Development of a Scale-Adaptive TKE-Based Subgrid Mixing Scheme in the WRF Model

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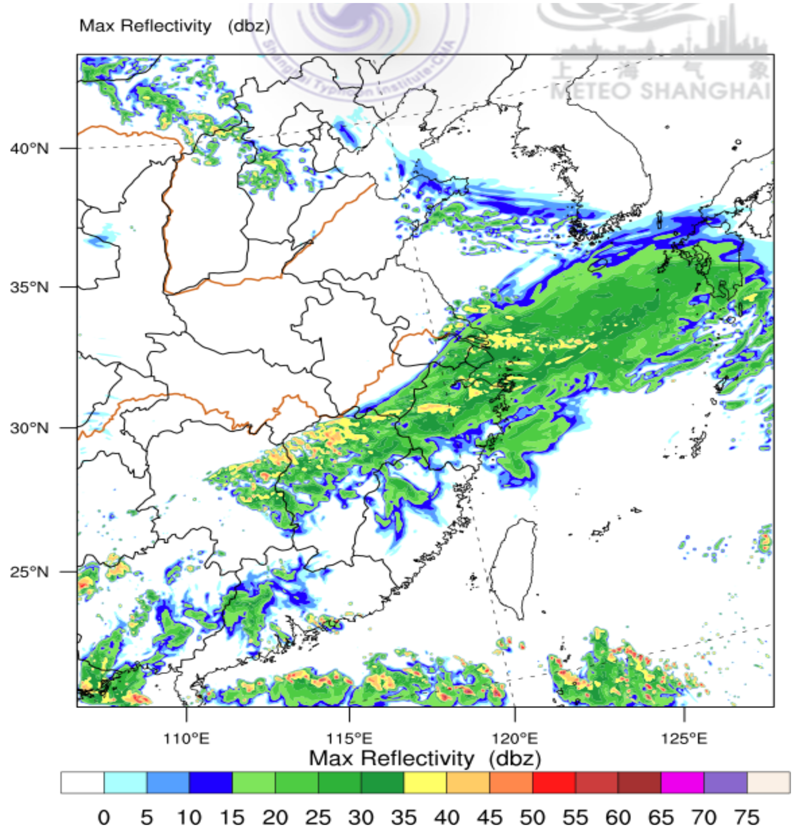
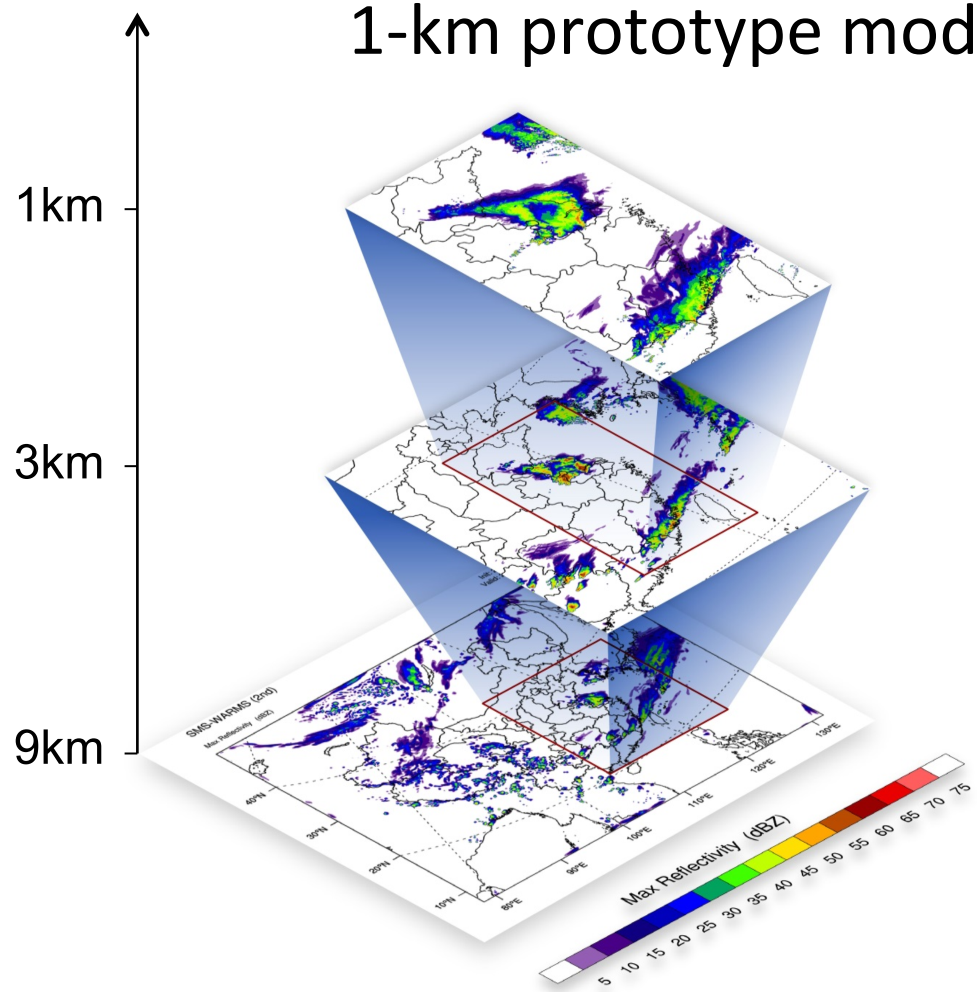
Background: An Overview of Regional NWP in SMS

