Improving Hurricane Model Physics using Aircraft Observations

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NOAA/AOML/Hurricane Research Division with University of Miami/CIMAS

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Acknowledgement

Collaborators and coauthors:

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Michael Montgomery, Gopal, and Vijay Tallapradada

EMC and HRD HWRF modeling team members

Scientists and aircraft crew who helped with collecting the data used in this study, in particular who participated the CBLAST experiment and Hurricanes Hugo, Allen and David missions.

Support from Hurricane Forecast and Improvement Program (HFIP)

Outline

- Background and objectives

- A developmental framework for improving hurricane model physics:

  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

- Ongoing and future work

As part of NOAA's Hurricane Forecast and Improvement Project (HFIP)

- To improve the accuracy and reliability of hurricane forecasts
- To extend lead time for hurricane forecasts with increased certainty
- To increase confidence in hurricane forecasts

"These efforts will require major investments in enhanced observational strategies, improved data assimilation, numerical model systems and expanded forecast applications based on high-resolution and ensemble-based numerical prediction systems".

Objectives of this work

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

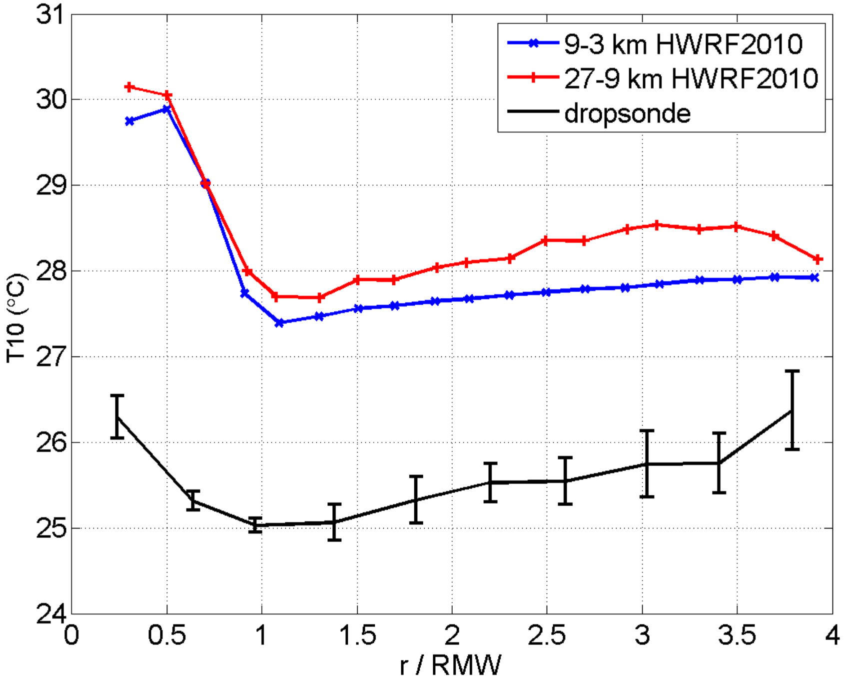
- To develop advanced model diagnostic techniques to support model improvements and identification of sources of model errors.

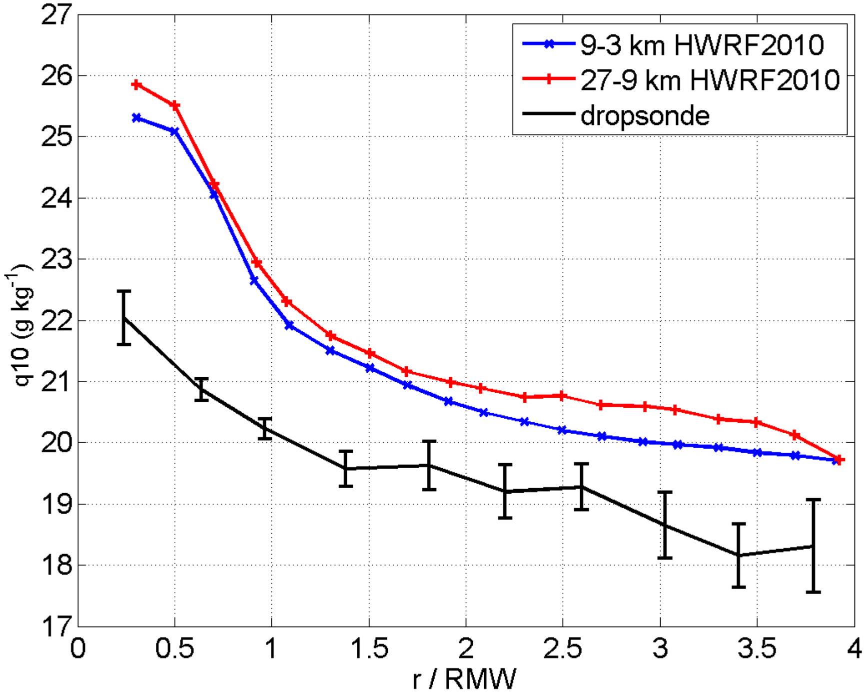
(1) *Develop advanced model diagnostics to identify model deficiency and errors through comparison with observations*

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. 2011 MWR)

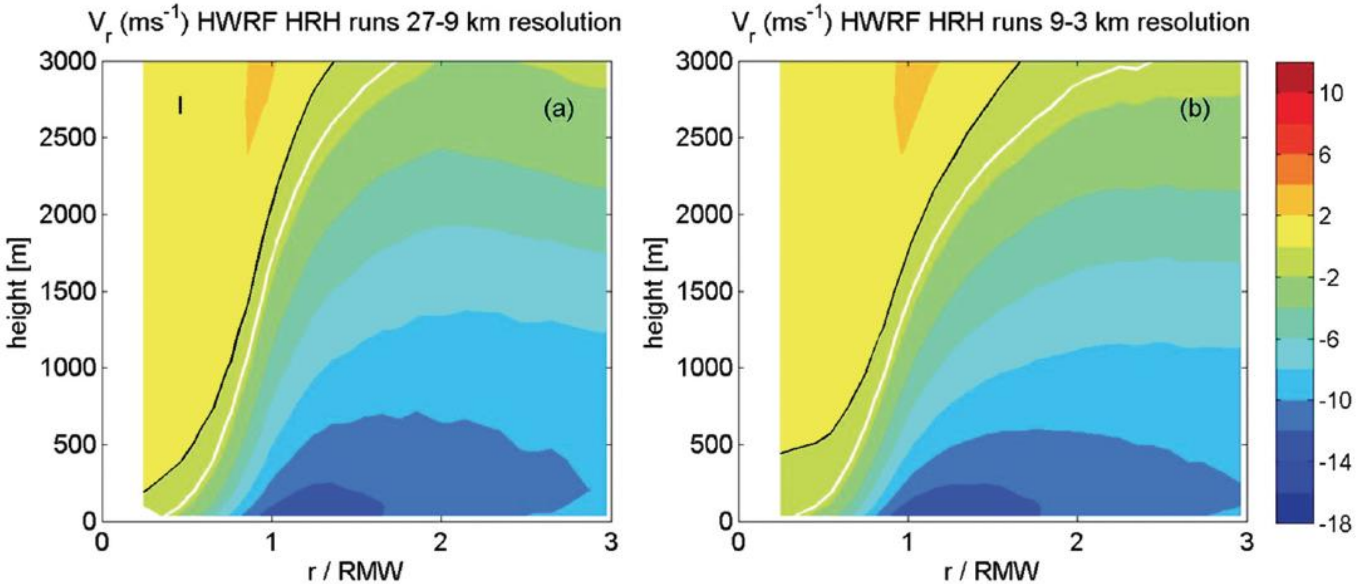


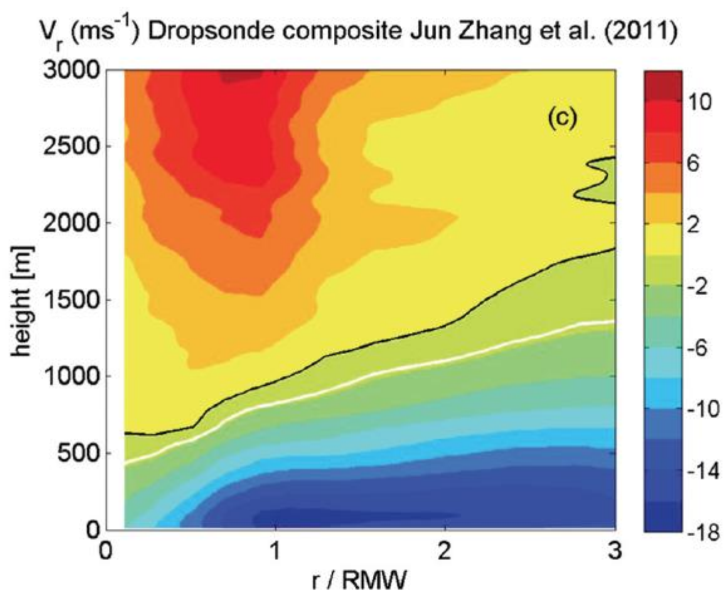


The simulated surface layer is too warm and too moist compared to observations.

Boundary-layer structure diagnostics

Model: 2010 version HWRF

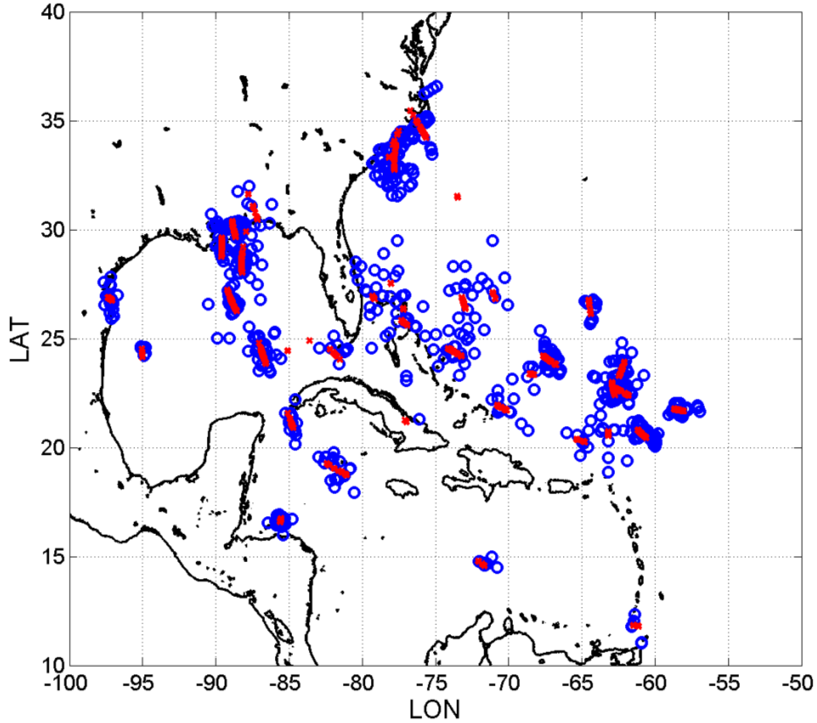


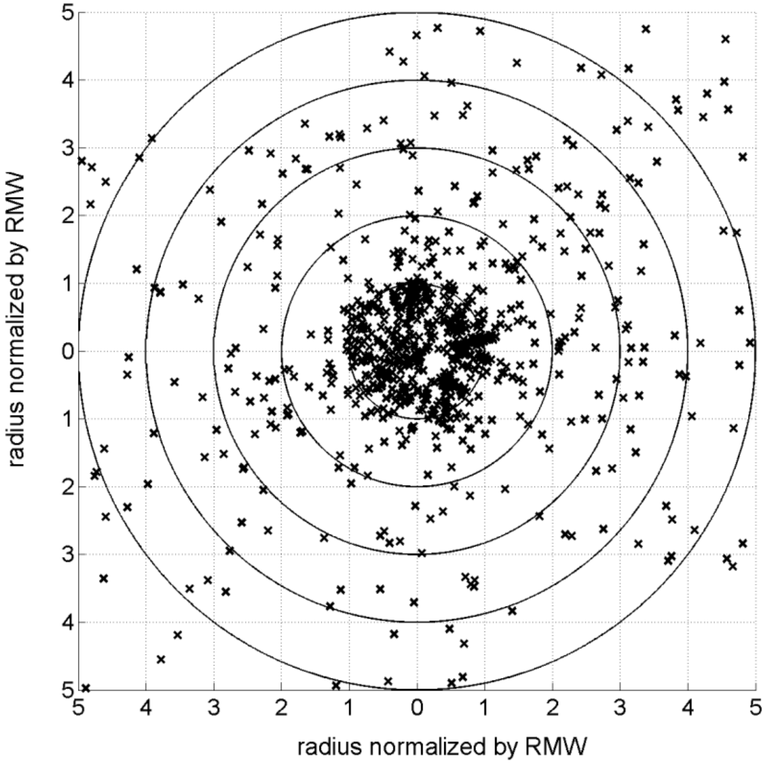


Simulated boundary layer is too deep compared to observations!

Compositing Dropsonde data

Zhang, Rogers, Nolan and Marks, 2011a MWR

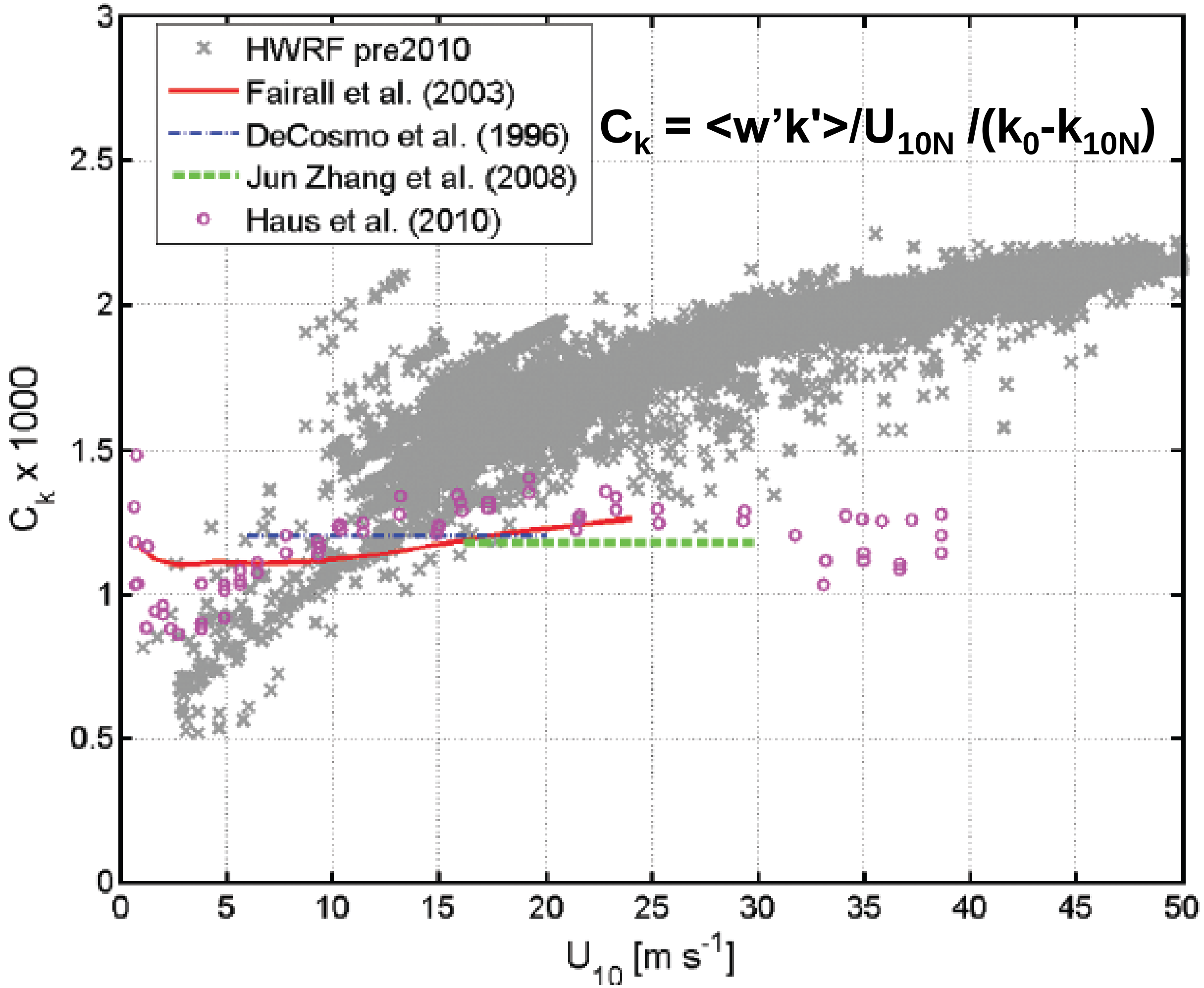




A total of 2231 dropsonde data from 13 hurricanes have been analyzed, and 794 of them are used in the final analysis that have surface (10 m) measurements.

