Modeling the Hurricane Boundary Layer:

Recent Results and Open Questions

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Outline

I. The basic structure of the hurricane boundary layer

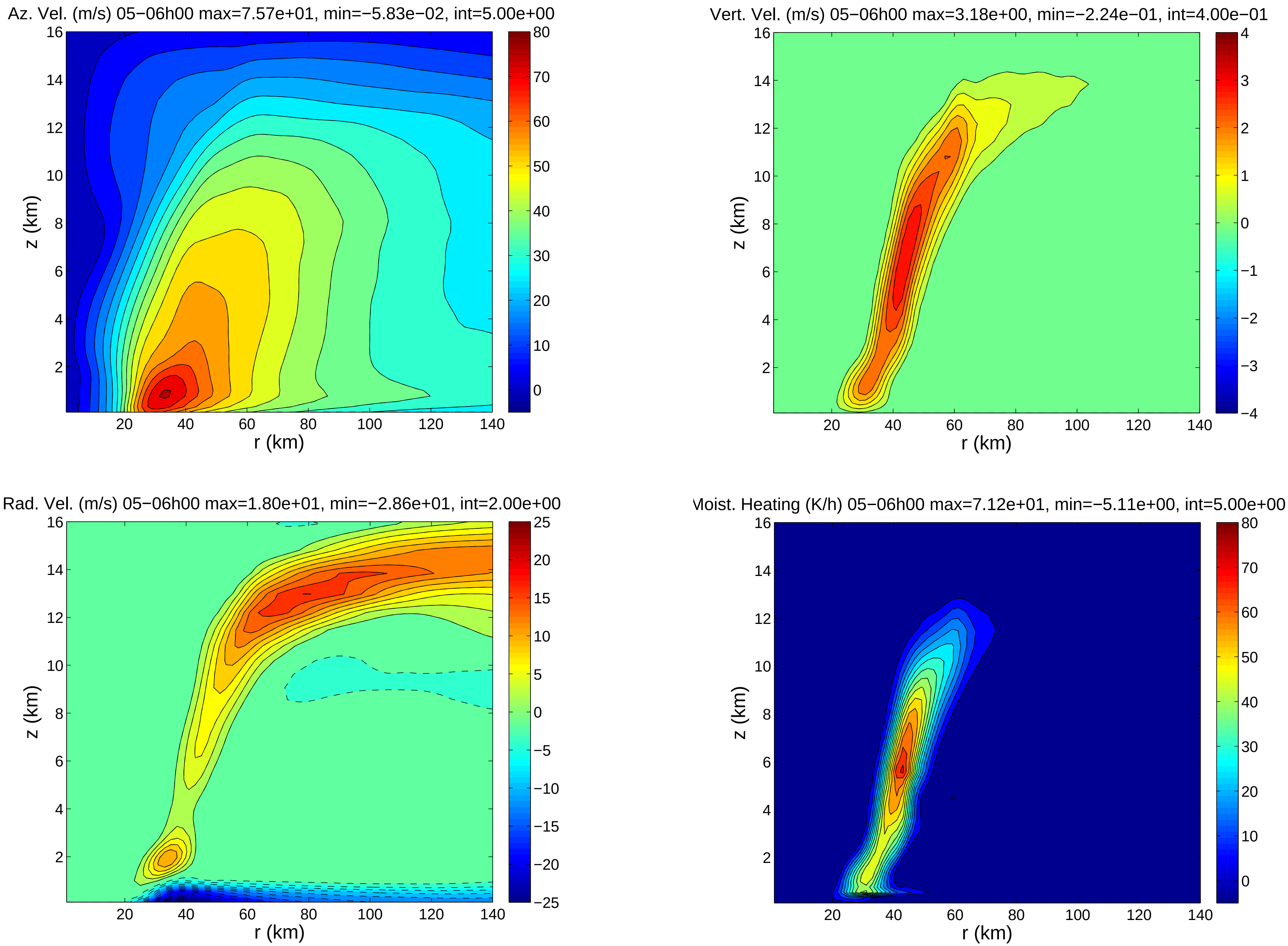
II. Competing views of hurricane intensification

