Update on Observed Eddy Diffusivity in the Hurricane Boundary Layer for Improving the HWRF Physics

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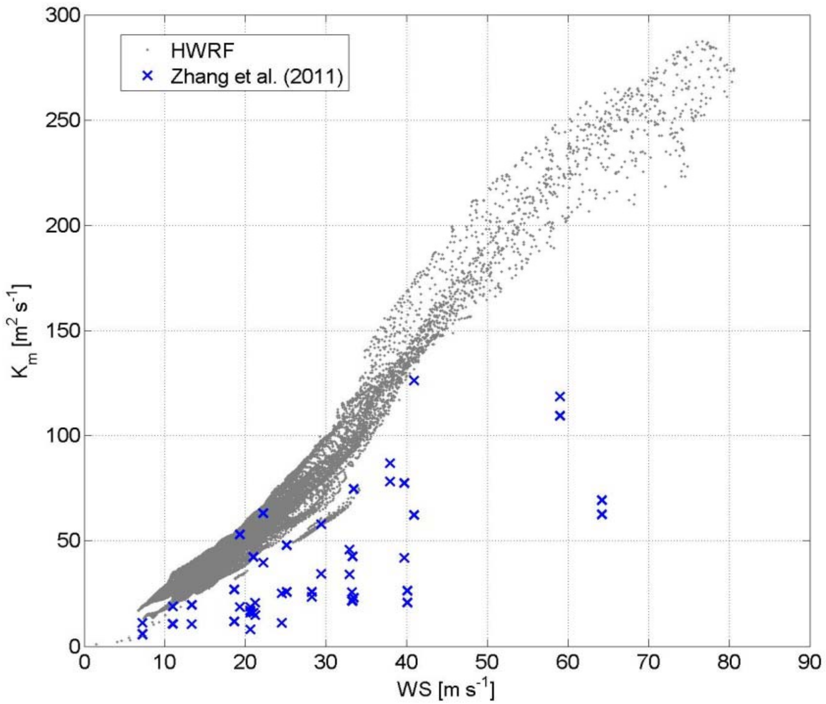
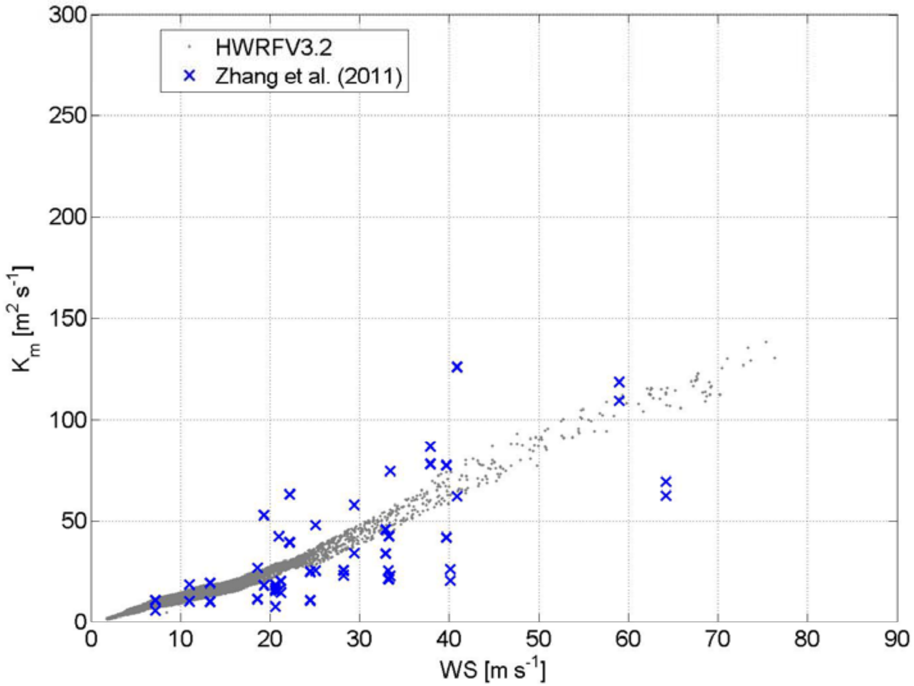
HWRF internal meeting, 05/03/2012

Use observations to improve PBL physics in operational hurricane models

Before modification (operational HWRF)



After modification (HWRF 2012)



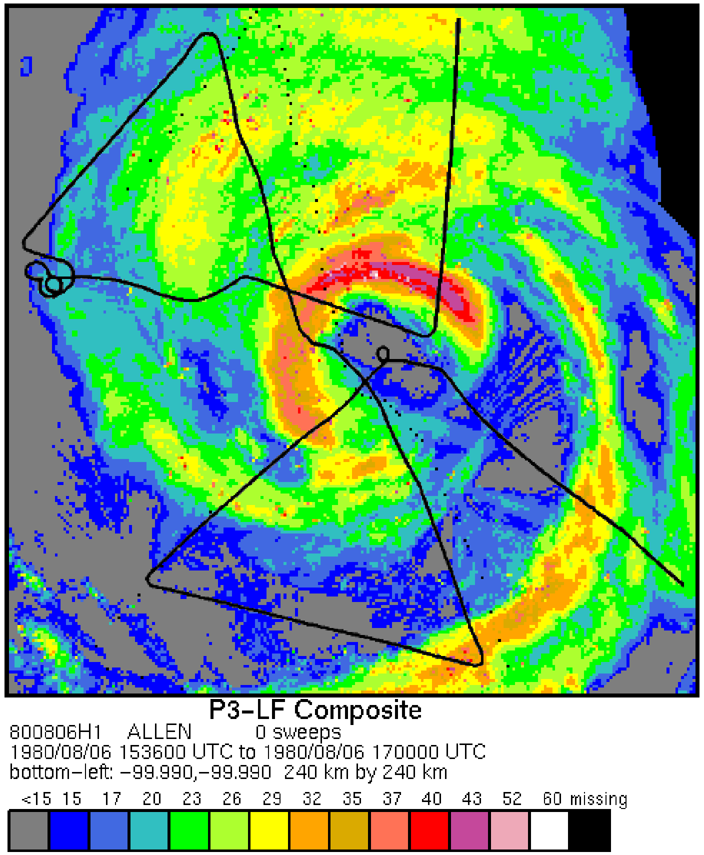
- An estimation of turbulent characteristics in the low-level region of intense Hurricanes Allen (1980) and Hugo (1989). *Mon. Wea. Rev*., Zhang, J. A., F. D. Marks, M.T. Montgomery, and S. Lorsolo, 2011.

- Observational Estimates of the Horizontal Eddy Diffusivity and Mixing Length in the Low-Level Region of Intense Hurricanes. *J. Atmos. Sci.*, Zhang, J. A. and M. T. Montgomery, 2012.

Data

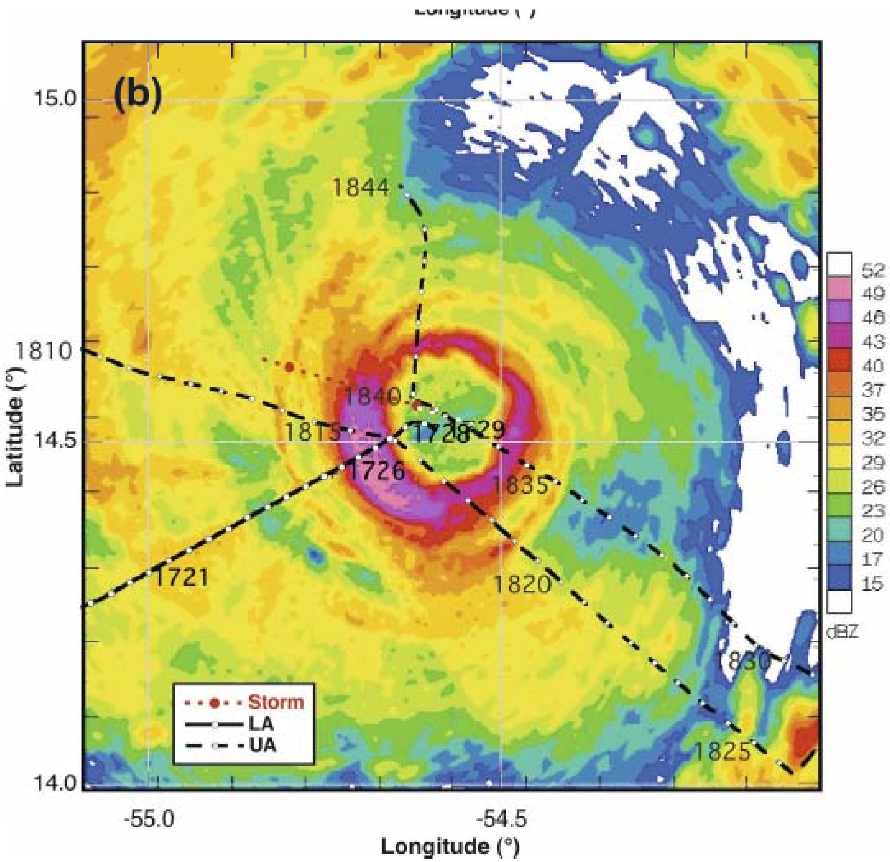
We use the flight-level data that were collected using the low-level eyewall penetrations of Hurricanes Allen (1980), Hugo (1989) and David (1979).