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

Why is the simulated surface layer too warm and moist?

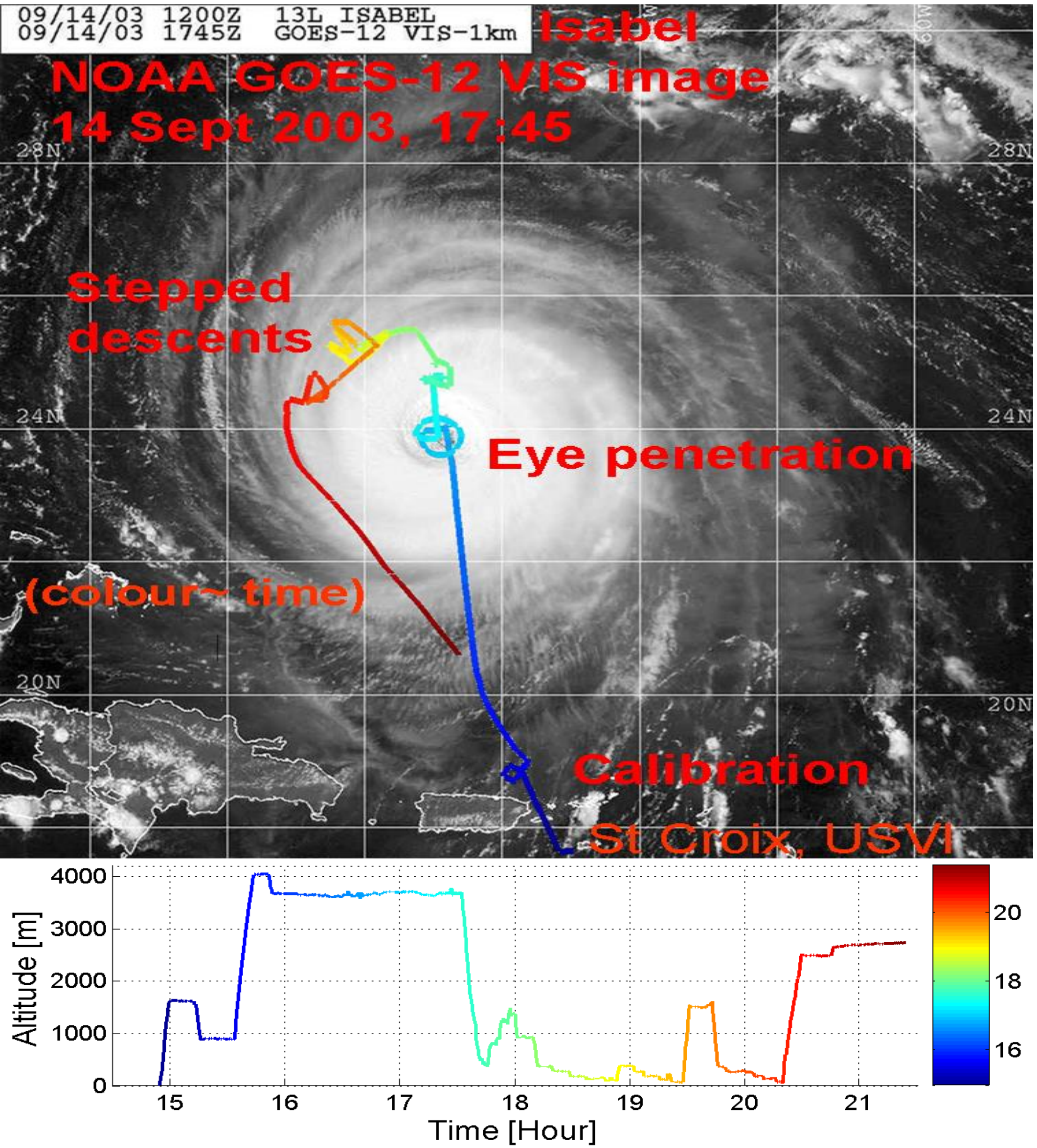


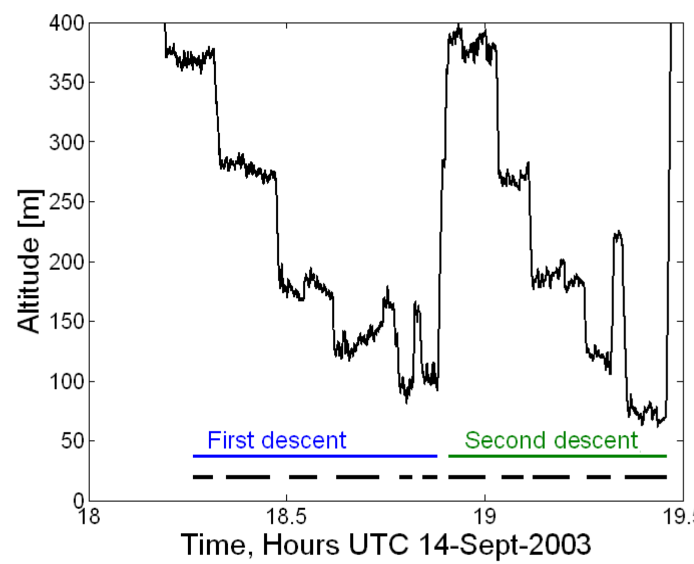
Feedback to Young Kwon and Bob Tuleya when they visited HRD

Surface enthalpy exchange coefficients (C_k) are too large!

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

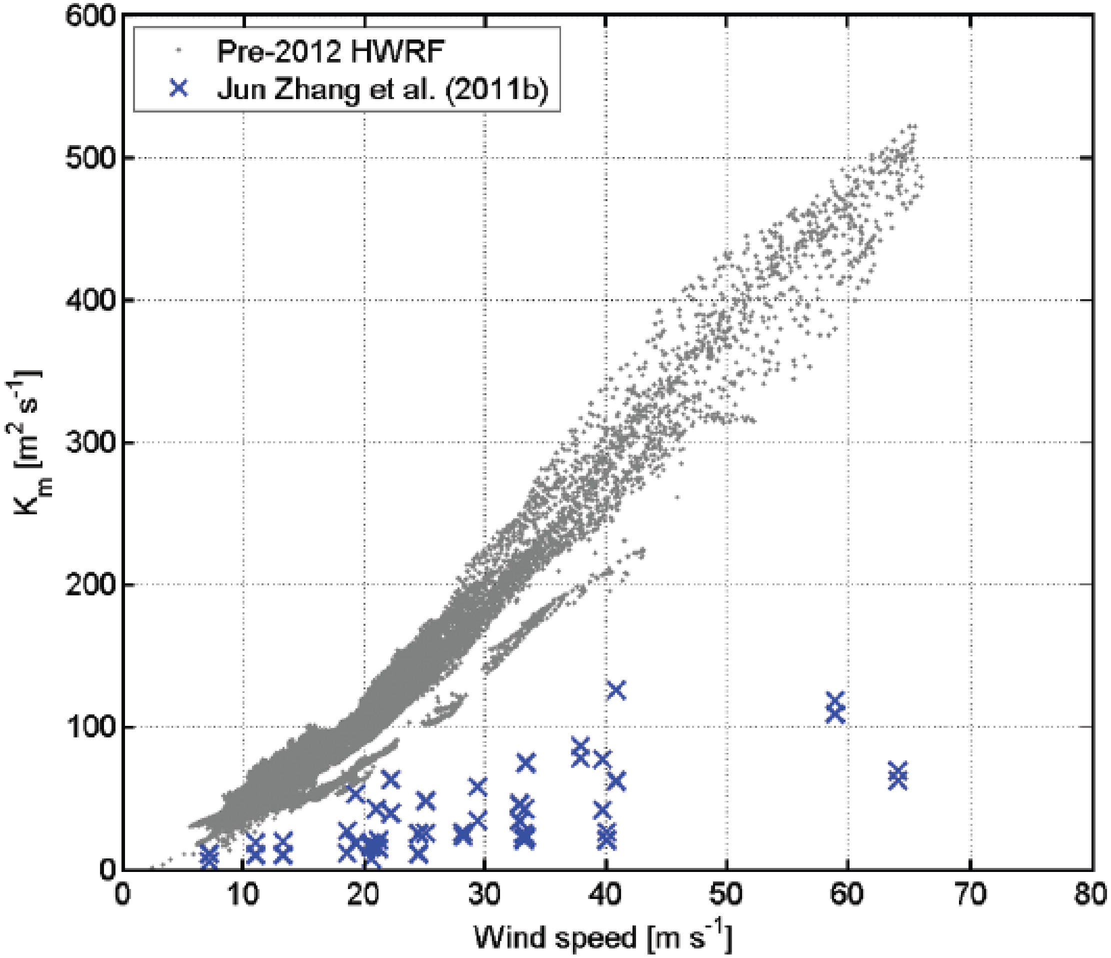
Jun Zhang et al. 2008 GRL





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

Working with Gopal and Frank Marks to identify the problem

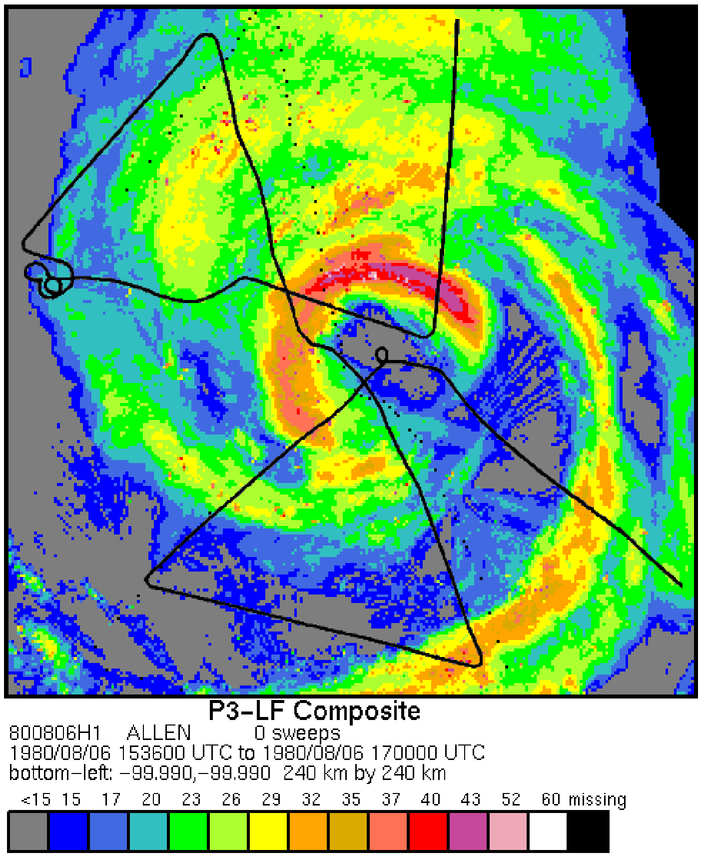
The PBL scheme used in prior 2011 version HWRF is too diffusive!

Data used for eddy diffusivity calculation

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

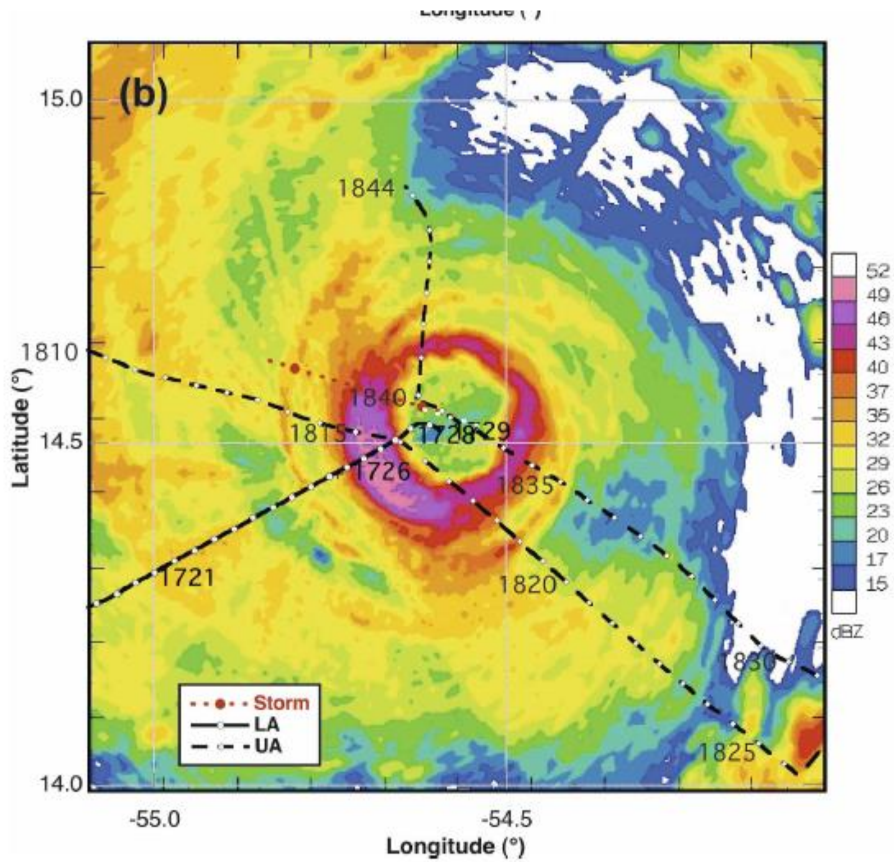
We use the flight-level data that were collected using the low-level eyewall penetrations of Hurricanes Allen (1980), Hugo (1989) and David (1979).

