Evaluation of planetary boundary layer (PBL) parameterizations using large-eddy simulations (LES) in a broad range of conditions

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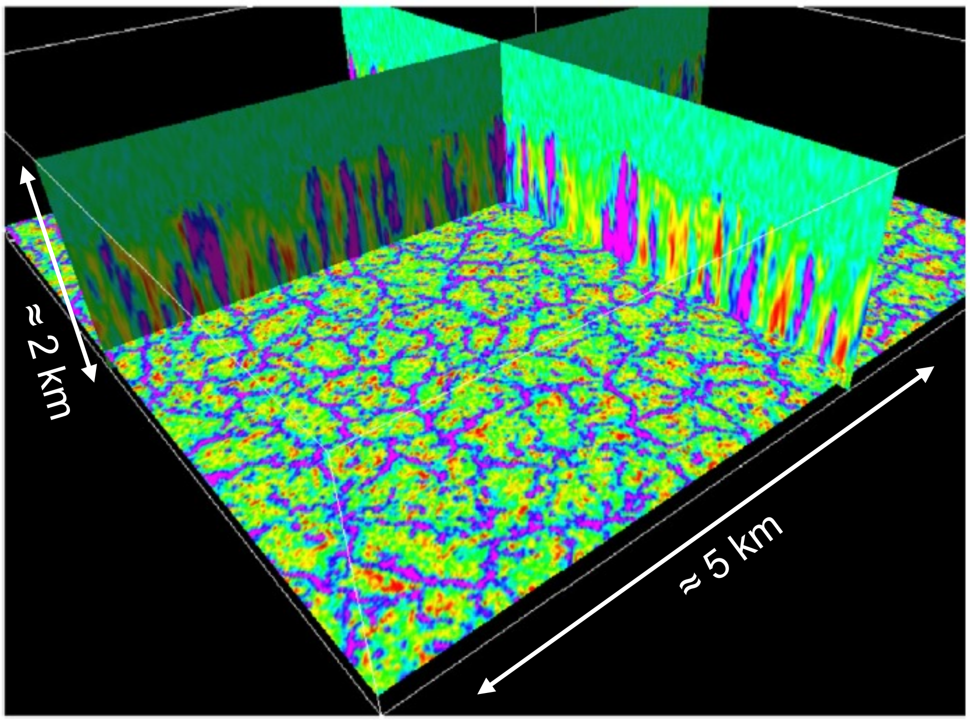
Ways to simulate the PBL (1/2)

Large-Eddy Simulation (LES)

- Integrate governing equations with eddy-resolving resolution
- Grid spacing < 100 m, time step < 1 s
- Computationally expensive!

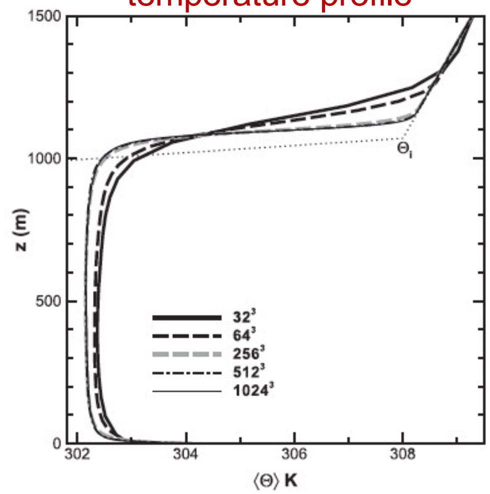
Instantaneous view



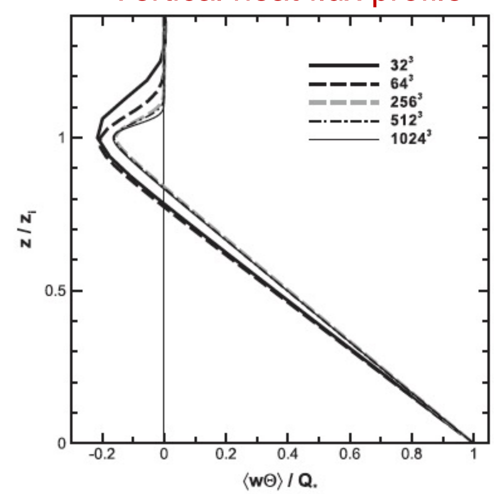
Moeng and Sullivan, 2015, Encyclopedia of Atmos. Sci.

diagnostics

Domain-average potential temperature profile



Vertical heat flux profile



Sullivan and Patton (2011)

Ways to simulate the PBL (2/2)

PBL Parameterization

- Integrate a simplified set of equations to represent effects of turbulence

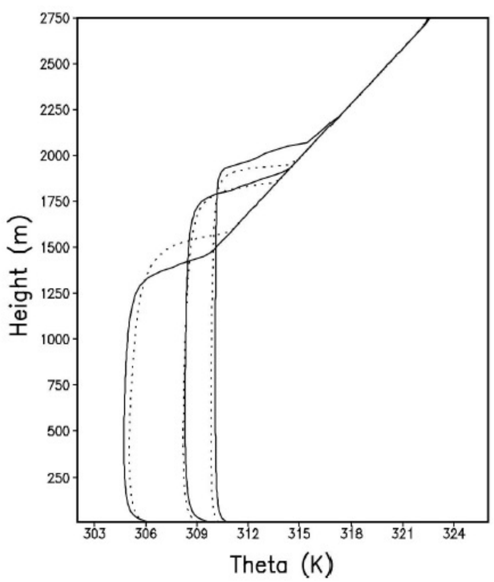
$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left[K_c\left(\frac{\partial C}{\partial z} - \gamma_c\right)\right]$$

MRF (Hong and Pan 1996)