III. The Schemes

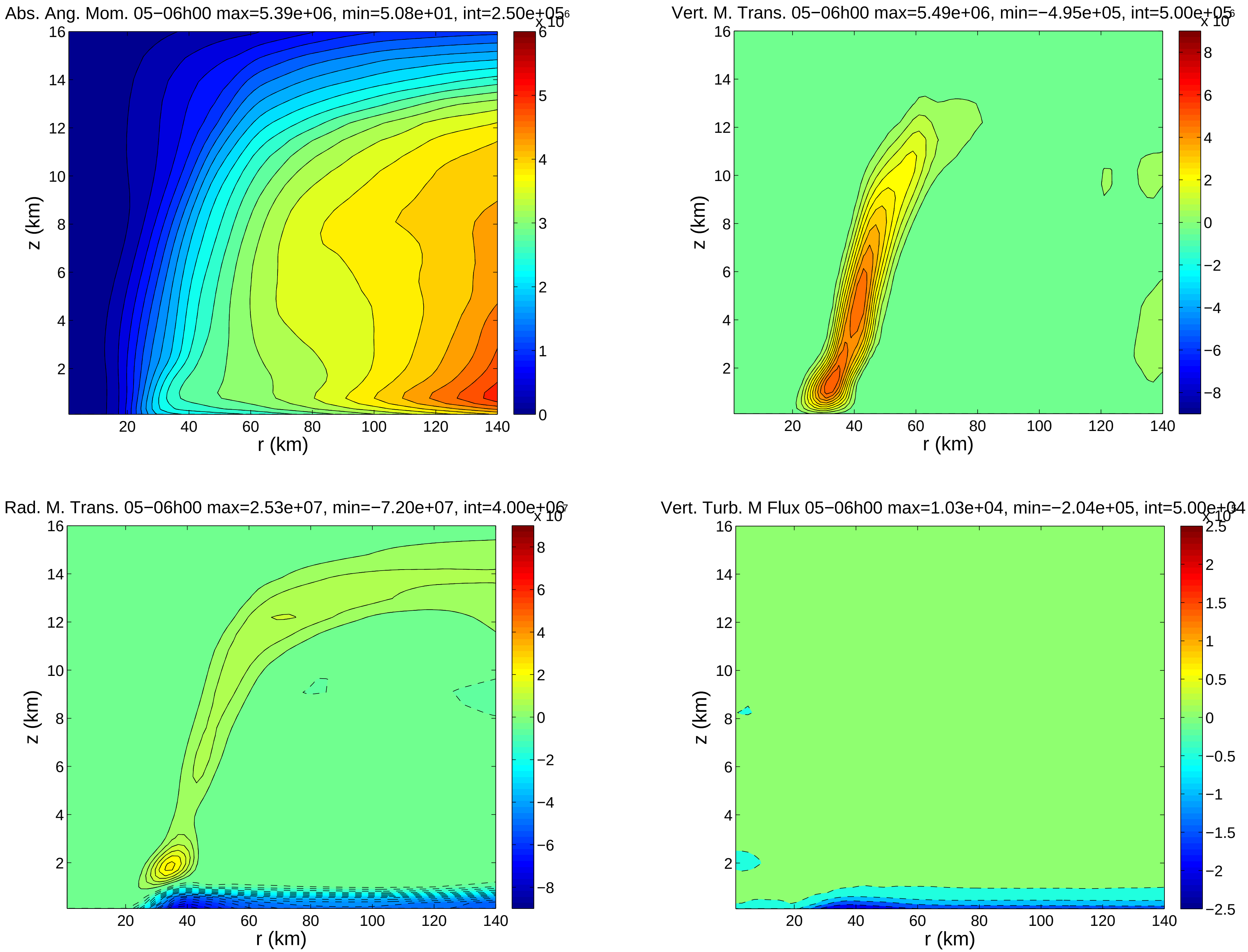
IV. Old Results and New Results

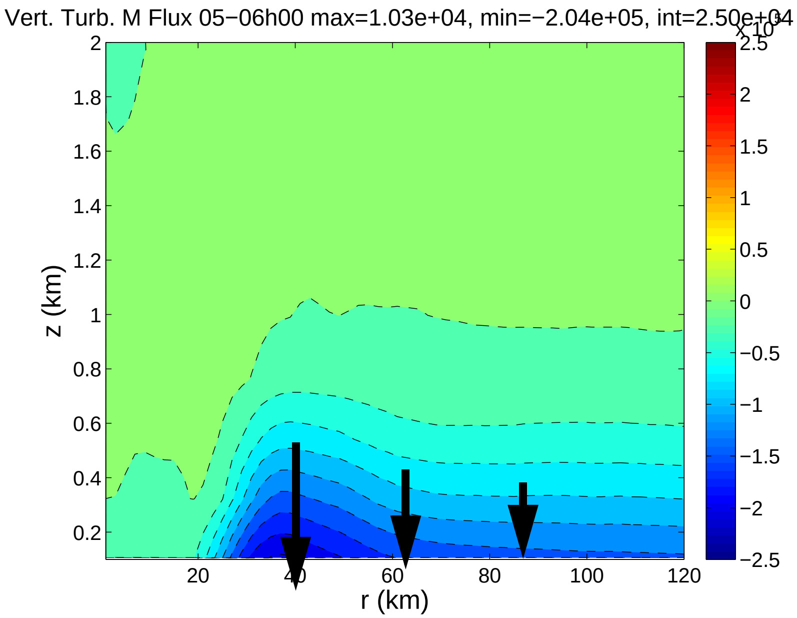
V. Remarks and Questions

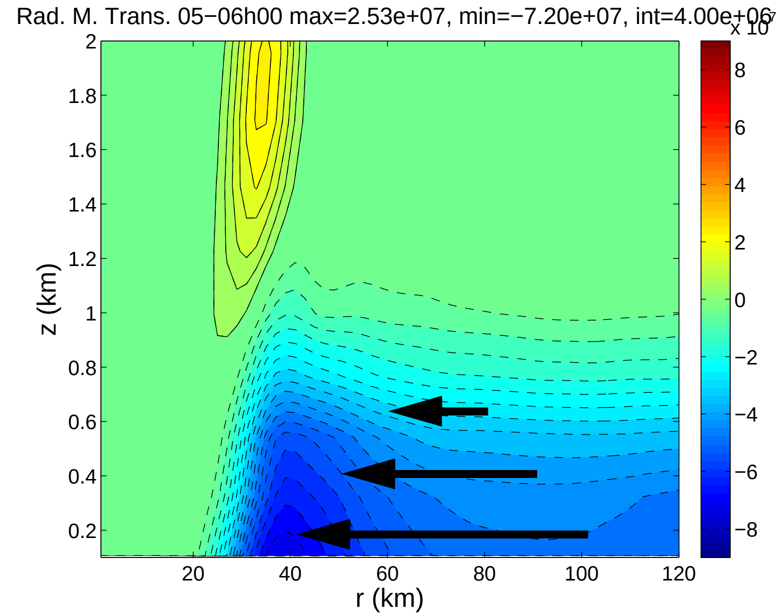
Azimuthally averaged and time-composite fields from a numerical simulation:



Transport of Angular Momentum: $M = rv + fr^2/2$

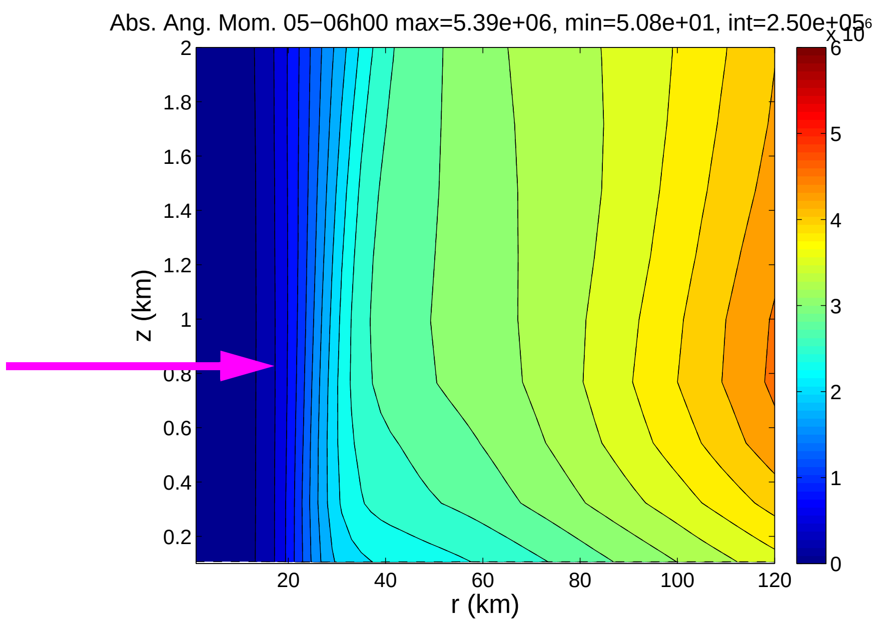


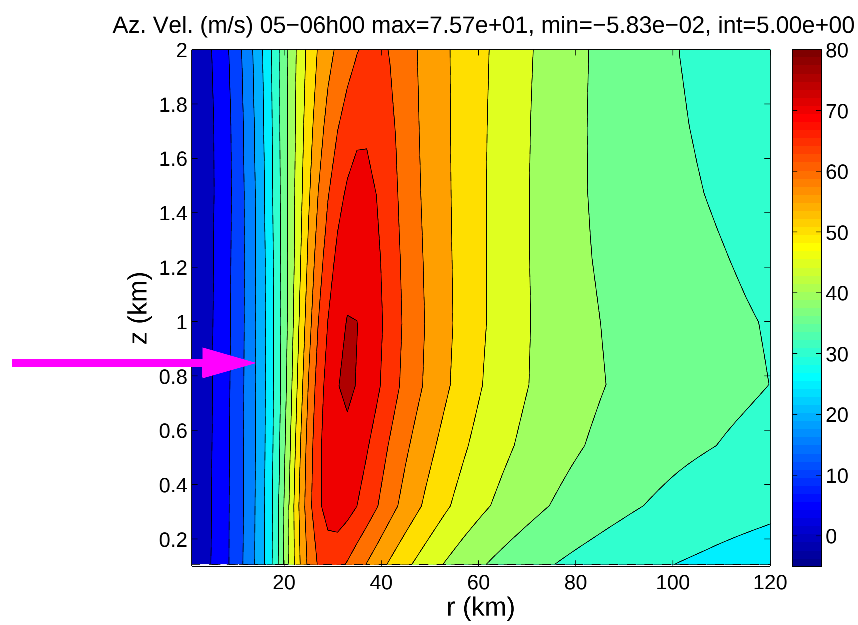




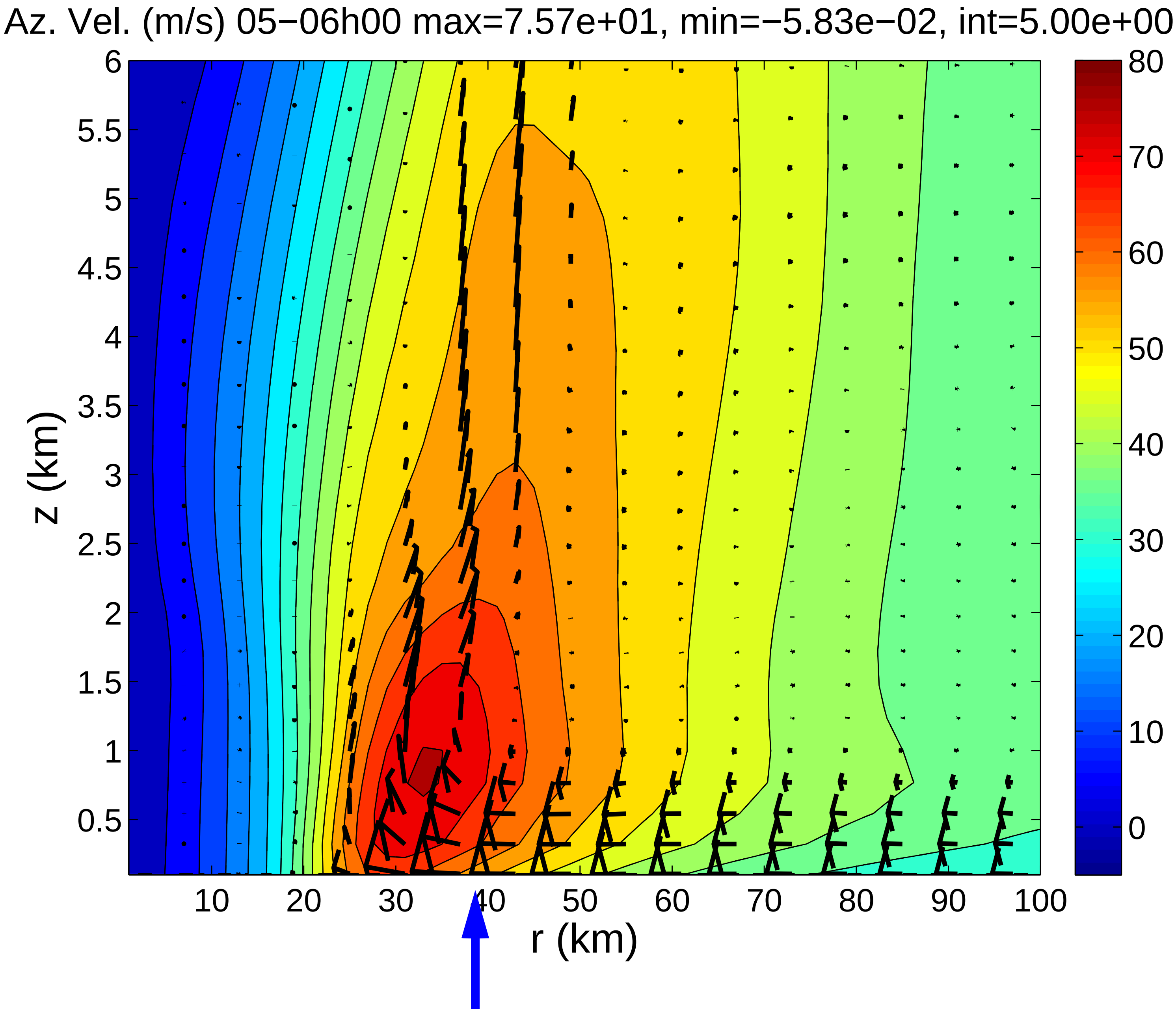
The loss of M by friction is balanced by strong radial inflow.