Allen, Aug. 6, 1980



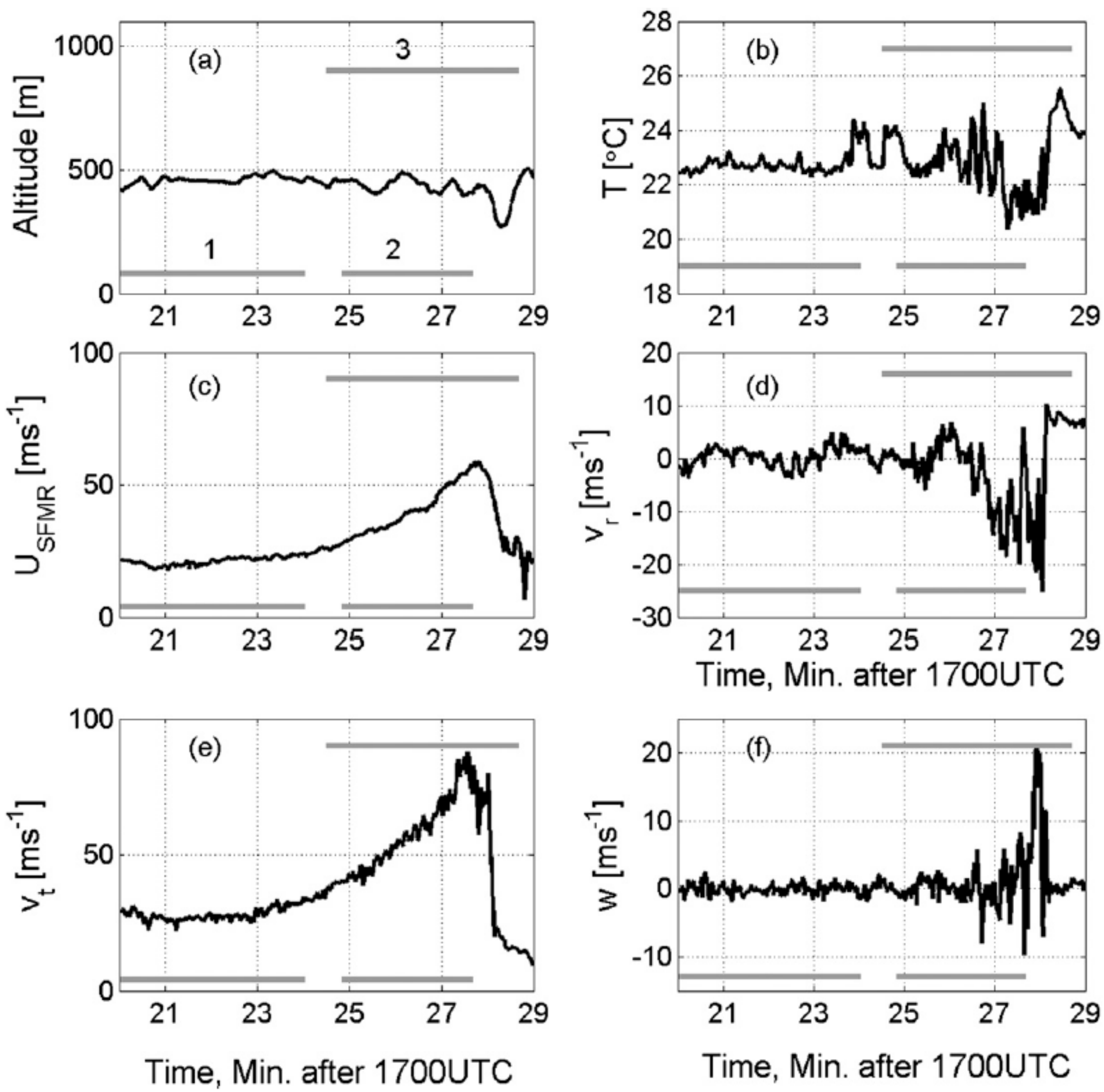
(Marks 1985)

Hugo, Aug. 15, 1989



(Marks et al. 2008 MWR)

Hurricane Hugo flight

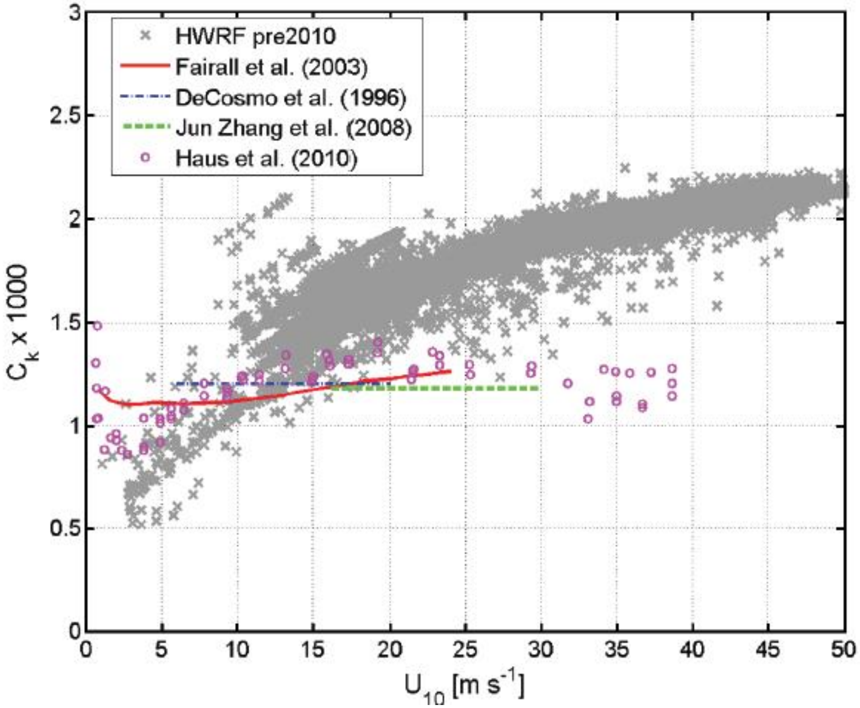


Run # 3 includes Eyewall Vorticity Maxima (EVM)

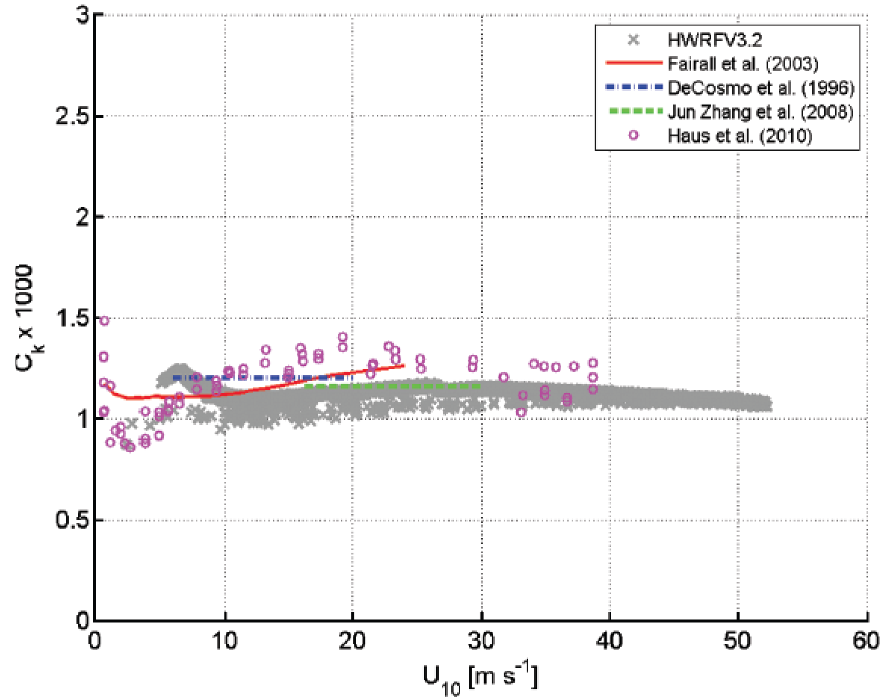
(3) *Work with model developers to improve model physics based on observations*

Implementation of observation-based physics in HWRF

Pre 2010 HWRF

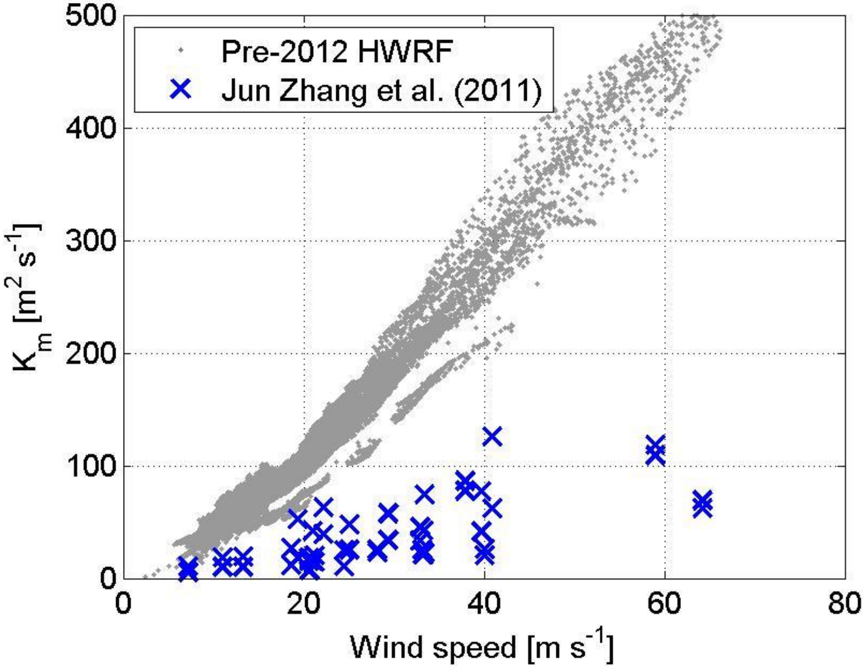


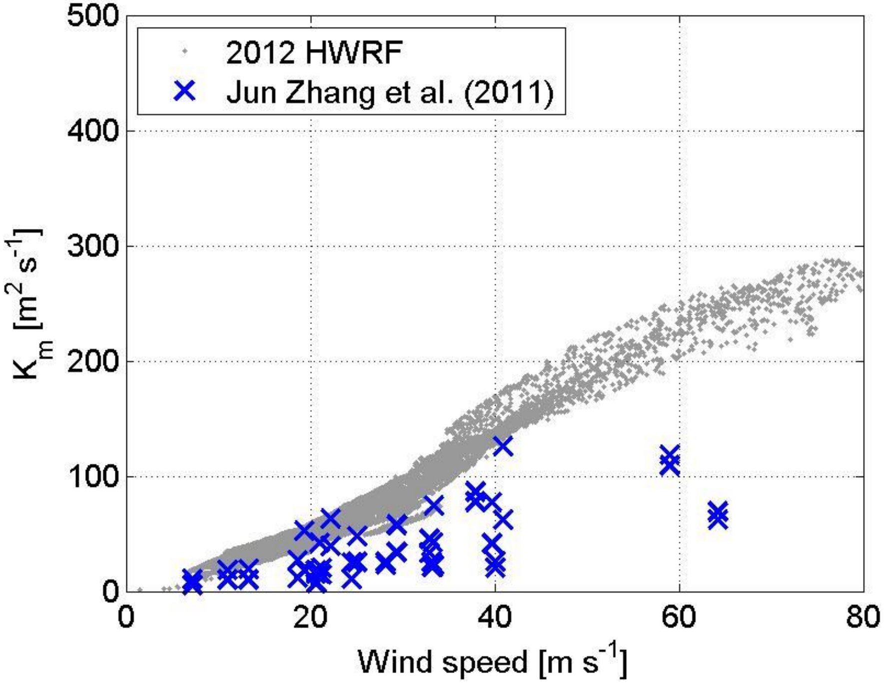
2010 HWRF and thereafter



Use observations to improve PBL physics in the operational hurricane HWRF

(Jun Zhang et al. 2012)

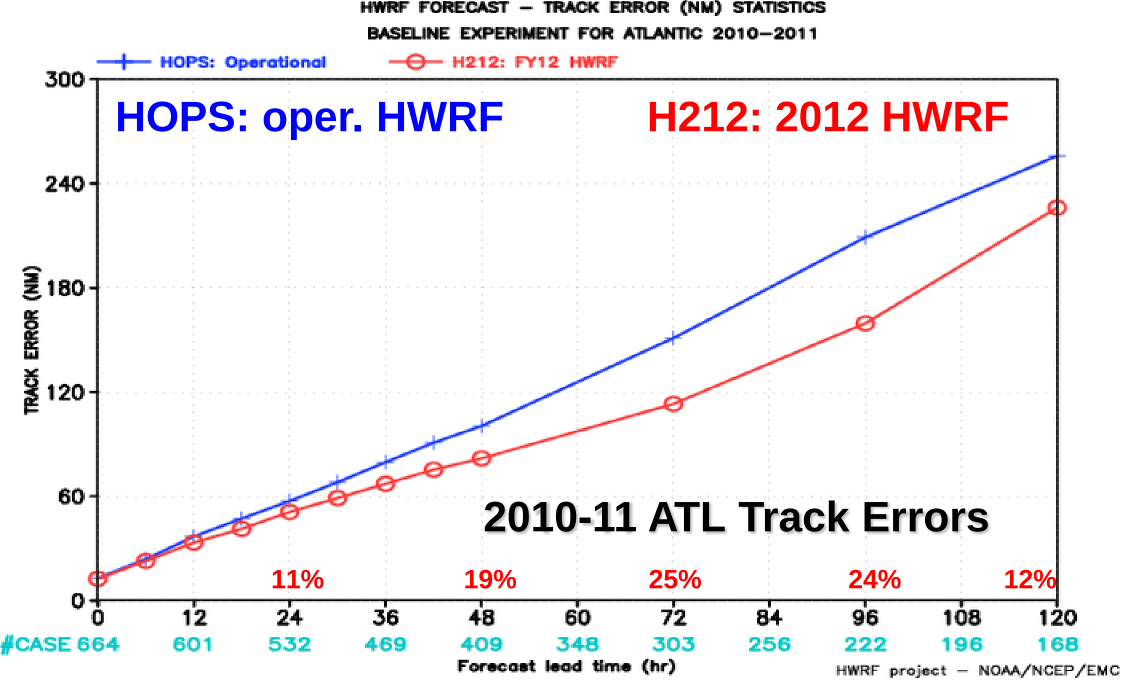


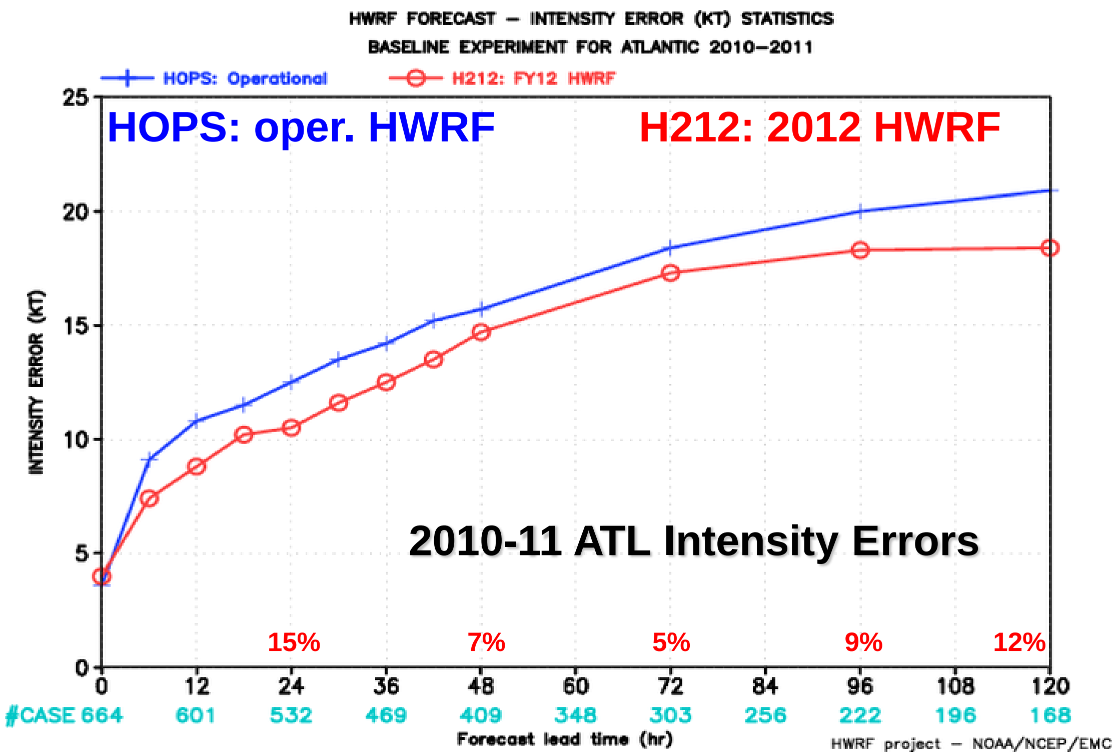


Before modification

After modification

(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

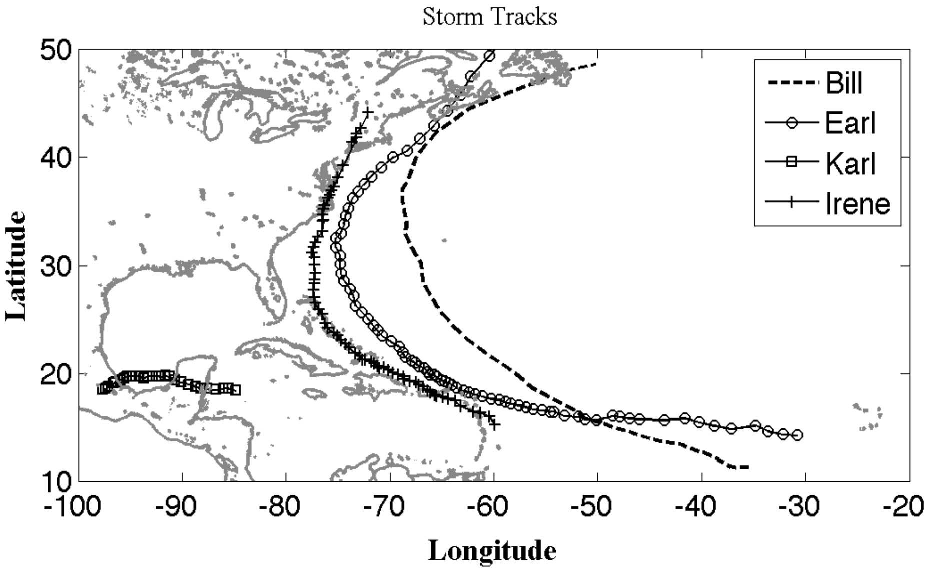
37 Storms

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)

