

Advanced diagnostics of tropical cyclone inner-core structure using aircraft observations

Jun Zhang, David Nolan, Robert Rogers,
Paul Reasor and Sylvie Lorsolo

HFIP Proposal Review, 5/15/2013

Acknowledgements

- Support from HFIP
- HWRF team collaborators: S. Gopalakrishnan, Xuejin Zhang, Thiago Quirino, Vijay Tallapragada, Young Kwon, Weiguo Wang, and J.-W. Bao
- HRD collaborators who helped with collecting the observational data used in this work during HRD's field programs , in particular, Eric Uhlhorn, John Gamache, Kathryn Sellwood, Sim Aberson, and Neal Dorst

Outline

- Objectives
- Results from observation analyses
- Results from HWRF modeling diagnostics
- 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.

Objective of the funded HFIP proposal

- To develop robust methods for comparing observations from HRD's extensive aircraft database and HWRF simulations.
- To create metrics to quantitatively evaluate deficiencies and biases in the inner-core structure created in HWRF.

Work plan

The work proposed (with 2 year duration) consists of three main tasks:

1. Analysis and compositing of observational and model datasets;
2. Design of metrics for inner-core structure evaluation and quantitative assessment of HWRF performance;
3. Report of model biases, deficiencies, and error statistics to EMC and/or National Hurricane Center (NHC) operations.

Observational data analysis for model diagnostics

Dropsonde

processed data from 18 hurricanes

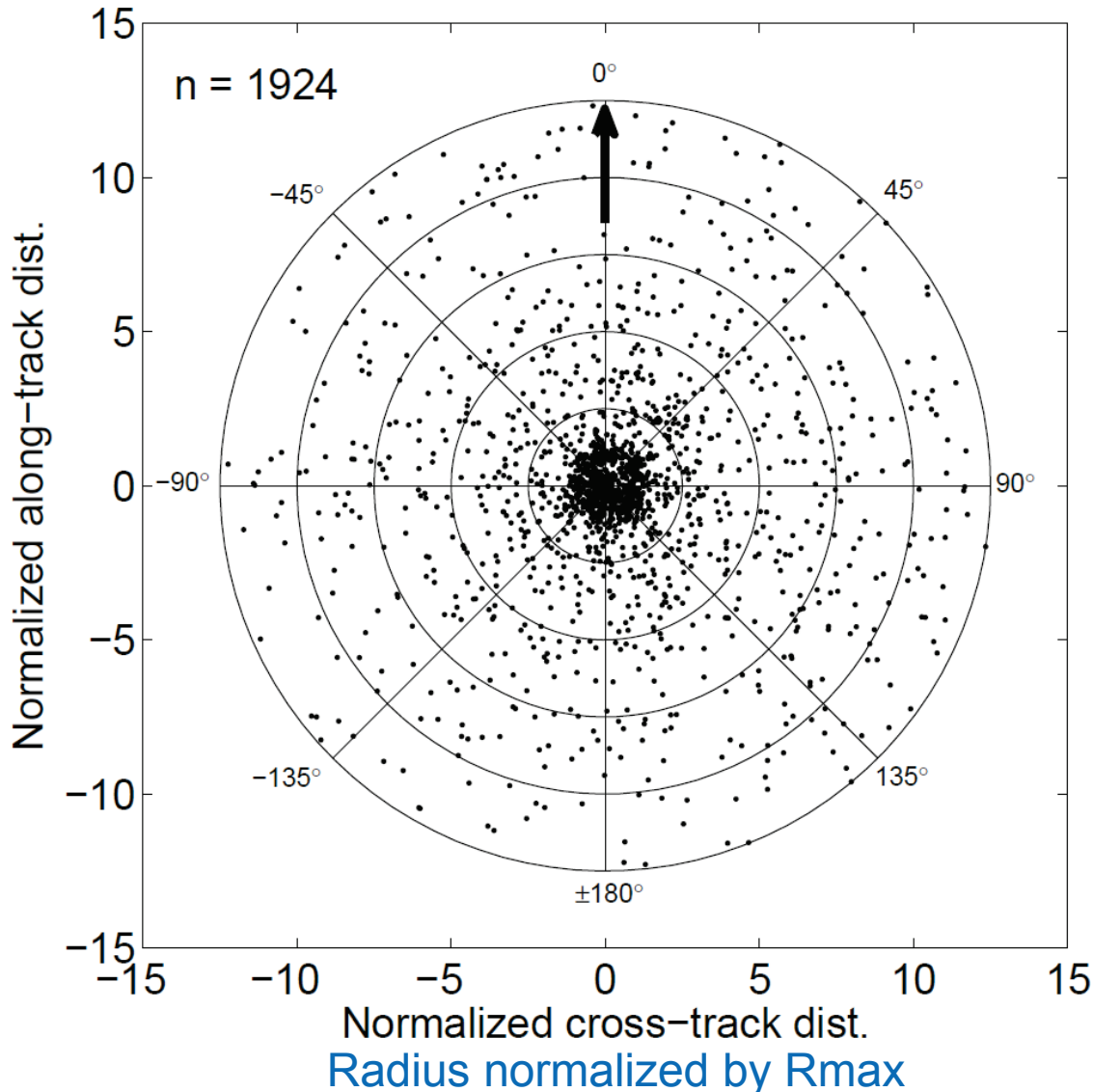
Doppler radar

processed data from 14 storms

Flight-level data

Hurricanes Hugo, Allen and Frances

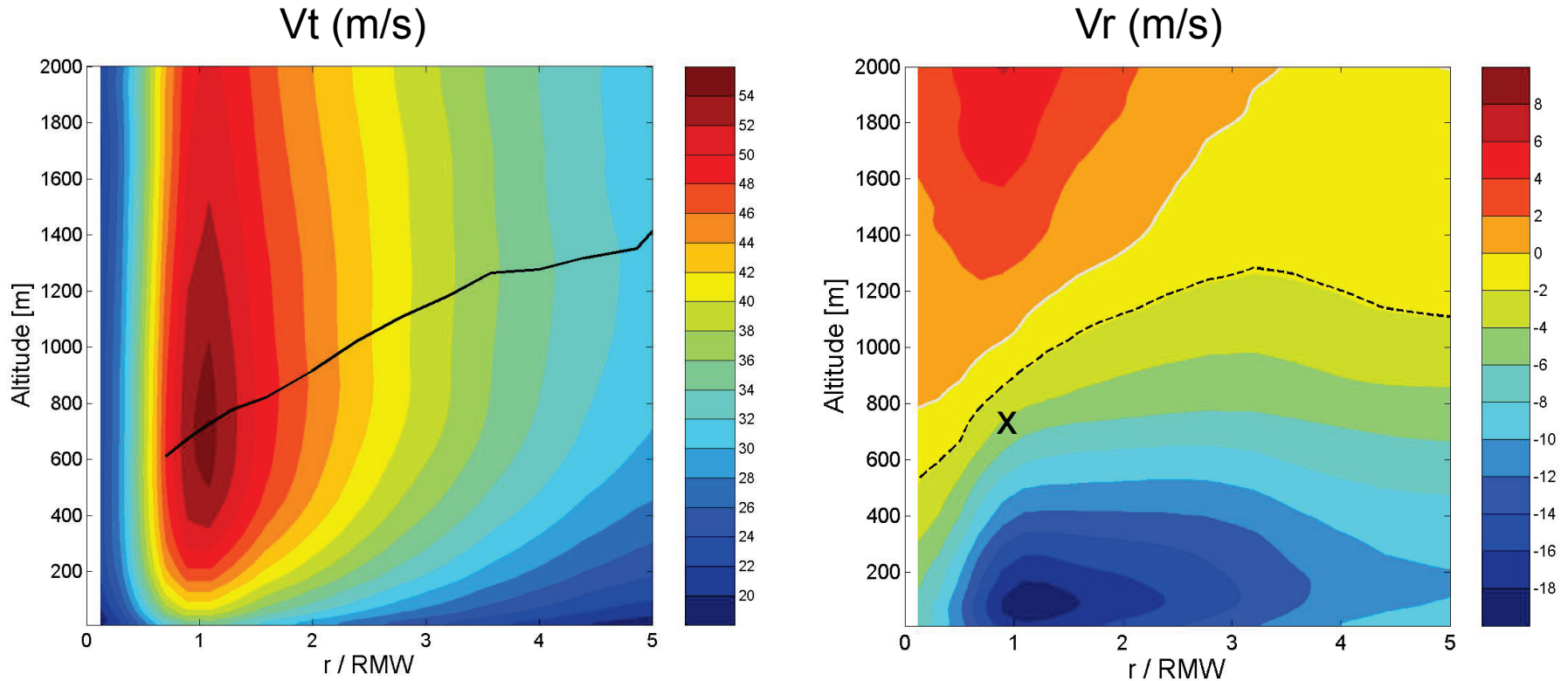
Dropsondes from 18 hurricanes (1997-2010)



The center positions have been determined using the flight-level data to fix the storm center using the algorithm developed by Willoughby and Chelmow (1982).

Values of radius of maximum wind speed (R_{max}) are determined using the SFMR surface wind profiles.

