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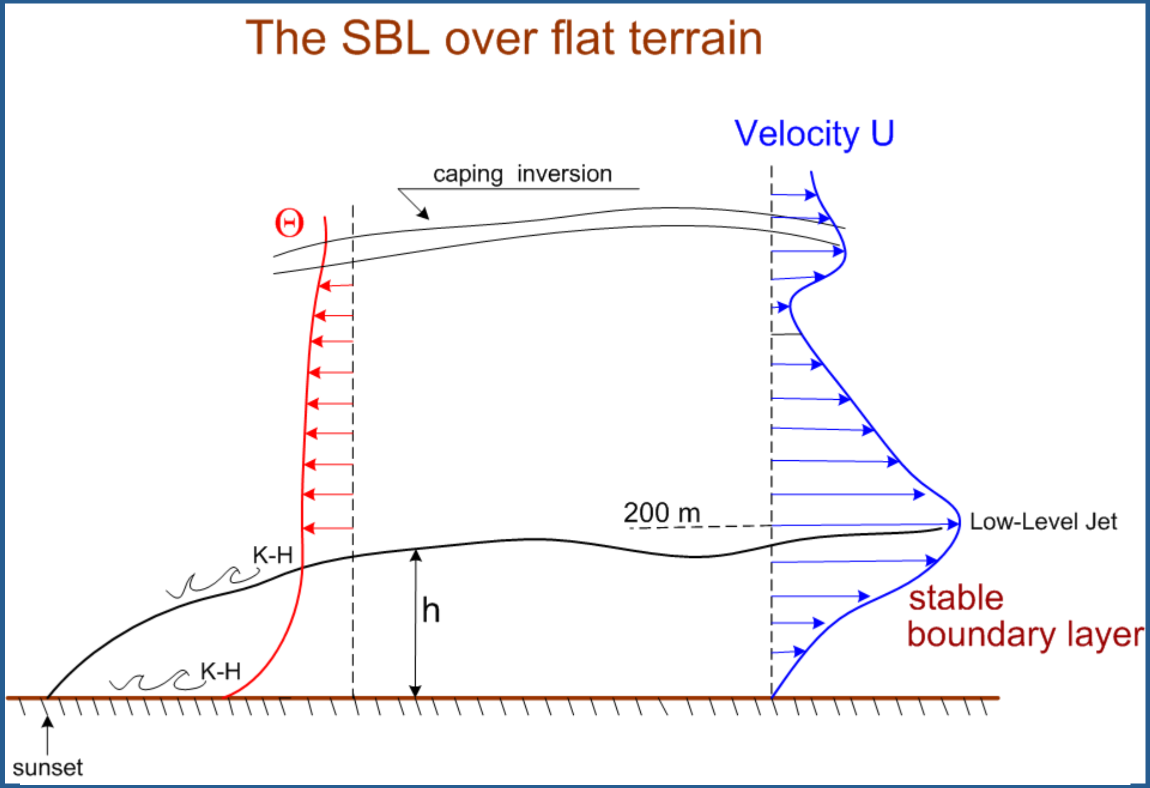
Eddy mixing in planetary boundary Layers under stronger stratification: study with mesoscale atmospheric model

A. F. Kurbatskiy

Institute of Theoretical and Applied Mechanics of Russian Academy of Sciences, Siberian Branch and Novosibirsk State University, Russia

Khristianovich Institute of Theoretical and Applied Mechanics of SB RAS

Study Motivation: ▶ **Stable boundary layer turbulence has scientifically intriguing nature and practical significance (e.g., pollutant transport). Indeed, the dynamics of stably stratified turbulence includes such phenomena as: occurrence of Kelvin-Helmholtz instability (K-H), gravity waves, low-level jets (LLJ).**



Three-parametr theory of stratified turbulence

$$\left(<uw>, <vw>\right) = -K_M\left(\frac{\partial U}{\partial z}, \frac{\partial V}{\partial z}\right)$$

$$K_M = E\tau S_M$$

$$<w\theta> = -K_H\frac{\partial \Theta}{\partial z} + \gamma_c$$

$$K_H = E\tau S_H$$

$$\tau_{p\theta} \neq \tau\left(=E/\varepsilon\right) \rightarrow$$

$$\tau_{p\theta} = \tau / [1 + a\tau^2 N^2]$$

Three-parameter theory of stratified turbulence

Turbulent kinetic energy

$E = (1/2)\langle u_i u_i \rangle$

$$\frac{DE}{Dt} + \frac{1}{2} D_{ii} = -\tau_{ij} \frac{\partial U_i}{\partial x_j} + \beta_i h_i - \varepsilon,$$

TKE dissipation, ε

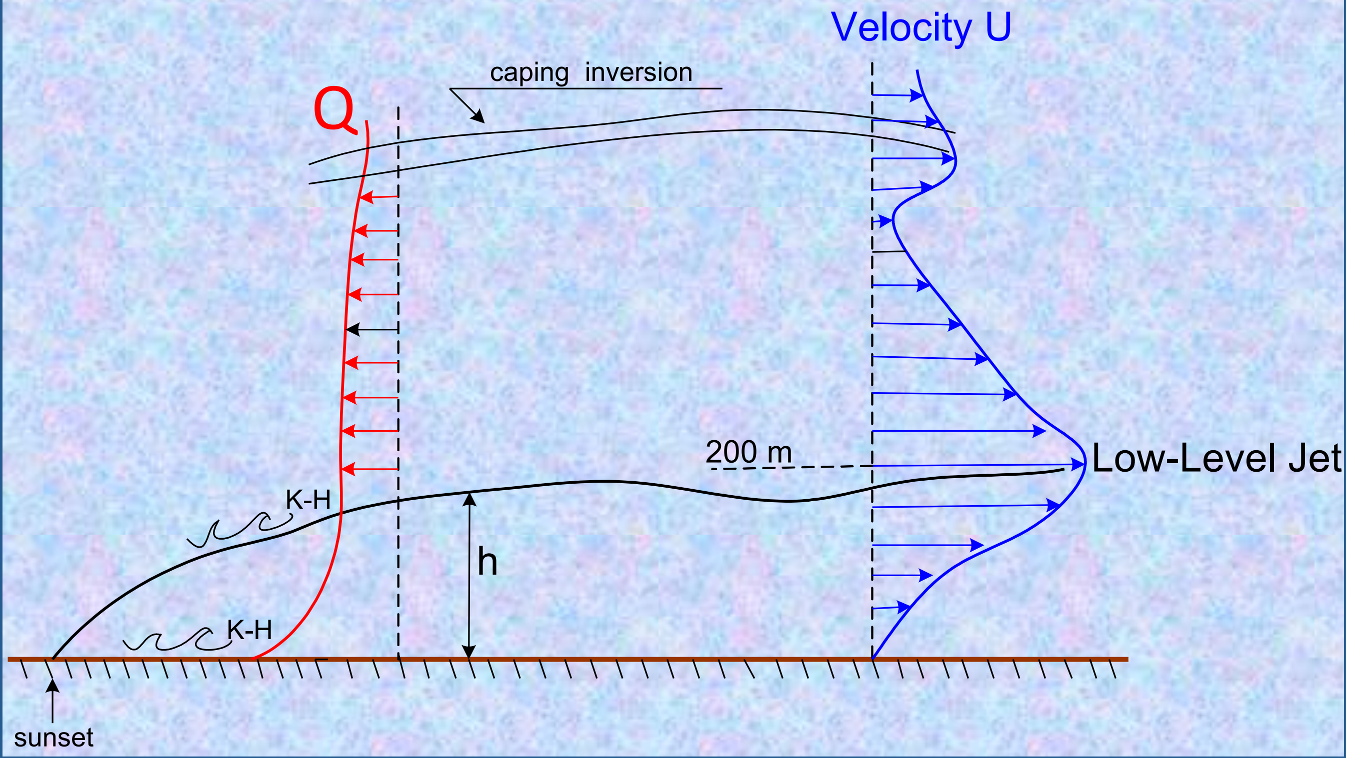
$$\frac{D\varepsilon}{Dt} + D_\varepsilon = c_{\varepsilon 1} \frac{\varepsilon}{E} \left(-\langle u_i u_k \rangle \frac{\partial U_i}{\partial x_k} + \beta g \delta_{i3} \langle u_i \theta \rangle \right) - c_{\varepsilon 2} \frac{\varepsilon^2}{E},$$