SMS-WARR : WRF_ADAS Rapid Refresh System

3-km resolution, making
12-hour prediction

1-km prototype model

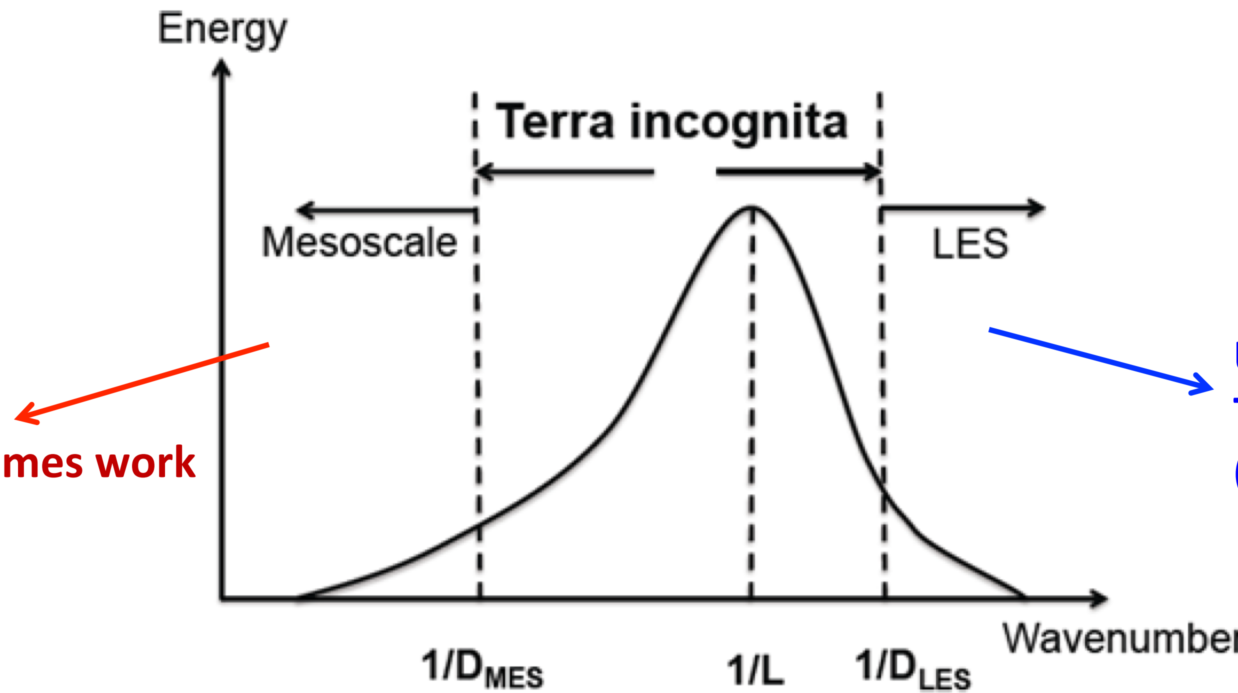




Outline

1. **Purposes**
2. **Methodology of development in WRF**
3. **Numerical results**
4. **Summary and future work**

This diagram shows the form of the spectrum of turbulent energy. The peak energy occurs at a length scale L which gives an idea of a typical size of a turbulent eddy. In the atmosphere, this varies over the course of the day but is typically between a few tens of meters up to a kilometer.



1D PBL schemes work well

Usually use 3D TKE model (Deardorff 1980)

The "Terra Incognita" region in which turbulence is neither fully resolved nor fully parameterized, it is referred to as the "grey zone".

Wyngaard (2004)

Purposes

- **Extend the original Deardorff (1980) model (3dTKE) that is usually used as LES subgrid-scale model to the mesoscale limit.**
- **Develop a single scale-aware 3D TKE-based model which can be used across resolutions, including the mesoscale and LES limits.**

Starting point of our development in WRF

$$\overline{u_i'u_j'} = -K_{ij}^{M}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) + \overline{u_i'u_j'}^{NL} \qquad (i \neq j)$$

$$\overline{u_i'\theta'} = -K_{ij}^{H}\frac{\partial \overline{\theta}}{\partial x_j} + \delta_{i3}\overline{u_i'\theta'}^{NL}$$

$$K_{horizontal}^{M} = C_{horizontal}^{M}\, e^{1/2}\, l_{horizontal} \qquad K_{vertical}^{M} = C_{vertical}^{M}\, e^{1/2}\, l_{vertical}$$

Minimal requirements for extending the 3D TKE subgrid-scale model to the mesoscale limit include the two key specifications:

- The diffusivities (i.e., horizontal and vertical length scales) suitable for the mesoscale.
- The nonlocal fluxes (i.e., terms other than the down-gradient ones).