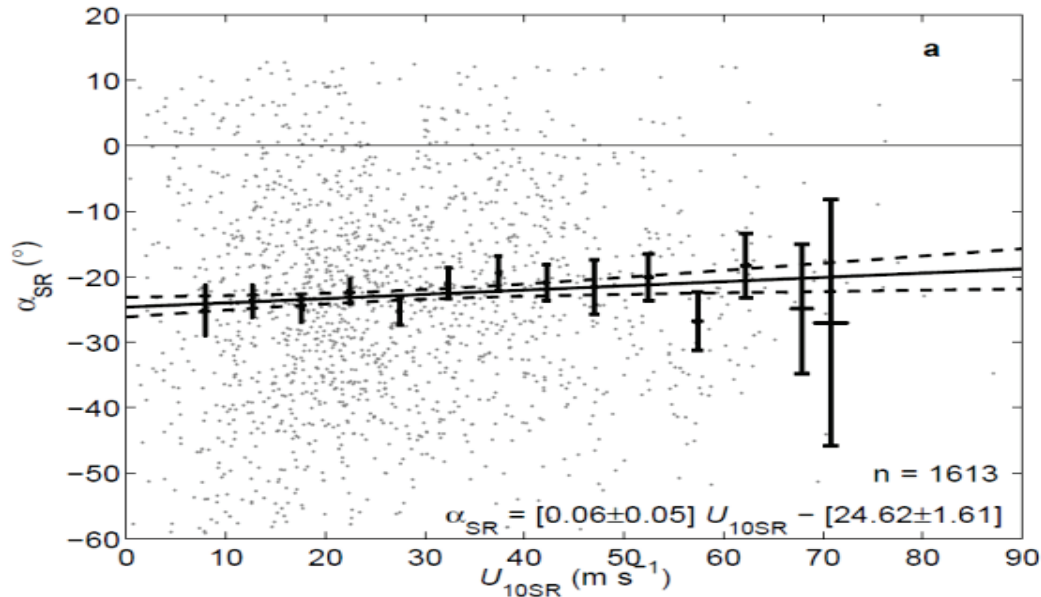
Axisymmetric boundary layer structure



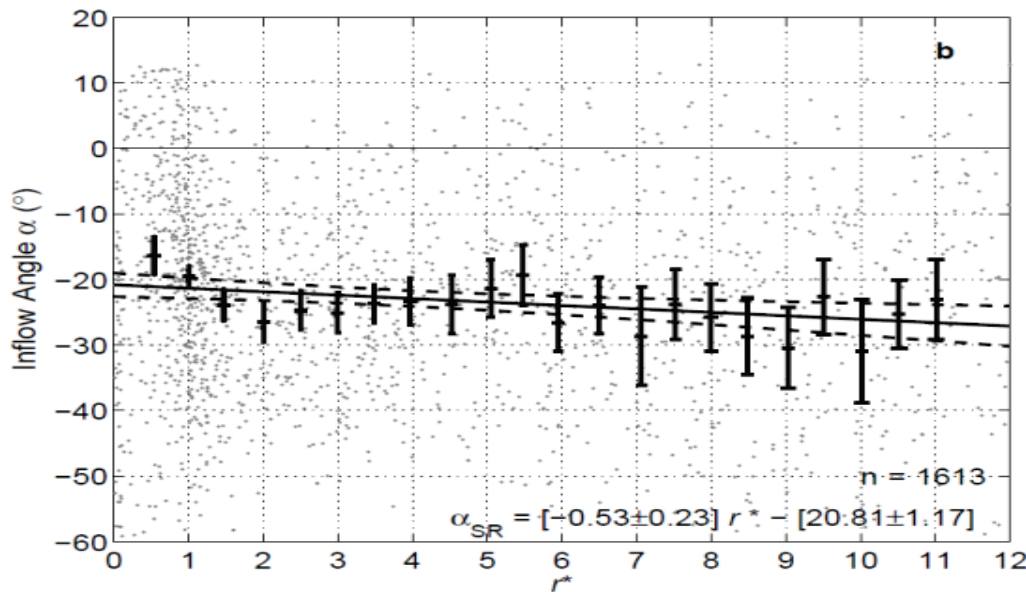
- The kinematic boundary layer heights decrease with radius toward the storm center;
- The boundary layer jet is located within the strong inflow layer;
- The height of the peak inflow is within the surface layer.

Surface Inflow Angle from dropsonde composites

Zhang and Uhlhorn (2012)

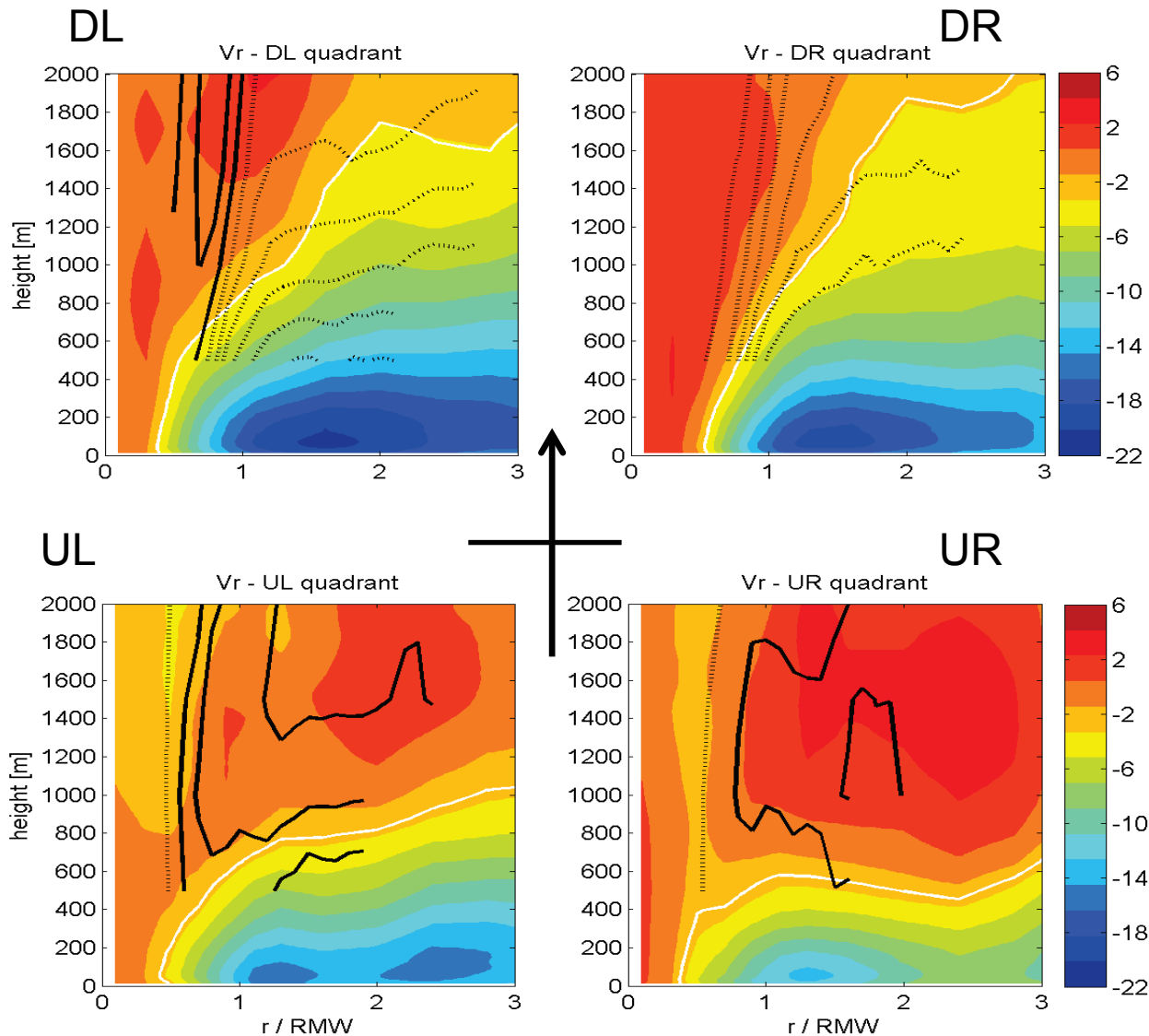


- Little dependence of axisymmetric inflow angle on local surface wind speed;



- A weak but statistically-significant dependence on the radial distance.

