On hurricane boundary layer parameterizations: Lessons learned from observations

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HFIP Physics workshop, 8/9/2011

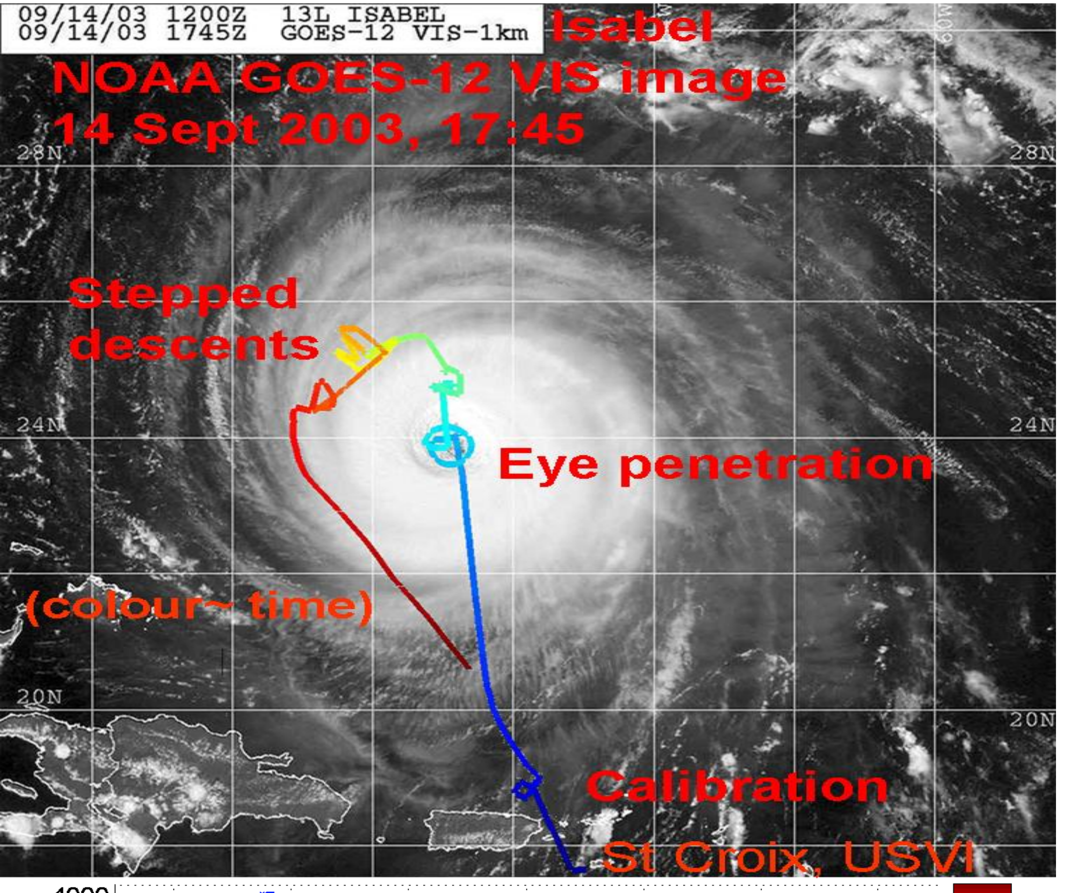
Outline

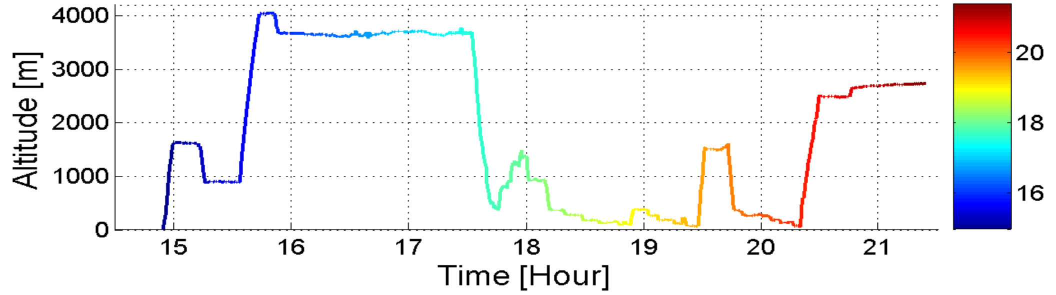
- Surface flux parameterization (Cd and Ck)

- Boundary layer parameterization
  a) PBL height
  b) Eddy diffusivity

- Parameterization of dissipative heating

The Coupled Boundary Layer Air-sea Transfer Experiment (CBLAST)

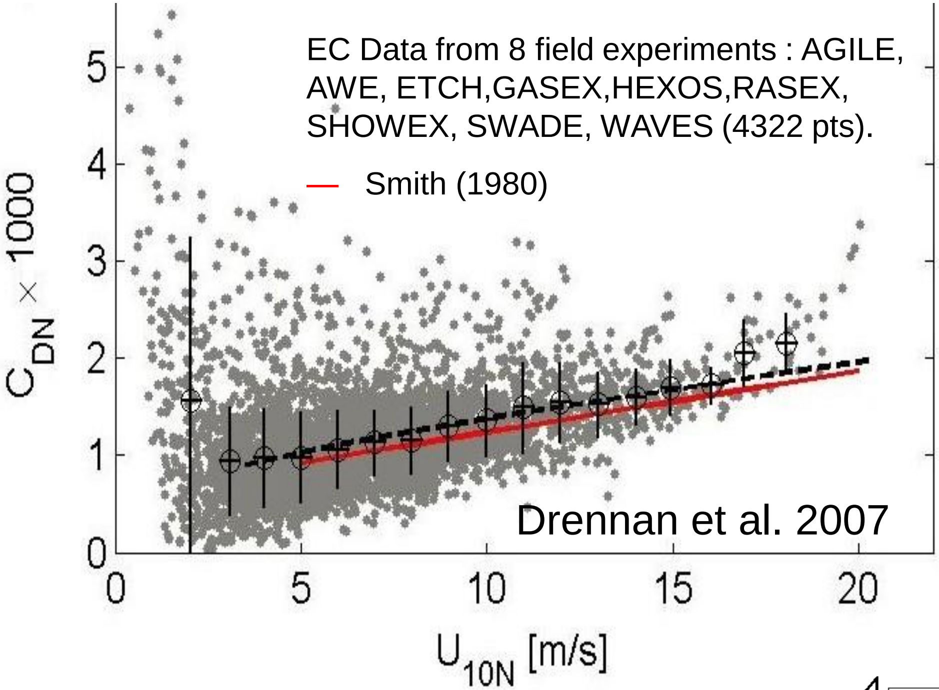




First direct measurement of turbulent fluxes in the hurricane boundary layer!

Black et al. 2007 BAMS
Drennan et al. 2007 JAS
French et al. 2007 JAS
Zhang et al. 2008a, b GRL, BLM
Zhang et al. 2009 JAS
Zhang 2010a,b QJ, JAS

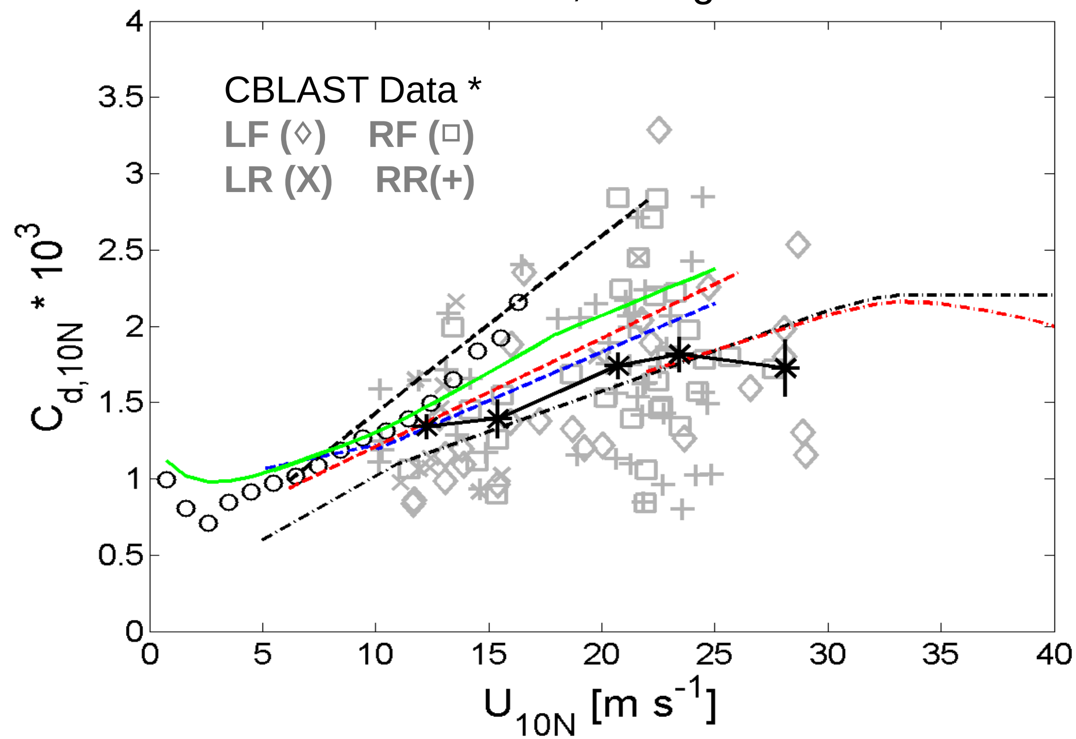
Drag coefficients



$$\hat{\tau} = \rho u_*^2 = \rho(-\overline{w'u'}\hat{i} - \overline{w'v'}\hat{j})$$