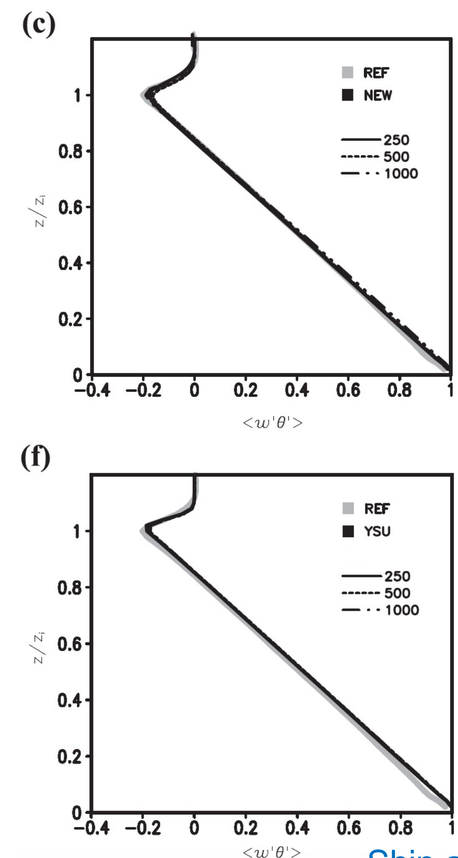
$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left[K_c\left(\frac{\partial C}{\partial z} - \gamma_c\right) - \overline{(w'c')_h}\left(\frac{z}{h}\right)^3\right]$$

YSU (Hong et al. 2006)

- Model grid spacing: >1 km
- Used in NWP/Climate models



Hong et al. (2006)

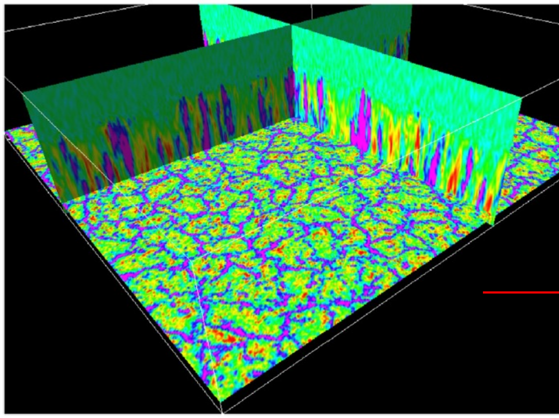


Shin and Hong (2015)

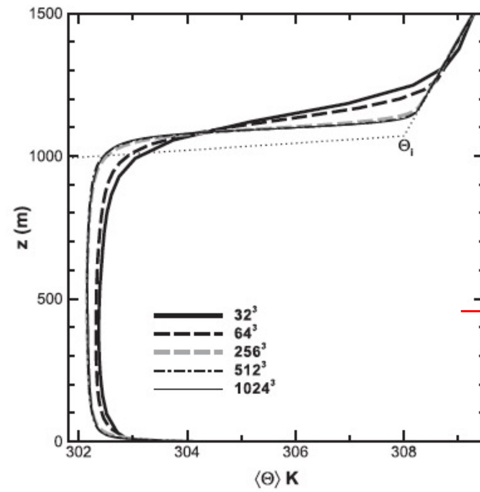
Use LES to evaluate PBL

For this study:

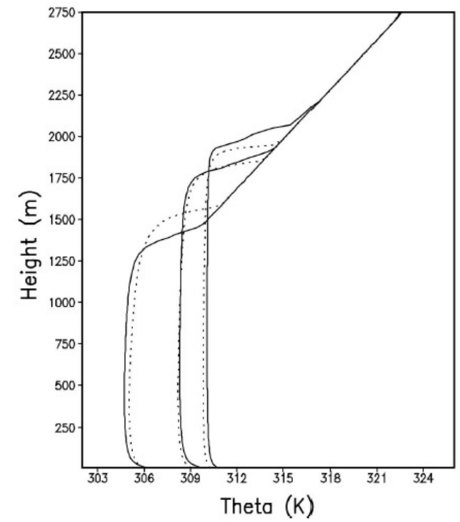
1. Run LES



2. Calculate diagnostics



3. Compare with PBL schemes



- Not a new idea…
  - There's a long history of evaluating PBL schemes with LES
  - e.g., Deardorff (1972), Ayotte et al. (1996)

- What's new here?
  - Study a broad range of conditions (unstable, stable, cumulus, stratocumulus, more?)
  - Higher-resolution LES

PBL Evaluation Project

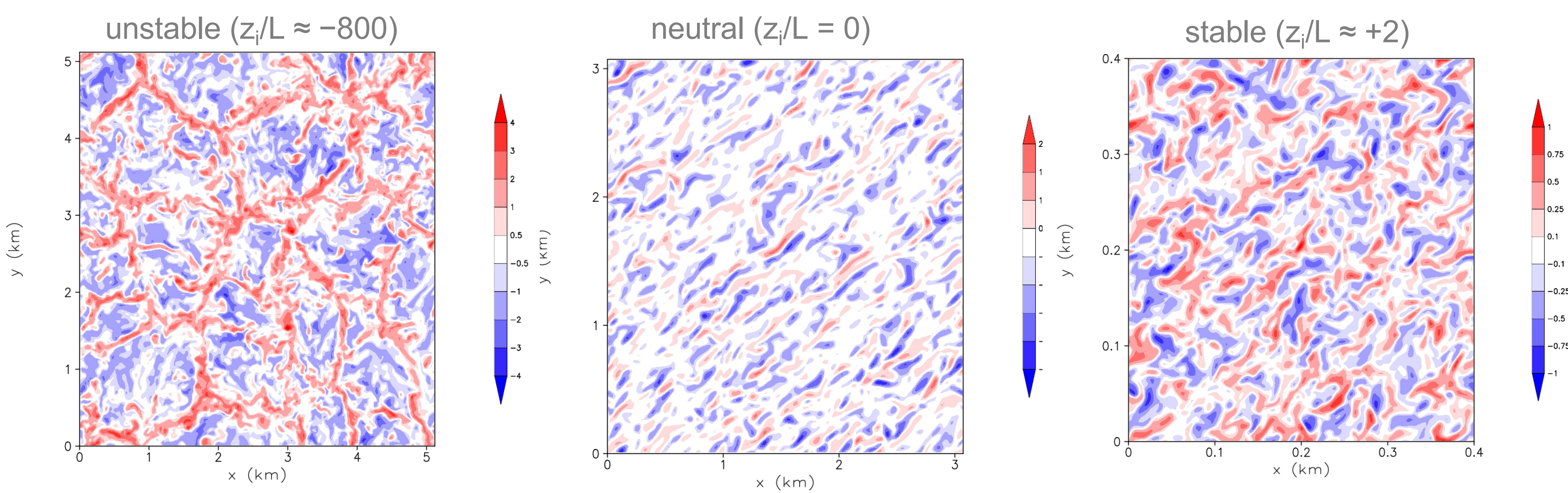
- A new project
  - Started approx. November 2020
  - Motivated by several projects at NCAR’s MMM Laboratory