Temperature variance, $\langle \theta^2 \rangle$

$$\frac{D\langle \theta^2 \rangle}{Dt} + D_{\theta^2} = -2 h_i \frac{\partial \Theta}{\partial x_i} - 2\varepsilon_\theta,$$

Modeling and Simulation of Stably Stratified Boundary layer

The SBL over flat terrain



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Low Level Jet: Computational Experiment

➔The boundary layer is driven by an imposed geostrophic wind, with a specified surface cooling rate.

→ A vertical domain of 400 m is used, with a grid mesh of 6.25m (64 vertical levels), and a timestep of 2.5 s.

→ A constant geostrophic wind with height, of 8 m/s in the x-direction, is prescribed.

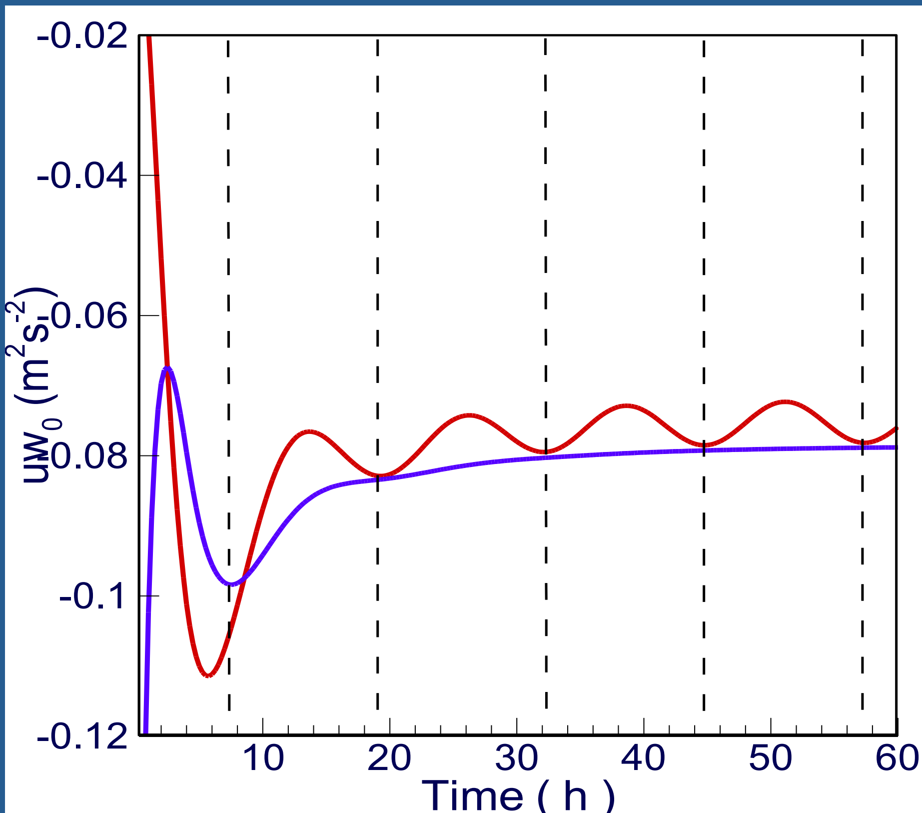
→ The initial potential temperature equals 265 K up to 100 m, and then it increases at a rate of 0.01 K/m until the domain top, where a value of 268 K is reached.

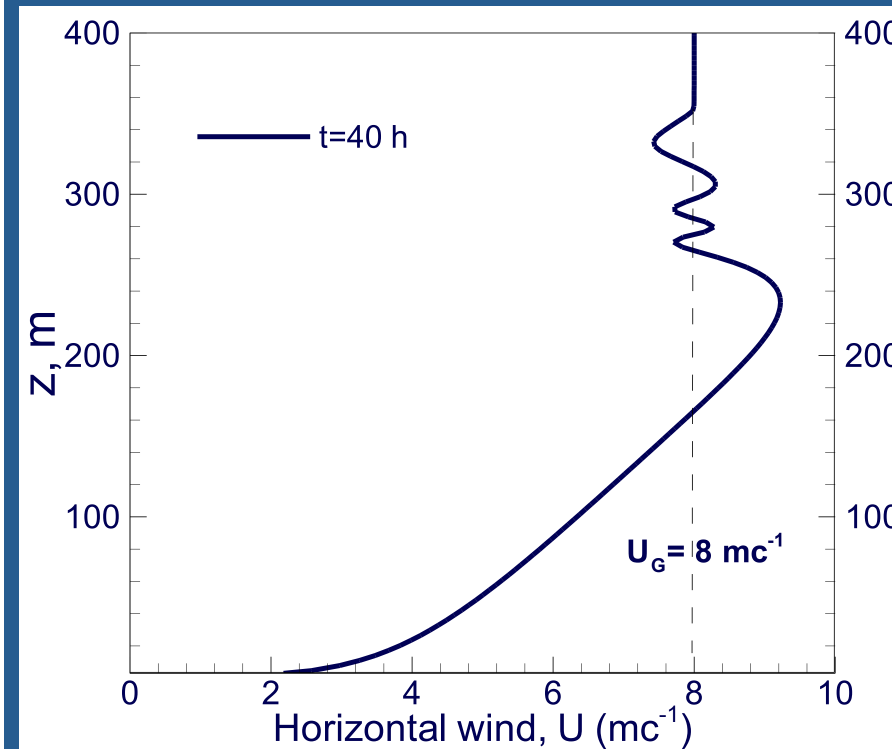
➔Surface boundary conditions:

→ The turbulent values are computed using the MOST according to the noniterative procedure of Louis (1979)

