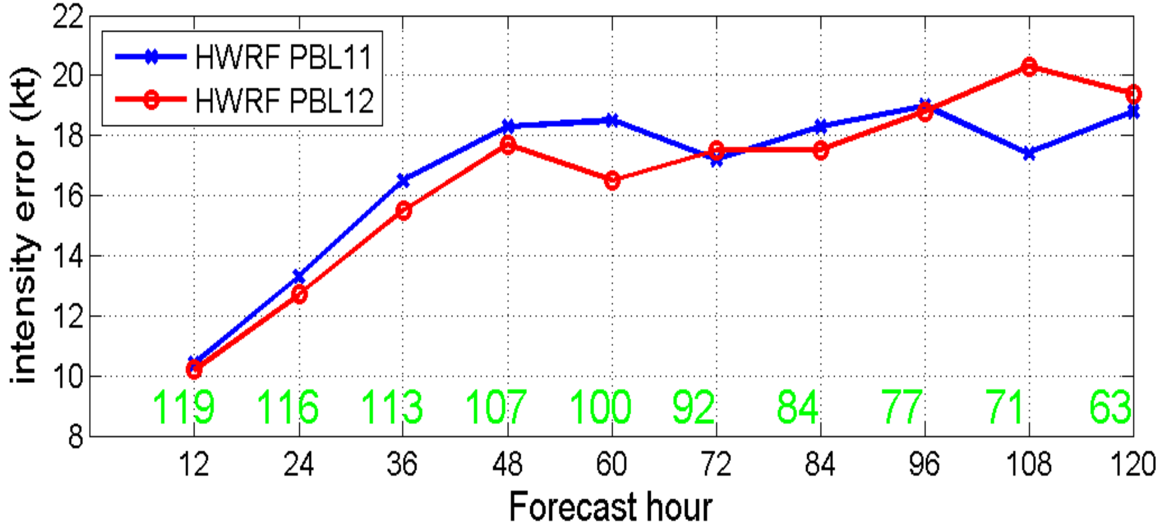
Storm name	Number of cycles of simulations	Starting time of the first cycle	Starting time of the last cycle
Bill	33	2009/08/15/18Z	2009/08/23/18Z
Earl	40	2010/08/25/18Z	2010/09/04/12Z
Karl	15	2010/09/14/18Z	2010/09/18/06Z
Irene	34	2011/08/20/18Z	2011/08/29/00Z

Thanks to Young Kwon who created the HWRF retrospective runs!

Further Evaluation: Improved Track and Intensity Forecasts based HWRF Retrospective Runs

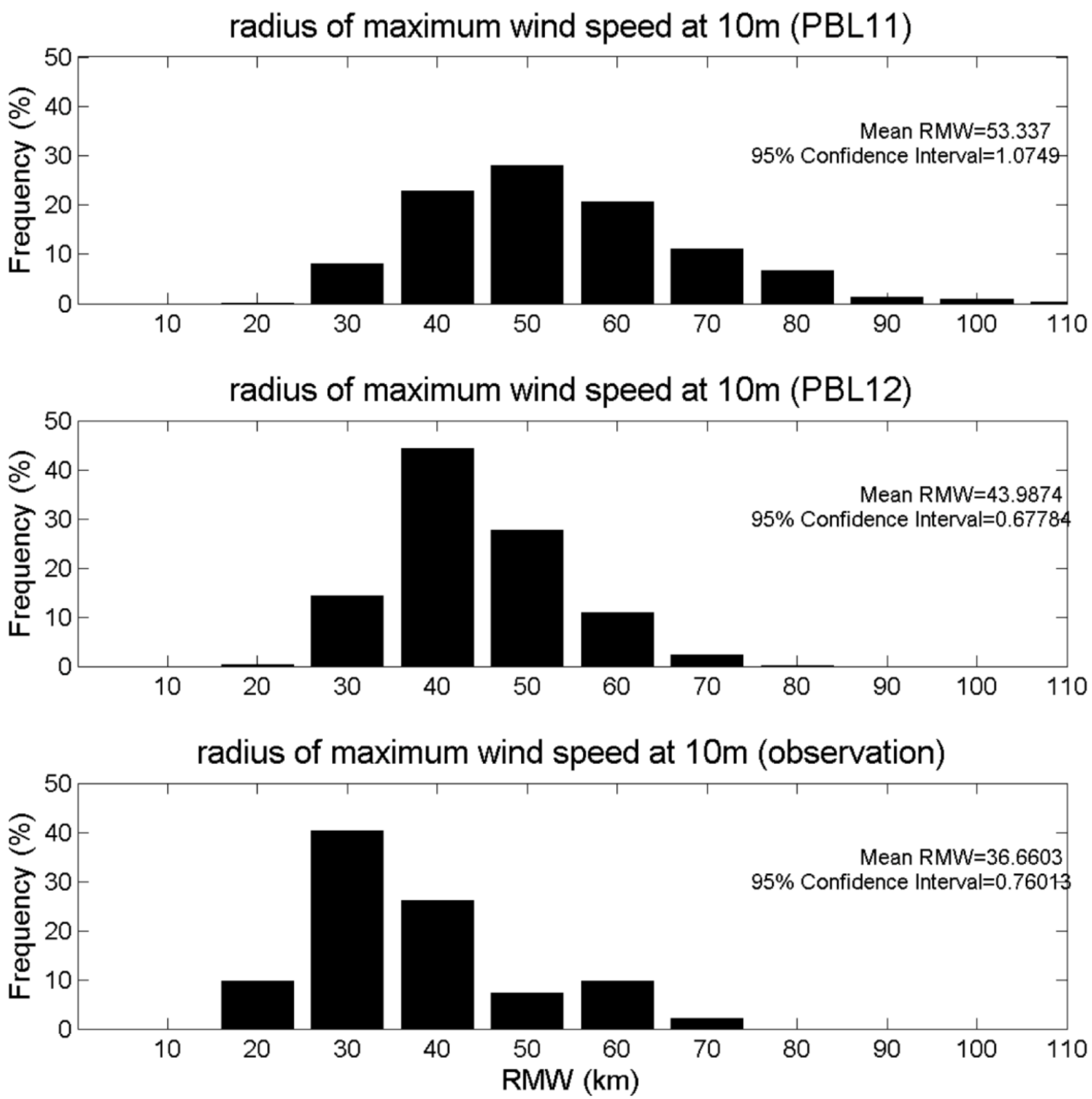
(J. Zhang, Nolan, Rogers, Tallagragada, 2015 MWR)





Further Evaluation: Improved Hurricane Structure

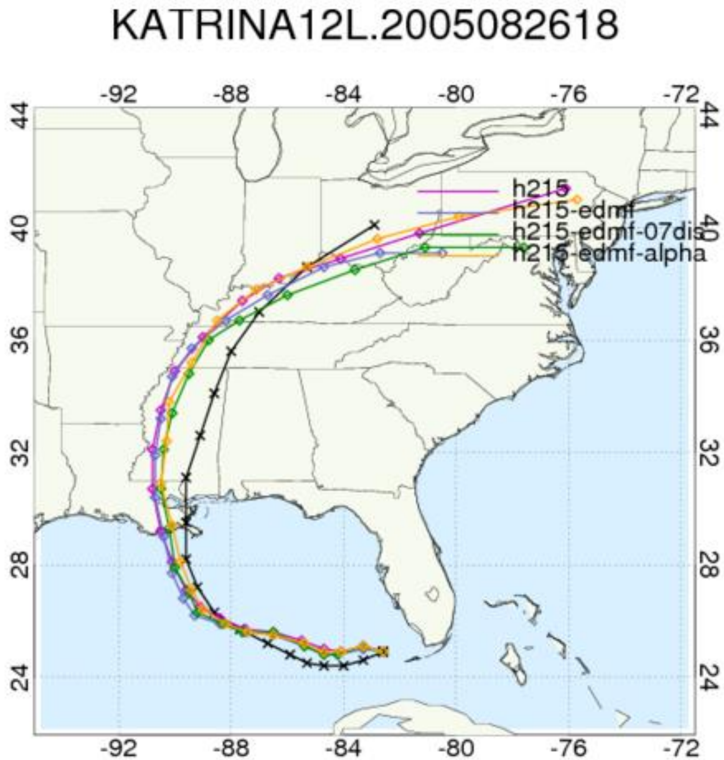
(Jun Zhang et al. 2015 MWR)

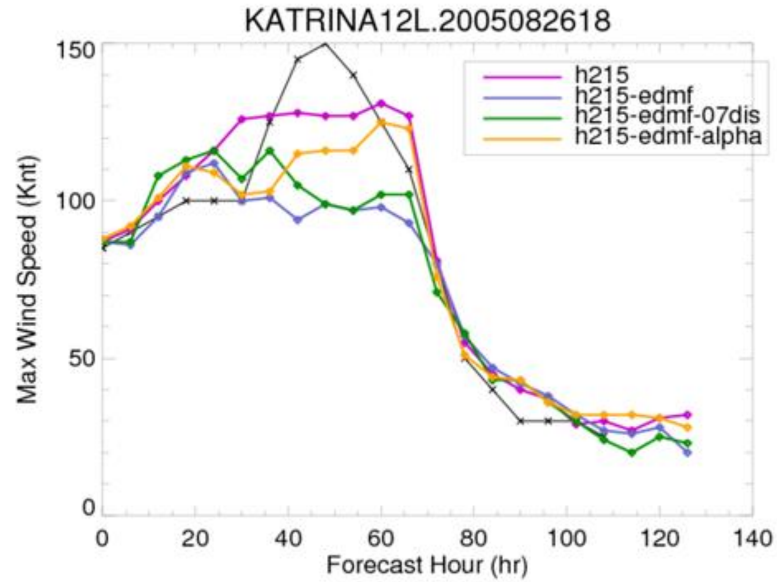


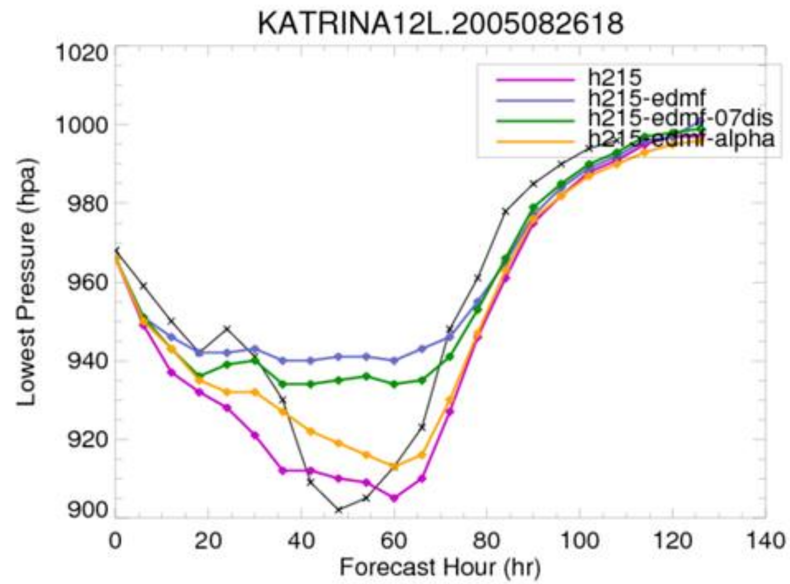
Recent HWRF upgrades based on the above-mentioned physics improvement framework

1. Implementation of EDMF PBL scheme in H215.
2. Modification of horizontal diffusion parameterization in H216.

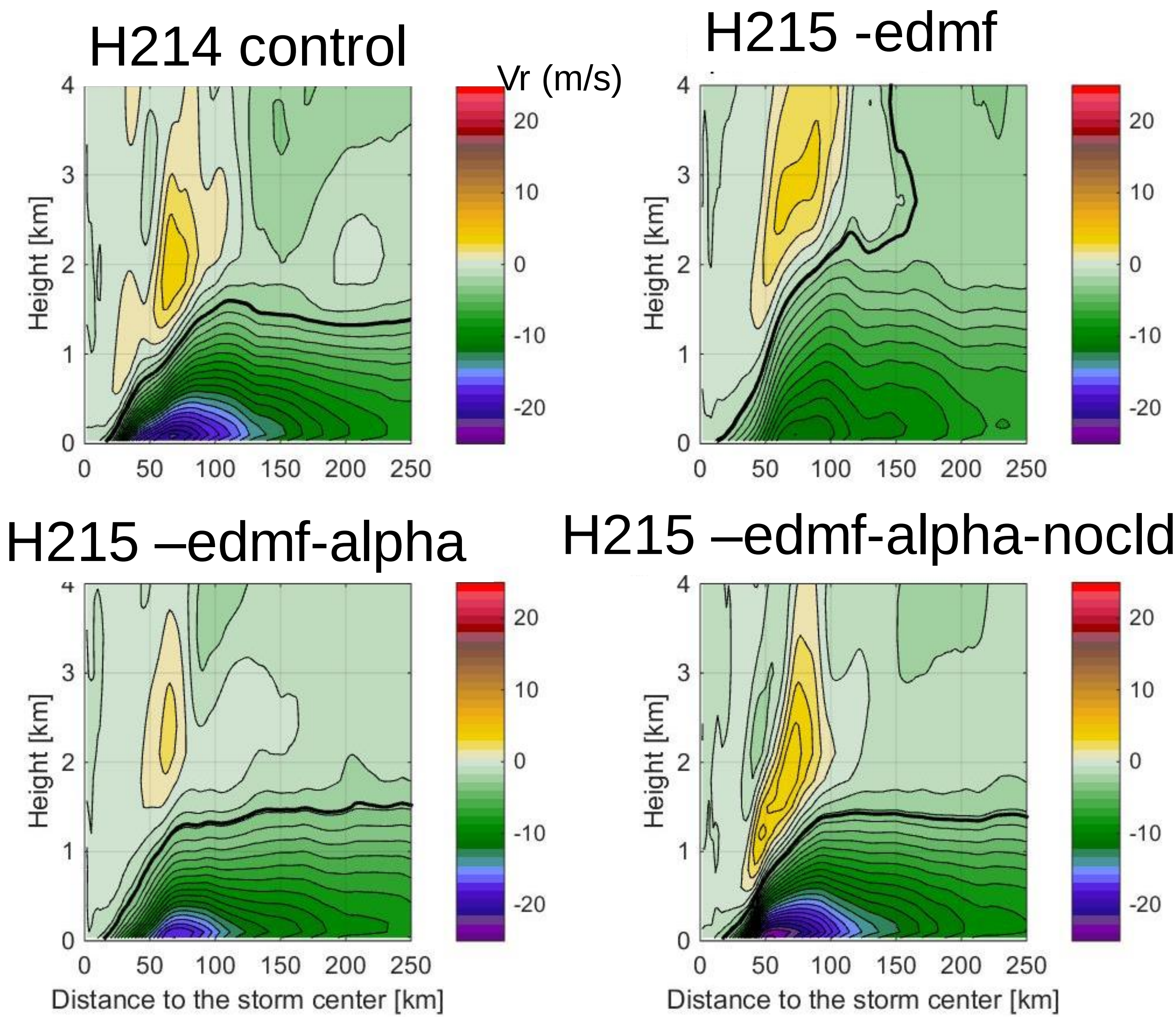
Using the alpha method to improve the EDMF PBL scheme in H215