- This is a work in progress!
  - Methodology is subject to change
  - Conclusions are preliminary
  - Input and feedback are welcome

Cases

- 3 cases without moisture/clouds:
  - Unstable (Sullivan and Patton 2011): $\Delta x = 10$ m
  - Neutral/sheared (Moeng and Sullivan 1994): $\Delta x = 16$ m
  - Stable (Beare et al. 2006): $\Delta x = 2$ m

w (m/s) at ≈ $z_i/10$

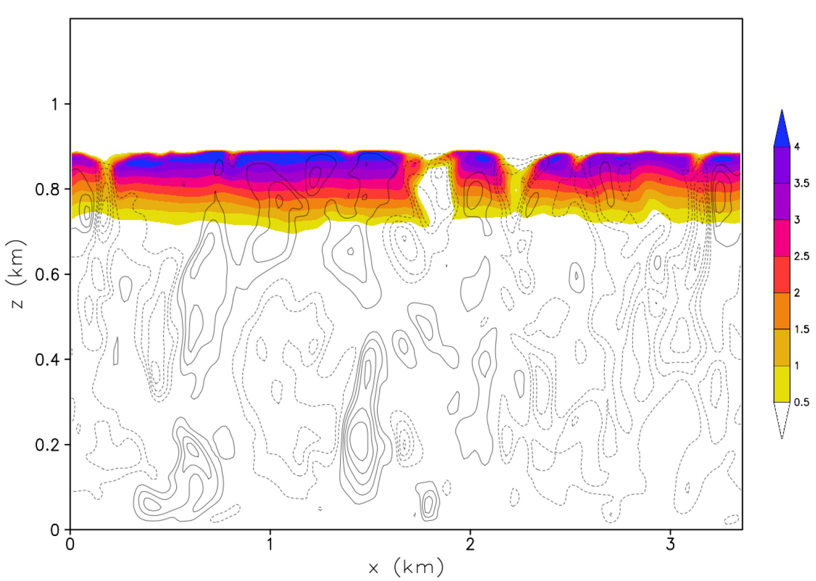


Cases

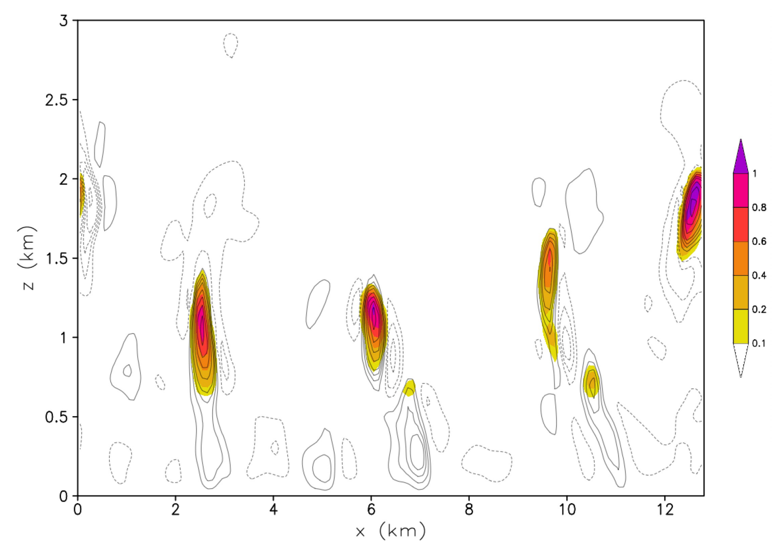
- 3 cases with clouds:
  - Oceanic stratocumulus (DYCOMS; Stevens et al. 2005): Δx = 17.5 m
  - Oceanic precipitating shallow cumulus (RICO; vanZanten et al. 2011): Δx = 50 m
  - Continental non-precipitating shallow cumulus (ARM-SGP; Brown et al. 2002): Δx = 33 m

Vertical cross sections (shading = q_c, contours = w)

Stratocumulus (DYCOMS)



Shallow cumulus (RICO)



Methodology: LES

- Run CM1 (Cloud Model 1) in “LES mode”
  - Why CM1?
    - More “test cases” than WRF (simplified physics, specified surface conditions, etc)
    - Simpler coordinate system (z instead of p)
    - Diagnostic output during model run (eg, fluxes, variances, TKE budget terms, etc)
  - All cases: roughly 200 x 200 x 200 gridpoints
    - (usually 2x resolution of original studies)
  - Approximately 5 km x 5 km x 3 km domain
  - SGS model: Deardorff (1980) TKE
    - (no PBL parameterization)

Methodology: Single-Column Model

- Goal: Evaluate PBL parameterizations from WRF (and beyond):
  - MYJ (WRFv4.2)
  - YSU (WRFv4.2)
  - Shin-Hong (WRFv4.2)
  - MYNN (*multiple versions, including WRFv4.2, MPASv6.1)
  - GFS-EDMF (WRFv4.2)
  - GFS-TKE-EDMF (CCPP, Dec 2020)
  - CLUBB (CESM)