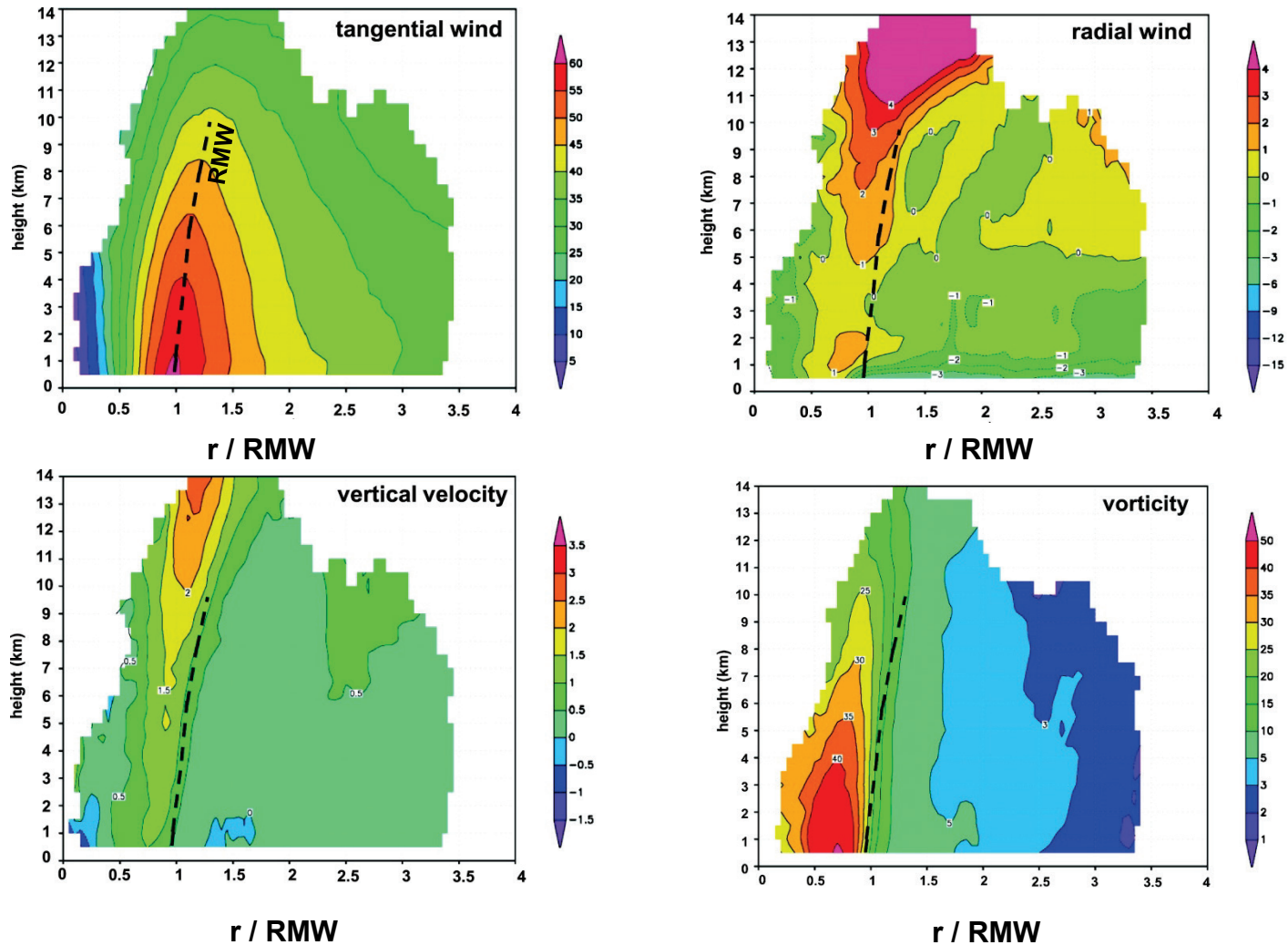
Asymmetric boundary layer structure from dropsonde composites



- The inflow layer is the deepest in the DR quadrant
- The DL quadrant has the strongest inflow and outflow
- The radial flow is stronger in the quadrants downshear than the upshear side
- The inflow layer is deeper in the quadrants downshear than the upshear side

Doppler radar composites -- axisymmetric structure

(Rogers et al. 2012)



- 40 radial penetrations in 8 different tropical cyclones
- composited based on normalized radius (RMW at 2 km altitude)

Doppler radar composites – Convective structure

- contoured frequency by altitude diagrams (CFADs), stratified by radial location
- useful for evaluation of model microphysics

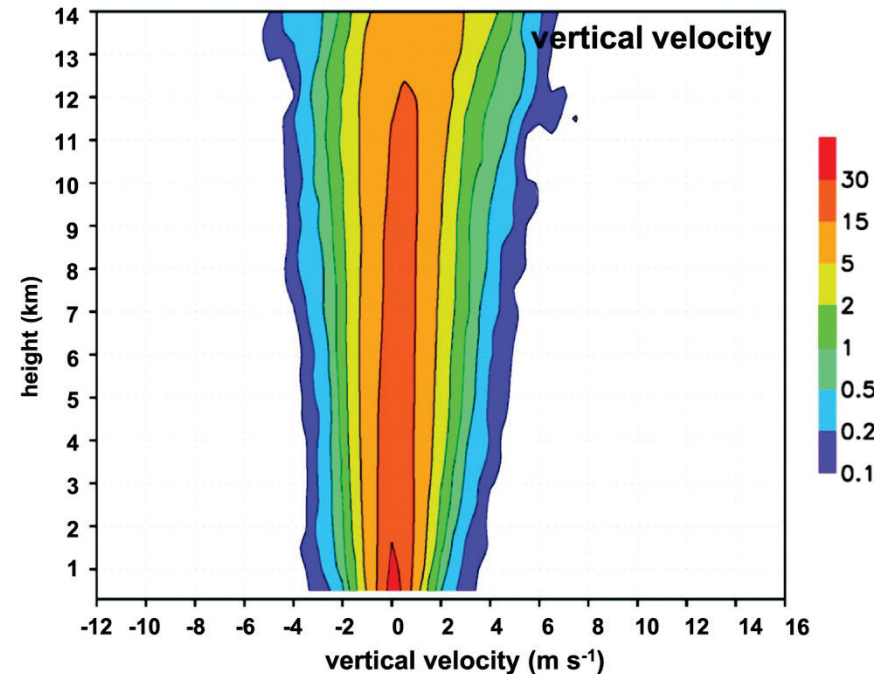
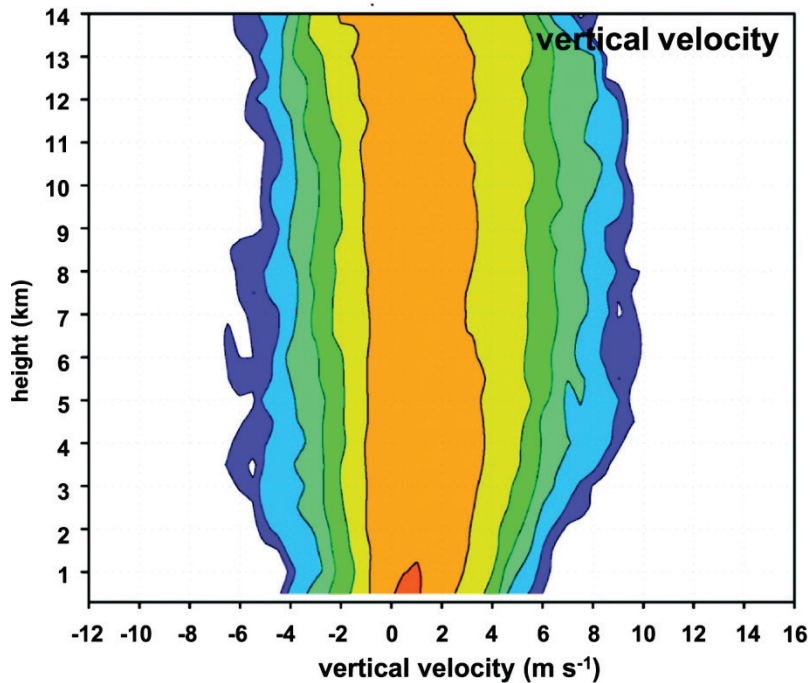
Inner eyewall

($0.75 < r/\text{RMW} < 1$)

(Rogers et al. 2012)

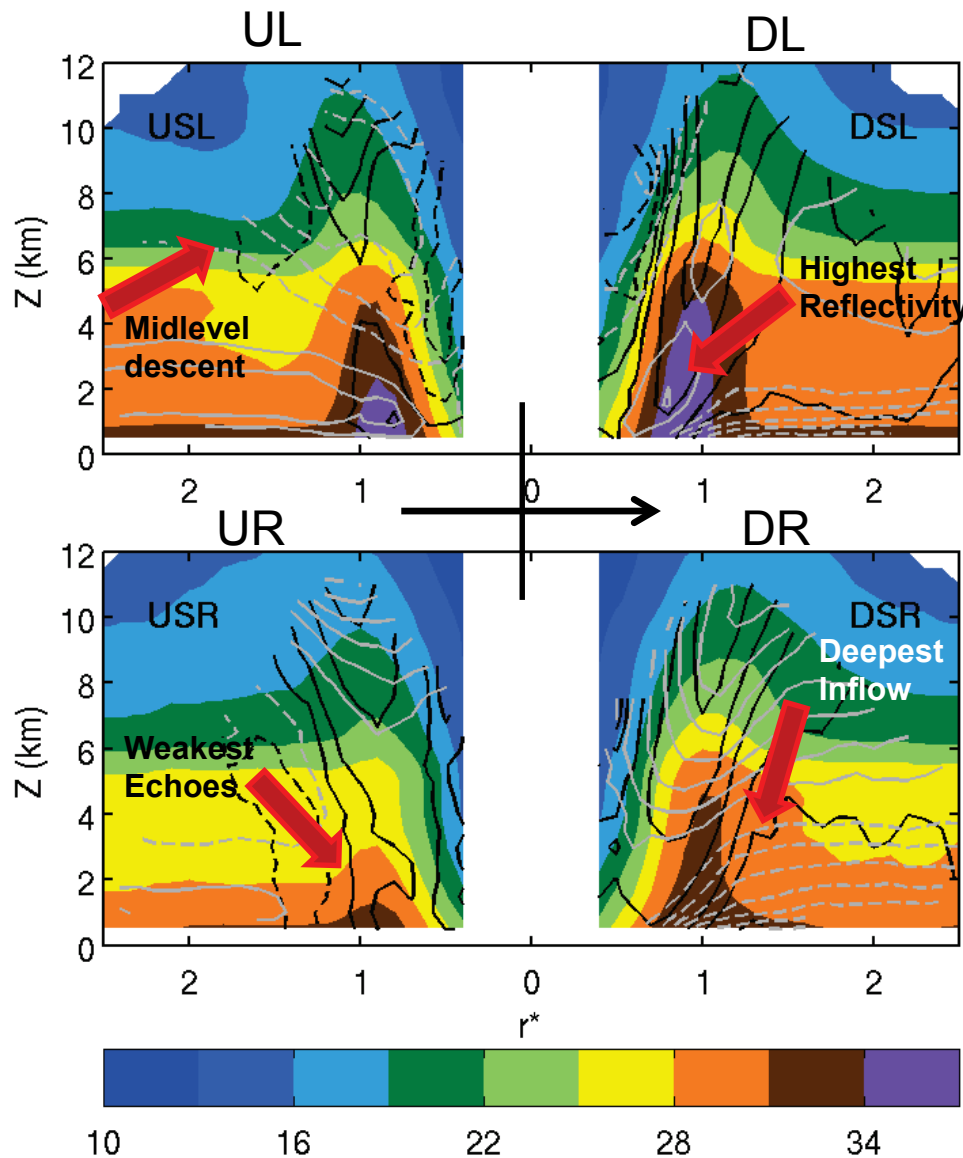
Outer radii

($r/\text{RMW} > 1.5$)



- The CAFD for the inner eyewall shows a broader spectrum of updrafts and downdrafts than the outer radii, with updraft peaks reaching 10 m/s;
- The bulk of the distribution (15%-30%) is found between -1 and 3 m/s for the inner eyewall, and between -1 to 1 m/s for the outer radii.