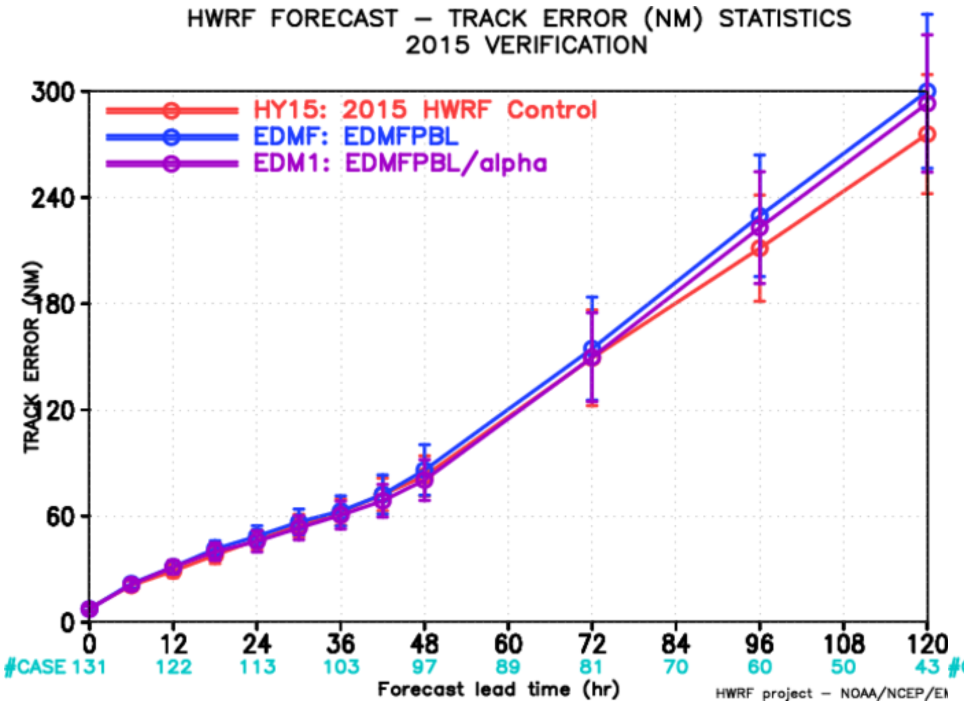


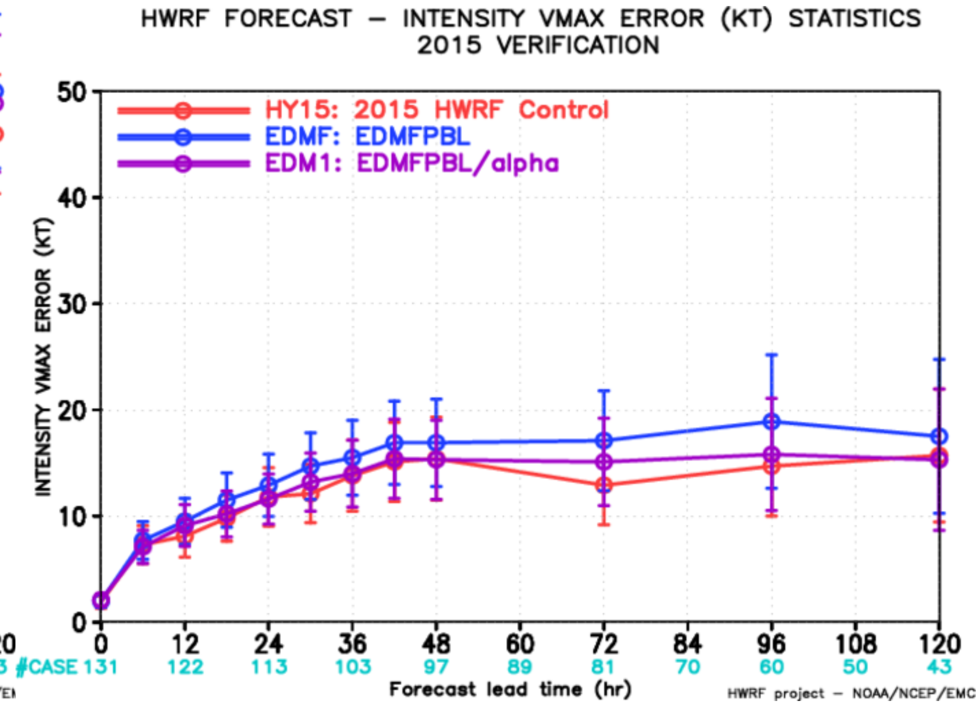


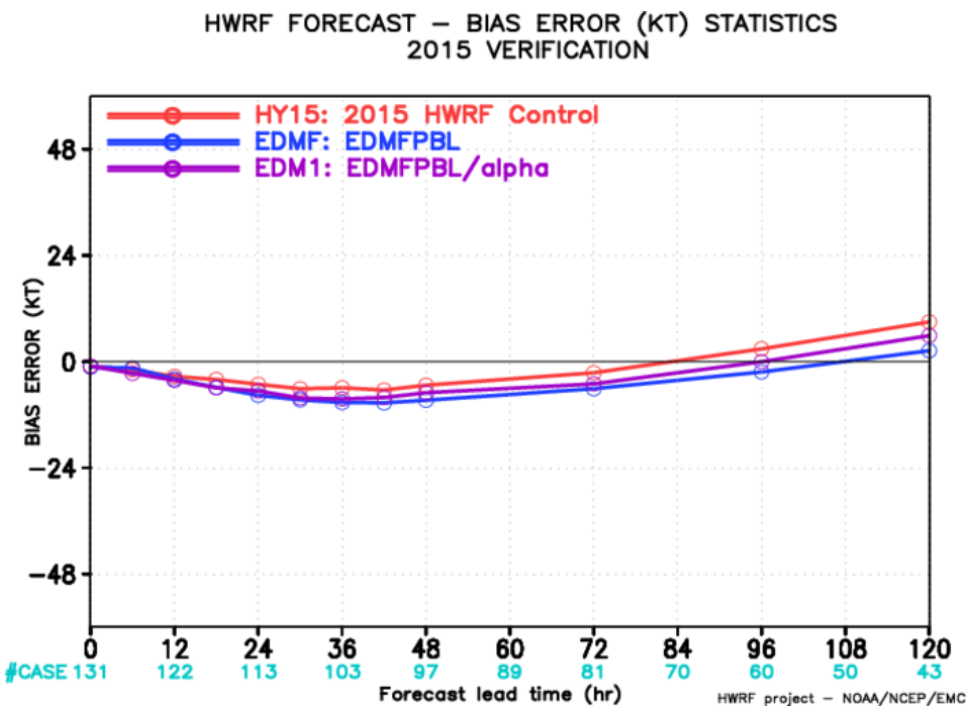


Thanks to Weiguo Wang (EMC)


H214 control
Vr (m/s)
H215 -edmf
H215 –edmf-alpha
H215 –edmf-alpha-nocld
Height [km]
Distance to the storm center [km]
0
50
100
150
200
250
0
1
2
3
4
20
10
0
-10
-20







ATL verification

Track: similar < 48hr
EDMF/1 degrade d > 72hr
Intensity: EDM1 better than EDMF
Similar to HY15 < 48hr

Thanks to Weiguo Wang and EMC colleagues!

Horizontal diffusion in HWRF

For the horizontal diffusion, the NMM uses a 2nd order, nonlinear Smagorinsky-type parameterization (Janjic 1990). The diffusion has the form:

$$\frac{\partial V}{\partial t} = \nabla \cdot (K_m \nabla V), \quad \frac{\partial H}{\partial t} = \nabla \cdot (K_h \nabla H). \qquad (9.1.1)$$

Here V and H stand for any ***v*** point or *h* point variable, respectively. In the NMM, the exchange coefficient K is flow dependant:

$$K_m = C d_{\min} |\Delta|, \qquad (9.1.2)$$

Here K_m is horizontal eddy diffusivity

where C is a constant, $d_{\min}$ is the minimum grid distance and Δ is proportional to the horizontal deformation, which in the NMM is modified by the presence of turbulent kinetic energy (Janjic 1990):

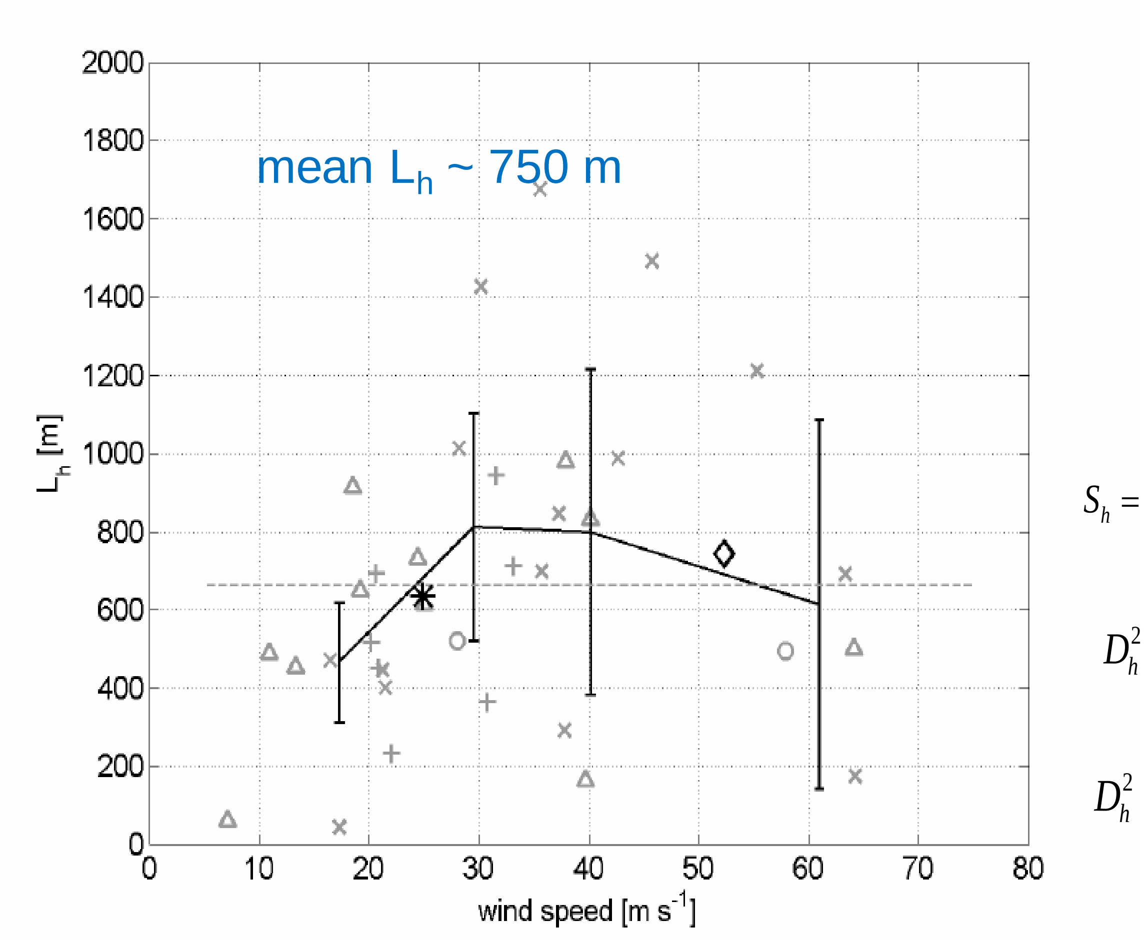
$$|\Delta| = \left[2\left(\Delta_x u - \Delta_y v\right)^2 + 2\left(\Delta_y u + \Delta_x v\right)^2 + 2\left(\Delta_x w\right)^2 + 2\left(\Delta_y w\right)^2 + \cancelto{\sim 0}{2C'' \frac{q^2}{2}} \right]^{1/2}.$$

$$L_h = (K_m / |\Delta|)^{1/2}$$

L_h is the horizontal mixing length

Horizontal mixing length from observations

(Jun Zhang and Mike Montgomery, 2012 JAS)



$$F_h = -\rho\,(\overline{v_t' v_r'}) = \rho\, K_h\, S_h$$

$$K_h = |F_h|\,(\rho\,|S_h|)^{-1},$$

$$L_h = (K_h\, D_h^{-1})^{1/2}$$

$$S_h = \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right) = \left(\frac{\partial v_t}{\partial r} - \frac{v_t}{r}\right)\cos 2\lambda + \left(\frac{\partial v_r}{\partial r} - \frac{v_r}{r}\right)\sin 2\lambda$$

$$D_h^2 = \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2$$

$$D_h^2 = 2\left(\frac{\partial v_r}{\partial r}\right)^2 + 2\left(\frac{v_r}{r}\right)^2 + \left(\frac{\partial v_t}{\partial r} - \frac{v_t}{r}\right)^2$$

Flight-level data collected during low-level eyewall penetrations of Hurricanes Allen (1980), Hugo (1989) and David (1979).