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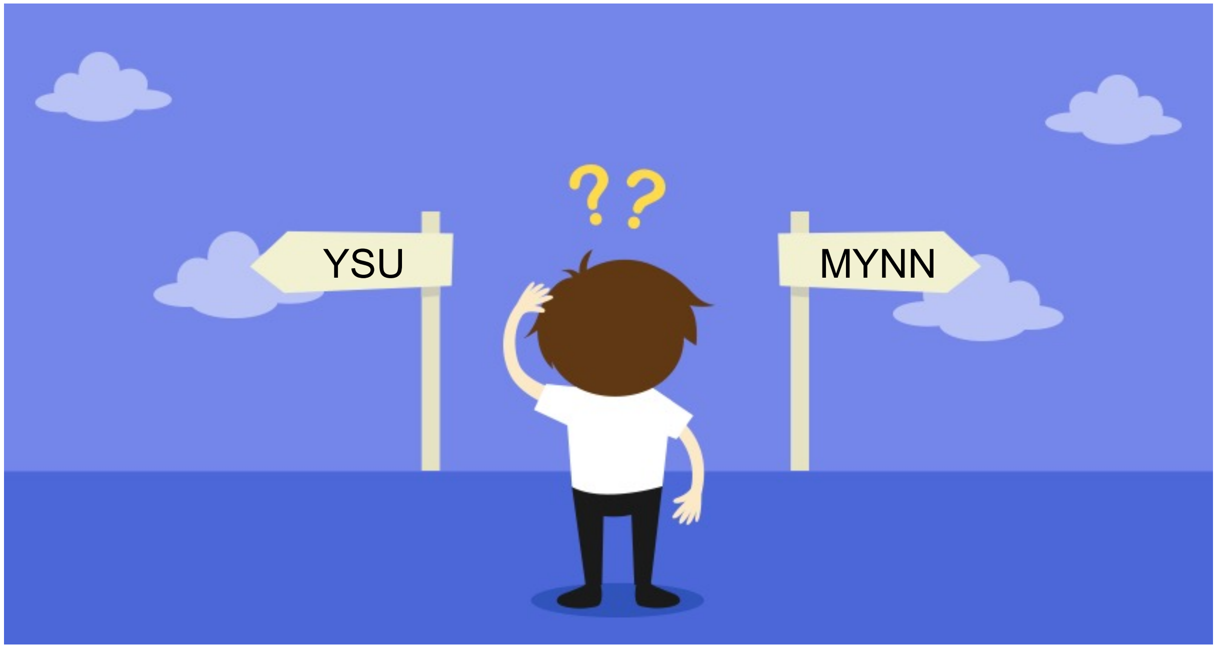
  - CLUBB (CESM)

- Methodology: Run CM1 in "Single-Column Model (SCM) mode"
  - Why CM1?
    - More "test cases" than WRF
    - Diagnostic output during model run (directly from PBL codes)
  - 1 x 1 x nk gridpoints
    - High res: nk ≈ 200 (same as LES)
    - Low res: nk ≈ 20
  - With PBL parameterization (without Deardorff SGS model)
  - Δx = 20 km (for scale-aware codes)

Are you going to tell me which PBL Parameterization Should I Use?

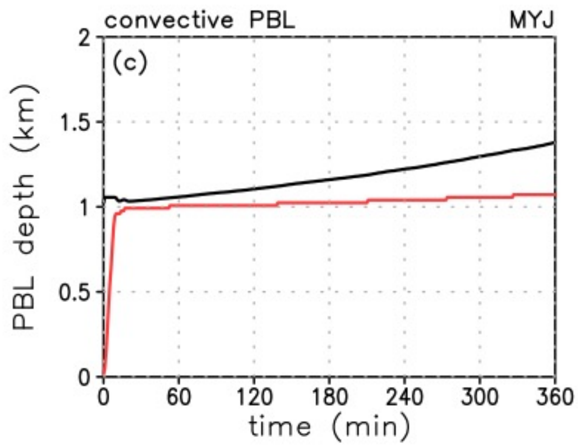


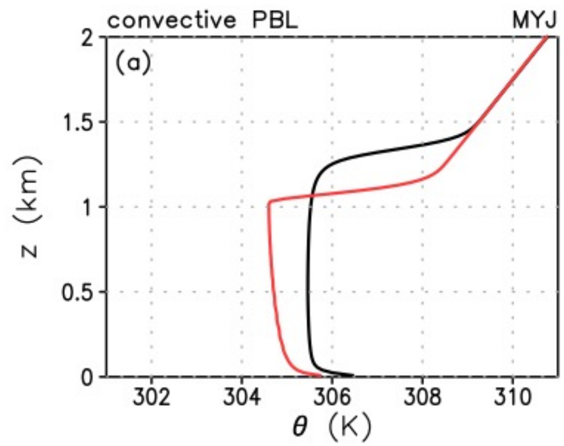
- No: none of these PBL schemes stand out as “best”

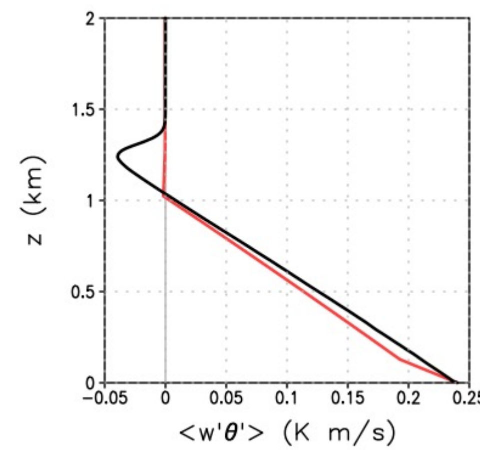
- This work points out some simple improvements that could be made to PBL schemes in WRF & MPAS