$$C_{D10N} = |\tau| / (\rho U_{10N}^2)$$

Black et al. 2007; Zhang 2007

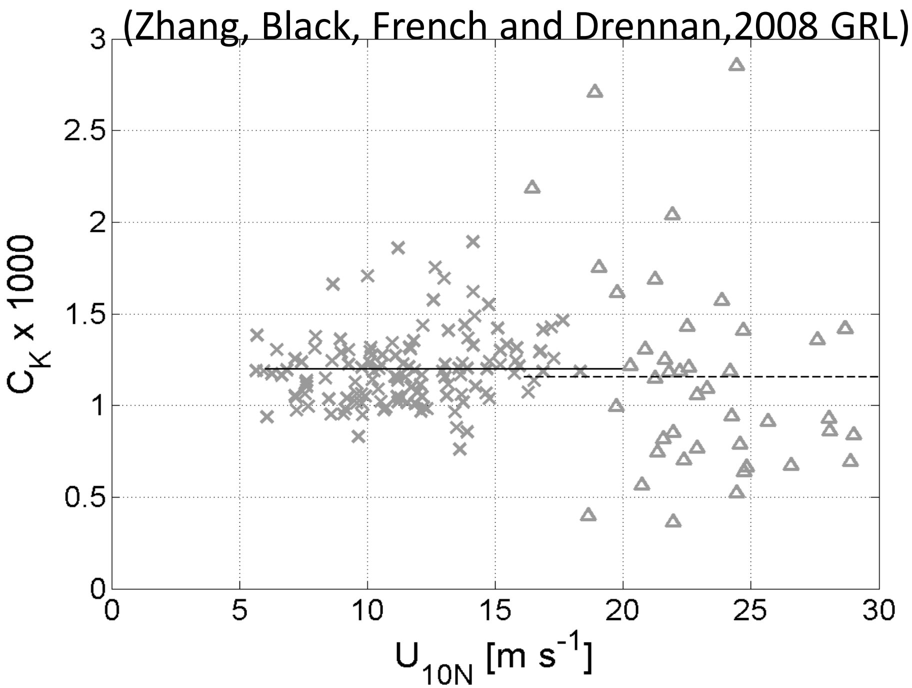


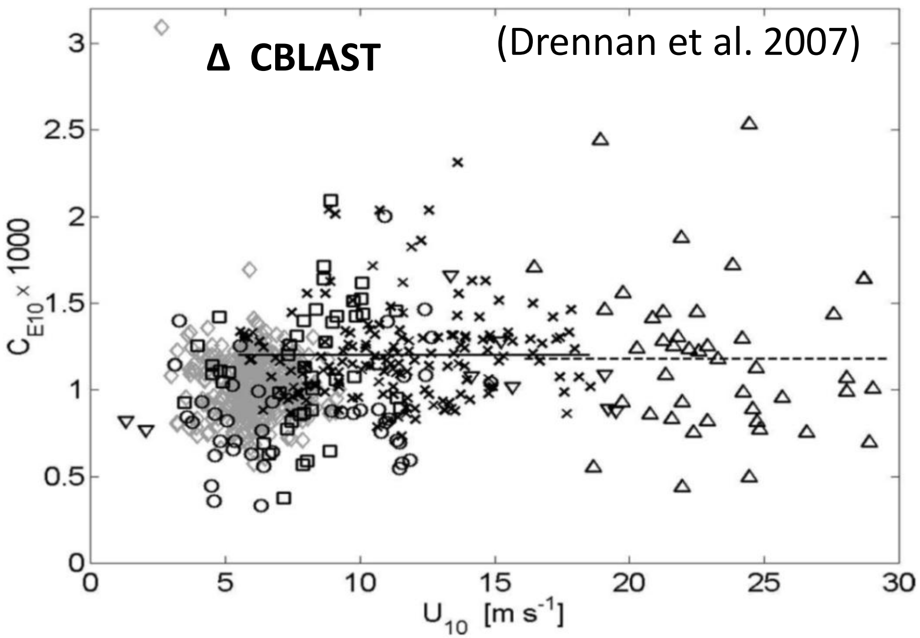
Smith (1992) ------
Large and Pond (1980) ------
Smith (1980) -------
COARE 3.0 —
CBLAST LOW (o) Edson et al. 2007
Powell et al. (2003) ·−−·−
Donelan et al. (2004) −·−·−−

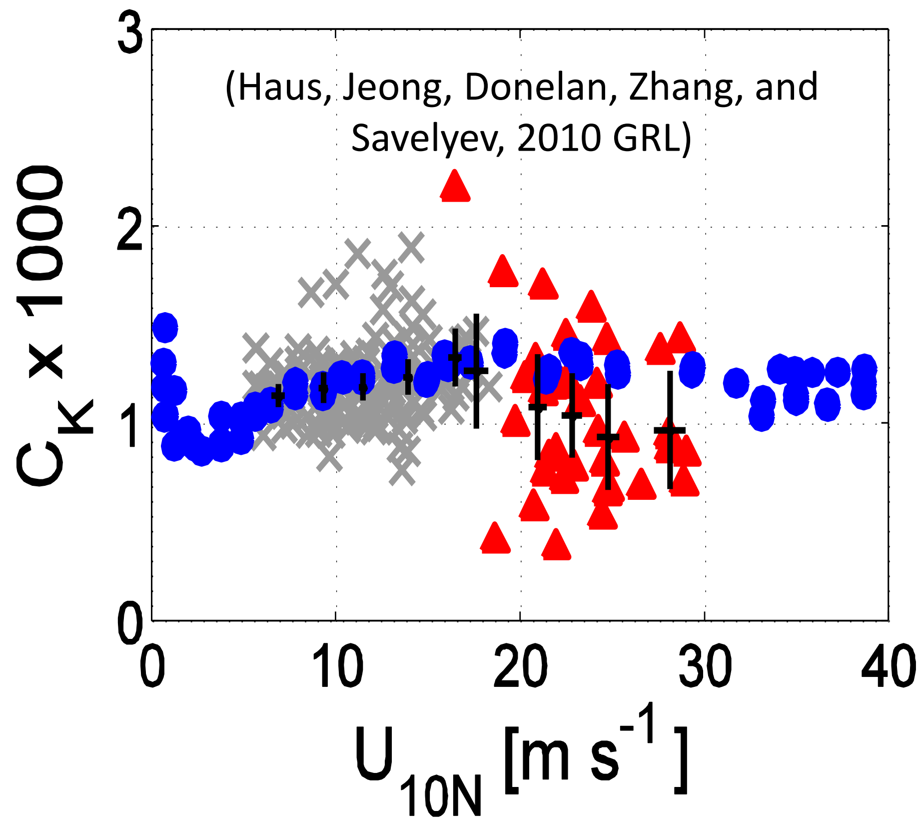
Exchange coefficients for enthalpy transfer

$$F_K = \rho \overline{k' w'}$$

$$C_K = F_K / [\rho U_{10N} (k_0 - k_{10N})]$$

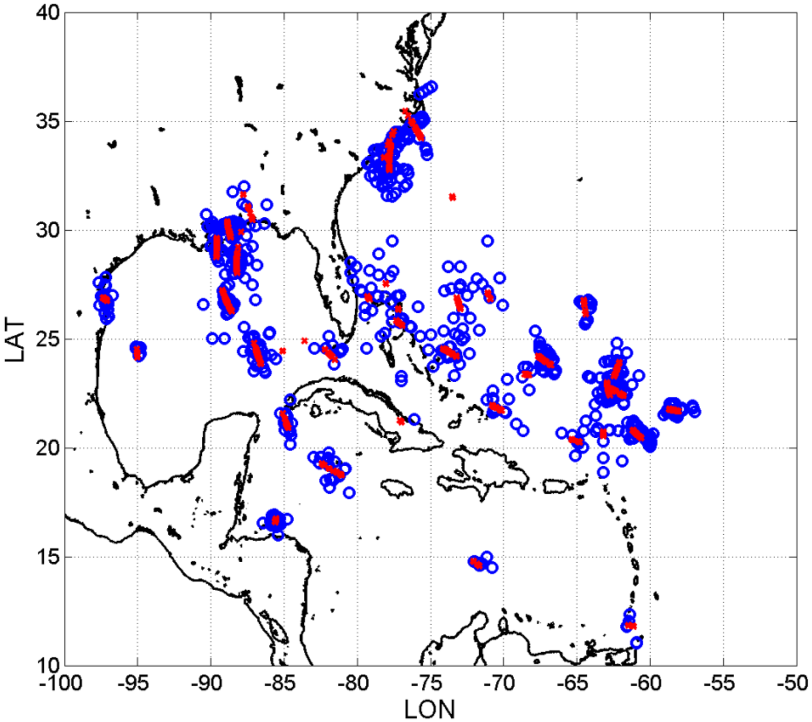


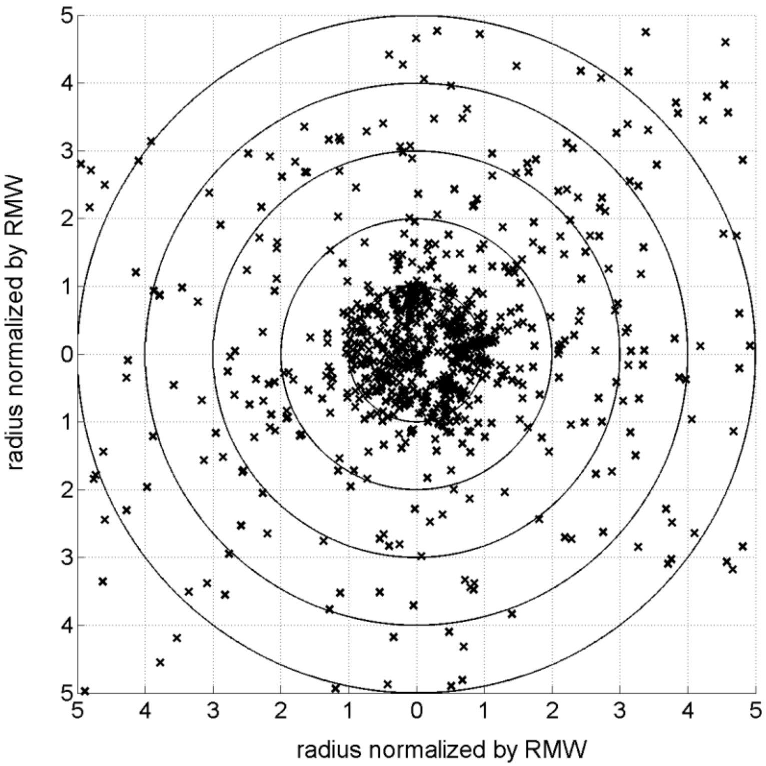




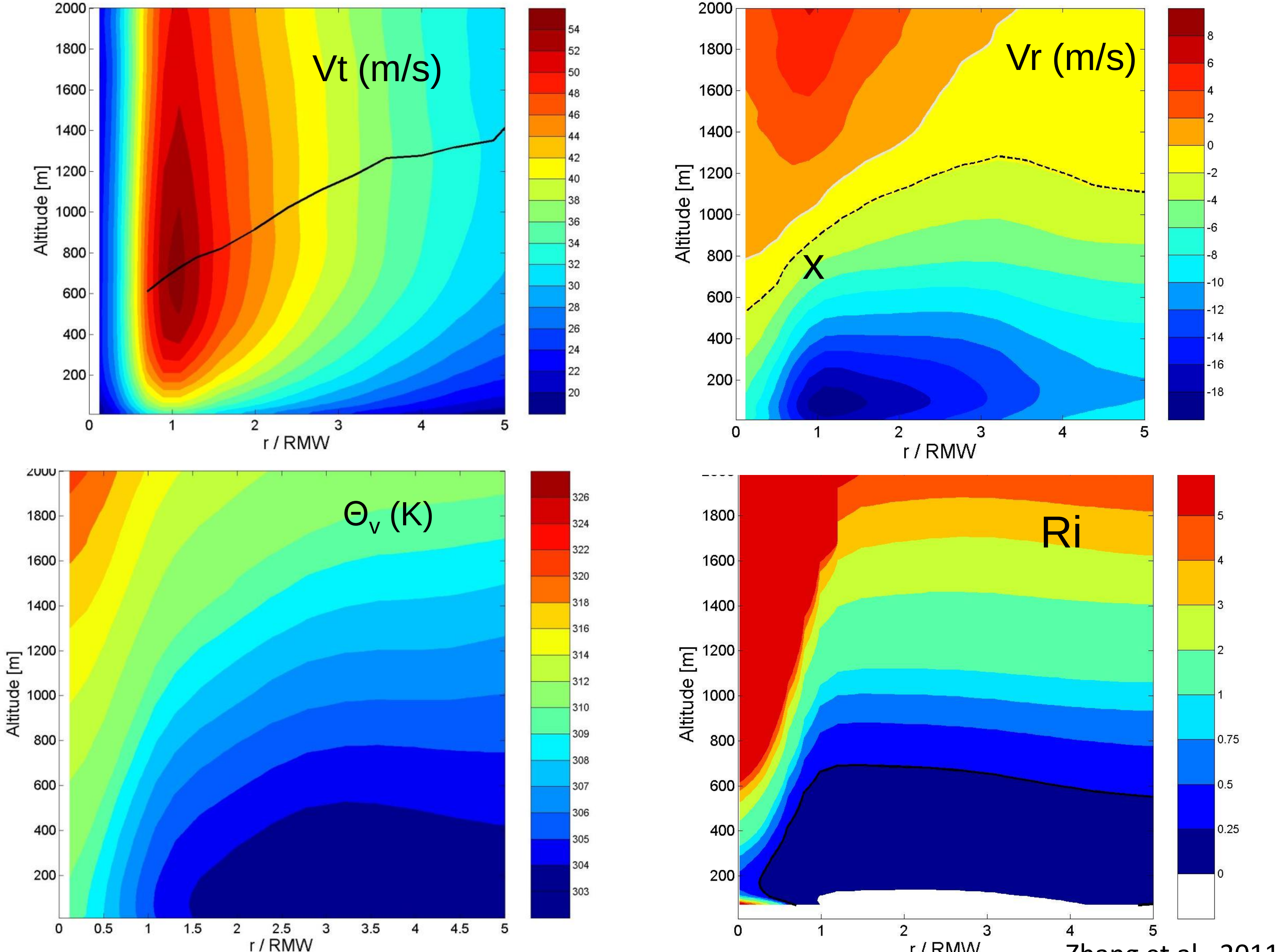
On the characteristic height scales of the hurricane boundary layer

Zhang, J. A., R. F. Rogers, D. S. Nolan, and F. D. Marks, *Mon. Wea. Rev.,* in press.