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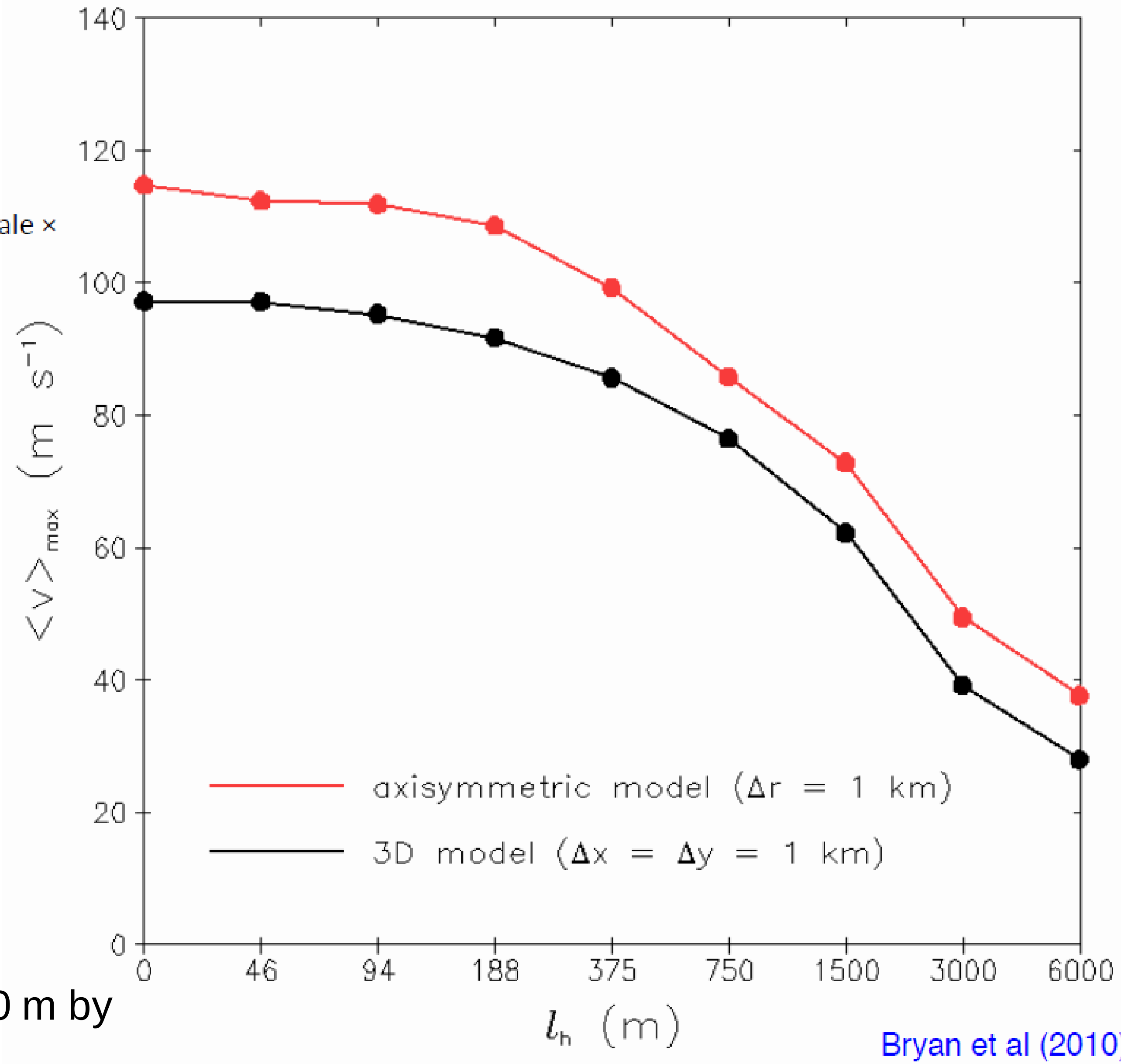
V_{max} from axisymmetric and 3d versions of the same model:



Bryan et al (2010)

Same type of turbulence parameterization:

$$\nu_h = l_h^2 S_h$$

(viscosity ~ turbulence length scale × deformation)

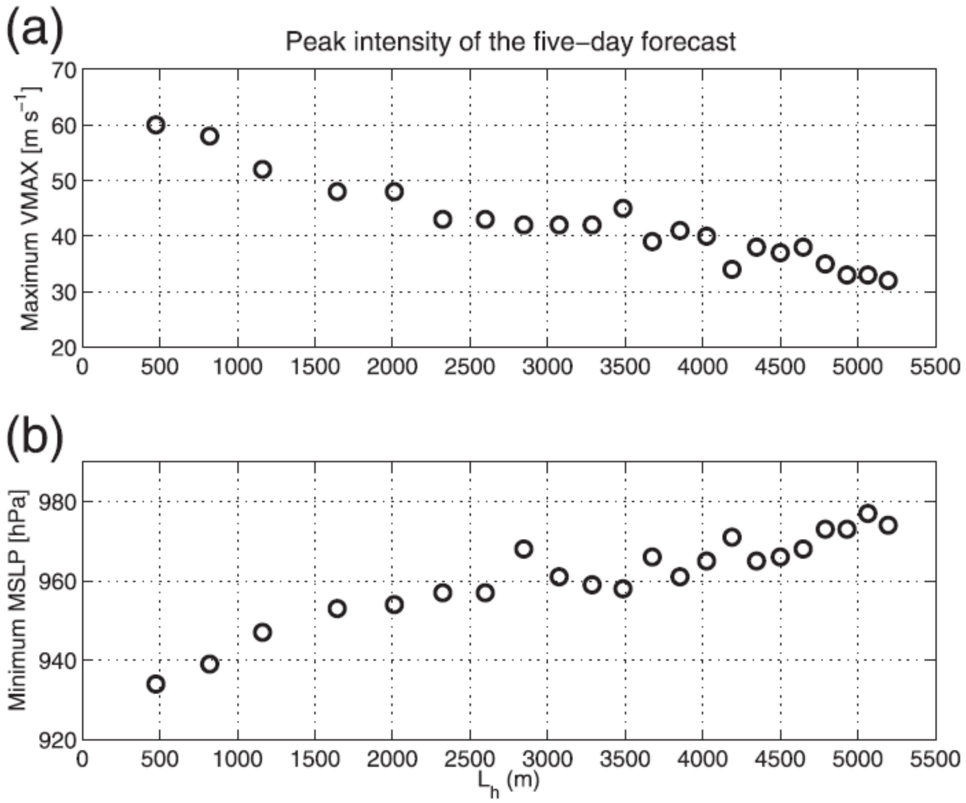
Two key points:

1. 3D model also has a strong response to l_h
2. V_{max} from the 3D model is consistently weaker (by ~10%) than V_{max} from the axisymmetric model

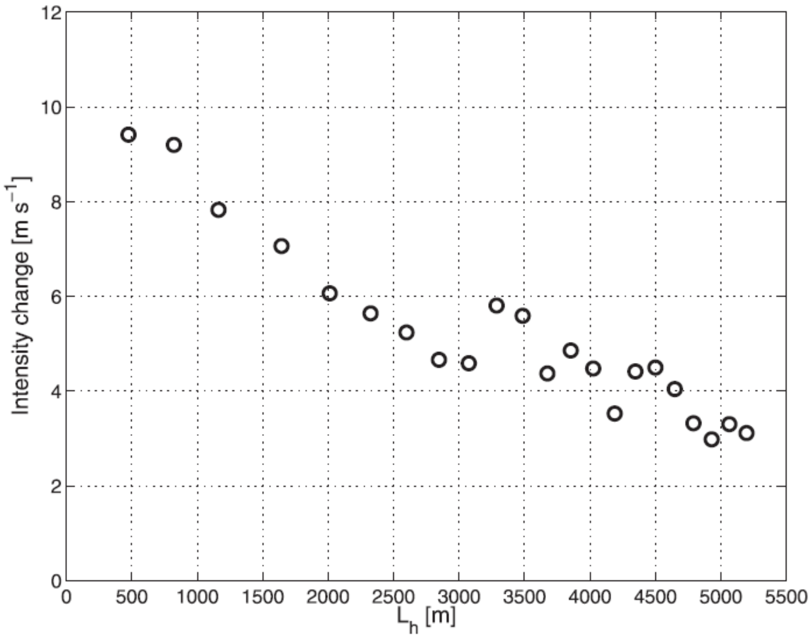
Recommended L_h=1000 m by Bryan et al. (2010)

Effects of horizontal diffusion on hurricane intensity and intensity change

(Jun Zhang and Frank Marks 2015, MWR)

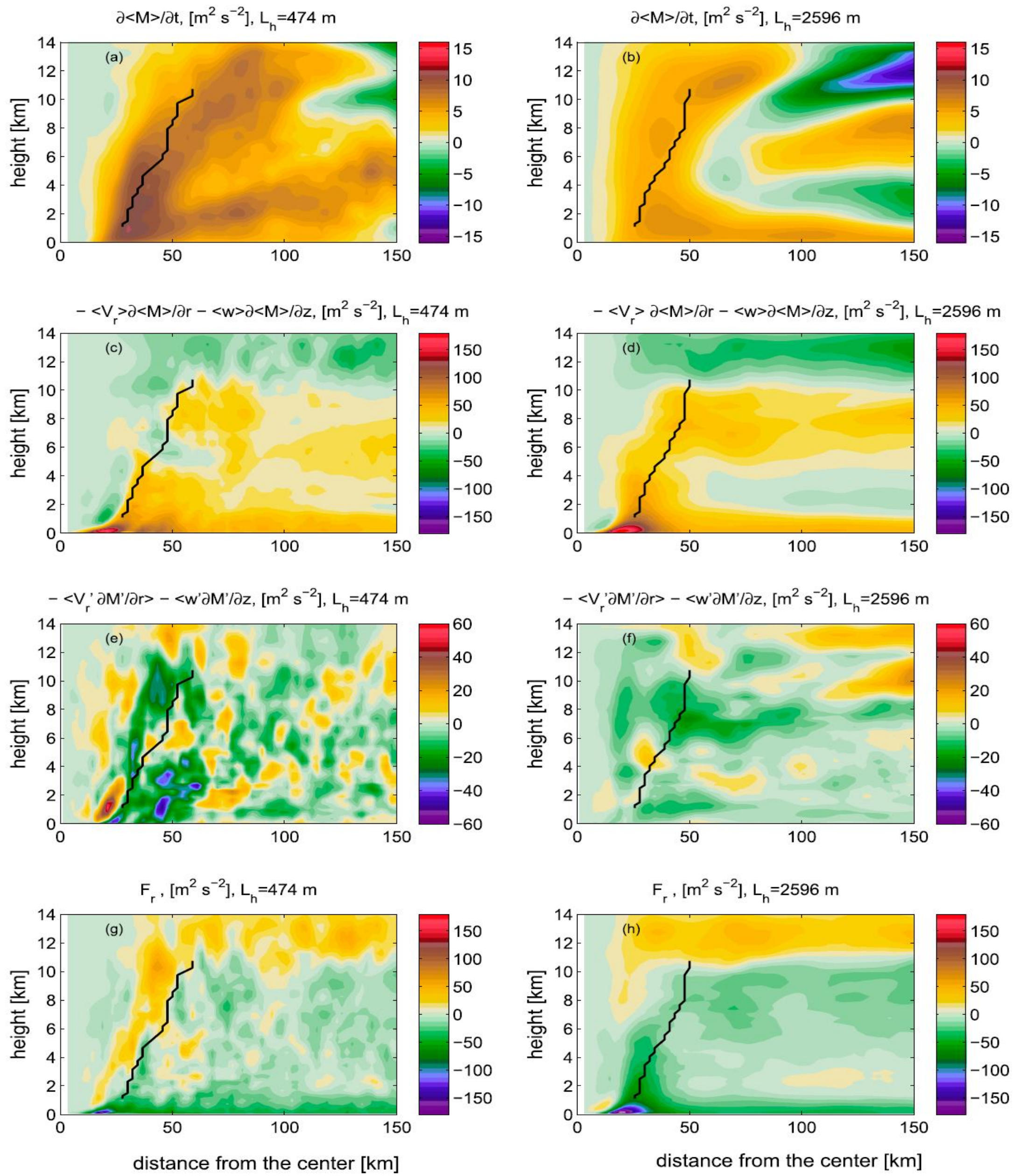


Idealized HWRF simulations



- Both the maximum intensity and intensity change rate are sensitive to the horizontal mixing length (Lh). This result is consistent with Bryan and Rotunno (2009); Bryan et al. (2010); Rotunno and Bryan (2012).