MYJ: convective PBL

Black: LES Red: MYJ





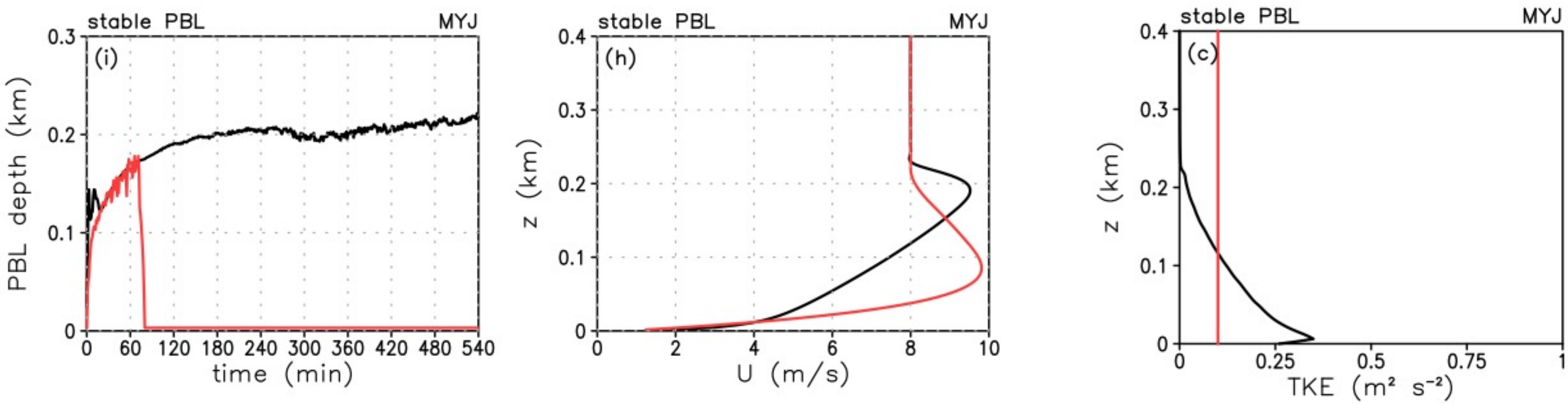


- No countergradient/entrainment-flux/mass-flux component; thus, essentially no “top-down” diffusion

- With moisture: too water vapor in PBL

MYJ: stable PBL

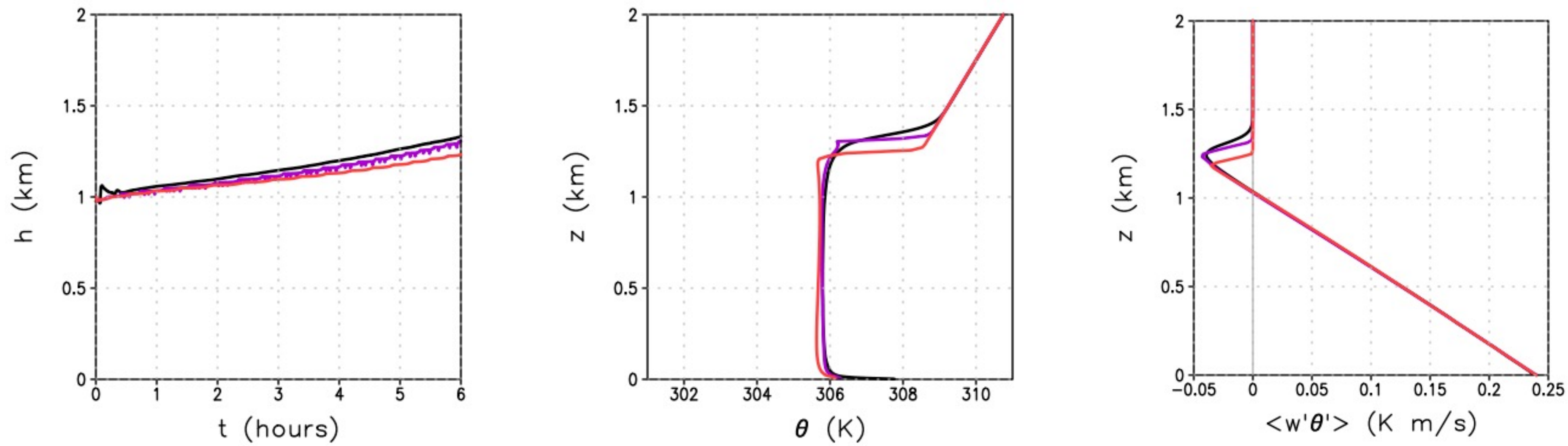
Black: LES Red: MYJ



- MYJ can be noisy/unstable at high resolution (not shown)

