Evaluating the Impact of Parameterized Turbulent Mixing and Boundary Layer Structure on Hurricane Forecasts

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Objectives:

- To increase usefulness of observations in high-resolution hurricane modeling systems (e.g., HWRF) .
- To develop advanced model diagnostic techniques to support model 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

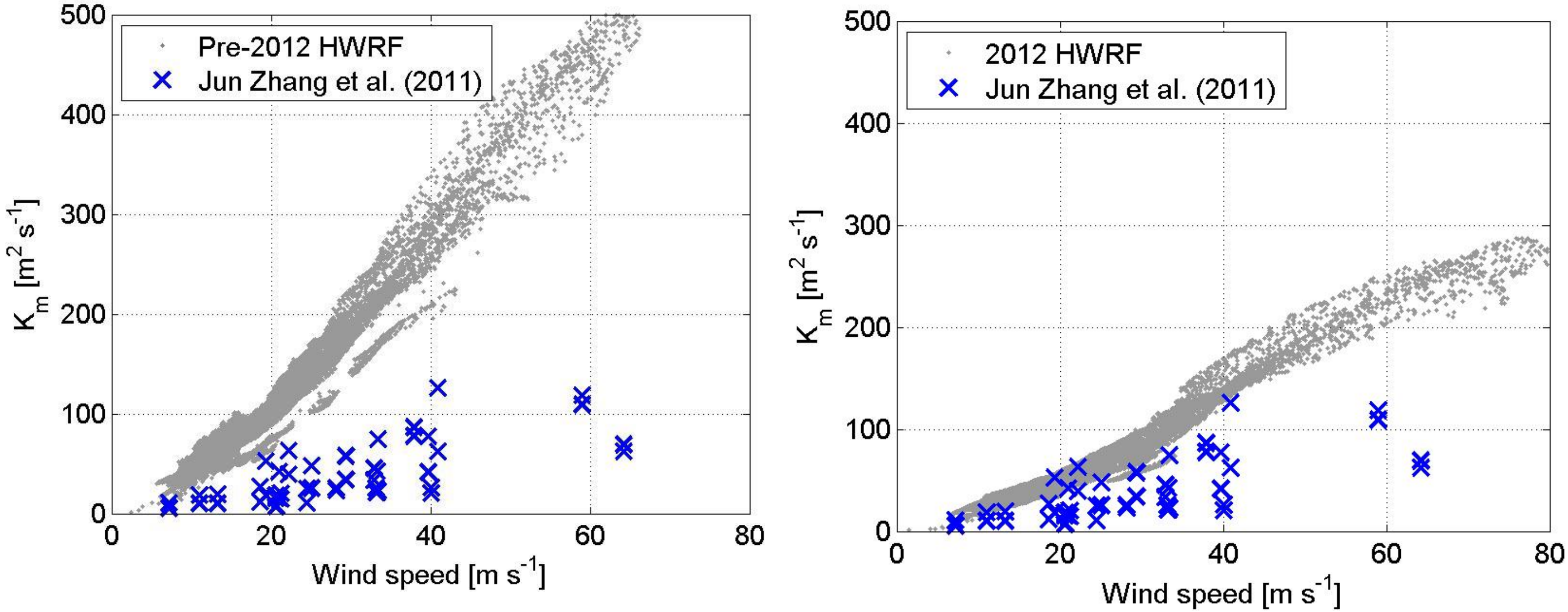
2. Development of new physics using observations

3. Observation-based model physics upgrade

4. Evaluation of the Impact of physics upgrade

Use aircraft observations to improve PBL physics in the operational hurricane HWRF

Before modification (HWRF 2011 and prior) After modification (HWRF 2012)



$\langle u'w' \rangle = - K_m \, du/dz$

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

(Gopal et al. 2013, JAS; Jun Zhang et al. 2012, TCRR)

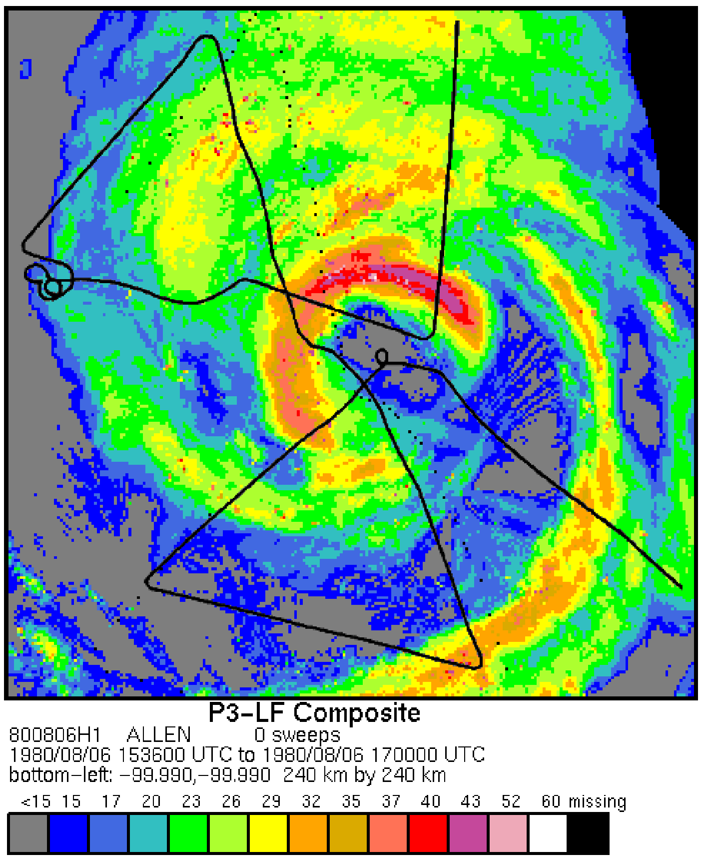
Observations were collected by P3 aircraft at ~450 m in Cat5 Hurricanes Hugo (1989) and Allen (1980). (Marks 1985; Marks et al. 2008; Jun Zhang et al. 2011a)

Data used for eddy diffusivity calculation

(Zhang et al. 2011a MWR)

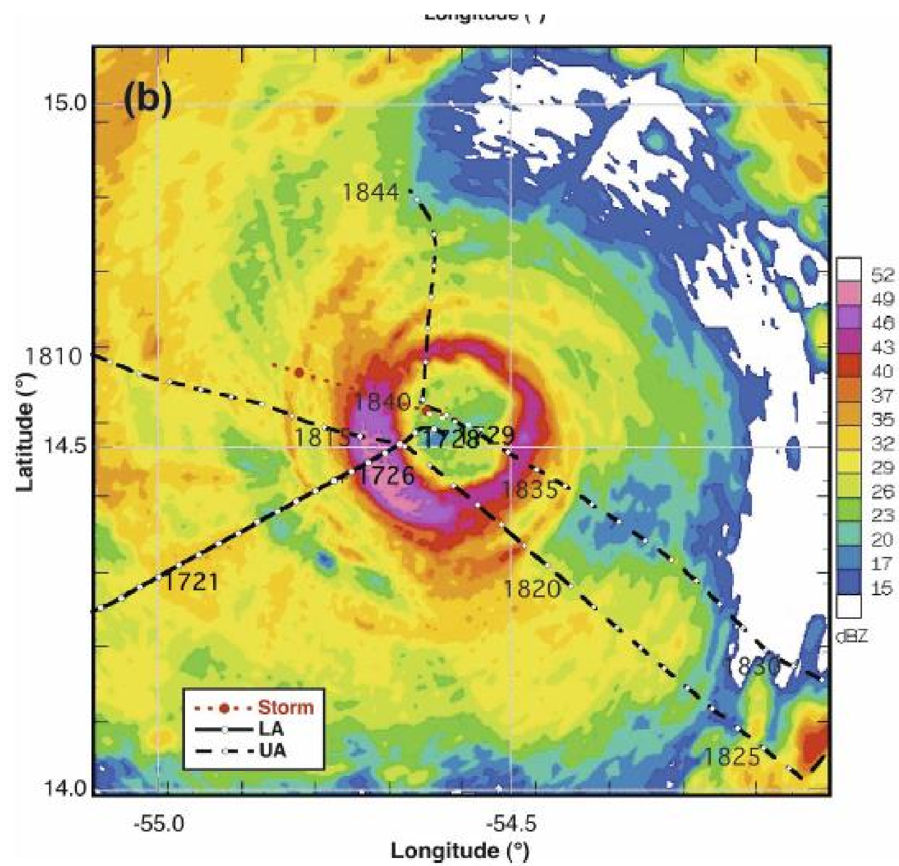
We use the flight-level data that were collected using the low-level eyewall penetrations of Hurricanes Allen (1980) and Hugo (1989).

