Parameterization of the Stable ABL in climate models: understanding the effects of increasing stability and model resolution

[1]**Jing Huang**, [1]Elie Bou-Zeid and [2]Jean-Christophe Golaz

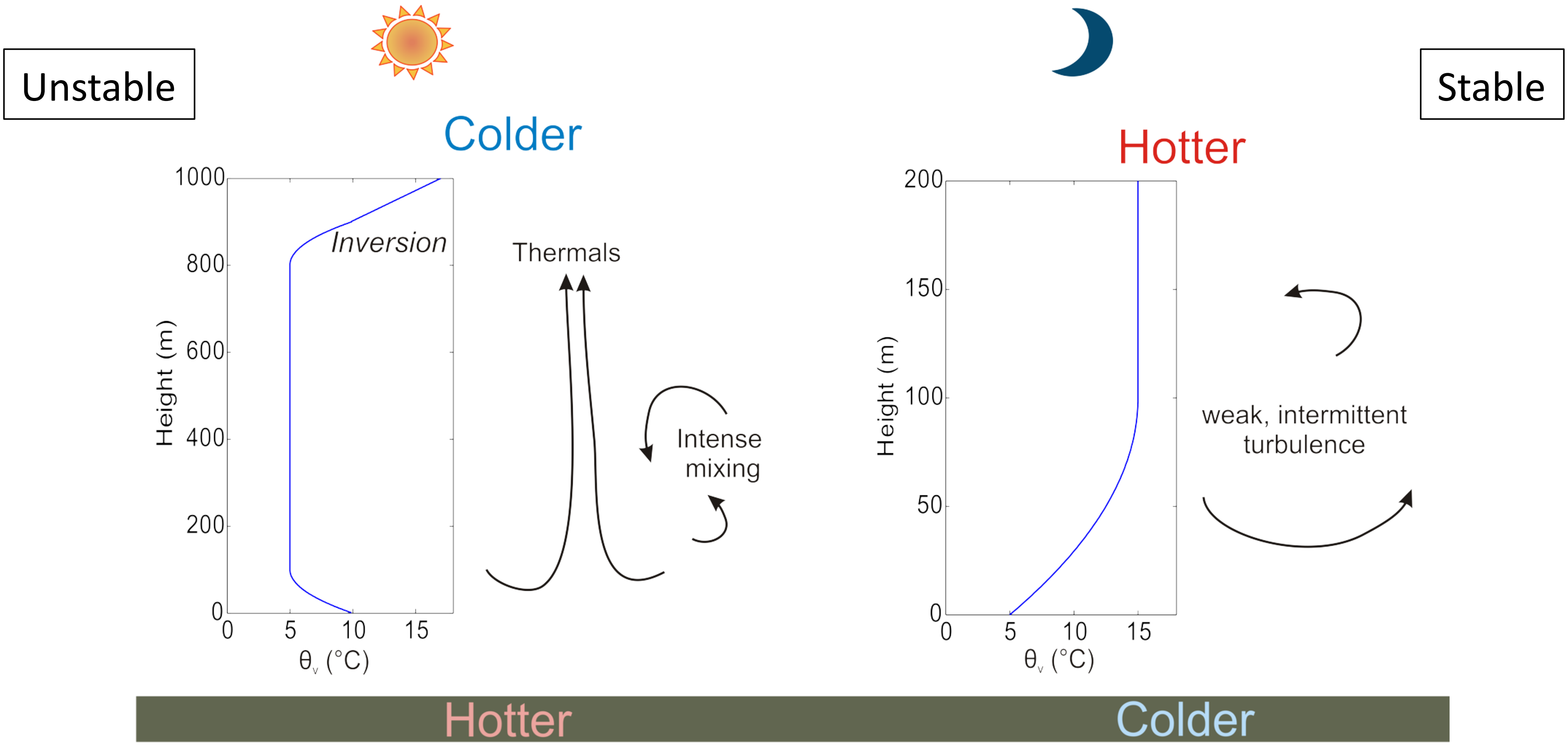
[1]Department of Civil and Environmental Engineering, Princeton University

[2]NOAA/Geophysical Fluid Dynamics Laboratory

Princeton University

civil and environmental engineering

The Stable Atmospheric Boundary Layer

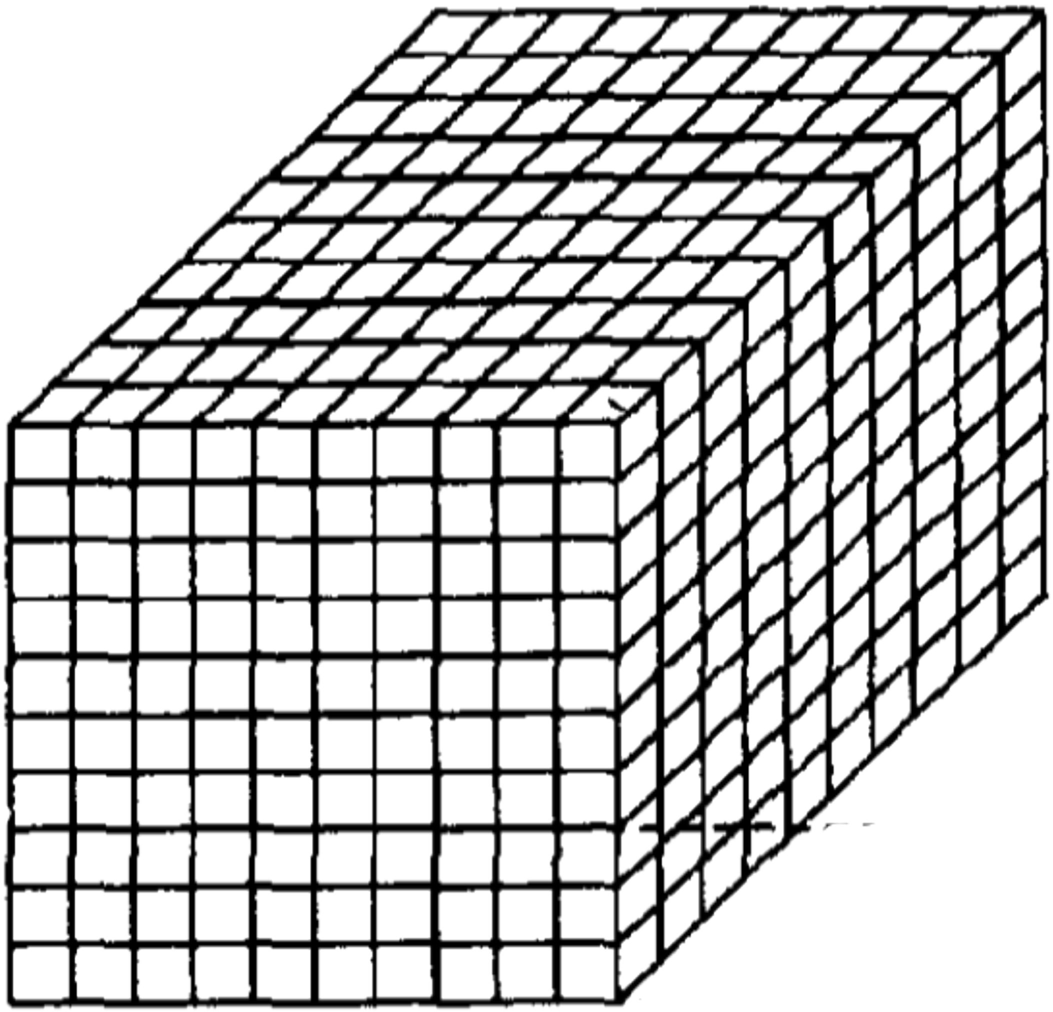


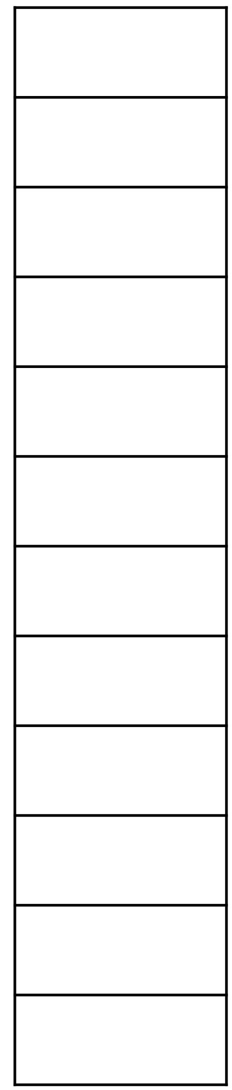
$$- \quad \Longleftarrow \quad Ri = \frac{\text{Buoyancy}}{\text{Shear}} \quad \Longrightarrow \quad +$$

Why focus on the stable boundary layer?