Radial inflow in the upper boundary layer advects undamped fluid inward, so that M and V are *greater* at the top of the boundary layer





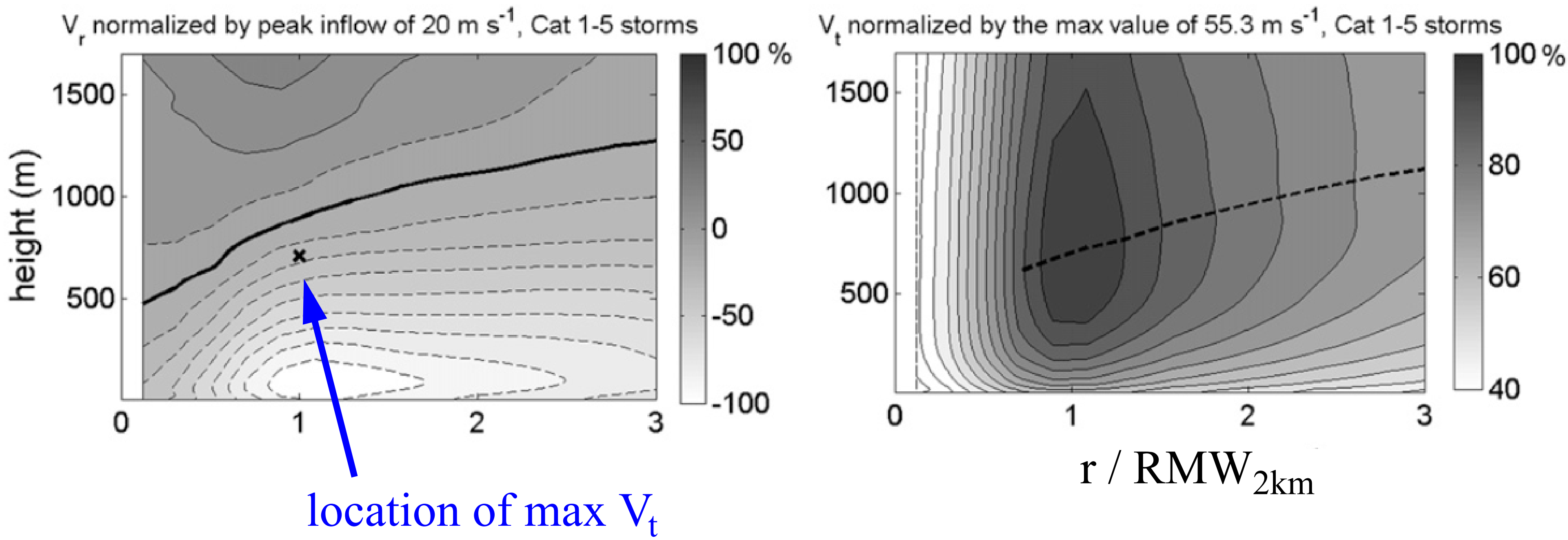
The “Supergradient Jet”



radial inflow “overshoots” the point of zero imbalance (Lagrangian interpretation)

Jun Zhang et al. (MWR, 2011):

Inner-Core PBL and Supergradient Jet from Dropsonde Composites



• Max V_t does *not* occur where $U = 0$, so purely Lagrangian view is incorrect.

The supergradient jet is maintained by inward radial advection of M, which is forced by upward advection and diffusion of radial momentum.

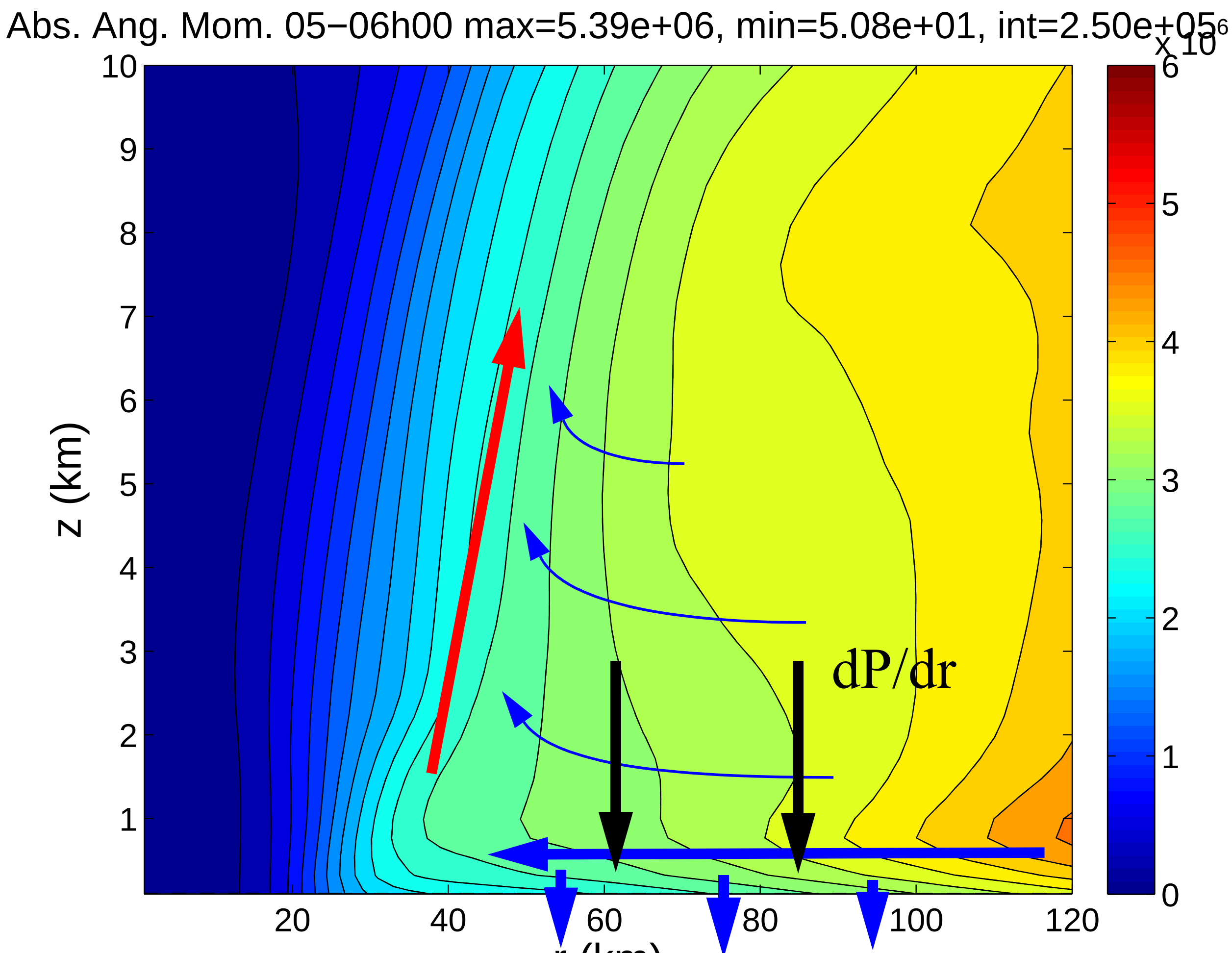
How does a hurricane intensify?

Paradigm 1: --> Convection intensifies;

--> Entrainment into eyewall advects free-atmosphere M inward

--> Low-level inward pressure gradient increases

--> Boundary layer intensifies in response



All "excess" boundary layer M is lost to friction

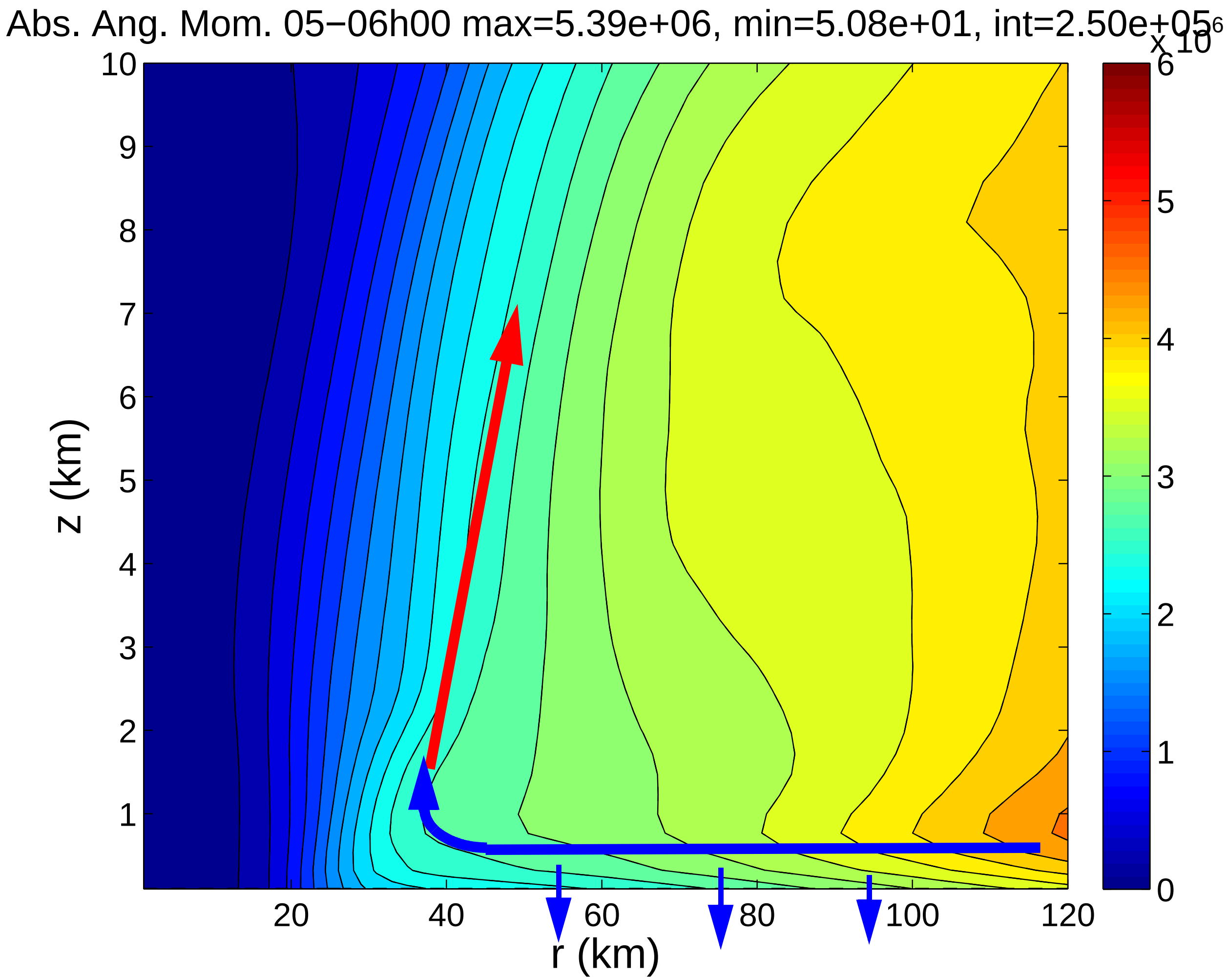
How does a hurricane intensify?