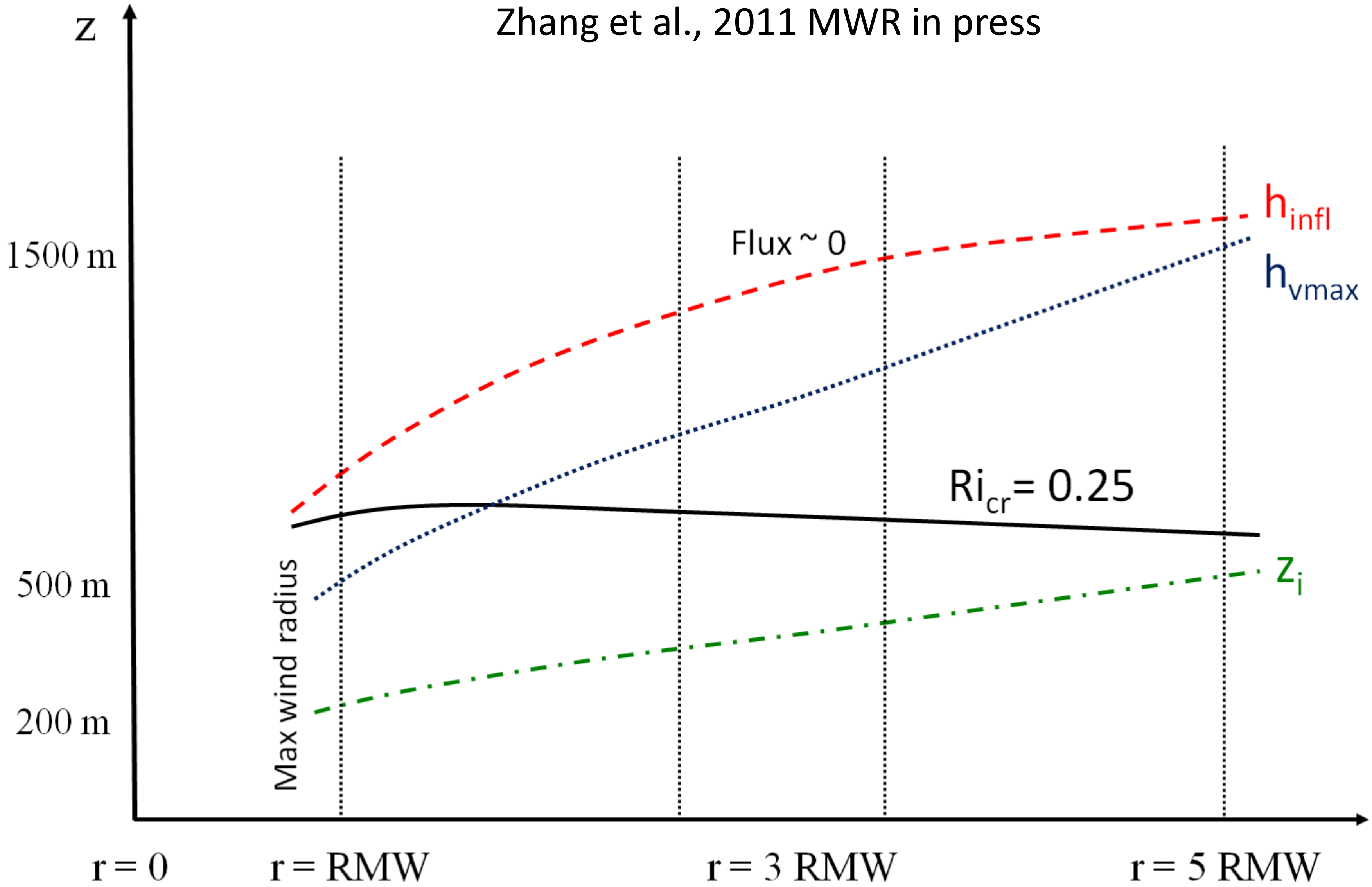
A total of 2231 dropsonde data from 13 hurricanes have been analyzed, and 794 of them are used in the final analysis.



Zhang et al., 2011

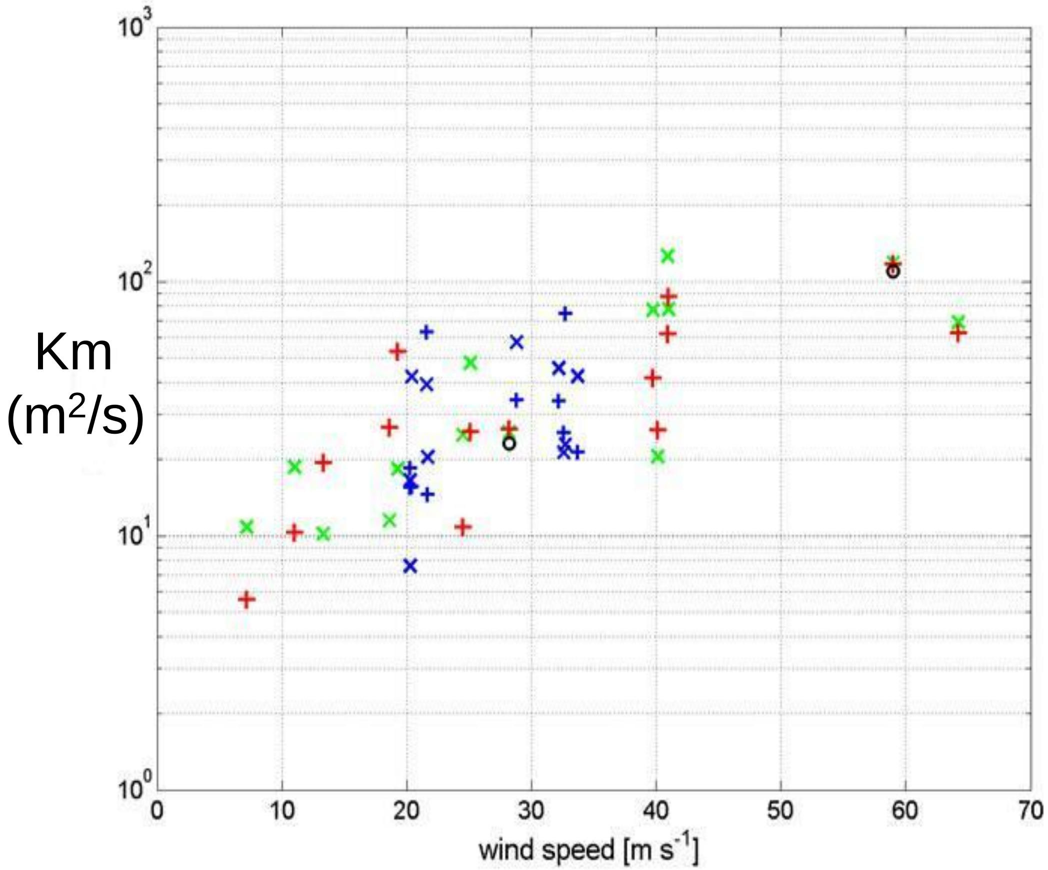
A schematic diagram of the characteristic height scales of the hurricane boundary layer

Zhang et al., 2011 MWR in press



An Estimation of turbulent characteristics in the low level region of intense Hurricanes Allen (1980) and Hugo (1989)

Zhang, J. A., F. D. Marks, M. T. Montgomery, and S. Lorsolo, 2011, *Mon. Wea. Rev.*, 139, 1447-1462.



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

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

Flight-level data (1 Hz) are analyzed from the legs during the eyewall penetrations of Cat4 Hurricane Allen and Cat5 Hurricane Hugo at altitude of ~450 m to estimate momentum flux, TKE and vertical eddy diffusivity of momentum flux.

Theory: dissipative heating

Zhang, 2010 JAS

$$-\overline{u'w'}\frac{\partial \bar{u}}{\partial z} - \overline{v'w'}\frac{\partial \bar{v}}{\partial z} = \varepsilon \quad \Longrightarrow \quad \frac{u_*^3}{\kappa z} = \varepsilon$$

$$Dissipative heating = \rho \bar{\varepsilon}\, z_1 = \rho \frac{u_*^3}{\kappa} \ln(\frac{z_1}{z_0})$$

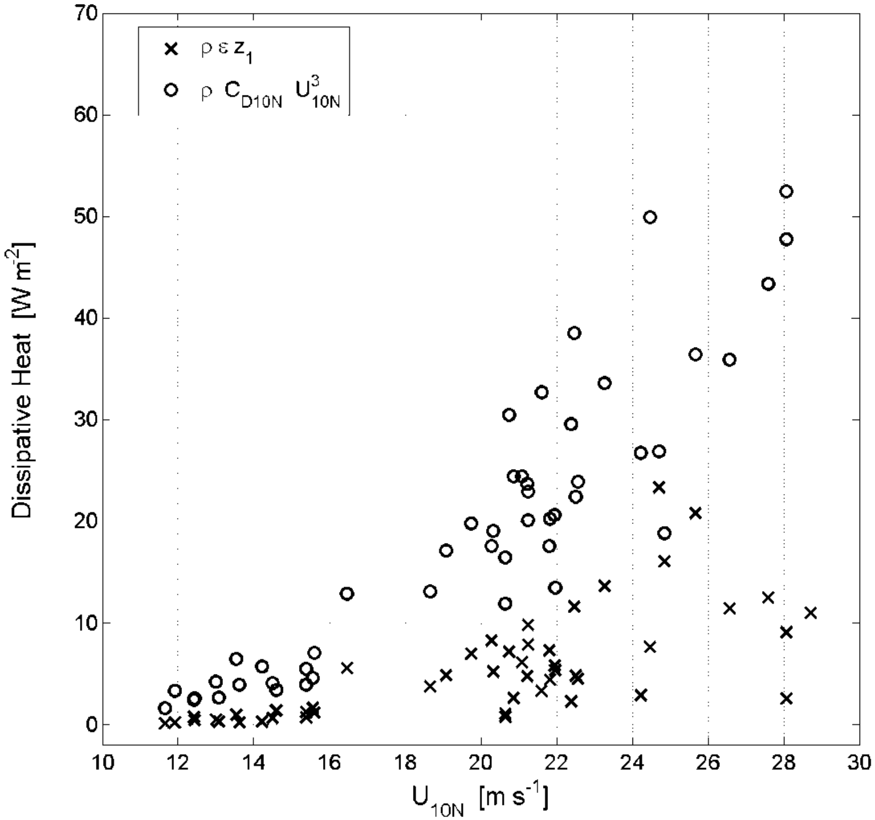
Surface layer similarity theory: $U = \frac{u_*}{\kappa} \ln(\frac{z_1}{z_0})$ $\quad u_*^2 = C_D U^2$