- A more difficult problem than the convective ABL
  - Smaller eddy sizes
  - Weaker or intermittent turbulence
  - Waves and other instabilities
  - Might need more computational resources to simulate
- Crucial to atmospheric models
  - Nocturnal/Polar boundary layers
  - Weather forecast (wind speed, temperature, humidity, etc.)
  - Near-surface meteorology and surface conditions
  - Estimation of fluxes to the free atmosphere

Large-eddy simulation (LES) vs Single-column model (SCM)





GFDL
Atmospheric
Model 2.1

Reynolds-Averaged N-S Equations solved in the SCM

- 1-D
- Horizontally homogeneous
- Dry boundary layer
- Without subsidence
- Driven only by a geostrophic wind (U_g, V_g)
- 6 variables governed by only 3 equations – parameterization is needed

$$\frac{\partial U}{\partial t} = f\left(V - V_g\right) - \frac{\partial \langle uw \rangle}{\partial z},$$

$$\frac{\partial V}{\partial t} = f\left(U_g - U\right) - \frac{\partial \langle vw \rangle}{\partial z},$$

$$\frac{\partial \Theta}{\partial t} = -\frac{\partial \langle w\theta \rangle}{\partial z},$$

The gradient-diffusion hypothesis

$$\langle uw \rangle = -K_m(z, Ri, \ldots)\frac{\partial U}{\partial z},$$

$$\langle vw \rangle = -K_m(z, Ri, \ldots)\frac{\partial V}{\partial z},$$

$$\langle w\theta \rangle = -K_h(z, Ri, \ldots)\frac{\partial \Theta}{\partial z},$$

$$\Pr = \frac{K_m}{K_h} = 1?$$

- Does this first-order closure work in stable conditions?
- If so, what is the *K*?

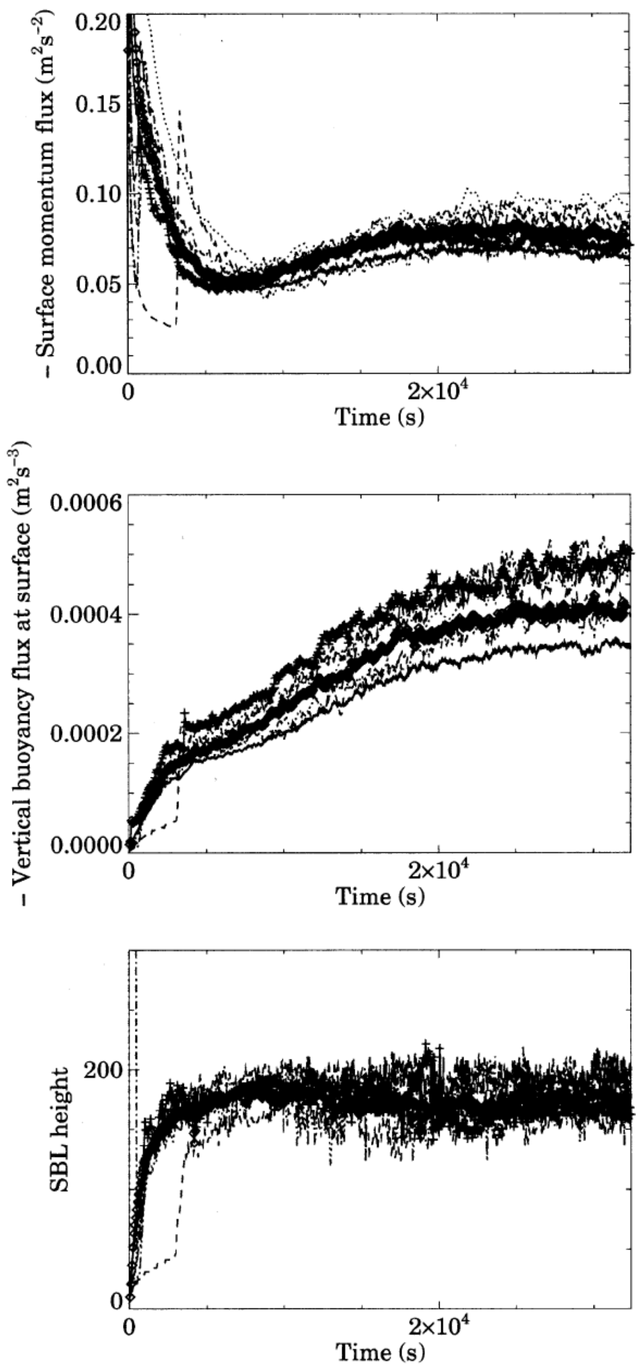
Description of the GABLS case

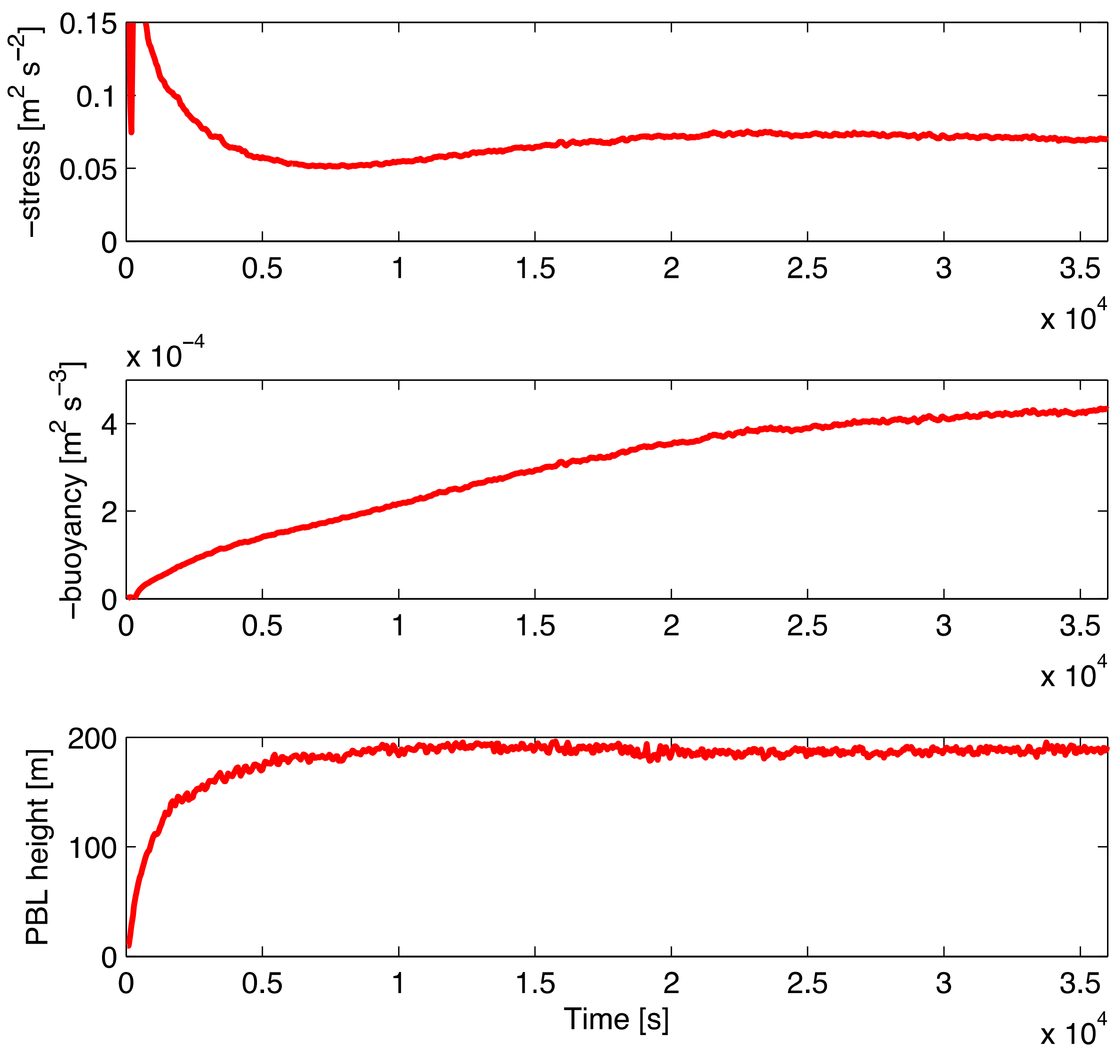
- Initial conditions
  - Geostrophic wind: U_g=8.0 m/s, V_g=0.0 m/s
  - Potential temperature: 265K up to 100m, then it increases at a rate of 0.01 K/m
- Boundary conditions
  - MOST wall model at surface and no stress and no penetration at the simulation domain top
  - Prescribed surface temperature with a constant decreasing rate of 0.25 K/h
  - Roughness length z_0 = 0.1 m
  - Temperature Roughness length z_{0h} = 0.01 m
- Higher stabilities
  - Increasing the surface cooling rate from 0.25K/h
  - **We also test much higher stabilities than GABLS, going up to 2.5K/h**