→ <u>The surface temperature is decreasing at a constant rate of 0.25 K/h.</u>

Inertial Oscillation and LOW- LEVEL- JET in Stably Stratified Boundary Layer

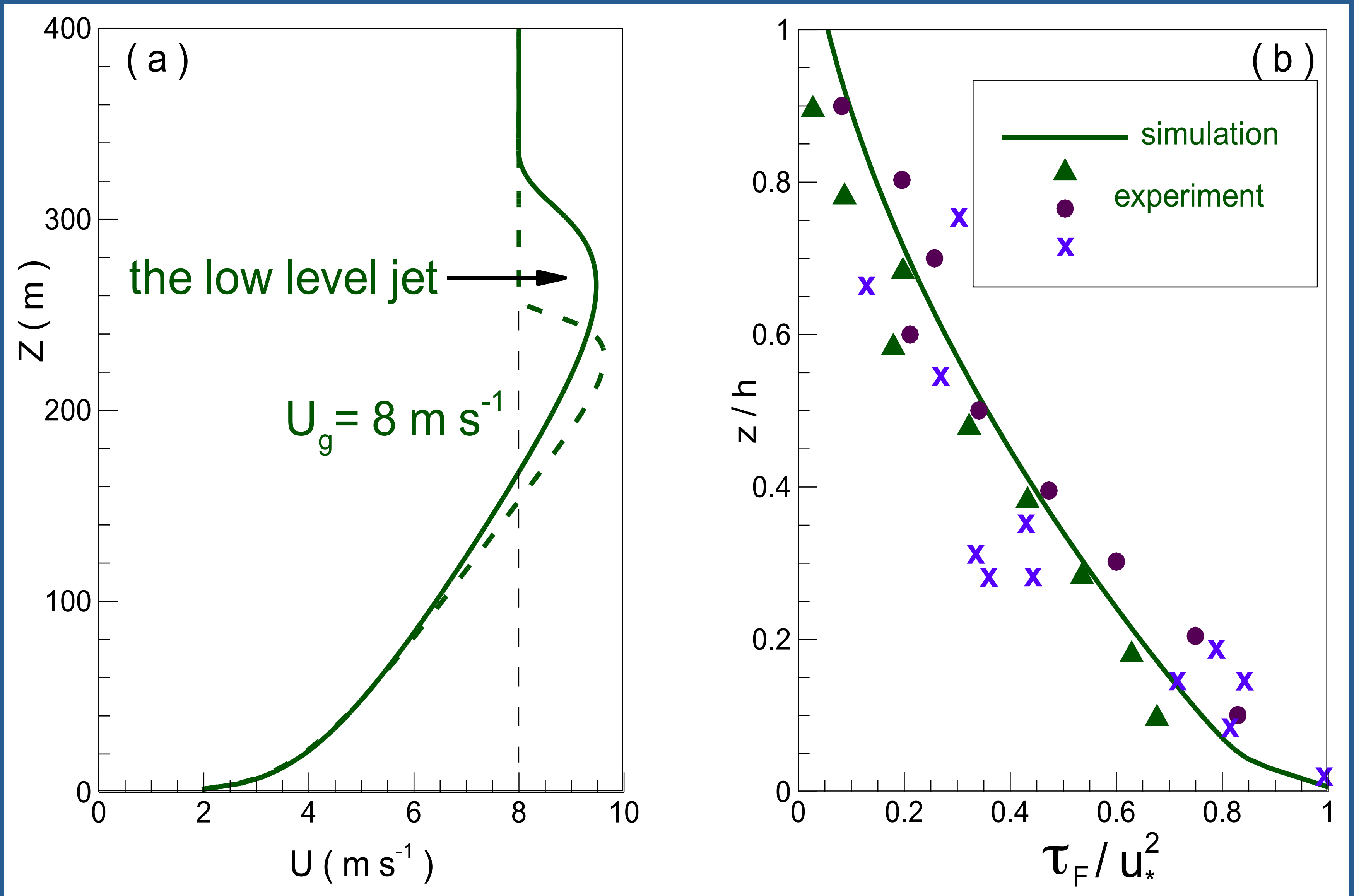




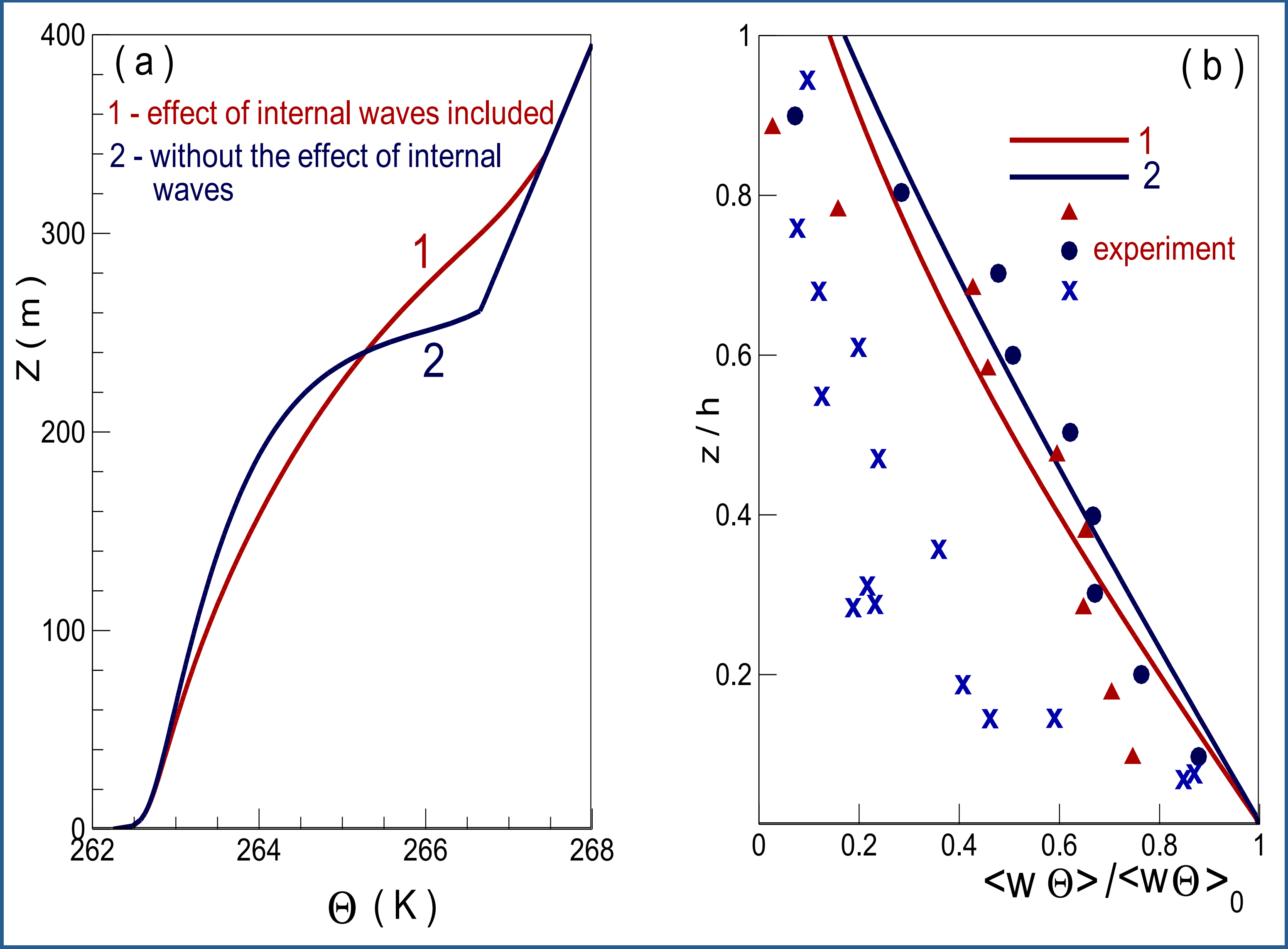
$$fV = \frac{\partial \overline{u'w'}}{\partial z}$$

$$f\int_0^\infty V dz = -\left(\overline{u'w'}\right)_0$$

Horizontal wind speed and full turbulent momentum flux in the stable boundary Layer: Numerical results