Effects of horizontal diffusion on the hurricane spin-up dynamics



Angular momentum budget

$$\frac{\partial\langle M\rangle}{\partial t} = -\langle V_r\rangle\frac{\partial\langle M\rangle}{\partial r} - \langle w\rangle\frac{\partial\langle M\rangle}{\partial z} - \left\langle V_r'\frac{\partial M'}{\partial r}\right\rangle - \left\langle w'\frac{\partial M'}{\partial z}\right\rangle + F_r$$

1. The total mean advection of <M> and the Fr term are the main contributors to the gain and loss of <M>, respectively;

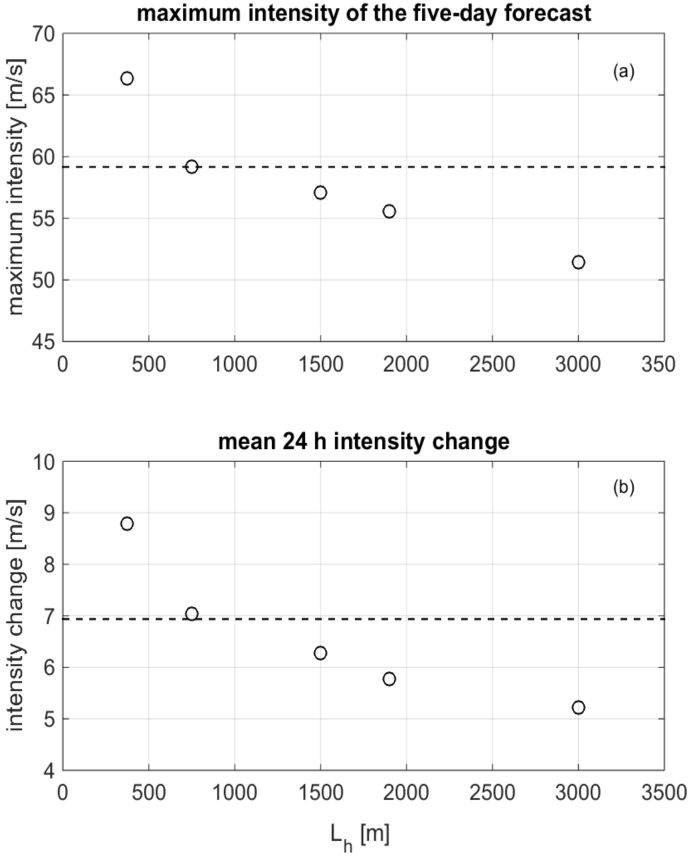
2. Convergence of <M> in the boundary layer is very important for hurricane intensification;

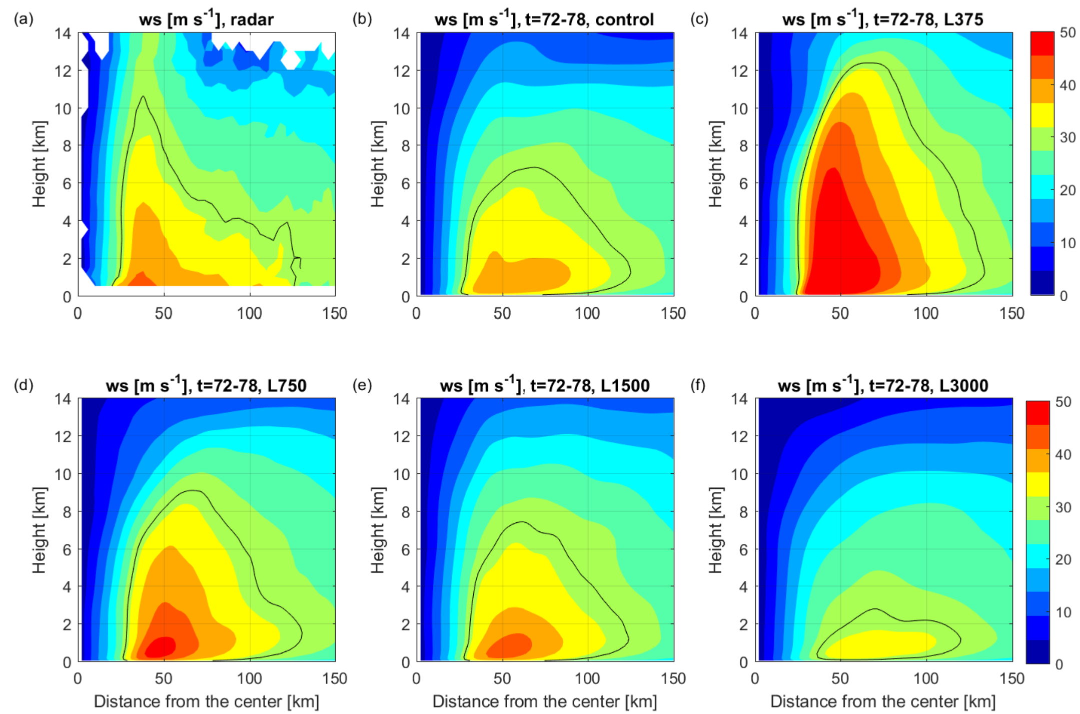
3. The resolved eddy advection of <M> is important for the spin-up of the low-level vortex inside the RMW when Lh is small.

(J. Zhang and F. Marks, 2015, MWR)

HWRF forecasts of Hurricane Earl (2010): Sensitivity to horizontal mixing length (L_h)

(Jun Zhang et al. 2017WAF under review)

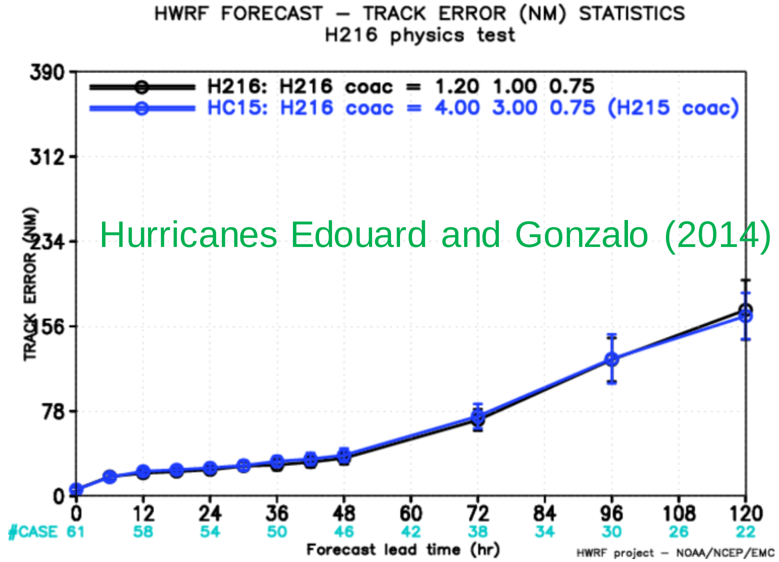


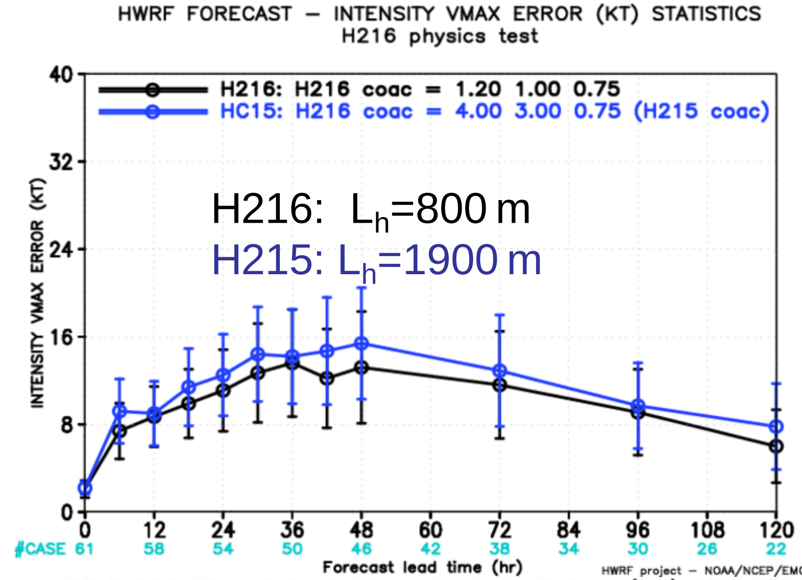


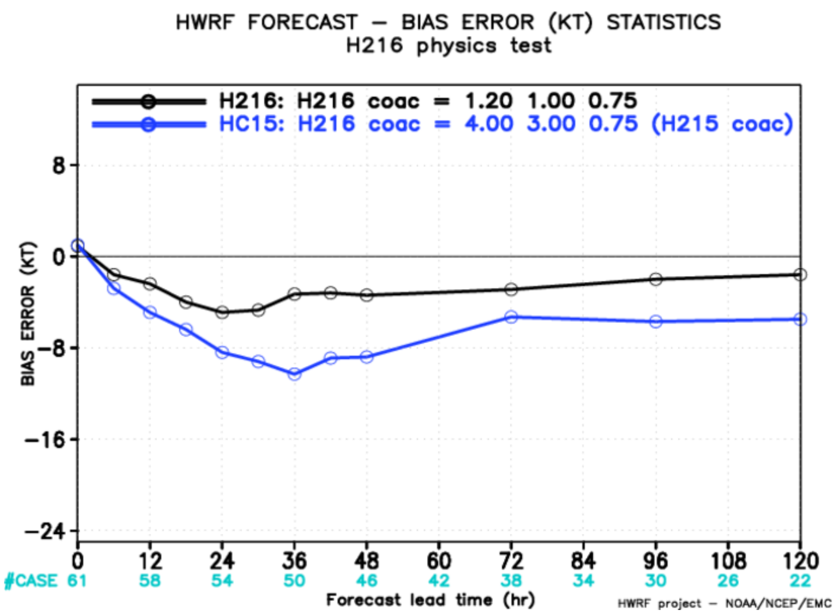
(Thanks to Xuejin Zhang who made HWRF runs using H215)

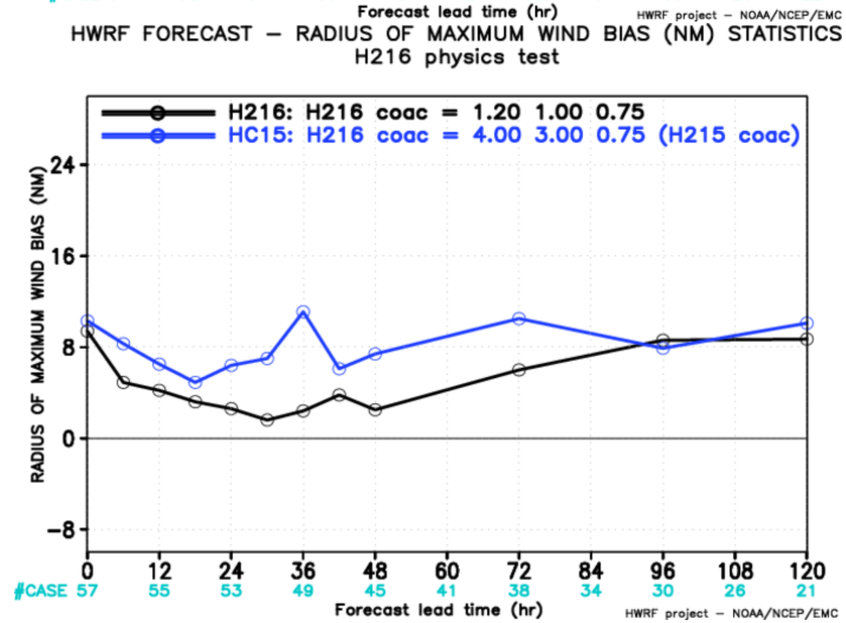
- The HWRF forecast with L_h=750 m simulated the storm intensity and structure of Hurricane Earl better than other forecasts with other values of L_h.
- In the control experiment L_h=1900 m, same as in the 2015 version operational HWRF model (H215). This value is too large based on the sensitivity test.