Allen, Aug. 6, 1980



(Marks 1985)

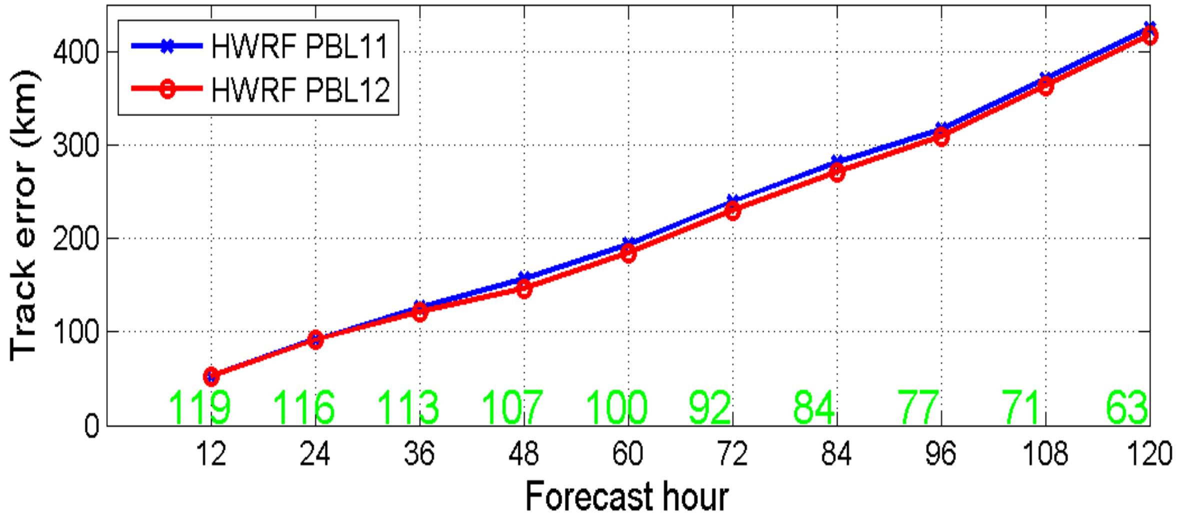
Hugo, Aug. 15, 1989



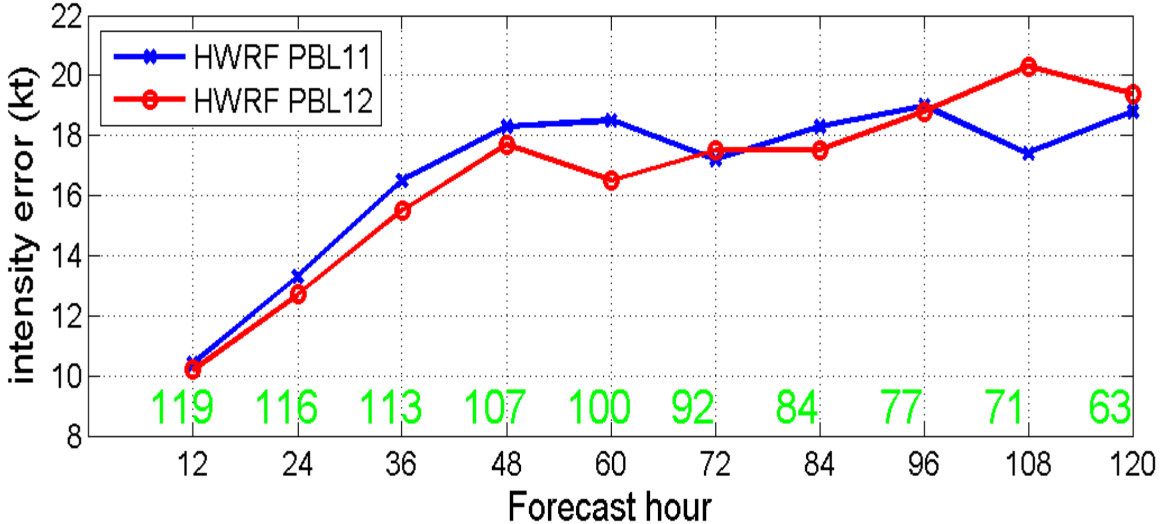
(Marks et al. 2008 MWR)

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

(Zhang et al. 2015 MWR)



Two sets of HWRF simulations of four hurricanes



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

$\alpha = 1$ in PBL11

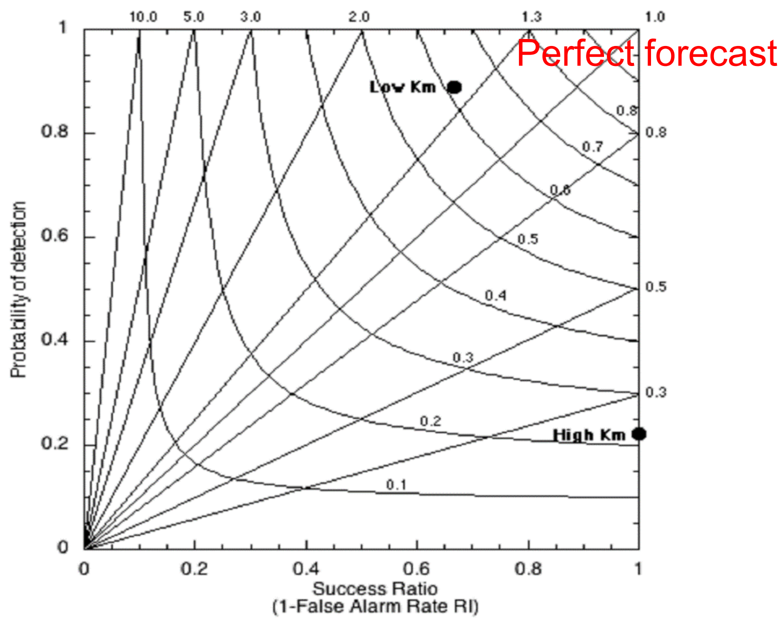
$\alpha = 0.5$ in PBL12

Composite study on impact of PBL changes on RI forecasts

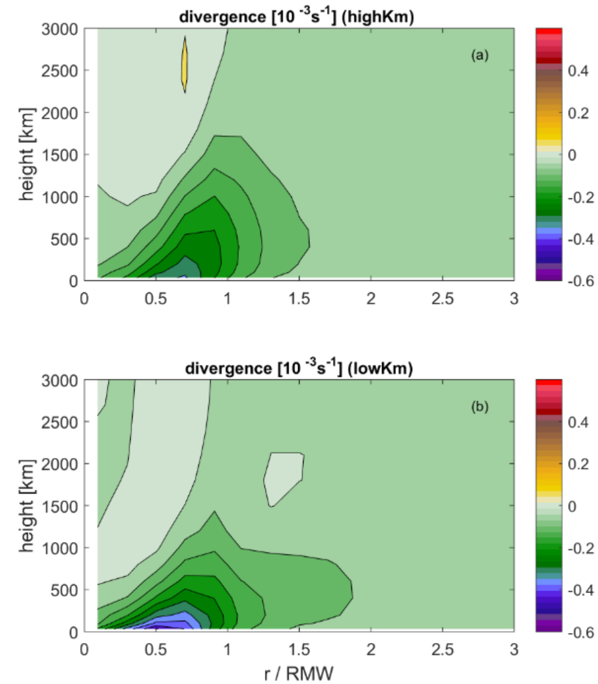
(Zhang et al. 2017MWR)

- Composite of HWRF forecasts of Earl (2010), Karl (2010)
- 55 forecasts in total for each PBL configuration
- Cycled forecasts, 3-km grid length
- Only difference was in K_m formulation