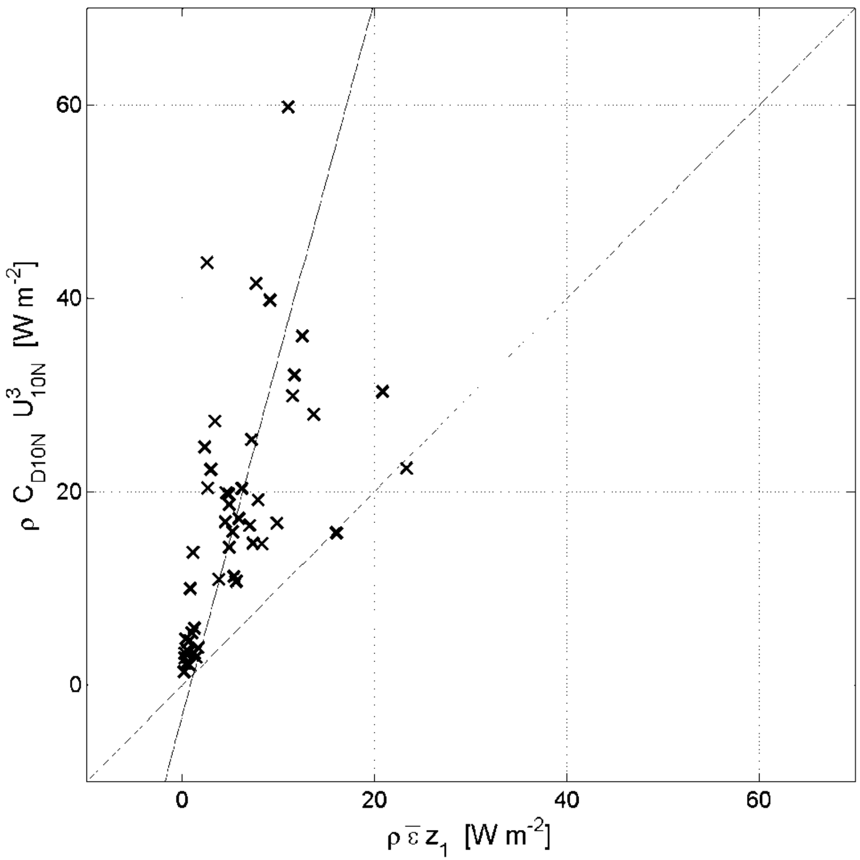
$$Dissipative heating = \rho \frac{u_*^3}{\kappa} \ln(\frac{z_1}{z_0}) = \rho C_D U^3$$

The above theoretical method has been firstly used by Bister and Emanuel (1998). Since then, dissipative heating has been included in a number of theoretical and numerical models simulating hurricanes.

Estimation of dissipative heating using low-level in-situ aircraft observations in the hurricane boundary layer

Zhang, J.A., 2010, J. Atmos. Sci., **67**, 1853-1862.

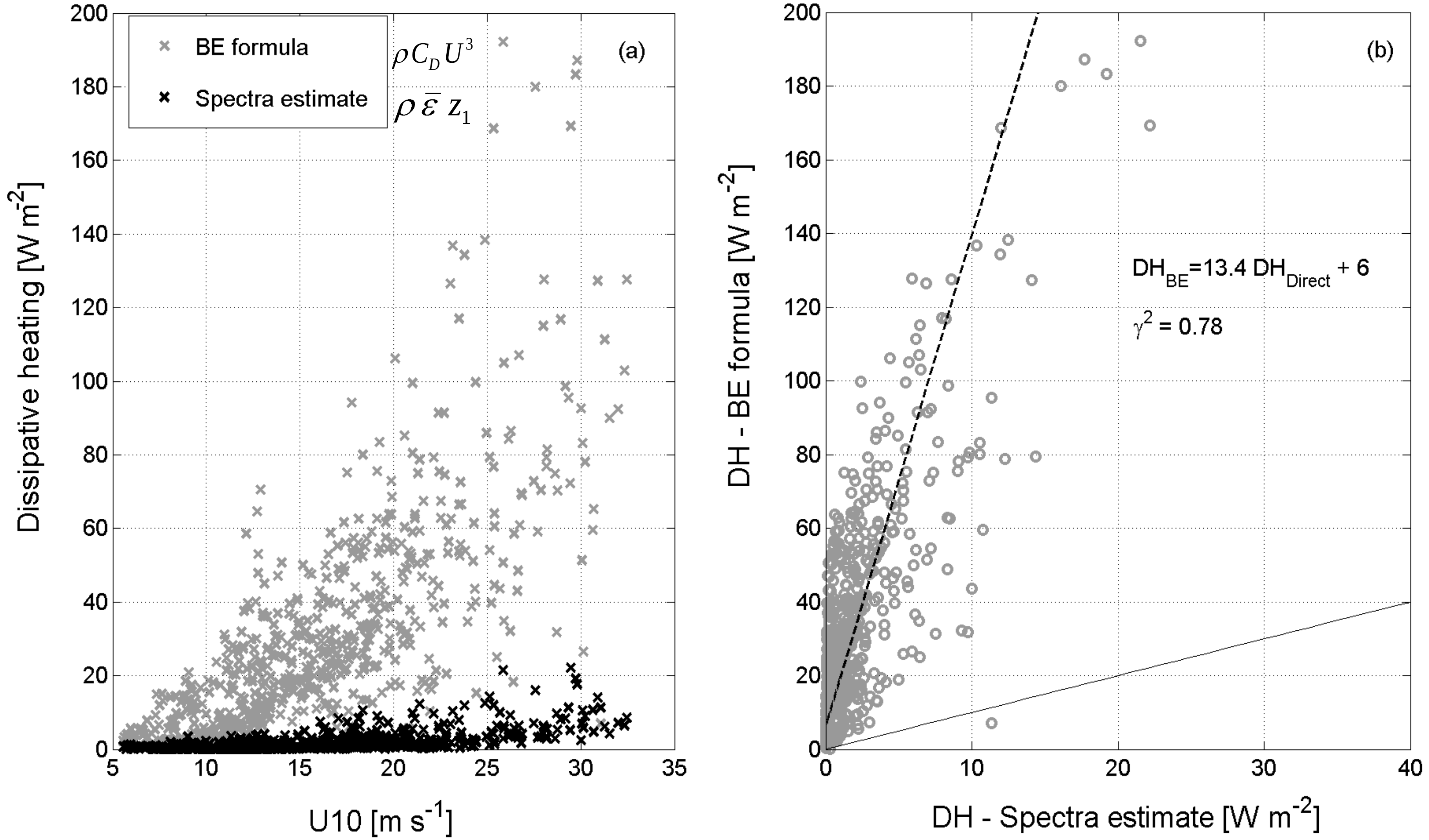




The theoretical method ($\rho C_d U^3$) would significantly overestimate the magnitude of dissipative heating.

On momentum transport and dissipative heating during hurricane landfalls

Zhang, J. A., P. Zhu, F. J. Masters, R. F. Rogers, and F. D. Marks, 2011, *J. Atmos. Sci.*, **68**, 1397-1404.



What have we leant from observations?

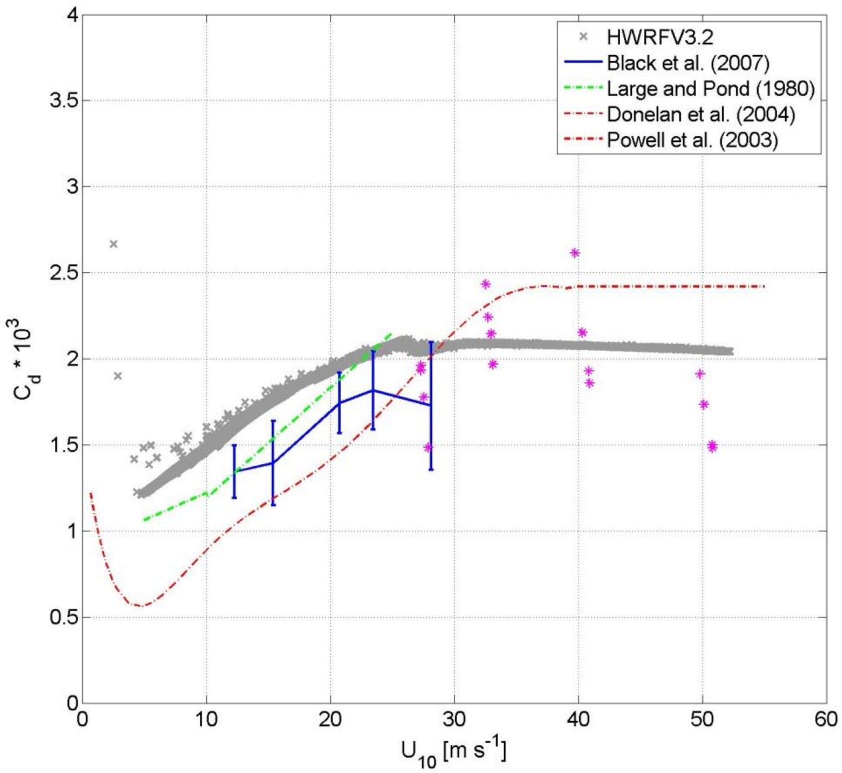
1. Drag coefficient increases with wind speed up to 25 – 40 m, then levels off. Ck is nearly independent of surface wind speed up to 40 m/s.

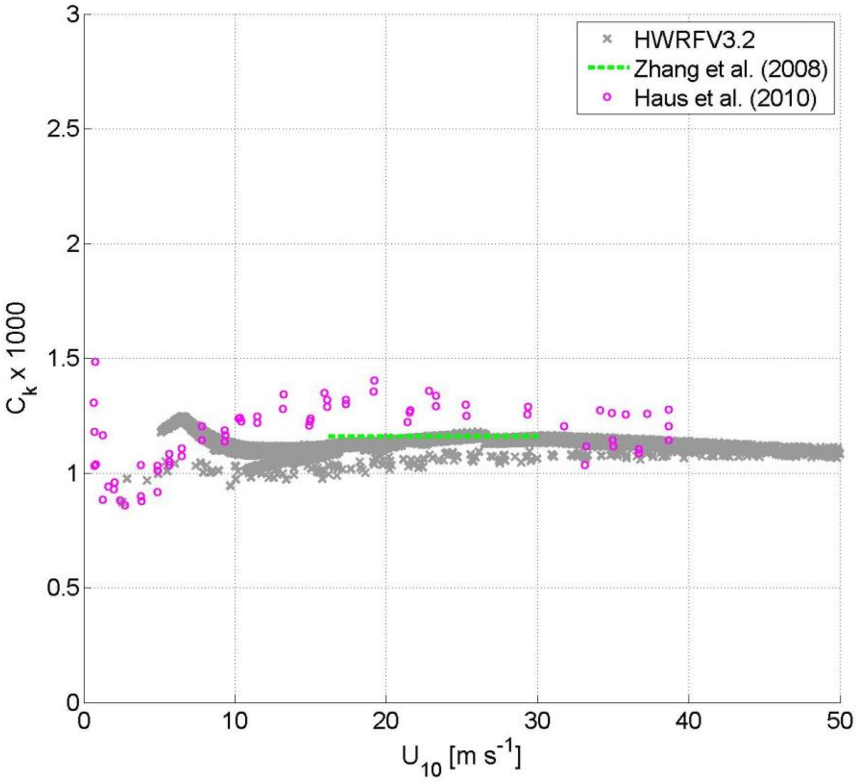
2. There are several types of height scales that may represent the top of the hurricane boundary layer. The inflow layer depth is thought to be a good representation of the hurricane boundary layer top according to vertical flux observations.