Doppler radar composites -- asymmetric structure



(Reasor et al. 2013, in press)

- 52 P-3 hurricane flights represented
- Storm-relative fields mapped to a norm. radial coordinate, $r^*=r/\text{RMW}$, and composited relative to SHIPS deep-layer shear direction (RMW at $Z=2$ km)

- Quadrant-average fields shown (DS=downshear; US=upshear)

- Reflectivity (dBZ, shaded)
- Vertical velocity (ms^{-1} , black)
- Radial velocity (ms^{-1} , gray)

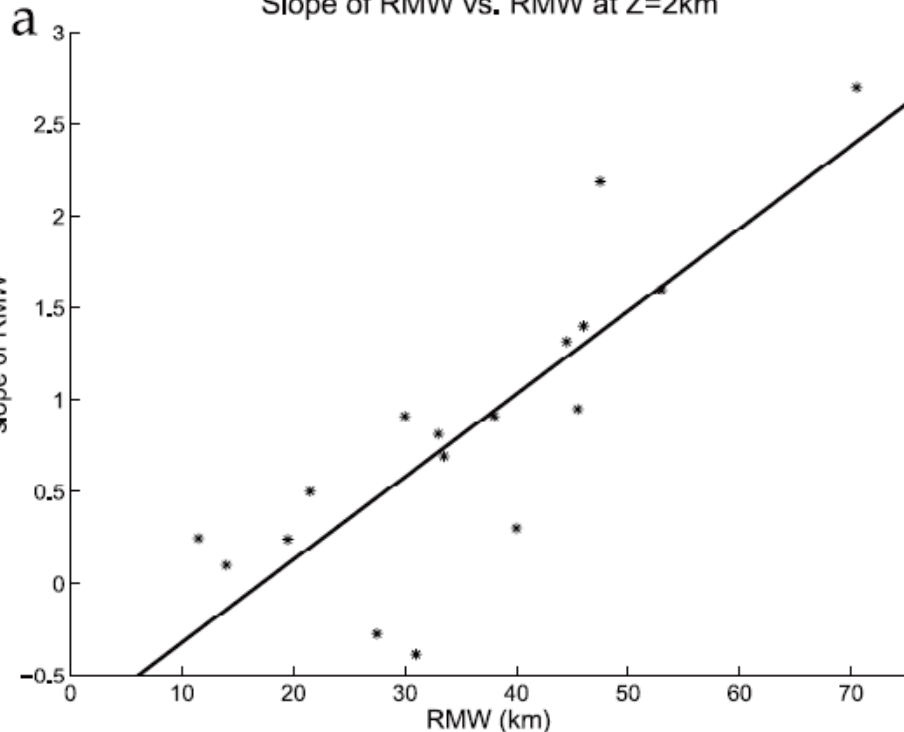
Contours --

Ascent (solid): 0.25, 0.5, 1, 1.5, 2, 2.5 ms^{-1}
 Descent (dashed): -0.25, 0 ms^{-1}

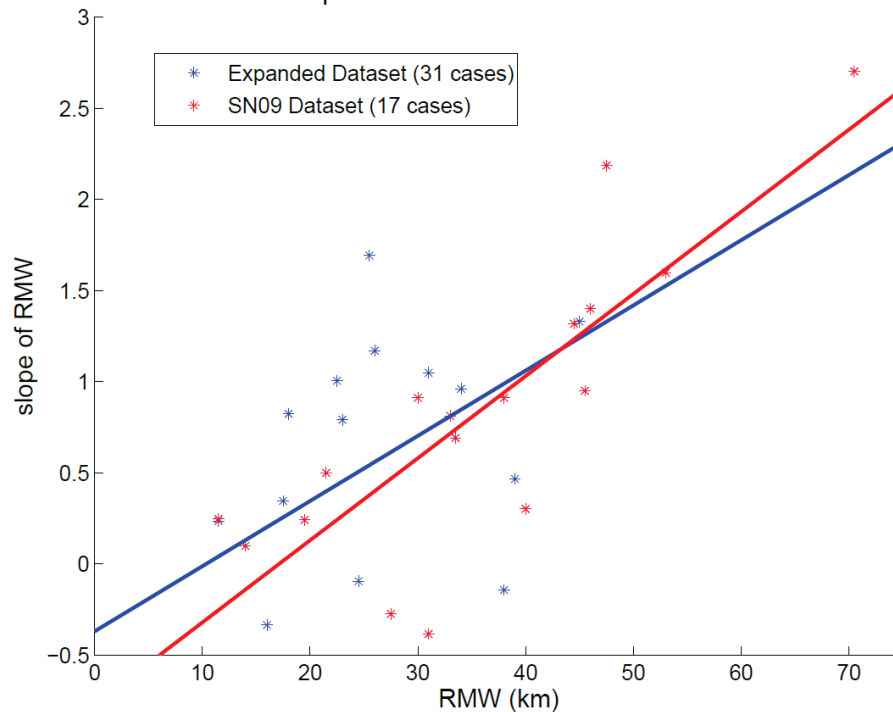
Outflow/inflow (solid/dashed): 1 ms^{-1} interval
 (0 not plotted)

Doppler radar composites: Outward slope of the eyewall (RMW at each height)

Slope of RMW vs. RMW at Z=2km



Slope of RMW vs. RMW at z=2km



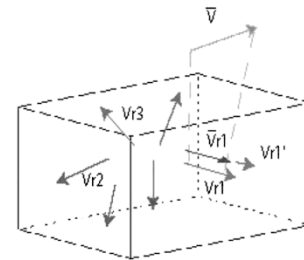
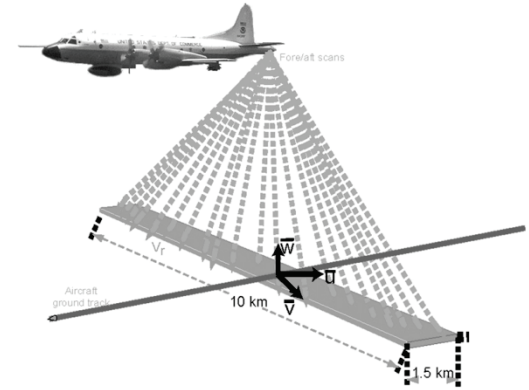
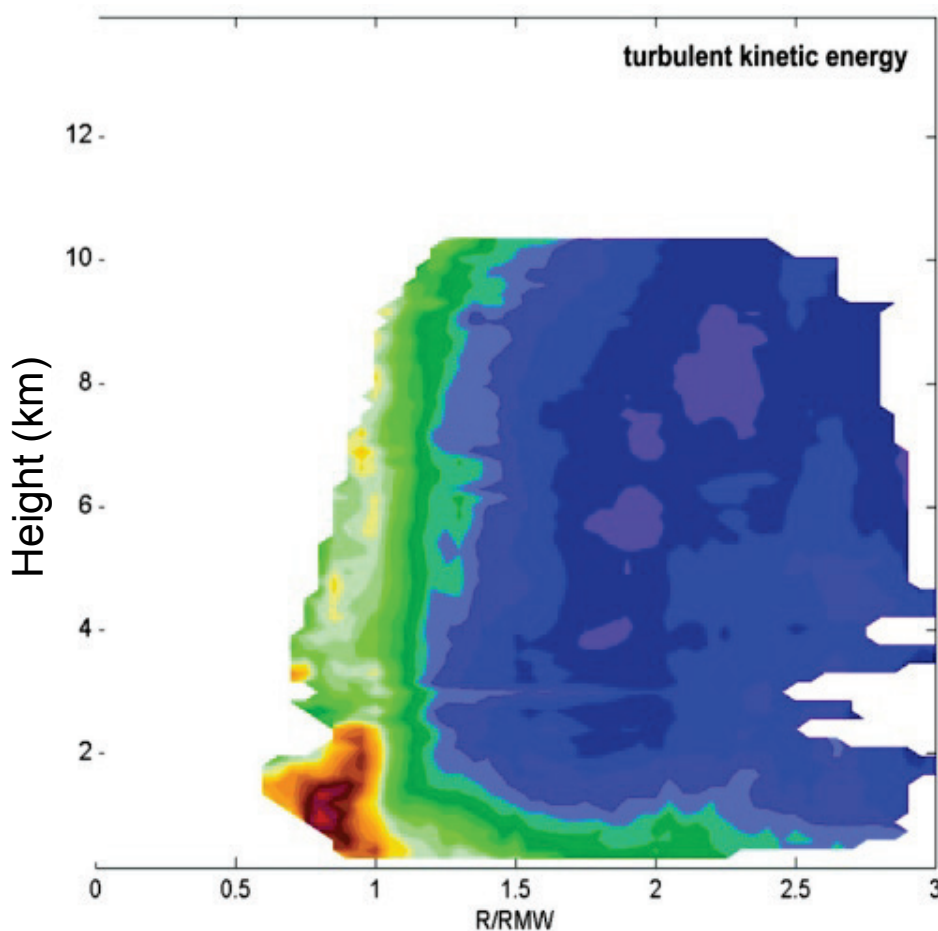
Stern and Nolan (2009):
Outward slope (of RMW) increases
with storm size (RMW at 2km)

Original data set of 17 cases
extended to 33 cases by
Brisbois et al. in summer 2011.