Allen, Aug. 6, 1980



(Marks 1985 MRW)

Hugo, Aug. 15, 1989



(Marks et al. 2008 MWR)

Methodology

1. Vertical and horizontal momentum fluxes:

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

2. Turbulent kinetic energy: $e = \frac{1}{2}(\overline{v_t'^2} + \overline{v_r'^2} + \overline{w'^2})$

3. Vertical eddy diffusivity :

1) definition: $K = |\hat{\tau}|(\frac{\partial V}{\partial z})^{-1}$

2) Hanna (1969) method: $K_1 = cl\sigma_w \qquad l = \sigma_w^3/\varepsilon$

3) TKE-closure method: $K_2 = c_2 e^2/\varepsilon$

4. Horizontal eddy diffusivity : $K_h = |F_h|(\rho|S_h|)^{-1}$, $L_h = (K_h D_h^{-1})^{1/2}$

$$F_h = \rho K_h S_h \qquad S_h = (\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}) \qquad S_h = (\frac{\partial v_t}{\partial r} - \frac{v_t}{r})\cos 2\lambda + (\frac{\partial v_r}{\partial r} - \frac{v_r}{r})\sin 2\lambda$$

$$D_h^2 = (\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y})^2 + (\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y})^2 \qquad D_h^2 = 2(\frac{\partial v_r}{\partial r})^2 + 2(\frac{v_r}{r})^2 + (\frac{\partial v_t}{\partial r} - \frac{v_t}{r})^2$$

Marks et al. 2008

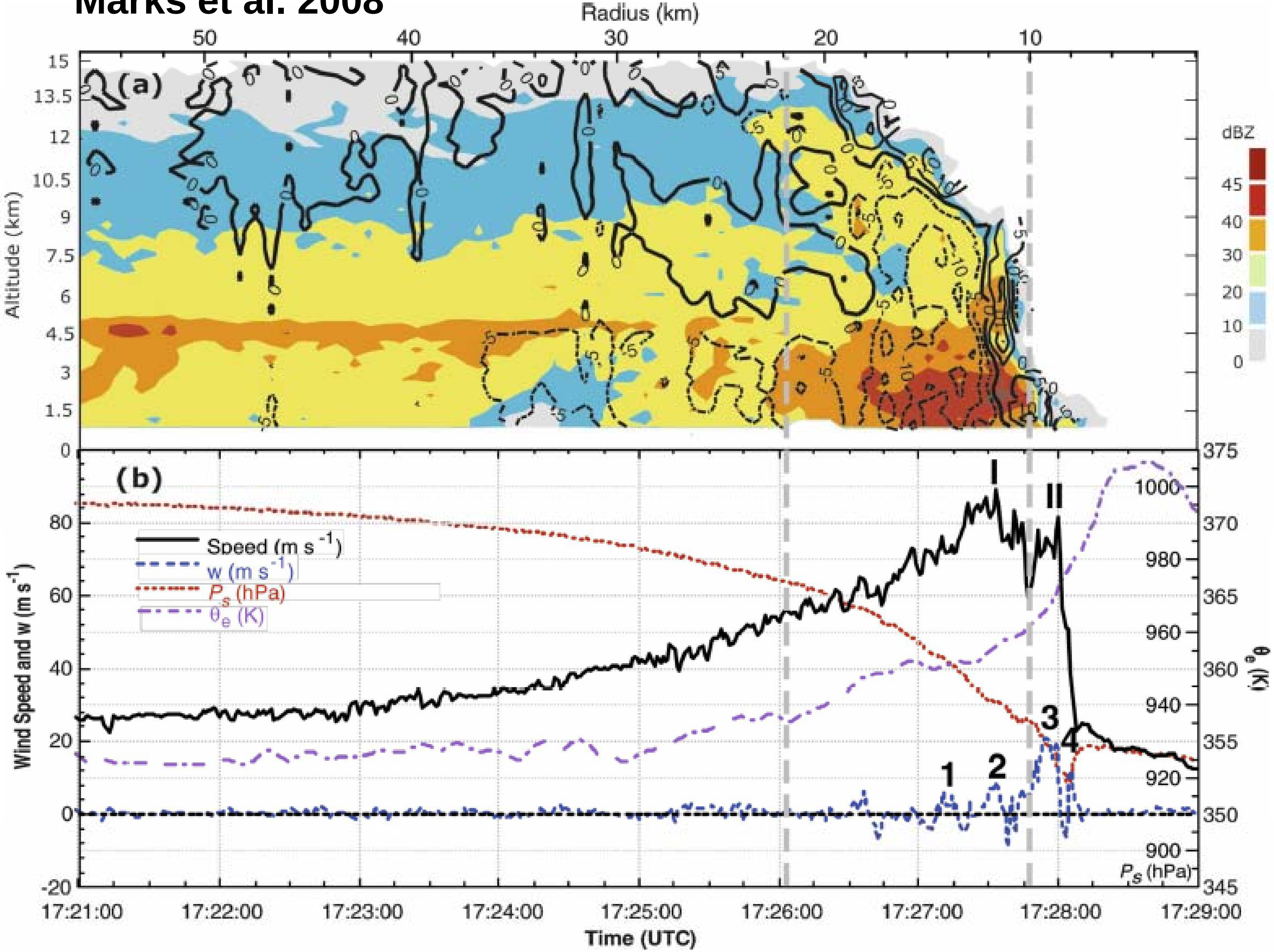
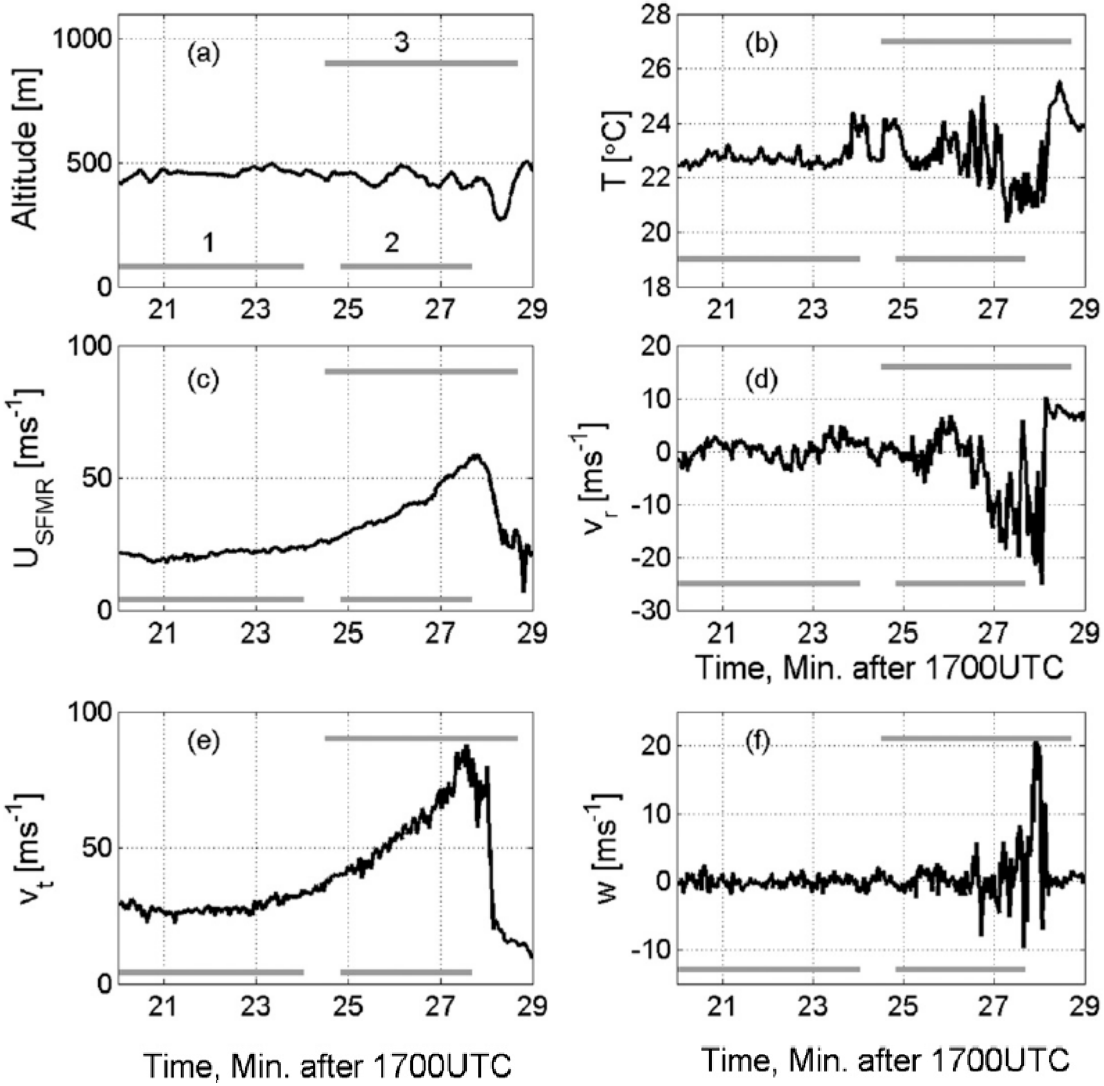