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

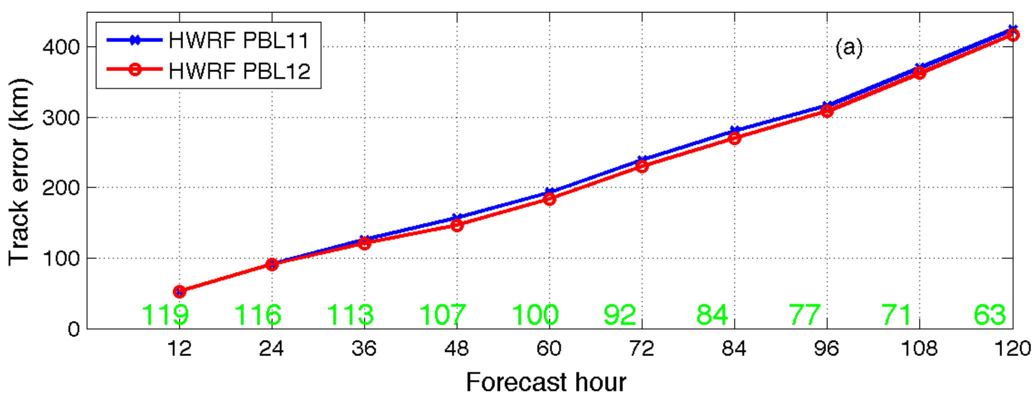
$\alpha = 1$ in PBL11

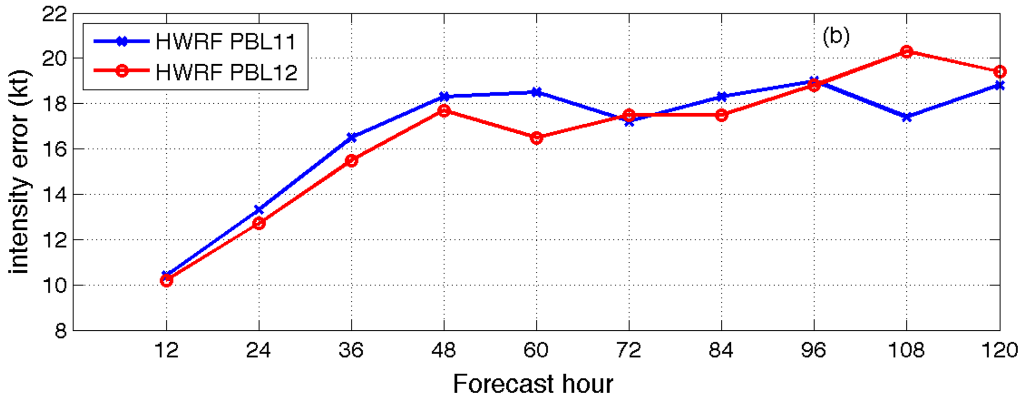
$\alpha = 0.5$ in PBL12

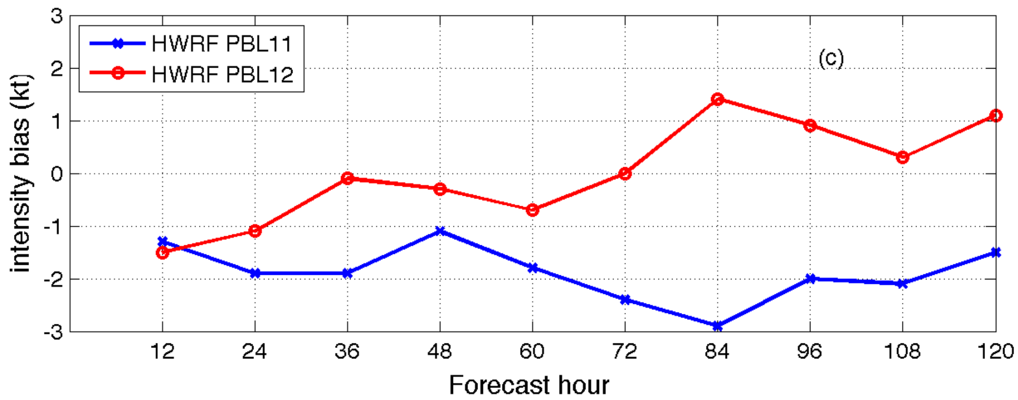
Storm name	Number of cycles of simulations	Starting time of the first cycle	Starting time of the last cycle
Bill	33	2009/08/15/18Z	2009/08/23/18Z
Earl	40	2010/08/25/18Z	2010/09/04/12Z
Karl	15	2010/09/14/18Z	2010/09/18/06Z
Irene	34	2011/08/20/18Z	2011/08/29/00Z

(Jun Zhang, Nolan, Rogers, and Tallapradada, 2015)

Track and Intensity Errors

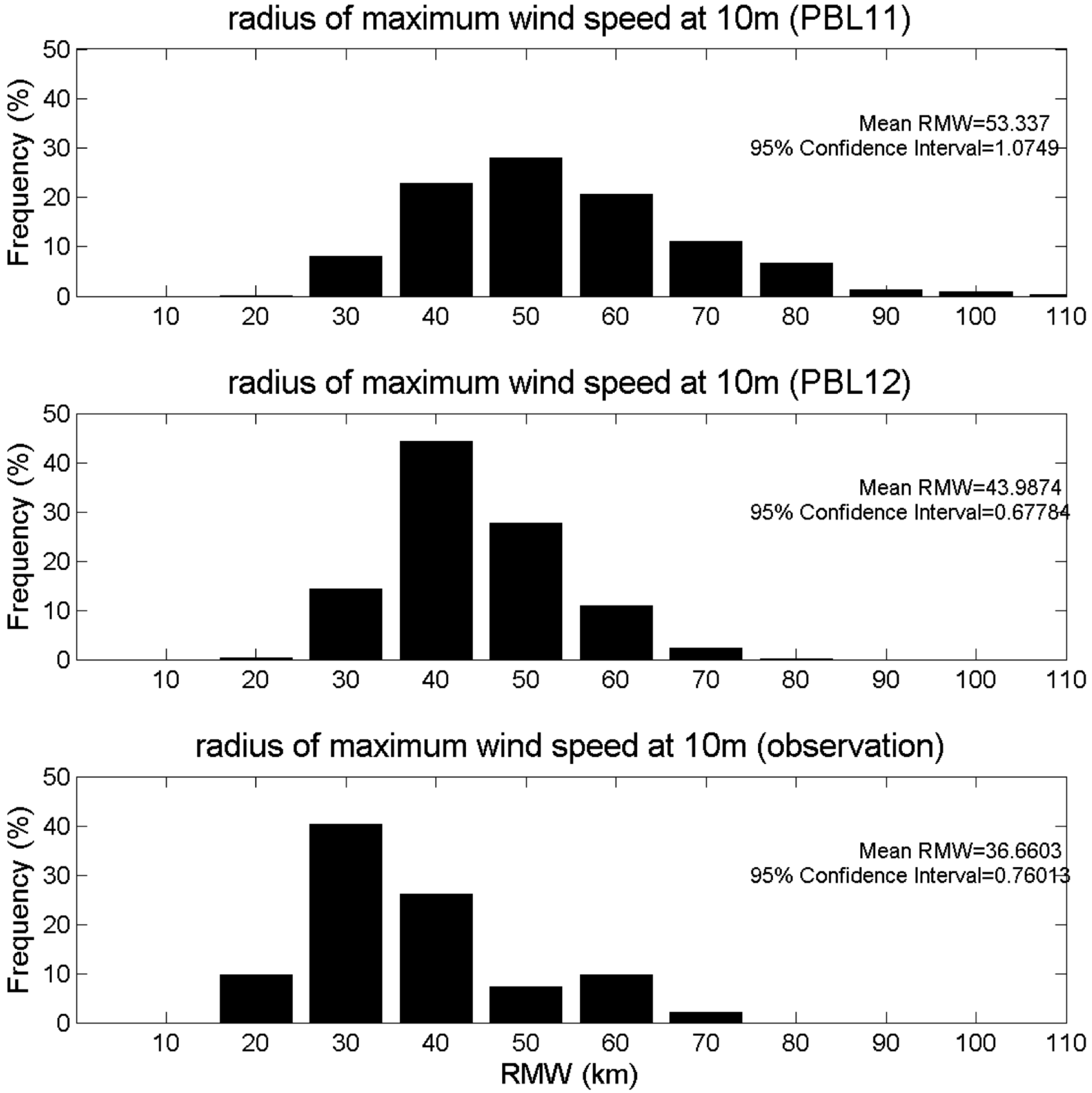




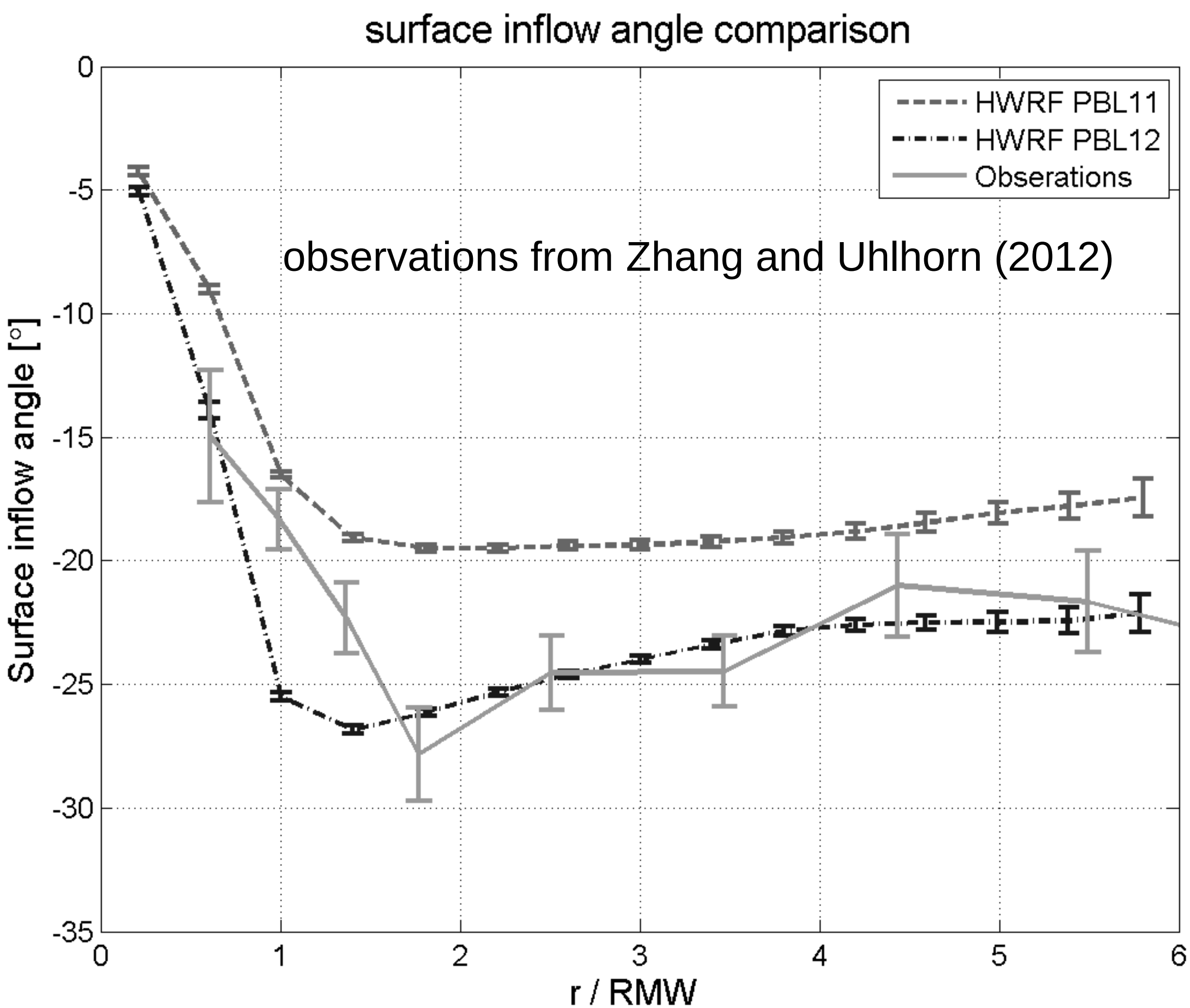


Storm Size

(Jun Zhang, Nolan, Rogers, and Tallapradada, 2015)



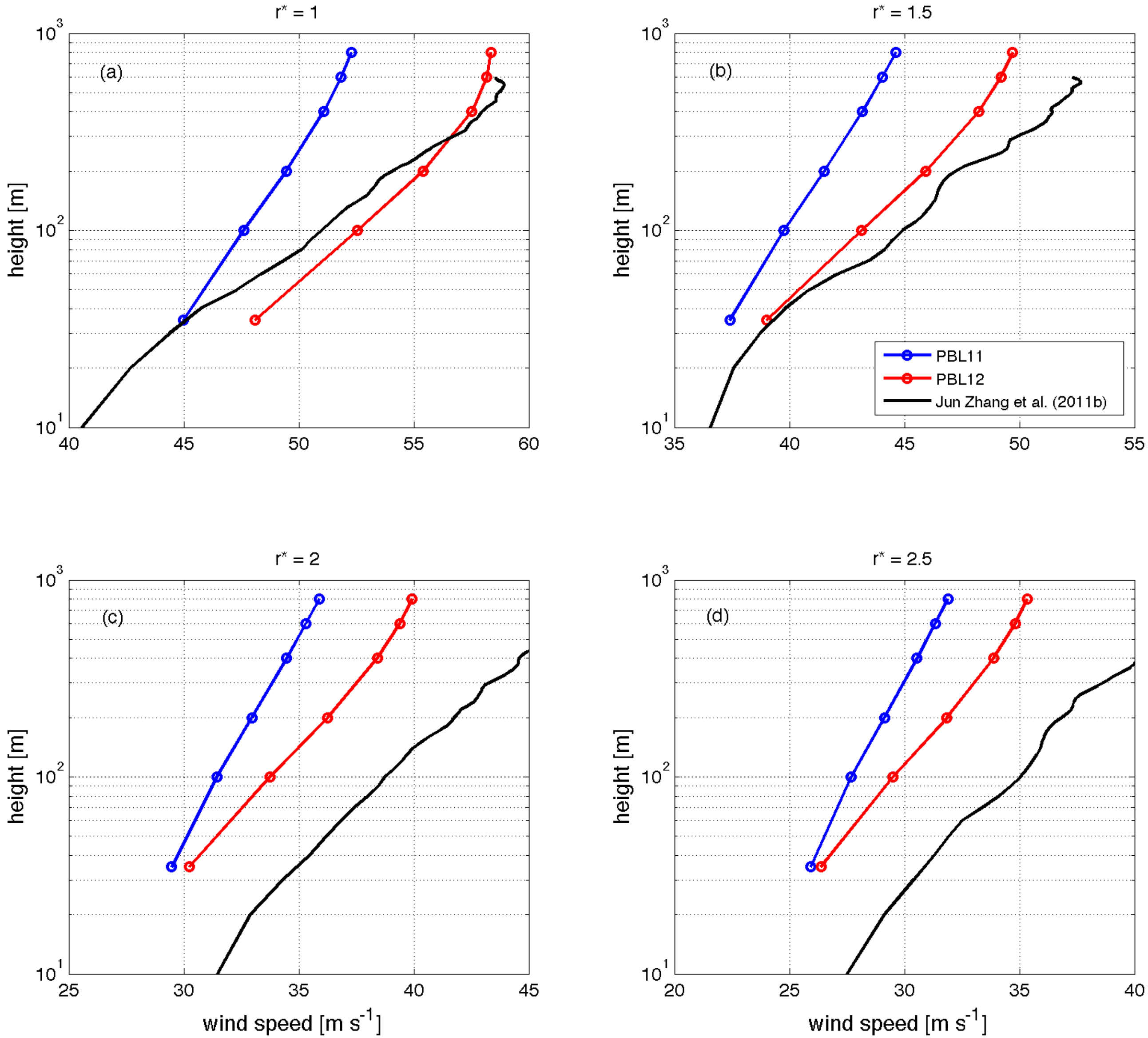
Surface inflow angle



(Jun Zhang, Nolan, Rogers, and Tallapradada, 2015)

