Evaluation of Planetary Boundary Layer Parameterizations in Tropical Cyclones by Comparison of in-situ Observations and High-Resolution Simulations of Hurricane Isabel (2003).

David S. Nolan (RSMAS/MPO)

Jun A. Zhang (NOAA/HRD)

Daniel P. Stern (RSMAS/MPO)

This work has been supported by NOAA/HRD through
a cooperative agreement with CIMAS/UM.

I. Background and Goals

- At the present time, substantial research and some *ad-hoc* forecasting is performed around the world using the WRF model and its variations
- One or the other of two parameterizations for the boundary layer are widely used: The Yonsei University (YSU) scheme or the Mellor-Yamada-Janjic (MYJ) scheme

  The choice between the two is frequently made with no knowledge of the strengths or weaknesses of the two schemes

- Here we address a number of questions:

  1. How does the use of each scheme affect predictions of intensity?
  2. Can modifications to the schemes make significant improvements?
  3. Can we go beyond the usual comparisons of track, MSLP, and peak wind speed when evaluating the performance of a numerical model?

  or

  4. How well do each of the schemes represent the *details* of the hurricane boundary layer?

The MYJ and YSU schemes represent the PBL in radically different ways:

- The MRF-YSU type scheme:

Hong and Pan (1996, MWR)

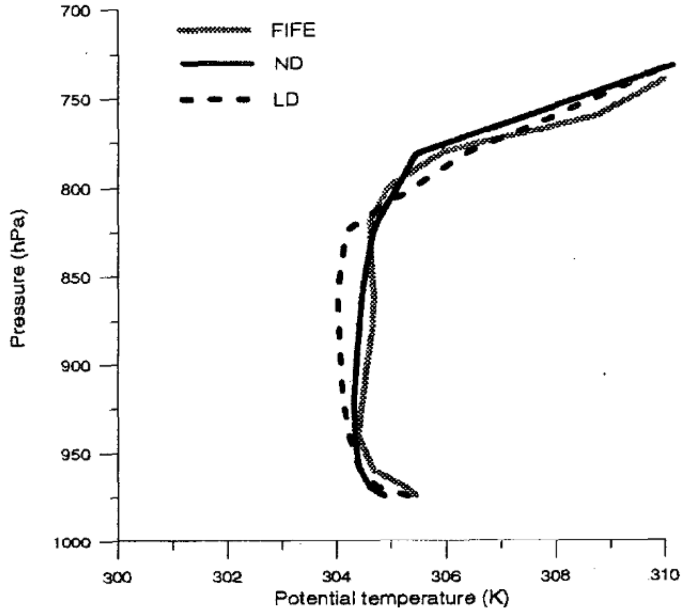


FIG. 3. Comparisons of boundary layer profiles of potential temperature (K) for the 9–10 August sonde averages (shaded lines) with averages from the nonlocal (solid lines) and local (dotted lines) schemes for (a) 1845 UTC and (b) 2145 UTC.

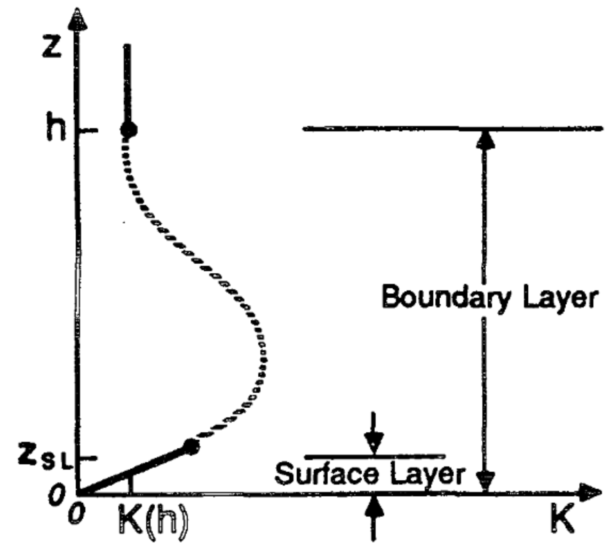


FIG. 1. Typical variation of eddy viscosity K with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

First, the depth of the boundary layer is estimated based on the profile of θ_v. Then a profile of vertical diffusivity is fit within the boundary layer depth.

Vertical fluxes are a combination of eddy diffusion, "non-local diffusion," and entrainment at the top of the PBL:

$$-\overline{w'\theta'} = K_T\left(\frac{\partial\theta}{\partial z} - \gamma_T\right) - \overline{w'\theta_h'}\left(\frac{z}{h}\right)^n$$ and a similar expression for $-\overline{w'u'}$

- The Mellor-Yamada-Janjic "Level 2.5" scheme uses an equation for the production, advection, diffusion, and dissipation of turbulent kinetic energy:

$$\frac{d}{dt}\left(\frac{q^2}{2}\right) - \frac{\partial}{\partial z}\left[lqS_q\frac{\partial}{\partial z}\left(\frac{q^2}{2}\right)\right] = P_s + P_b - \varepsilon \quad \text{(TKE)}$$

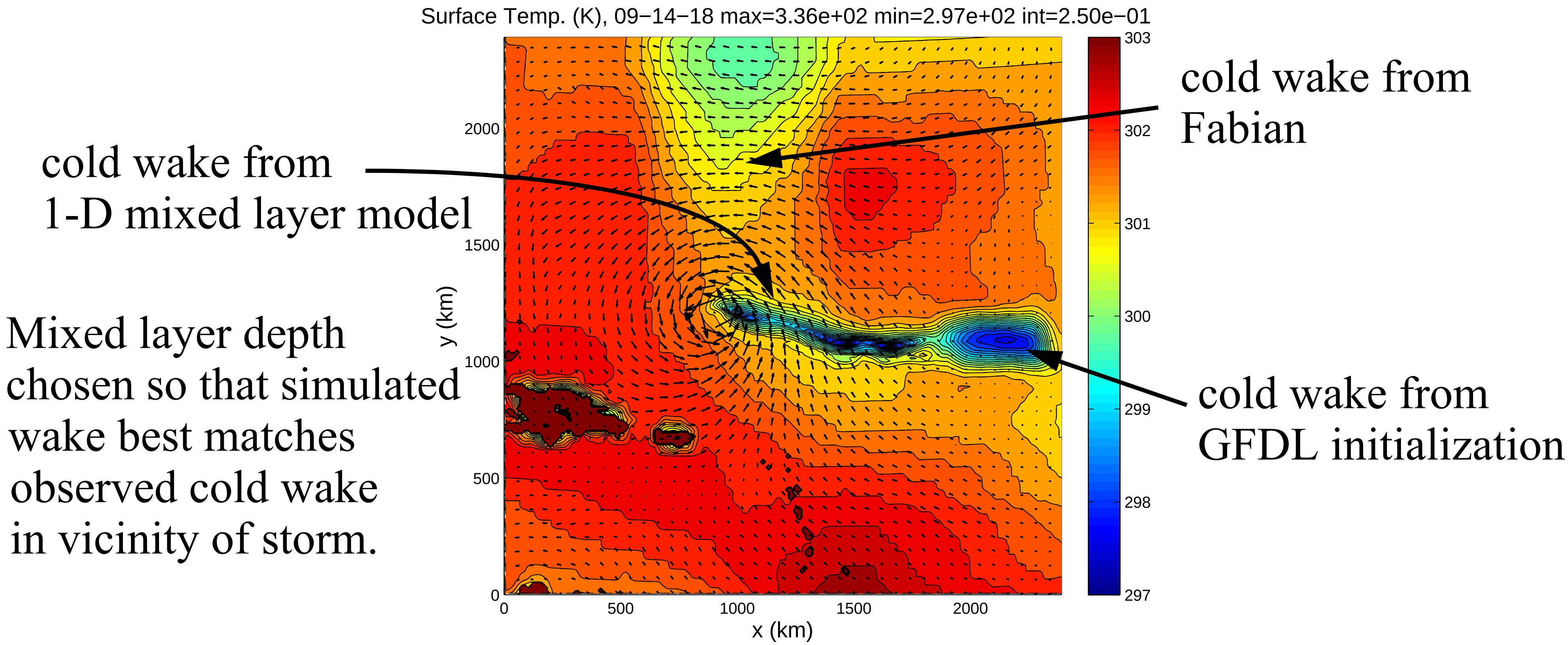
The eddy diffusivity then is computed from the TKE, a length scale, and the shear of the local flow:

$l = l_0\kappa z(\kappa z + l_0)^{-1}$ (geometrically prescribed length scale varies from 0 to l_0)

$K_M = lqS_M$, and $K_T = lqS_T$ (eddy diffusivities of momentum and temperature)

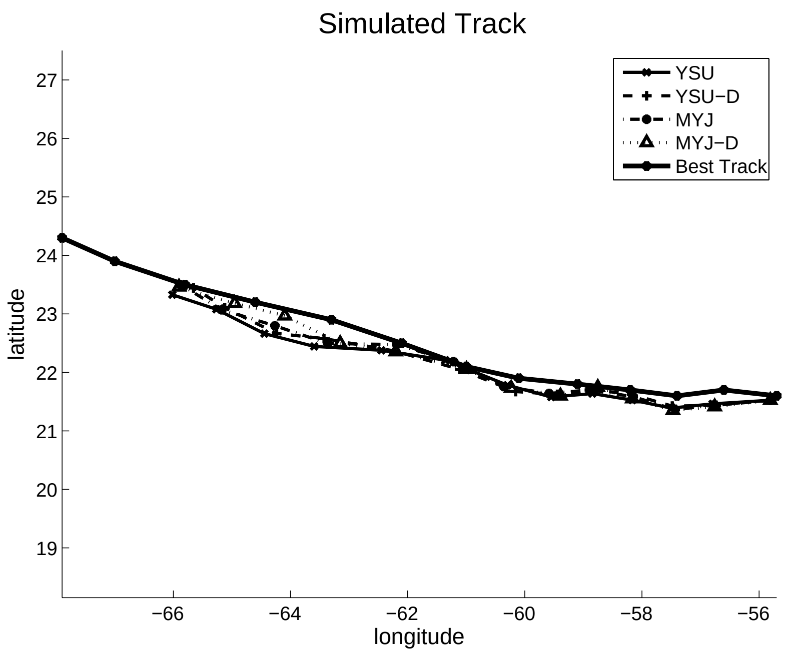
II. Method

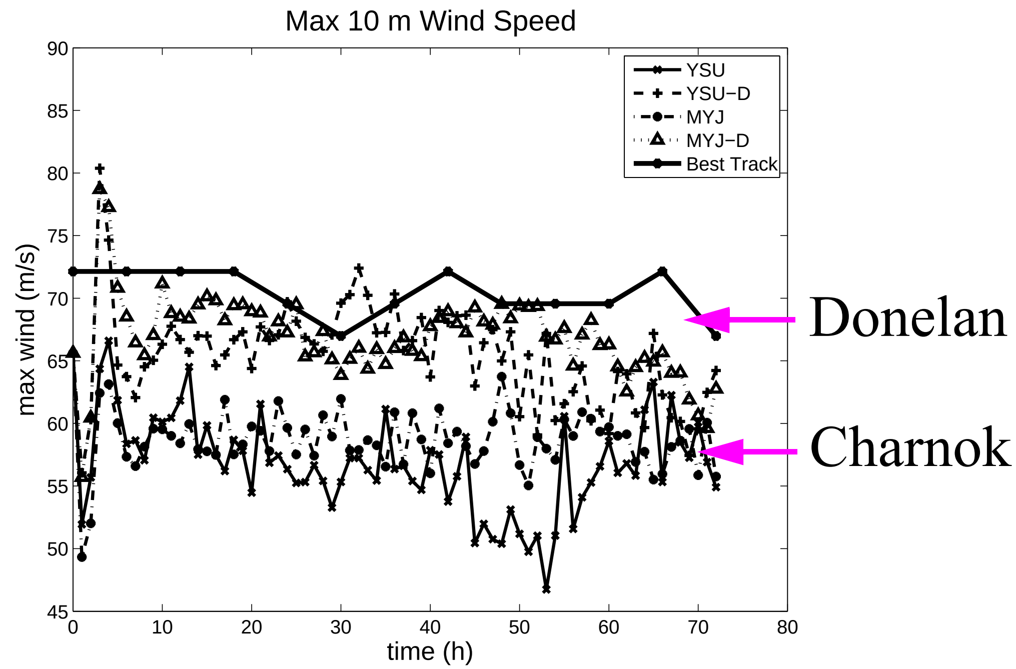
- High-resolution simulations of Hurricane Isabel (2003):
    * WRF 2.2.1, plus some modifications as in Davis et al. (2008, "AHW")
    * Moving nests with 12/4/1.33 km resolution. 40 vertical levels, 10 below 2 km.
    * Initialization and boundary conditions with GFDL analysis fields from 00Z 12 September to 00Z 15 September.
    * Coupled to one-dimensional mixed layer model to provide ocean cooling.



Mixed layer depth chosen so that simulated wake best matches observed cold wake in vicinity of storm.

III. Track and Maximum Surface Wind

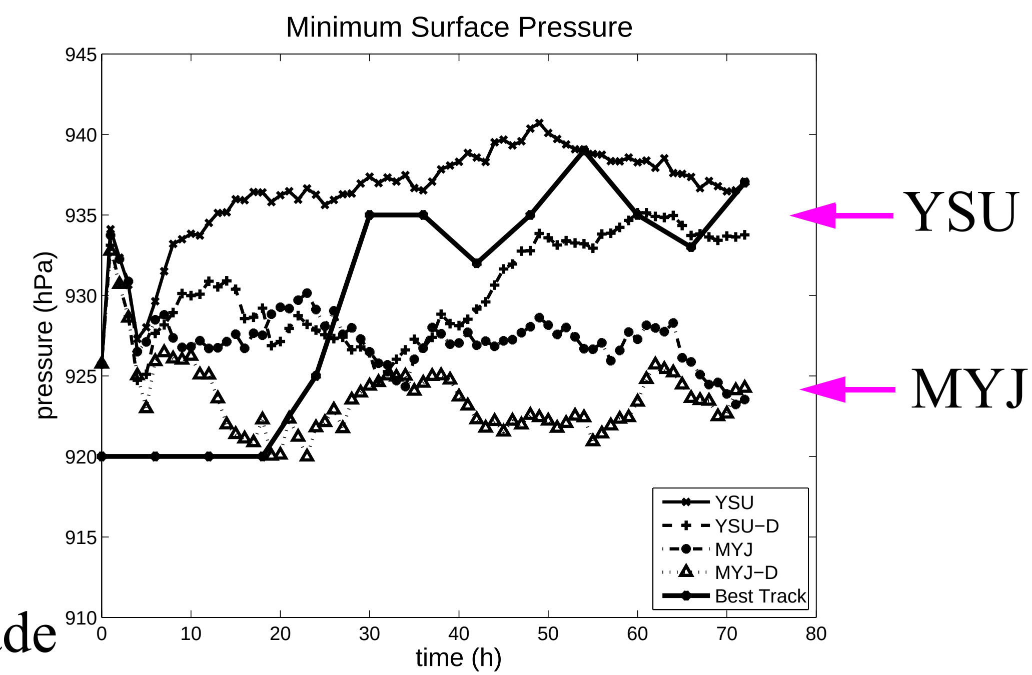




* The "-D" refers to schemes modified from Charnok roughness length formula to one modeled after Donelan et al. (2004) laboratory results