Paradigm 2: Smith, Montgomery, and Sang (2009); also Da-Lin Zhang et al. (2001)

--> Convection intensifies;

--> Secondary circulation intensifies;

--> *M* transported through boundary layer reaches eyewall



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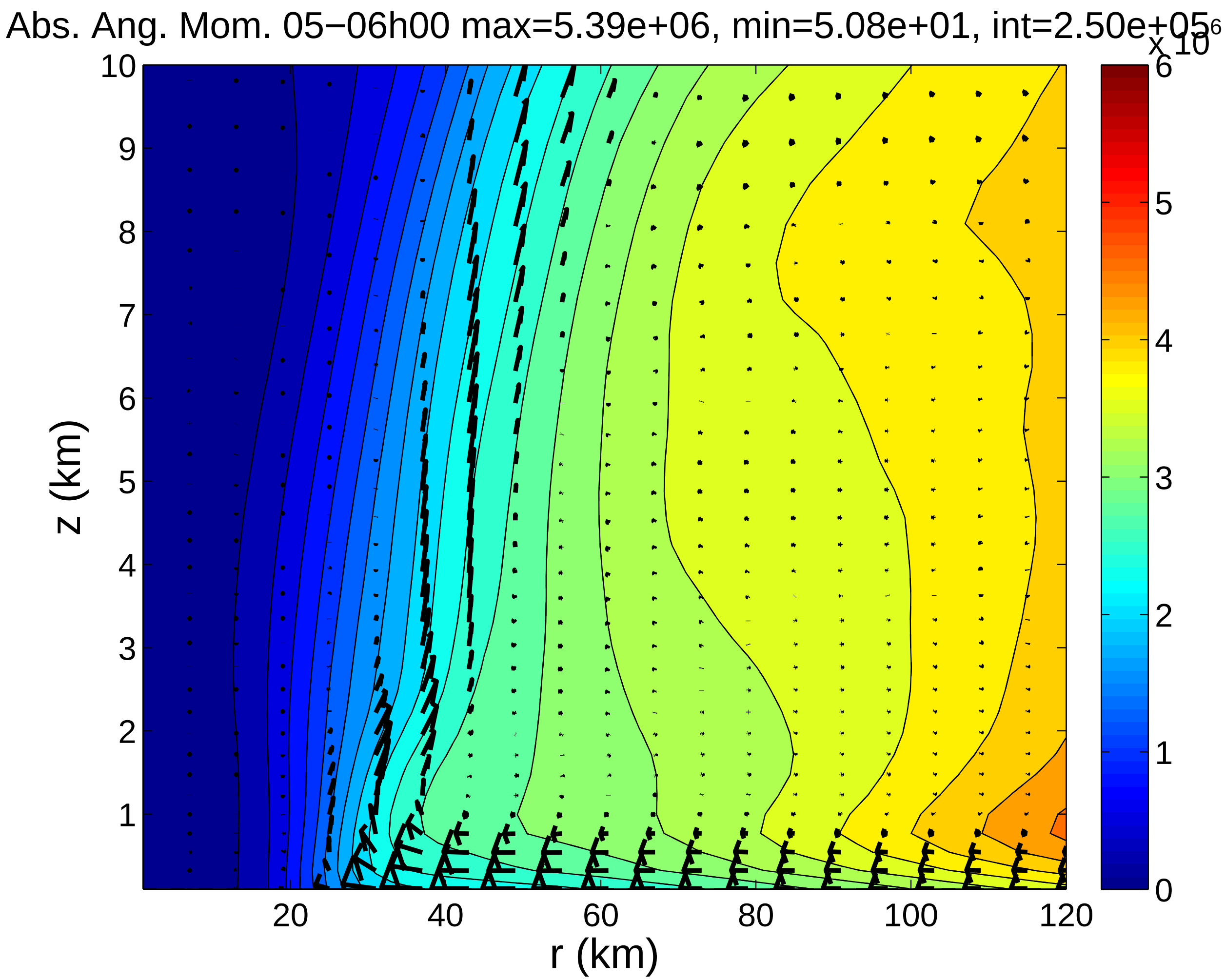
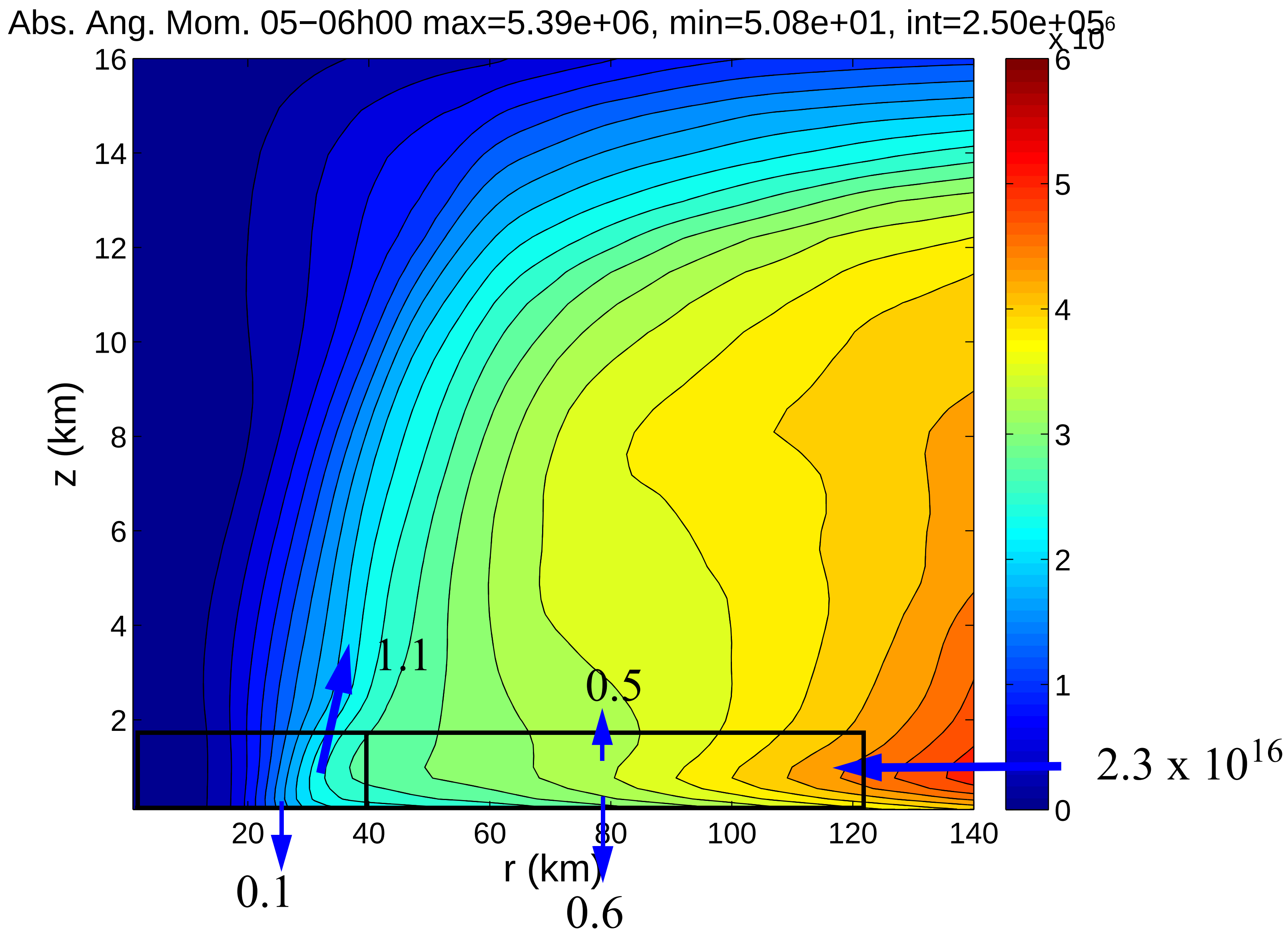
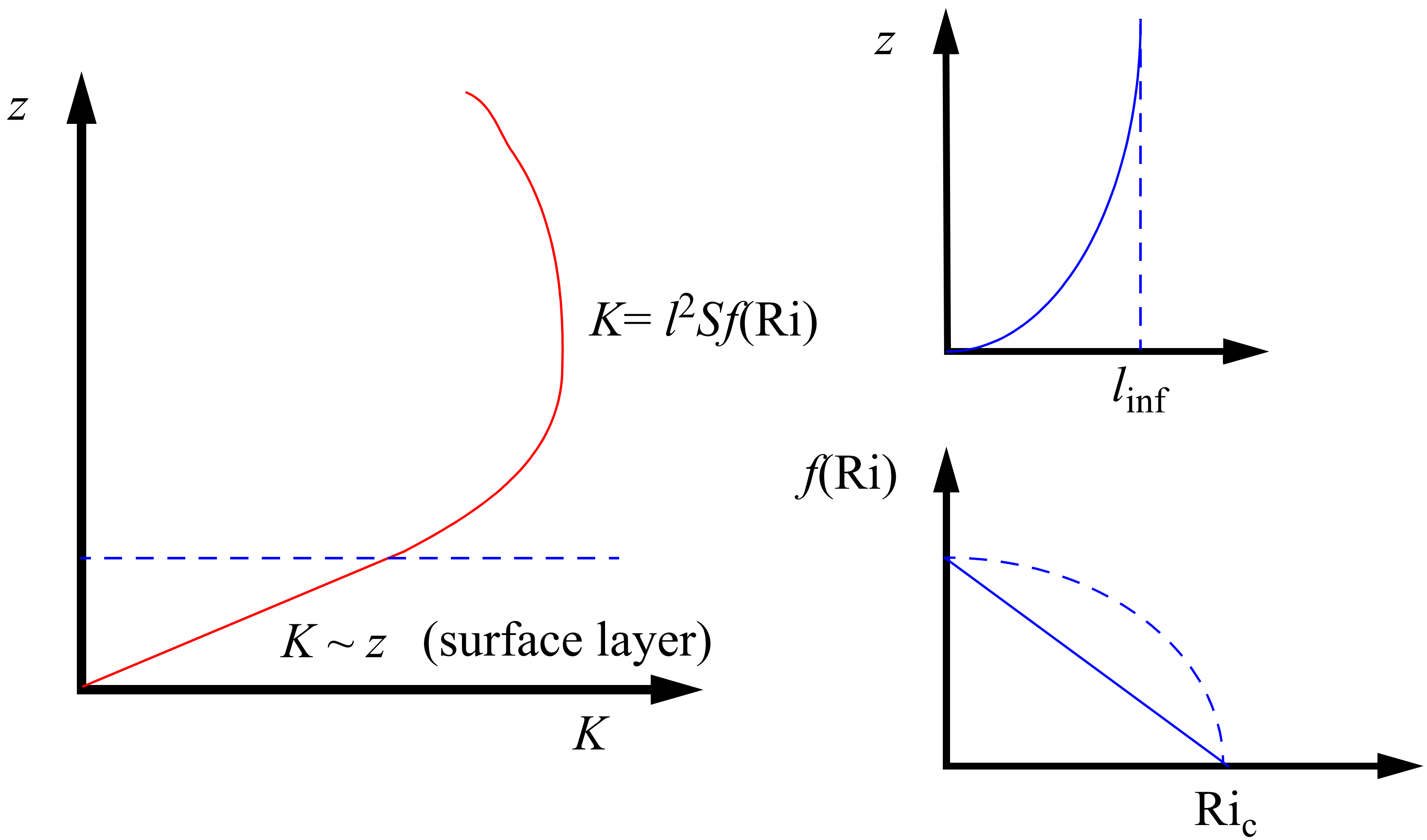