FIG. 3. (a) Time–height cross section of vertical incidence tail radar reflectivity (dBZ) from LA for 1721–1728 UTC. The LA flight track was at 450 m. Solid and dashed lines denote vertical velocity, and radar reflectivity is denoted by colors using the color scale on the right. (b) Time series plots of w, horizontal wind speed, P_s, and θ_e for the period 1721–1730 UTC. Updrafts labeled 1, 2, 3, and 4 and wind speed peaks I and II are described in the text. The thick dashed lines in (b) approximately delineate the outer and inner radii of strong eyewall reflectivity maxima in the lower troposphere ($1 < z < 5$-km altitude).

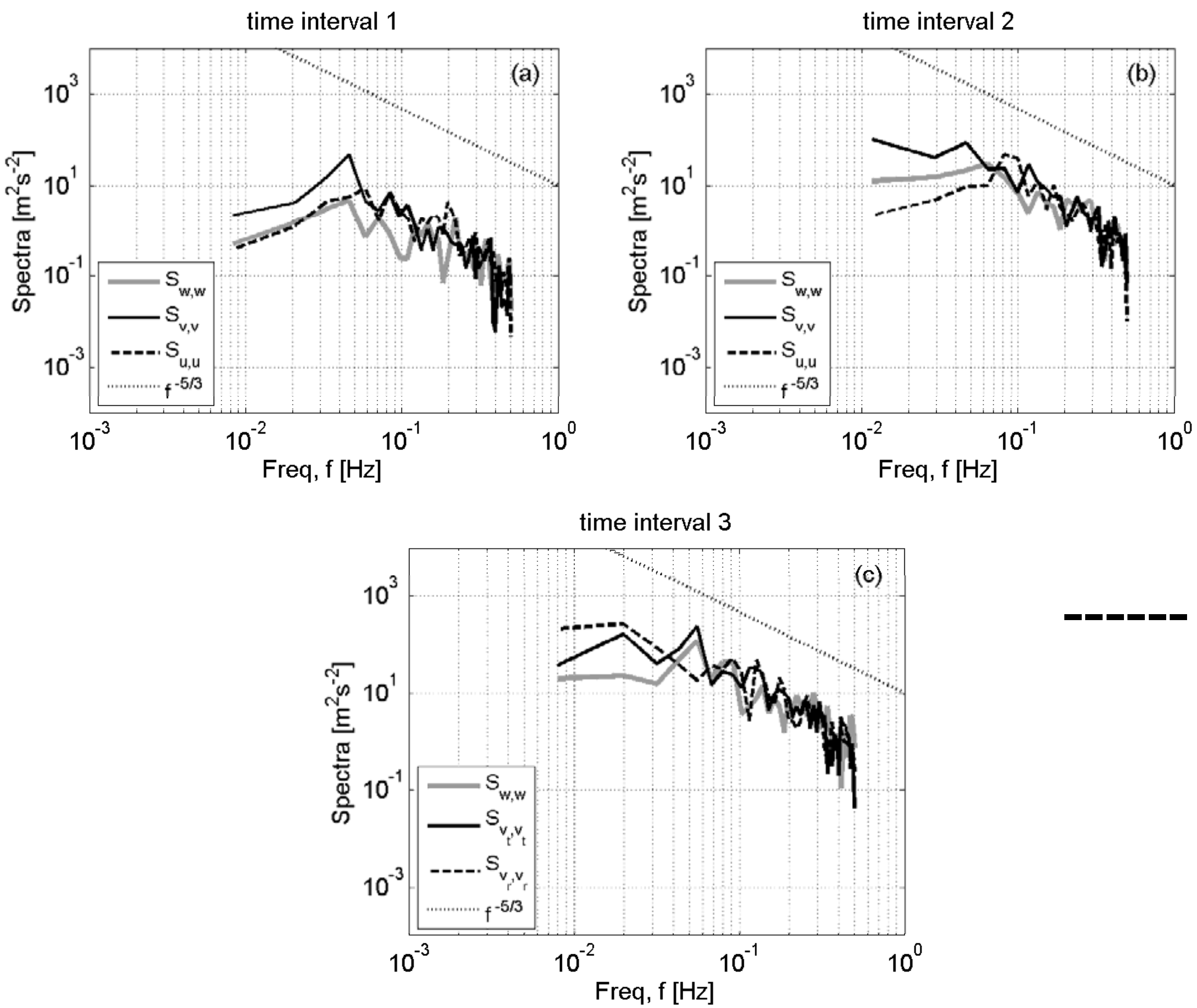
Hurricane Hugo flight



Run # 3 includes Eyewall Vorticity Maxima (EVM)