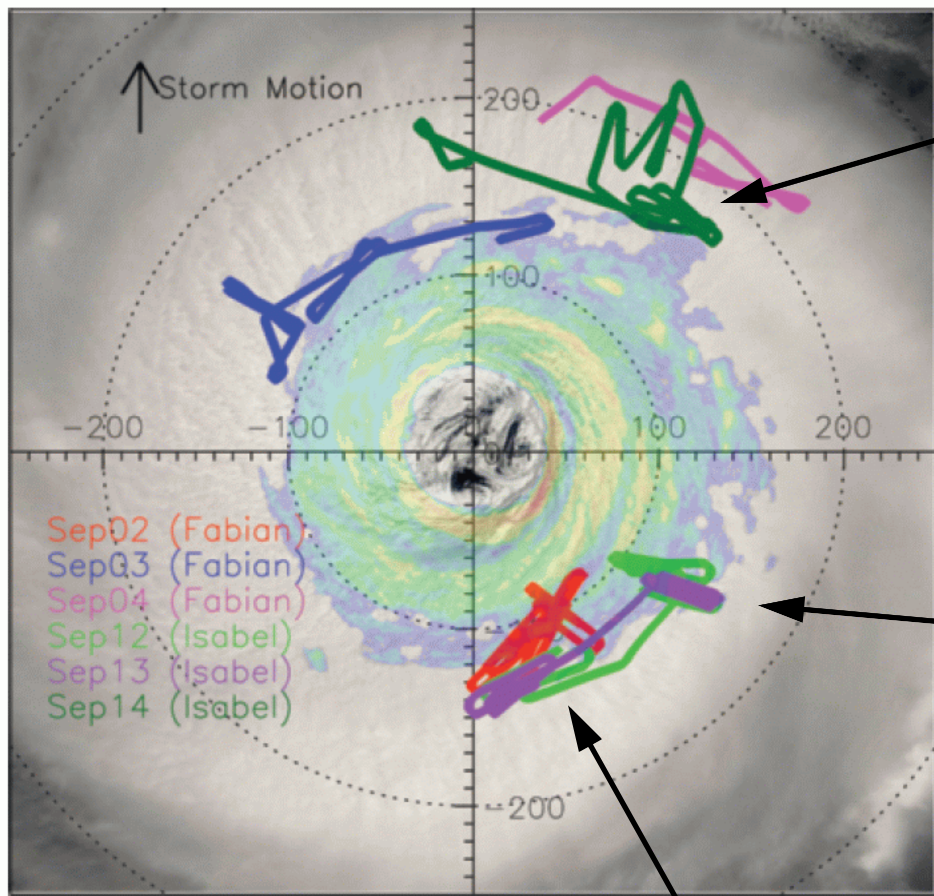
* Track is "right on" but too slow

* All comparisons to data use the model output for when the hurricane is closest to the same *location* when obs. were made



IV. Outer-core Boundary Layer

Fig. 4 of P. Black et al. (2007, BAMS)