Doppler radar composites

Turbulent Kinetic energy (TKE)

Lorsolo et al. 2010; Rogers et al. 2012



$$\sigma_{V_R}^2 = \frac{1}{N} \sum_{\text{Overgridcell}} (V_R - \bar{V}_R)^2 = \frac{1}{N} \sum_{\text{Overgridcell}} V_R^2$$

Large values of TKE were observed in the boundary layer and in the eyewall region

Summary of observation work

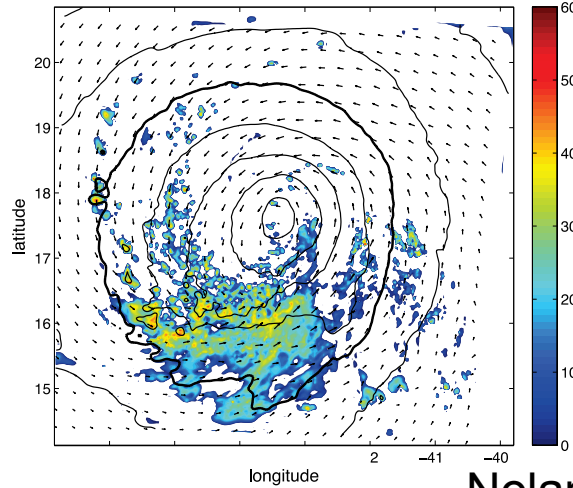
- Our proposed work for year 1 focusing on the observational data analysis has been successfully completed;
- The observational data were analyzed in a composite sense, ready for use to do model diagnostics;
- Structural metrics have been developed which include boundary layer heights, inflow angle, eyewall slope, TKE, CFADs of vertical velocity, and so on.

Model diagnostics

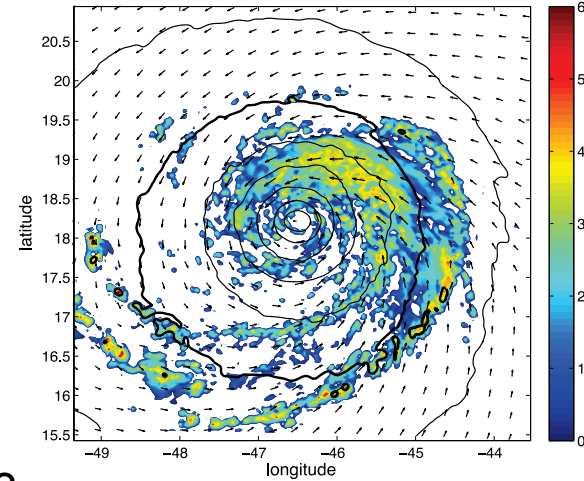
- Nature run used to test the structural metrics
- HWRF case study with focus on evaluating the impact of vertical eddy diffusivity

The Hurricane Nature Run: A very high quality hurricane simulation that serves as a benchmark for operational models

Simulated DBZ at z = 2.9 km, 08-02-00h00Z max=58.1 min=-30.0 int=2.0

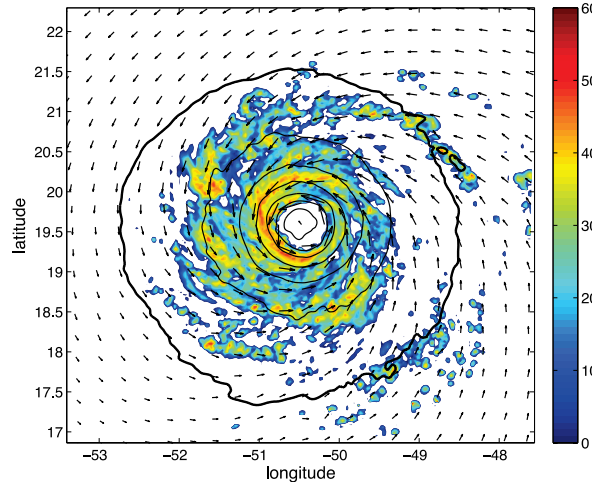


Simulated DBZ at z = 2.9 km, 08-03-00h00Z max=77.6 min=-30.0 int=2.0

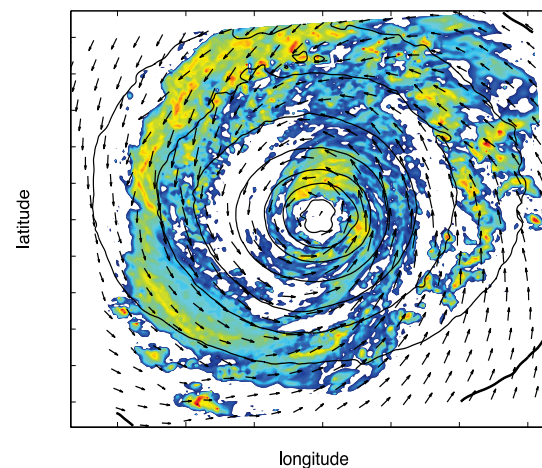


Nolan et al. 2013

Simulated DBZ at z = 2.9 km, 08-04-00h00Z max=57.9 min=-30.0 int=2.0



Simulated DBZ at z = 2.9 km, 08-10-00h00Z max=73.4 min=-30.0 int=2.0

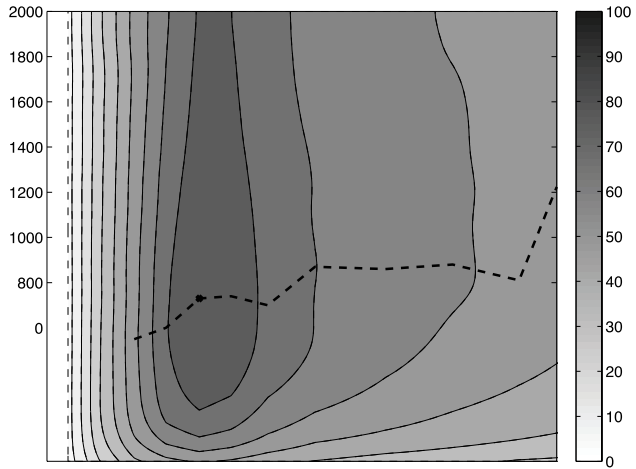


1km grid spacing, 60 vertical levels, very “expensive” parameterizations

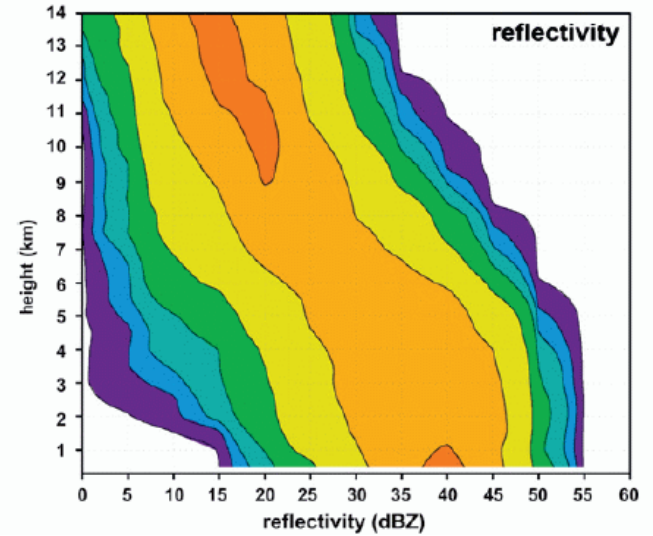
In some ways, the nature run compares extremely well to the observational composites

(Nolan et al. 2013)

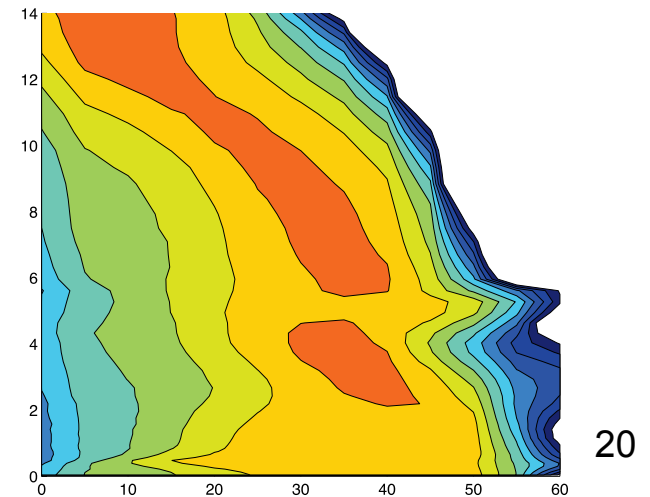
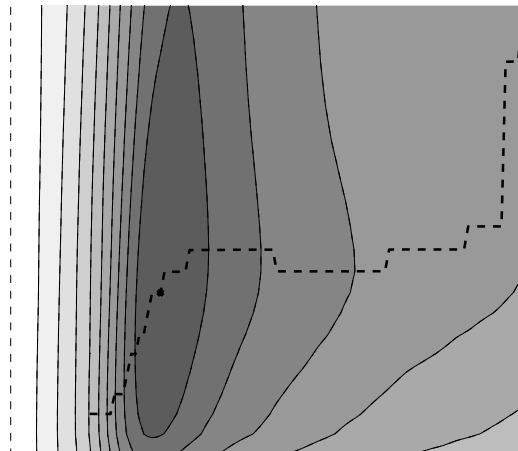
OBS