Length scale suitable for LES

In the LES limit, Deardorff's length scale is applied:

$$l_{vertical} = l_{LES} = \begin{cases} \min\left[0.76 e^{1/2} \left| \frac{g}{\theta} \frac{\partial \theta}{\partial z} \right|^{-1/2}, \Delta s \right] & \text{for } N^2 > 0 \\ \Delta s & \text{for } N^2 \le 0 \end{cases}$$

$$\Delta s = \left(\Delta x \Delta y \Delta z \right)^{1/3}$$

Length scale suitable for mesoscale

In the mesoscale limit, following MYNN Level-3 scheme, the vertical length scale is given as:

$$\frac{1}{l_{vertical}} = \frac{1}{l_{MESO}} = \frac{1}{l_S} + \frac{1}{l_T} + \frac{1}{l_B}$$

where $$l_S = \alpha_1 kz \qquad l_T = \alpha_2 \frac{\int_0^\infty e^{1/2} z dz}{\int_0^\infty e^{1/2} dz}$$

$$l_B = \begin{cases} \left[\alpha_3 e^{1/2} + \alpha_4 e^{1/2} (q_c / l_T N)^{1/2}\right] / N, & \partial\bar{\theta}/\partial z > 0 \\ \infty, & \partial\bar{\theta}/\partial z \le 0 \end{cases}$$

l_S is the length scale in the surface layer controlled by the effects of wall and stability, l_T the length scale depending on the turbulent structure of the PBL and l_B the length scale limited by the thermal stability.

Scale-adaptive transition between LES and mesoscale limit

$$\overline{w'\theta'}^{\Delta x} = -K_H^{\Delta x}\frac{\partial\overline{\theta}}{\partial z} + \overline{w'\theta'}^{\Delta x,NL} = \overline{w'\theta'}^{\Delta x,L} + \overline{w'\theta'}^{\Delta x,NL}$$

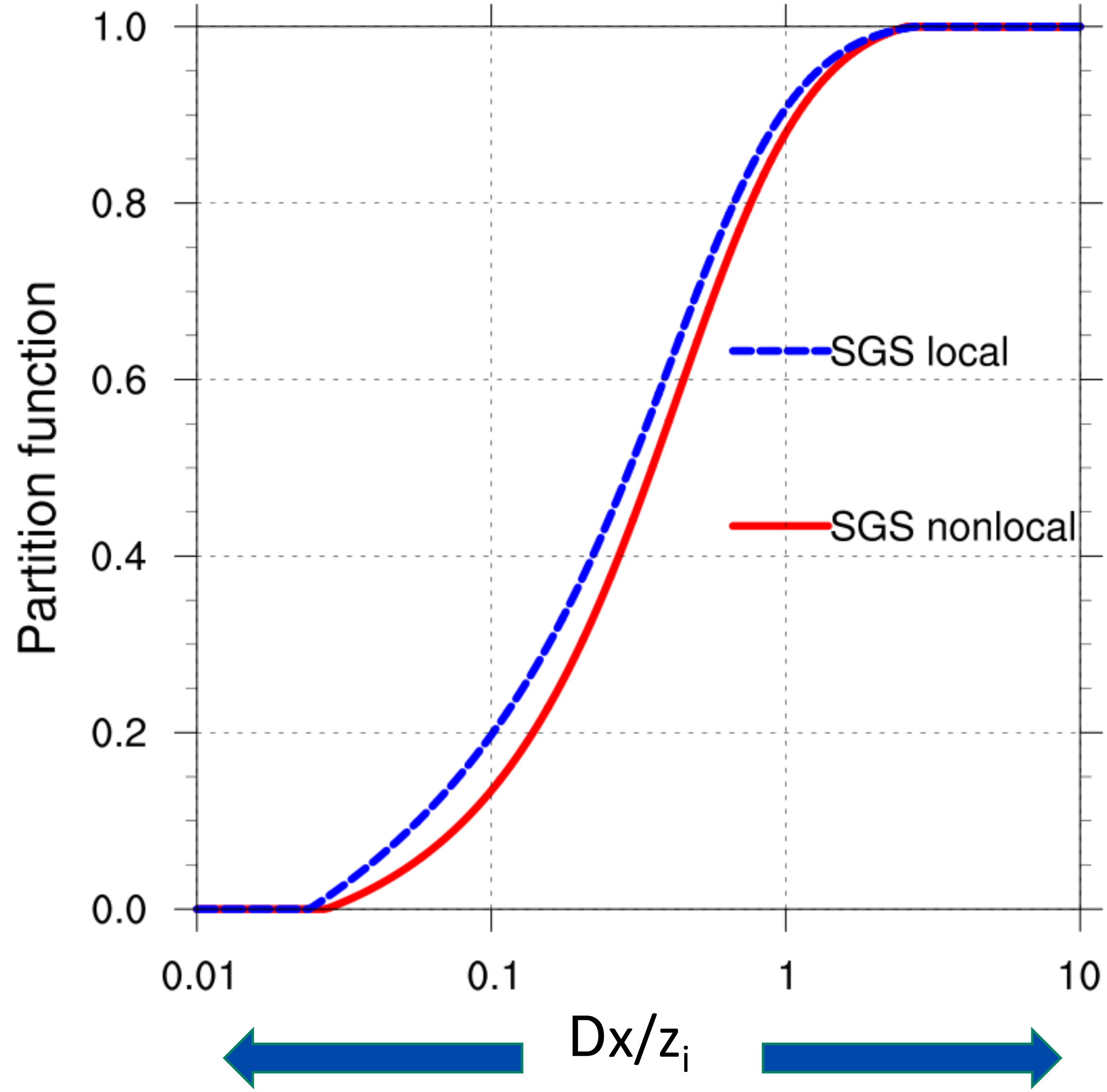
$$\overline{w'\theta'}^{\Delta x,NL} = \overline{w'\theta'}^{NL} P_{NL}(\Delta x/z_i) \qquad \overline{w'\theta'}^{\Delta x,L} = -K_{\Delta x}^{H}\frac{\partial\overline{\theta}}{\partial z}^{\Delta x}$$