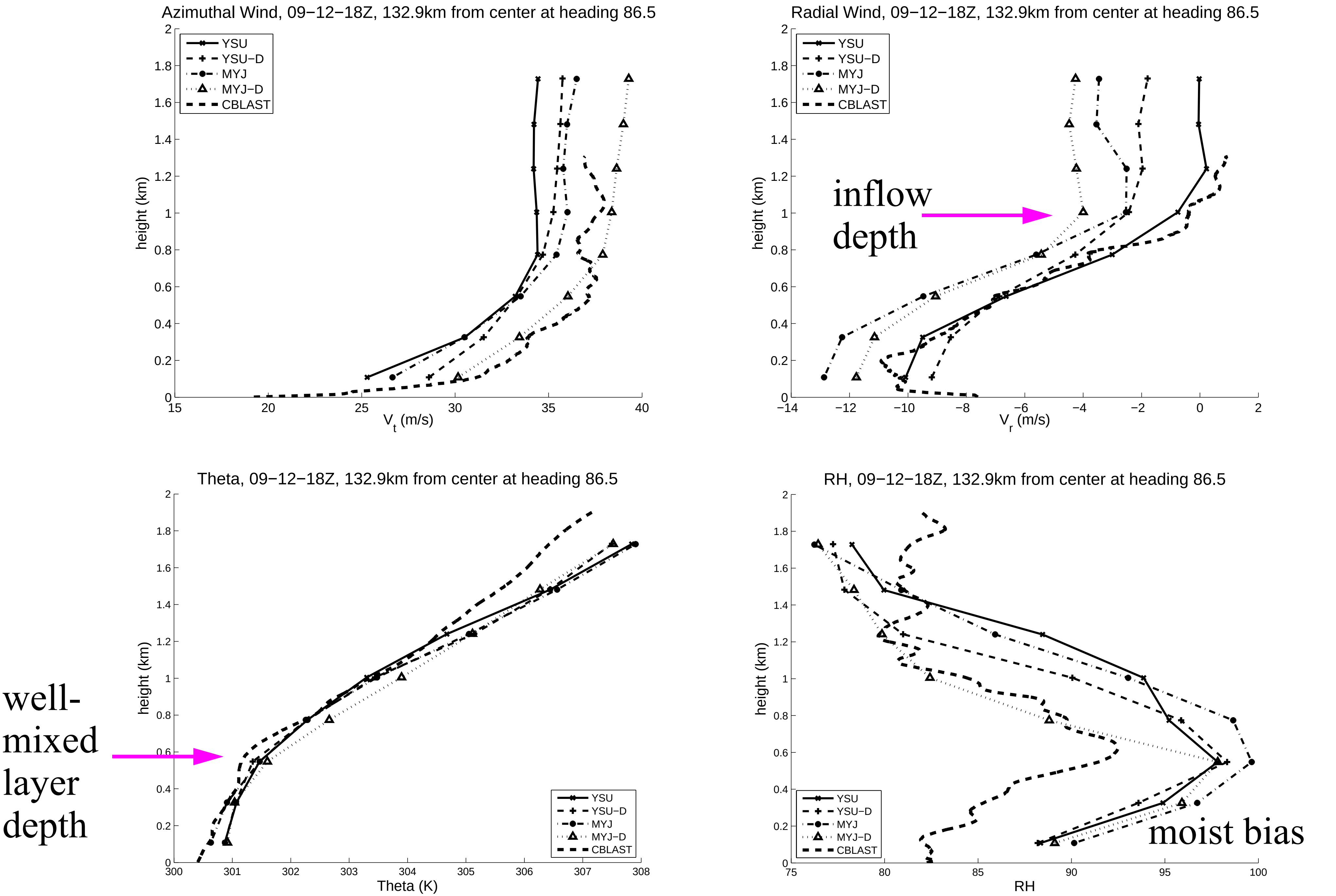


14th: flight level data

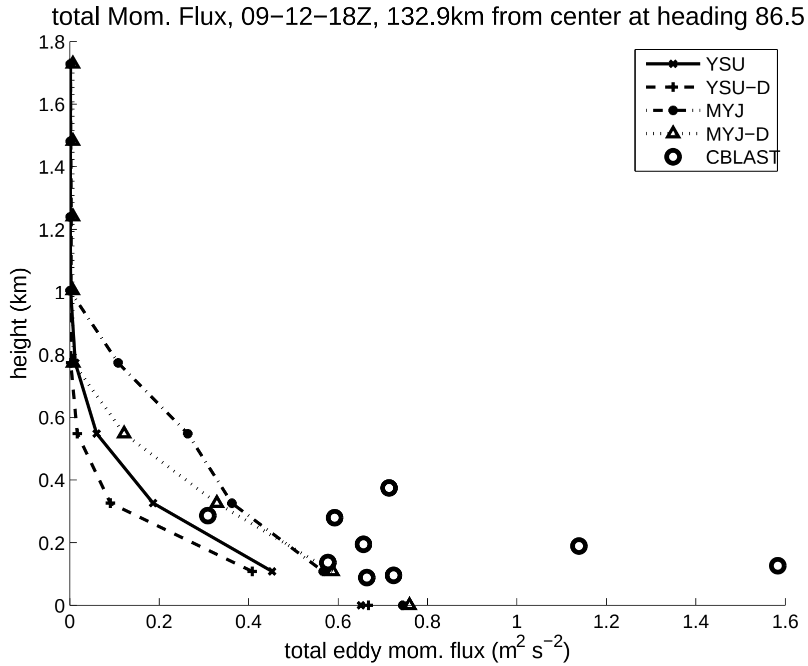
13th: flight level data

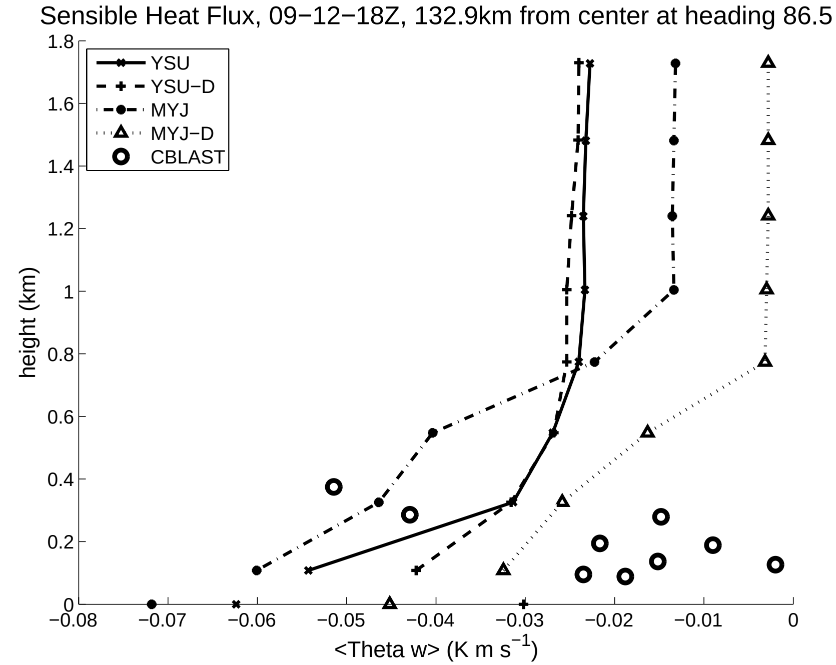
12th: dropsondes
fluxes
flight level data

September 12th Outer-Core Boundary Layer Profiles



September 12th Outer-core Fluxes

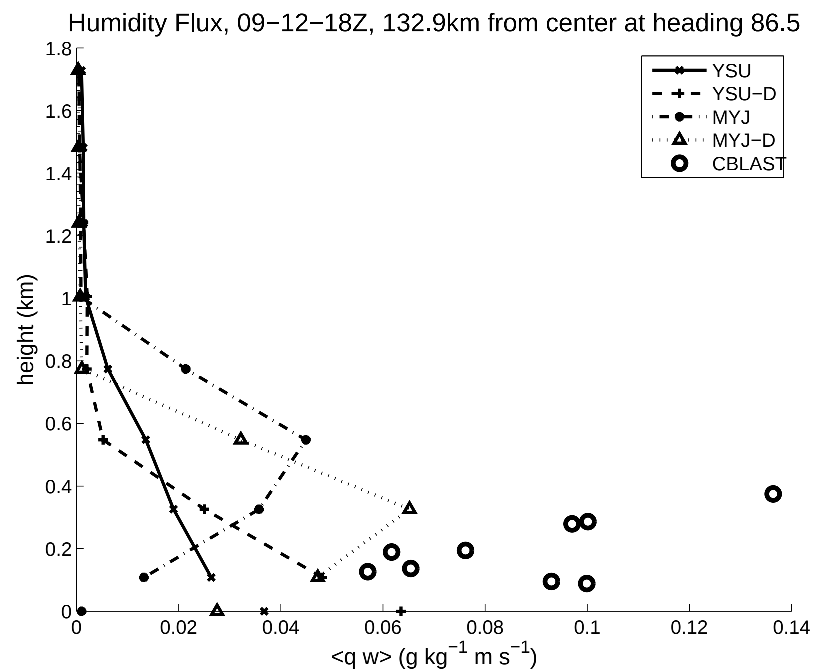




* Momentum and heat fluxes are "in the ballpark"

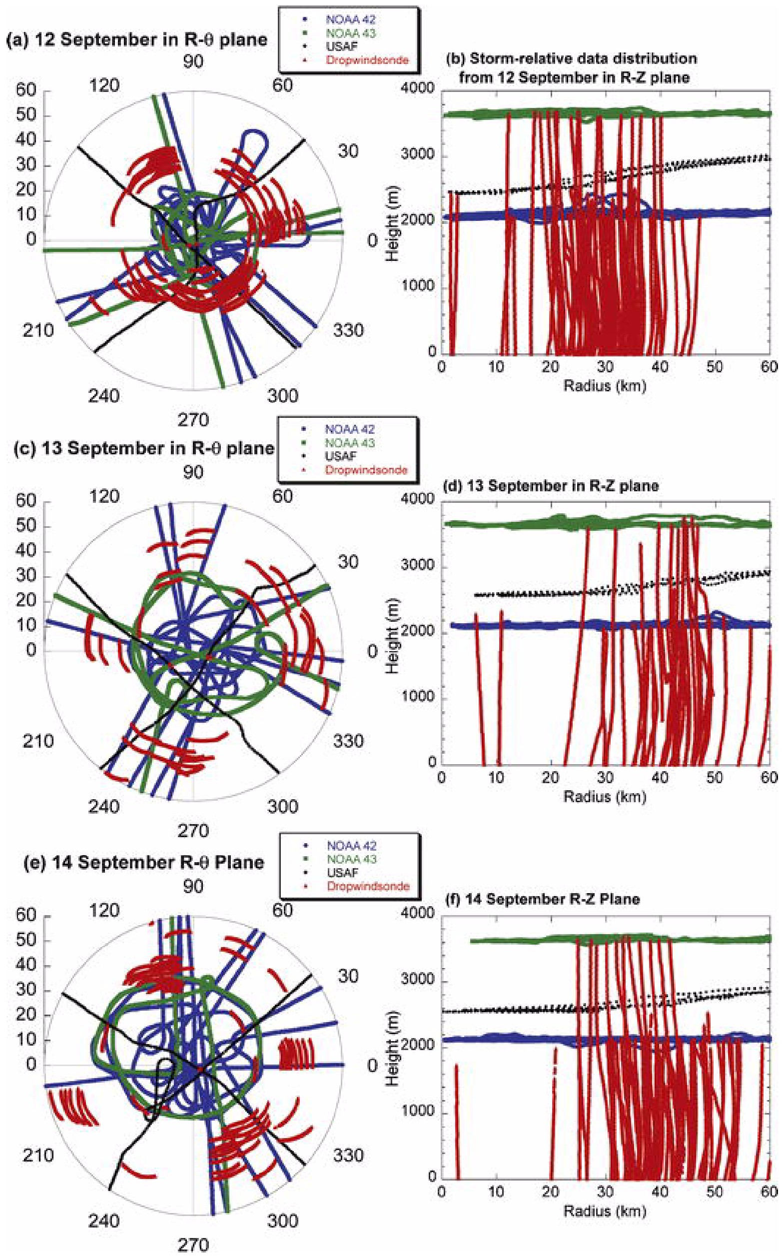
* Measurements over cold wake lead to negative heat fluxes; not captured without the coupled model

