Turbulence and Vertical Fluxes in the Stable Atmospheric Boundary-Layer: Large-Eddy Simulation & Parametrization in Single-Column Models

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

1. Department of Civil and Environmental Engineering, Princeton University 2. NOAA/GFDL

Motivation

⊙ Parameterization of the stably-stratified atmospheric boundary-layer is of crucial importance to large-scale atmospheric models, especially in Polar Regions.

⊙ However, the performance of most available parameterization schemes are very stability-sensitive such that operational climate models have to impose excessive turbulence mixing to prevent decoupling of the atmospheric component from the land component under strong stability.

⊙ We develop and test a general turbulence mixing model of the stable boundary-layer that works well under varying stabilities using large-eddy simulations (LES) and a Single-Column Model (SCM).

Study Cases

We study cases based on the one used by the Global Energy and Water Cycle Experiment Atmospheric Boundary-Layer Study (GABLS) (Beare et al. 2006; Cuxart et al. 2006). A horizontally homogeneous land surface and a constant geostrophic wind is assumed. Six cases with steady surface cooling rates and two cases with unsteady surface cooling rates are used:

Case	Cooling rate (K h^{-1})	h (m)	u_* (m s^{-1})	θ_* (K)	L (m)
A	0.25	173	0.253	0.0406	105
B	0.5	149	0.234	0.0699	52.1
C	1	126	0.217	0.123	25.0
D	1.5	113	0.207	0.169	16.1
E	2	103	0.198	0.211	11.7
F	2.5	96.2	0.191	0.249	9.03

Table 1. Statistics for cases with steady surface forcings: Case A - F.

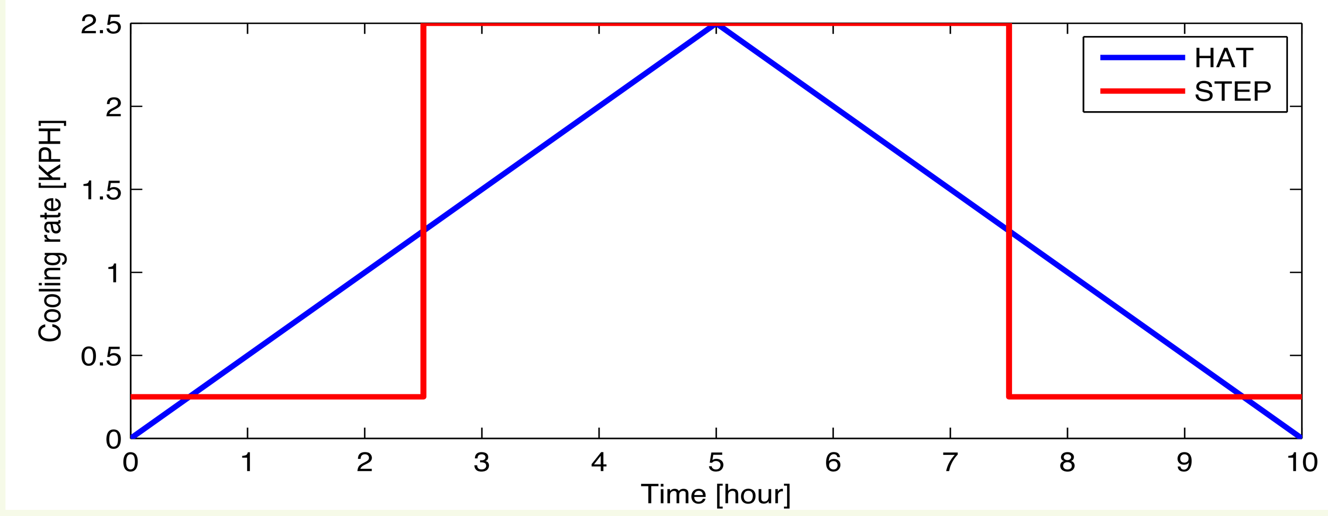

Figure 1. Surface cooling rates of the two unsteady cases: HAT and STEP.