Inner eyewall

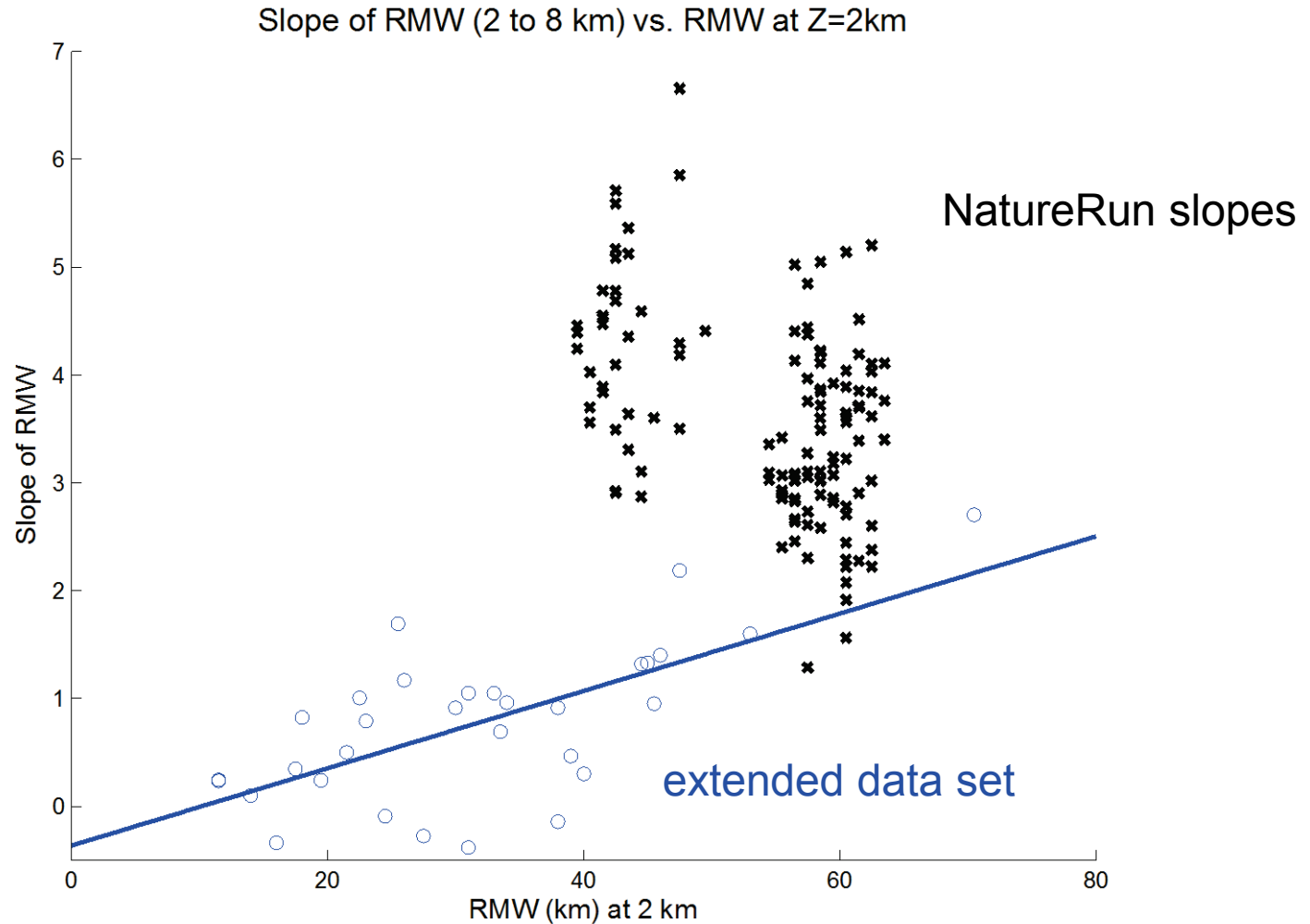


Nature Run

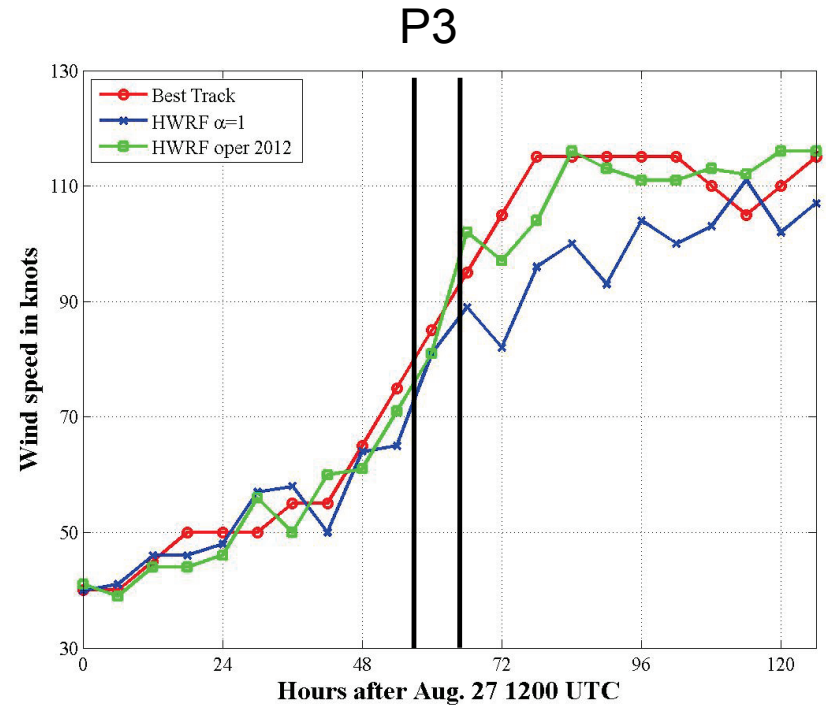
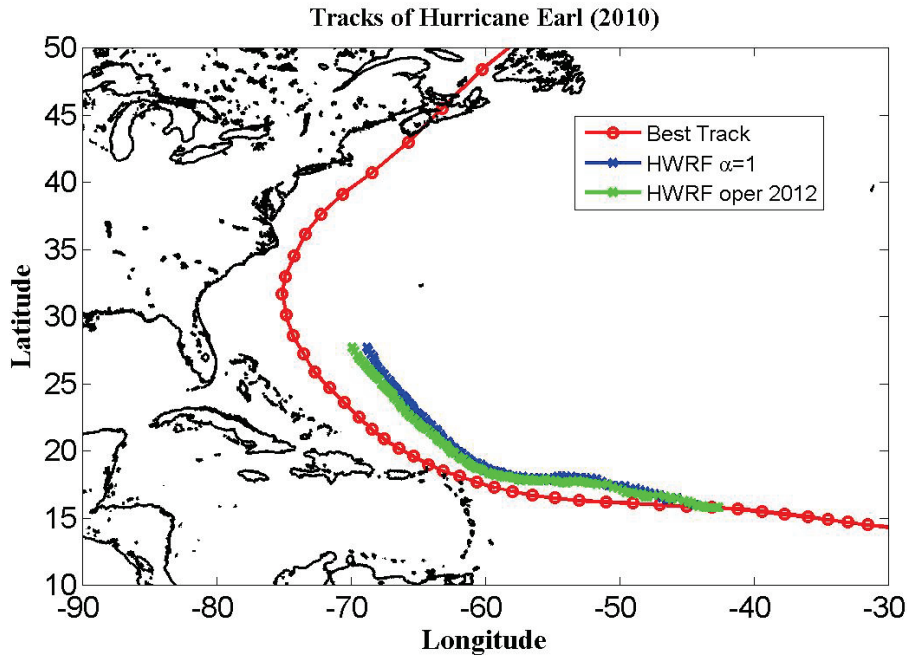


20

But the eyewall (RMW) slope relationship is not as good



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

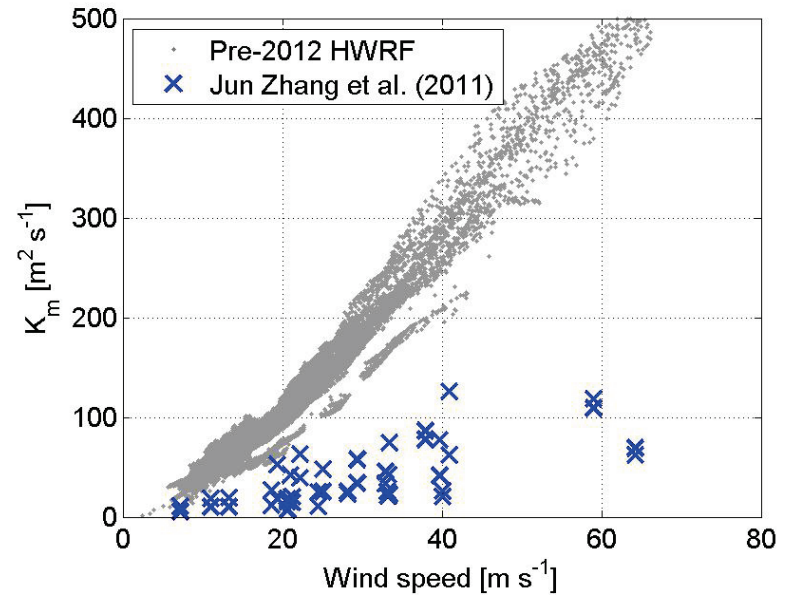
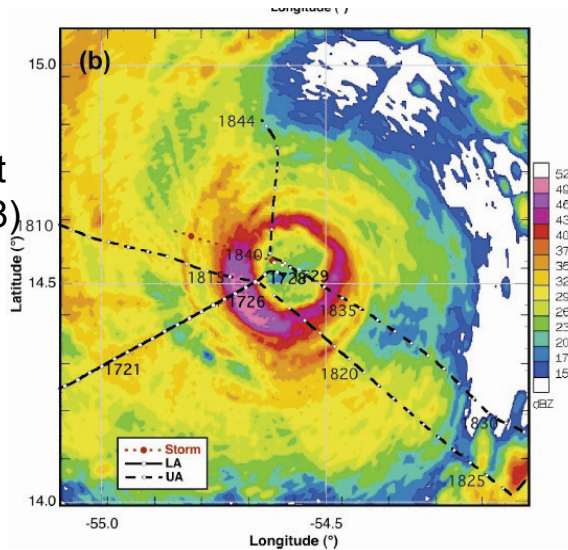