POD



SR = 1 – False Alarm Ratio

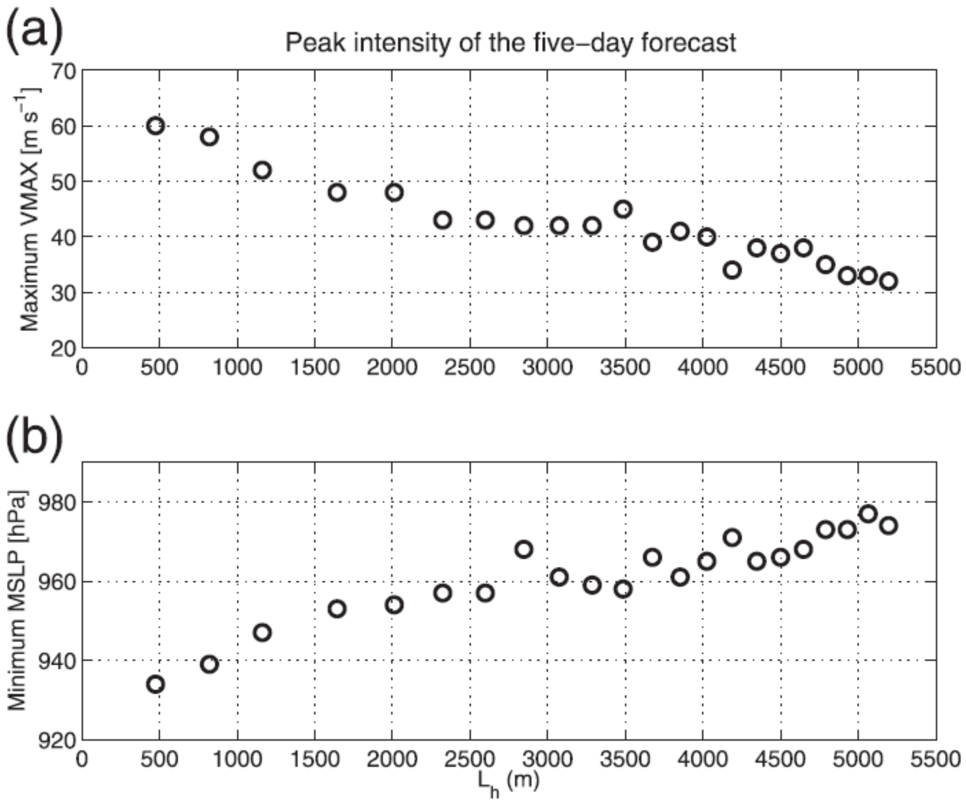


➢ Low-Km forecasts produce more RI events, fewer misses, more hits, but slightly more false alarms.

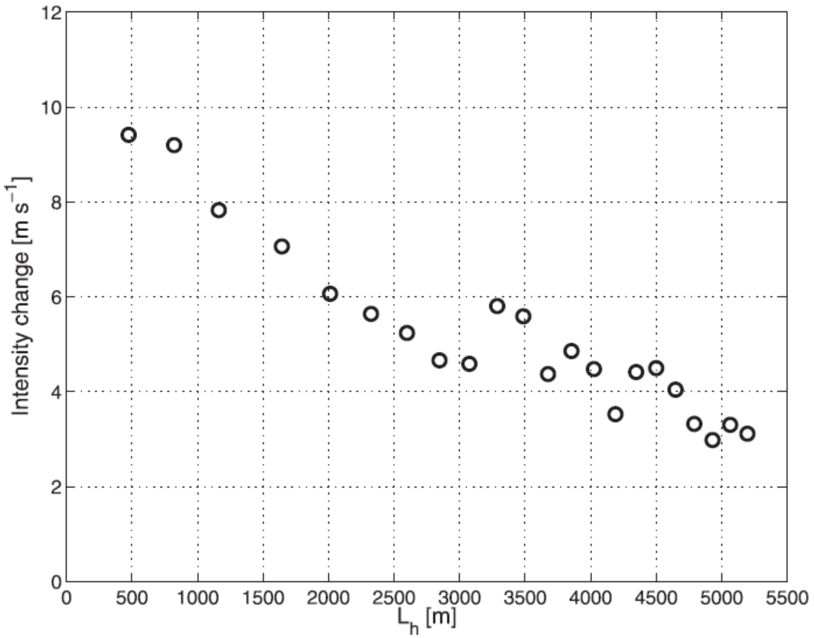
➢ Composite analysis of axisymmetric structure shows that low-Km forecasts have stronger inflow, stronger and deeper convection that is located further inward from the RMW, and stronger boundary-layer convergence at the RI onset.

Effects of horizontal diffusion on hurricane intensity and intensity change

(Zhang and Marks 2015, MWR)



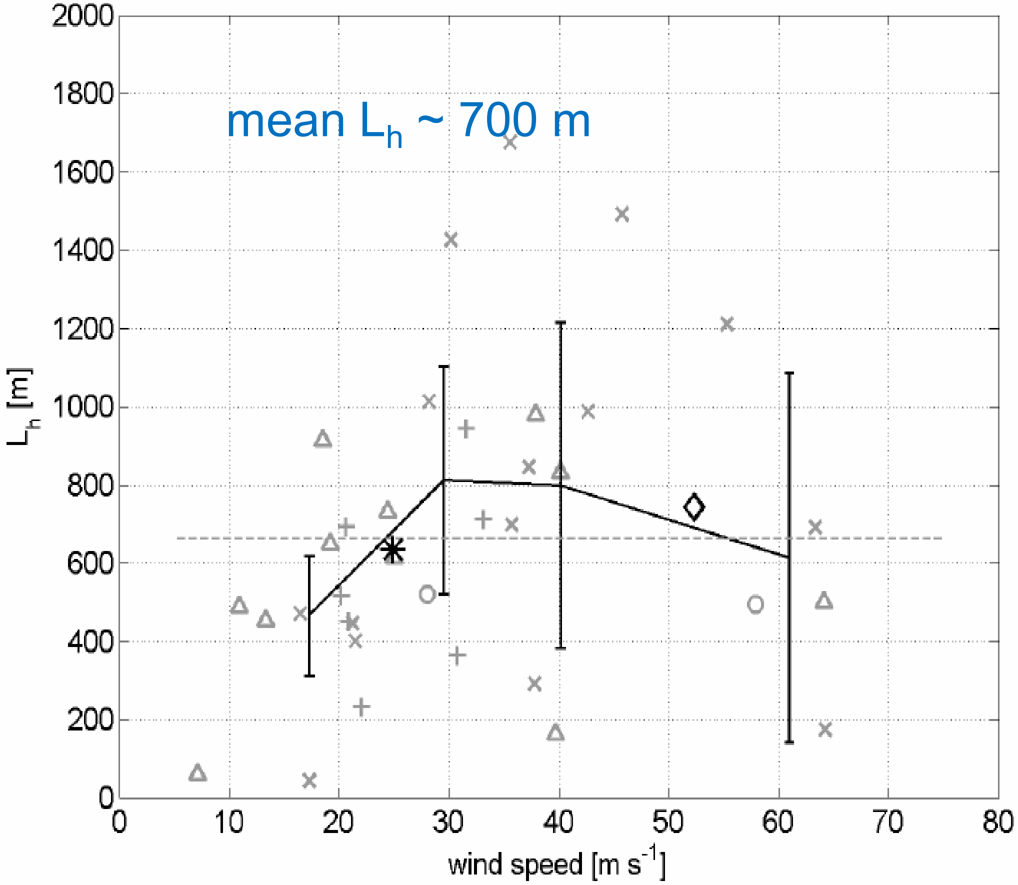
Idealized HWRF simulations



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

Horizontal mixing length from observations

(Zhang and Montgomery, 2012 JAS)



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

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

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

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

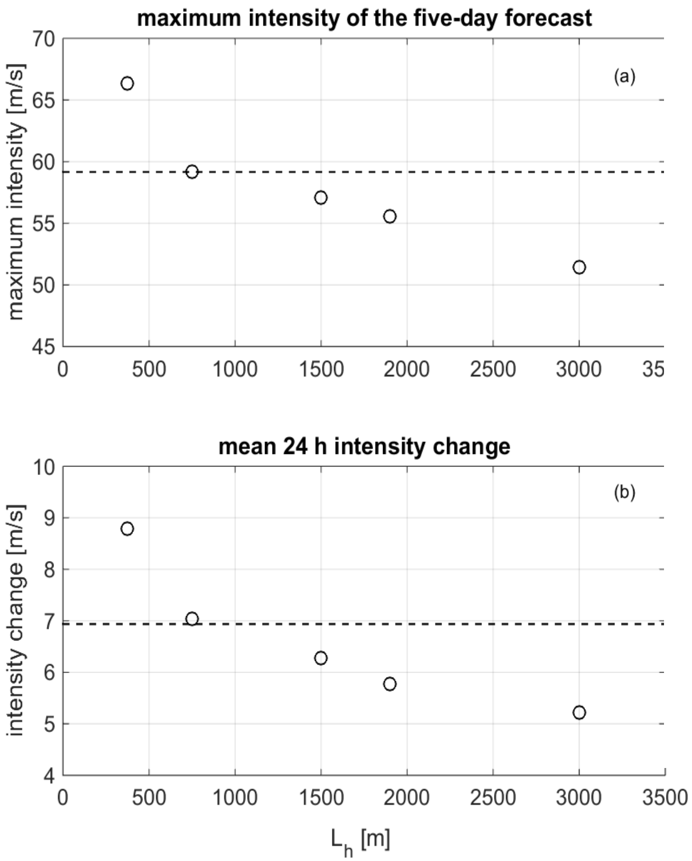
$$D_h^2 = \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2$$