Impact of reduced L_h in H216 on HWRF forecasts





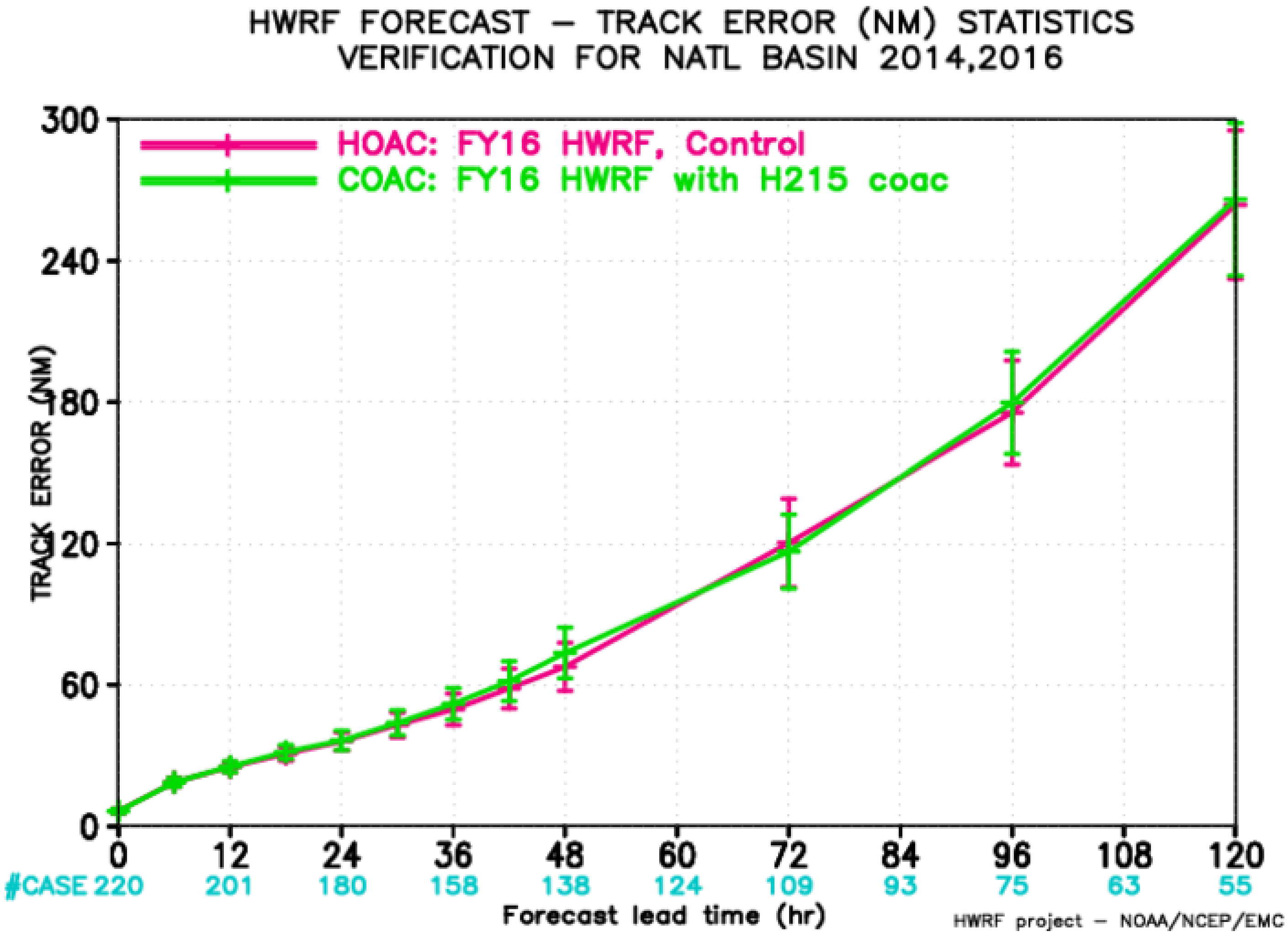




Thanks to Jason Sippel

Impact of reduced L_h in H216 on HWRF forecasts

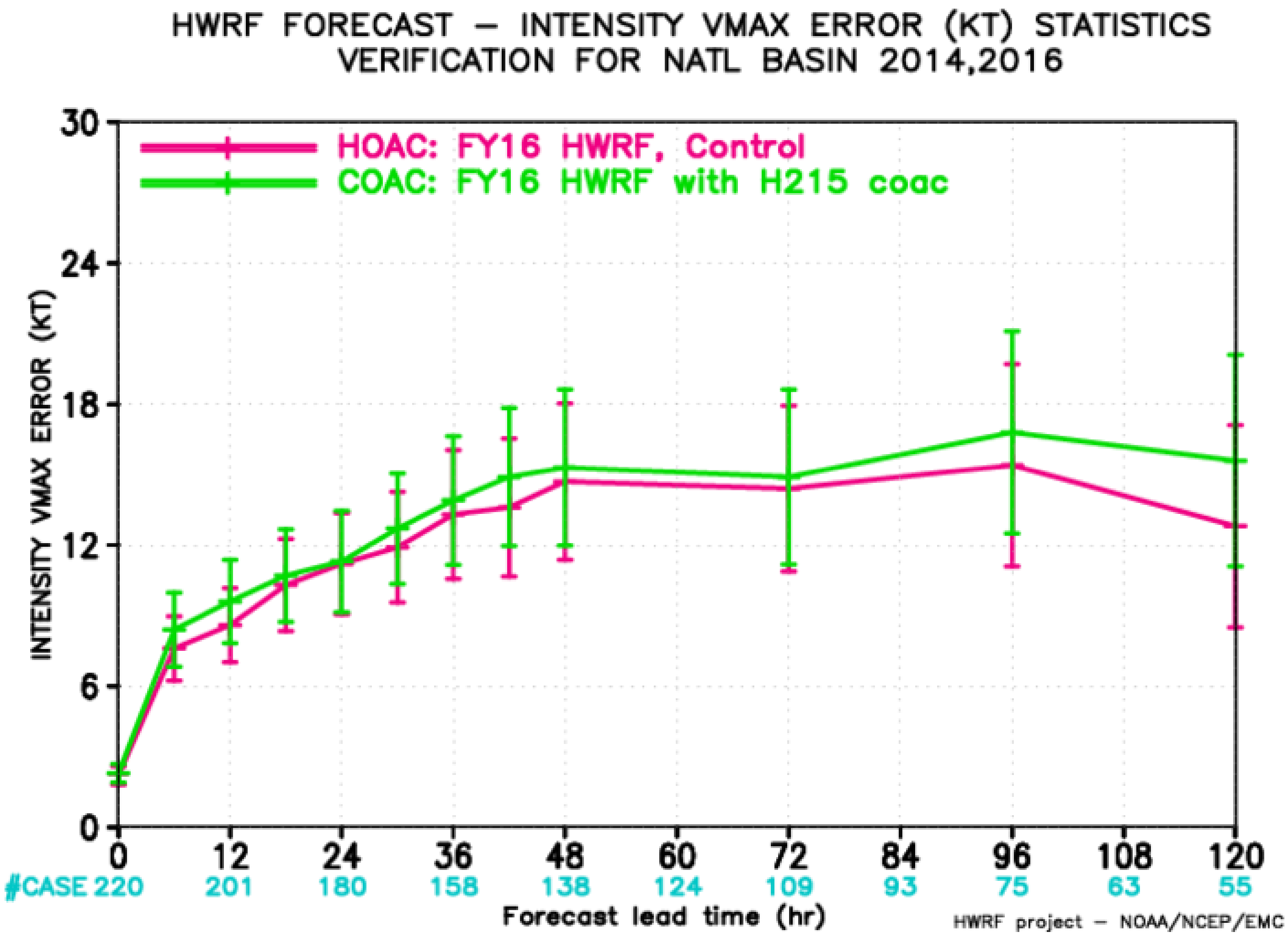
(Jun Zhang et al. 2017WAF under review)



Thanks to Zhan Zhang who created the retrospective forecasts!

Impact of reduced L_h in H216 on HWRF forecasts

(Jun Zhang et al. 2017WAF under review)