Potential temperature and vertical heat flux in stably stratified boundary layer: Numerical results



Efficiency of eddy mixing in stable atmospheric shear flows

Behavior of inverse turbulent Prandtl number $\mathrm{Pr}_t^{-1} \equiv K_H / K_M$ and the flux Richardson number

$$R_f = \frac{-\overline{b'w'}}{-\overline{u_i' u_j'}\left(dU_i / dx_j\right)}$$

obtained in the diurnal simulation of atmospheric boundary layer

Flux Richardson number as the mixing efficiency in stably stratified geophysical flows

$$R_f = \frac{-\overline{b'w'}}{-\overline{u_i' u_j'}\left(dU_i / dx_j\right)}$$

$$\frac{\partial E}{\partial t} + U_j \frac{\partial E}{\partial x_j} = \overline{u_i' u_j'} \frac{\partial U_i}{\partial x_j}\left(1 - R_f\right) + \mathrm{Diff}_E - \varepsilon$$

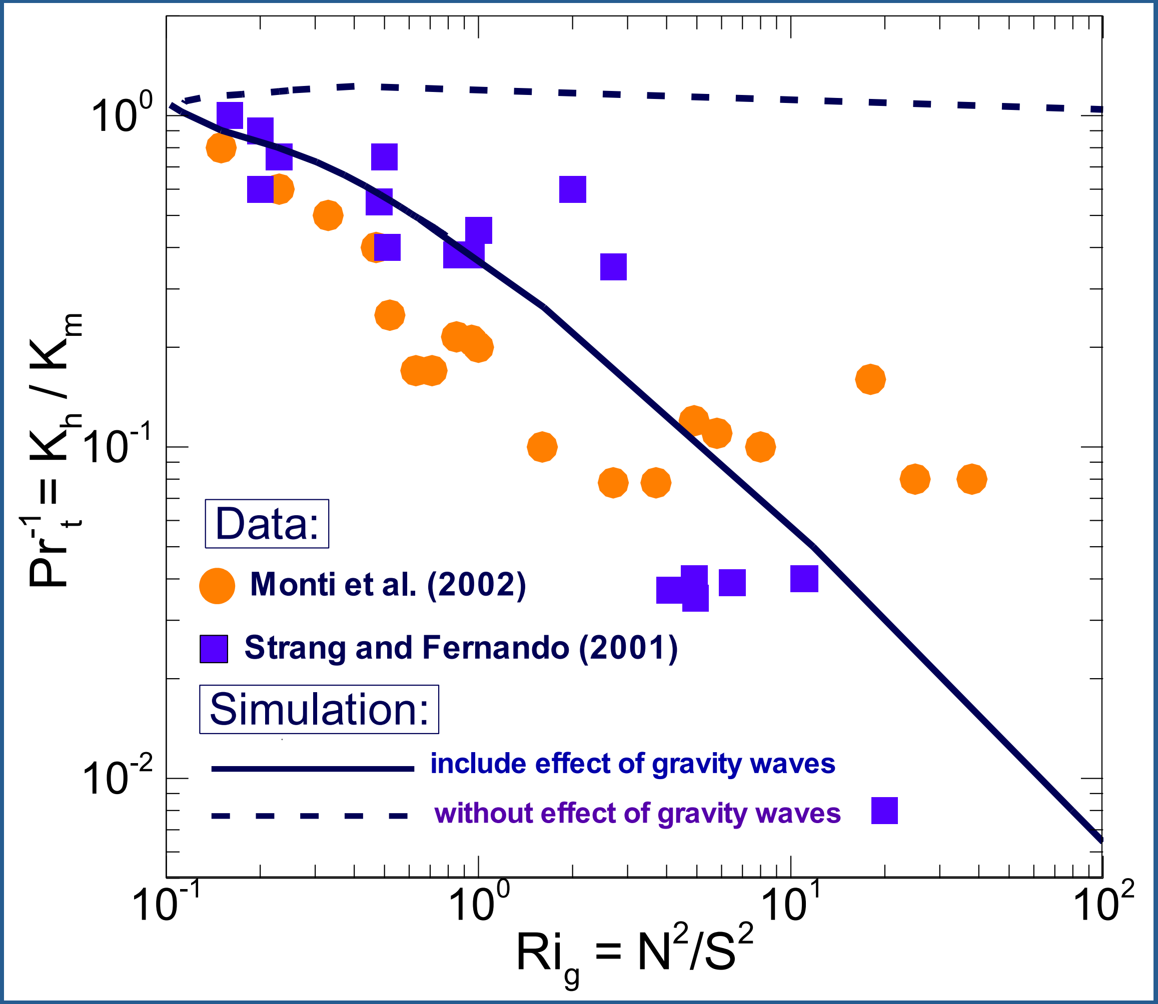
The flux Richardson number is a key parameter in modeling of geophysical flows.

For the non-homogeneous shear stratified flows , the improved three parameter turbulence model gives the following expression