Near surface layer wind profile

(Jun Zhang, Nolan, Rogers, and Tallapradada, 2015)



Kinematic boundary layer heights

(Jun Zhang, Nolan, Rogers, and Tallapradada, 2015)

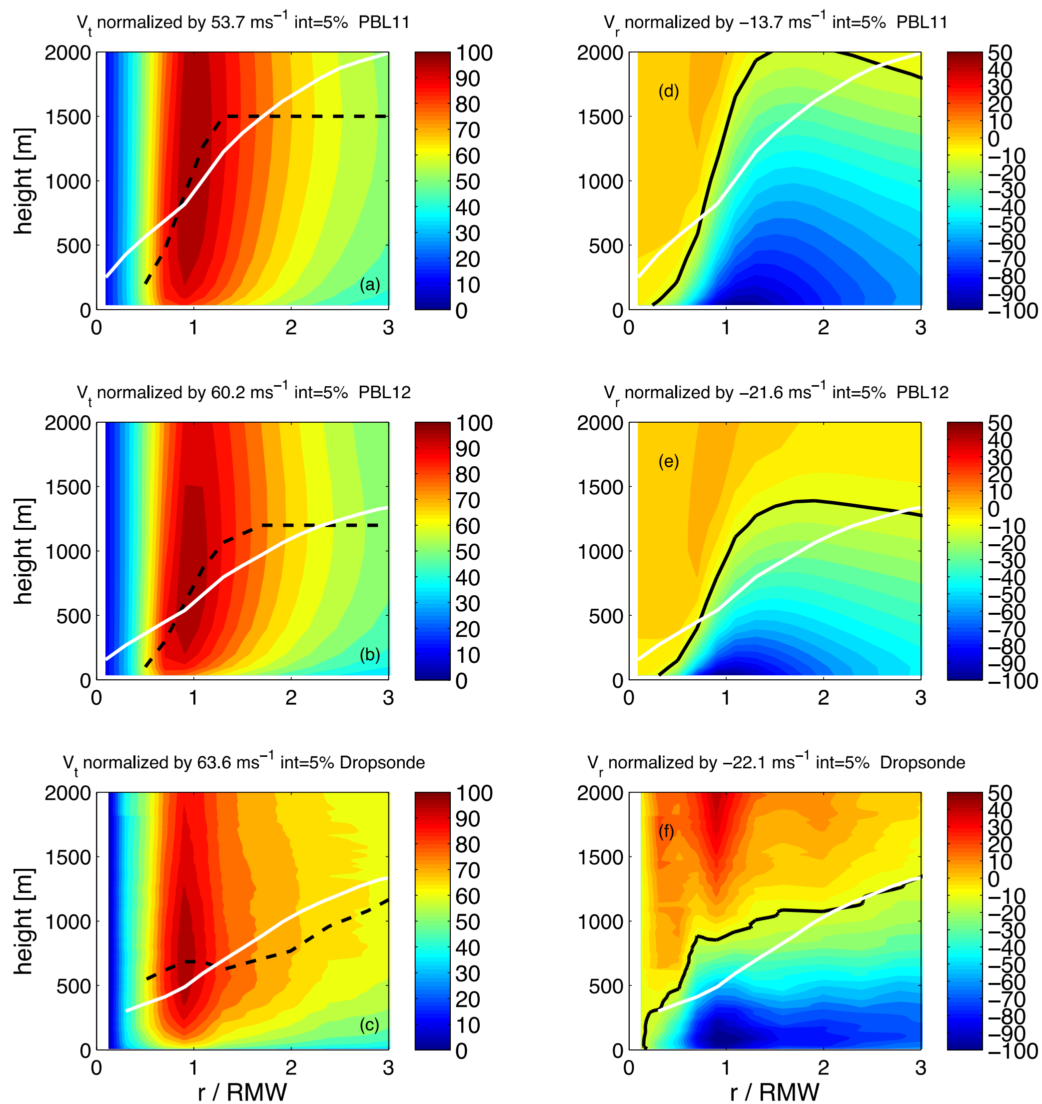
HWRF PBL11

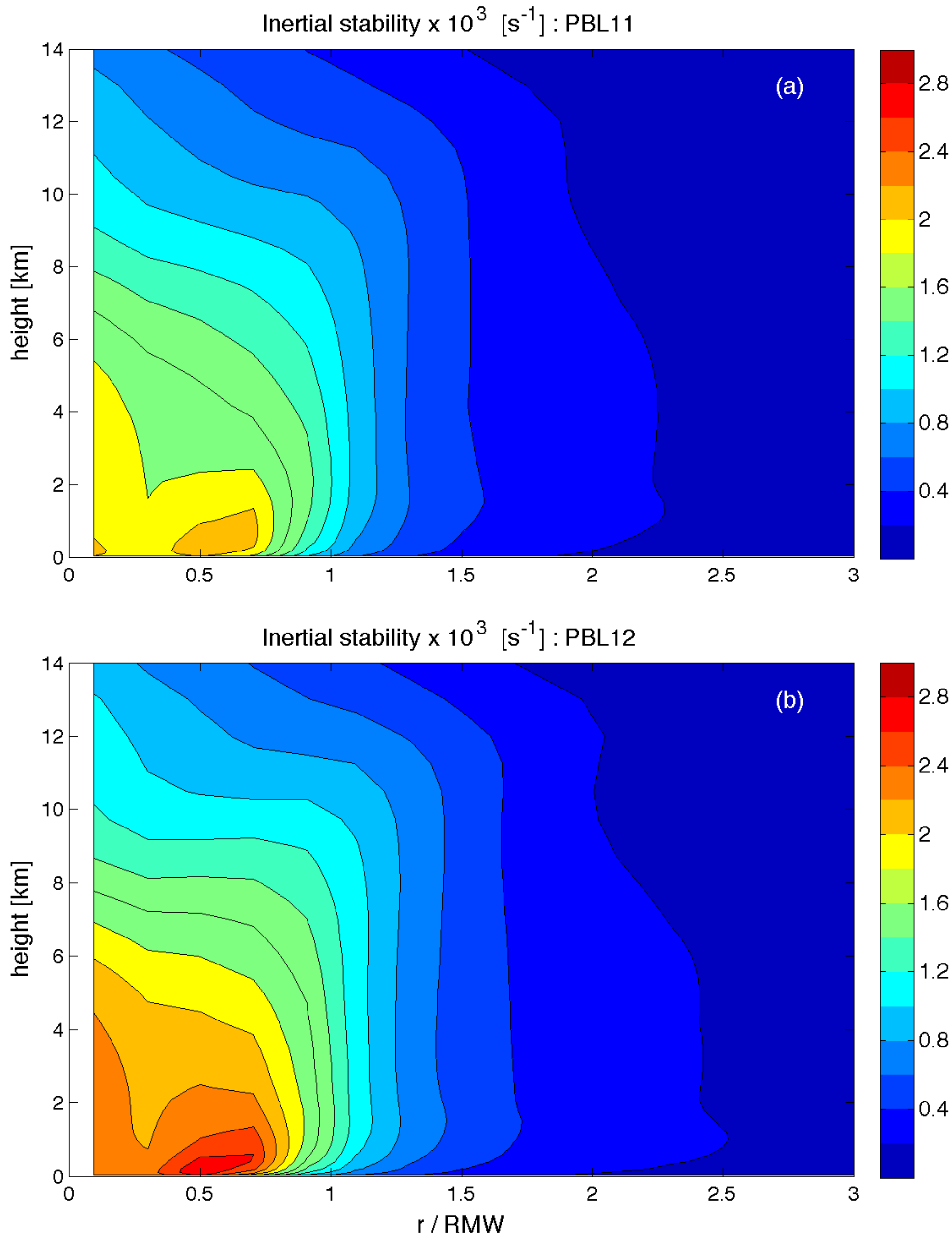
HWRF PBL12

Dropsonde

Composite

(Jun Zhang et al. 2011a)





$h = (2K_m/I)^{1/2}$

In linear hurricane boundary layer theory, the height of the maximum tangential wind speed (or boundary layer jet) is a function of vertical eddy diffusivity and inertial stability.

K_m in PBL12 is smaller than that in PBL11.

Thermodynamic boundary layer height

(Jun Zhang, Nolan, Rogers, and Tallapradada. 2015)

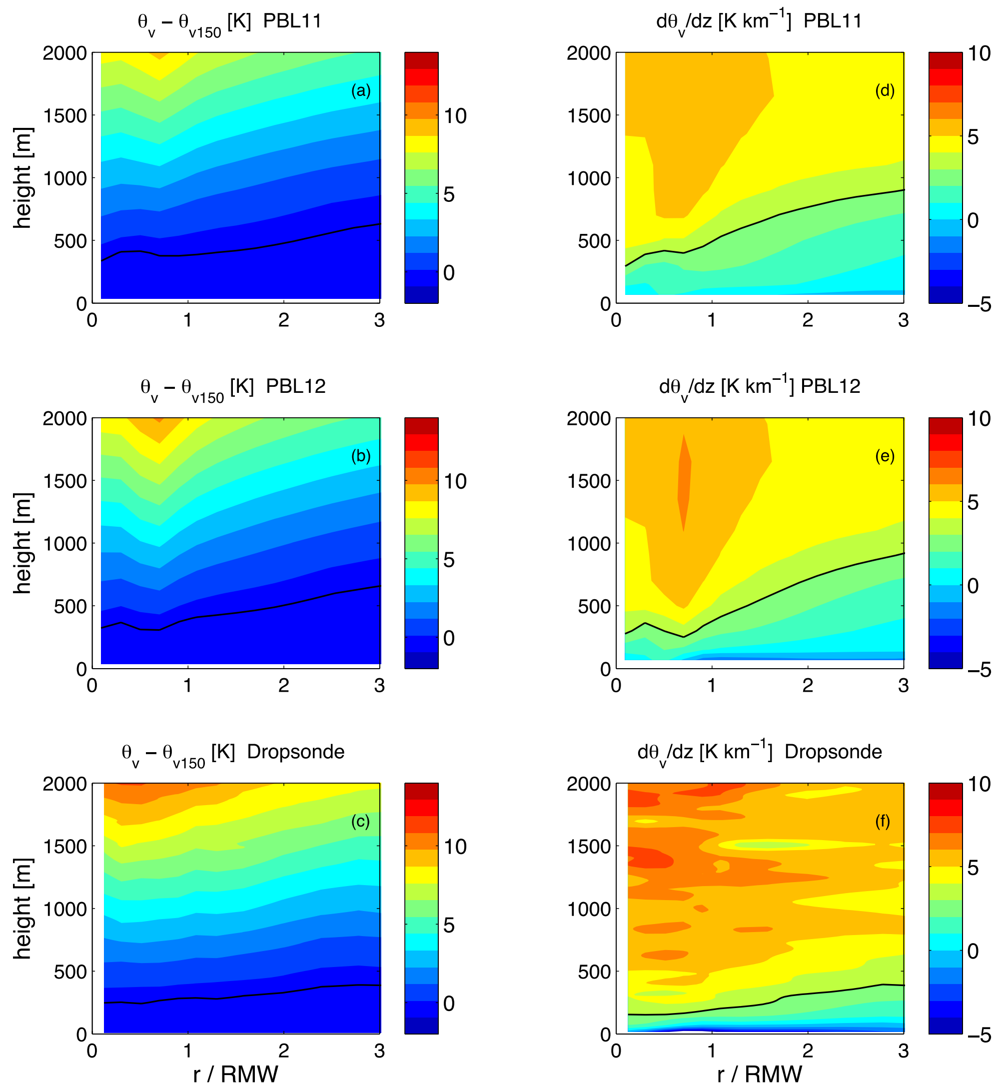
HWRF PBL11

HWRF PBL12

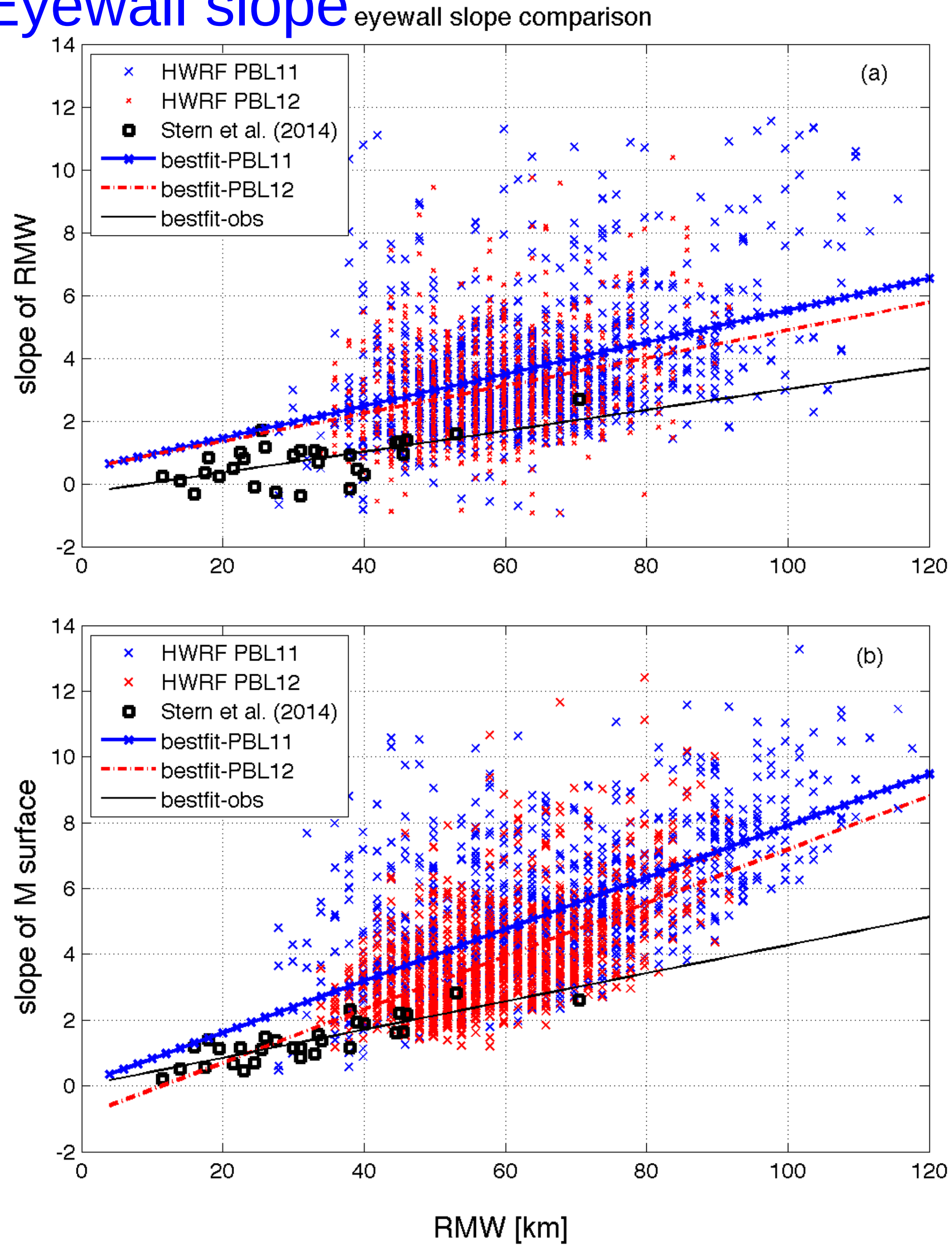
Dropsonde

Composite

(Jun Zhang et al. 2011a)



Eyewall slope



(Jun Zhang, Nolan, Rogers, and Tallapradada, 2015)

Convective scale structure

(Jun Zhang, Nolan, Rogers, and Tallapradada, 2015)