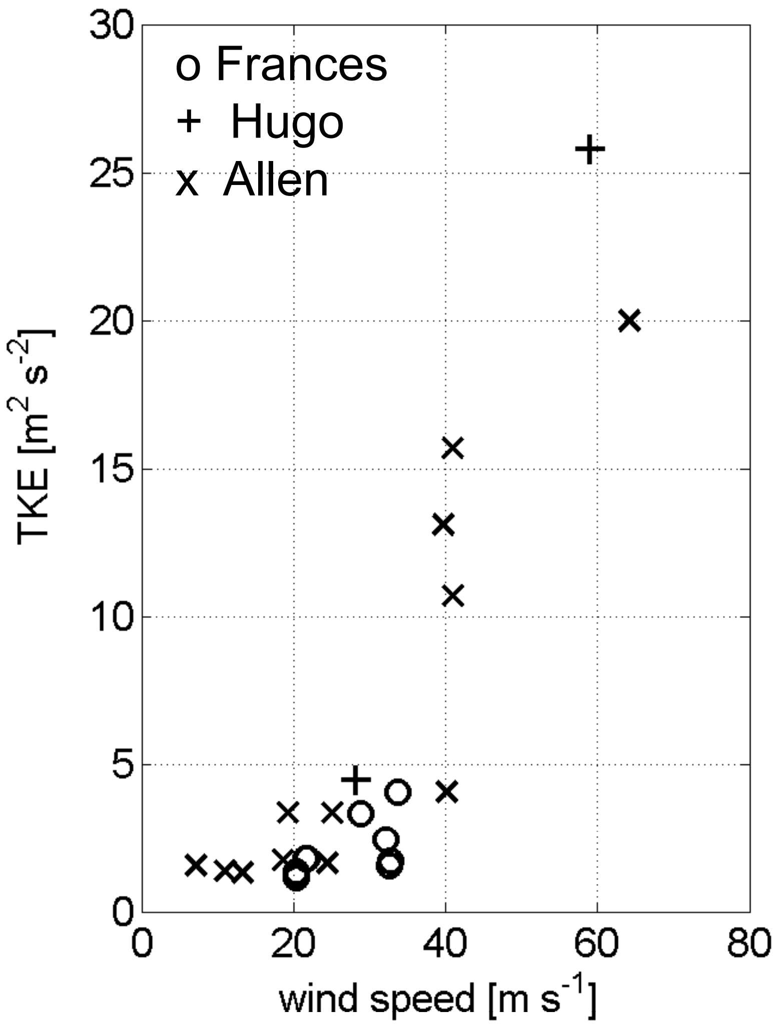
Spectral Analysis

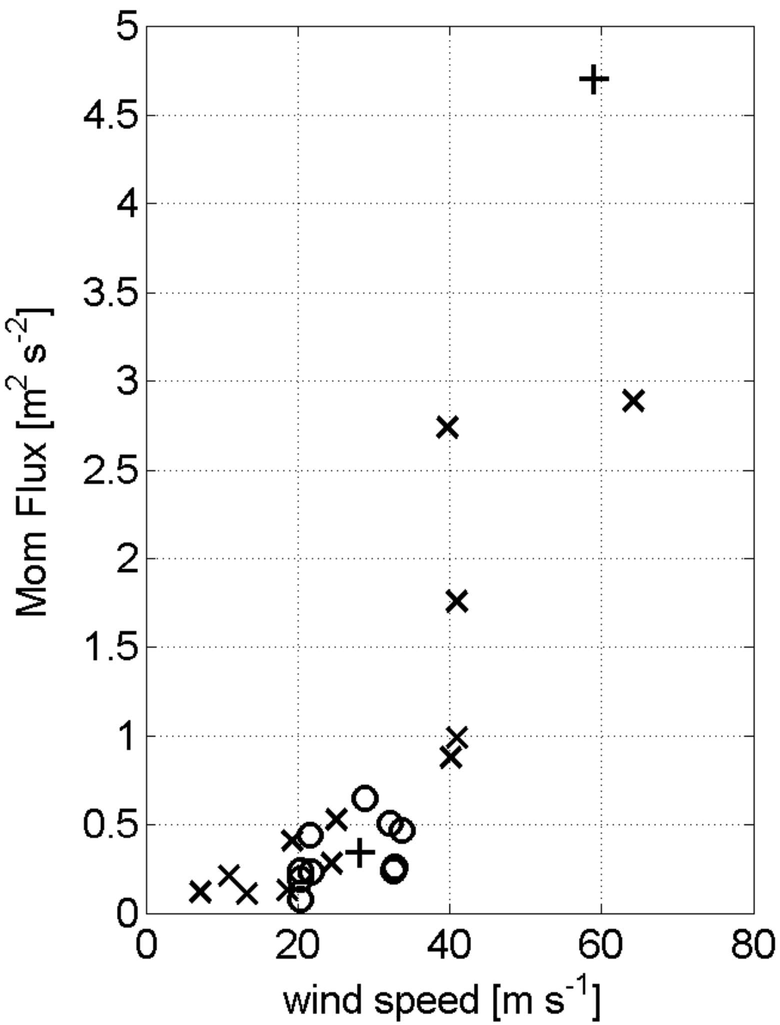
(Three time intervals from the Hugo flight)



------ $f^{-5/3}$

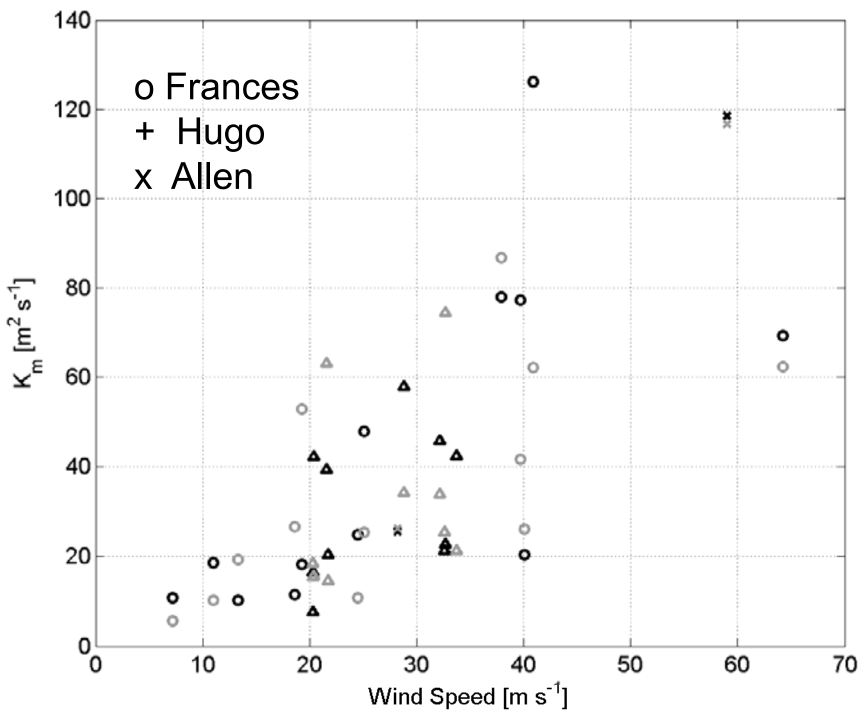
TKE and vertical momentum fluxes

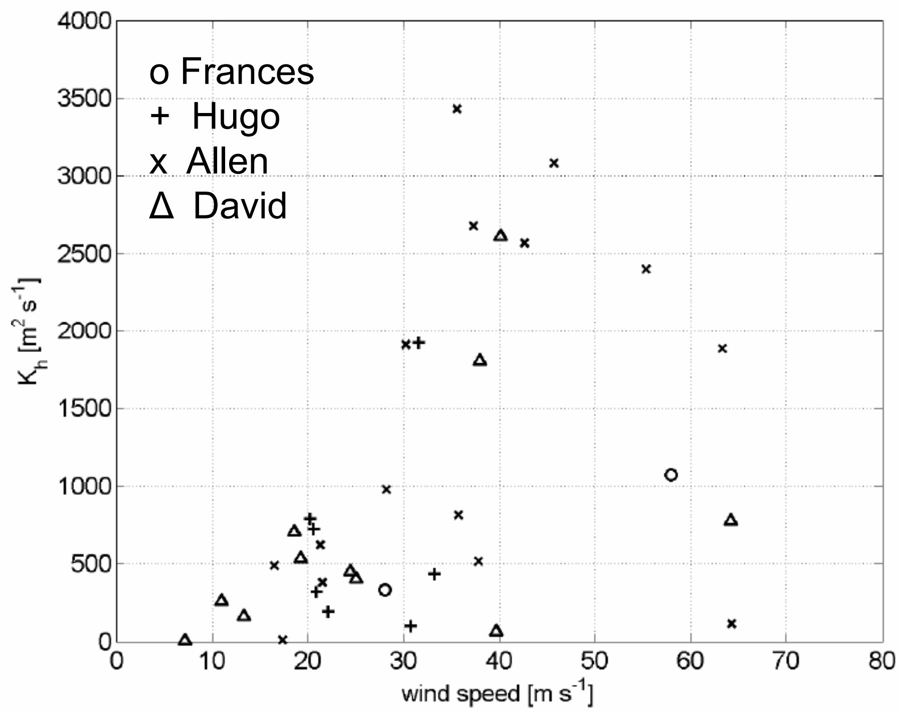




Both the vertical momentum flux and TKE increase with wind speed.