YSU and Shin-Hong: Convective PBL

Black: LES Red: MYJ Purple: Shin-Hong



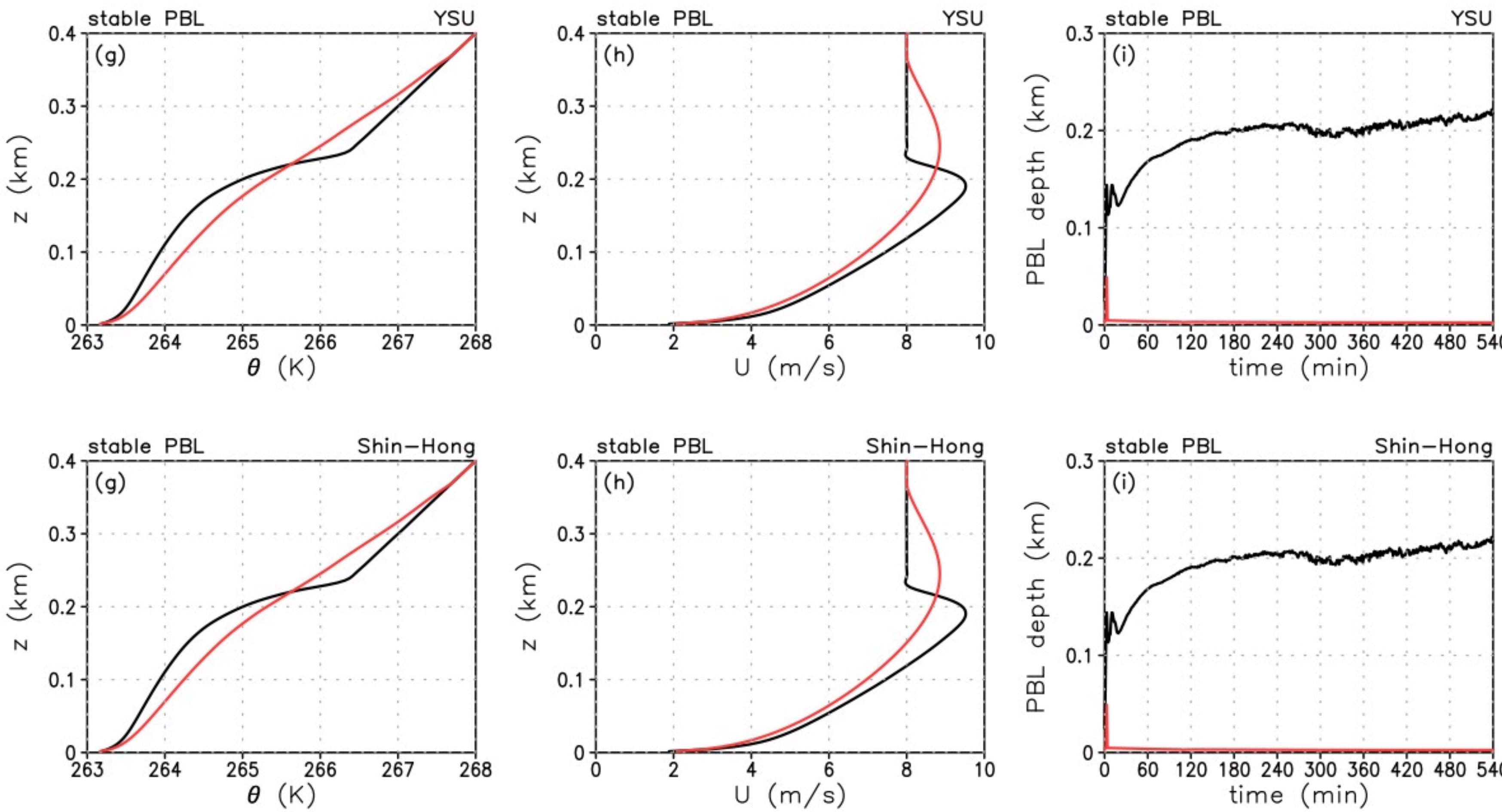
- YSU and Shin-Hong rock the daytime boundary layer!

YSU and Shin-Hong: Stable PBL

Black: LES   Red: PBL

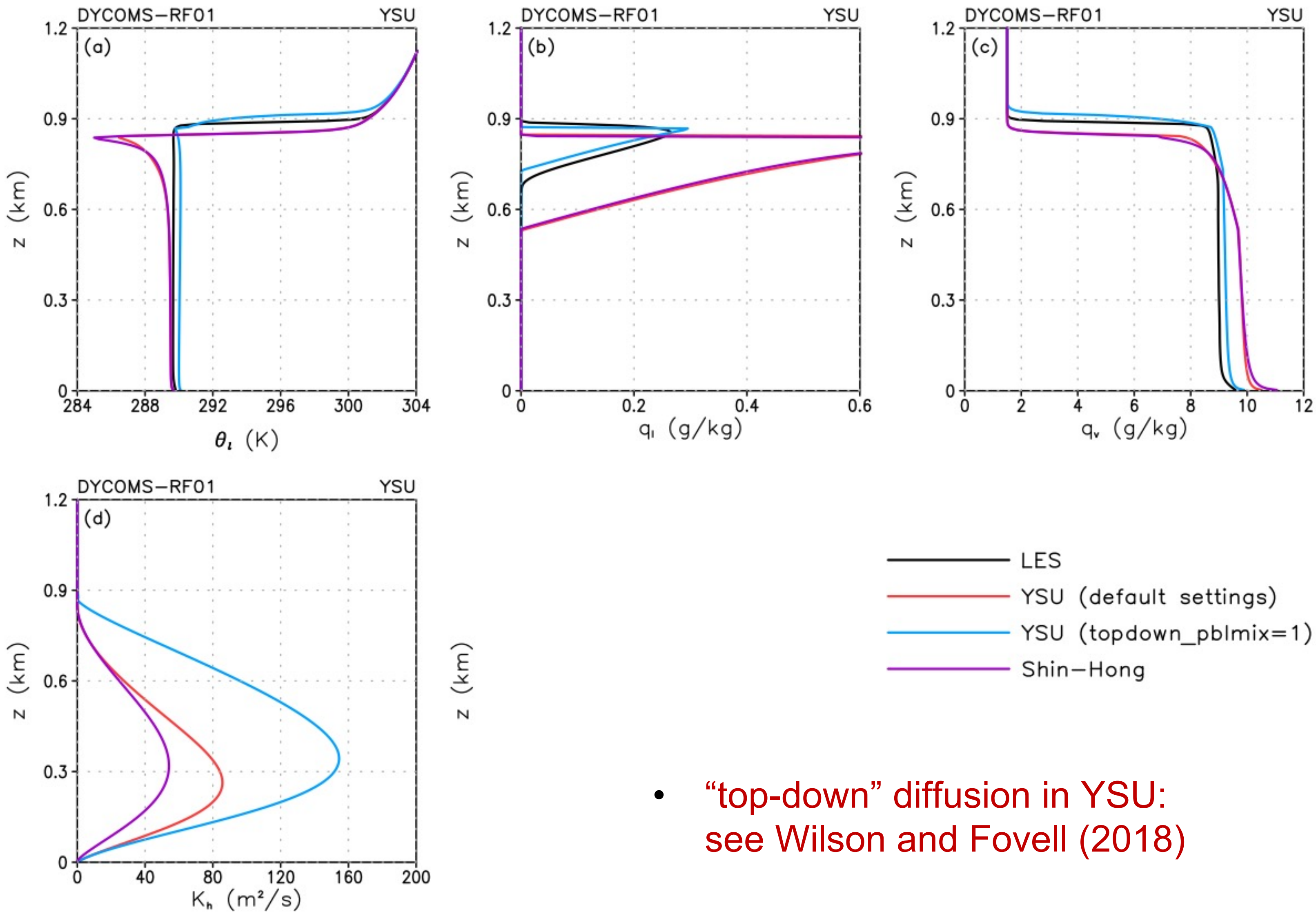
YSU:

Shin-Hong:



- YSU and Shin-Hong struggle with stable boundary layer
- In stable conditions, both using mixing-length model with l = 30 m
- Diagnosis of PBL depth essentially neglects shear (D. Nolan, personal comm.)