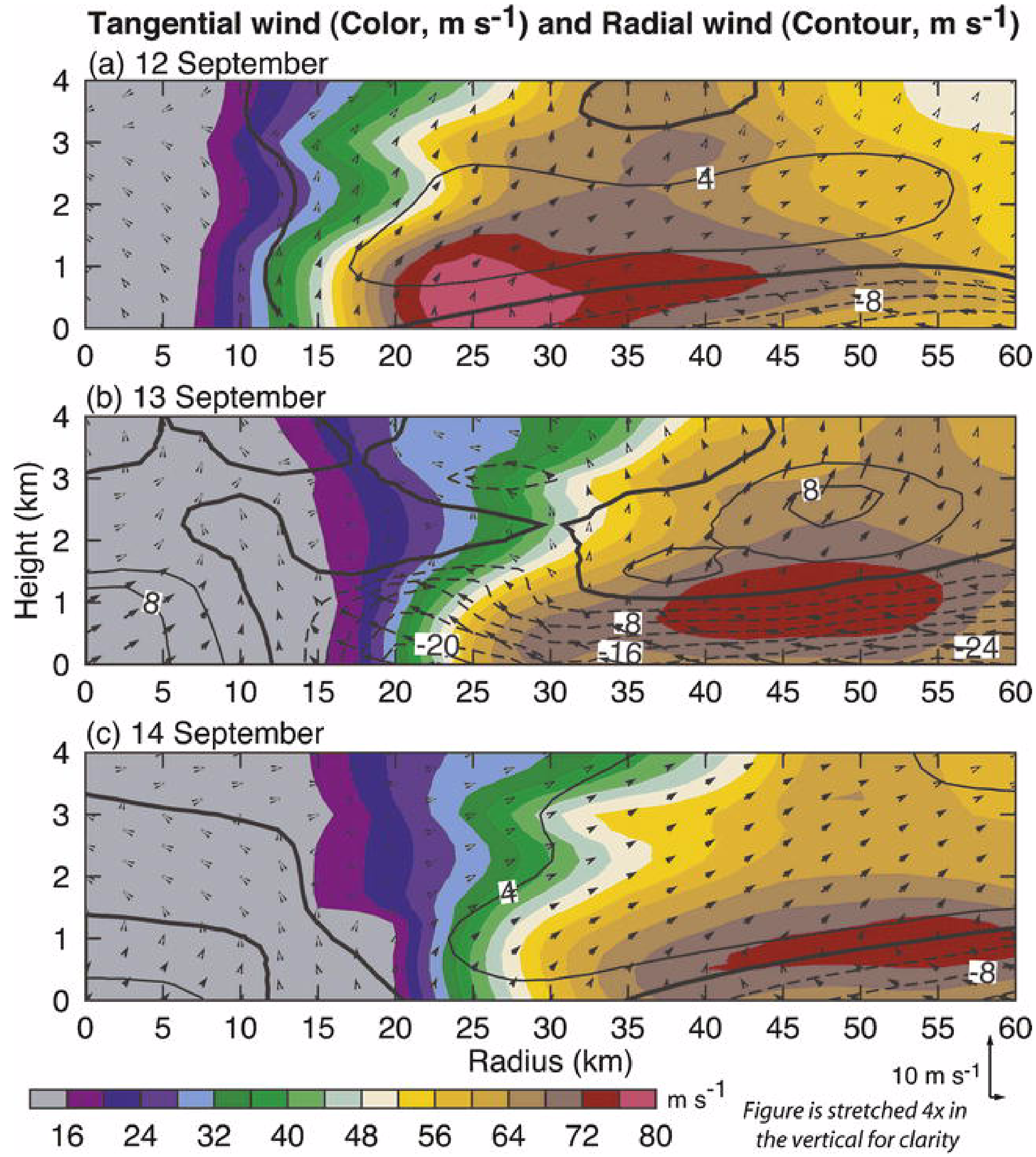
* Low bias in moisture fluxes probably due to high RH bias in boundary layer



V. Inner-core Boundary Layer

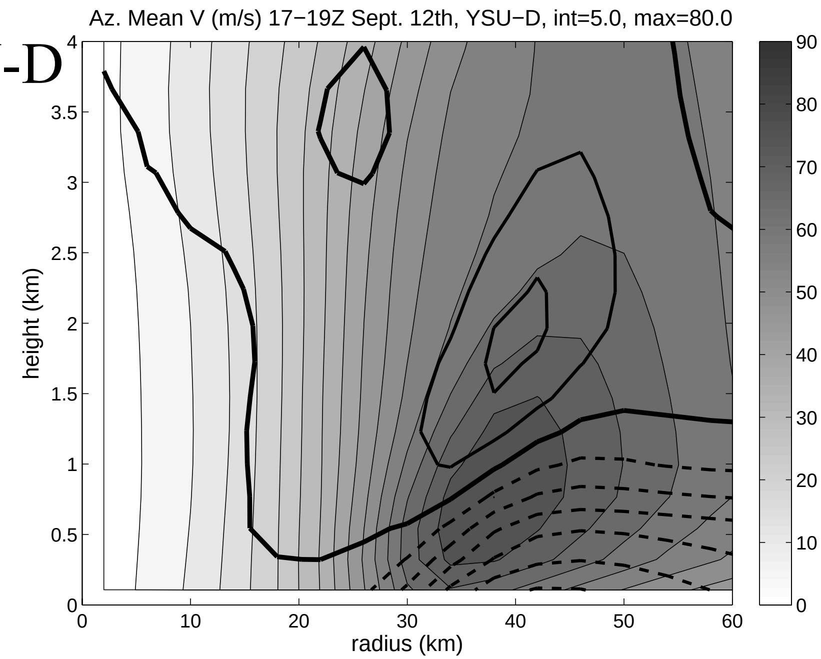
- Bell and Montgomery (2008, MWR), assimilated both flight level observations and *numerous* inner-core dropsondes into a single azimuthal-mean analysis