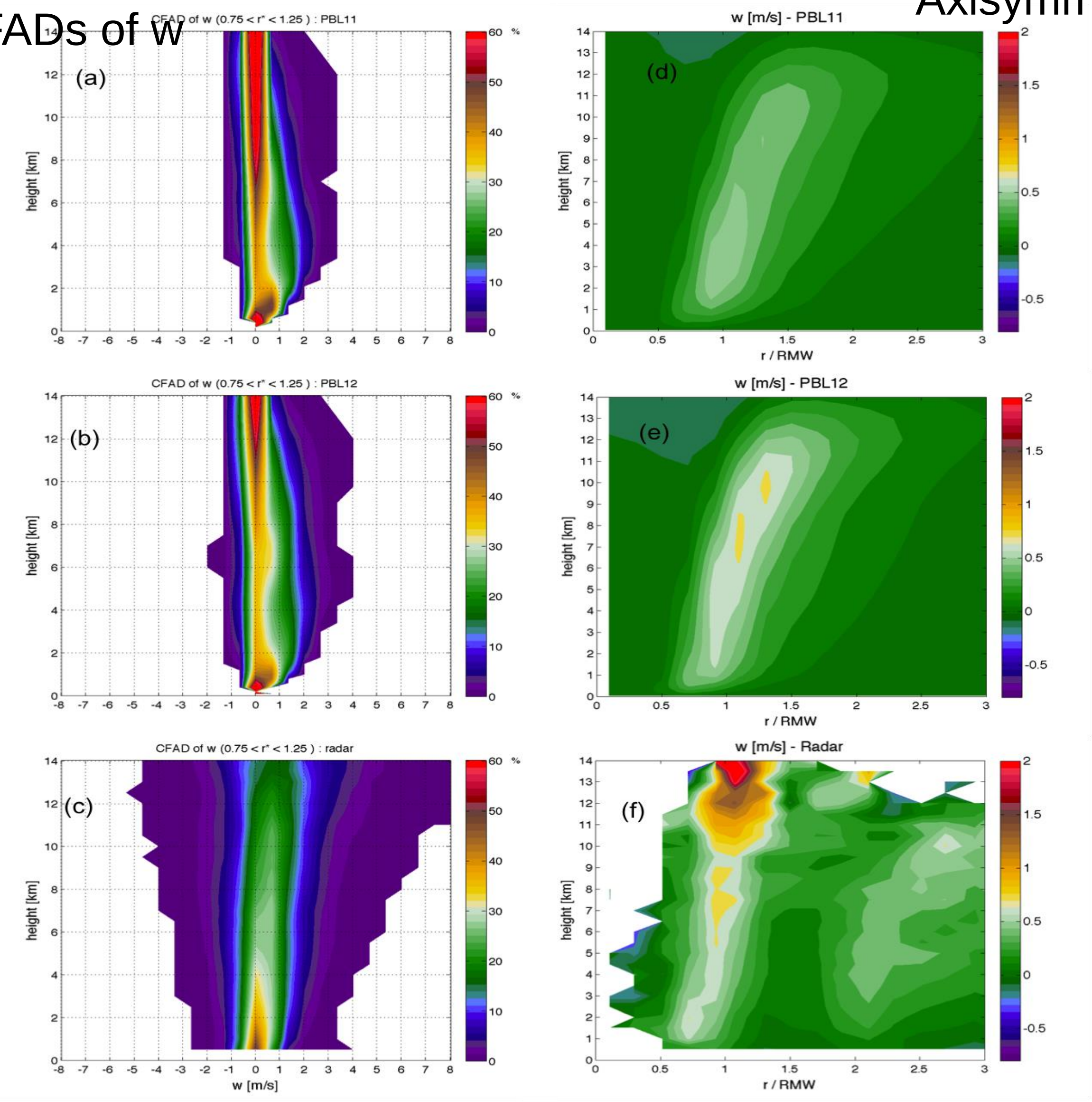
CFADs of w

Axisymmetric w

HWRF PBL11

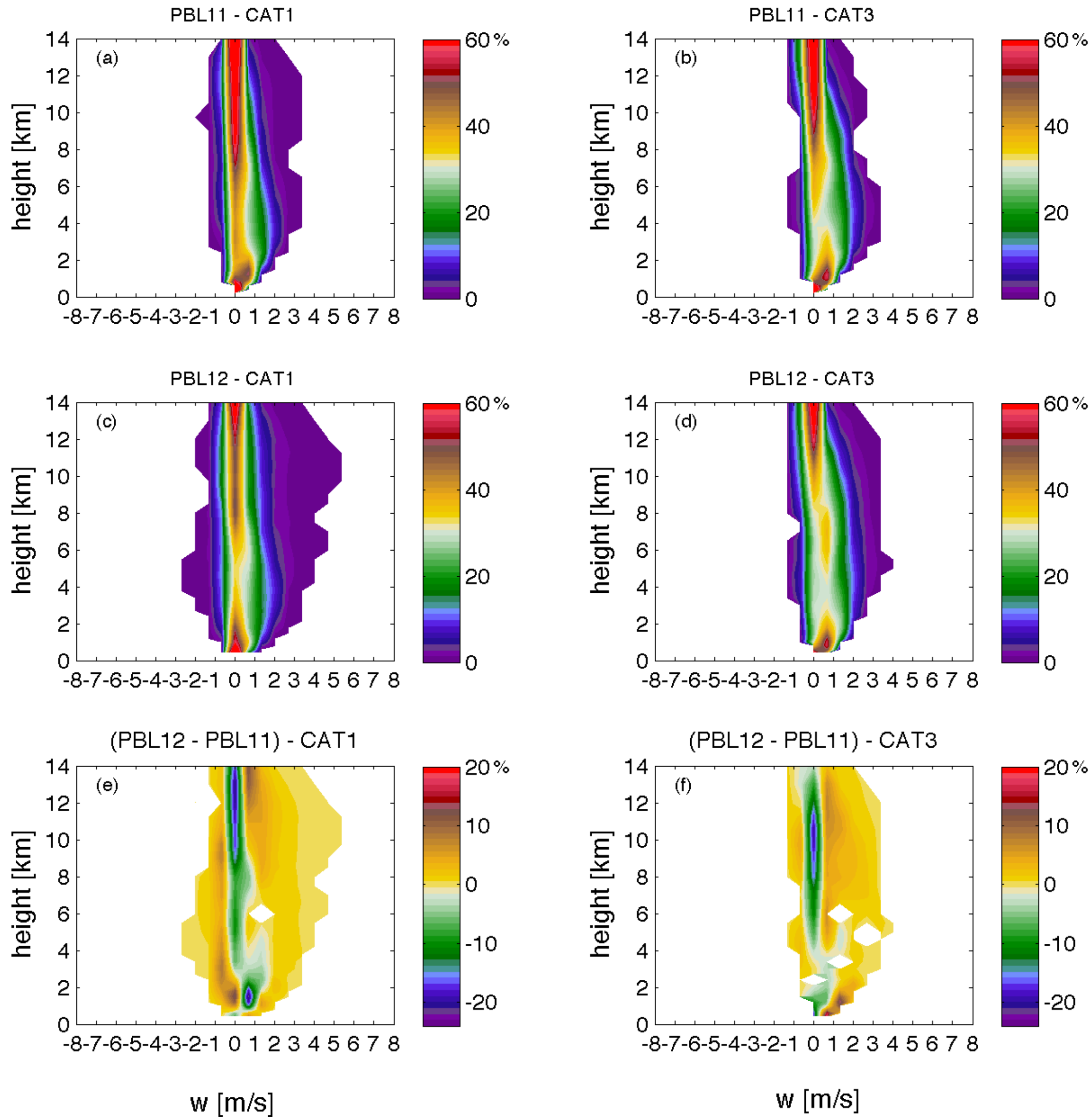
HWRF PBL12

Doppler radar data



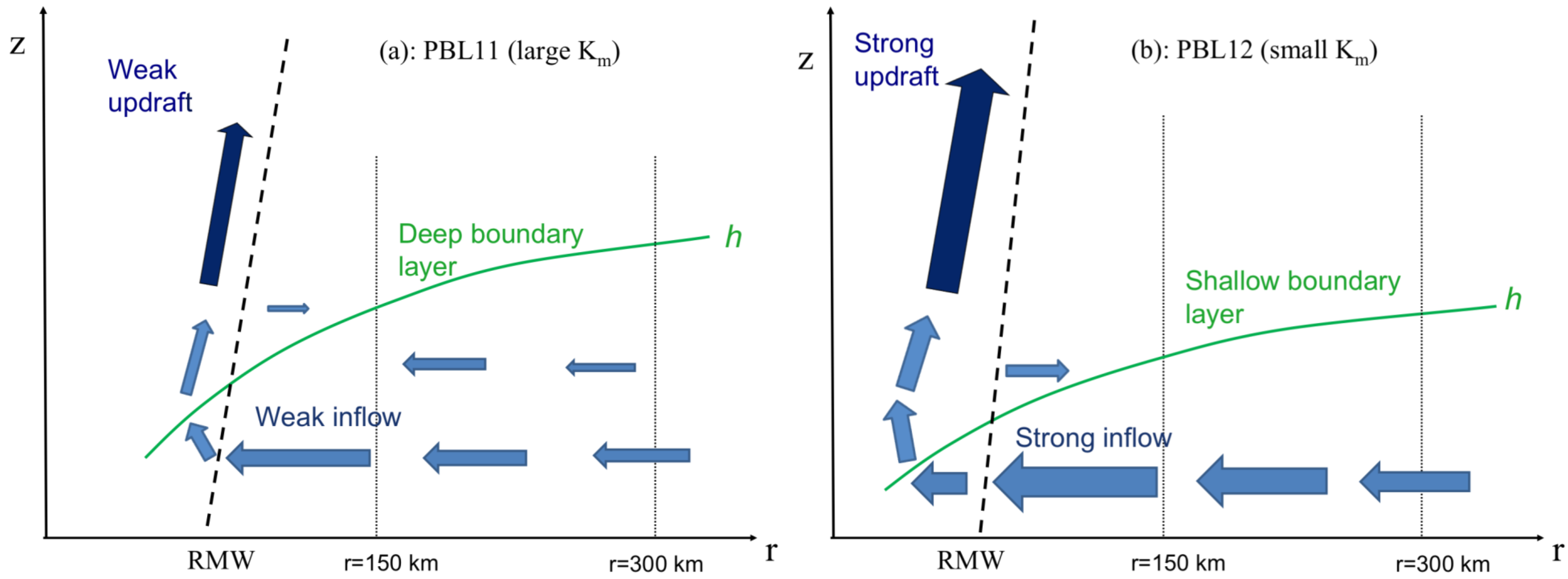
Convective scale structure

(Jun Zhang, Nolan, Rogers, and Tallapradada, 2015)



Schematic diagram

(Jun Zhang, Nolan, Rogers, and Tallapradada, 2015)



Why does the vertical diffusion 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.

Summary

1. A developmental framework for improving hurricane model physics is successfully built and tested.

2. HRD's aircraft observation data are unique for model diagnostics in terms of hurricane structure.

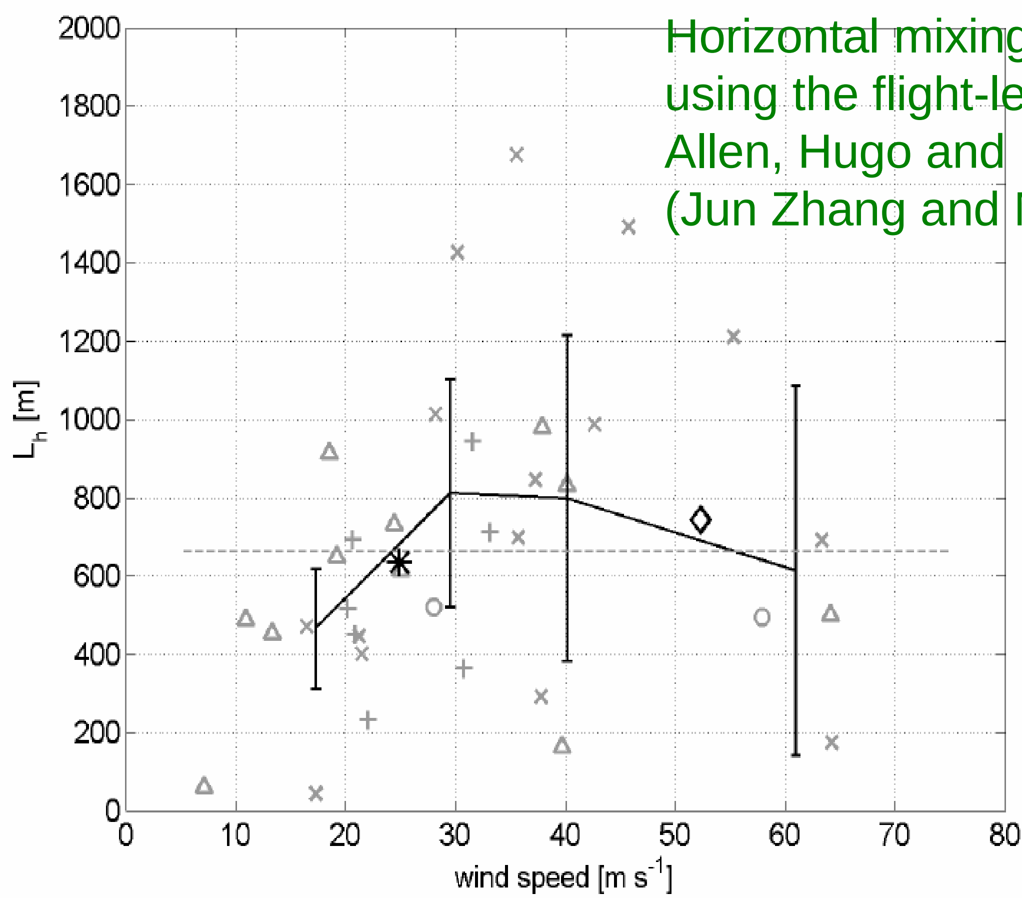
3. Observations also provide baseline for physics development and improvement in hurricane models.

4. Model deficiency can be identified through model diagnostics of TC structures based on observations.

5. Feedback to model developers leads to model improvements.

Ongoing and Future work

To improve other part of the model physics in HWRF and other hurricane models using aircraft observations (e.g., horizontal diffusion, microphysics)



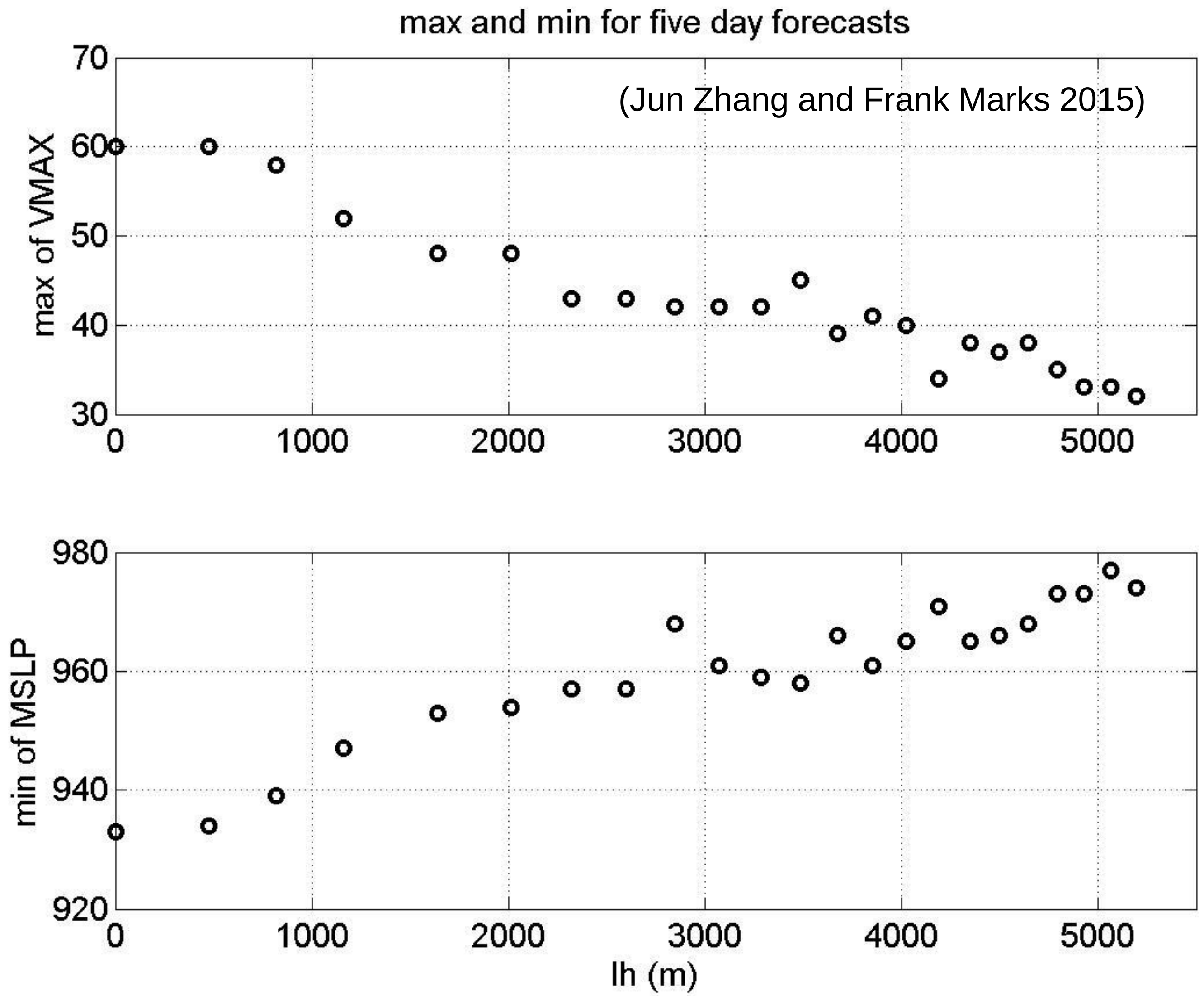
Horizontal mixing length estimated using the flight-level data in Hurricanes Allen, Hugo and David
(Jun Zhang and Montgomery 2012)