My Attempted Budget for M:



The Schemes

- Bulk/Blackadar/Louis and other “simple” schemes:



- The Mellor-Yamada-Janjic “Level 2.5” (that is, one and a half *order*) scheme:

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

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

$$K_M = lqS_M, \text{ and } K_T = lqS_T \quad \text{(eddy diffusivities of momentum and temperature)}$$

where S_M and S_T are dynamical shear parameters, and the model operates in columns only (boundary layer approximation).

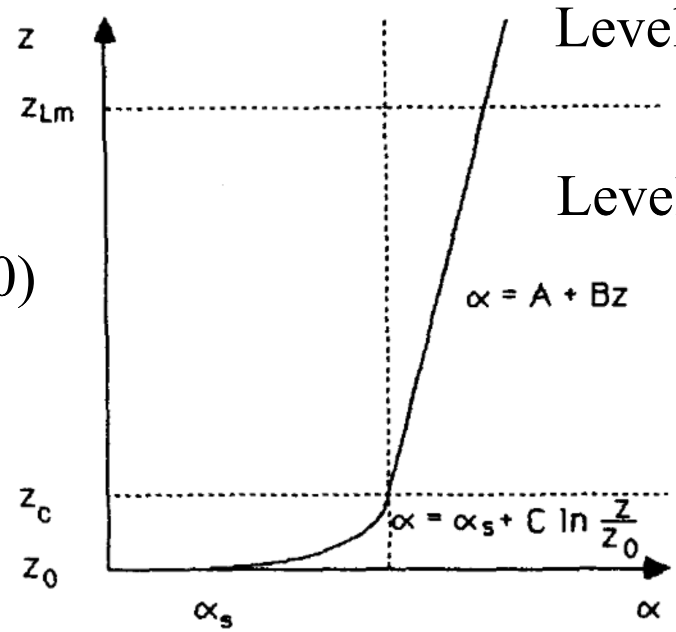


figure from Janjic (1990)

Also, the Level 2.5 scheme is connected to the surface layer with a “Level 2” scheme with diagnosed TKE.

- The MRF-YSU-KPP type scheme:

Hong and Pan (1996, MWR)

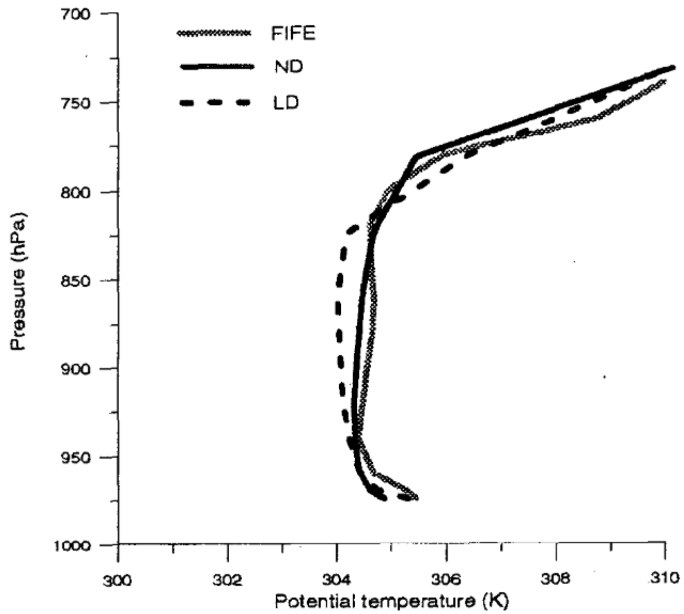


FIG. 3. Comparisons of boundary layer profiles of potential temperature (K) for the 9–10 August sonde averages (shaded lines) with averages from the nonlocal (solid lines) and local (dotted lines) schemes for (a) 1845 UTC and (b) 2145 UTC.

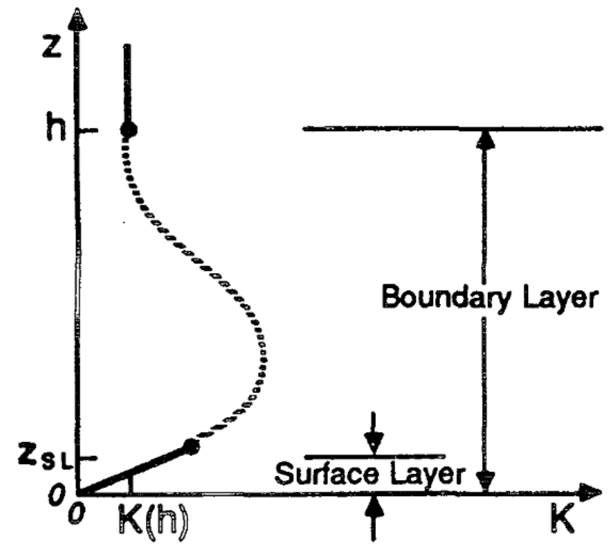


FIG. 1. Typical variation of eddy viscosity K with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

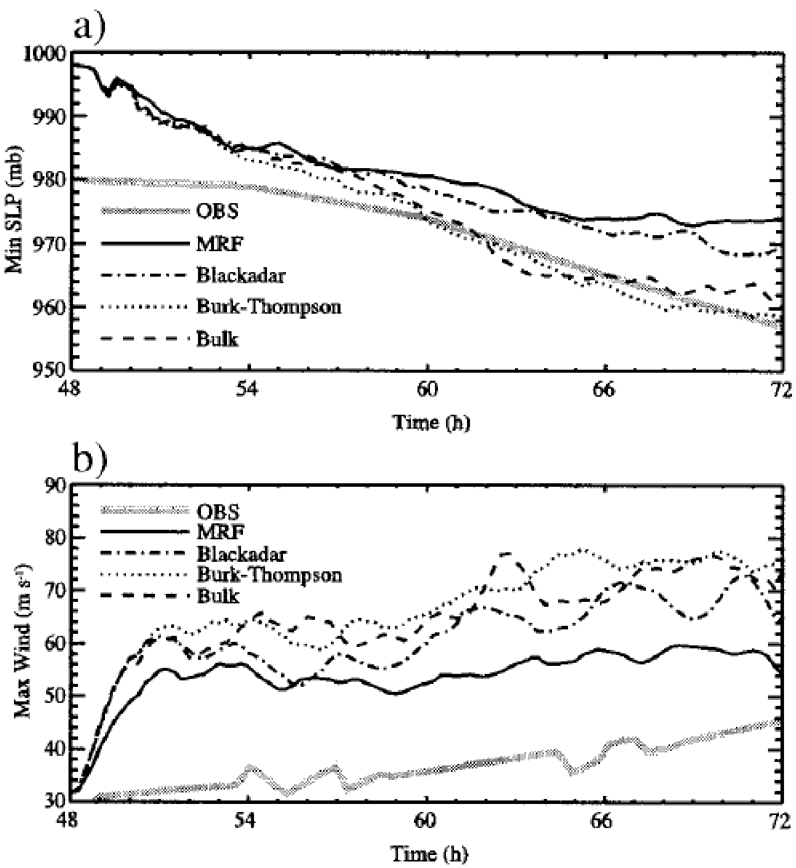
First, the depth of the boundary layer is estimated based on the profile of θ_v