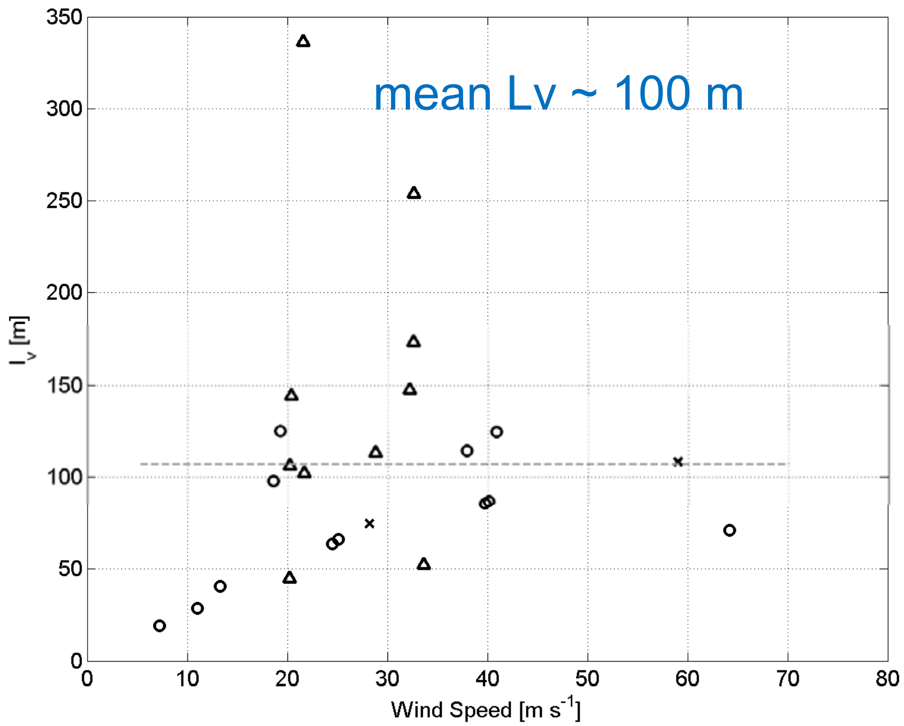
Vertical and horizontal eddy diffusivities

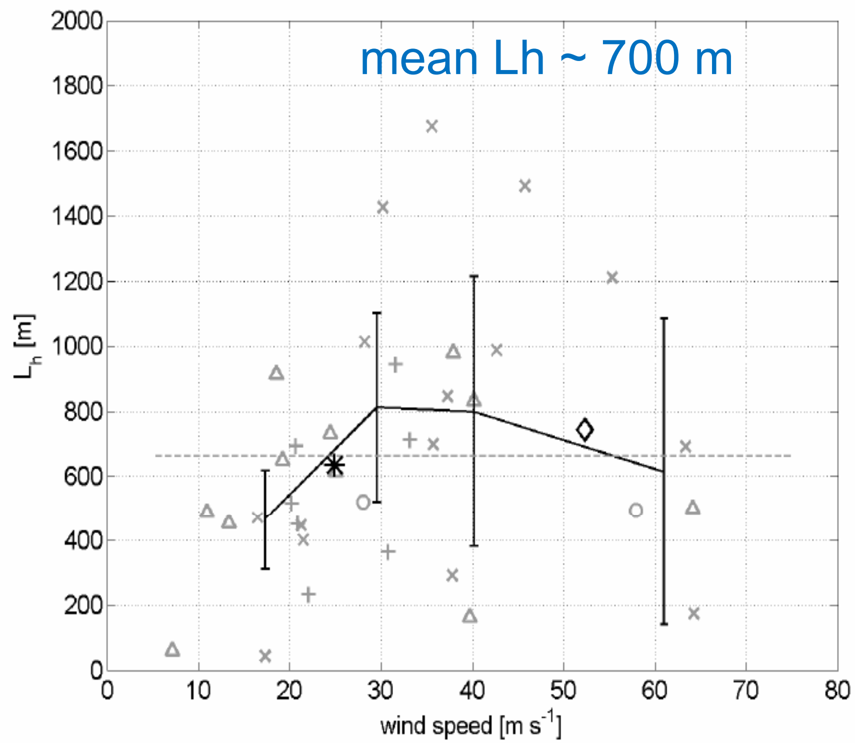




The horizontal eddy diffusivity is an order of magnitude larger than the vertical eddy diffusivity.

Vertical and horizontal mixing length



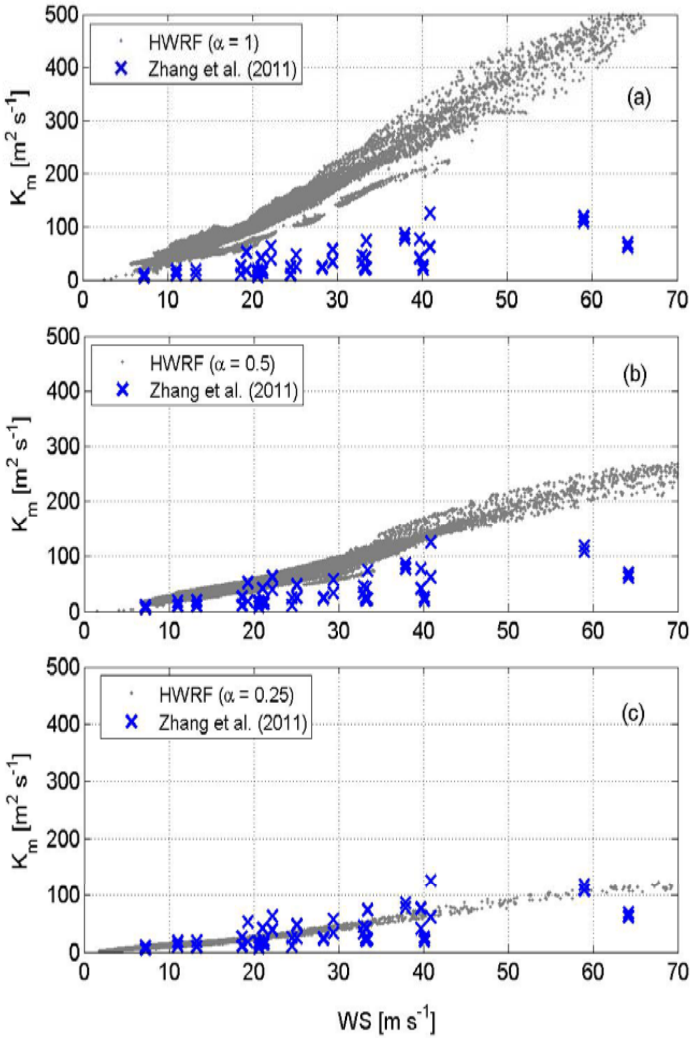


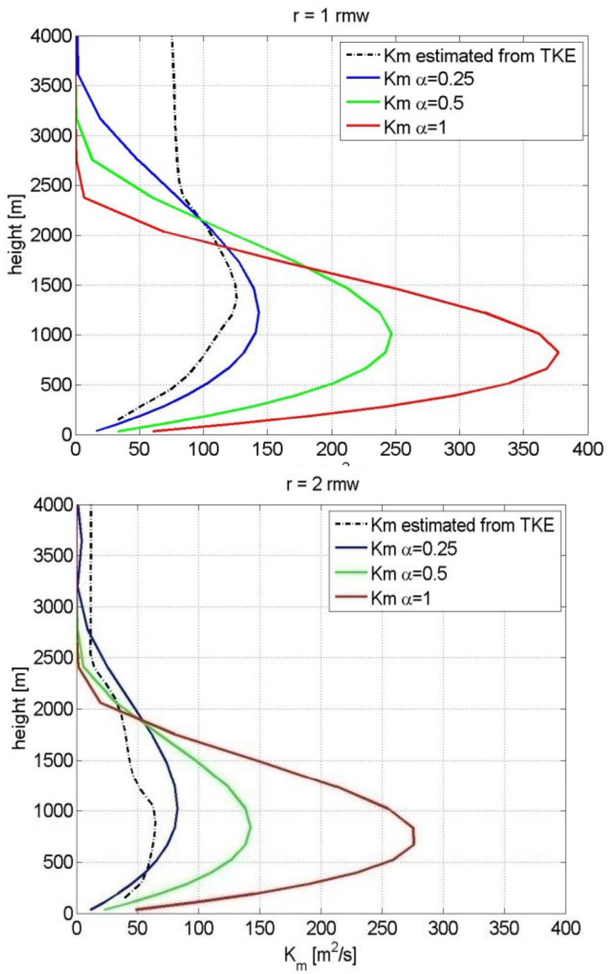
The vertical and horizontal mixing lengths have little dependence on the wind speed.