3. Vertical eddy diffusivity of momentum flux (Km) is found to increase with wind speed. The maximum value of Km is on the order of 100 m^2/s.

4. The formulation of drag coefficient multiplying the cubic of surface wind speed would significantly overestimate the magnitude of dissipative heating.

Cd and Ck in HFIP stream 1.5 version HWRF

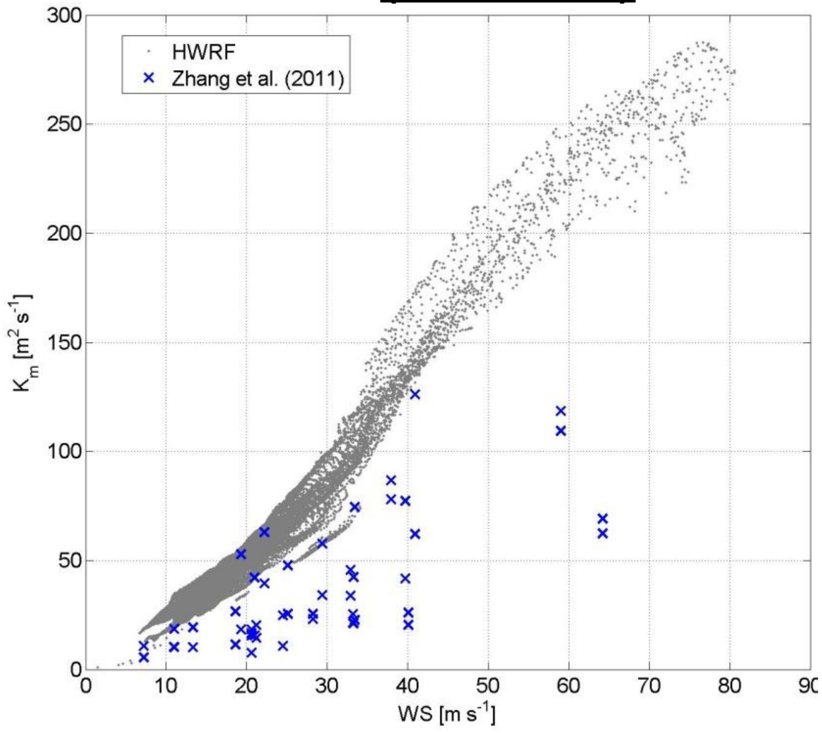




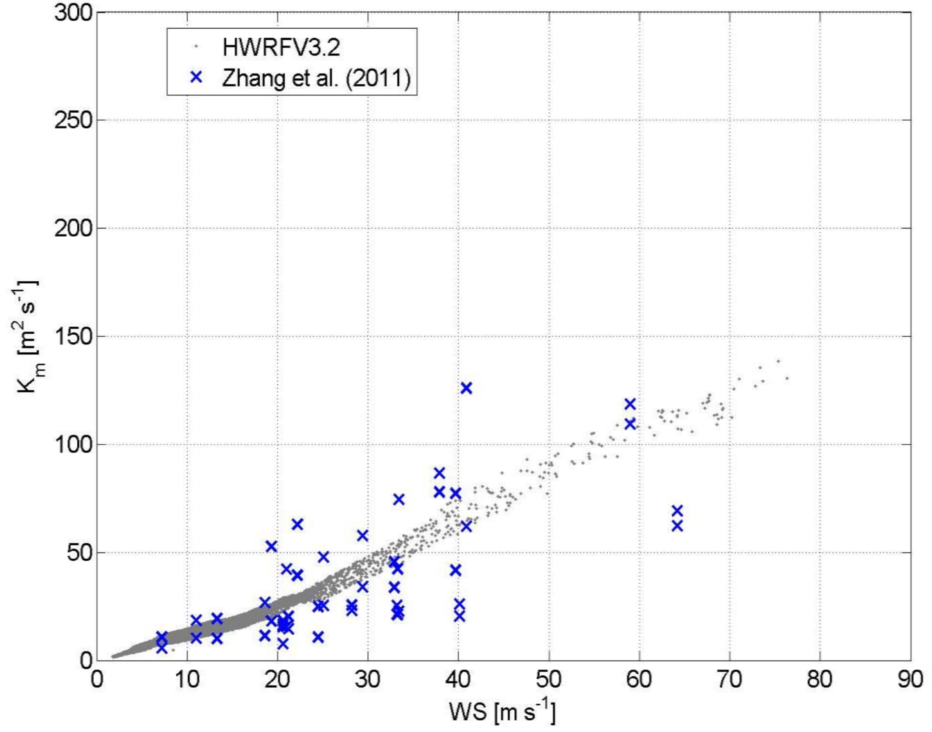
Cd and Ck in the high resolution (3km) HWRF are generally consistent with observations.

Km used in HFIP stream 1.5 version HWRF

Original Km in HWRF (baseline)



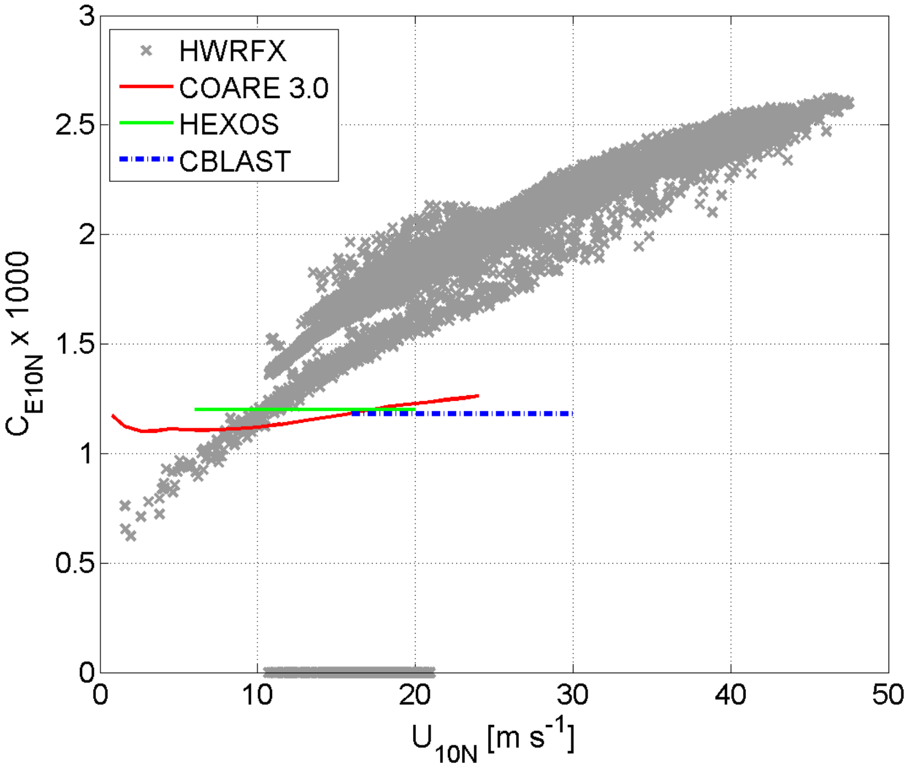
Km reduced 75% (alpha=0.25)

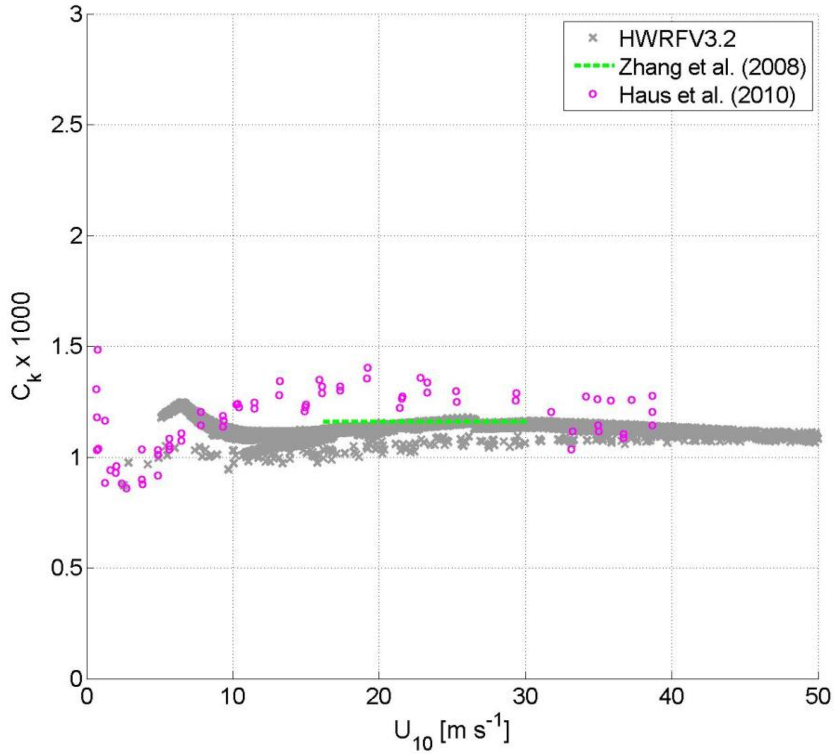


The vertical eddy diffusivity of momentum flux in the original HWRF is 5 times that based on observations at the same level.