$$K_{\Delta x}^{H} = C_{vertical}\, l_{\Delta x} e^{1/2}$$

$$l_{\Delta x} = P_L(\Delta x/z_i)\, l_{MESO} + \left[1 - P_L(\Delta x/z_i)\right] l_{LES}$$

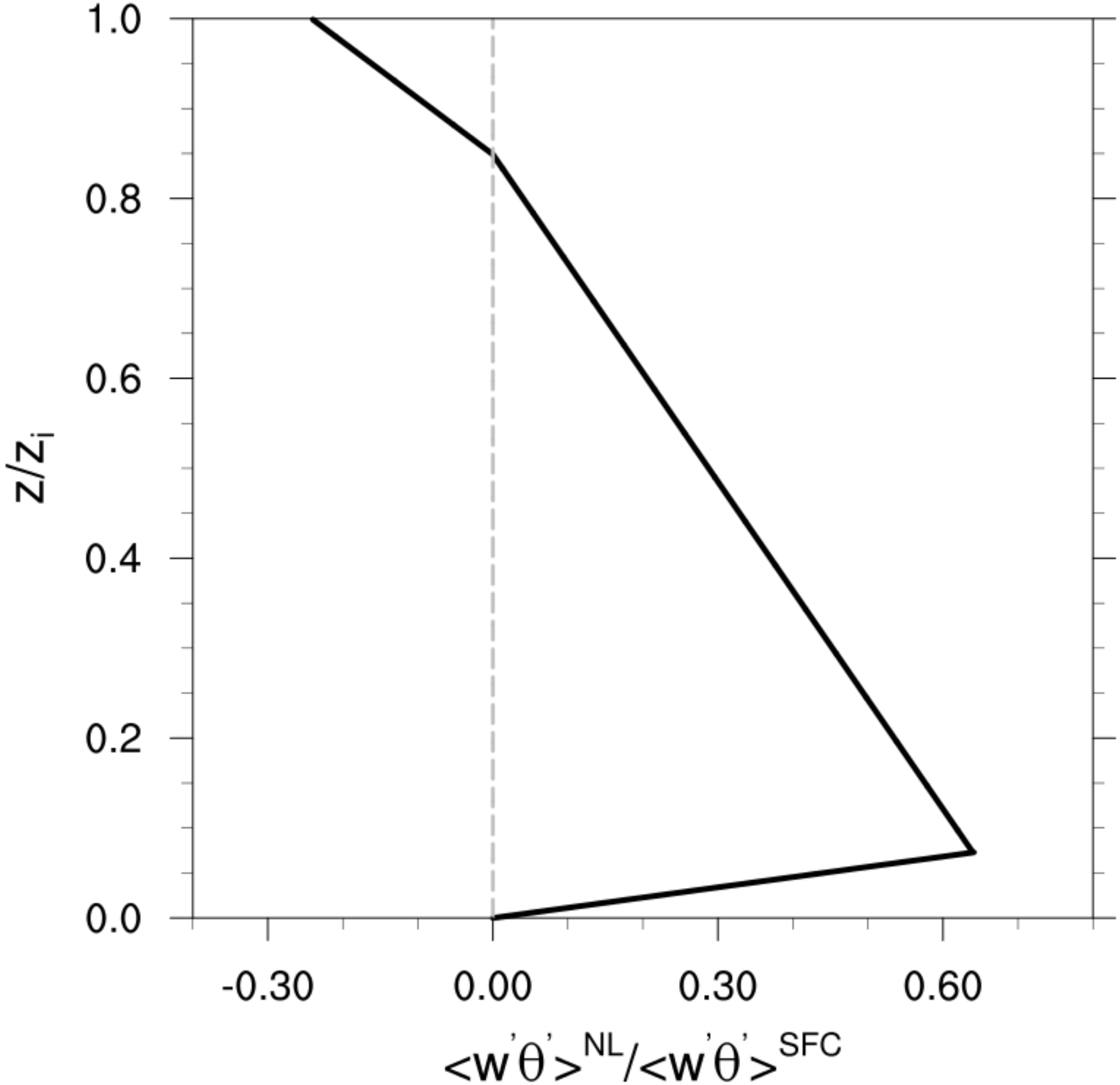
$P_L(\Delta x/z_i)$ and $P_{NL}(\Delta x/z_i)$ are scale-adaptive transition weighting functions.