YSU and Shin-Hong: Radiatively-driven Stratocumulus



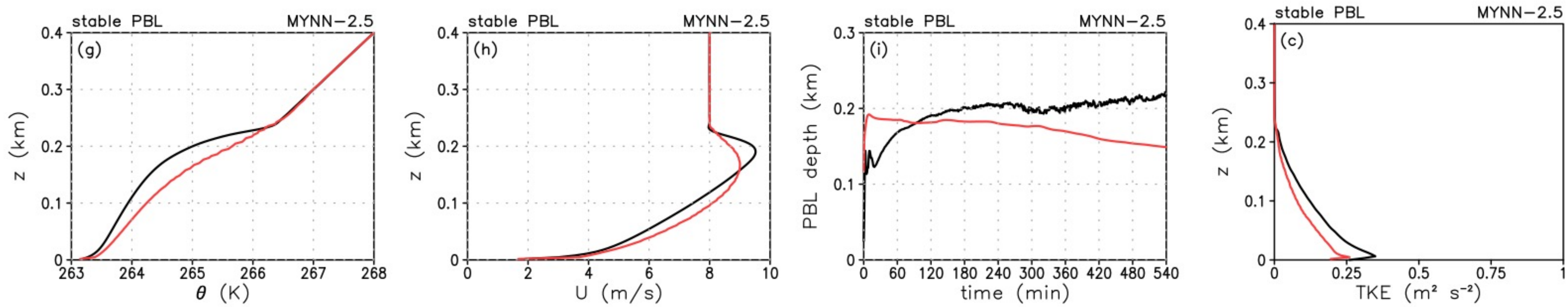
- “top-down” diffusion in YSU: see Wilson and Fovell (2018)

- Suggests that topdown_pblmix should be “on” by default (and should be added to Shin-Hong)

MYNN

- Results depend greatly on which version of the MYNN code is used (It's changed *a lot* over 10 years)
  - e.g., modified length scales
  - big change: addition of mass-flux scheme (EDMF) in WRFv3.8

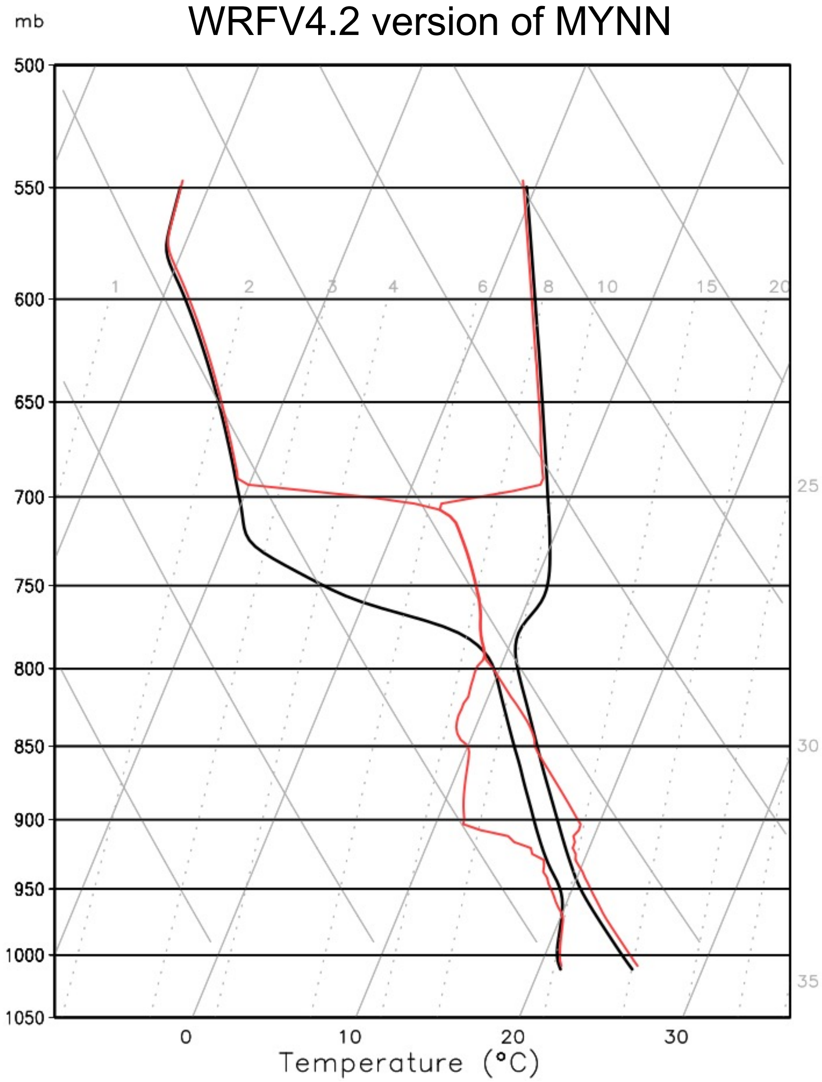
- Works well for stable PBL: (here, WRFv4.2 version of MYNN)