Two simulations with small K_m ($\alpha=0.5$) vs large K_m ($\alpha=1$)

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

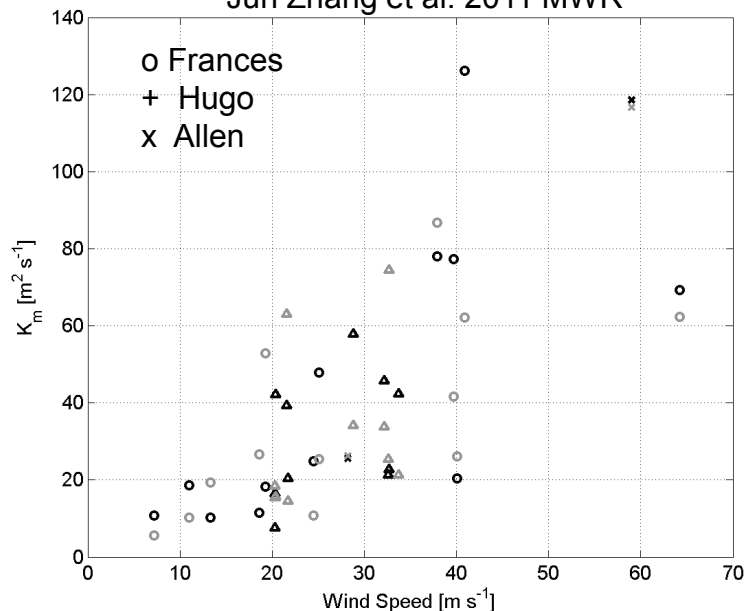
Evaluation and Improvement of the PBL physics in HWRF

Hugo (1989) flight
Marks et al. (2008)

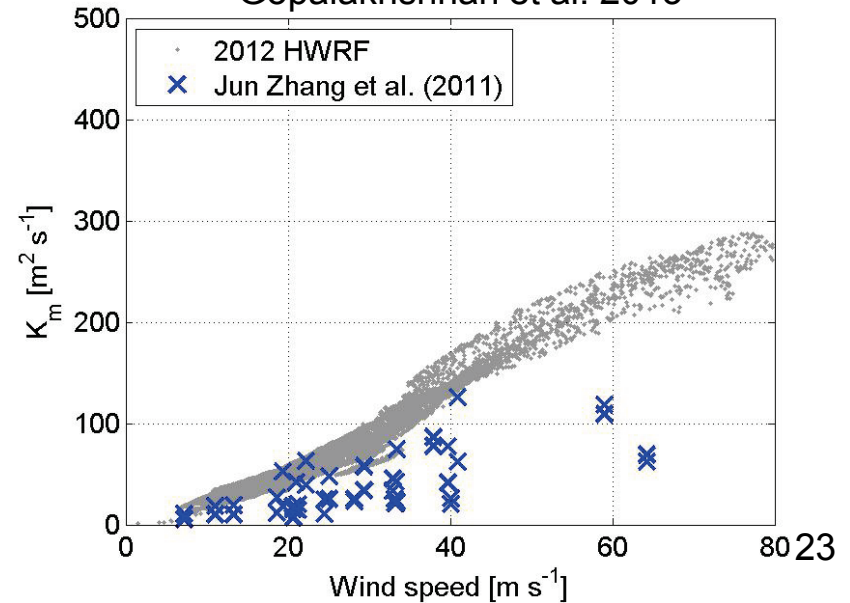


Observed vertical eddy viscosity

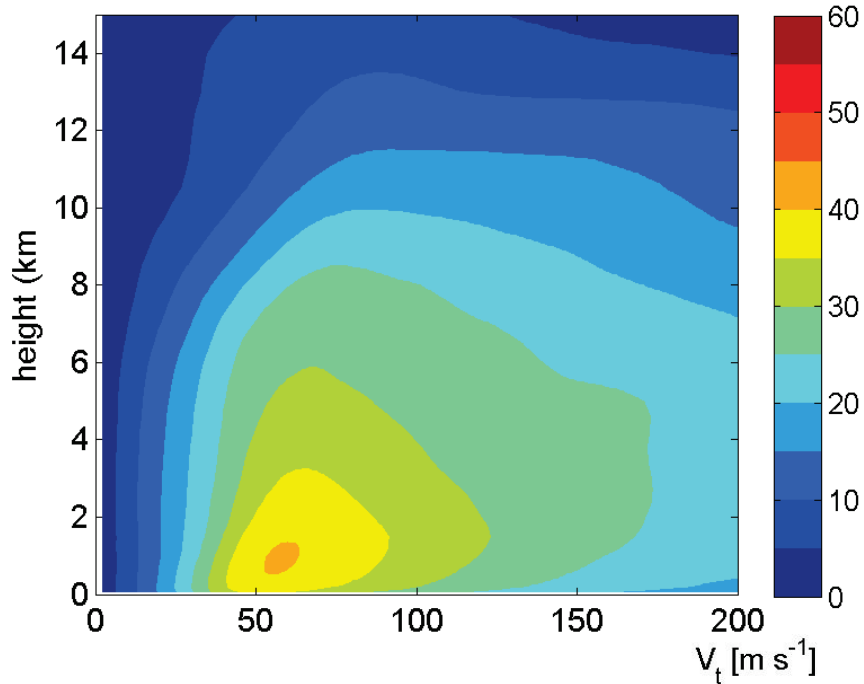
Jun Zhang et al. 2011 MWR



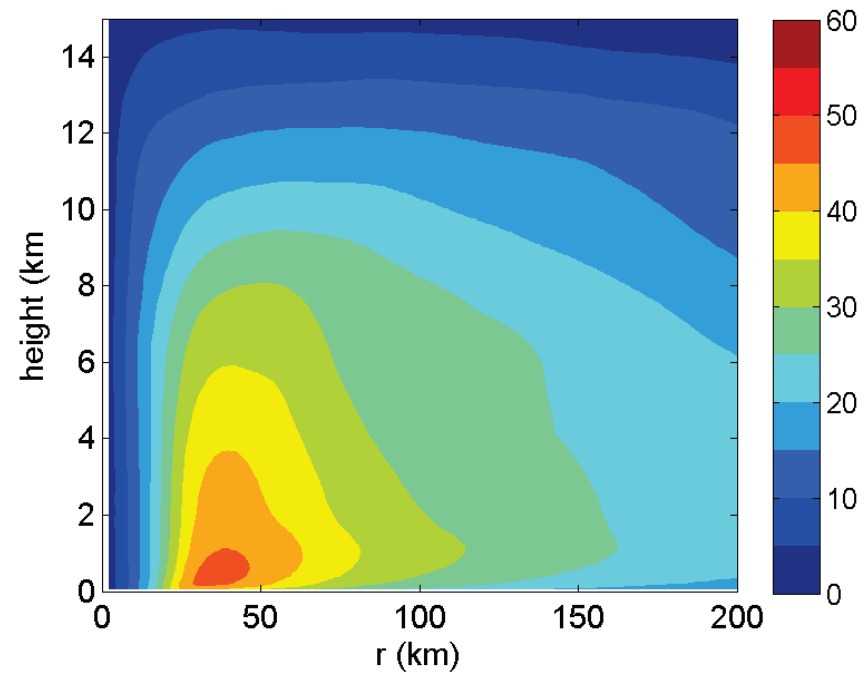
Gopalakrishnan et al. 2013



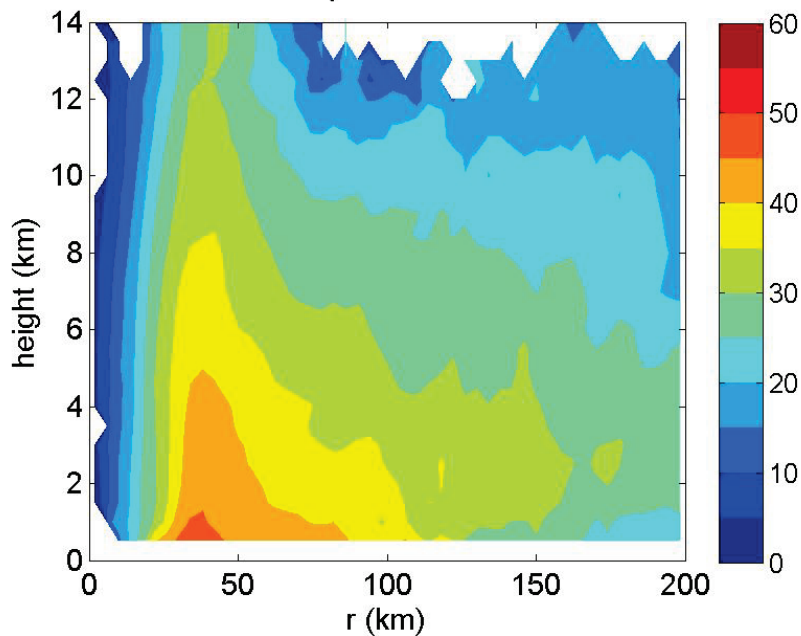
HWRF large Km V_t [m s^{-1}]