LES setup

- Simulation domain
  - 64X64X64 grid points
  - 800X800X400 m^3
- SGS model: Lagrangian scale-dependent dynamic (Bou-Zeid et al. *Phys. Fluids* 2005)
- Time step: Δt=0.05 s
- Total physical run time: 10 hours
- Statistics were obtained with the results of the last half hour

For validation and more details about the code, including new scalar SGS models, see poster A280 in the poster part of this session (15:30 – 17:00 today)





[Beare et al. 2006]

Local Richardson number similarity

$$K_m = l^2 \left| \frac{\partial U}{\partial z} \right| f_m(Ri),$$

$$\frac{1}{l} = \frac{1}{k(z+z_0)} + \frac{1}{\lambda_0},$$

Monin-Obukhov Similarity Theory (MOST):

$$f_m(Ri) = \begin{cases} (1-5Ri)^2 & 0 < Ri \le 0.2 \\ 0 & Ri > 0.2 \end{cases}$$

Jing's model #1:

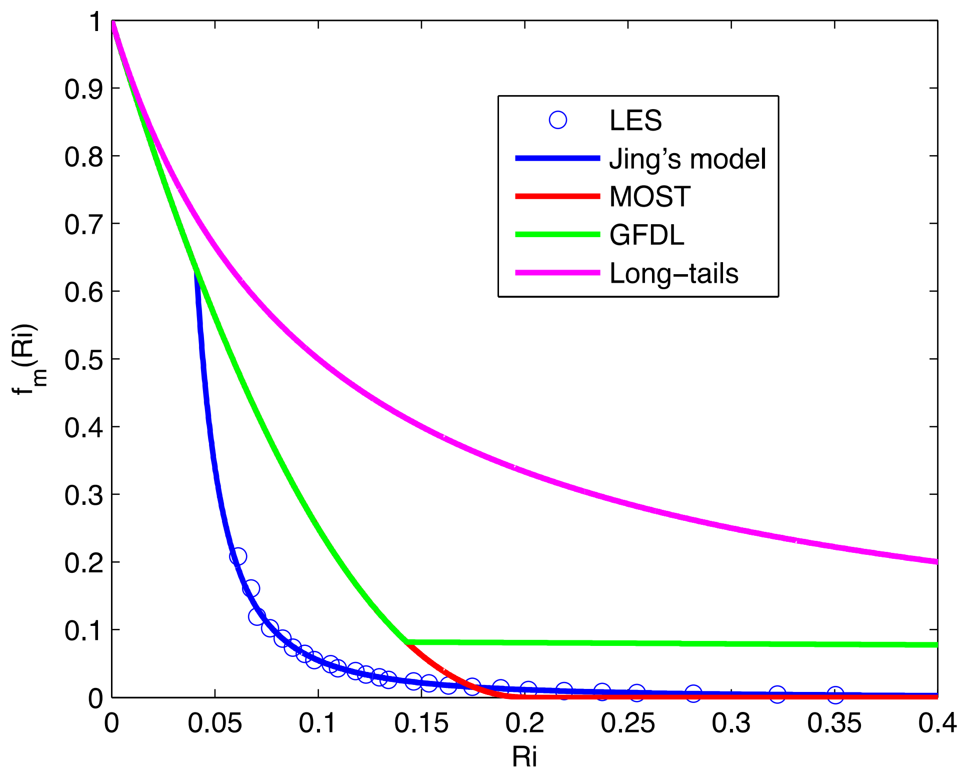
$$f_m(Ri) = \begin{cases} (1-5Ri)^2 & 0 < Ri \le 0.04 \\ (51Ri - 0.8)^{-2} & Ri > 0.04 \end{cases}$$

Current GFDL model:

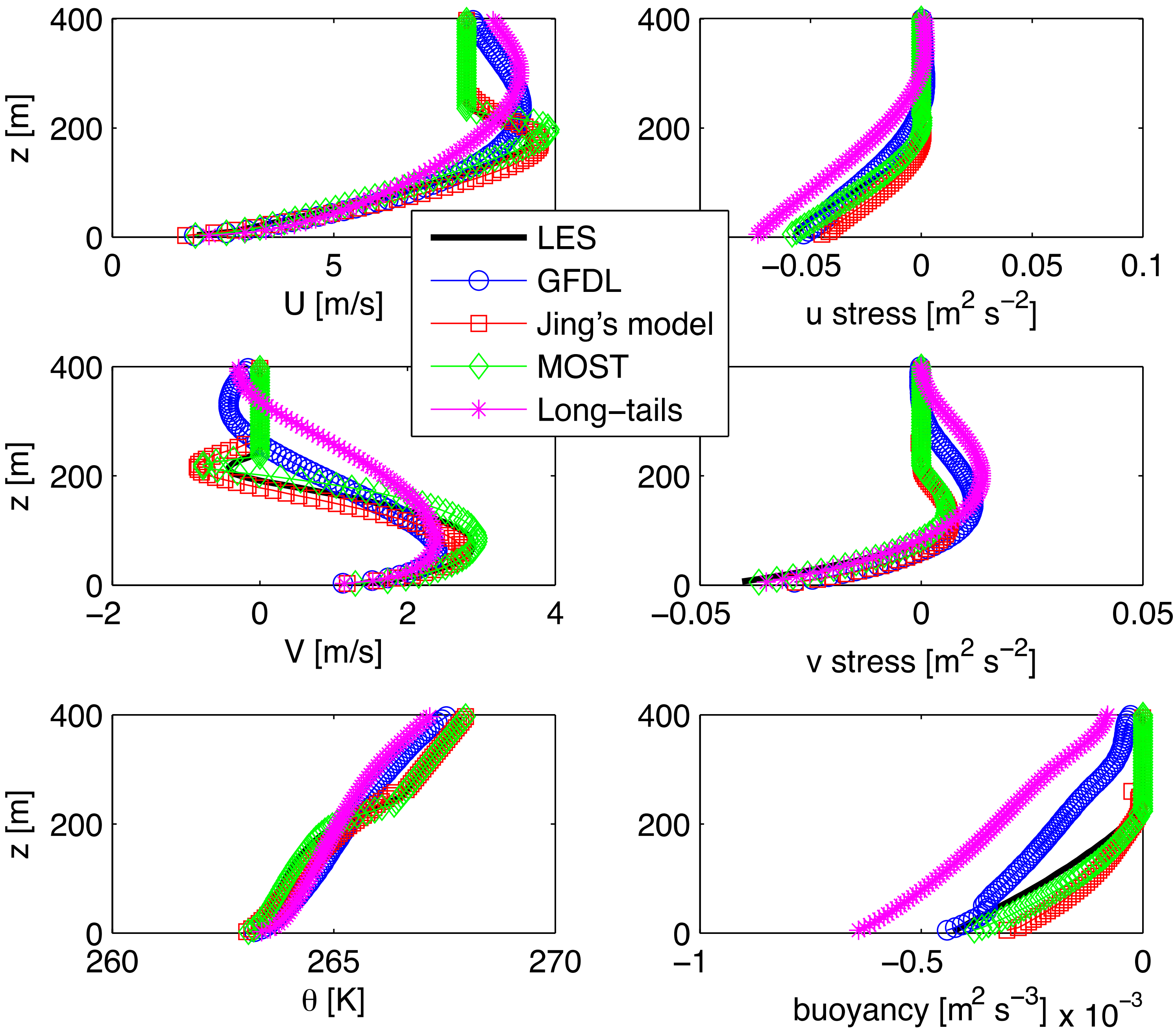
$$f_m(Ri) = \begin{cases} (1-5Ri)^2 & 0 < Ri \le 1/7 \\ \left(\frac{1-0.1Ri}{3.45}\right)^2 & 1/7 < Ri \le 10 \\ 0 & Ri > 10 \end{cases}$$