Observation Based GFS PBL Parameterization Schemes

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

Gopalakrishnan et al. 2011, JAS (under revision)

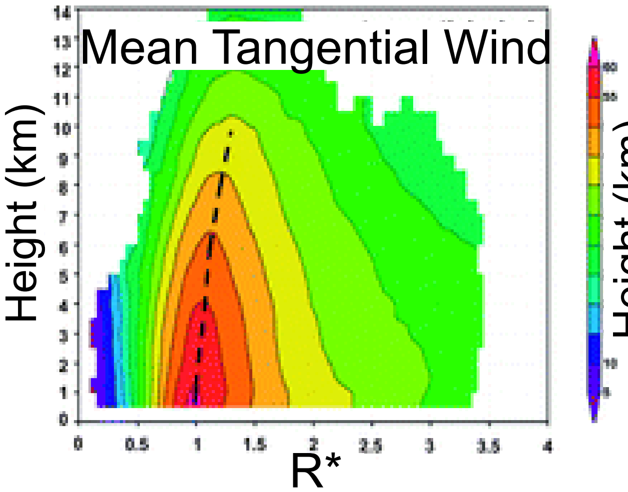


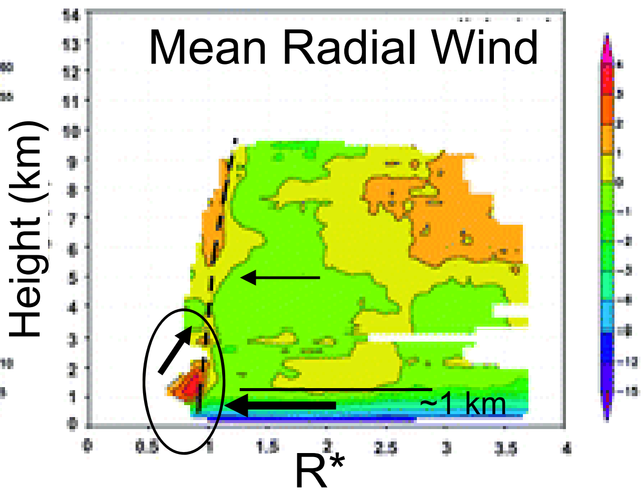


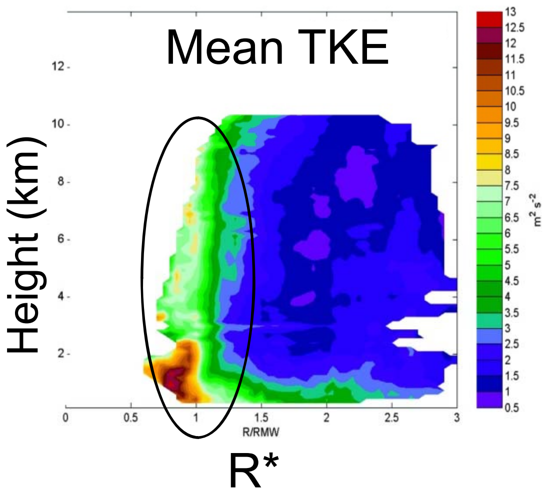
$$K_m = c\, l\, (TKE)^{1/2}$$

Use of PBL observations for Advancing the HWRF system

--A pathway from research to operation







(1) 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.

(2) Lorsolo, S., J. Zhang, F.D.Marks, J. F. Gamache, 2010: Estimation and Mapping of Hurricane Turbulent Energy Using Airborne Doppler Measurements, *Mon. Wea. Rev.*, **138**, 3656–3670

(3) Robert Rogers, Sylvie Lorsolo, Paul Reasor, John Gamache, Frank Marks, 2010: Multiscale Analysis of Tropical Cyclone Kinematic Structure from Airborne Doppler Radar Composites, *Mon. Wea. Rev.*, **140**, 77-99

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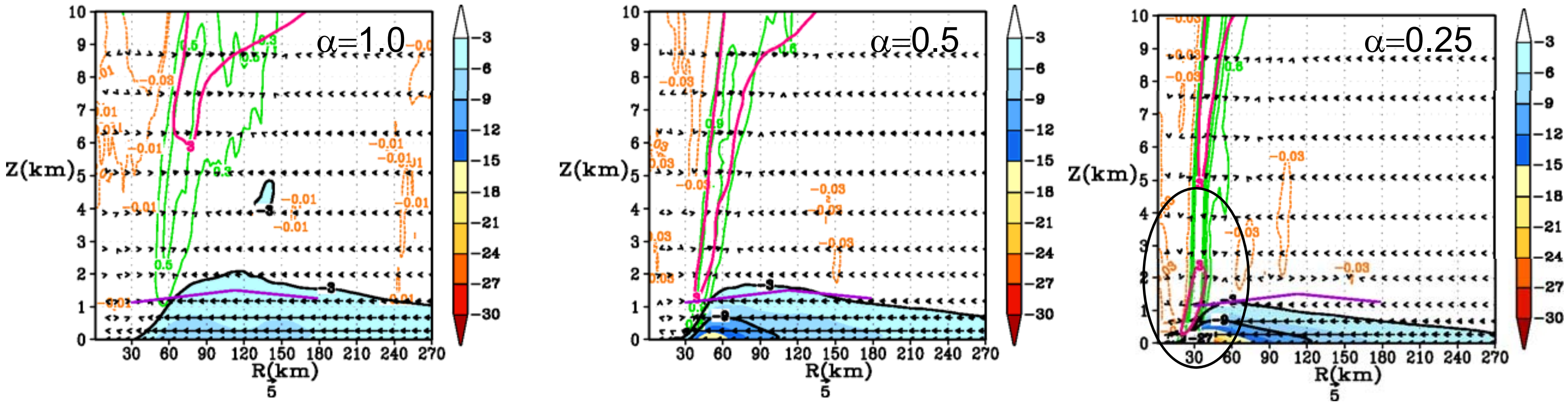
Improved Structure Predictions



Tangentially averaged, 6-hourly time averaged, radius-height cross-section of the secondary circulation at 93 hours for (a) control (α=1), (b) Km reduced to half (α=0.50), and (c) Km reduced to a quarter (α=0.25). Presented in purple color are the estimates of the inflow layer depth from Zhang et al. (2011b).

- Enhanced cross isobaric flow
- Height of inflow layer more consistent with observations
- Significant differences occurs only within the PBL
- Vertical diffusion negates gradients. Stronger the diffusion, weaker are the gradients and the subsequent radial frictional forces
- Weaker the diffusion, stronger is the frictional forces in the PBL, stronger the radial acceleration of the flow in the PBL.

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Summary

1. Turbulence characteristics in the low-level troposphere (~ 450 m) of Hurricanes Hugo (1989), Allen (1980) and David (1979) have been investigated;

2. Momentum fluxes and TKE for the eyewall penetration legs are an order of magnitude larger than those in the outer core;

3. The vertical and horizontal mixing lengths are approximately 100 m and 750 m, respectively, in the eyewall region.

4. Both vertical and horizontal eddy diffusivities increase with wind speed;

5. Horizontal diffusivity is one order of magnitude larger than vertical diffusivity.

6. The observed diffusivity was used to improve the HWRF PBL physics.

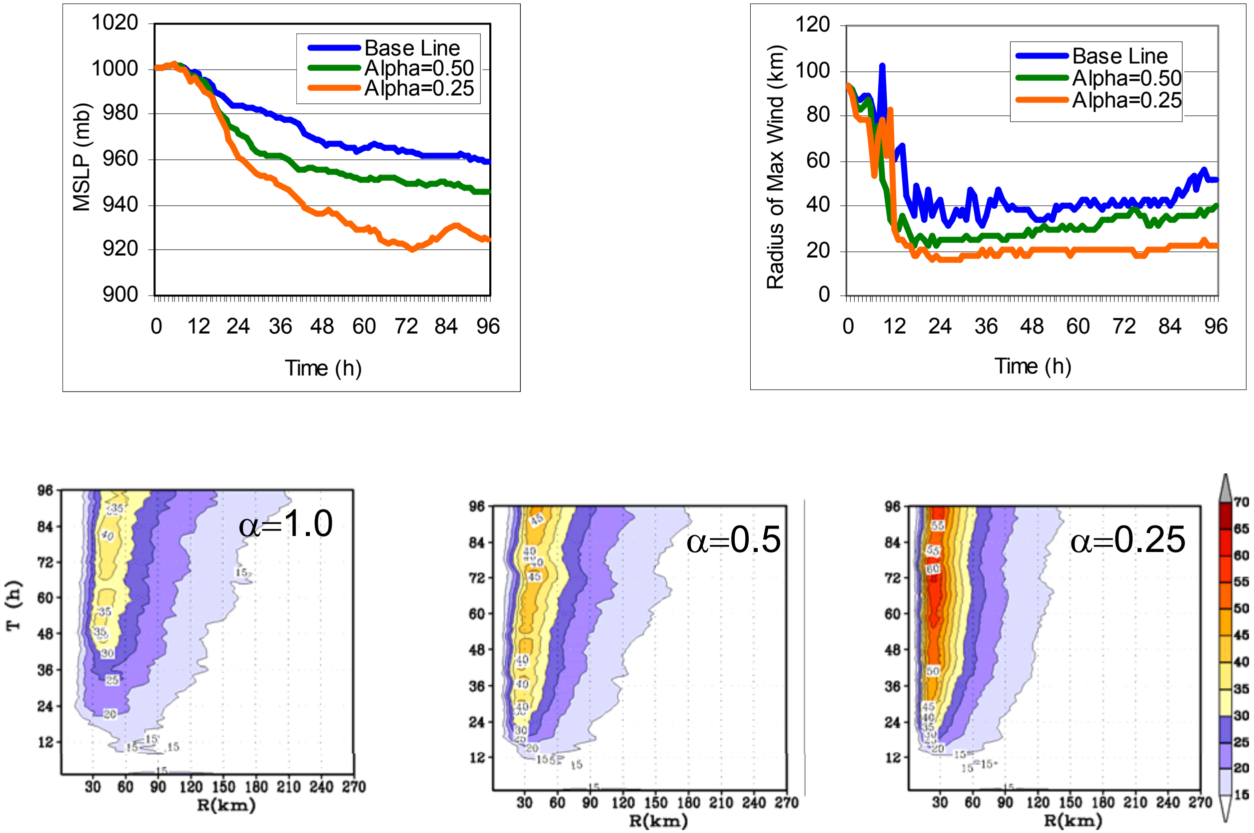
Acknowledgements:

Support of NOAA/HFIP

NOAA Hurricane Research Division

NOAA/OMAO
Aircraft Operations Center

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).

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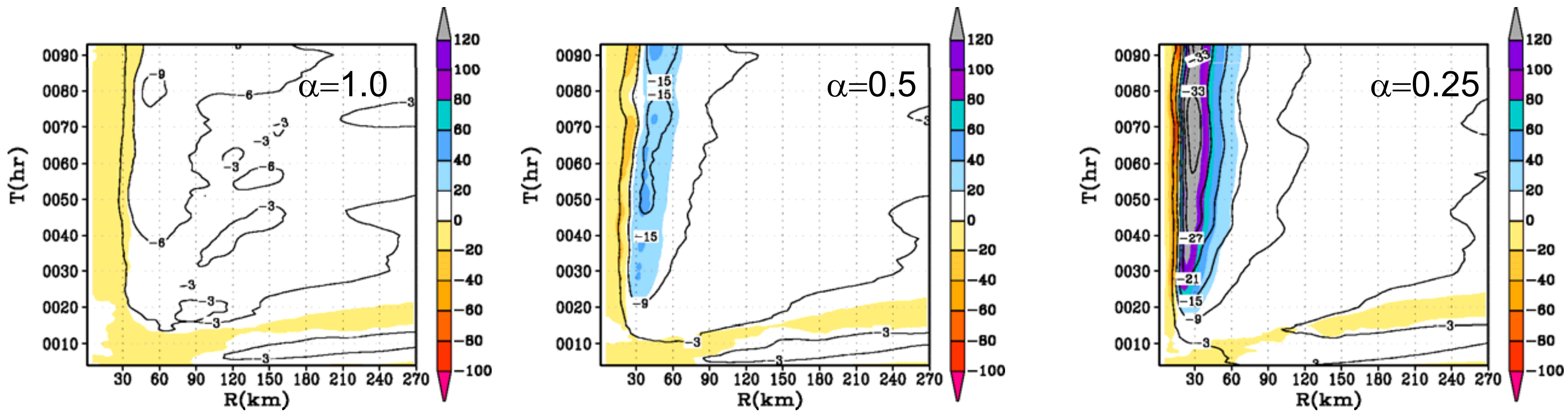
Interactions Between Primary and Secondary Circulation

$$\frac{dv_\lambda}{dt} = -\frac{1}{\rho r}\frac{\partial p}{\partial \lambda} \boxed{-\frac{u_r v_\lambda}{r} - f u_r} + D_{v\lambda}$$

Generalized Coriolis

$$\frac{du_r}{dt} = \boxed{-\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{v_\lambda v_\lambda}{r} + f v_\lambda} + D_{ur}$$

Gradient wind imbalance



Hovemoller diagram of the tangentially averaged, 6-hourly time averaged radial component of velocity (in m s^{-1}). Superposed on the contour lines is the generalized Coriolis term (i.e., term A in equation 2 in text) *with the addition of a frictional effect* shaded in color for the HWRF runs with (i) α=1, (ii) α=0.5, and (iii) α=0.25 runs at the 30-m level. The blue end of the spectrum represents tangential acceleration (contributing towards the “spin up”), and the red end of the spectrum represents deceleration within the inner eyewall region. Units of the forcing term are in m s^{-1} h^{-1}.

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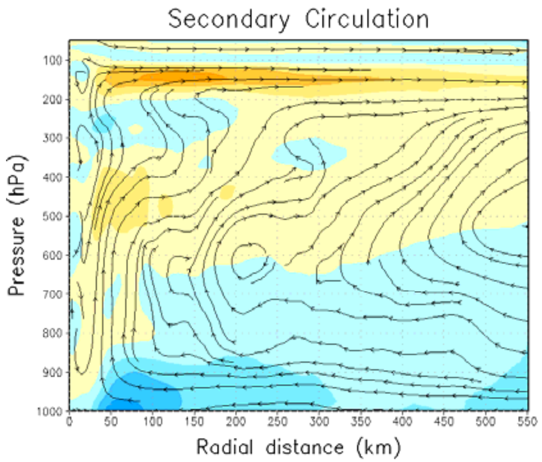
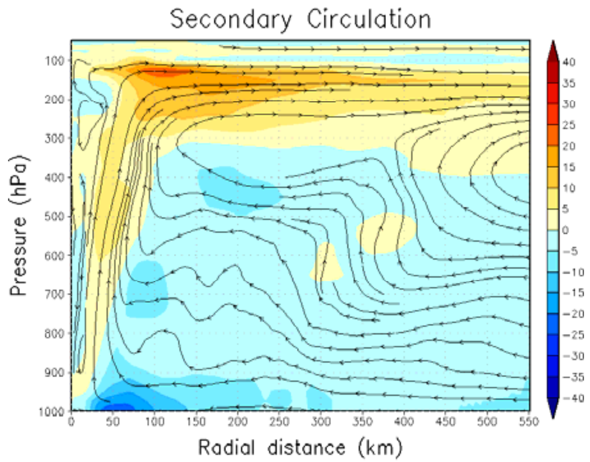
Operational HWRF Findings

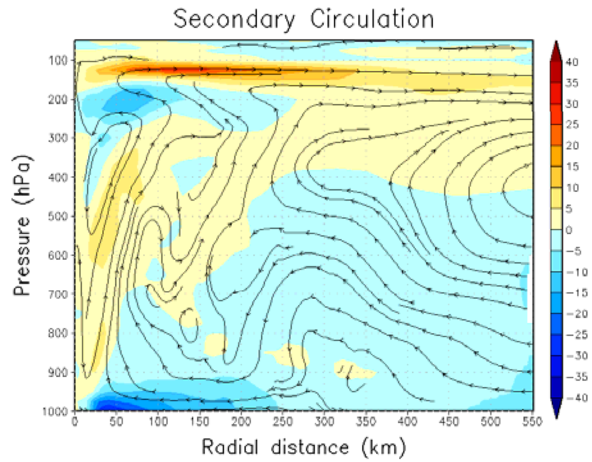
Hurricane Irene 2011082212 30h fcst



A100, IRENE 09l, d23, Azimuthally averaged, Init. date: 2011082212, 30 h FCST
Radial wind (shaded), Min=−17.7875 kts, Max=17.6946 kts
Radial−vertical flow (streamline), Pressure velocity peak=−5.61479 Pa/s