Pre 2010 HWRF

2010 Version HWRF and V3.2

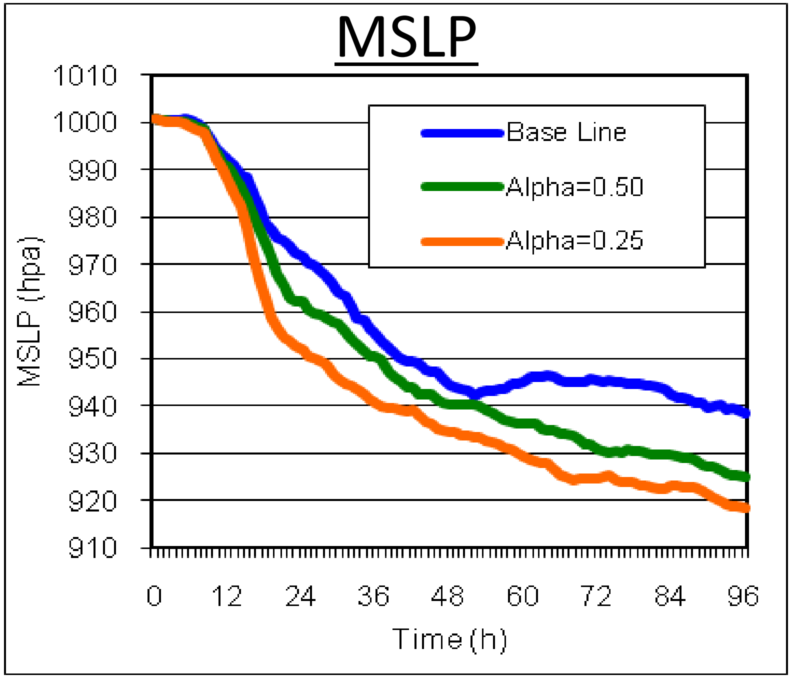


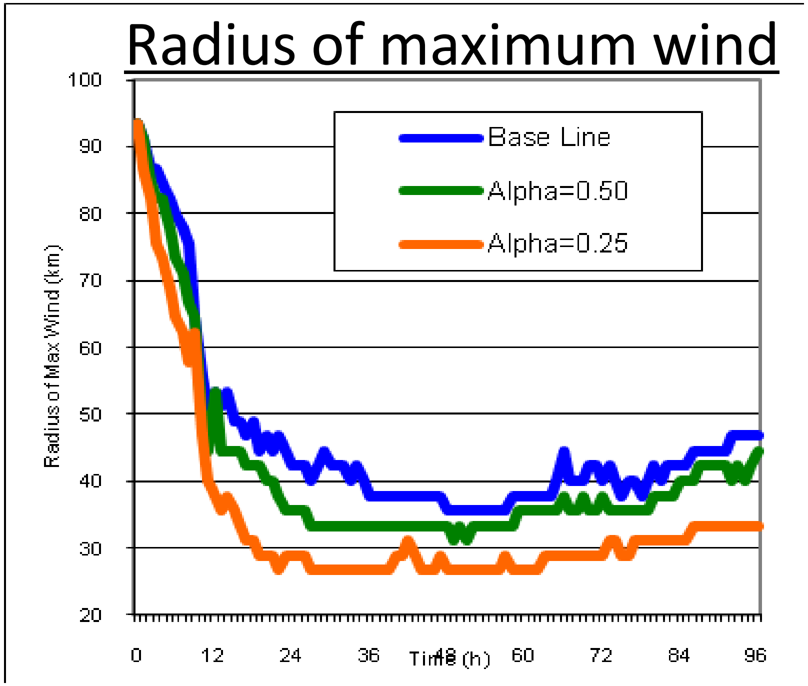


- When high values of Ck (Bender et al. 2007) were used in the operational HWRF before 2010, the model tends to have a high biased intensity forecast.
- When smaller values of Ck was used in 2010 version HWRF following observations, the model has a low bias in intensity forecast.

Sensitivity of simulated intensity and storm size to vertical eddy diffusivity using idealized HWRF

(Gopal et al. 2011, in preparation)





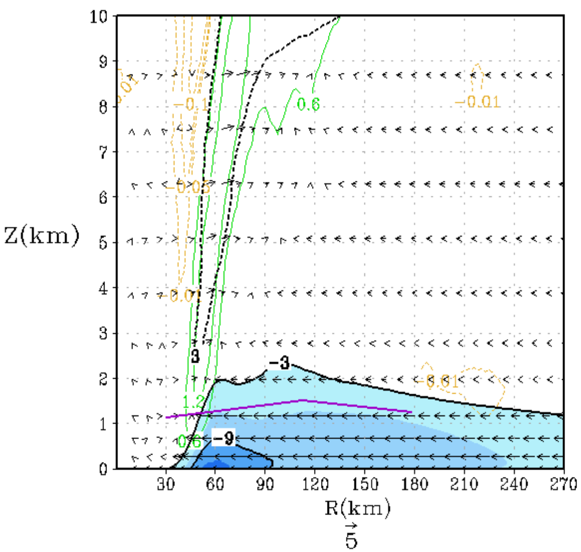
- idealized storm stronger with reduced Km
- size of storm (as measured by RMW) smaller with reduced Km

Note that Ck is set to constant in the above simulations

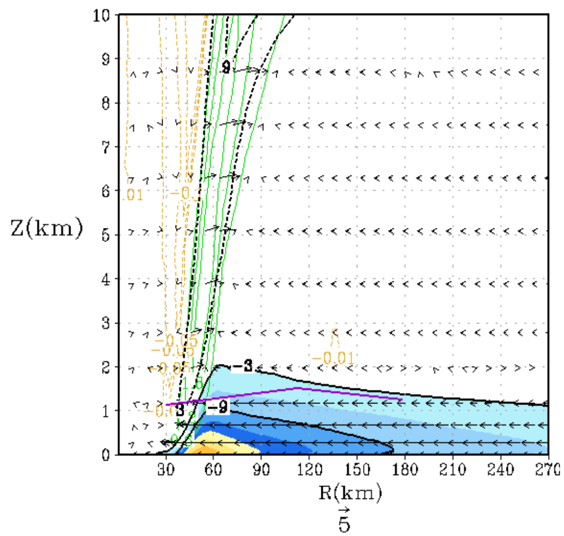
Sensitivity of axisymmetric radial wind to vertical eddy diffusivity

(Gopal et al. 2011, in preparation)

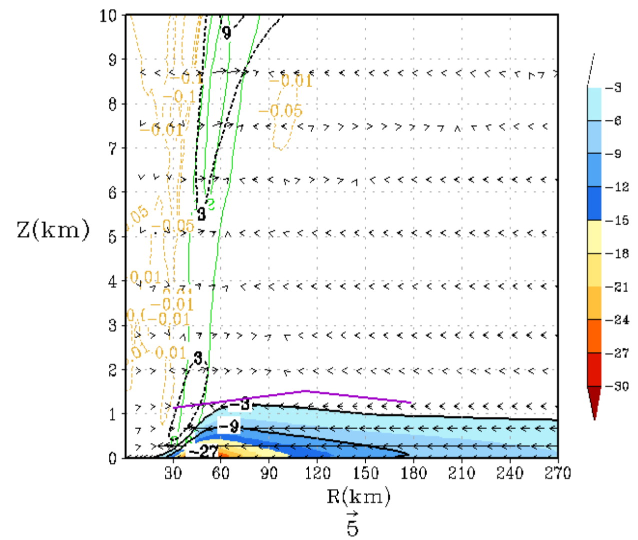
Original Km in HWRF (baseline)



Km reduced 50% (alpha=0.5)



Km reduced 75% (alpha=0.25)



The simulated inflow layer depth is indicated by the -3 m/s contour line;
The purple line is the inflow layer depth from dropsonde composite.

- peak radial inflow stronger with more accurate Km
- depth of inflow layer more consistent with dropsonde composites using more accurate Km

Summary and ongoing work

- The hurricane intensity is sensitive to different surface layer and boundary layer parameterizatons. In order to improve the model for better intensity forecast, multiple physical processes should be considered.

- HRD' aircraft observational data such as presented in this talk are unique not only in understanding the physics, but providing the baseline for model physics development and evaluation.

- In terms of model evaluation, we have proposed to develop new metrics (such as PBL height, eyewall slope, etc.) to evaluate the hurricane BL and inner core structure using aircraft observations, beyond the three numbers (track, minimum pressure, intensity) used in model verification.

- For the purpose of obtaining more observations in the hurricane boundary layer and rest parts of the storm, we continuously design new instrumentation and field experiments at HRD.


End
Thanks!

References

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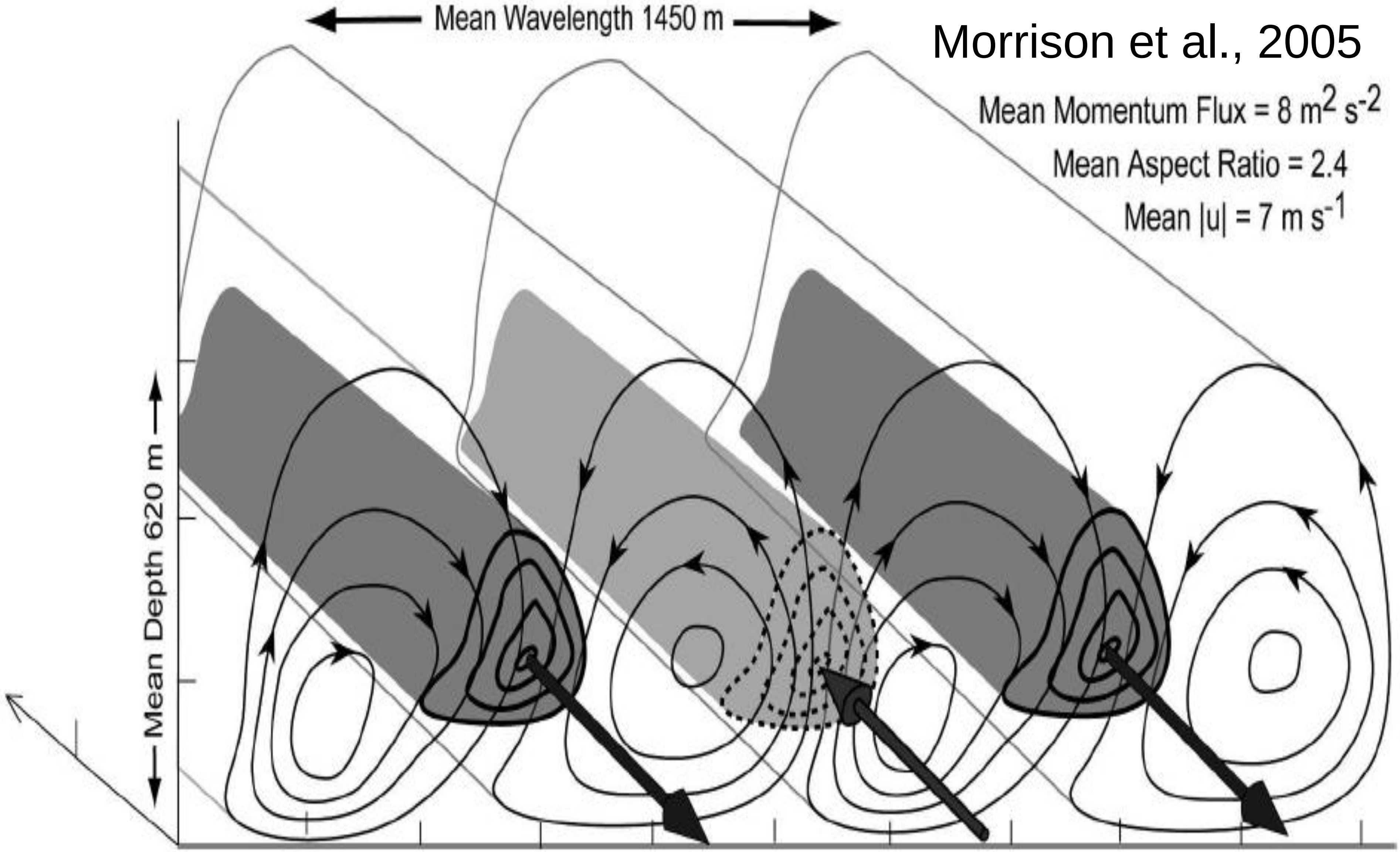
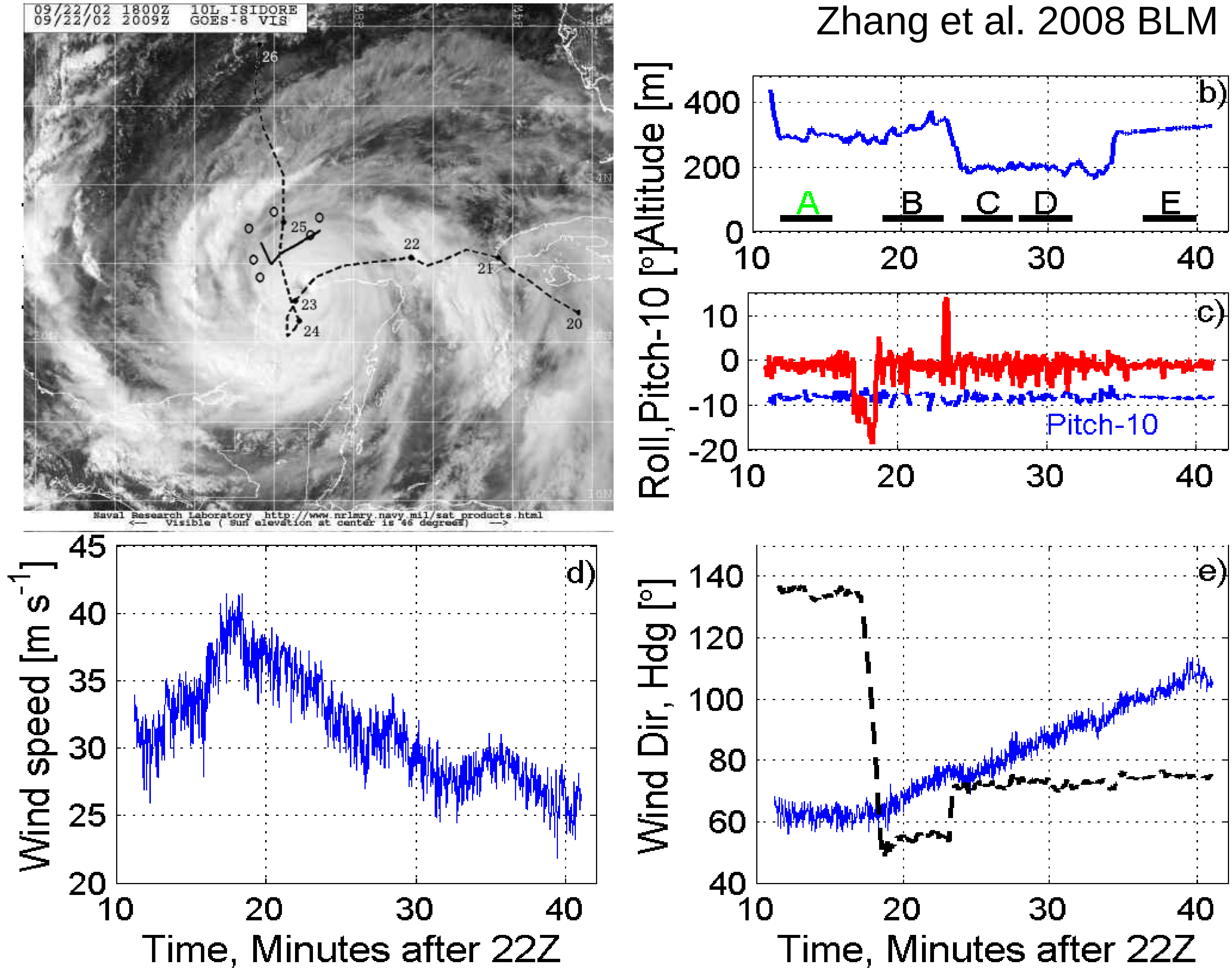
Hurricane Boundary Layer Rolls