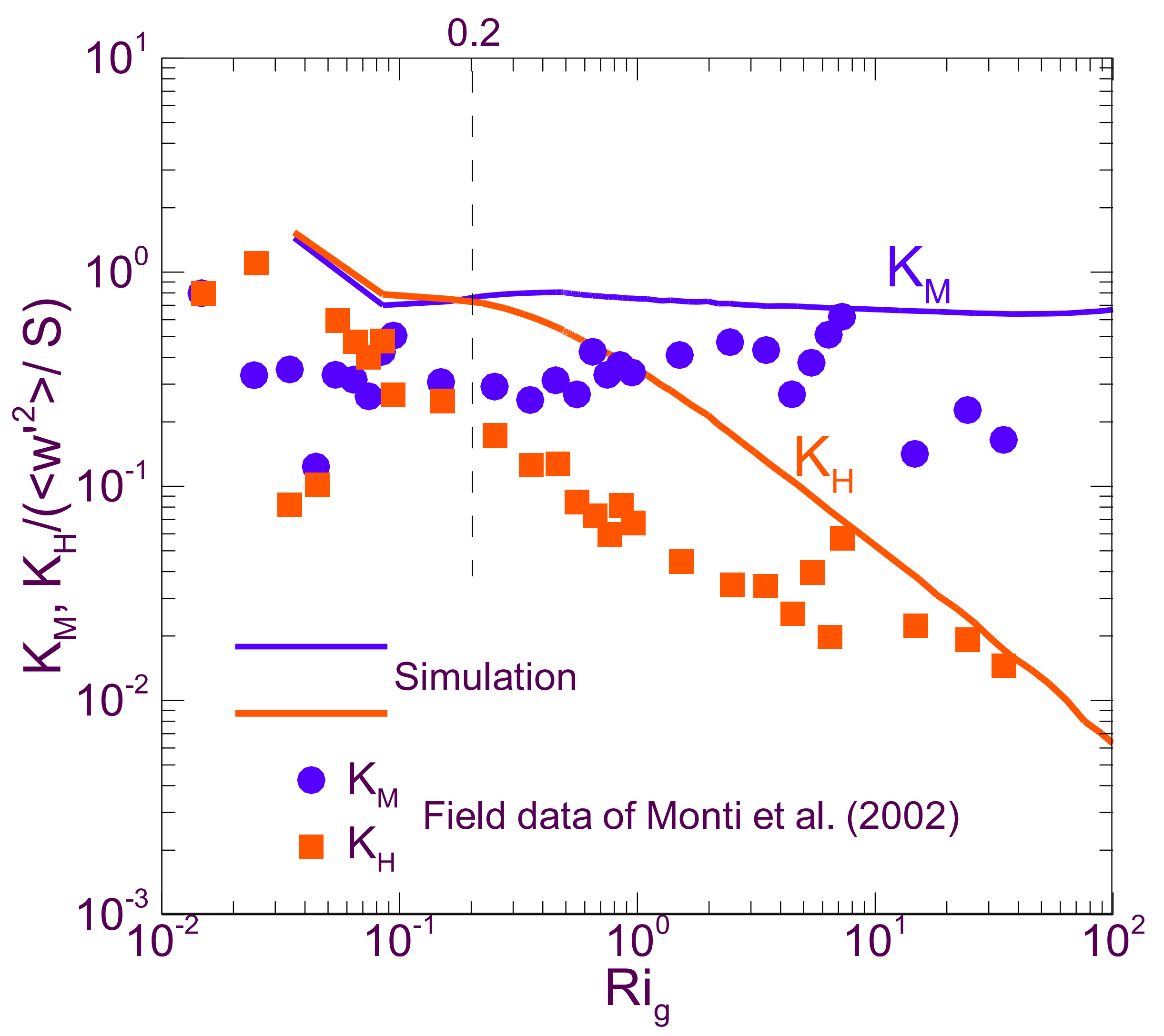
$$R_f = \mathrm{Pr}_t^{-1}\,\mathrm{Ri}_g - \frac{\beta g}{P}\gamma_c$$

$$P \equiv -\overline{u'w'}\left(\partial U / \partial z\right) - \overline{v'w'}\left(\partial V / \partial z\right) = K_m\left(\left(\partial U / \partial z\right)^2 + \left(\partial V / \partial z\right)^2\right)$$

Inverse Turbulent Prandtl Number in the SBL



Eddy diffusivities of momentum and heat



The flux Richardson number is a key quantity embedded in turbulence modeling of geophysical flows.

- **By solving a set of simplified equations for the Reynolds stresses and heat flux, Mellor and Yamada (MY 1982) proposed**

$$R_f = 0.725\left[Ri_g + 0.186 - (Ri_g^2 - 0.316Ri_g + 0.0346)^{1/2}\right]$$

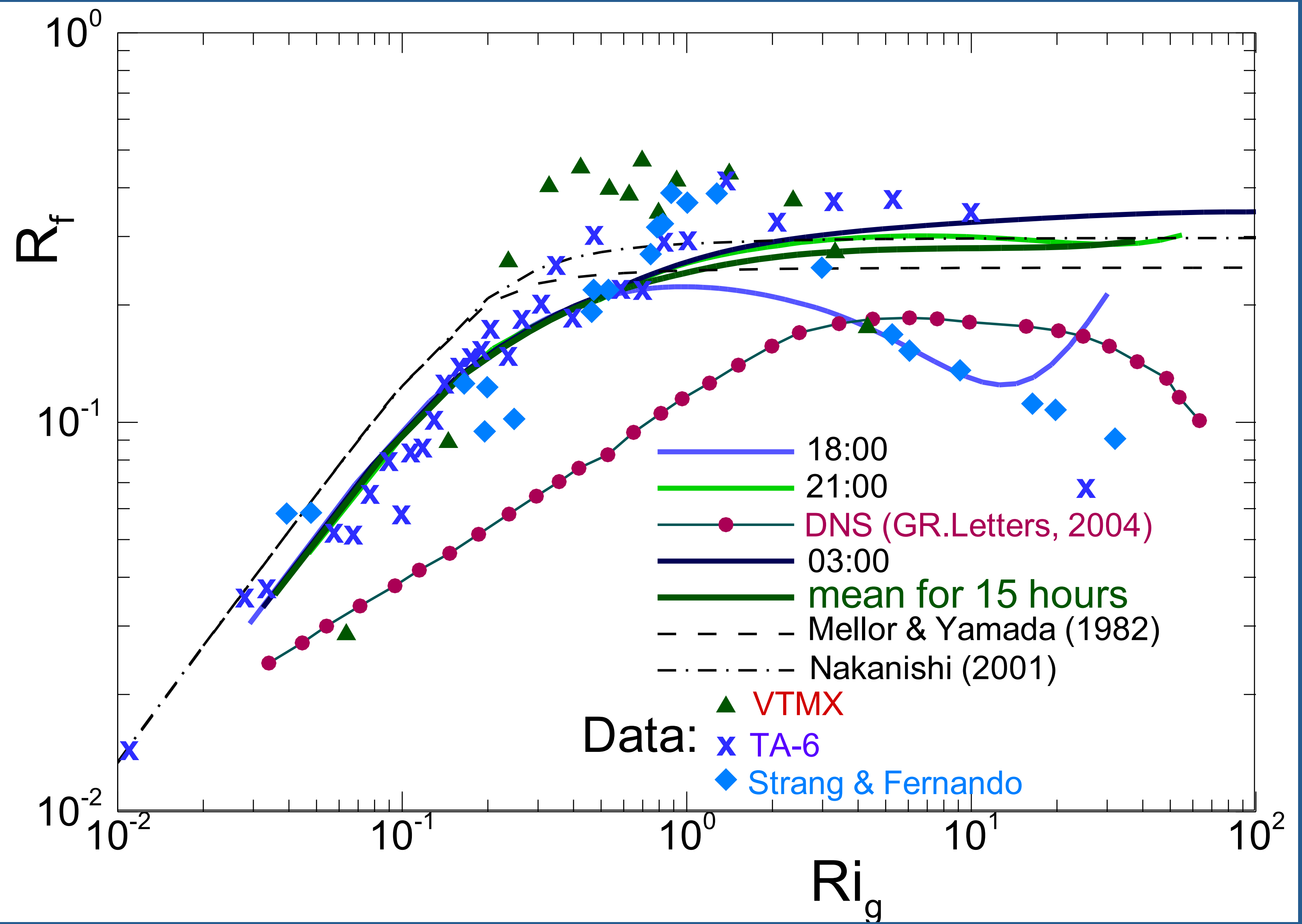
which yields the monotonic behavior with a maximum flux Richardson number of 0.25.