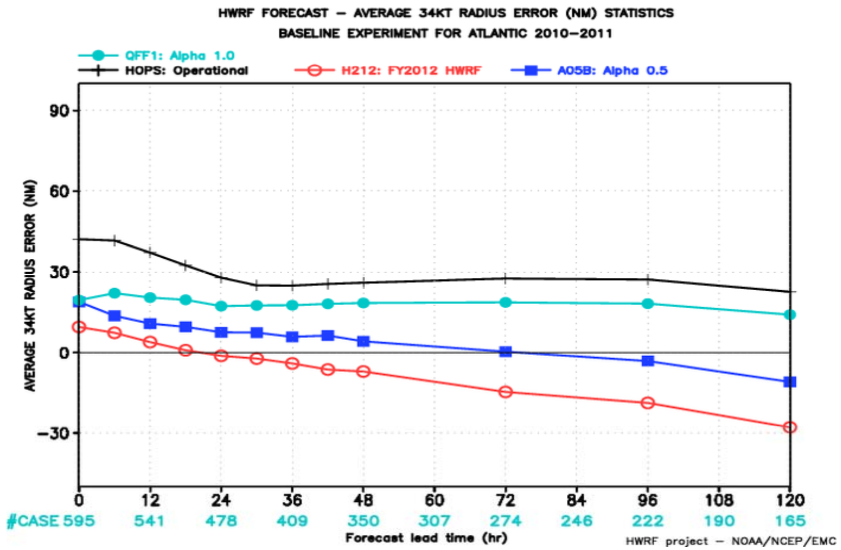


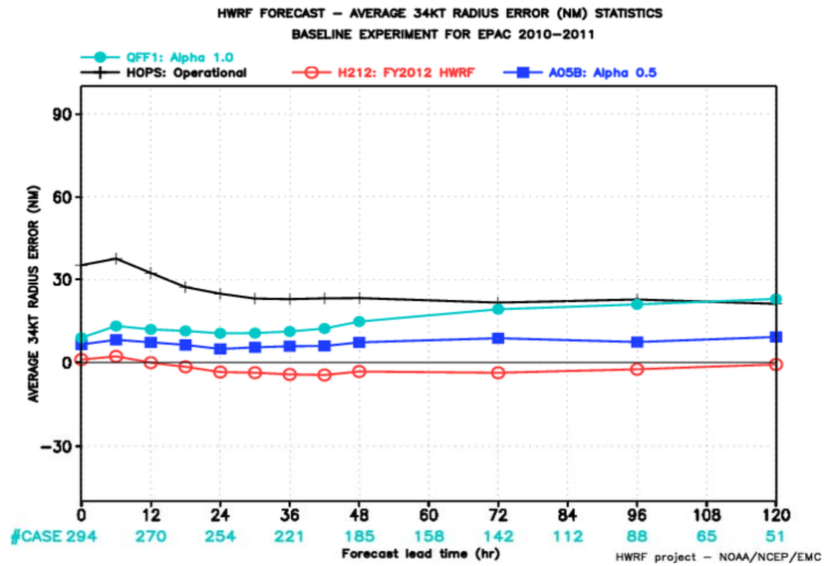
A050, IRENE 09l, d23, Azimuthally averaged, Init. date: 2011082212, 30 h FCST
Radial wind (shaded), Min=−23.5483 kts, Max=24.3886 kts
Radial−vertical flow (streamline), Pressure velocity peak=−6.76019 Pa/s

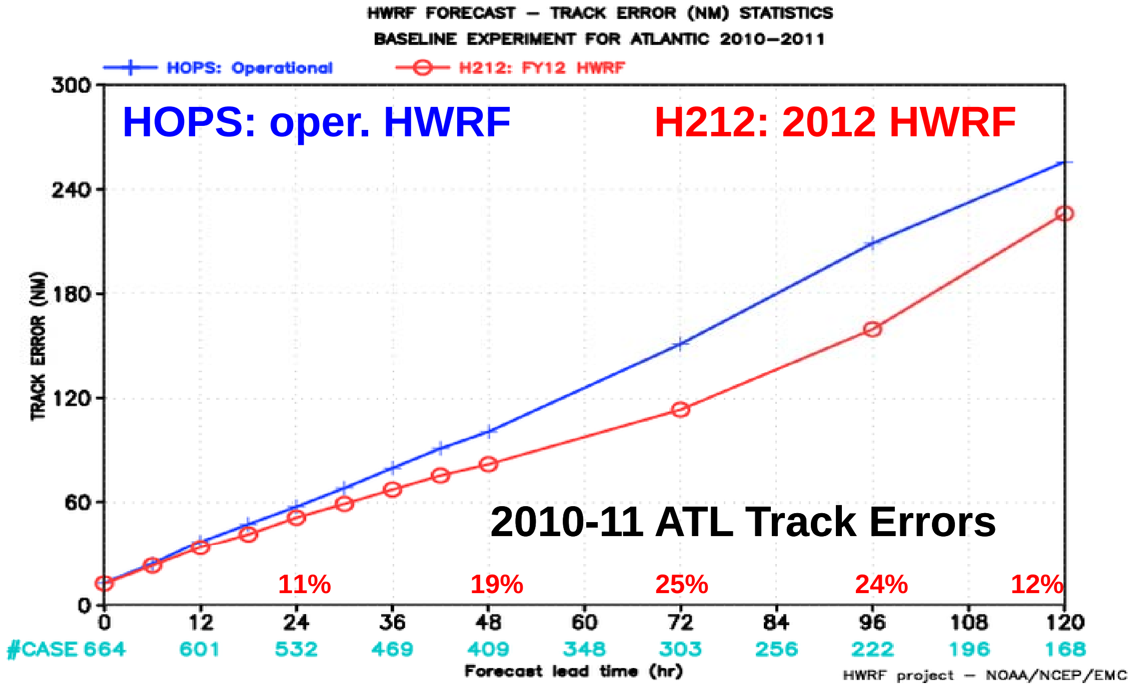


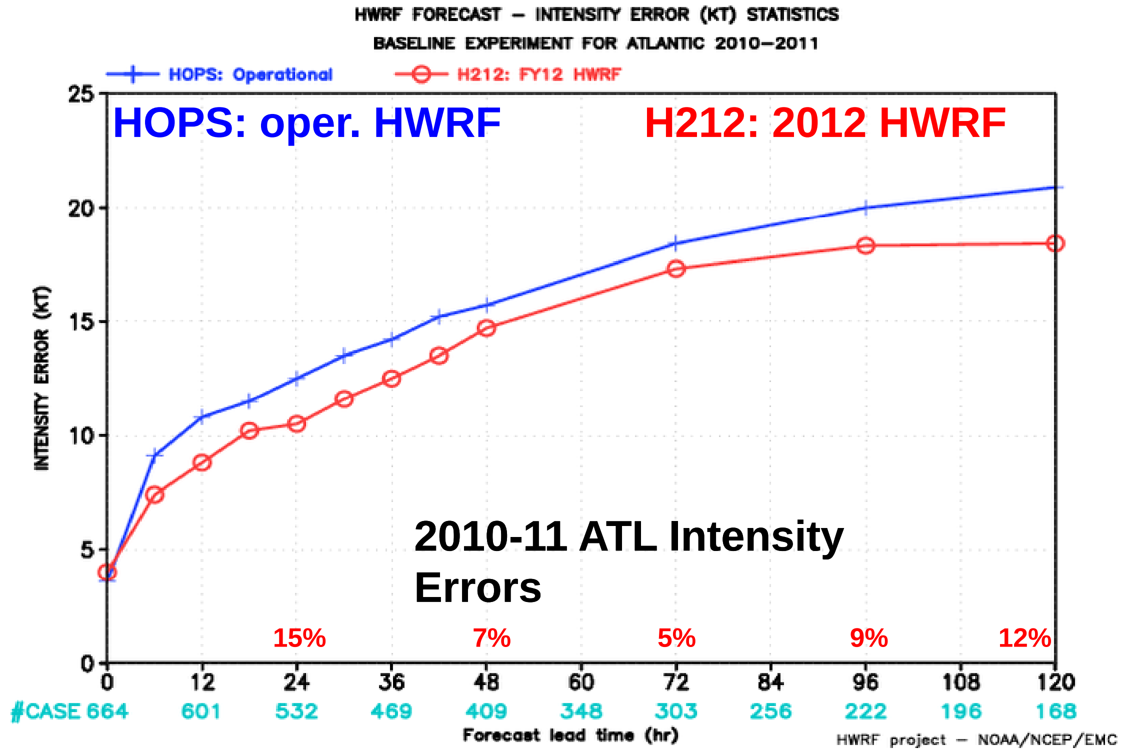
A025, IRENE 09l, d23, Azimuthally averaged, Init. date: 2011082212, 30 h FCST
Radial wind (shaded), Min=−31.1554 kts, Max=27.0283 kts
Radial−vertical flow (streamline), Pressure velocity peak=−4.47606 Pa/s

HWRF Structure Statistics









EMC verification of the 2012 version HWRF model with new surface and boundary layer physics with 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 of Vijay Tallapradada (HWRF team leader)