Morrison et al., 2005



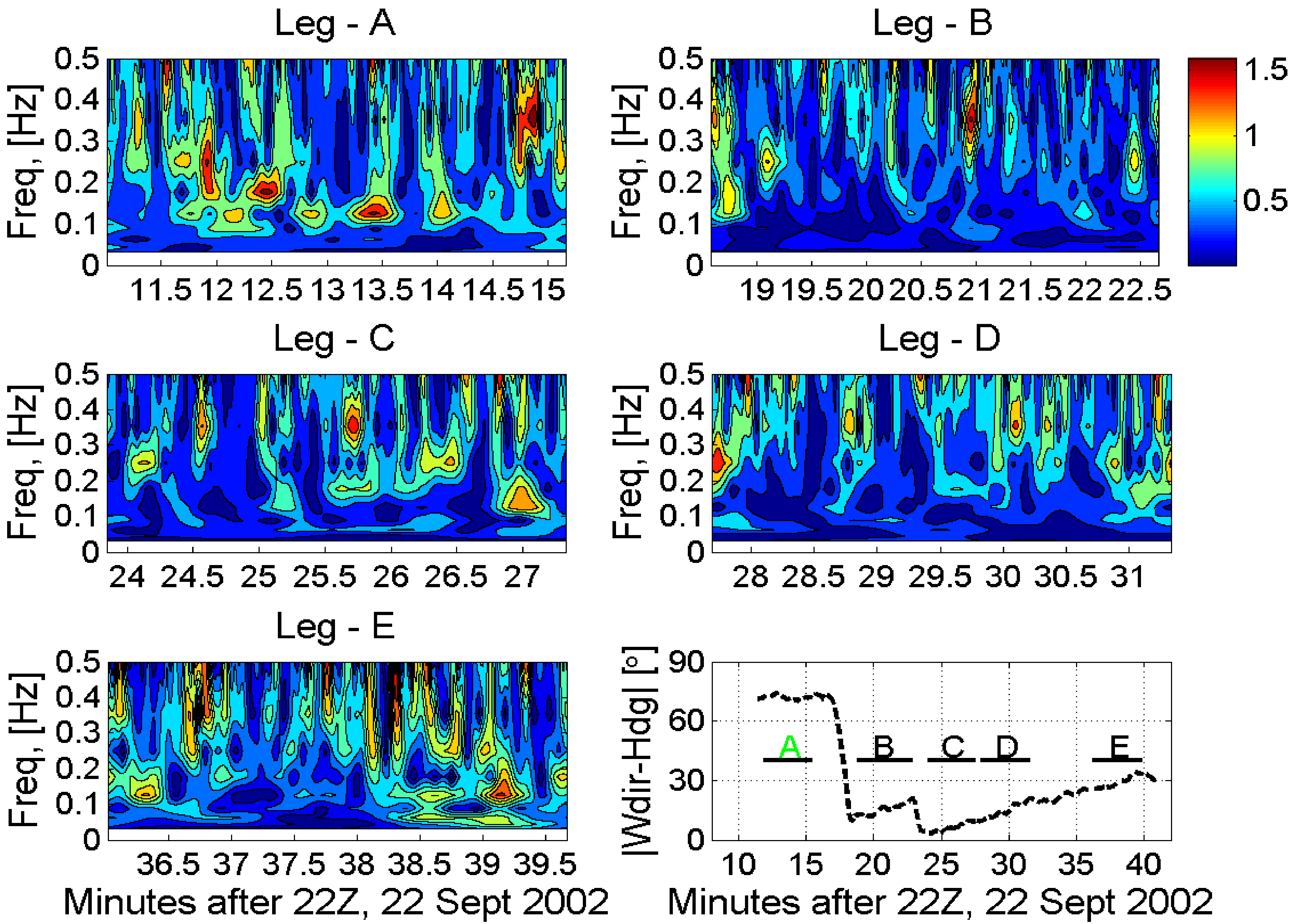
Boundary Layer Flight in Hurricane Isidore