- **Nakanishi (2001) used LES for non-neutral periods to improve the My82 parameterization,**

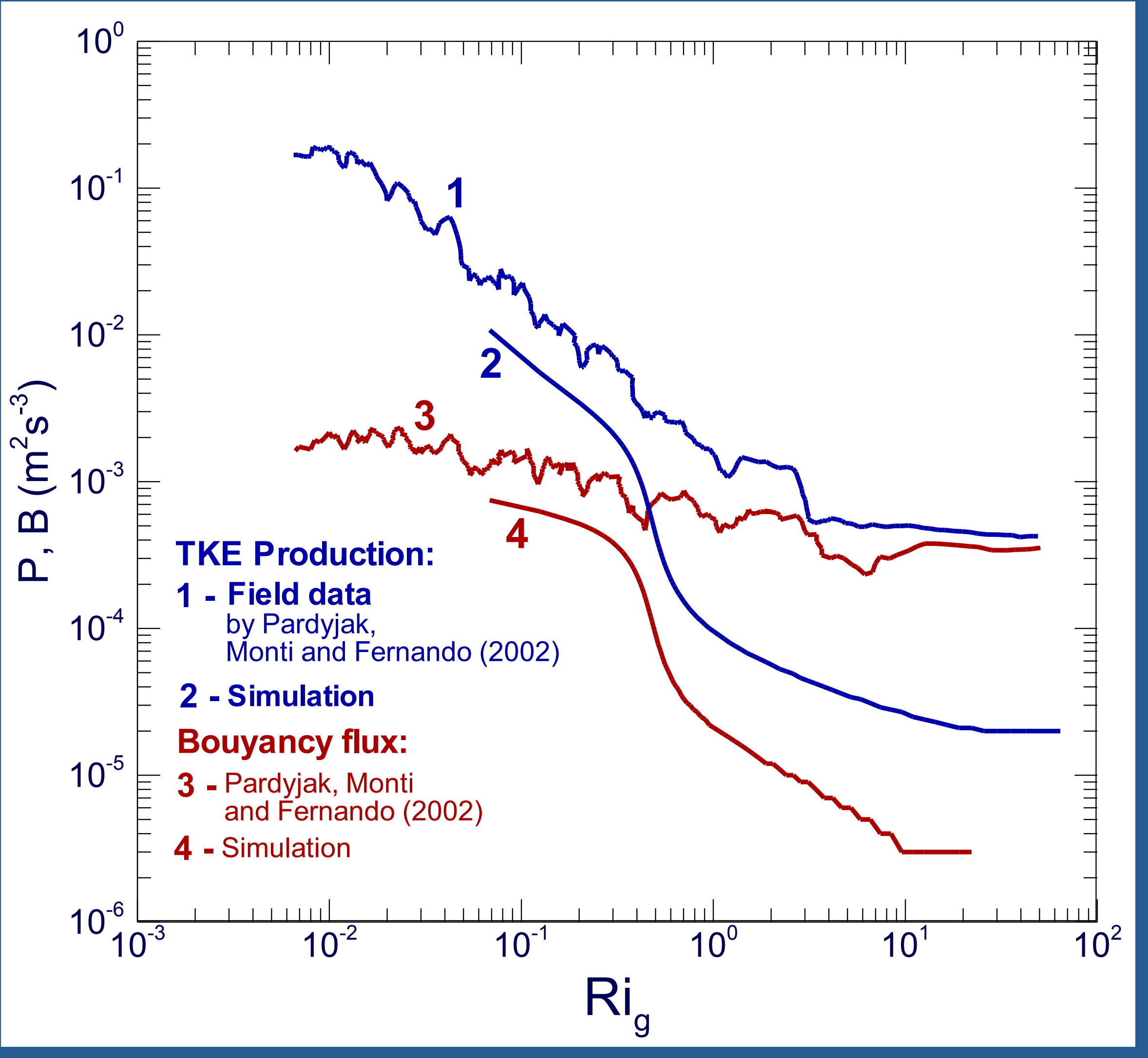
$$R_f = 0.774\left[Ri_g + 0.220 - (Ri_g^2 - 0.328Ri_g + 0.0484)^{1/2}\right]$$

with the limited flux Richardson number of 0.30.

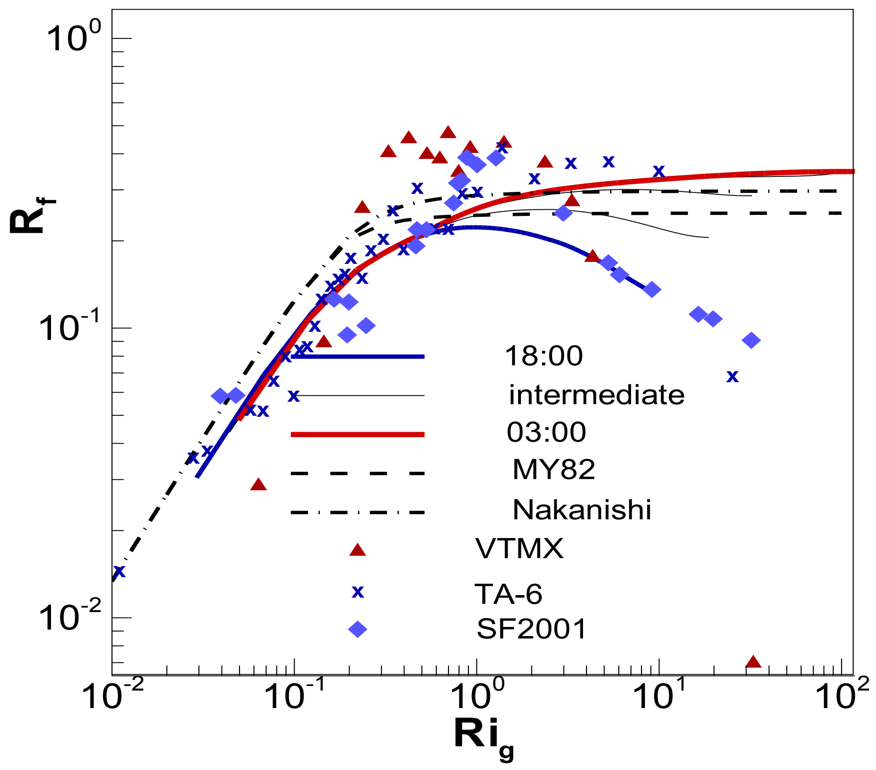
Mixing Efficiency in SBL: the non-monotonic dependence of R_f on Ri_g