HWRF 2012 V_t [m s^{-1}]



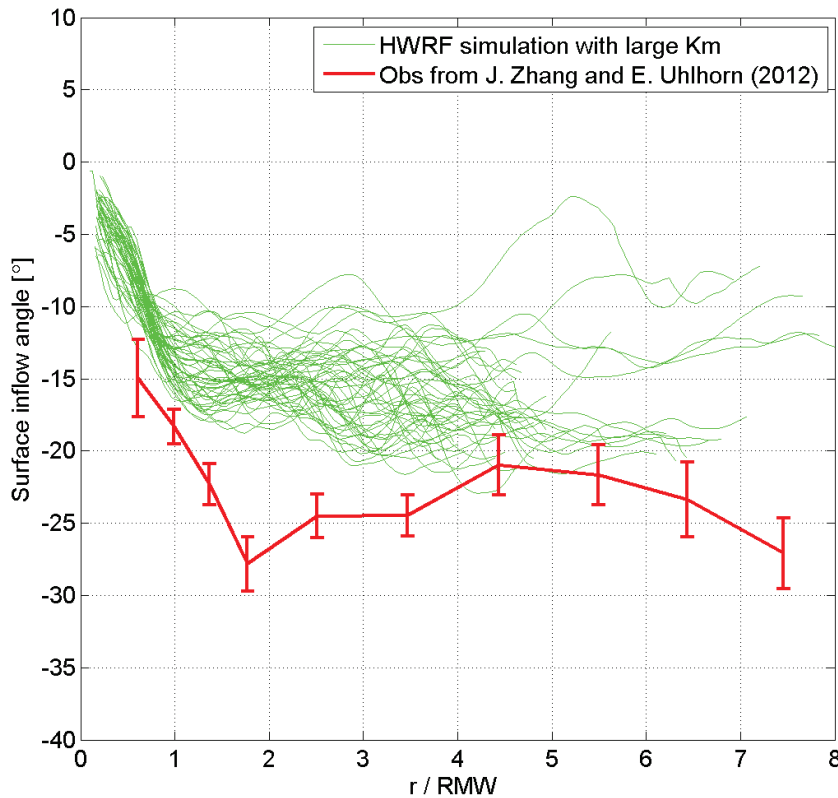
Doppler radar observation



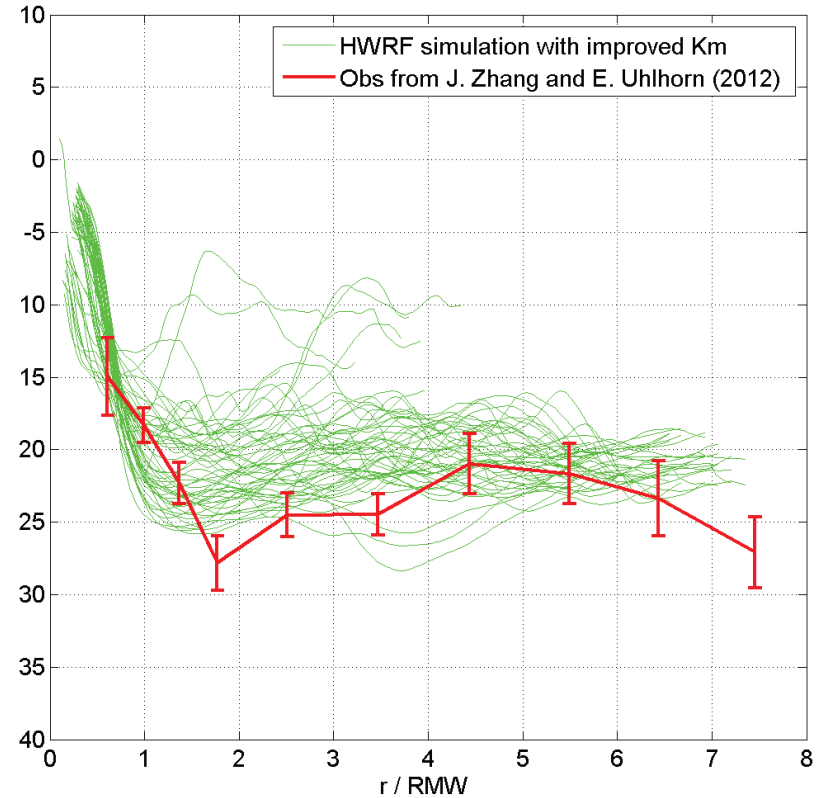
Smaller Km leads to a stronger, deeper and smaller vortex which is more consistent with observations.

Diagnostics of inflow angle using aircraft data

HWRF 2011



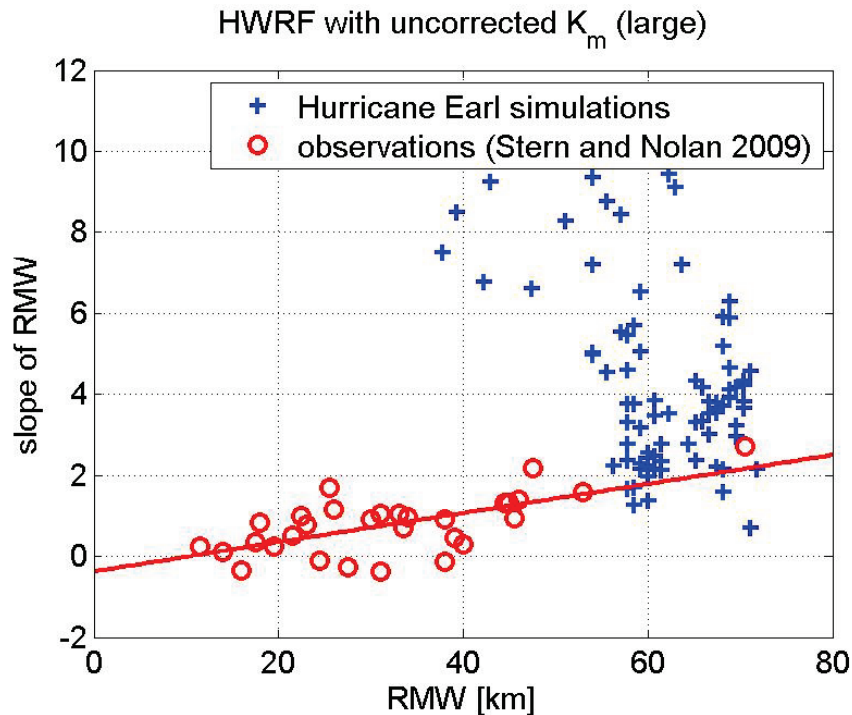
HWRF 2012



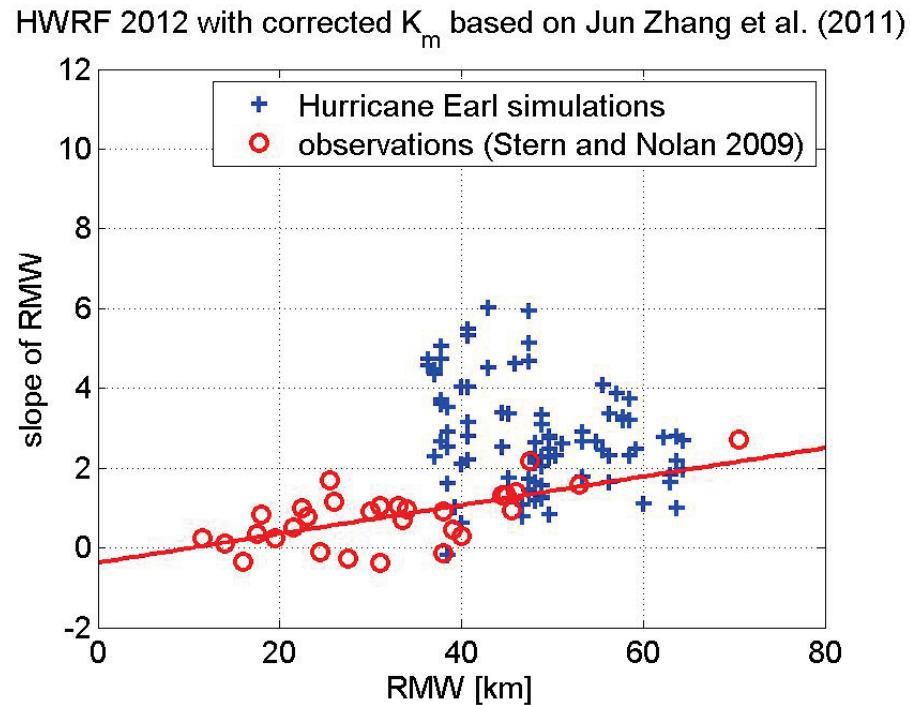
The simulated inflow angle is much closer to observations using HWRF with improved vertical eddy diffusivity (K_m) than that without correction.

Eyewall Slope Diagnostics

HWRF 2011



HWRF 2012



- On average, the sizes of simulated storms are smaller for using HWRF with corrected K_m than that without correction;
- The simulated eyewall slope is closer to observations for using HWRF with corrected K_m than that without correction.

Summary of the modeling work

1. Structural metrics were successfully tested in the hurricane nature run (Nolan et al. 2013).
2. Structural metrics were also tested in Hurricane Earl simulations using HWRF with two different PBL physics.
3. Our results show significant improvement in simulated multiscale structure with the 2012 operational HWRF model.

Ongoing and future work

1. Evaluating the asymmetric structure using Hurricane Earl simulations, with focus on vortex scale and convective scale structures;
2. Further evaluating multiscale inner-core structures in HWRF (2012) simulations in the composite framework;
3. Evaluating the 2013 version HWRF model in terms of structural metrics.