Weighting functions $P_{NL}(\Delta x/z_i)$ and $P_L(\Delta x/z_i)$



LES limit **Mesoscale limit**

Prescribed nonlocal heat flux from Shin and Hong (2015)



Nonlocal momentum flux

Following the suggestion by Brown and Grant (1997) and Noh et al. (2003), the effect of nonlocal momentum flux is included in the momentum flux profile as

$$-\overline{u'w'} = K_M \left(\frac{\partial \overline{u}}{\partial z} + \frac{\partial \overline{w}}{\partial x} - \gamma_m \frac{u}{\sqrt{u^2 + v^2}} \right)$$

$$-\overline{v'w'} = K_M \left(\frac{\partial \overline{v}}{\partial z} + \frac{\partial \overline{w}}{\partial y} - \gamma_m \frac{v}{\sqrt{u^2 + v^2}} \right)$$

The counter-gradient term γ_m of momentum flux is given as

$$\gamma_m = -S_m \frac{u_*^2}{w_s z_i} \left(\frac{w_*}{w_s} \right)^3$$

$$w_s = \left(u_*^3 + 8 k w_*^3 z / h \right)^{1/3} \qquad w_* = (g / \theta_0 Q_0 z_i)^{1/3}$$

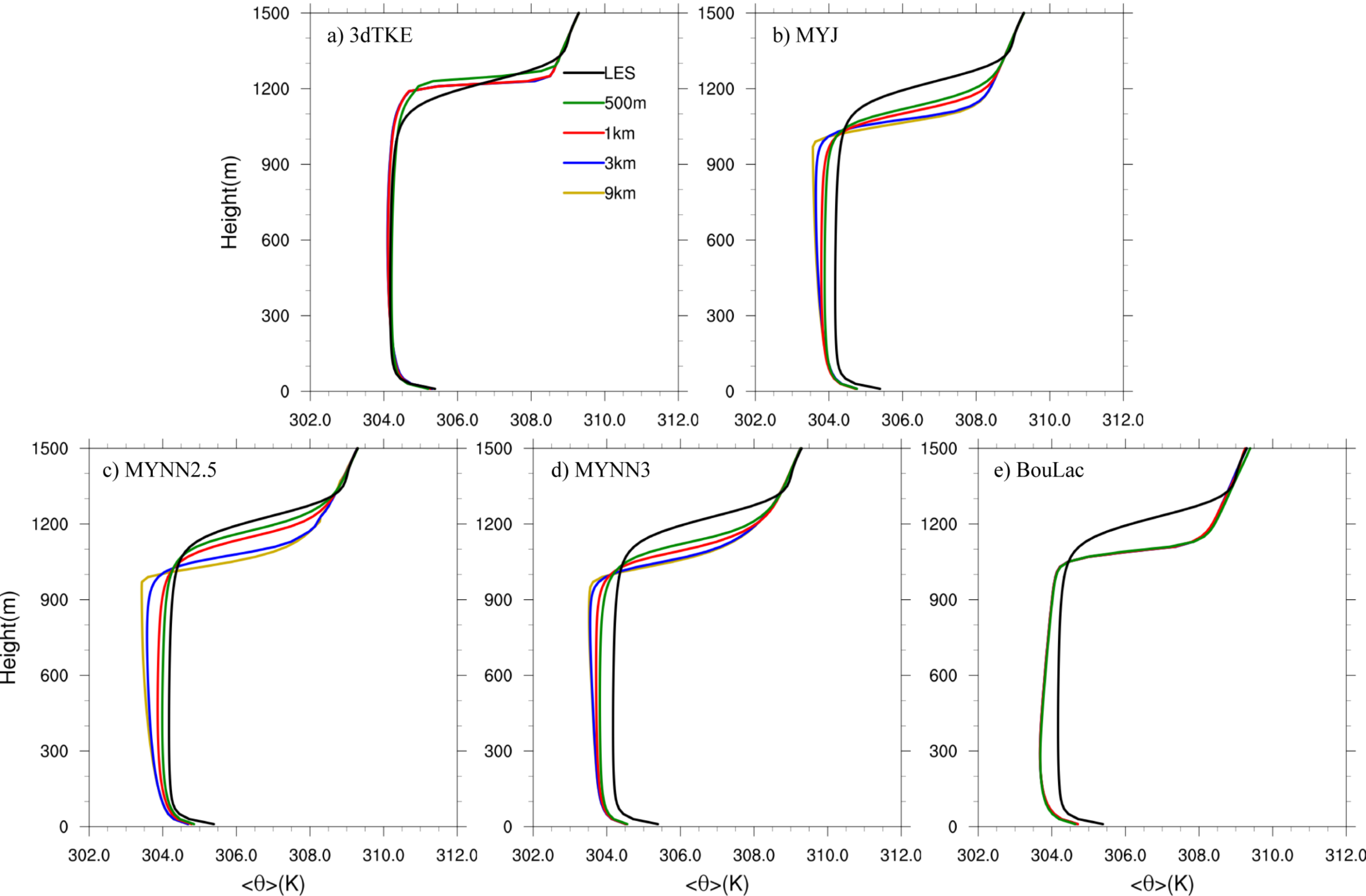
Comparisons of the newly developed 3dTKE scheme with conventional 1D TKE-based PBL schemes (MYJ, MYNN2.5, MYNN3, BouLac) against LES data