Zhang et al. 2008 BLM



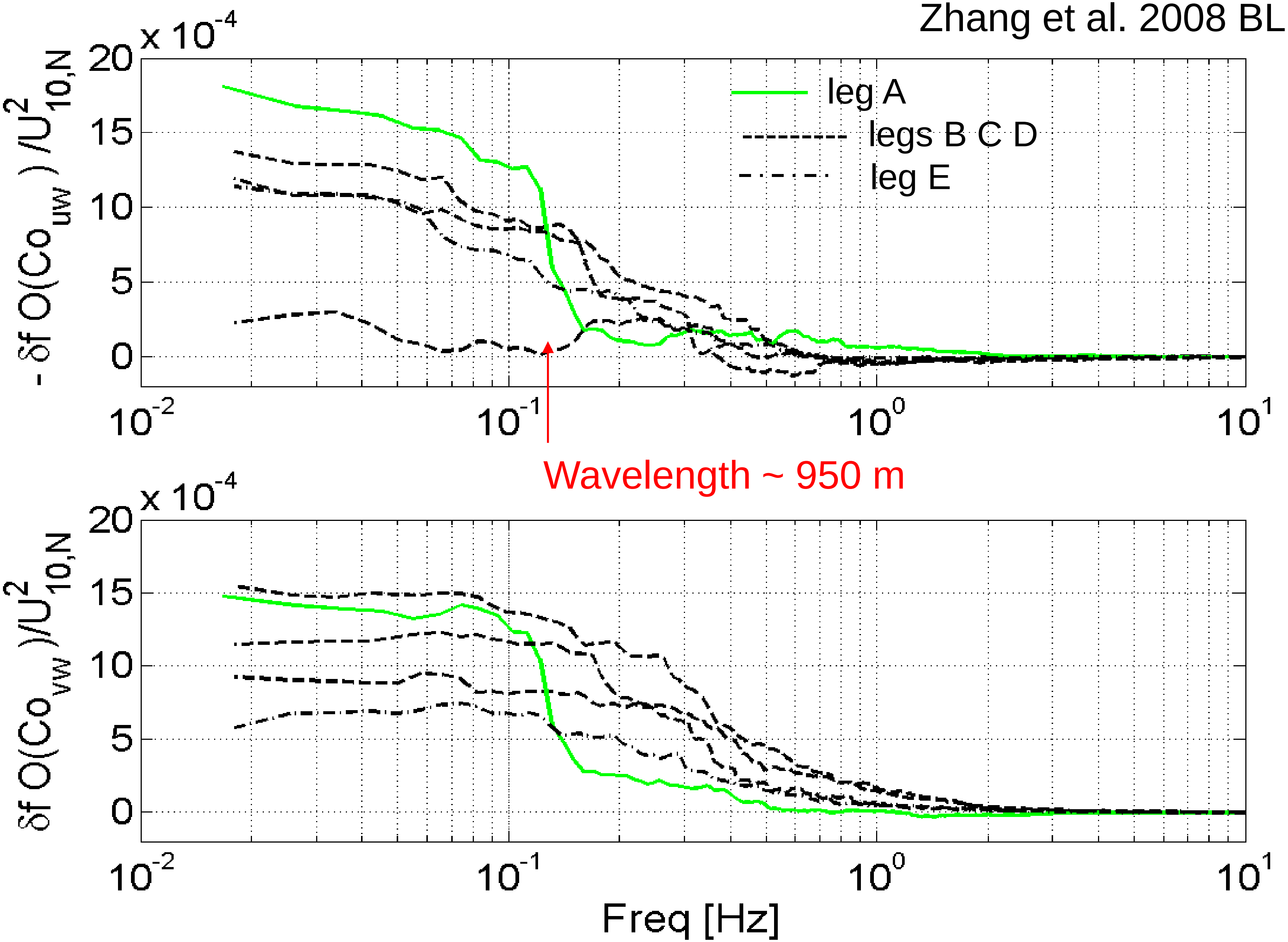
Wavelet Analysis

Zhang et al. 2008 BLM



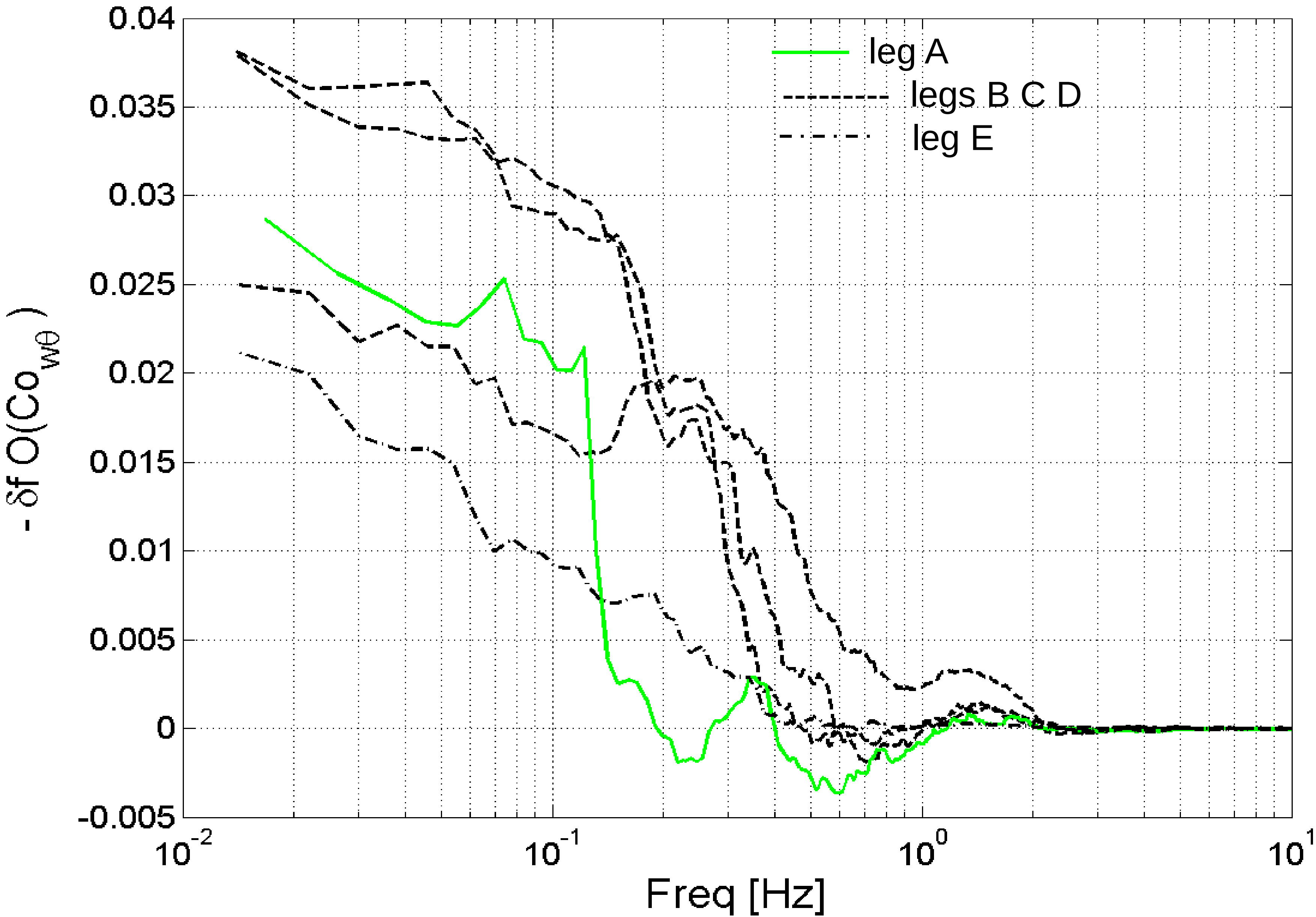
Momentum Flux

Zhang et al. 2008 BLM



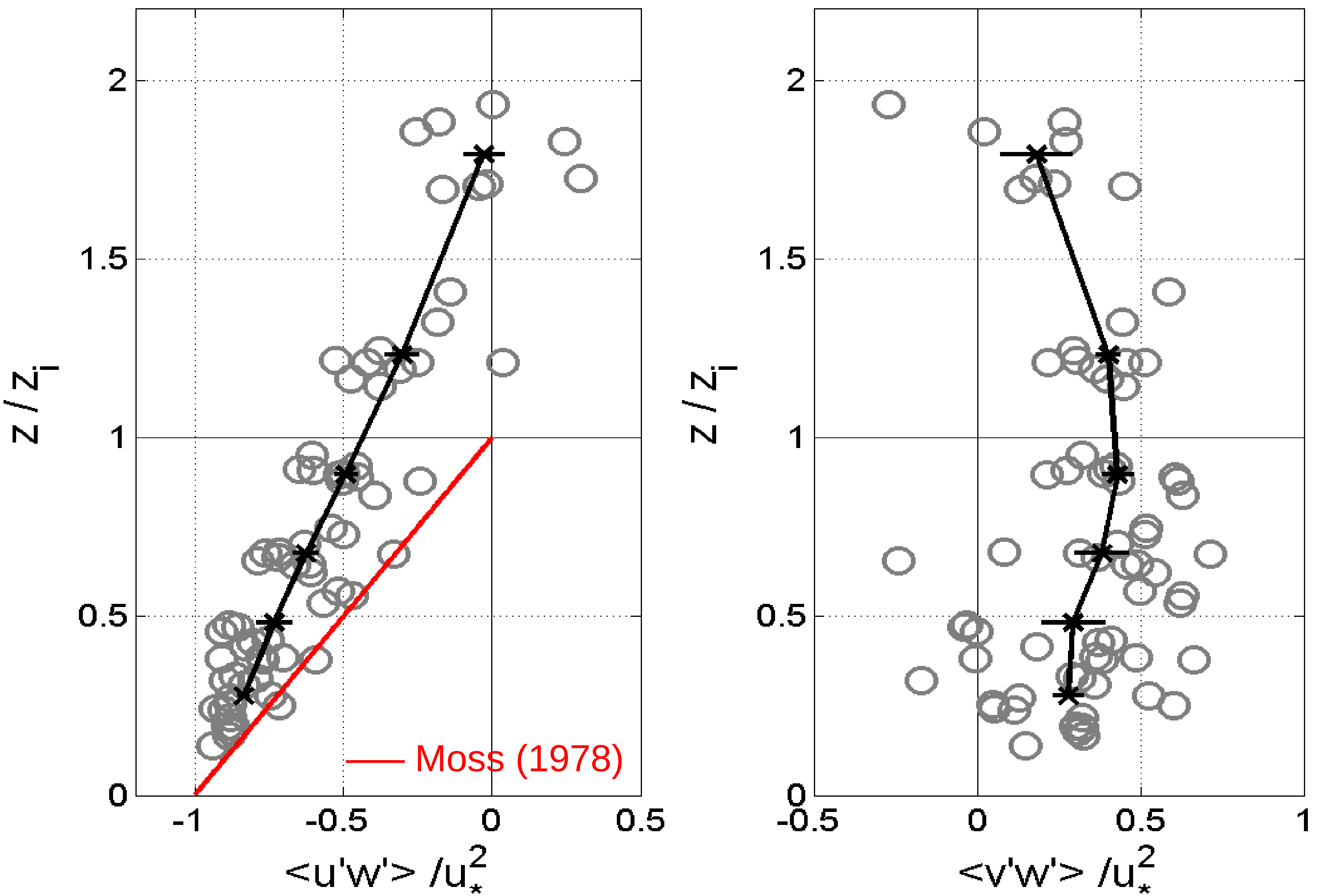
Sensible Heat Flux

Zhang et al. 2008 BLM



Vertical Structure of Momentum flux

Zhang, Drennan, French and Black, 2009 JAS



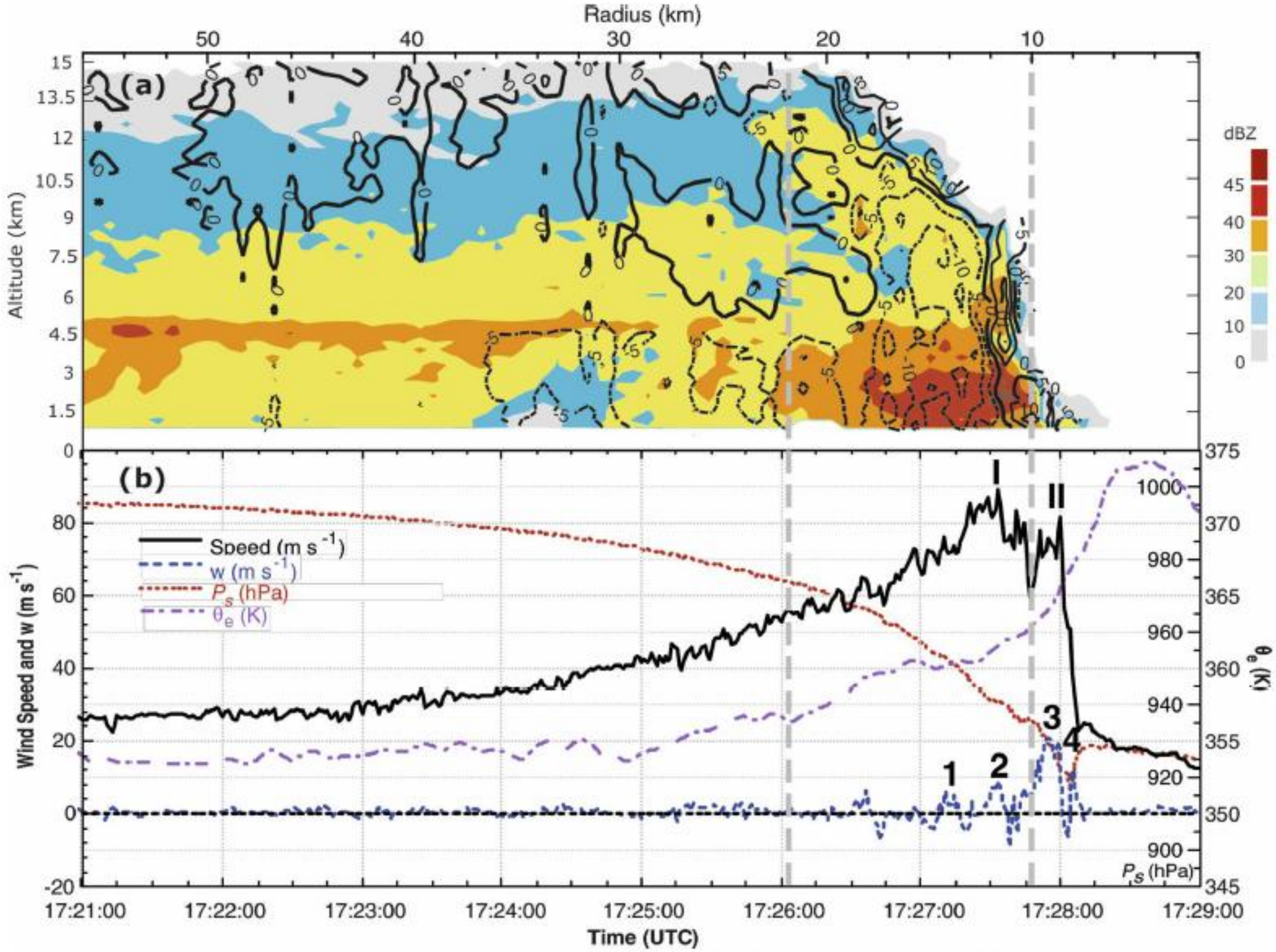


FIG. 3. (a) Time–height cross section of vertical incidence tail radar reflectivity (dBZ) from LA for 1721–1728 UTC. The LA flight track was at 450 m. Solid and dashed lines denote vertical velocity, and radar reflectivity is denoted by colors using the color scale on the right. (b) Time series plots 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).

Marks et al.

Hurricane Allen flight track