Then a profile of vertical diffussivity 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 $-\overline{w'u'}$

Braun and Tao 1998-1999 (2000), using MM5 version 2.5:



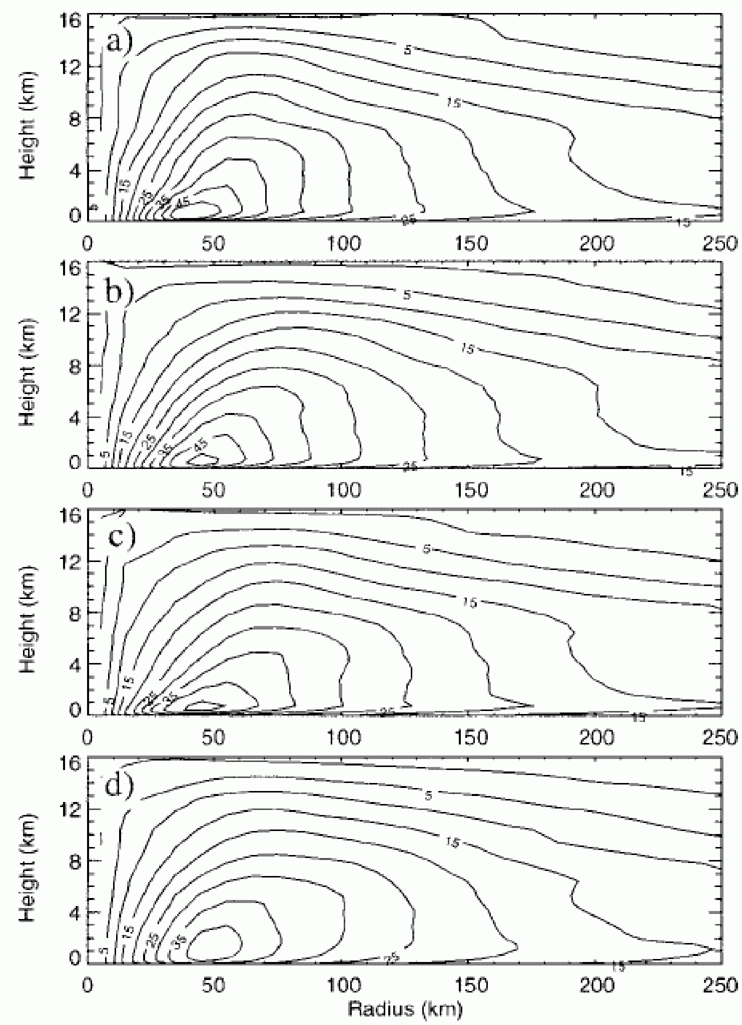


FIG. 9. Same as in Fig. 8 but for tangential velocity. The contour interval is 5 m s^{-1}.

Burk-Thompson

Blackadar

Bulk

MRF

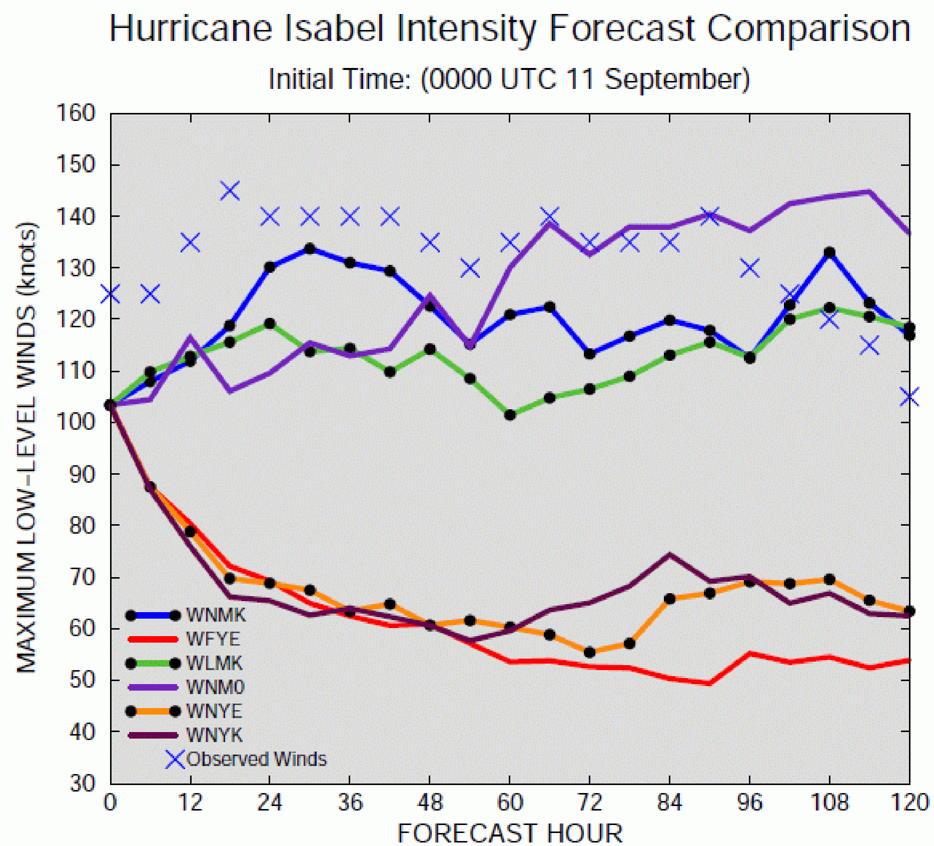
•Conclusions:

* Burk-Thompson (MYJ-like), Blackadar, and "Bulk" schemes similar

* MRF scheme: Too diffusive, makes hurricane too weak

Dave Nolan and GFDL friends: 2002-2004, WRF version 1.3

Impact of Various Physics Parameterizations, 1/6 deg:



MRF runs

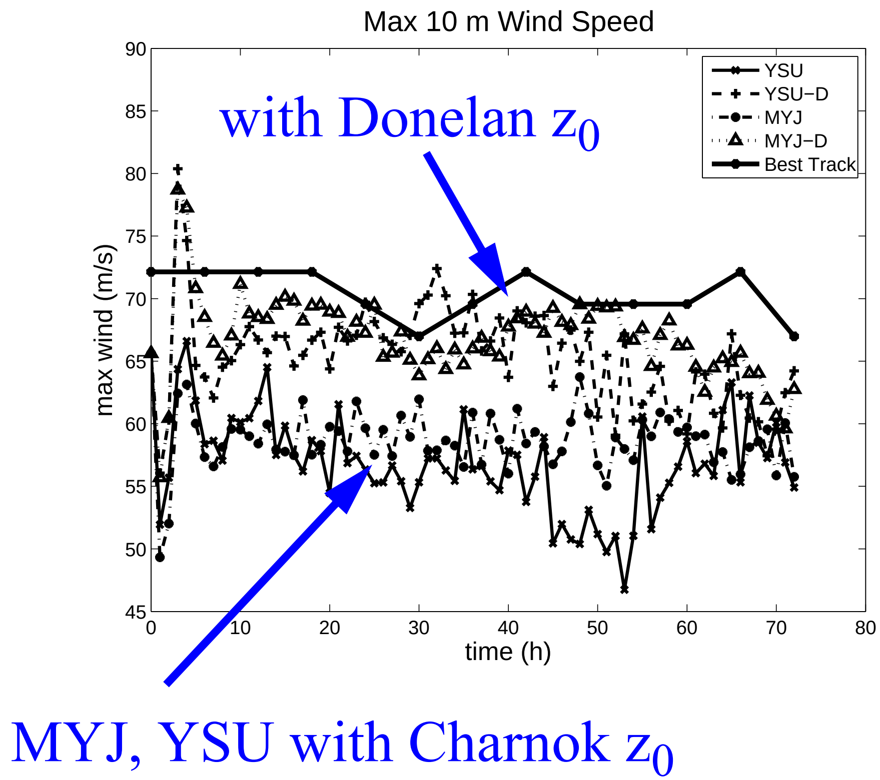
MYJ runs

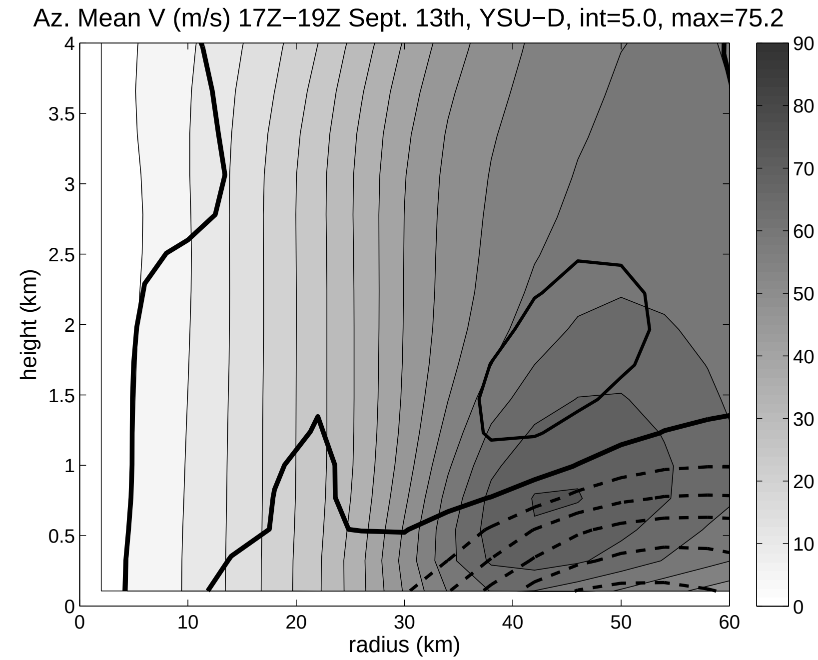
• Curves above are labelled as 'W-Microphyics-PBL-Cumulus', where:

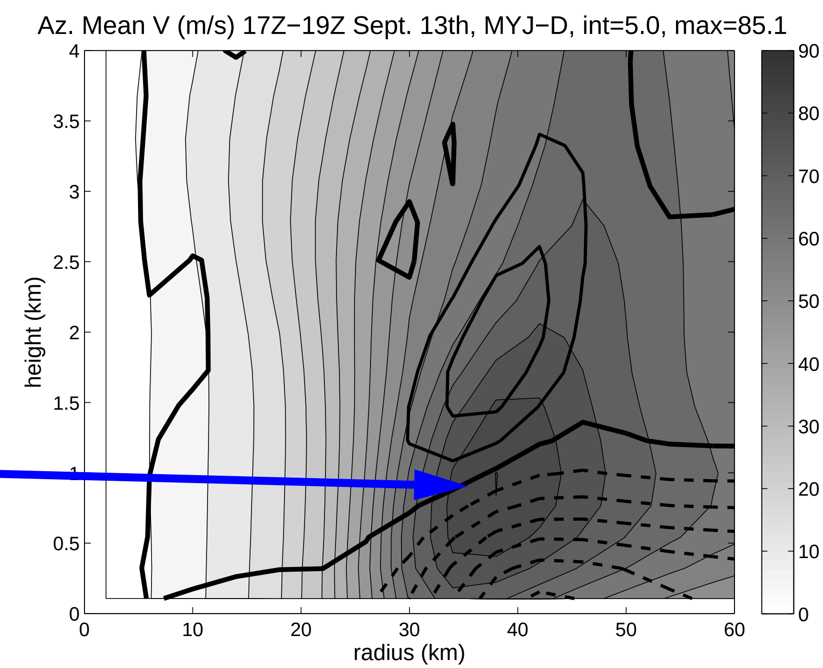
Microphysics:	N = NCEP 5-Class	L = Lin et. al. scheme	F = Ferrier (ETA)
Boundary layer:	M = MRF scheme	Y = Mellor-Yamada-Janjic (ETA)	
Cumulus:	K = Kain-Fritsch	E = ETA Kain-Fritsch	0 = None.

• Conclusion: MRF scheme works much better now...MYJ is terrible.

Dave Nolan, Jun Zhang, Dan Stern, 2007-2009 (2009): WRF 2.2.1







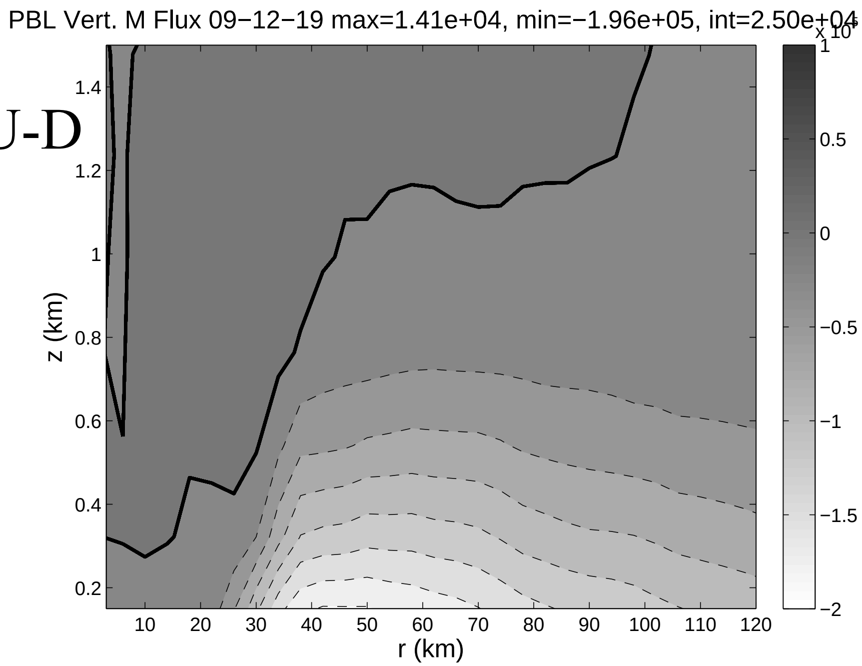
* MYJ and YSU now quite similar for "intensity"

* Compared to OBS (not shown), MYJ produces excessive radial inflow and over-intense super-gradient jet

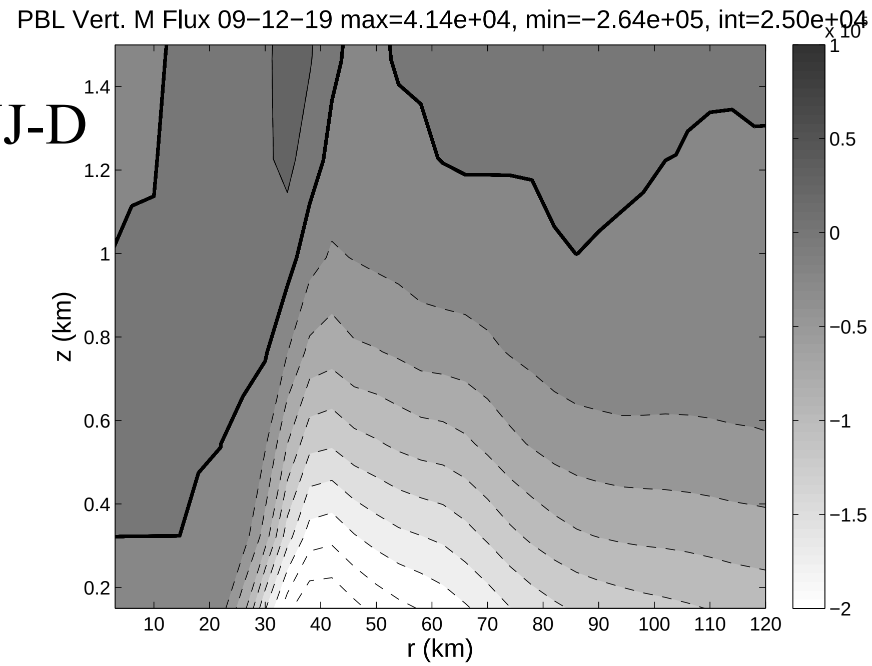
- Why did the MYJ-D boundary layer have a stronger secondary circulation, even though it has exactly the same C_d as YSU-D?

Vertical flux of angular momentum caused by the PBL schemes:

YSU-D



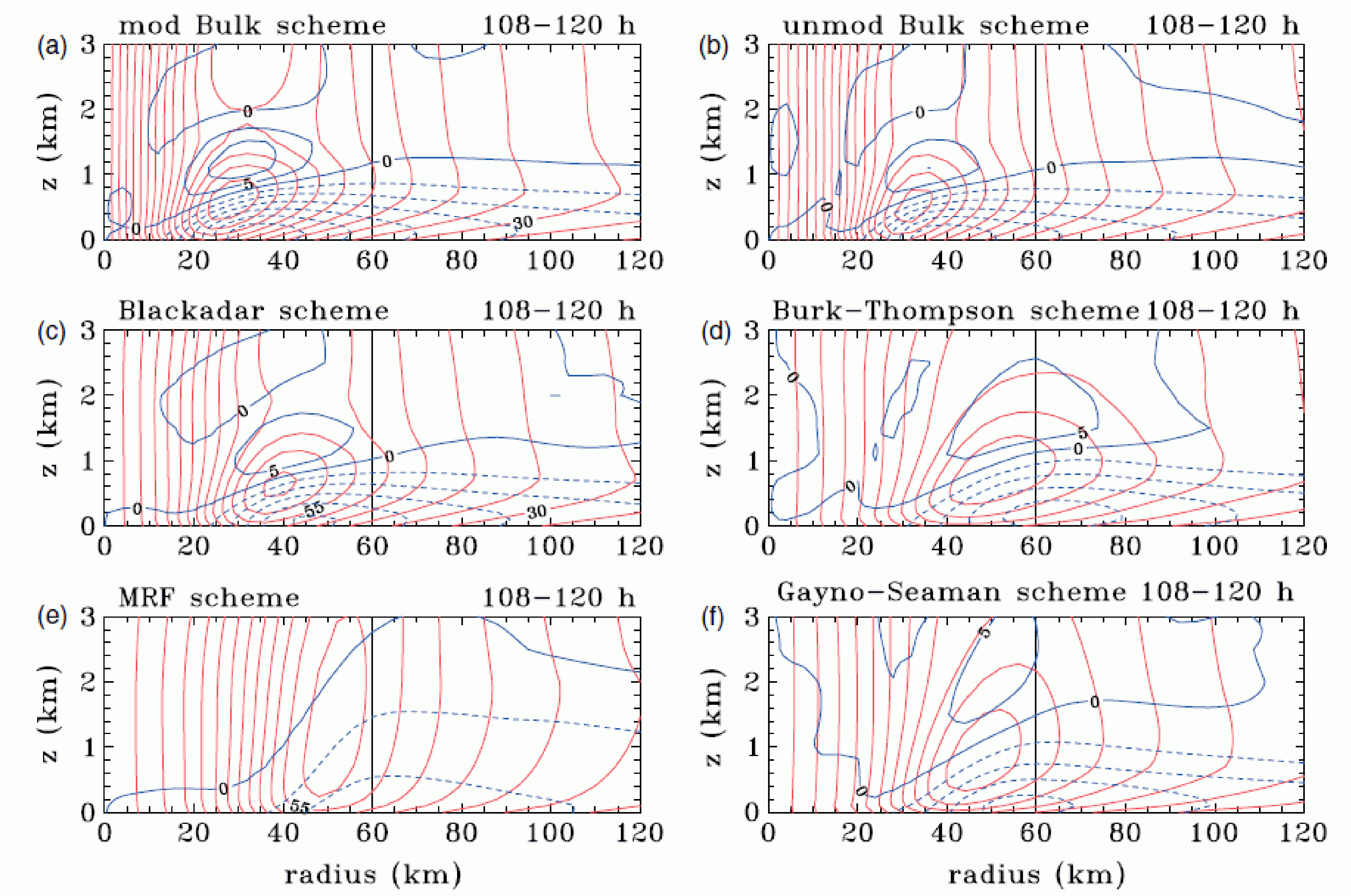
MYJ-D



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. Why?

- The MYJ scheme, *in WRF, does not advect TKE horizontally.* Large TKE "accumulates" under the eyewall where shear production is largest.

Roger Smith and Gerald Thomsen 2008-2009 (2010): MM5 version 3.6



•Results: Bulk and Blackadar poor; BT + GS (MYJ-type) good; MRF bad (again)

Very similar to Braun and Tao. Why? ...they used a 6 year old version of MM5.

Jeff Kepert, 2010-2011 (2011): Kepert+Wang 3D BL model

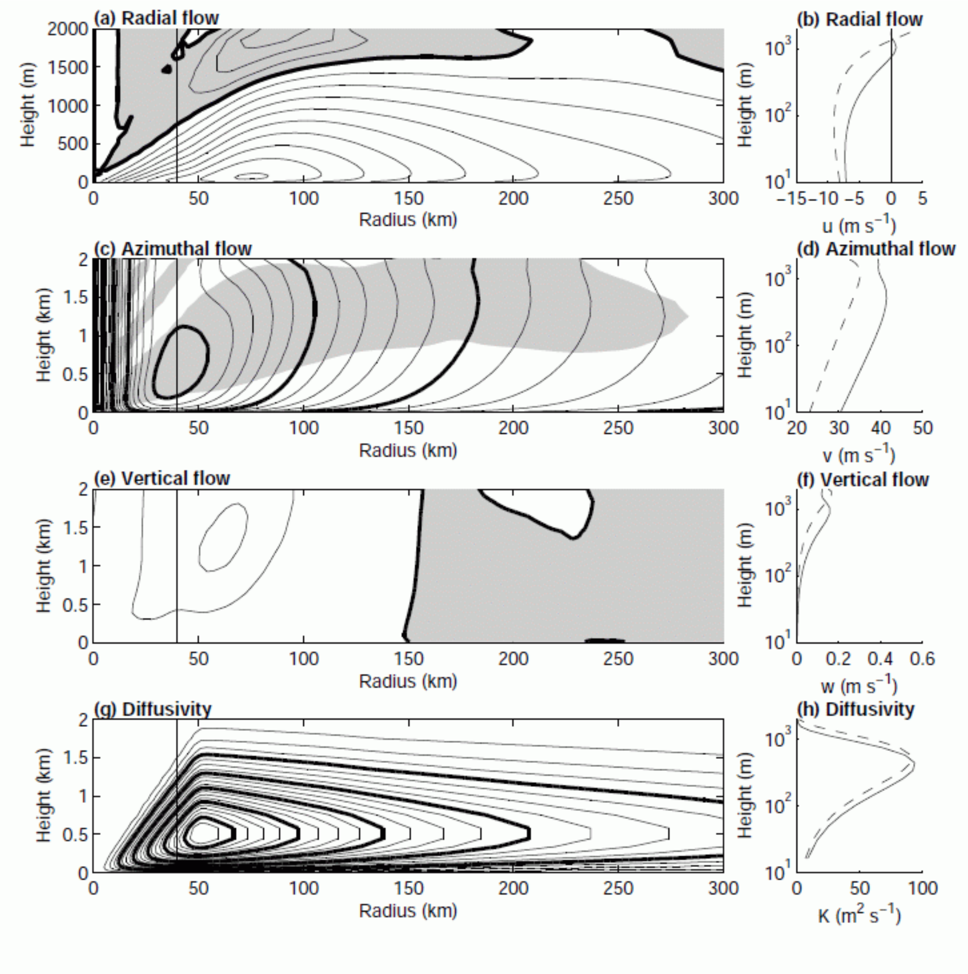


FIG. 4. As for Fig. 1, except for the nonlocal KPP closure with h varying with radius and $p = 4$.

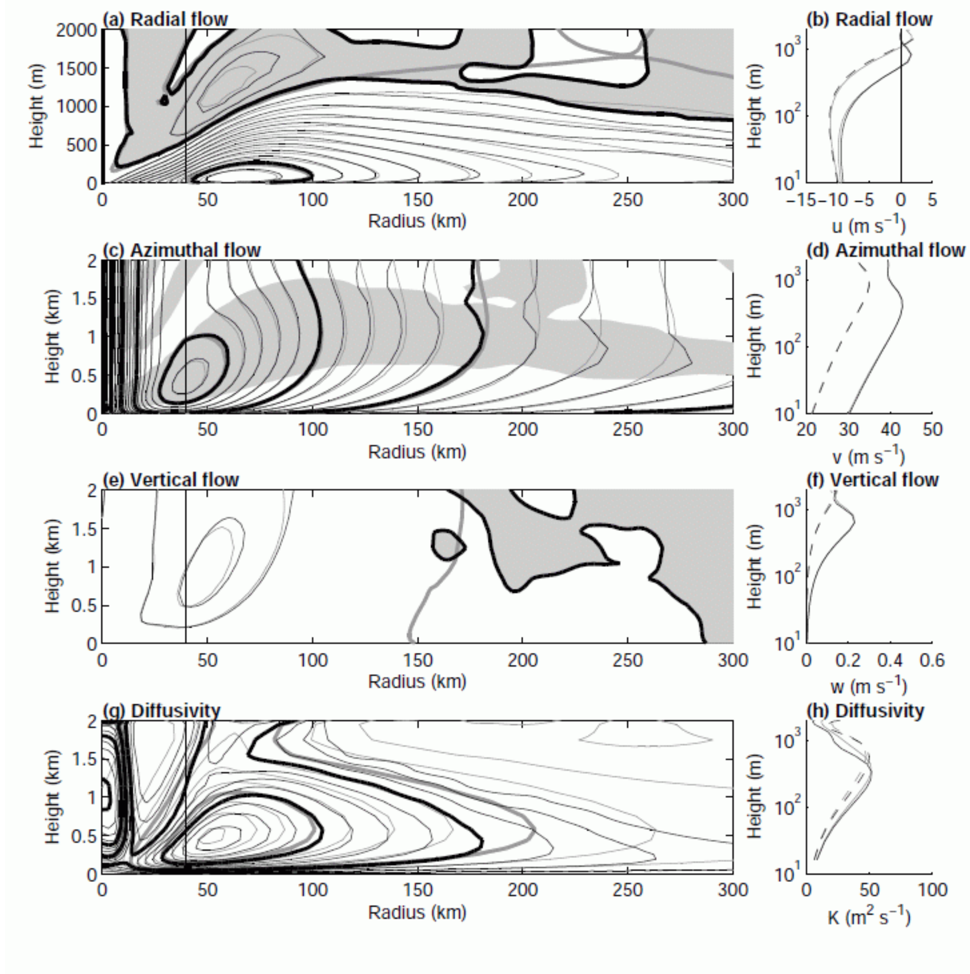


FIG. 5. As for Fig. 1, except for the Mellor-Yamada level 2.25 scheme. The grey contours and curves are for the neutral version of this scheme.

- Jeff's conclusions: Old schemes ("Bulk," "Blackadar,") pretty bad, unphysical

  KPP/MRF/YSU schemes pretty good; PBL depth must be tuned

  MYJ-type schemes probably the best

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* The question remains: KPP or MYJ?

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* Validation against composites and case studies from observations are now possible. *This is where to start, not what to do last.*

* The question remains: KPP or MYJ? Probably, MYJ. Because, I am guessing that...

  1) Good MYJ implementation will beat YSU;
  2) MYJ has less sensitivity to resolution changes;
  3) MYJ will be better over land as it can handle upstream roughness.