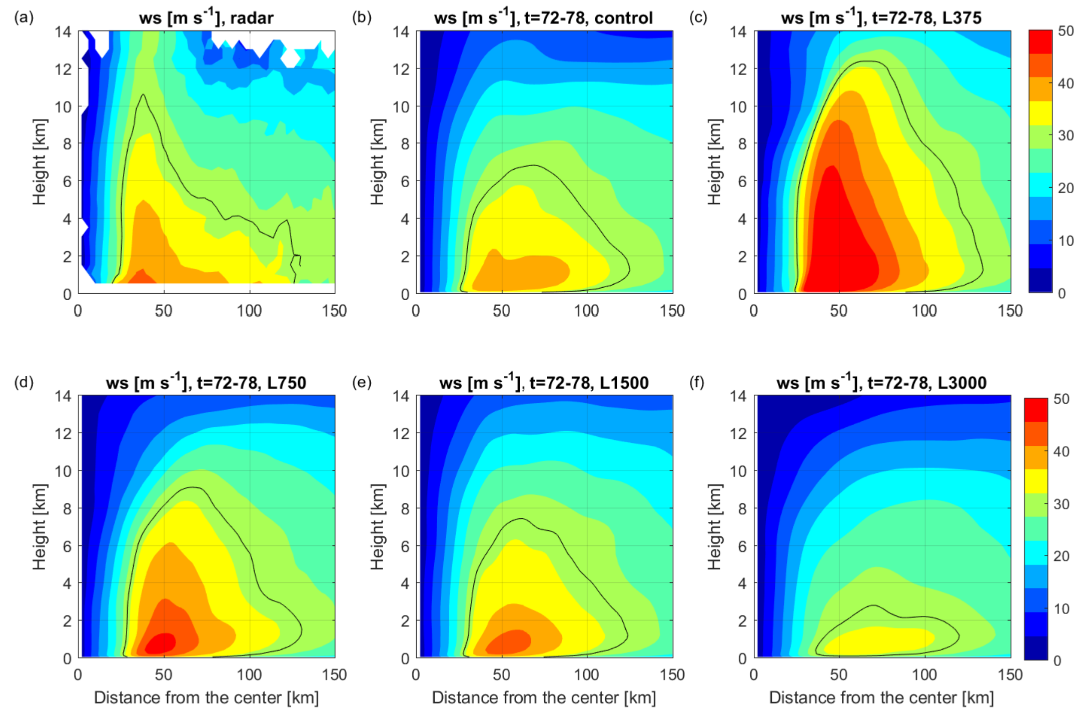
$$D_h^2 = 2\left(\frac{\partial v_r}{\partial r}\right)^2 + 2\left(\frac{v_r}{r}\right)^2 + \left(\frac{\partial v_t}{\partial r} - \frac{v_t}{r}\right)^2$$

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

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

(Zhang et al. 2018WAF)

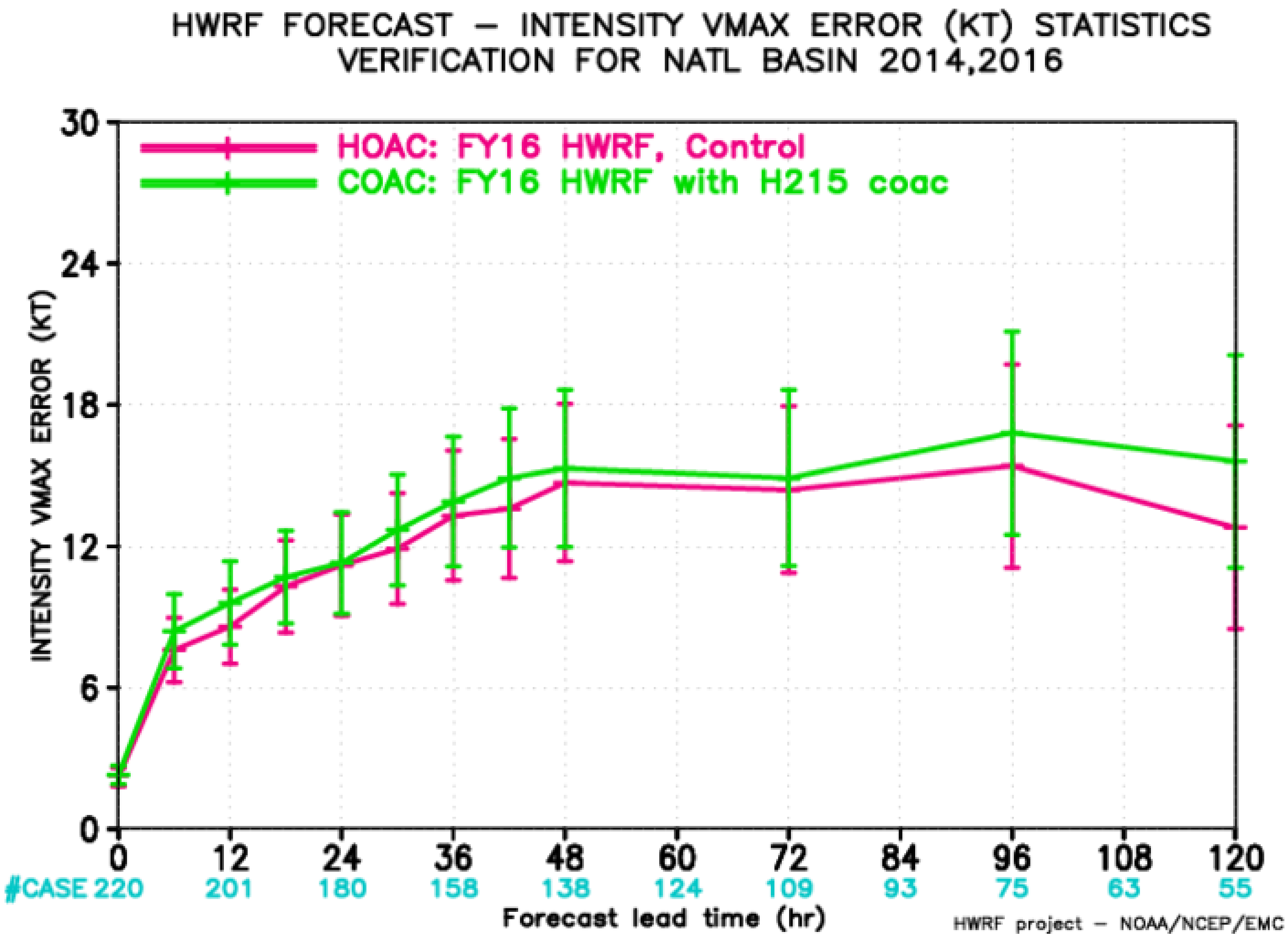




- The HWRF forecast with L_h=750 m simulated the storm intensity and structure of Hurricane Earl better than other forecasts with other values of L_h.
- In the control experiment L_h=1900 m, same as in the 2015 version operational HWRF model (H215), which is too large based on the sensitivity test.