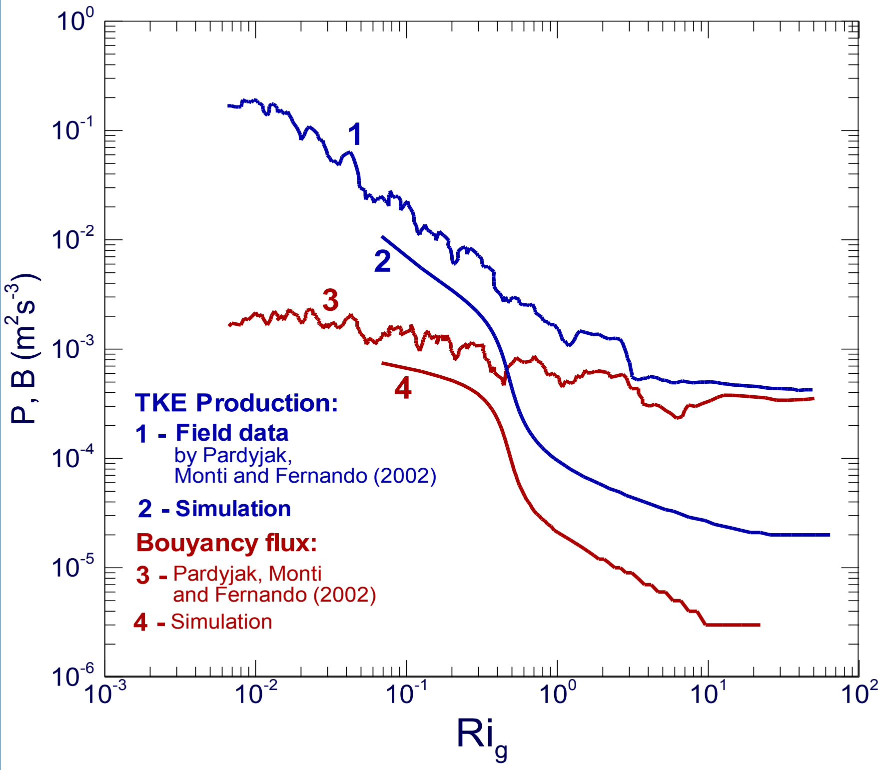


Mixing Efficiency: the variation of shear production and buoyancy flux

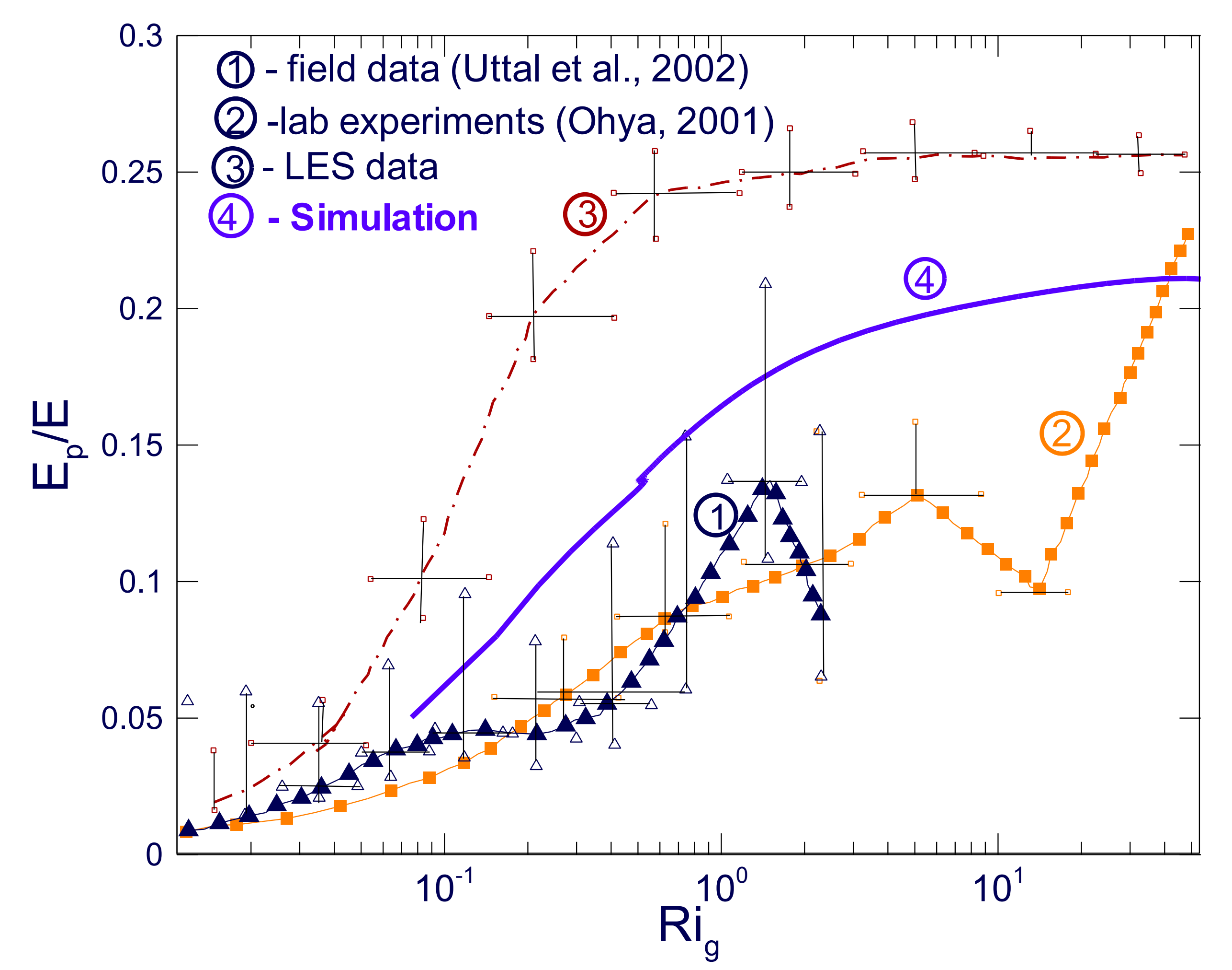


Flux Richardson number:
Strong and weak mixing regimes





Turbulence energetics in stably stratified boundary layer: Strong and weak mixing regimes