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

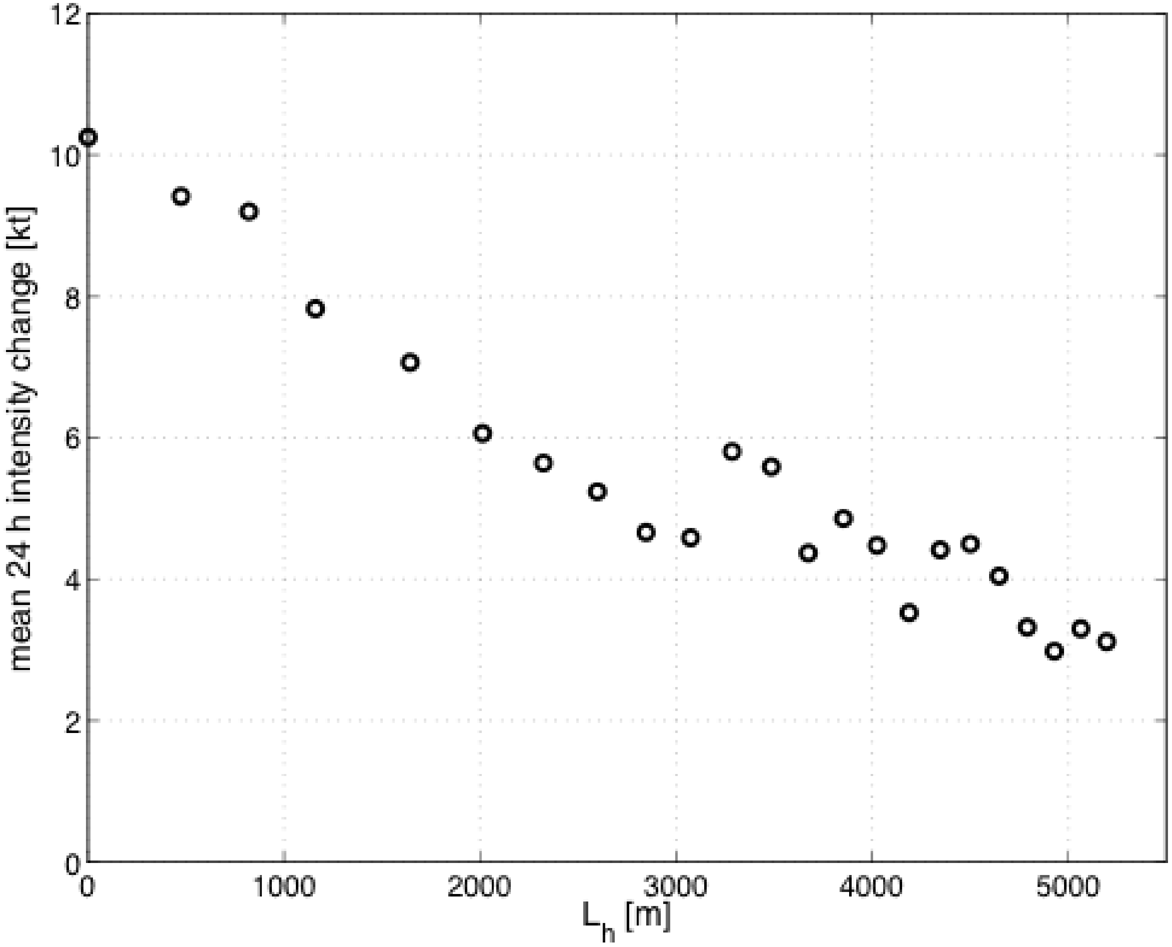
$$K_h = |F_h|\,(\rho\,|S_h|)^{-1},$$

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

Sensitivity of simulated hurricane intensity to horizontal mixing using idealized HWRF simulations

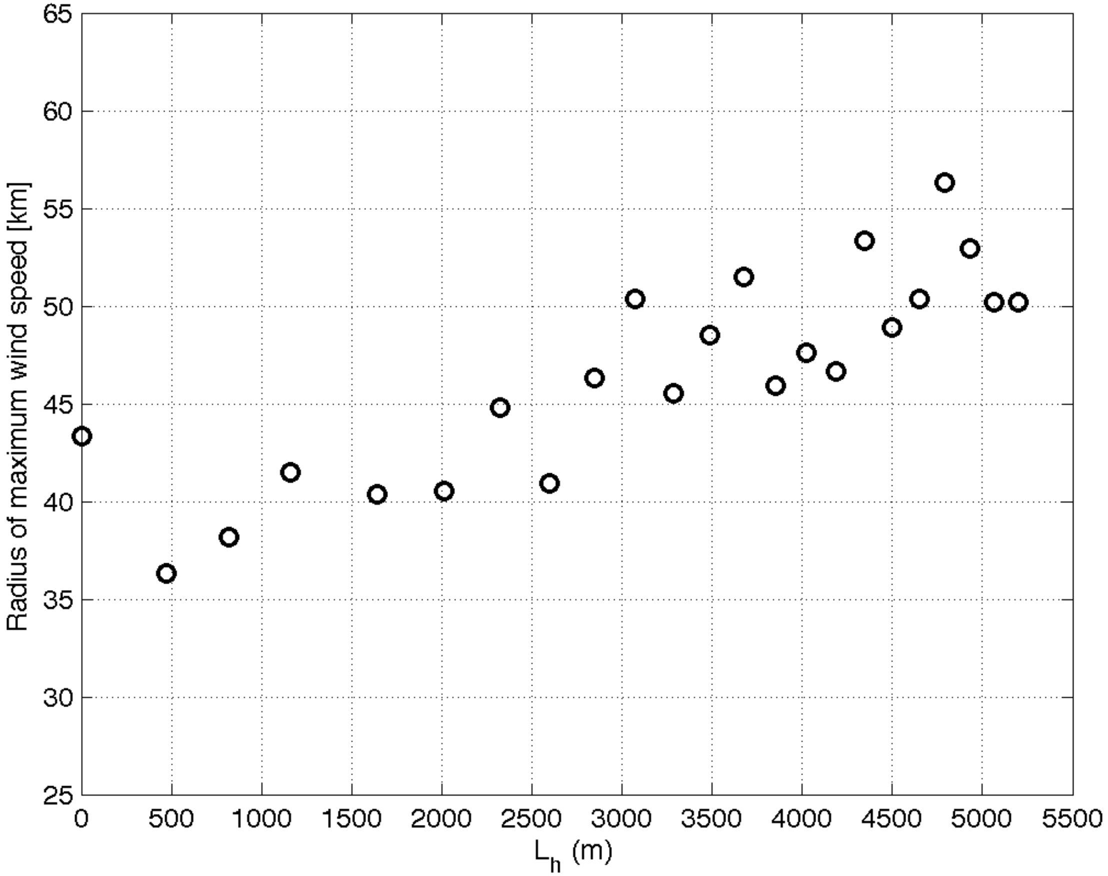


Intensity change vs L_h



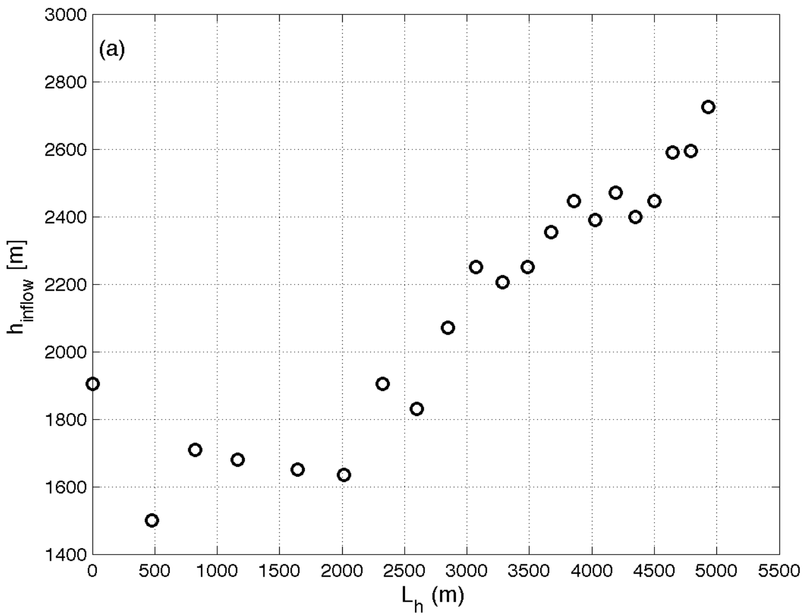
RMW vs L_h

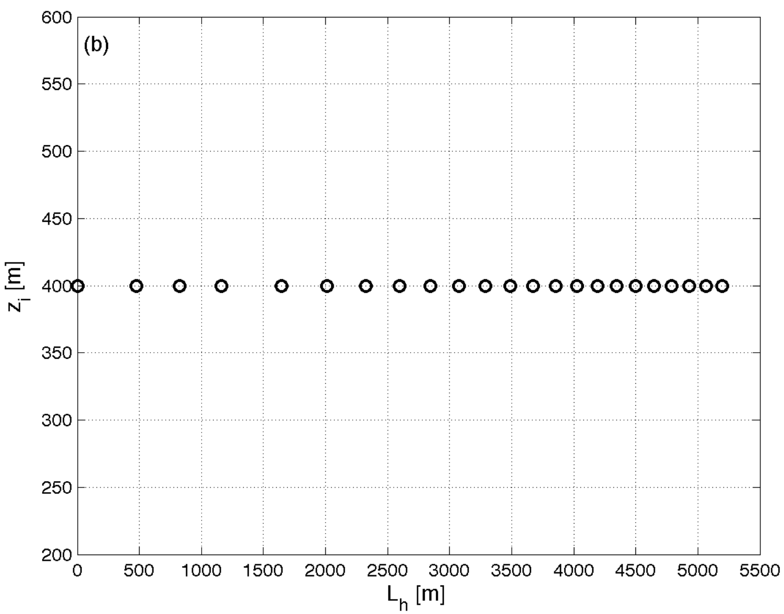
(Jun Zhang and Frank Marks 2015)



Sensitivity of PBL heights to L_h

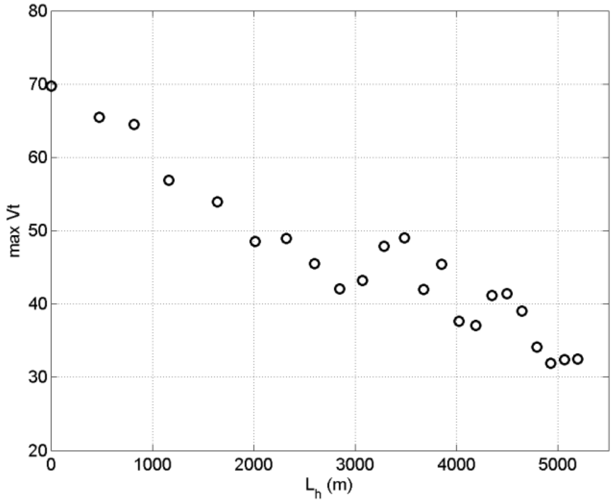
(Jun Zhang and Frank Marks 2015)

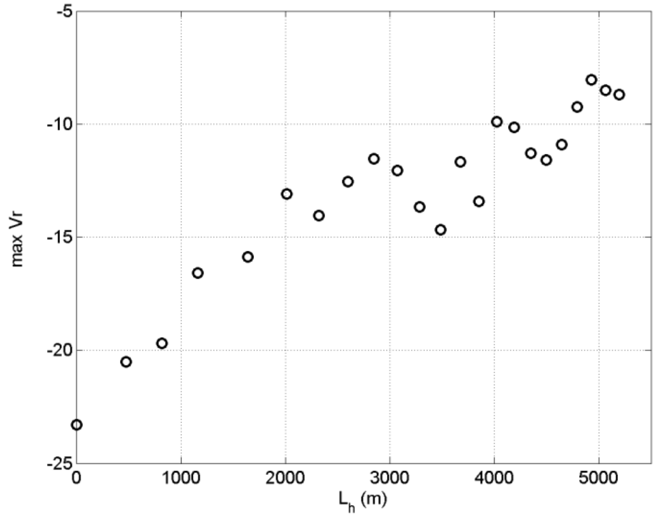


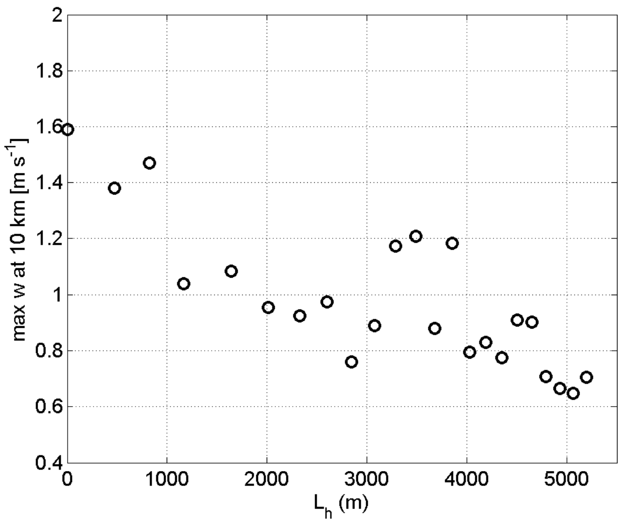


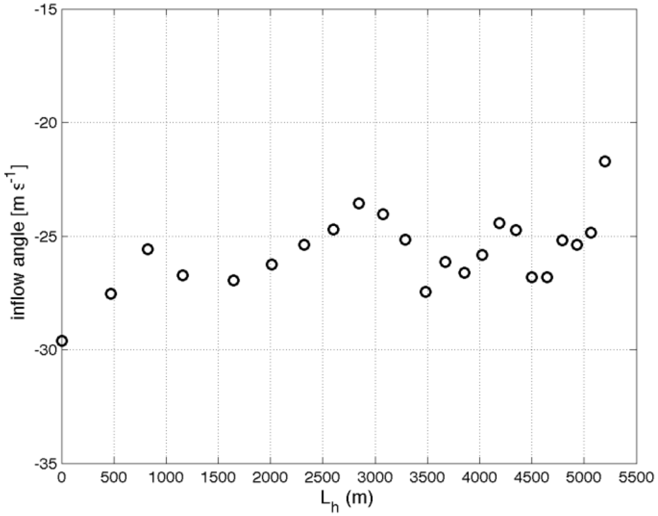
Maximum V_τ, V_r, w and inflow angle vs L_h

(Jun Zhang and Frank Marks 2015)