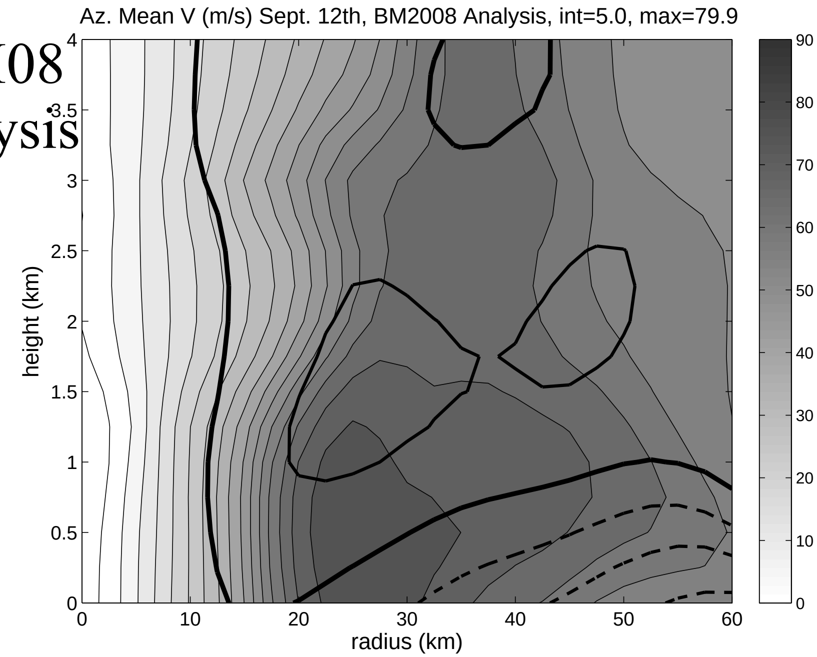


September 12th Inner-core Boundary Layer

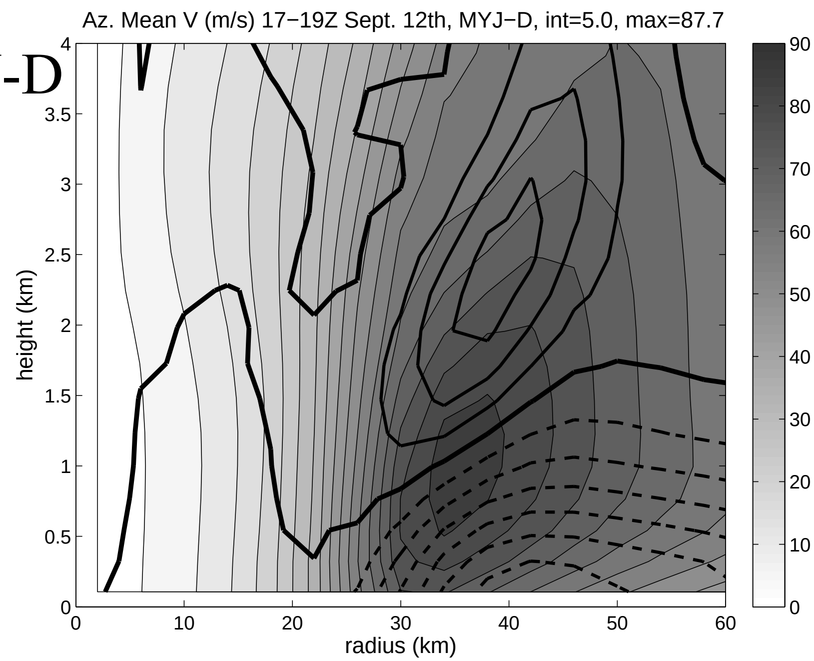
YSU-D



BM08 analysis



MYJ-D



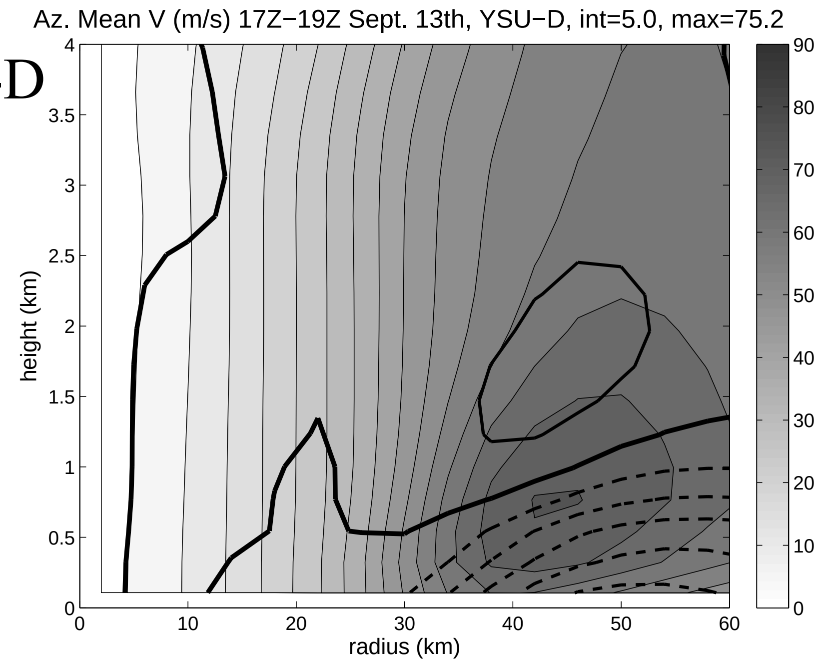
* Simulated eyewalls too large at this time

* Radial inflow and outflow too strong for both PBL schemes, especially MYJ-D

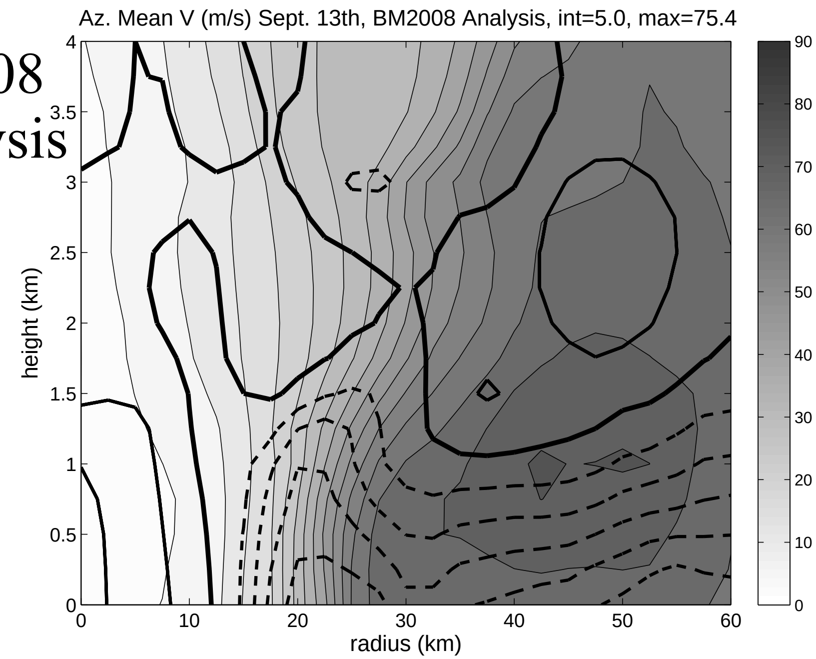
* As a result, MYJ-D supergradient jet is excessively strong