Setup of experiments: Convective Boundary Layer

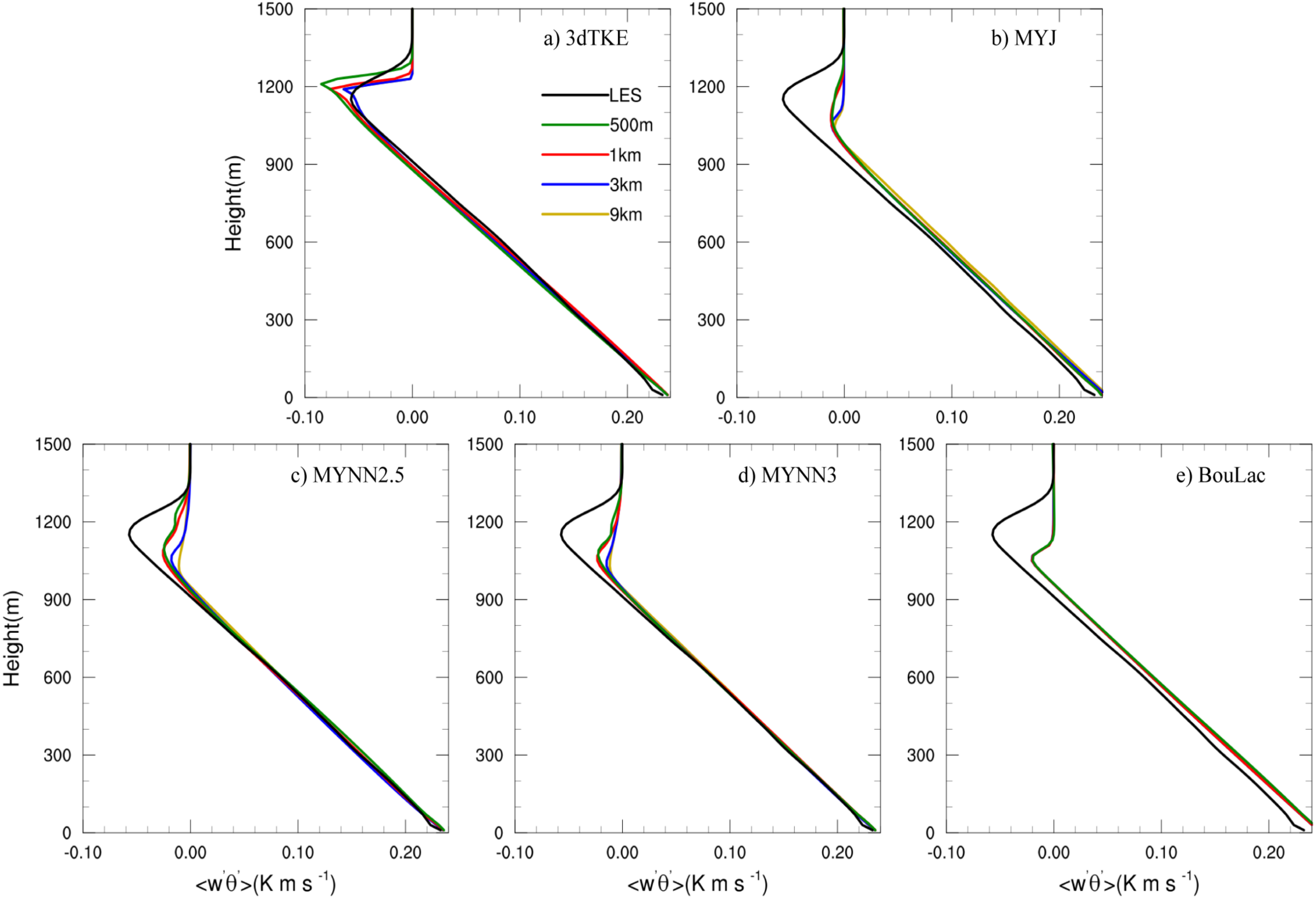
Name of experiments	H-Diff.	V-Diff.	Vertical grid size	Horizontal grid size
Benchmark LES	3dTKE	3dTKE	20m	50m
New 3dTKE	3dTKE	3dTKE	20m	9 km, 3km, 1 km, 500 m
MYJ	2D Smag	MYJ	20m	9 km, 3km, 1 km, 500 m
MYNN2.5/MYNN3	2D Smag	MYNN	20m	9 km, 3km, 1 km, 500 m
BouLac	2D Smag	BouLac	20m	9 km, 3km, 1 km, 500 m