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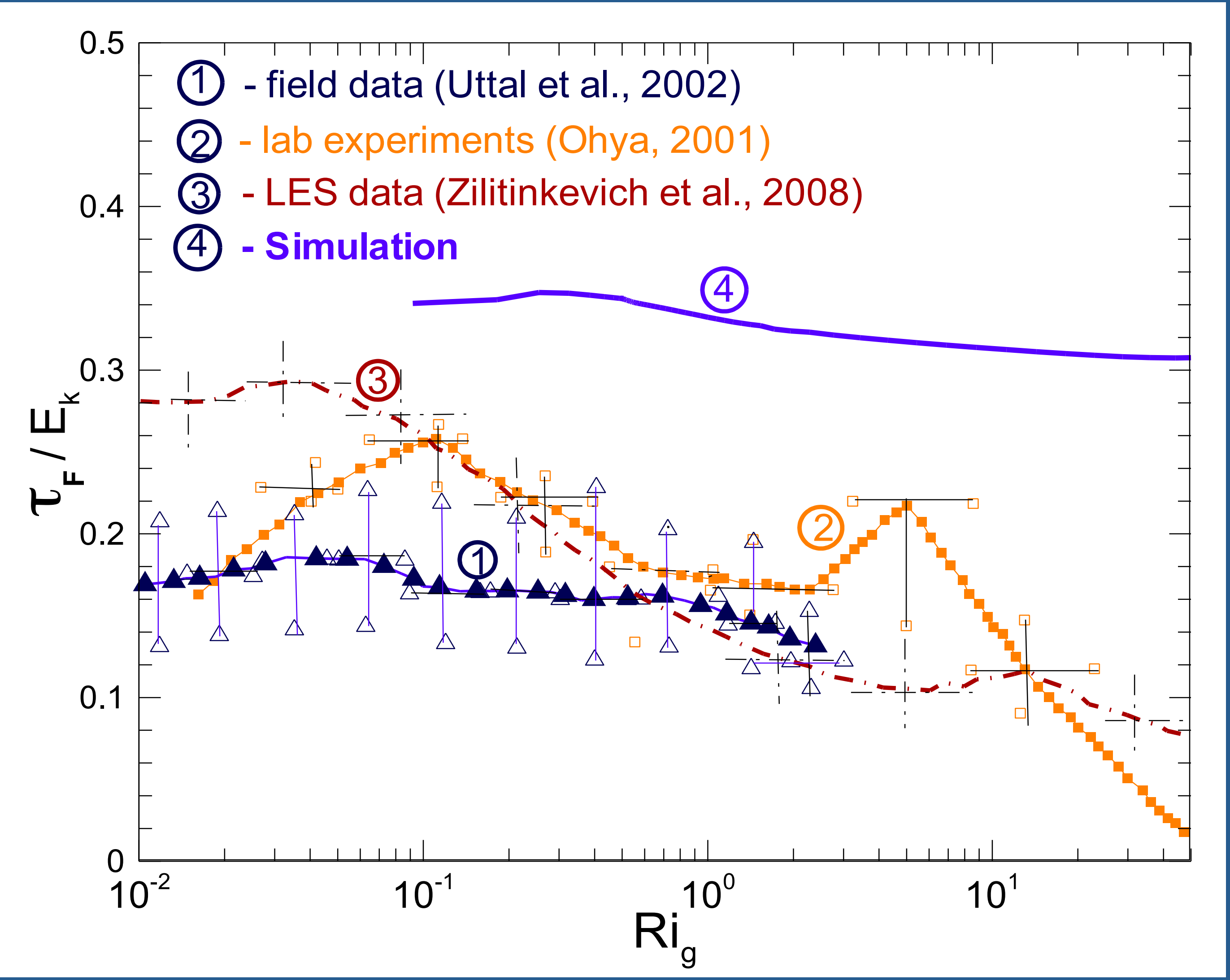
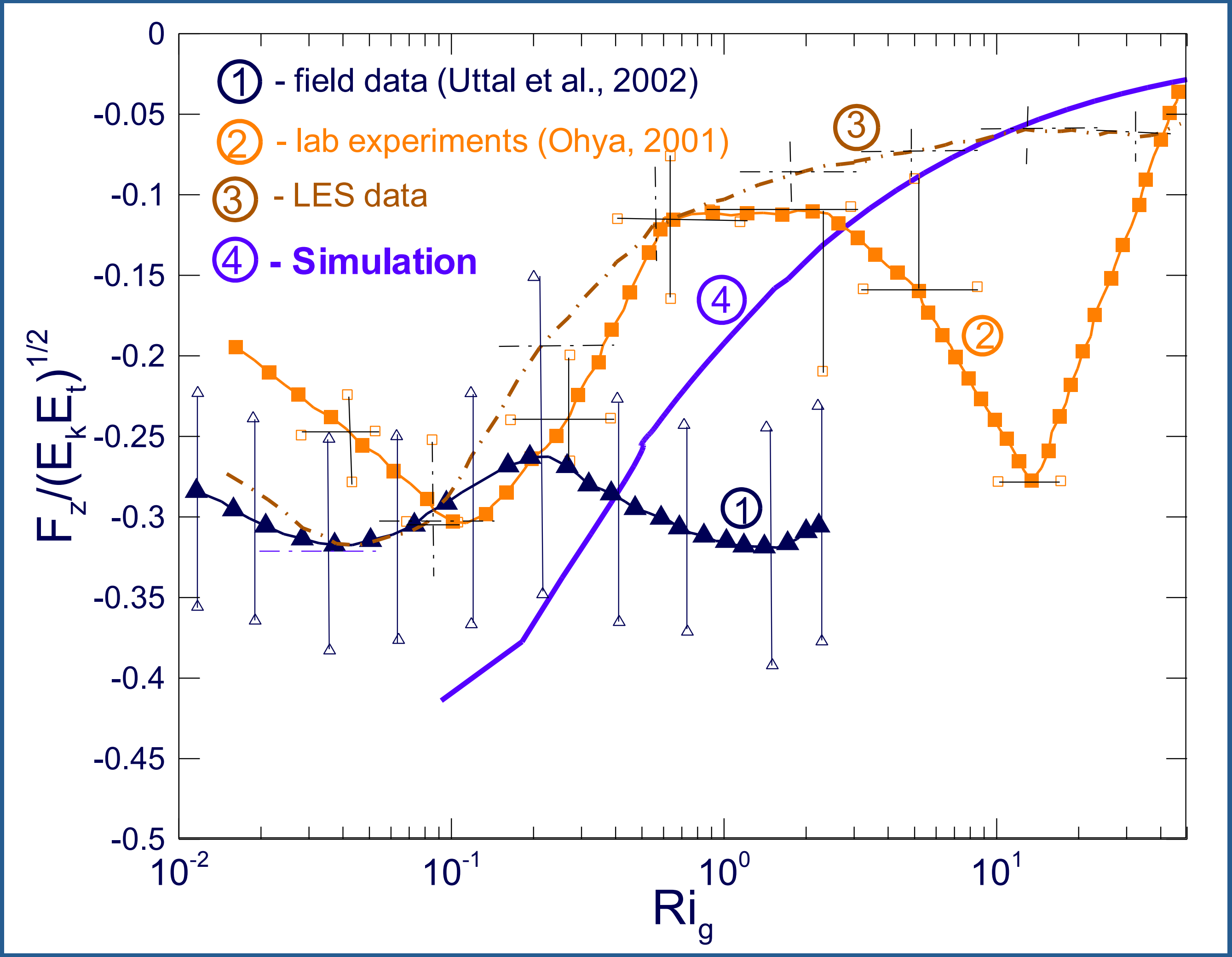


Turbulence energetics in stably stratified boundary layer: Strong and weak mixing regimes



CONCLUSION

- The improved three-parameter theory of turbulence for describing the stratified flows was presented. The modification of the buoyancy time scale is the key ingredient that allows the improved model to perform well for the arbitrary large gradient Richardson number.
- It is shown that with a single change of the buoyancy time scale the improved turbulence model reproduces the decreasing trend of inverse turbulent Prandtl number with increase of gradient Richardson number in agreement with measurements data.
- Our numerical results indicated that with increase stability the non-monotonic dependence of Rf on Rig in the transition periods to the stronger stable state is fixed.

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