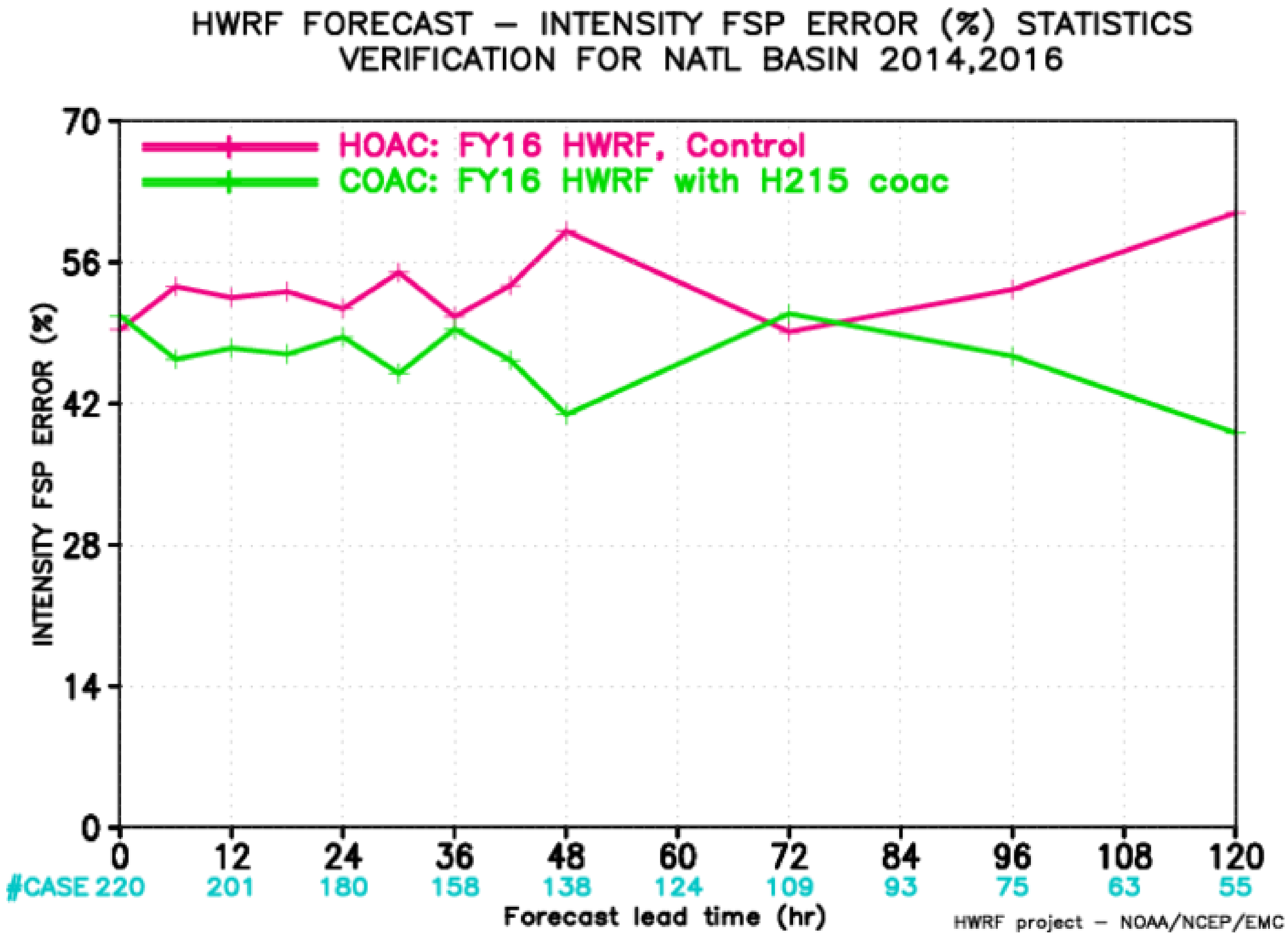
Impact of reduced L_h in H216 on HWRF forecasts

(Zhang et al. 2018WAF)



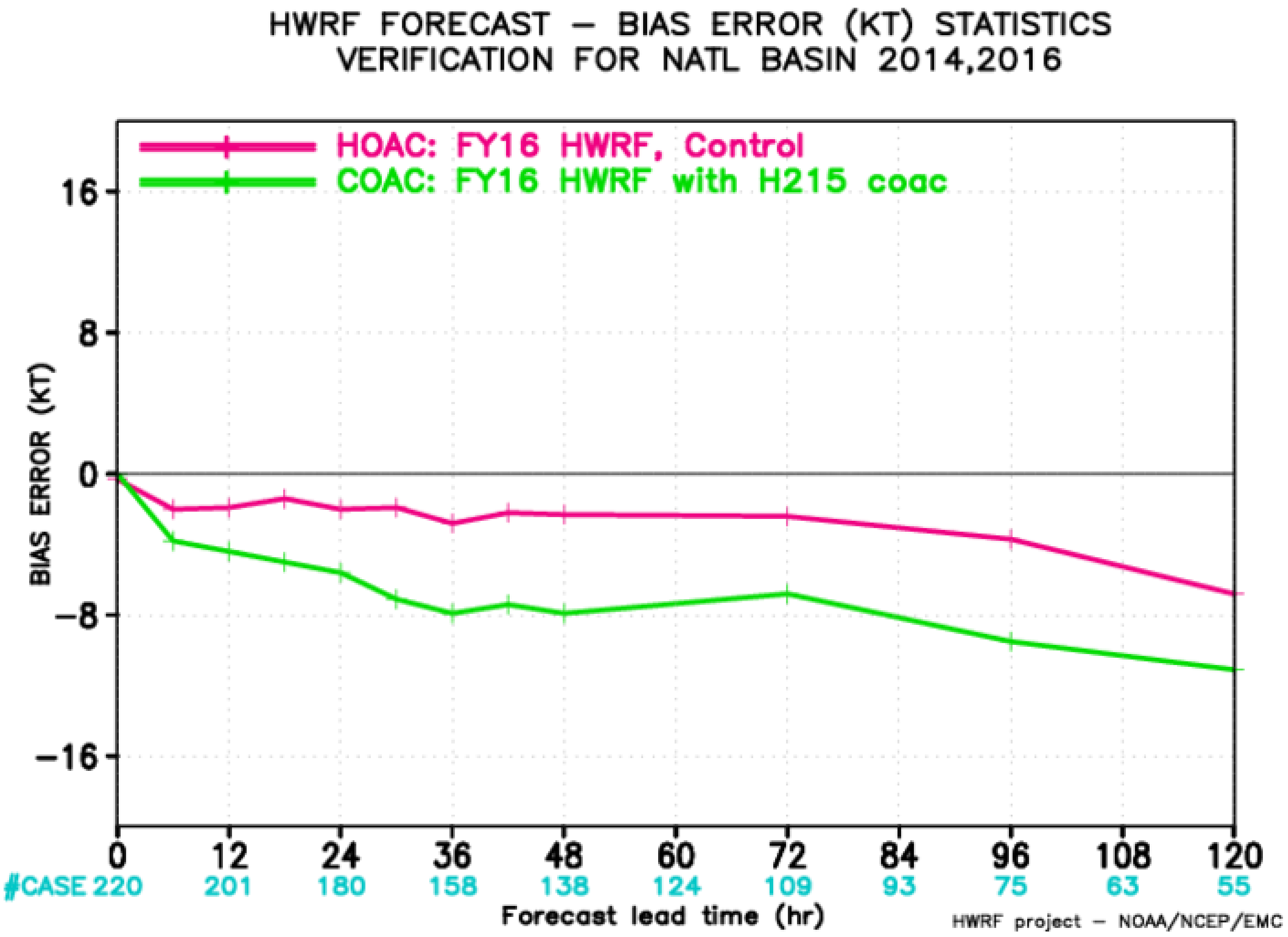
Impact of reduced L_h in H216 on HWRF forecasts

(Zhang et al. 2018WAF)



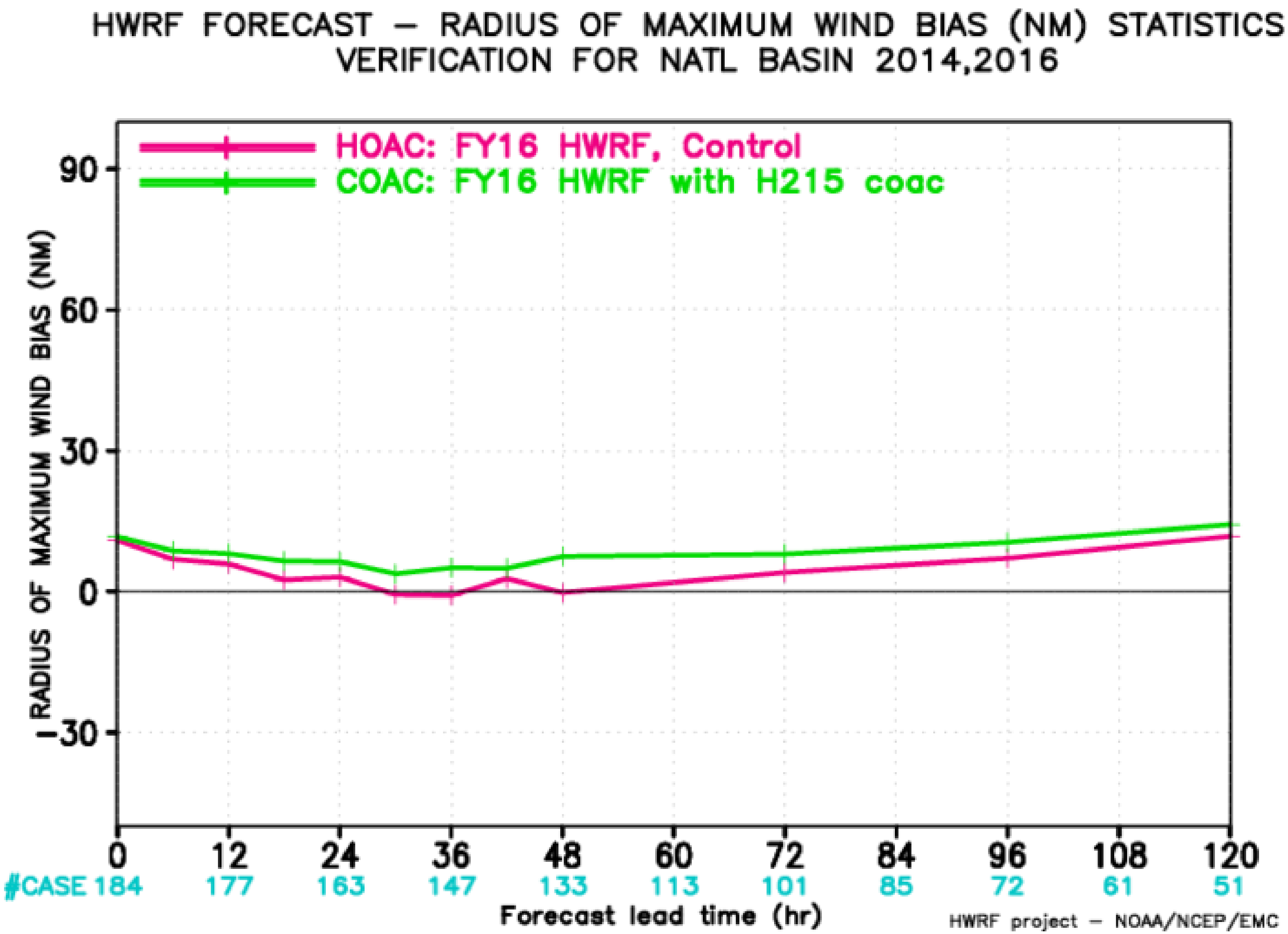
Impact of reduced L_h in H216 on HWRF forecasts