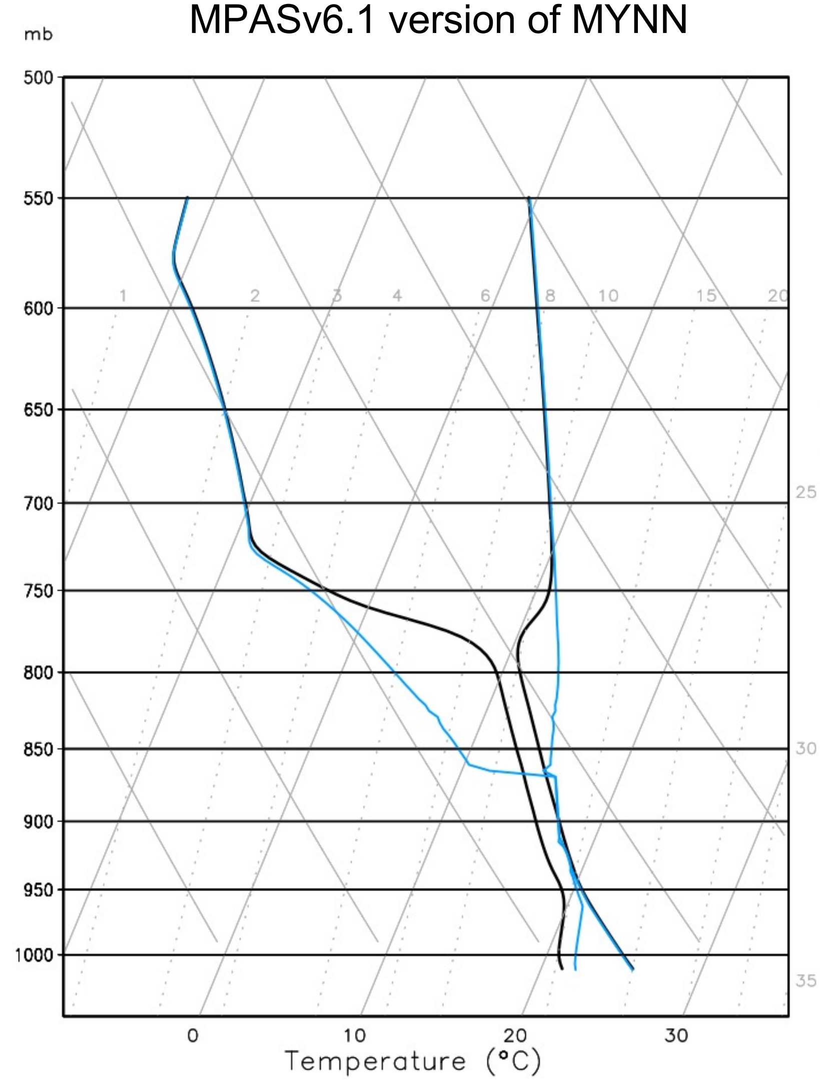
- Items for improvement:
  - Modifications near surface for high-wind conditions (e.g., hurricanes)
  - Noisy eddy diffusivity profiles
  - For high resolution (Δz < 100 m): mass-flux scheme remains "off"

RICO: precipitating cumulus over ocean

WRFV4.2 version of MYNN



MPASv6.1 version of MYNN



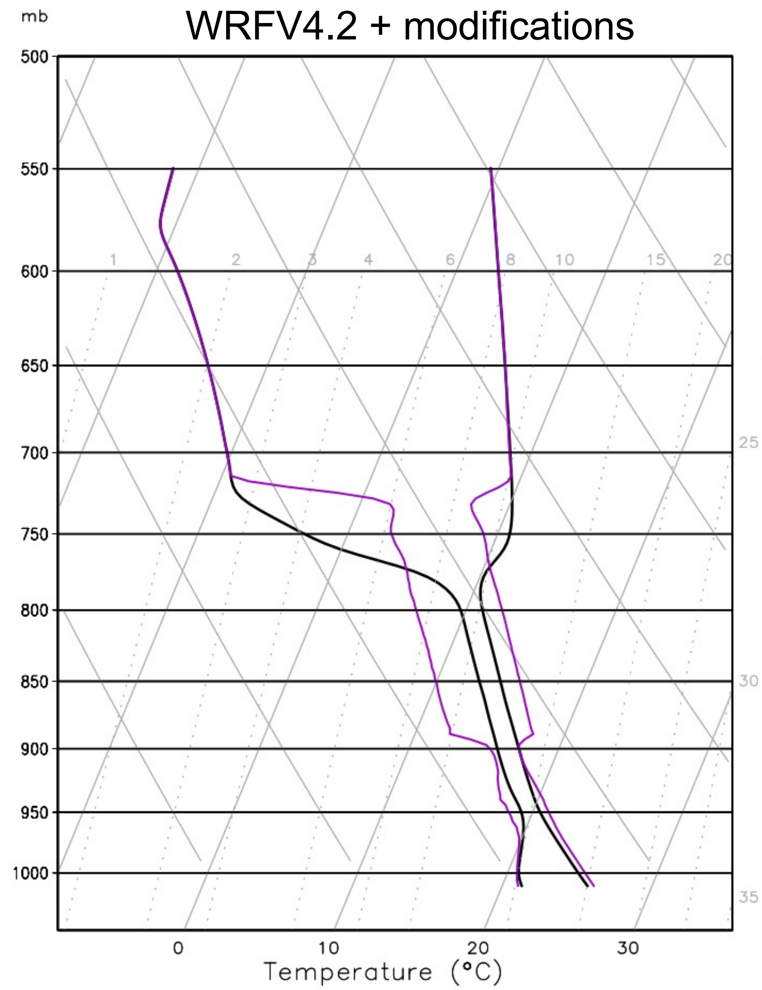
Black: LES
Red: MYNN (WRFv4.2)

Black: LES
Red: MYNN (MPASv6.1)

RICO: precipitating cumulus over ocean

Black: LES

Red: MYNN (WRFv4.2 + mods.)



- Re-instituted a limit on the Prandtl number in stable clouds (this was removed in WRFv4.0 version of MYNN)
- Modified criterion for activation of mass-flux code to allow scheme to work in slightly unstable conditions (as opposed to only very unstable conditions)
- Some other minor stuff …

Next Steps

- Possibly: run high-resolution LES “benchmark” simulations
  – Domains with (at least) 1000 x 1000 x 1000 gridpoints
  – A project for new NCAR supercomputer (derecho)?
- Implement changes into WRF & MPAS
  – But, will need to evaluate on real-data cases first
- Other PBL schemes?
  – EEPS (energy-dissipation) scheme
  – CLUBB (CESM … so, SIMA, EarthWorks?)
- Collaborations?
  – email: gbryan@ucar.edu