Long-tails:

$$f_m(Ri) = (1+10Ri)^{-1} \qquad Ri > 0$$



Effects of *f(Ri)*

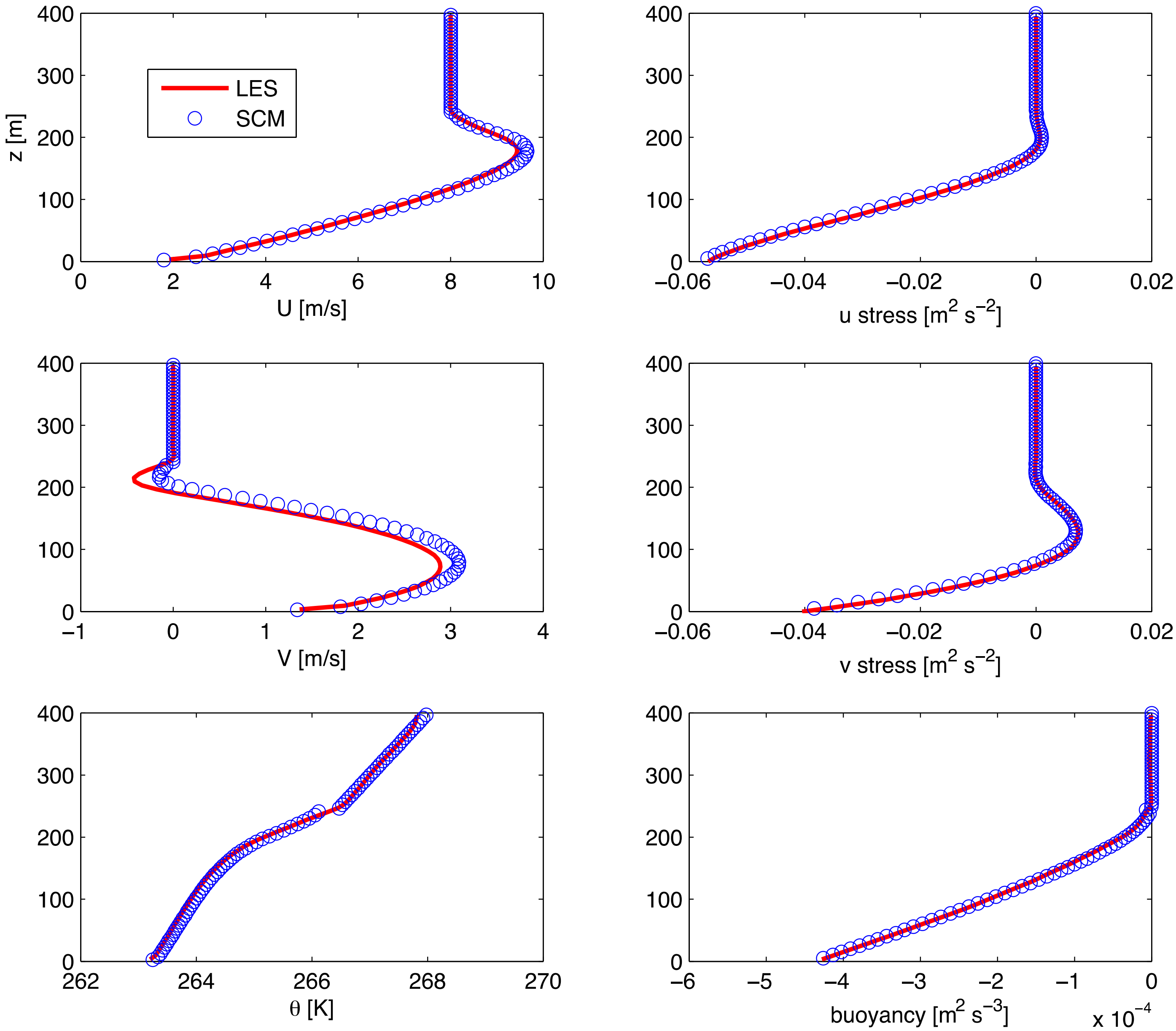


Δt = 60 s
Δz = 2 m
Pr = 1

The GFDL and the long-tails schemes perform poorly!

The buoyancy is underestimated by Jing's model and MOST

Imposing LES diffusivities

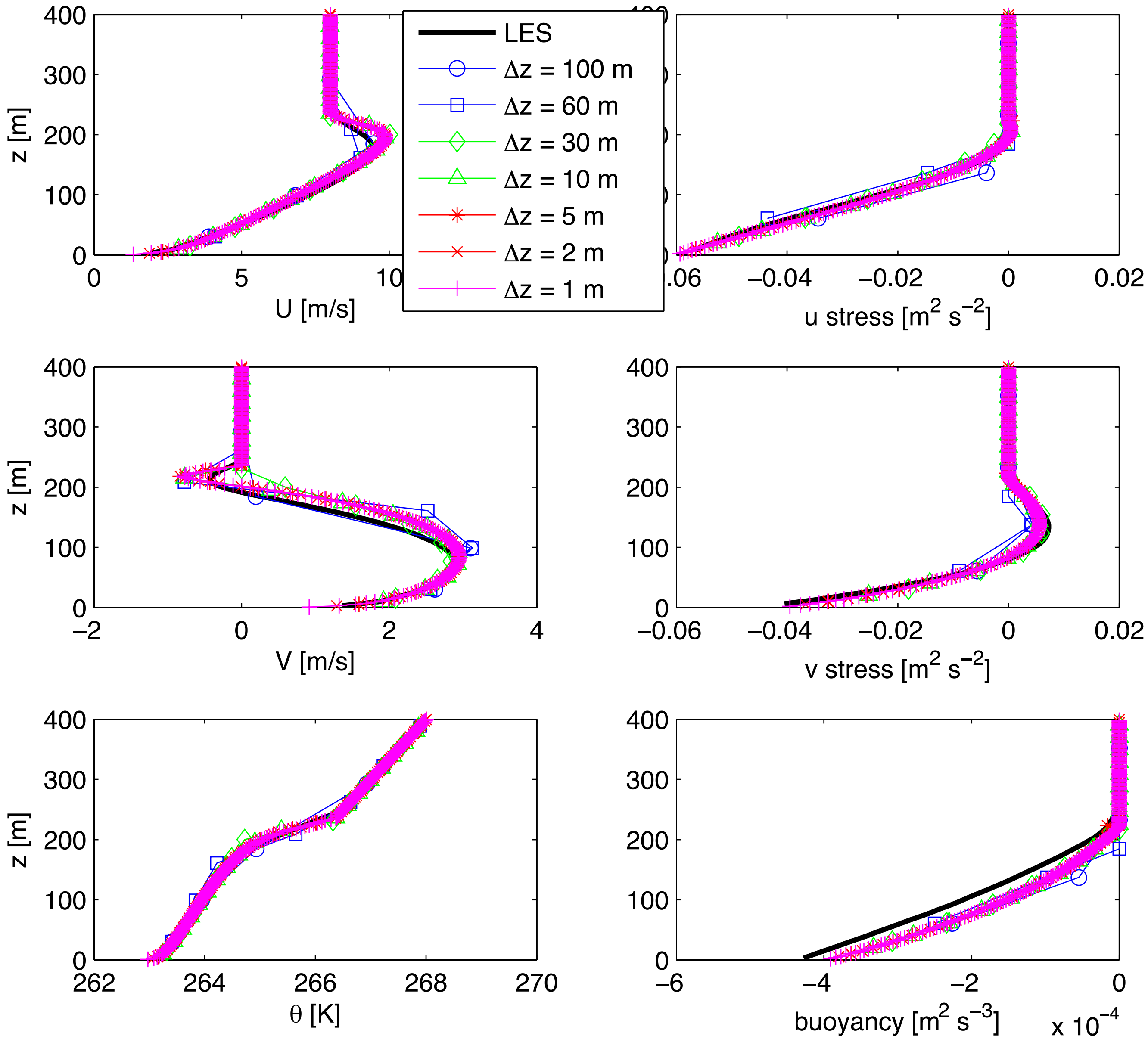


$\Delta t = 900$ s
$\Delta z = 2$ m

The same K_m work well for U and V → local diffusion gradient works well for these components

It is possible for the SCM to match the LES results!