(Zhang et al. 2018WAF)



Impact of reduced L_h in H216 on HWRF forecasts

(Zhang et al. 2018WAF)



Summary

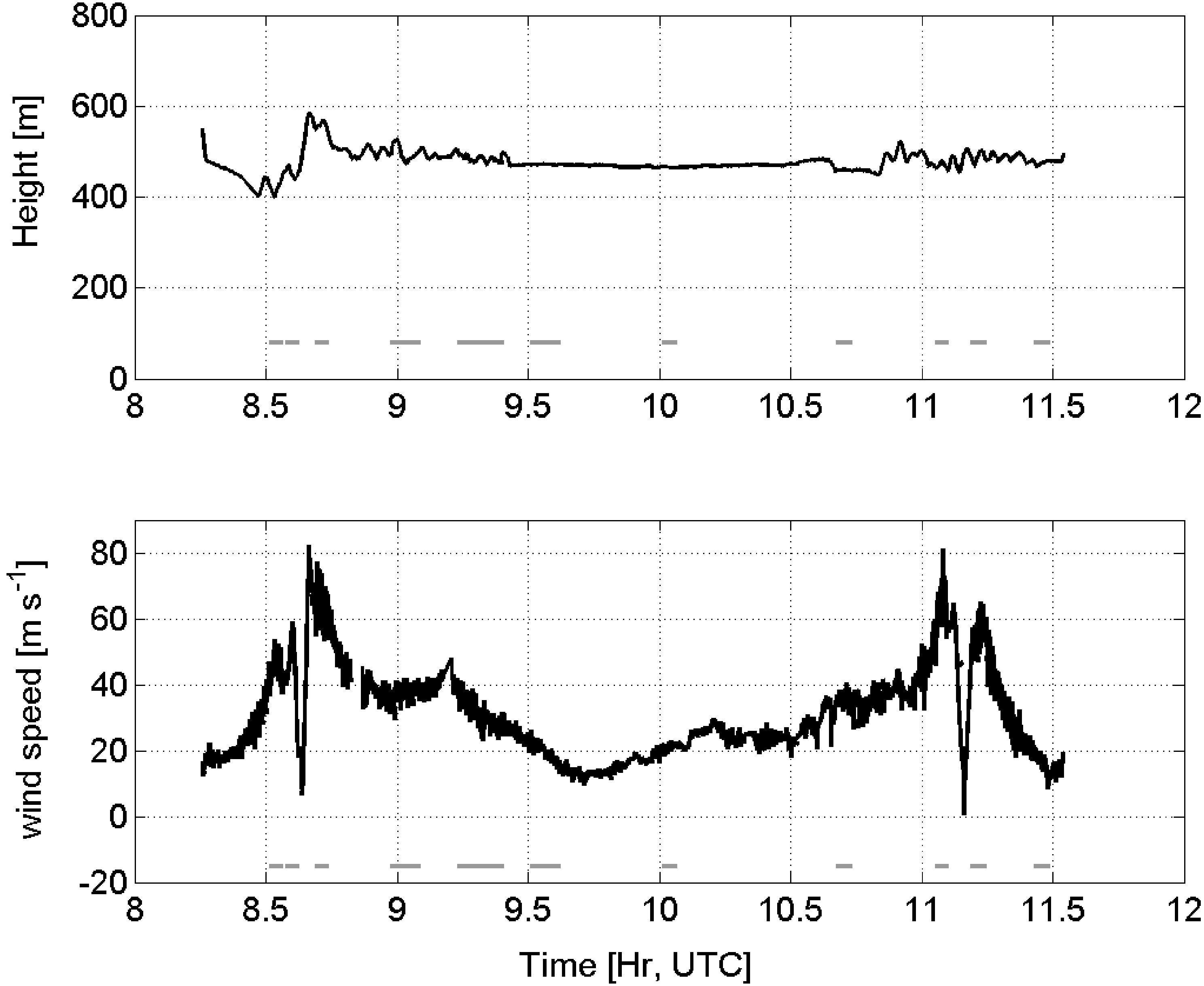
1. Successful Examples of Research to Operations (R2O) are shown in terms of using observational data to improve turbulence parameterizations in HWRF.

2. Model deficiency can be identified through model diagnostics of TC structures against observations.

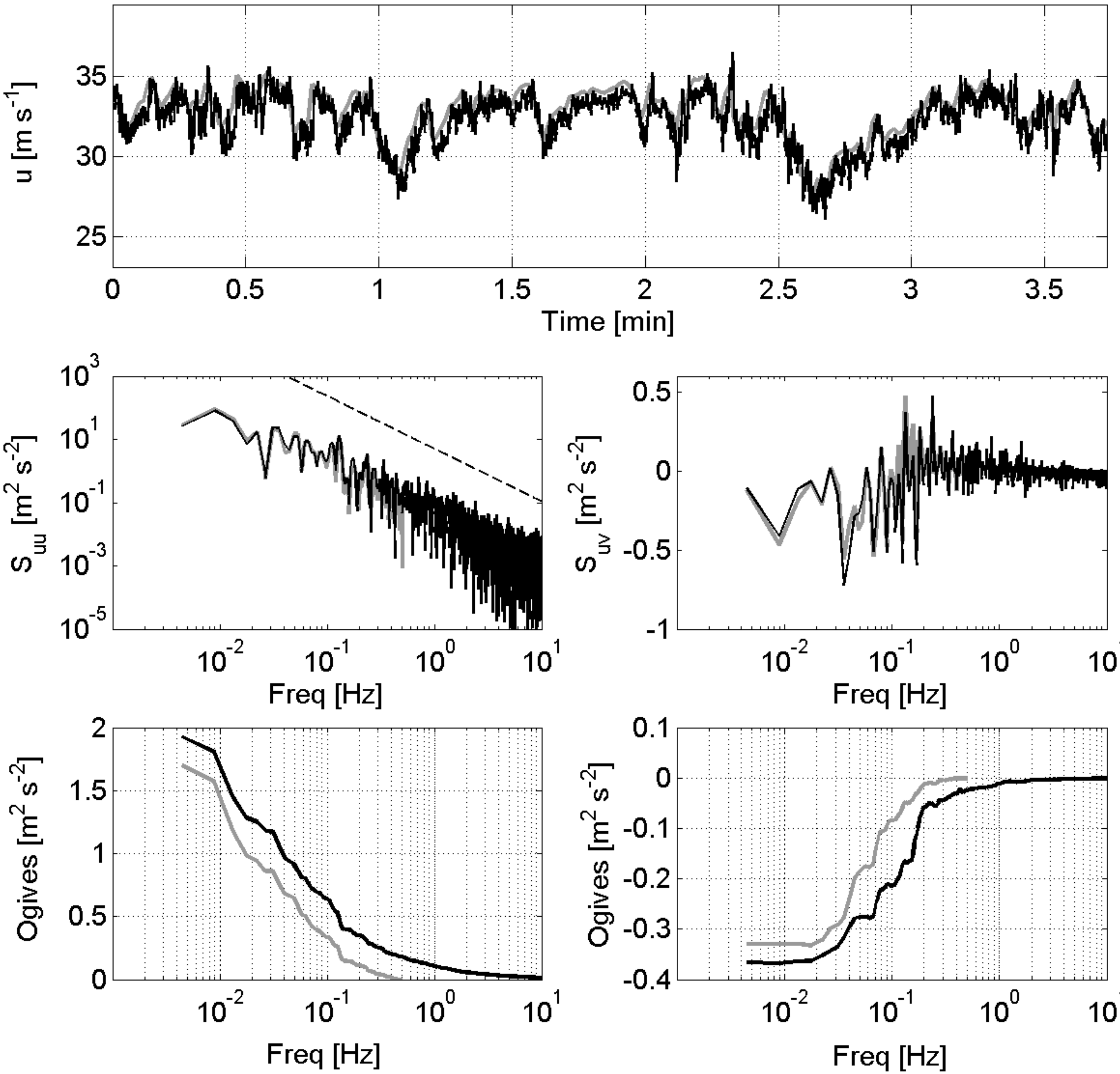
3. Turbulence observations provide baseline for model physics improvement.