Impact of reduced L_h in H216 on HWRF forecasts

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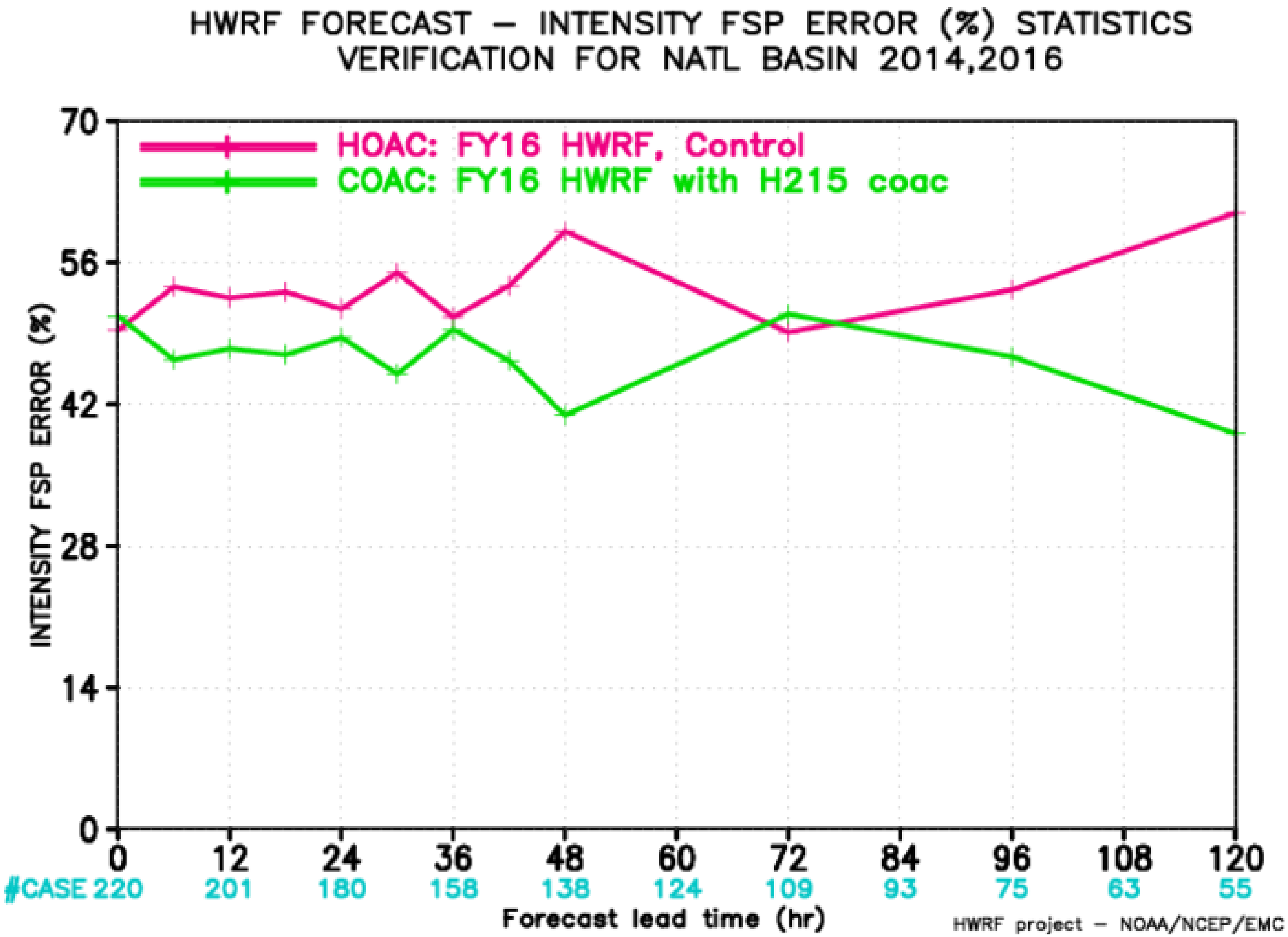
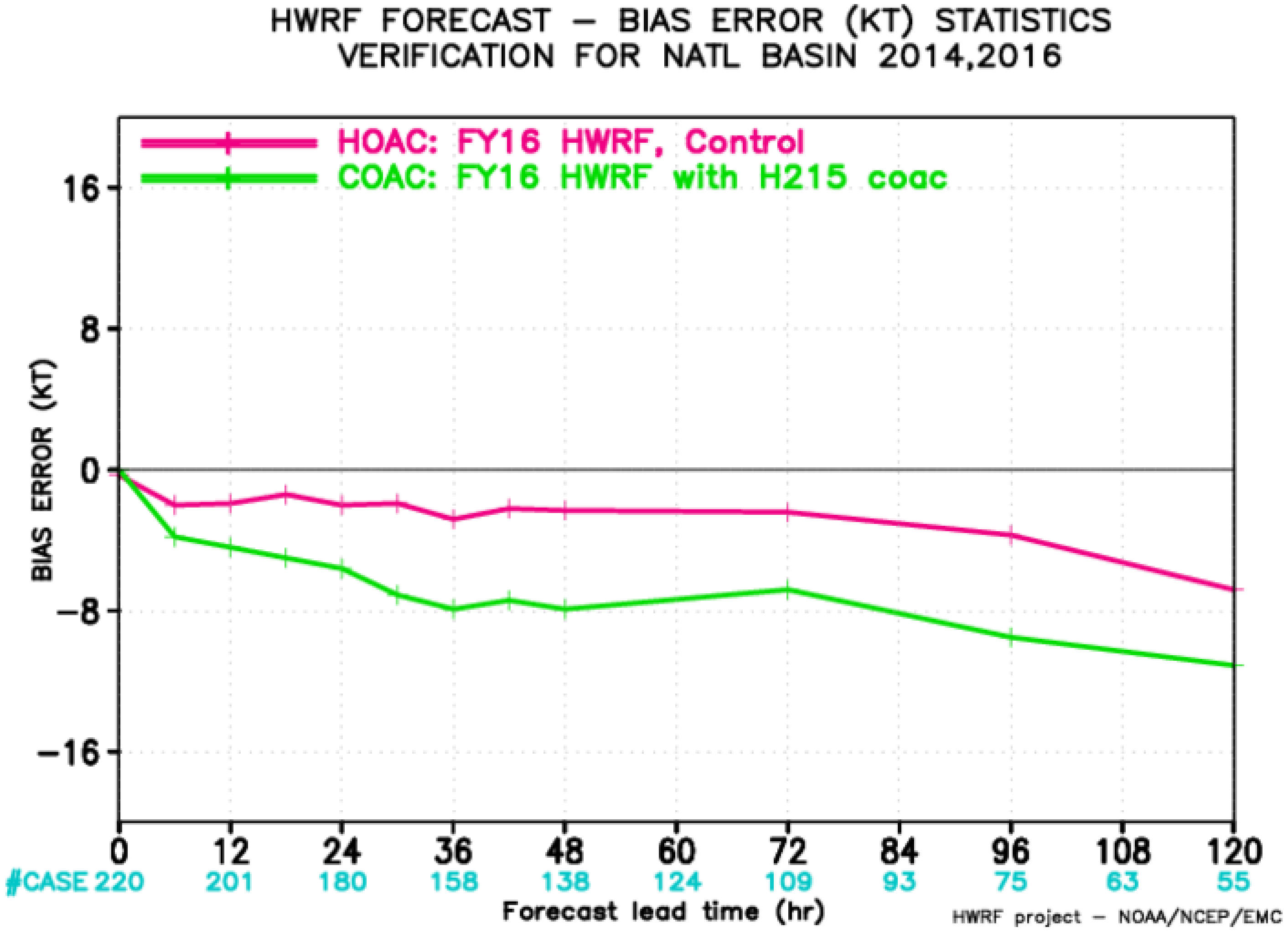
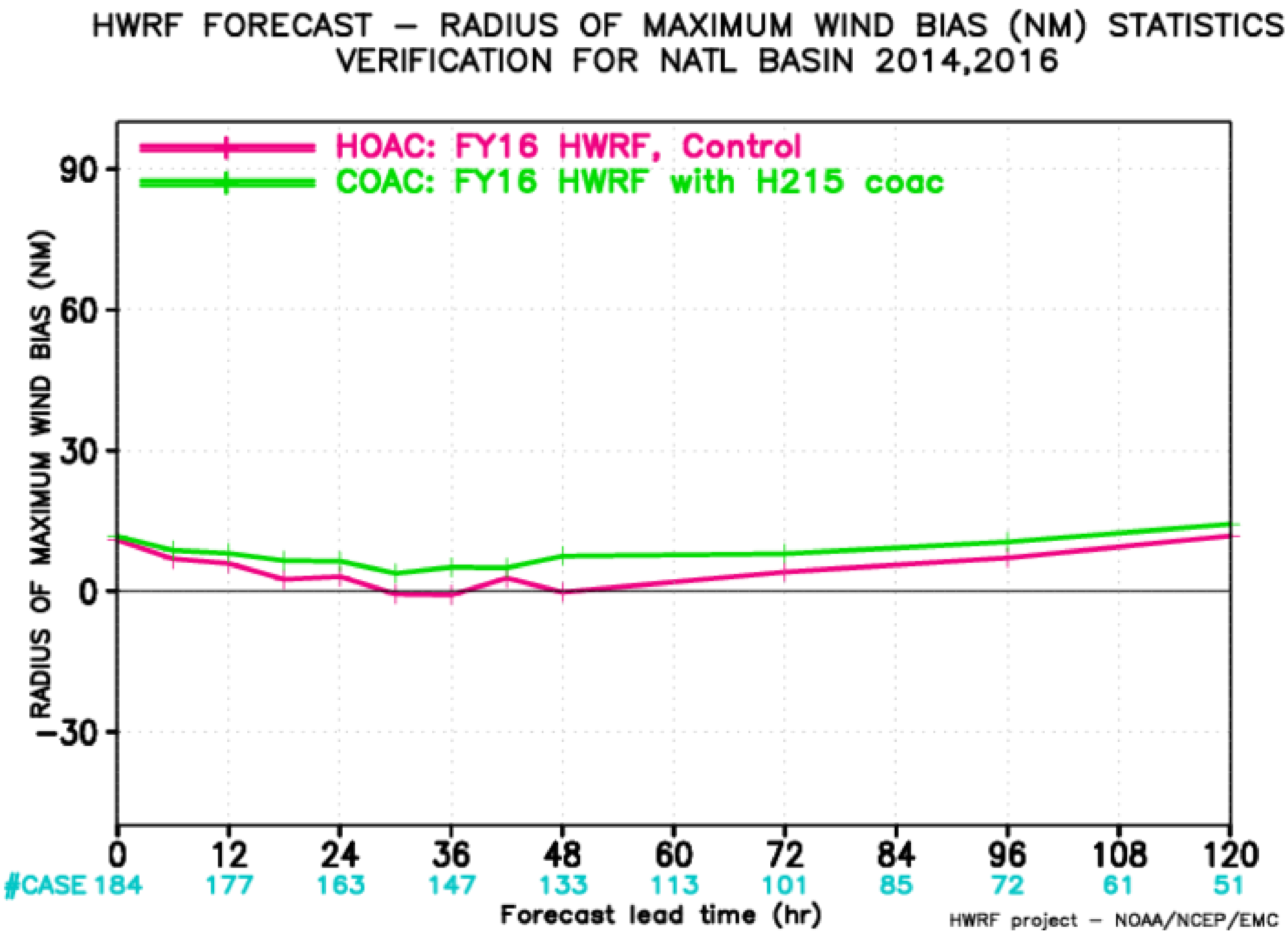


Impact of reduced L_h in H216 on HWRF forecasts



Impact of reduced L_h in H216 on HWRF forecasts

(Jun Zhang et al. 2017WAF under review)

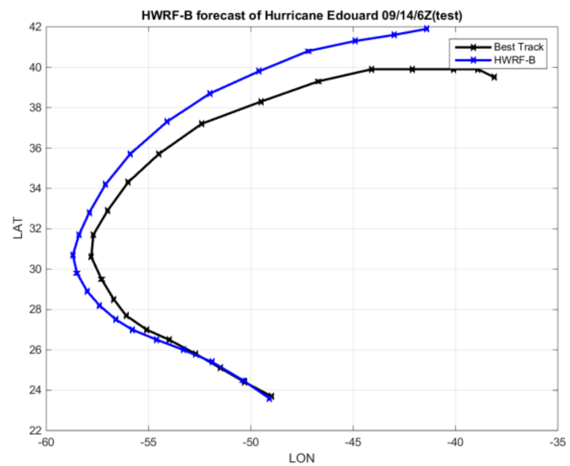


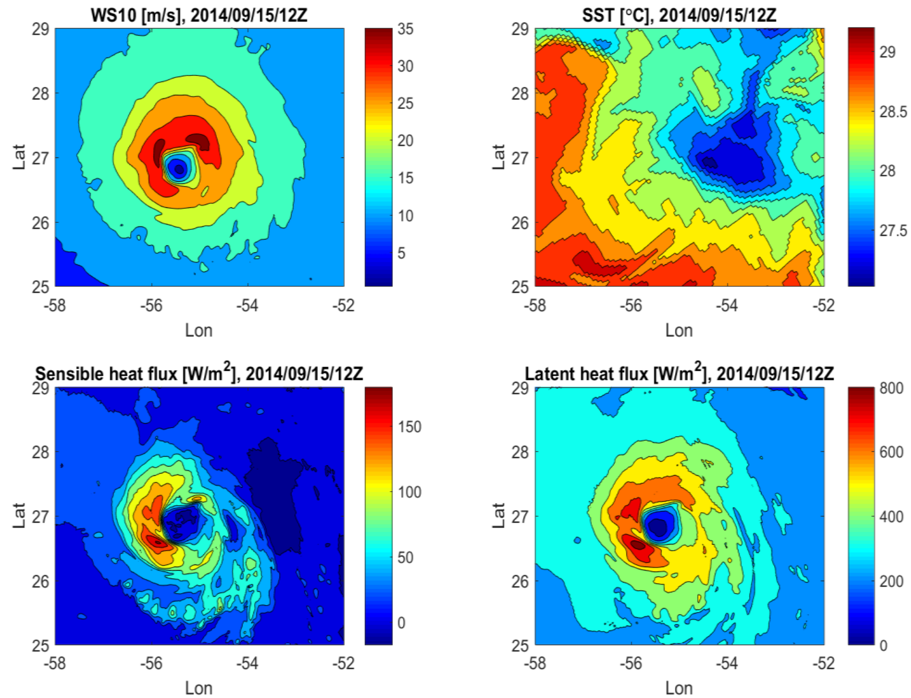
Ongoing work to test other aspects of the HWRF physics

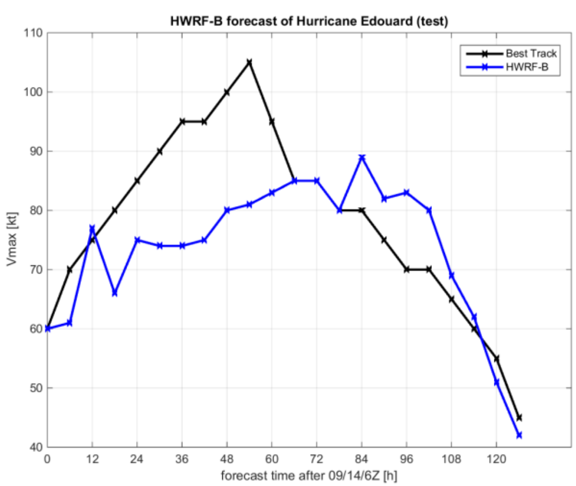
- Air-sea coupling
- PBL height
- TKE scheme
- Microphysics (e.g., snow fall velocity)
- In-cloud turbulence

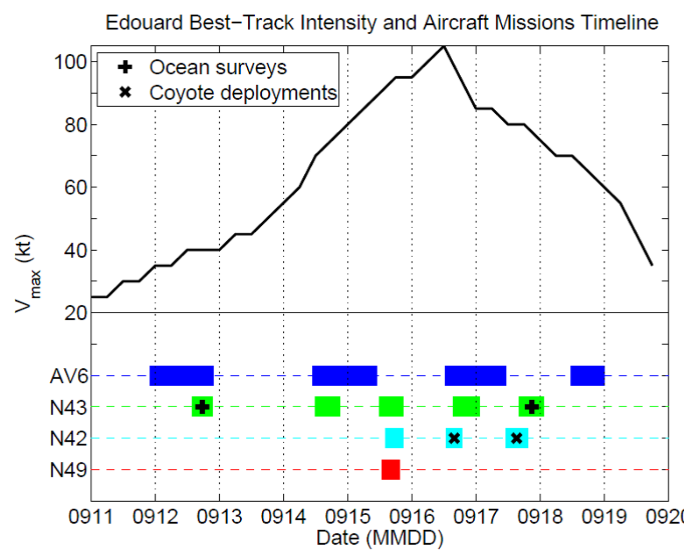
Air-sea Coupling in Basin-Scale HWRF (preliminary result)