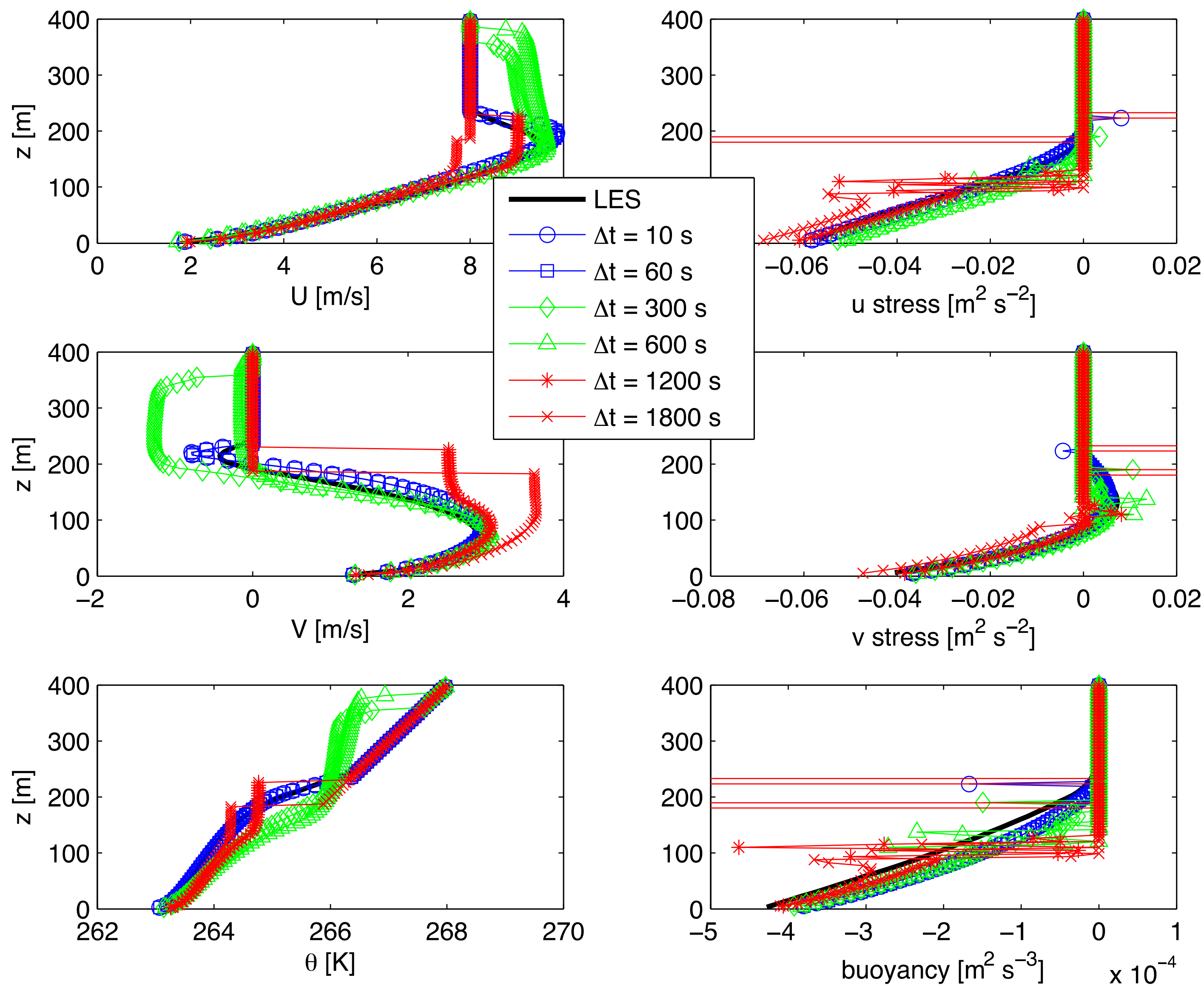
Effects of vertical resolution (MOST)



The performance of the SCM is rather insensitive to vertical resolution

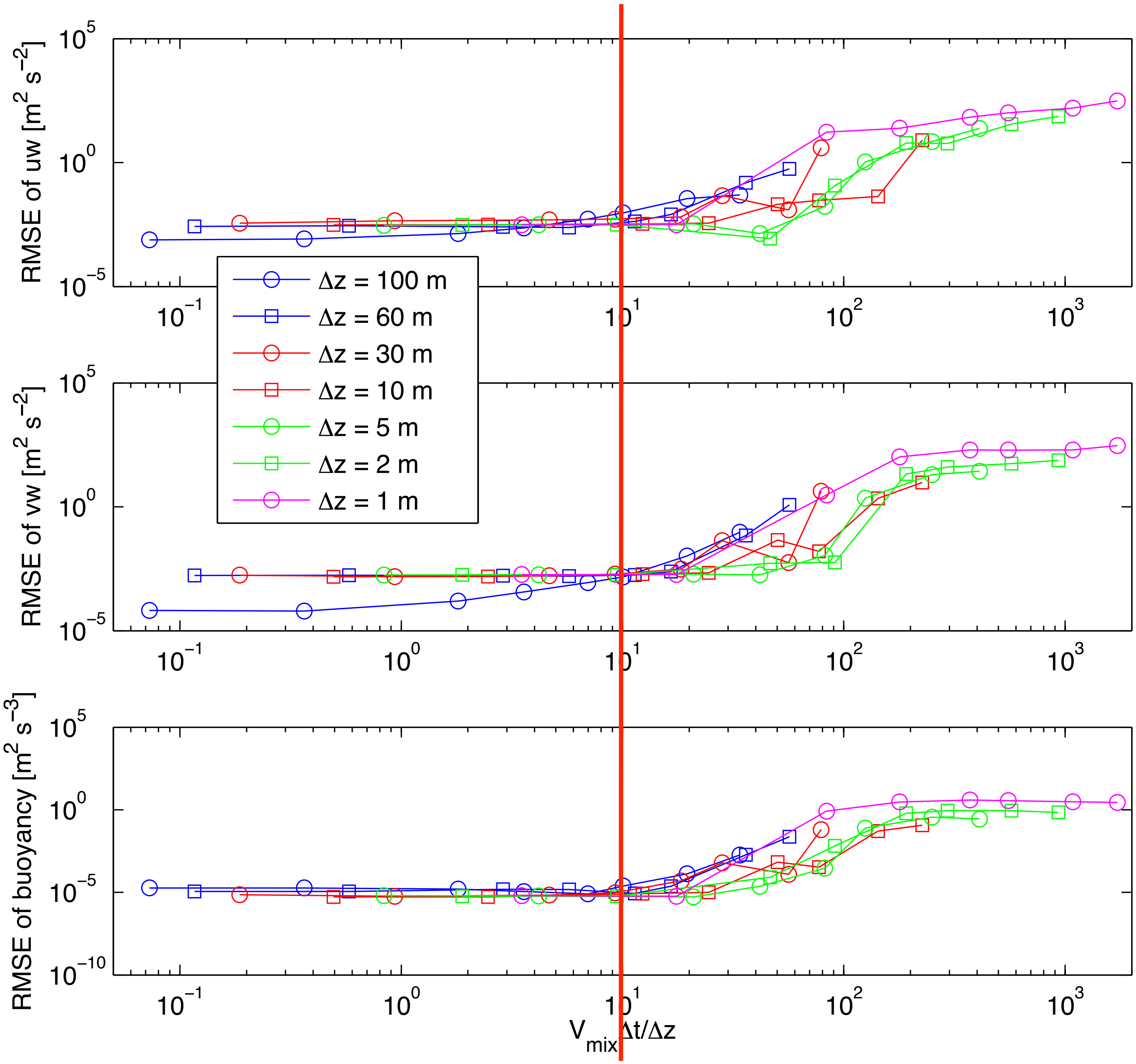
$\Delta t = 60$ s

Effects of time step (MOST, Δz = 2 m)