Sepetmber 13th Inner-Core Boundary Layer

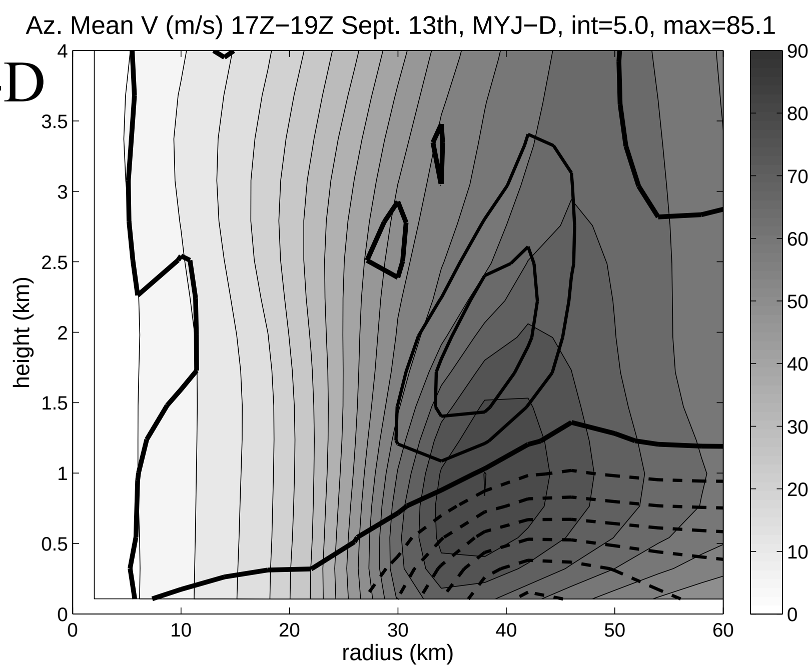
YSU-D



BM08 analysis



MYJ-D



* BM08 analysis has “unrepresentative” radial inflow feature

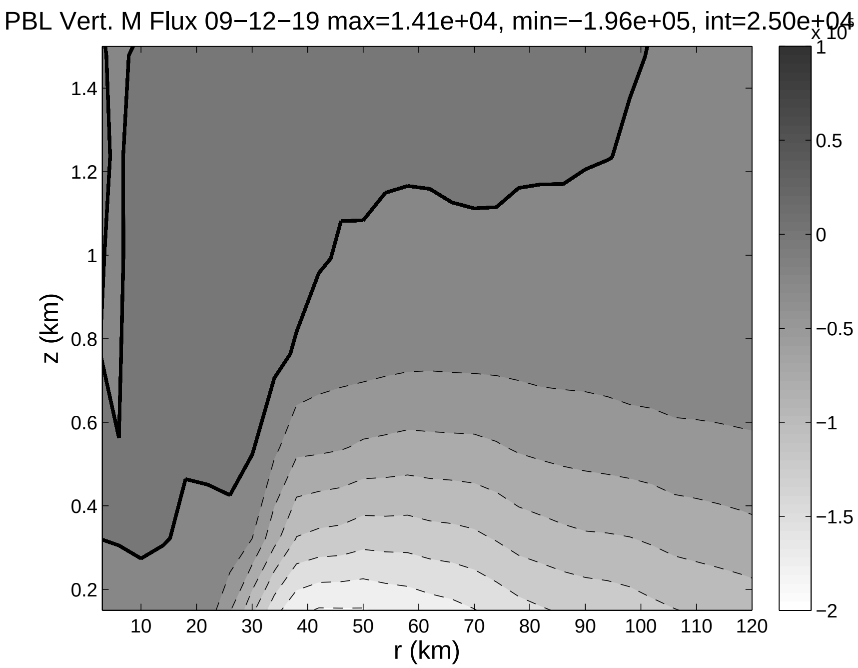
* YSU-D is remarkably good match

* MYJ-D again has excessive radial inflow, radial outflow, and supergradient jet

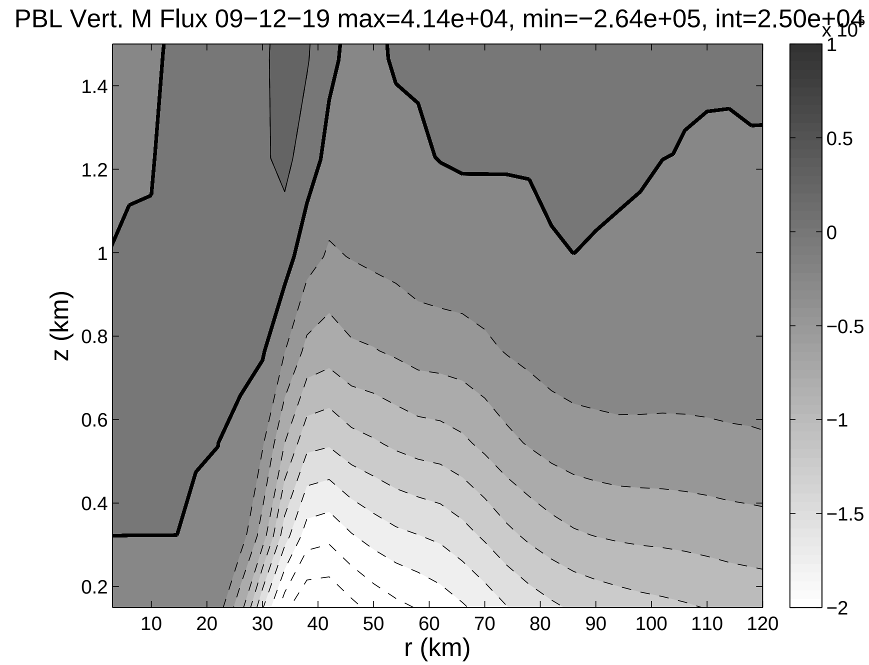
- Why does the MYJ-D boundary layer have a stronger secondary circulation, even though it has exactly the same C_d as YSU-D?

Vertical flux of angular momentum caused by the PBL schemes:

YSU-D



MYJ-D



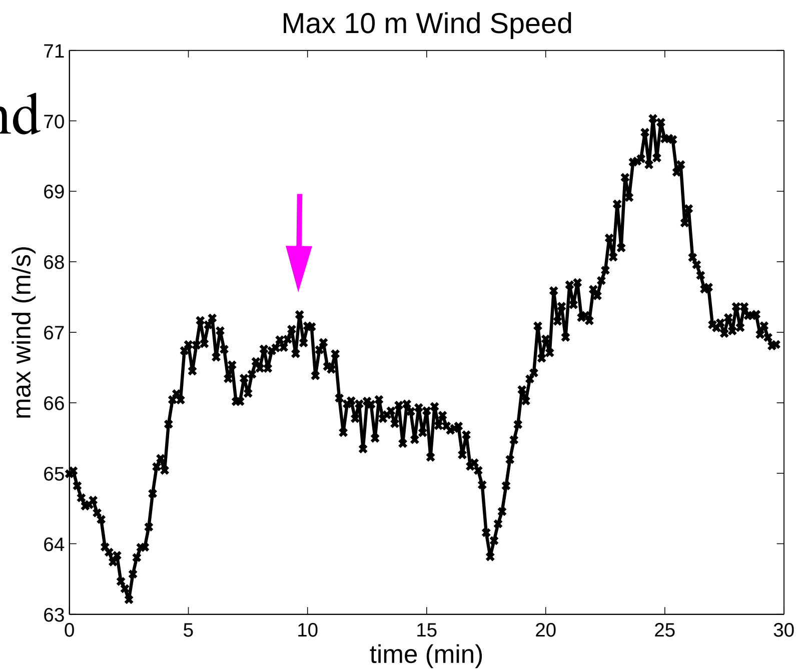
- Despite having nearly identical surface wind profiles at this time, the MYJ-D scheme fluxes more angular momentum into the surface than the YSU-D scheme.

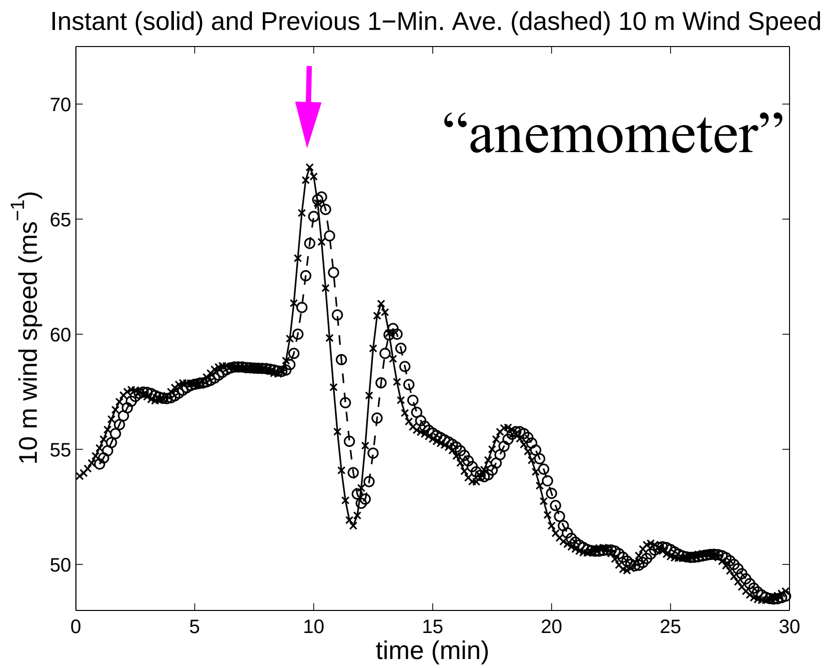
This larger loss of momentum leads to a stronger frictionally driven inflow, stronger supergradient jet, and stronger rebounding outflow.

V. Model Wind Speeds versus One-minute Winds

- As we go to smaller and smaller grid spacing, what is the relationship between instantaneous winds and one-minute averages?