Thanks to Xuejin Zhang who coupled HWRF-B with POM



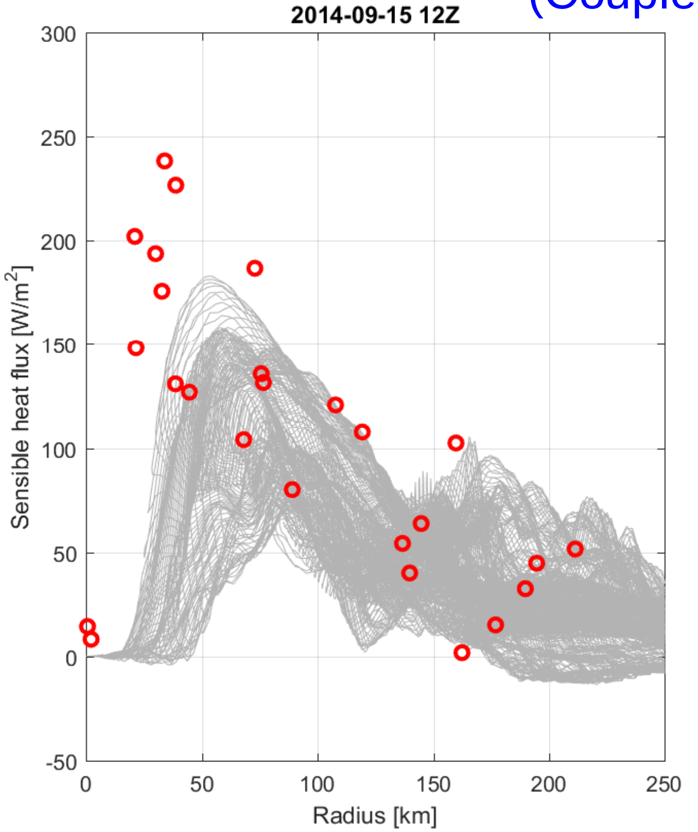


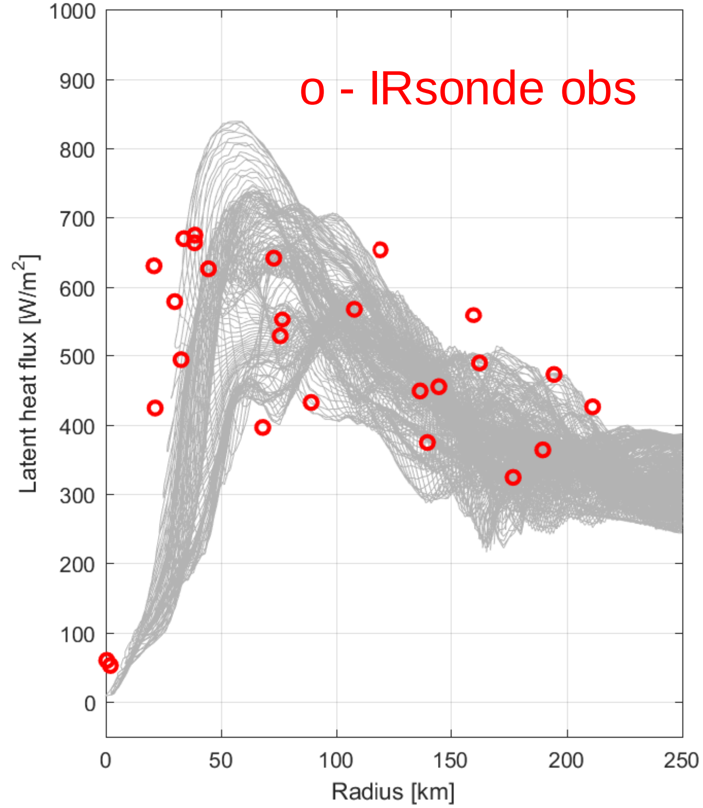


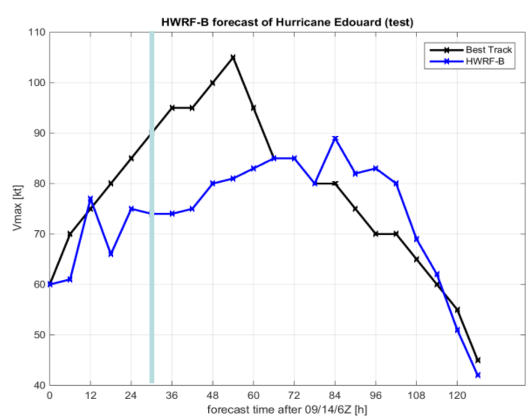


Aircraft missions into Edouard (2014)

(Coupled HWRF-B evaluation - preliminary result)





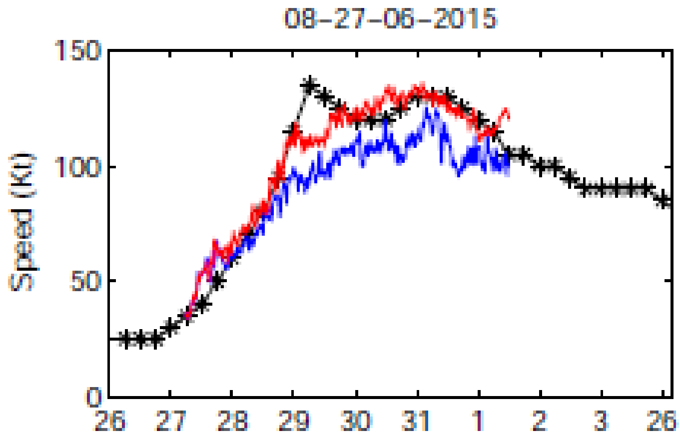


- Why is there a low bias in the intensity forecast when the modeled enthalpy fluxes are comparable to the observed ones?
- What is the role of air-sea coupling in hurricane intensification?

Effect of In-cloud turbulence parameterization on RI forecast

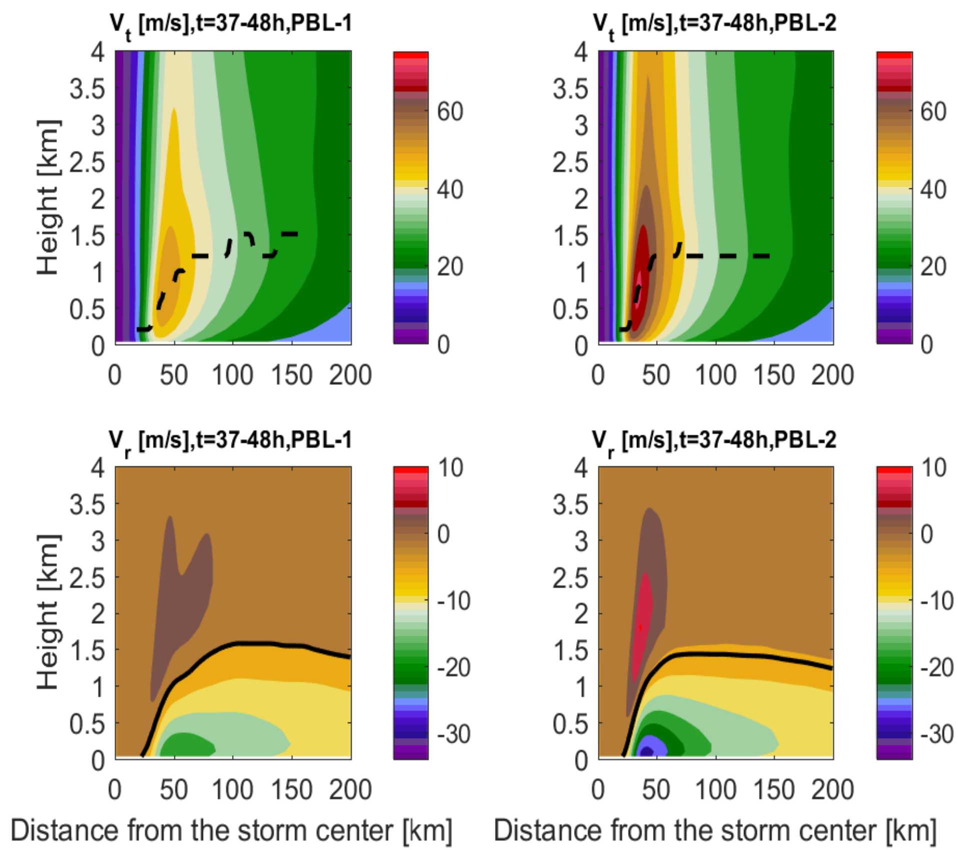
(Ping Zhu, Jun Zhang, Bryce Tyner, Kathryn Sellwood, Sergio Arbaca, Lin Zhu)

Hurricane Jimena (2015)



H217

H217 + new turbulence configuration

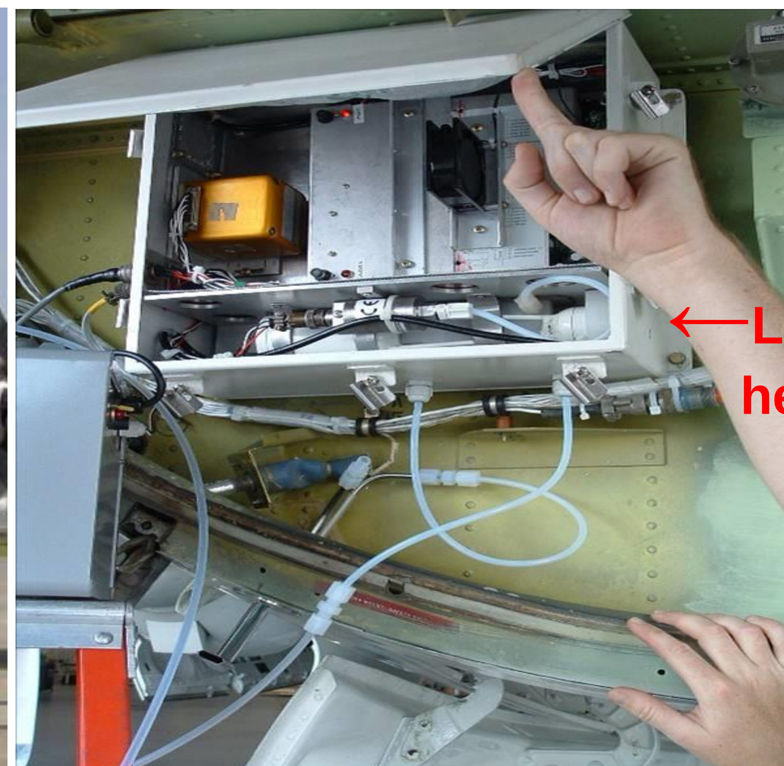


- We are at the stage of turning the model physics based on model to model comparisons.
- We need observational data to guide the model physics change.

Can we measure in-cloud turbulence?

NOAA P3 aircraft flux instrumentation:

- **Rosemount Gust probes in radome and fuselage**
- **Rosemount temperature sensors**
- **LICOR LI-7500 hygrometer (to be re-calibrated)**
- **BAT ("Best Aircraft Turbulence") probe to be put back on the boom**
- **New turbulence sensor under development at AOC**



Summary

1. We show a framework for evaluating and improving physical parameterizations in hurricane models using aircraft observations .

2. We demonstrate the usefulness of this framework for model physics development, which led to improvements in HWRF forecasts of hurricane intensity and structure.

3. We emphasize the importance of developing new physics using observational data from research aircraft or other types of platforms.

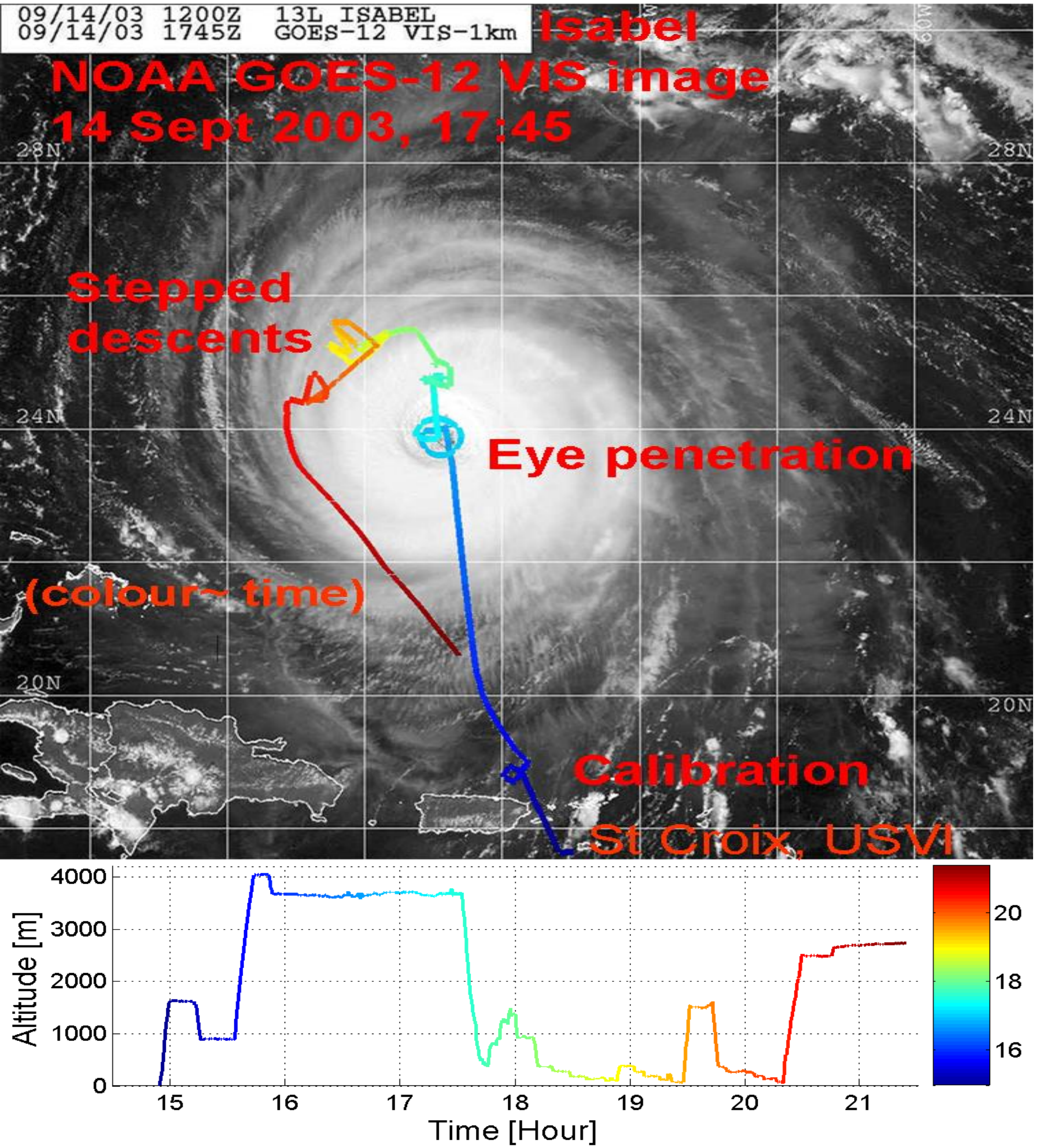
The end

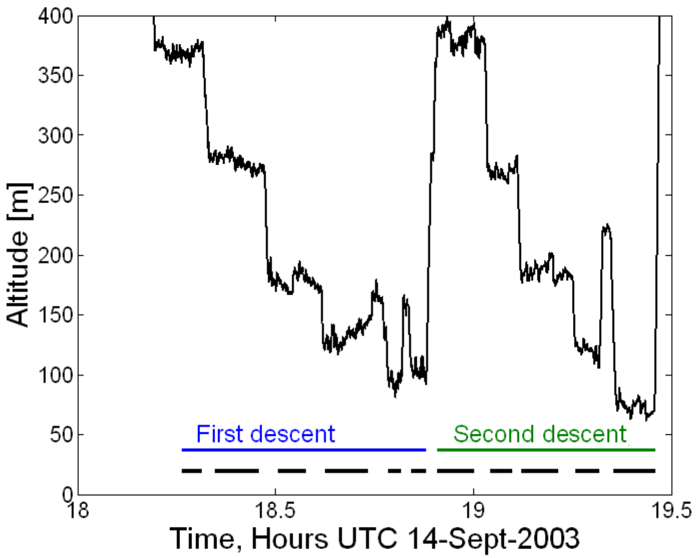
Thanks!