Too large time steps cause the SCM collapse at high vertical resolution

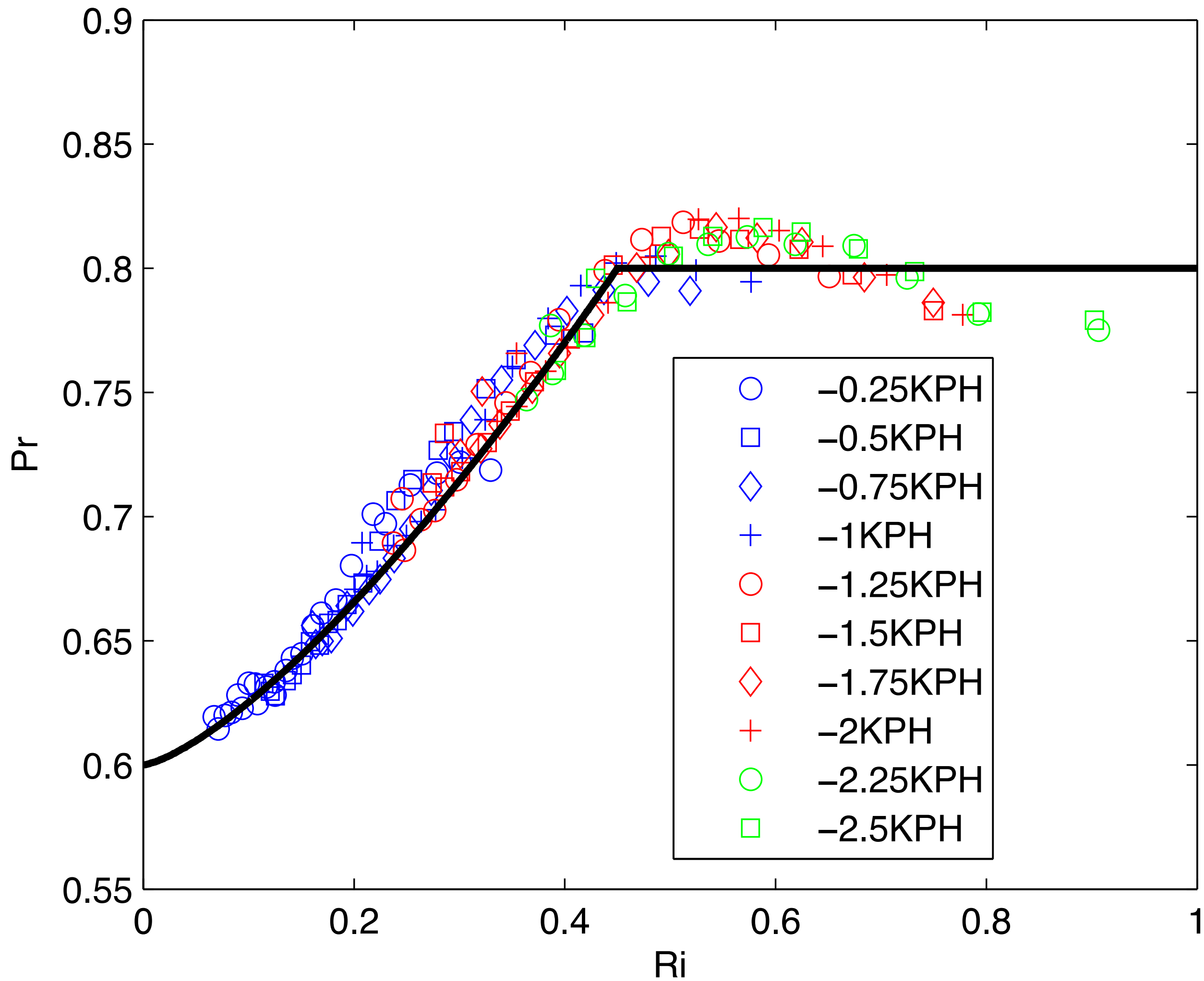
Error vs Δt/Δz



$V_{mix}\Delta t/\Delta z < 10$

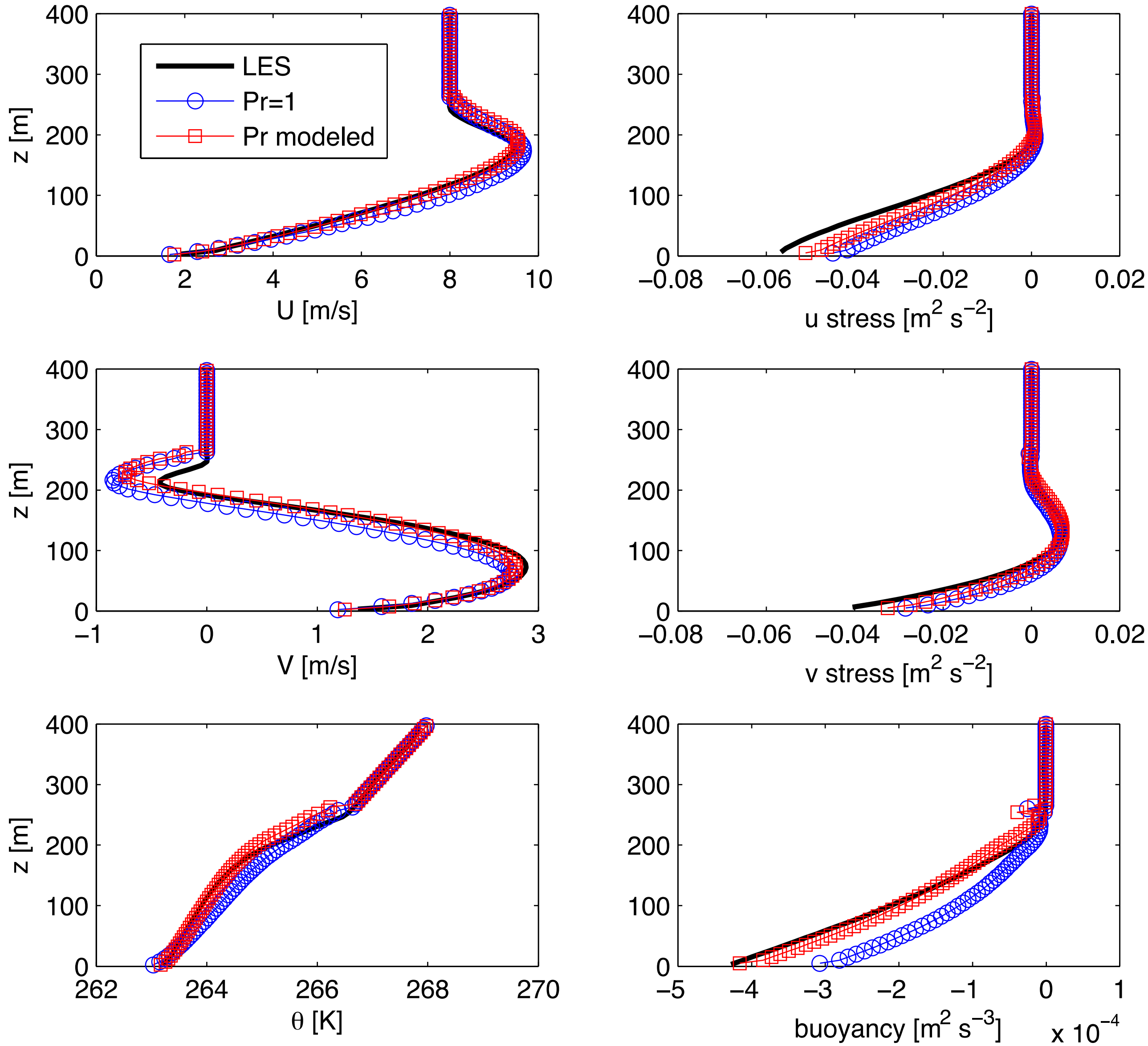
Pr vs Ri

$$\Pr = \begin{cases} 0.6\left(1 + Ri^{1.4}\right) & Ri \le 0.45 \\ 0.8 & Ri > 0.45 \end{cases}$$



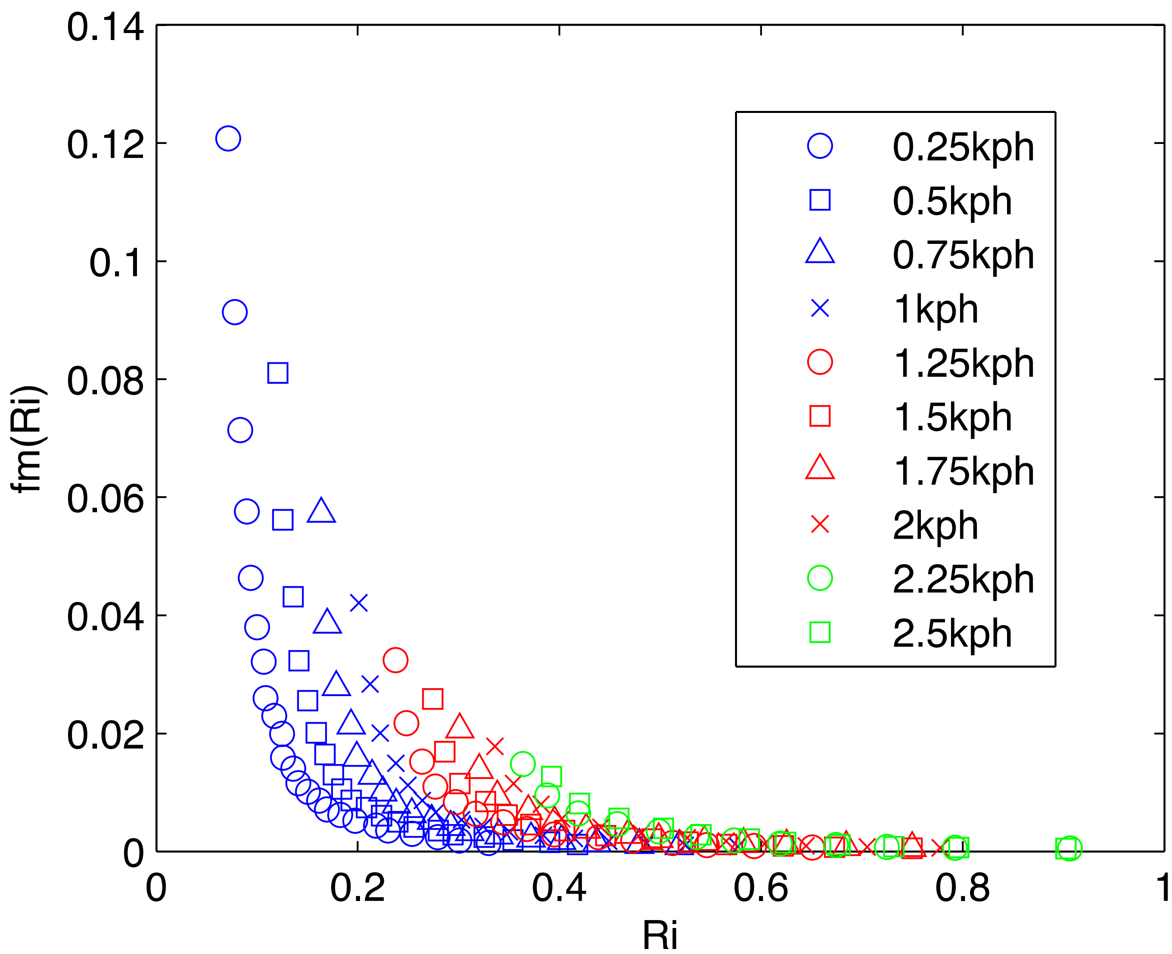
Venayagamoorthy and Stretch, *JFM*, 2009
Bou-Zeid et al., *JFM,* 2010
Li and Bou-Zeid, *BLM*, 2011

Jing's model #1



The underestimation of the buoyancy flux is fixed

How good is the current mixing-length formulation under higher stabilities?