4. Observation-based turbulence parameterizations led to improvements in hurricane intensity and structure forecasts.

Backup slides

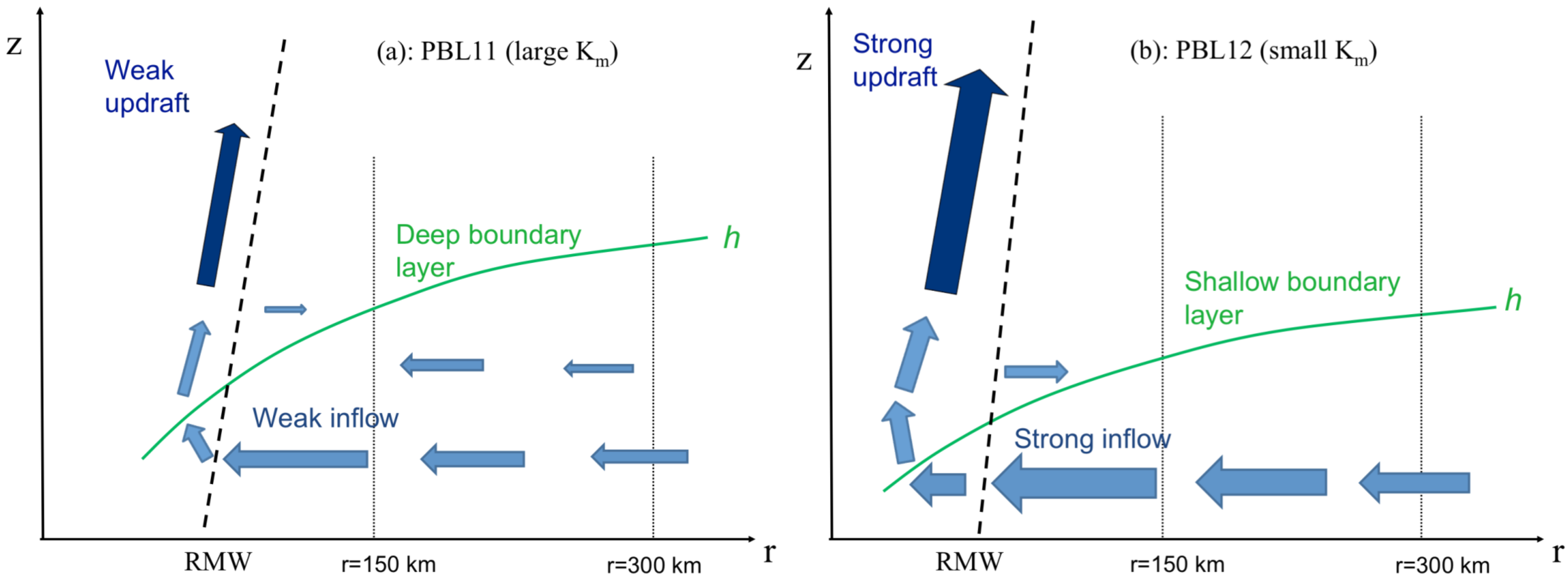


800
600
400
200
0
Height [m]
8
8.5
9
9.5
10
10.5
11
11.5
12
80
60
40
20
0
-20
wind speed [m s^-1]
8
8.5
9
9.5
10
10.5
11
11.5
12
Time [Hr, UTC]



u [m s-1]
35
30
25
0
0.5
1
1.5
2
2.5
3
3.5
Time [min]
S uu [m2 s-2]
10^3
10^1
10^-1
10^-3
10^-5
10^-2
10^-1
10^0
10^1
Freq [Hz]
S uv [m2 s-2]
0.5
0
-0.5
-1
Freq [Hz]
Ogives [m2 s-2]
2
1.5
1
0.5
0
Freq [Hz]
Ogives [m2 s-2]
0.1
0
-0.1
-0.2
-0.3
-0.4
Freq [Hz]

Effects of vertical diffusion on hurricane structure

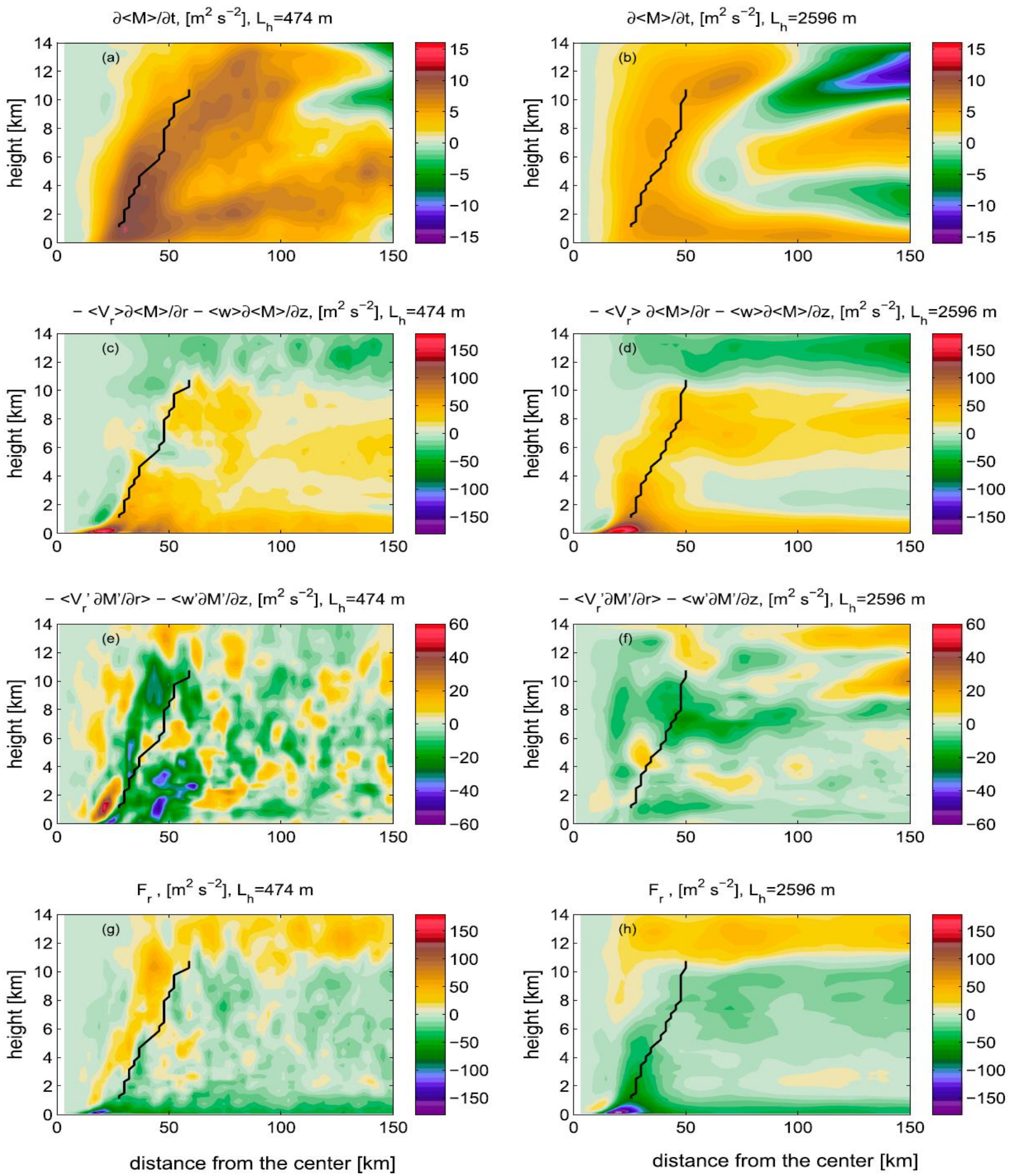


Why does the vertical diffusion in the boundary layer have such a profound effect on the structure and intensity of hurricanes?