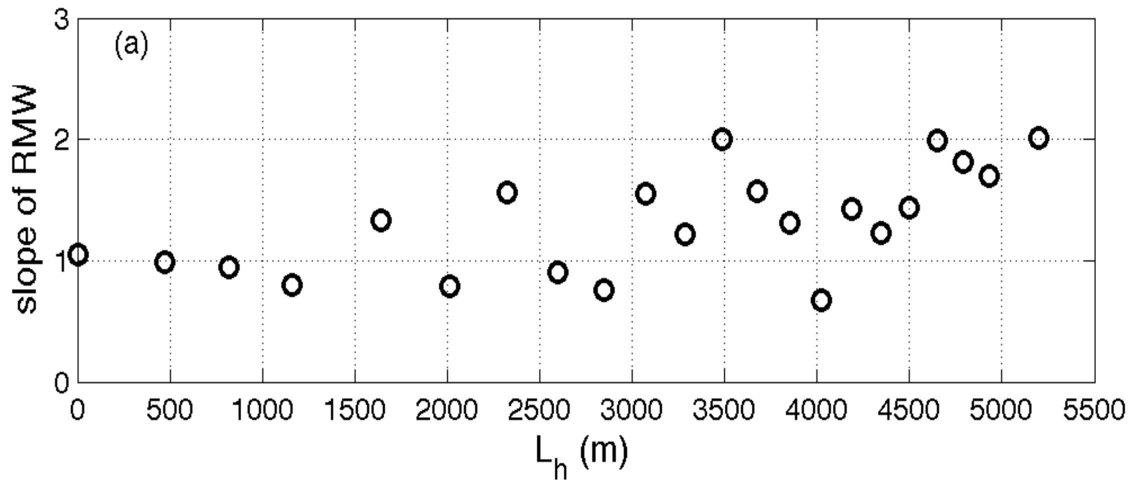


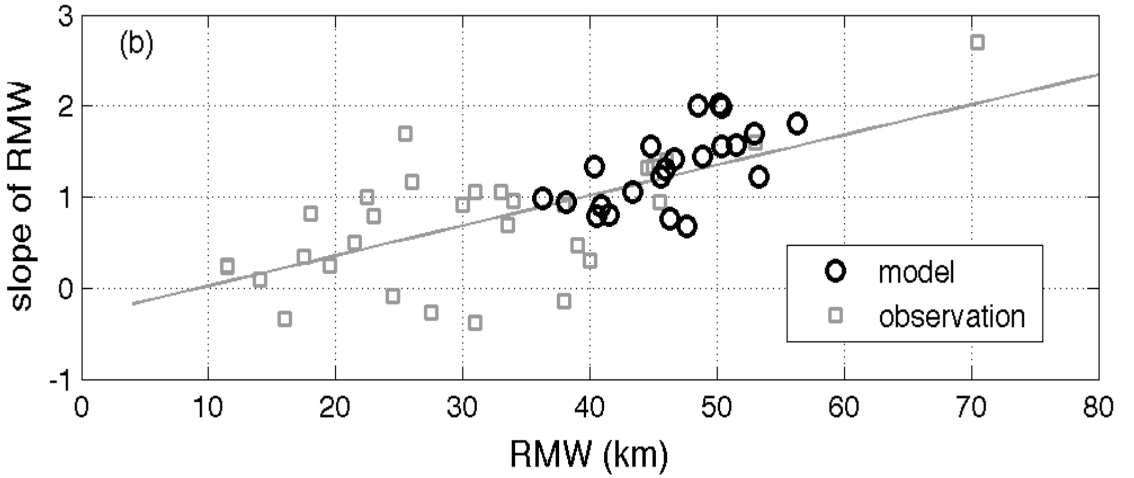




Eyewall slope vs L_h

(Jun Zhang and Frank Marks 2015)

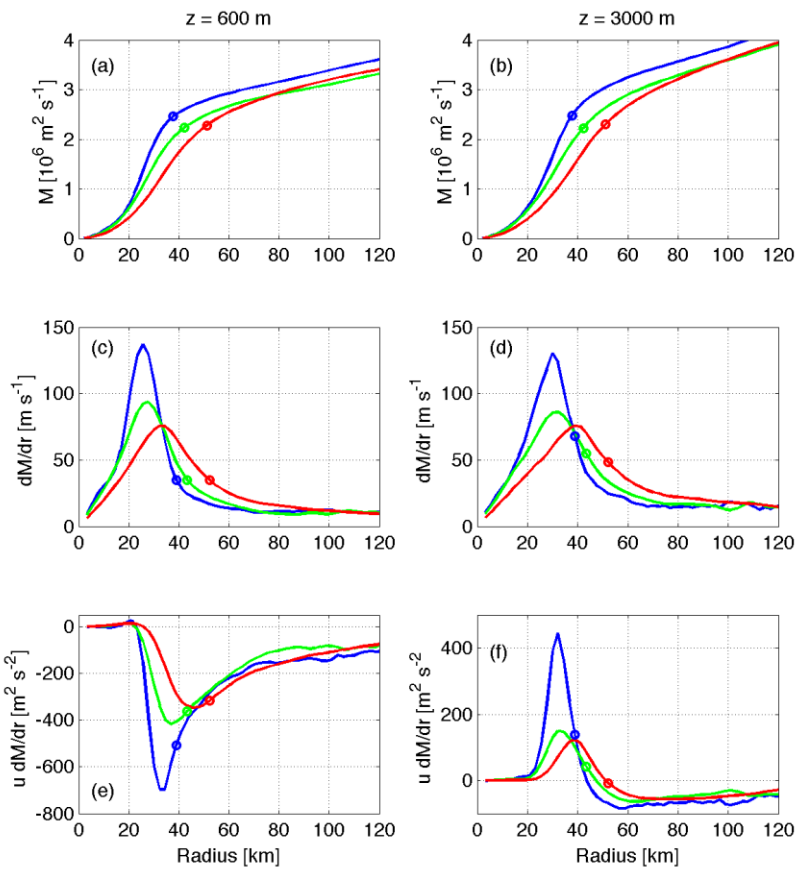


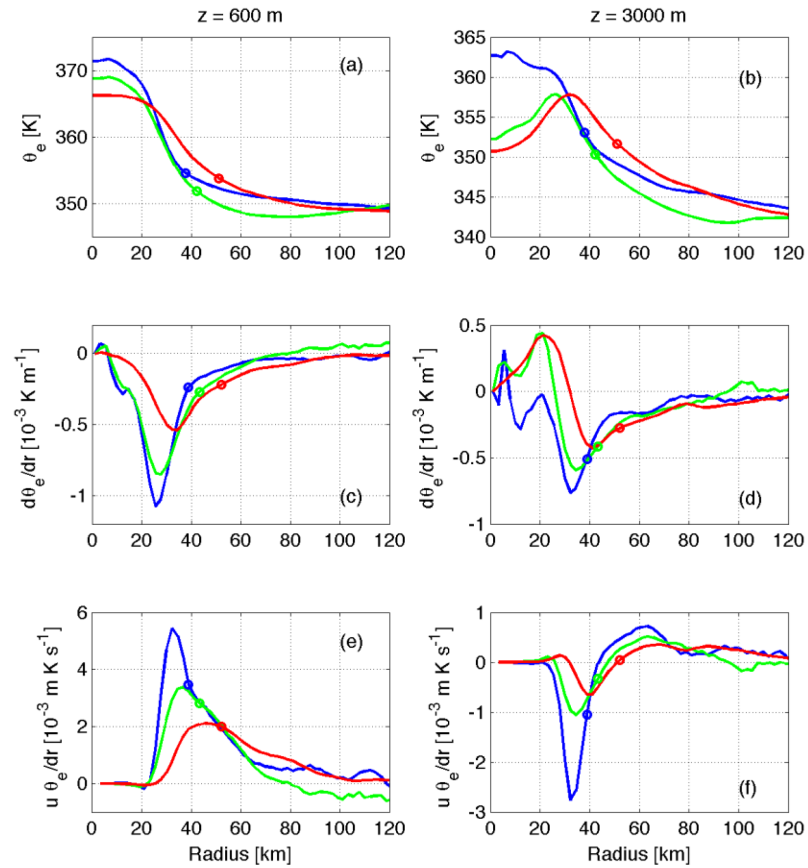


Observational data are from Stern et al. (2014)

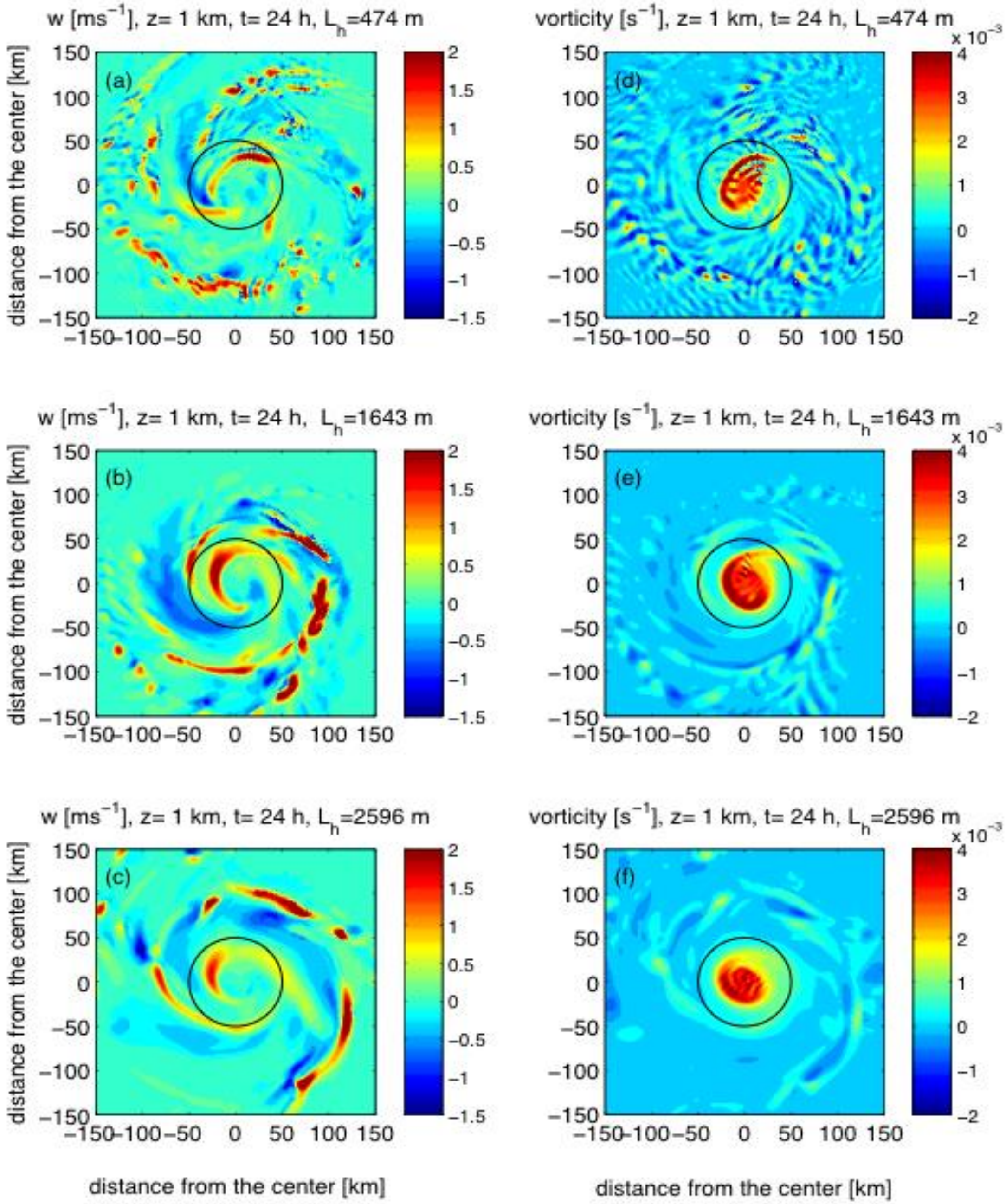
Convergence of angular momentum and θ_e

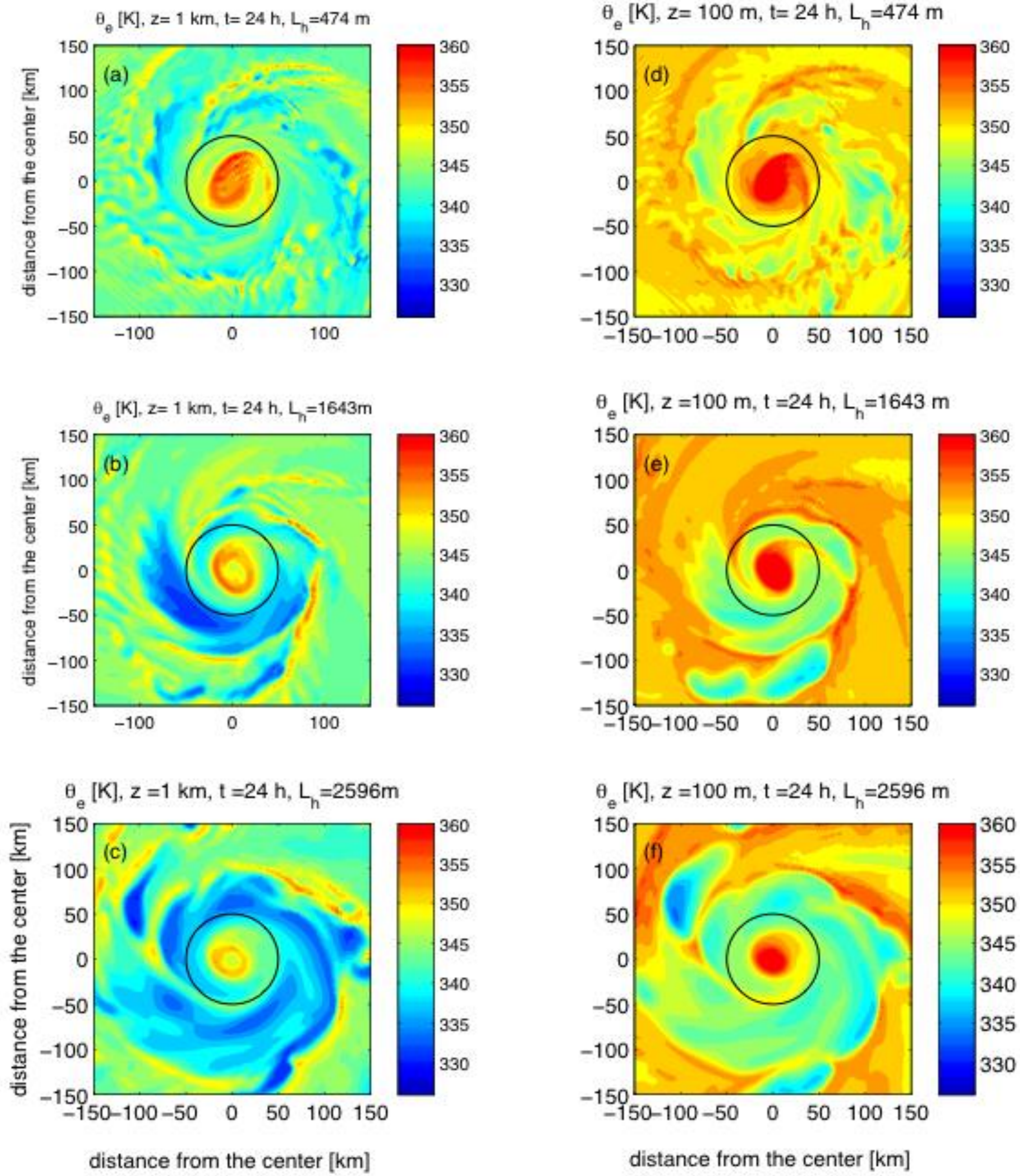
(Jun Zhang and Frank Marks 2015)





Blue – Lh=822m; Gree – Lh=1643 m; Red – Lh=2506m


w [ms^-1], z= 1 km, t= 24 h, L_h=474 m
vorticity [s^-1], z= 1 km, t= 24 h, L_h=474 m
w [ms^-1], z= 1 km, t= 24 h, L_h=1643 m
vorticity [s^-1], z= 1 km, t= 24 h, L_h=1643 m
w [ms^-1], z= 1 km, t= 24 h, L_h=2596 m
vorticity [s^-1], z= 1 km, t= 24 h, L_h=2596 m
(a)
(b)
(c)
(d)
(e)
(f)
x 10^-3
distance from the center [km]
distance from the center [km]
distance from the center [km]



θe [K], z= 1 km, t= 24 h, Lh=474 m
(a)
θe [K], z= 100 m, t= 24 h, Lh=474 m
(d)
θe [K], z= 1 km, t= 24 h, Lh=1643m
(b)
θe [K], z =100 m, t =24 h, Lh=1643 m
(e)
θe [K], z =1 km, t =24 h, Lh=2596m
(c)
θe [K], z =100 m, t =24 h, Lh=2596 m
(f)
distance from the center [km]
distance from the center [km]

The end

Thanks!

Questions?

List of References

- Zhang, J. A**.** and F. D. Marks, 2014: Sensitivity of tropical cyclone intensity and structure to horizontal diffusion in idealized three-dimensional numerical simulations. *Mon. Wea. Rev.*, conditionally accepted.
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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):

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

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