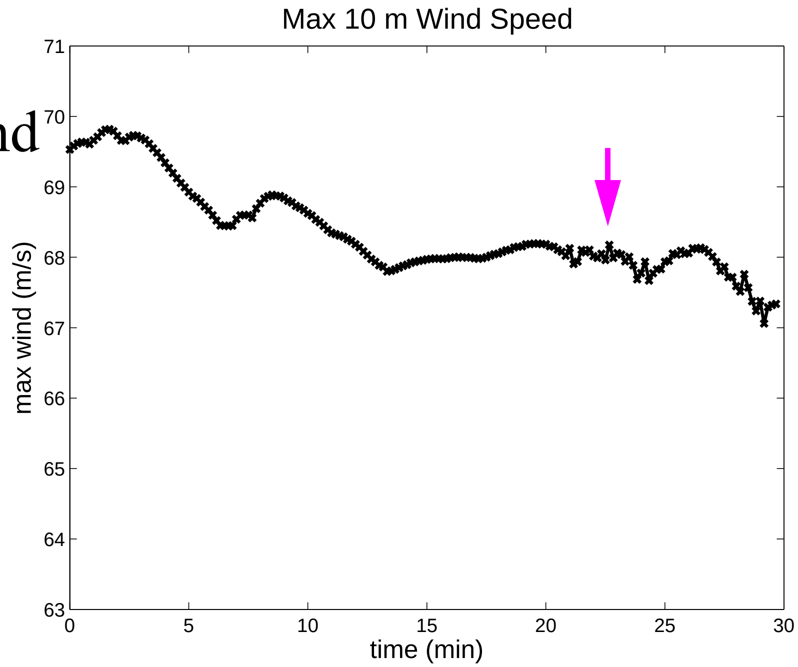
YSU-D
10-second
output

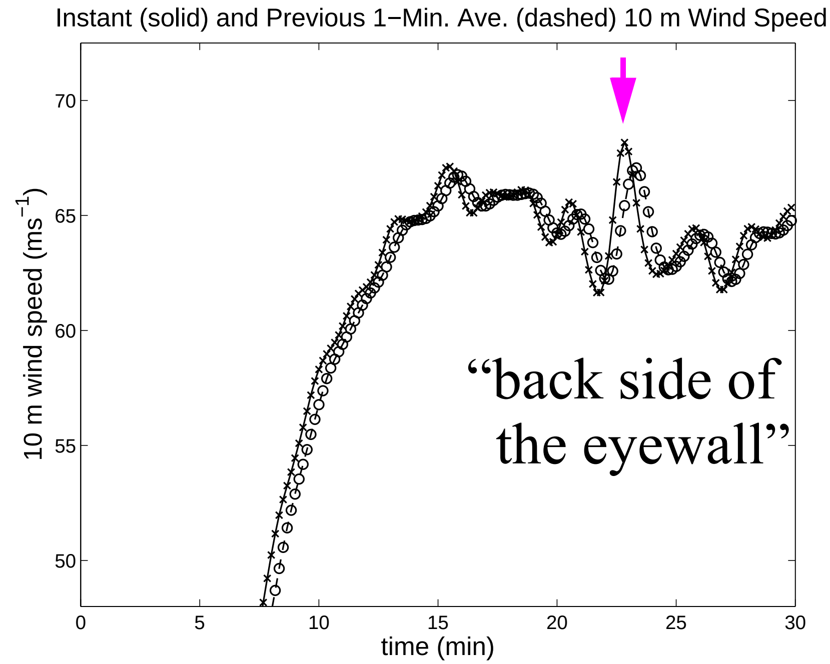




- There is large variability of peak wind speed on time scales of 5 minutes
- The peak wind speed “event” appears to be the passage of a small-scale vortex
- Even at 1.33 km grid spacing, the peak instantaneous winds are only 1-2 m/s faster than the one-minute average wind speeds!

MYJ-D
10-second
output

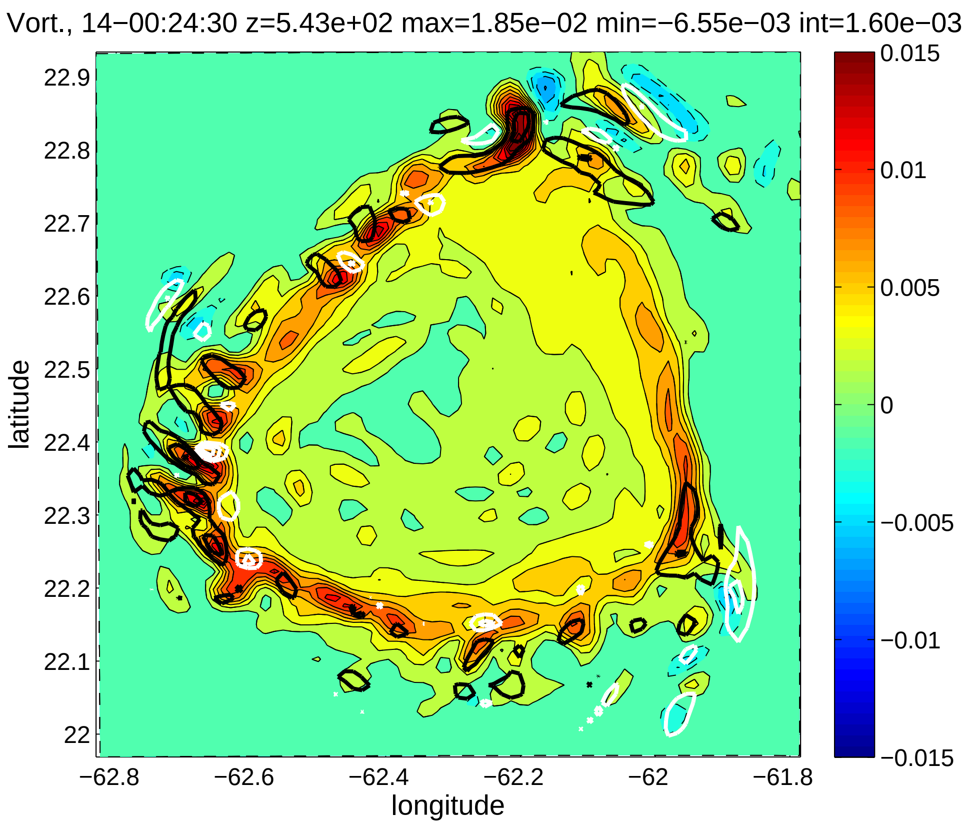




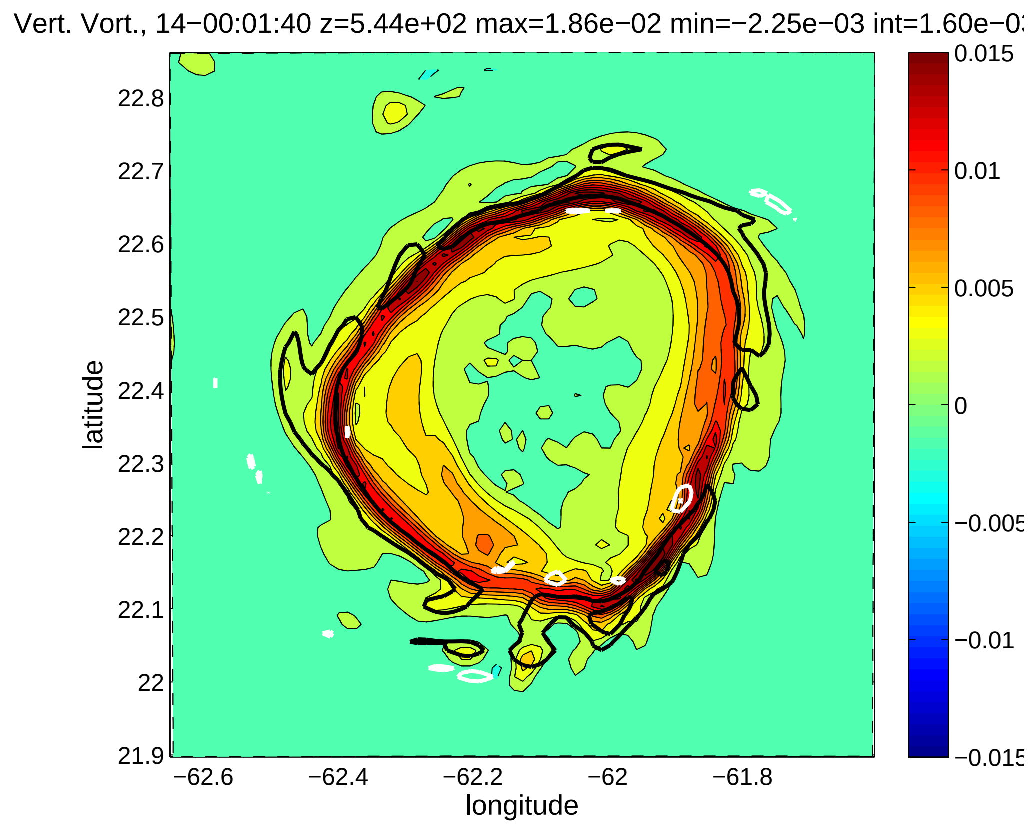
- MYJ-D peak wind speeds show much less short-term variability
- Instantaneous winds are even closer to the one-minute sustained winds

These differences are related to the horizontal structure of the simulated eyewalls:

YSU-D



MYJ-D



Plots show vorticity (color), updrafts (black), and downdrafts (white) at z = 500 m.

- We know from observations such as in Aberson et al. (2006) and Marks et al. (2008) that the YSU-D eyewall is much more realistic.

VI. Other Results

•Numerous other results on

* The effects of increasing horizontal resolution down to 444 meters;
* The effects of increasing vertical resolution;
* The observed and simulated asymmetric boundary layer flows;

can be found in:

Nolan, David S., Jun A. Zhang, and Daniel P. Stern, 2009: Validation and comparison of planetary boundary layer parameterizations in tropical cyclones by comparison of in-situ data and high-resolution simulations of Hurricane Isabel (2003). Part I: Initialization, maximum winds, and outer core boundary layer structure. Submitted to *Mon. Wea. Rev.*

Nolan, David S., Daniel P. Stern, and Jun A. Zhang, 2009: Validation and comparison of planetary boundary layer parameterizations in tropical cyclones by comparison of in-situ data and high-resolution simulations of Hurricane Isabel (2003). Part II: Inner-core boundary layer and eyewall structure. Submitted to *Mon. Wea. Rev.*

which can be obtained from the web site *www.davenolan.com*