- The benchmark LES run was driven by constant kinematic heat flux (Q_0 = 0.24 K m s^{-1}) and geostrophic wind in the *x* direction (U_g = 10 m s^{-1}).
- In the PBL and new 3dTKE experiments, the surface heat flux is prescribed with the same value as the LES (0.24 K m s^{-1}) .

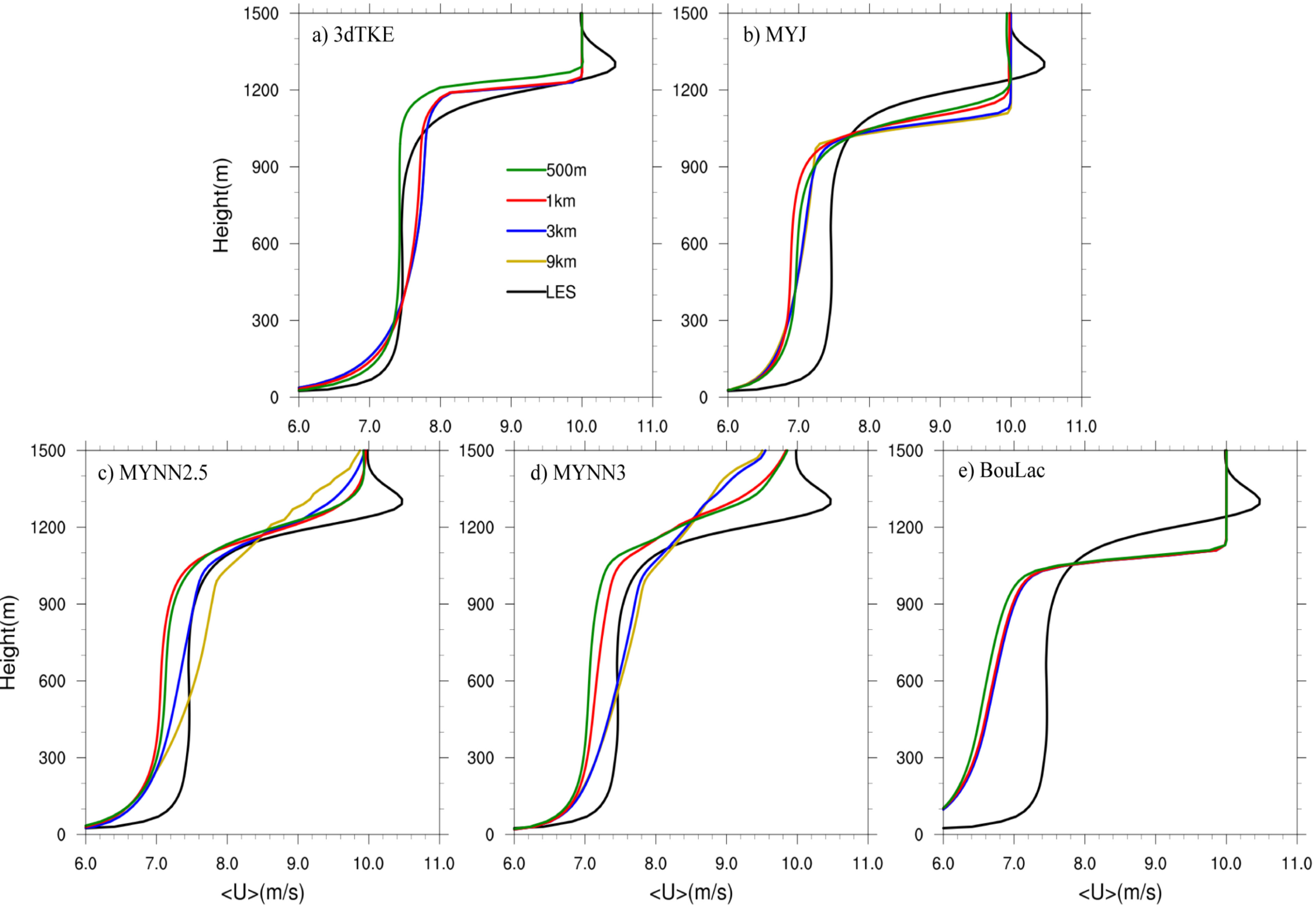
Mean profiles of potential temperature



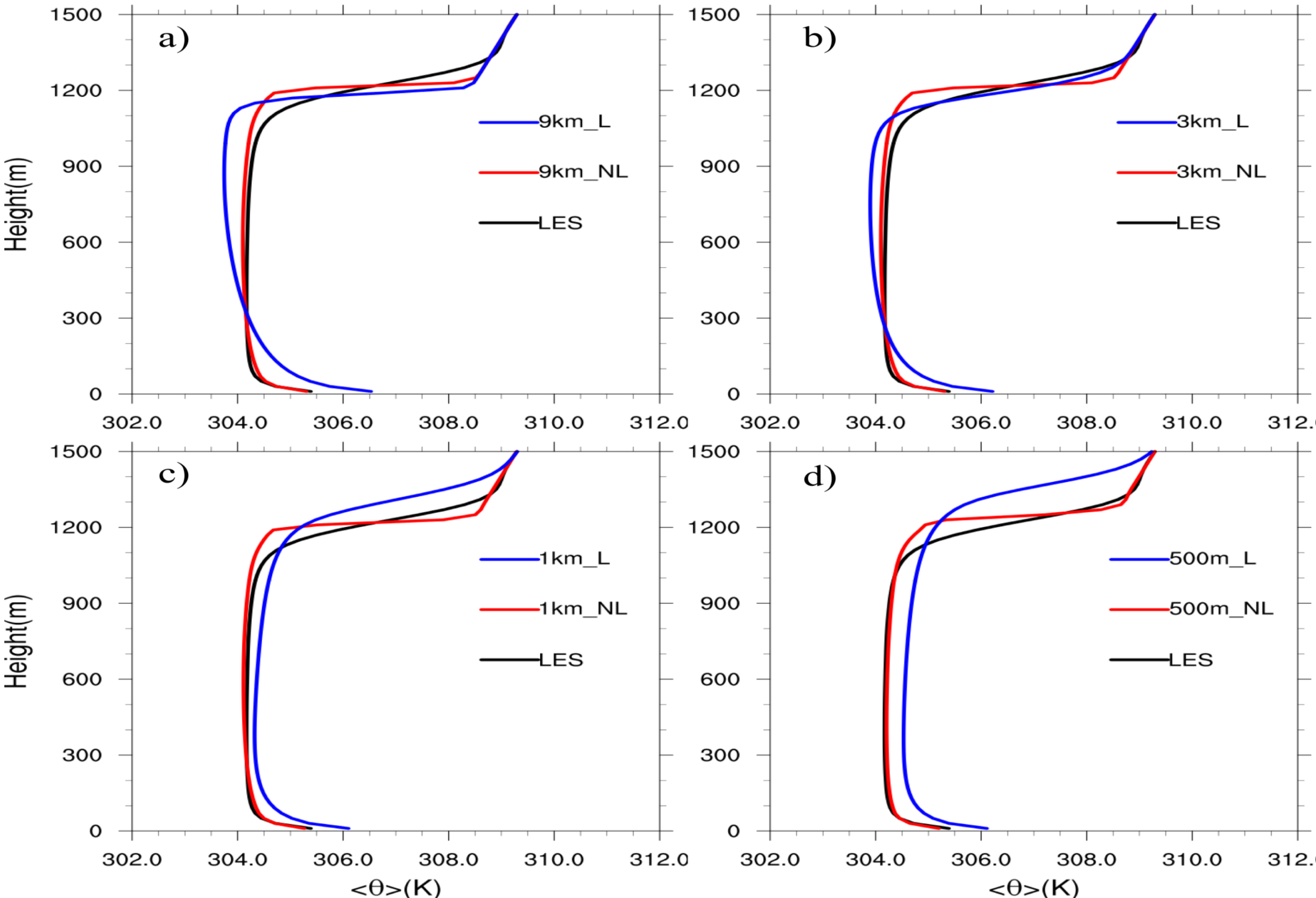
Mean profiles of total vertical heat flux



Mean profiles of horizontal winds



Sensitivity of the new scheme to nonlocal heat fluxes



Summary and future work

- A scale-adaptive parameterization scheme based on the general form of the TKE equation has been developed in the WRF model to simulate 3-D subgrid turbulent mixing.

- The scheme holds the promise of making the transition between the mesoscale and LES limits smooth, not only in the amount of subgrid mixing, but also in the parameterization formula (an appealing feature for nesting simulations)

- It is feasible to apply the new scheme in lieu of conventional planetary boundary layer parameterization schemes.

- Including the nonlocal fluxes (momentum and heat) is important for mesoscale simulations.

- Further evaluation and improvement in more realistic cases are underway.

Thank you for your attention!