(Jun Zhang et al. 2015, MWR)

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.

Effects of horizontal diffusion on the hurricane spin-up dynamics

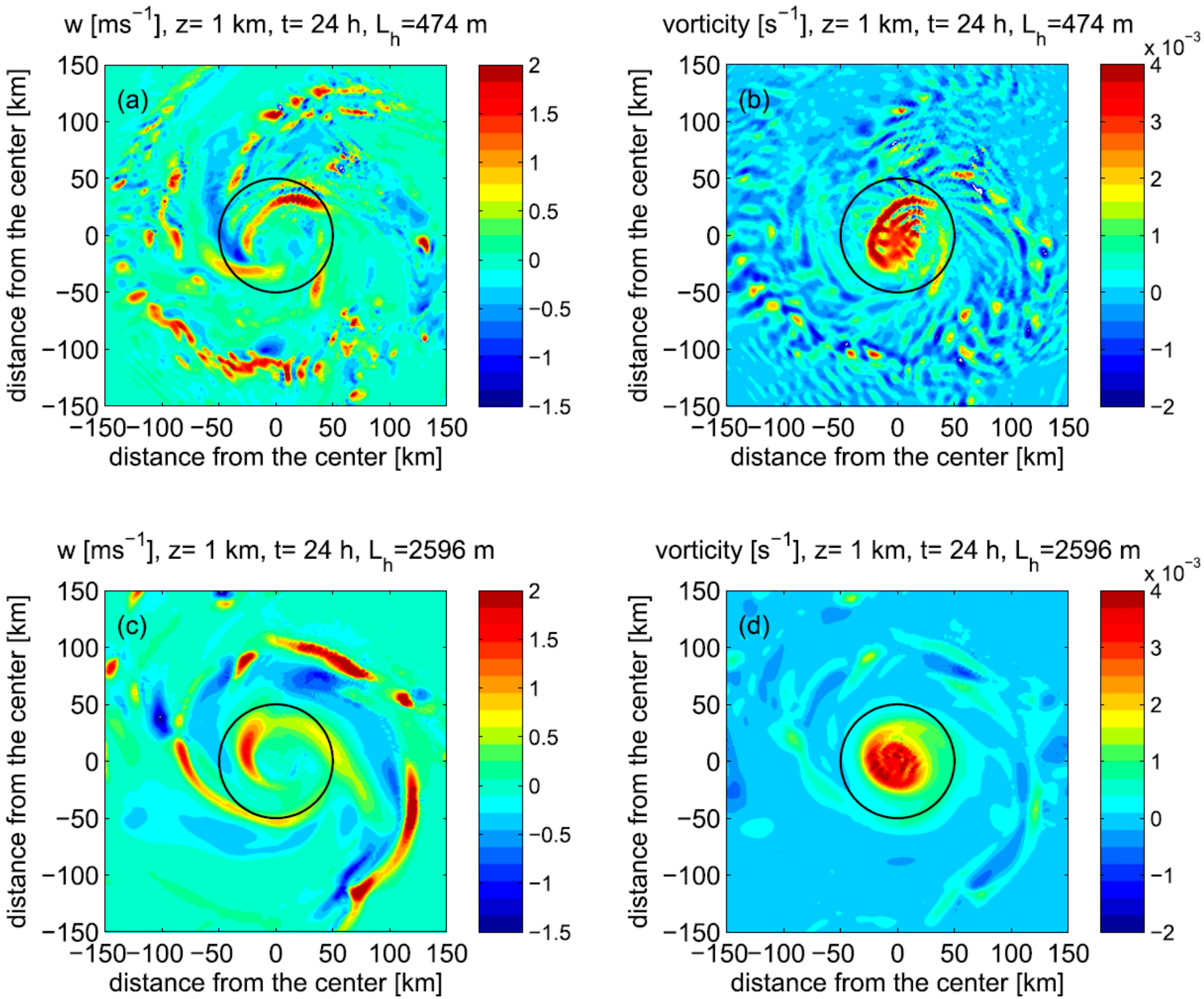


Angular momentum budget

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

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)



(Jun Zhang and F. Marks 2015, MWR)

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:

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

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):

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

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

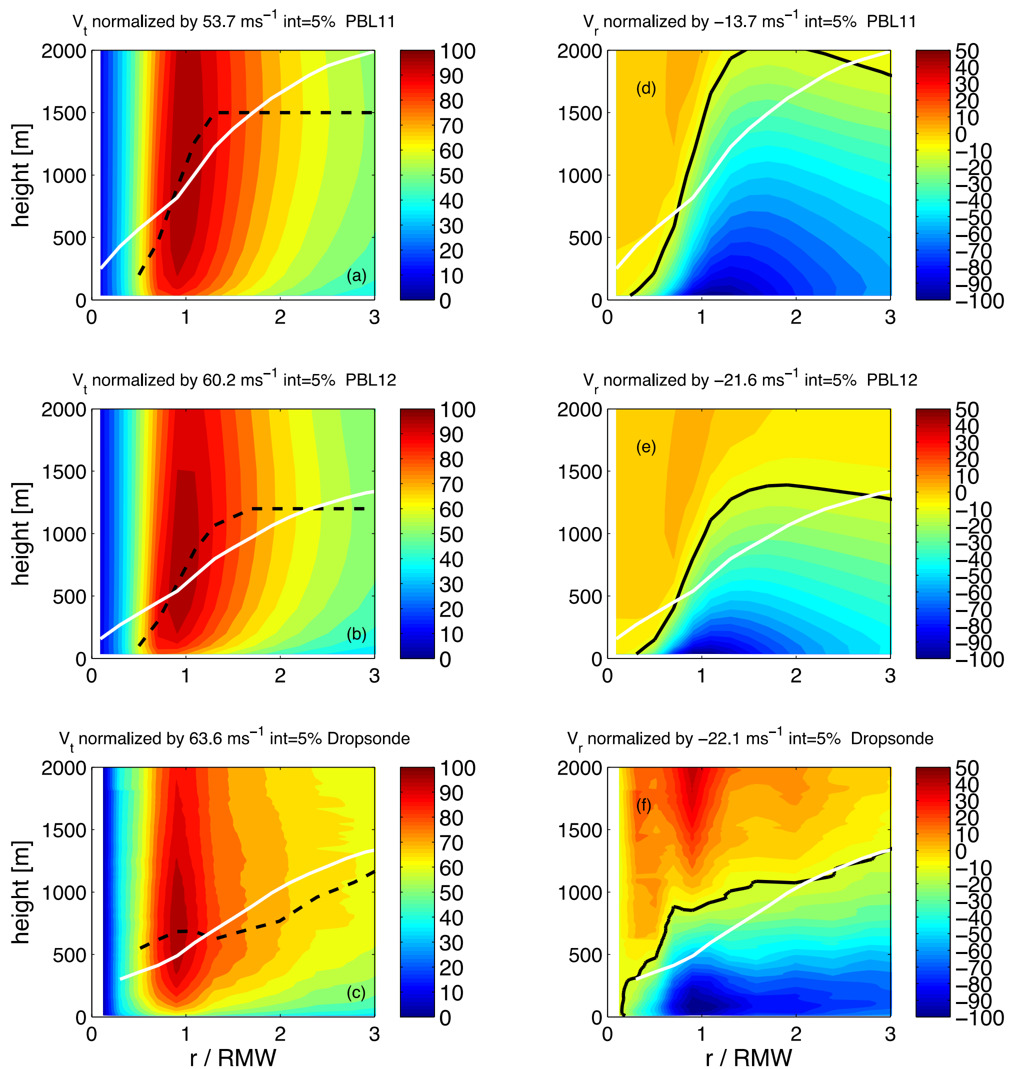
Further Evaluation: Improved Hurricane Structure

PBL11 :

PBL12 :

Dropsonde Composite :

(Jun Zhang et al. 2011b MWR)



Model composites of 120 HWRF forecasts of four hurricanes (PBL11 and PBL12)