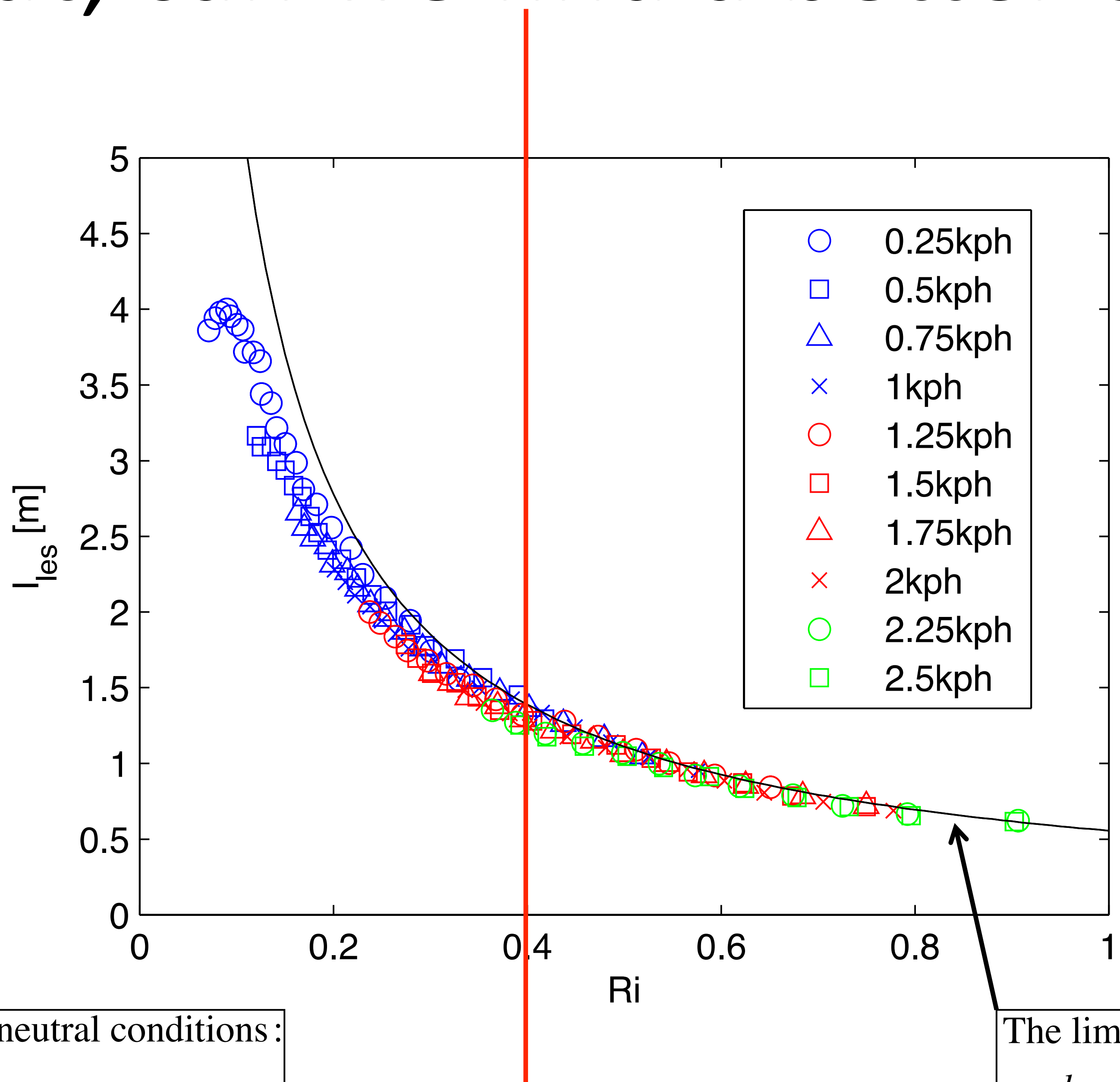


$$K_m = l^2 \left| \frac{\partial U}{\partial z} \right| f_m(Ri),$$

$$\frac{1}{l} = \frac{1}{k(z+z_0)} + \frac{1}{\lambda_0},$$

Not so good from our LES results!

But, can we find a better one?



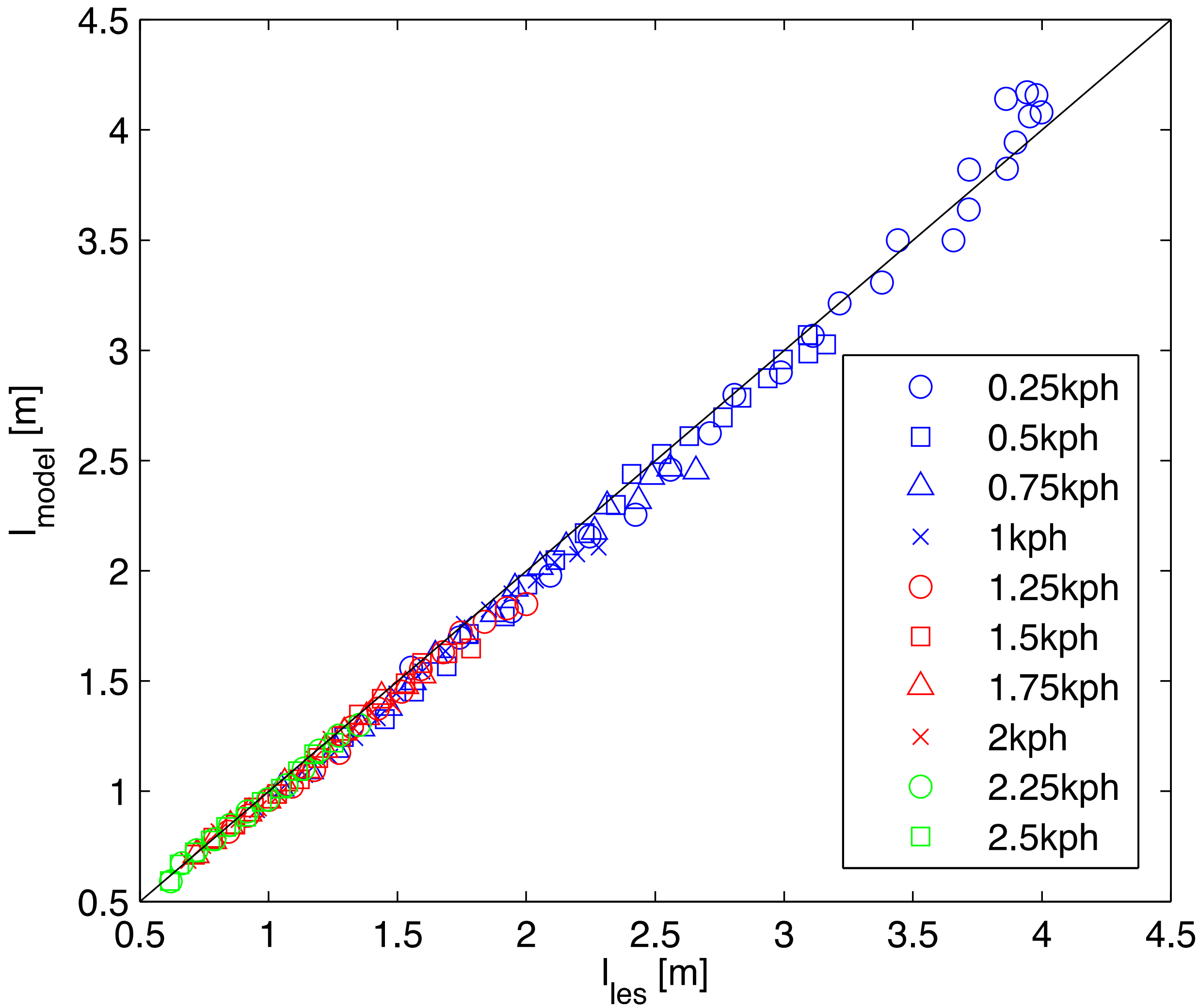
The limit under neutral conditions:

$$\frac{1}{l} = \frac{1}{k\left(z + z_0\right)} + \frac{1}{\lambda_0}.$$

The limit under stable conditions:

$$l = \frac{l_0}{Ri}.$$

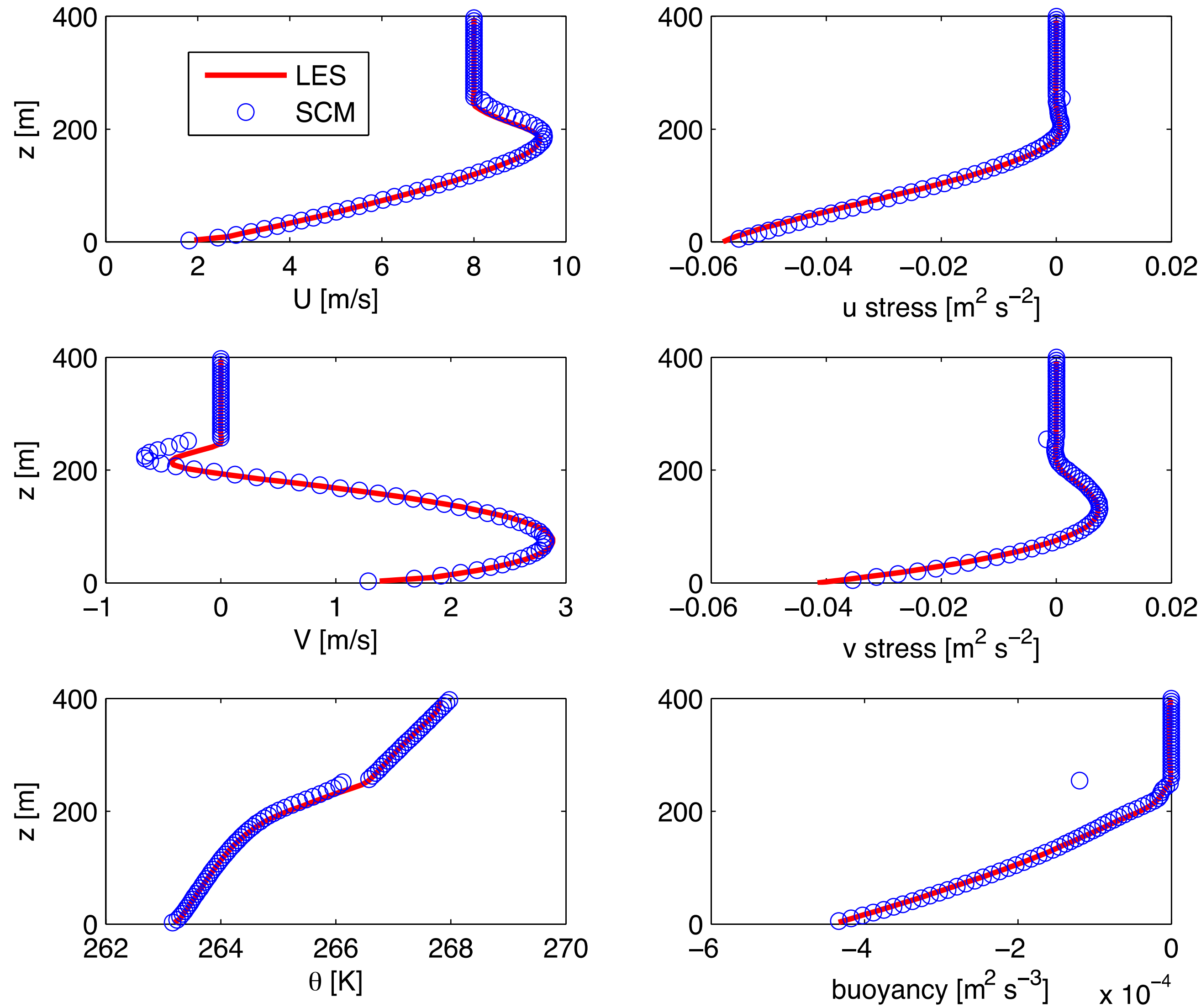
Jing's model #2



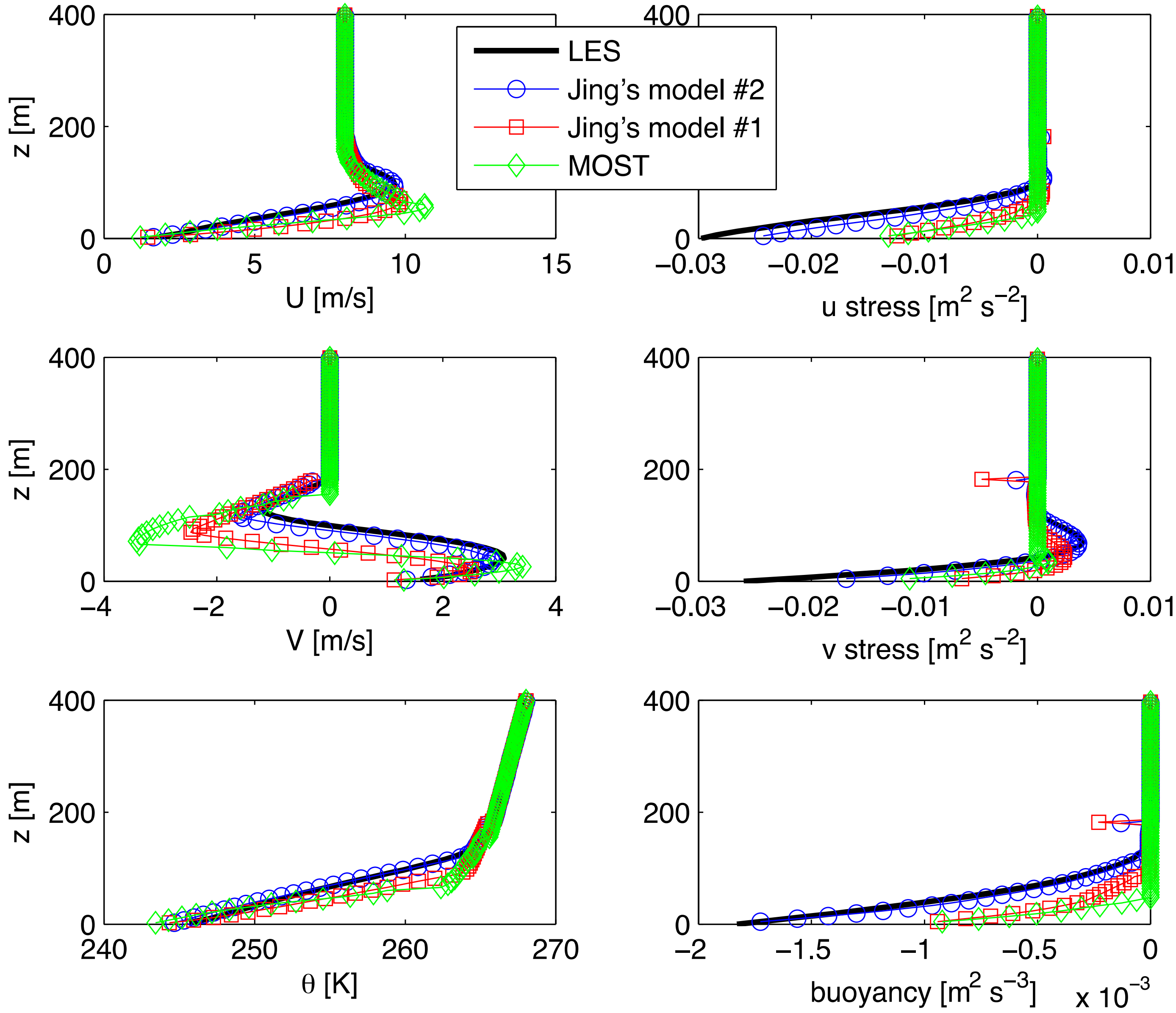
$$K_m = l^2 \left| \frac{\partial U}{\partial z} \right|,$$

$$\frac{1}{l} = \frac{1}{k(z + z_0)} + \frac{1}{\lambda_0} + \frac{R_i}{l_0}.$$

Performance for the GABLS case



Higher stabilities (2.5kph)



Conclusions

- The atmospheric component in climate models does not need artificially enhanced turbulent diffusivities to obtain accurate mean and flux profiles
- The 1st order closure using the local gradient *Ri* similarity is able to produce accurate profiles of both the mean quantities and the turbulent fluxes
- The scheme with *f(Ri)*, which is currently widely used in operational climate models, does not work for moderately high stabilities
- Instead, we have proposed a more universal scheme based on *Ri*
- A time step smaller than a critical value is needed to prevent the single column model from crashing, but the accuracy of the model is rather insensitive to vertical resolution
- A *Pr* less than 1 is needed to obtain accurate buoyancy profiles

Acknowledgement

- Siebel Energy Grand Challenges, Princeton University
- NSF grant AGS-1026636
- Stimit Shah for assistance on the LES code