Questions?

First Direct Measurements of Enthalpy Flux in the Hurricane Boundary Layer as part of the CBLAST Experiment

Jun Zhang et al. 2008 GRL



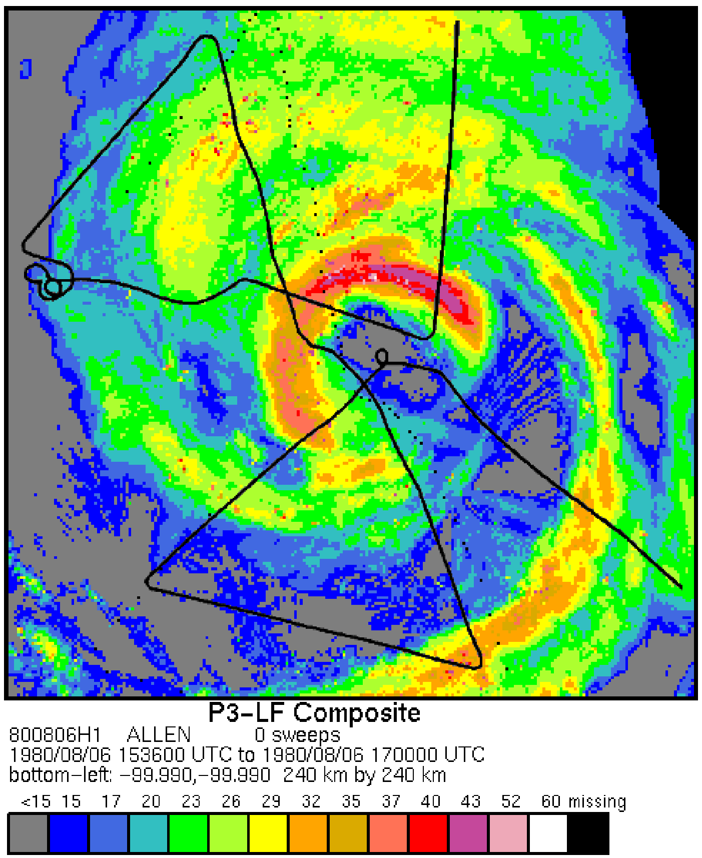


Data used for eddy diffusivity calculation

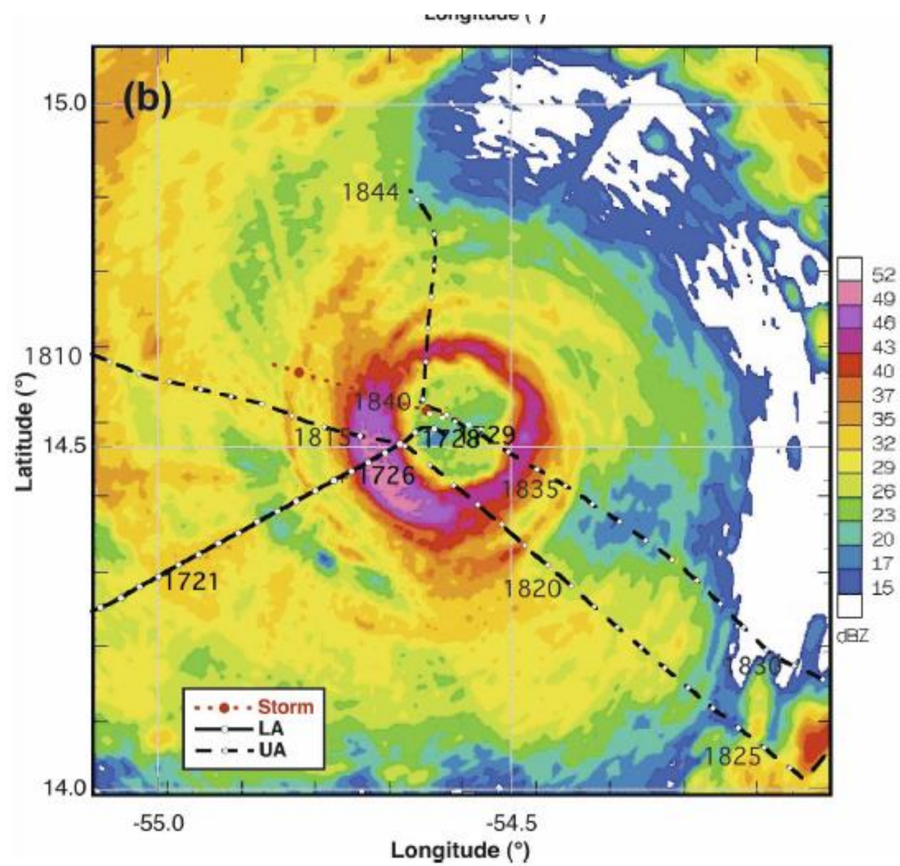
(Jun Zhang, F. Marks, M. Montgomery and S. Lorsolo 2011b MWR)

We use the flight-level data that were collected using the low-level eyewall penetrations of Hurricanes Allen (1980), Hugo (1989) and David (1979).

Allen, Aug. 6, 1980 *Hugo, Aug. 15, 1989*



(Marks 1985)



(Marks et al. 2008 MWR)

Further Evaluation: Improved Hurricane Structure

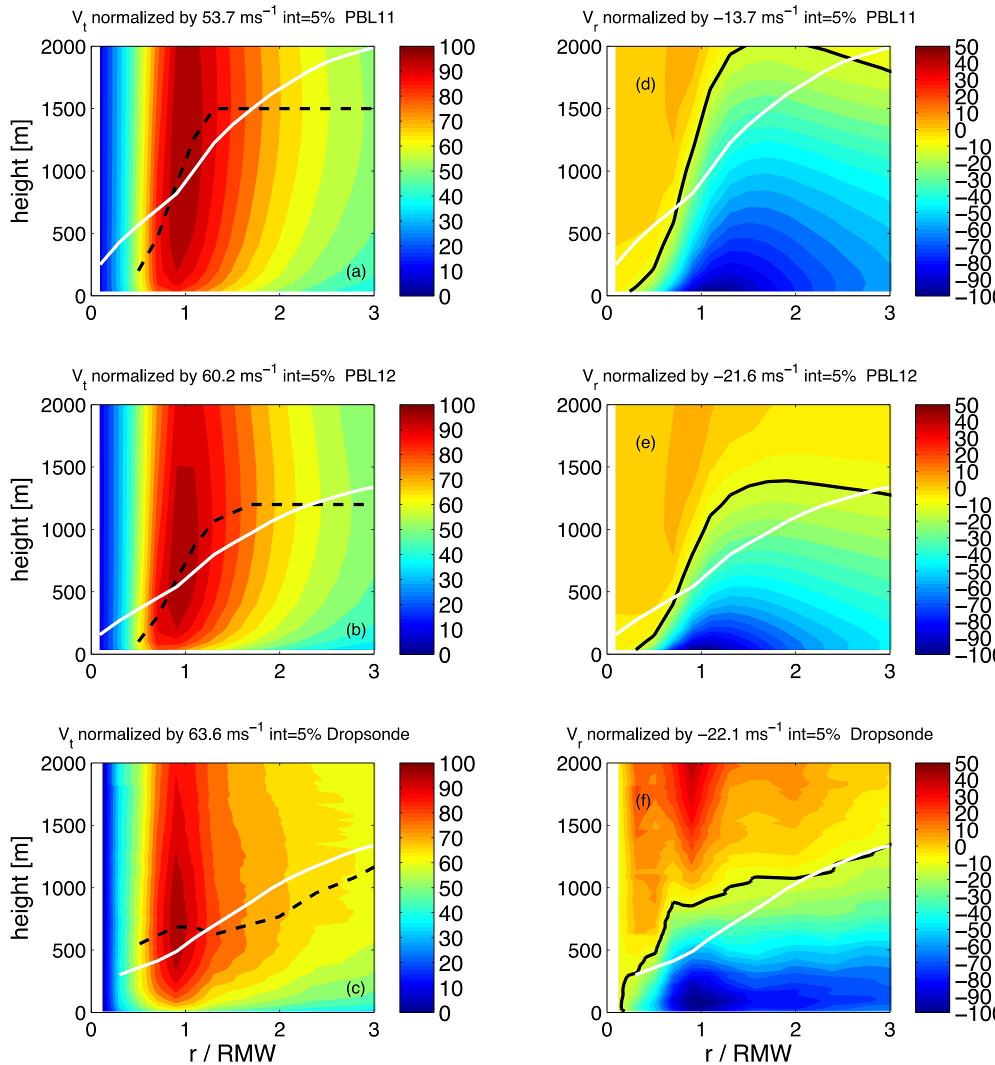
(Jun Zhang et al. 2015 MWR)

PBL11 :

PBL12 :

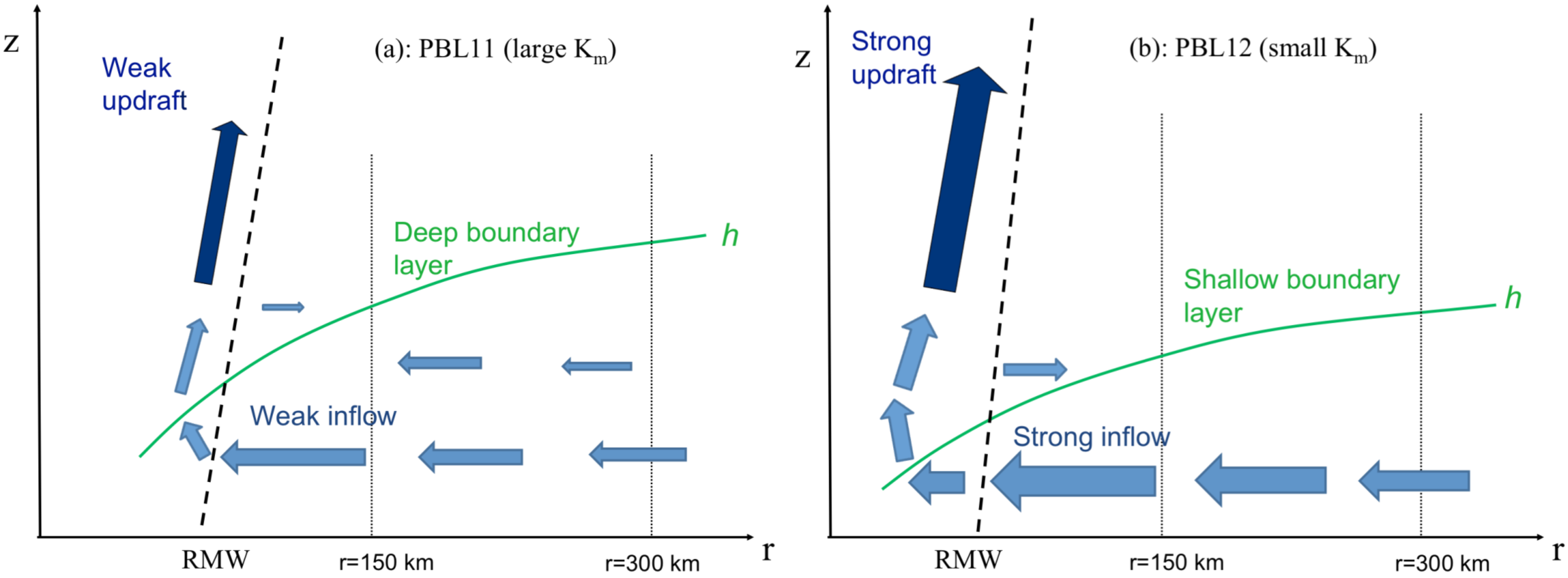
Dropsonde Composite :

(Jun Zhang et al. 2011b MWR)



Dynamical Explanation

(Jun Zhang et al. 2015, MWR)



Why does the vertical turbulent mixing in the boundary layer have such a profound effect on the structure and intensity of hurricanes?

1. The radial inflow is stronger for the case with the weaker diffusion.
2. As this radial inflow travels past the point of gradient wind balance (near the RMW), its greater inertia will carry it further inward, leading to a stronger azimuthal wind maximum in the boundary layer.
3. Furthermore, the base of the eyewall updraft will be at smaller radius, which further favors intensity due to the greater inertial stability there.