⊙Major features of LES and SCM:

⊙Scale-dependent Lagrangian dynamic subgrid-scale (SGS) model

⊙Dynamic SGS *Pr* number

⊙LES: 162×162×160 nodes & 800×800×400 m^3

⊙SCM: vertical resolution of 2.5 m

Model Formulation

Traditionally the mixing length under stable conditions has been formulated as:

$$l_m = l_N f_m^{1/2}\left(Ri_g\right)$$

where l_N is the mixing length under neutral conditions, Ri_g is the gradient Richardson number and f_m is an empirical correction function. We show in Figure 2 that f_m is not a universal function of Ri_g. We propose instead the following form of l_m, and the comparison between the LES computed mixing length and the one given by this model is shown in in Figure 3.

$$\frac{1}{l_m} = \frac{1}{l_N} + \frac{Ri_g}{\lambda}$$

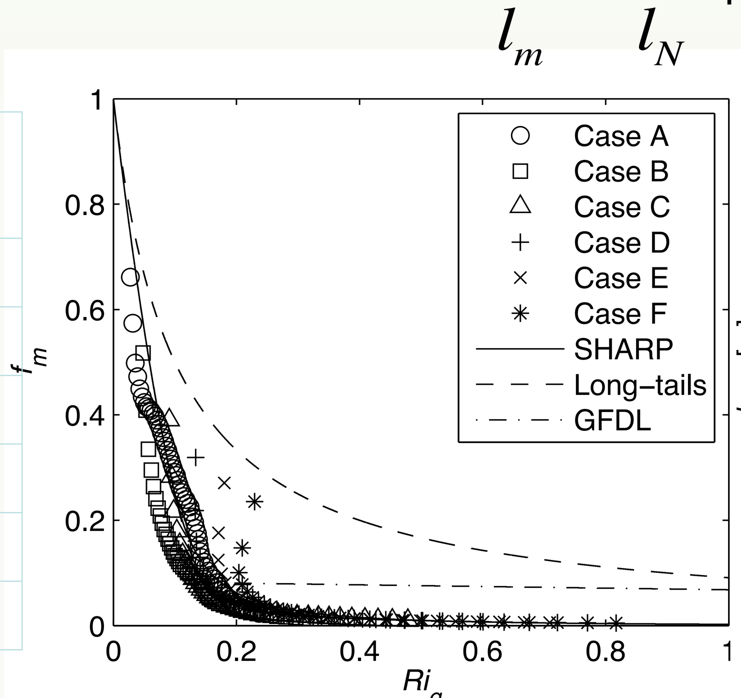

Figure 2. Traditional model.

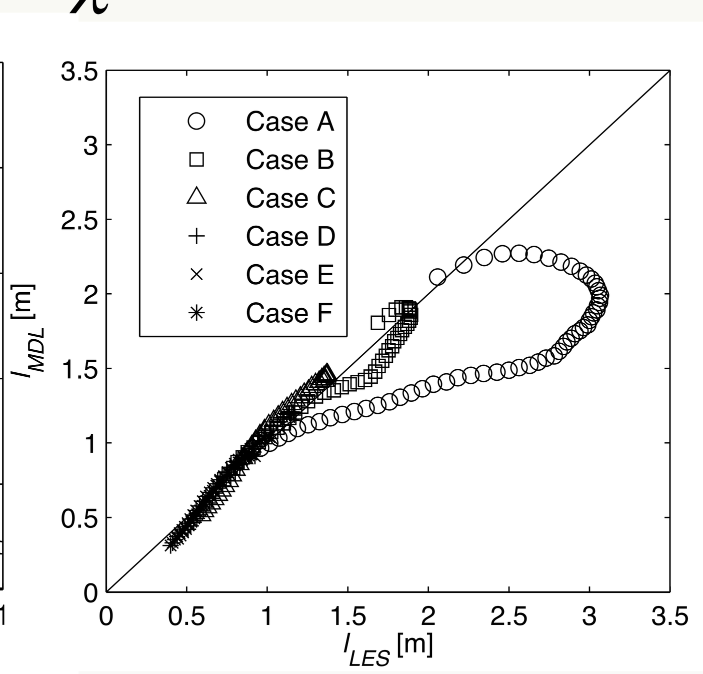

Figure 3. Our model (HBG).

Results

For cases with steady forcings:

⊙ All three models perform well for Case A.

⊙ Only the HBG model works well for B-F.

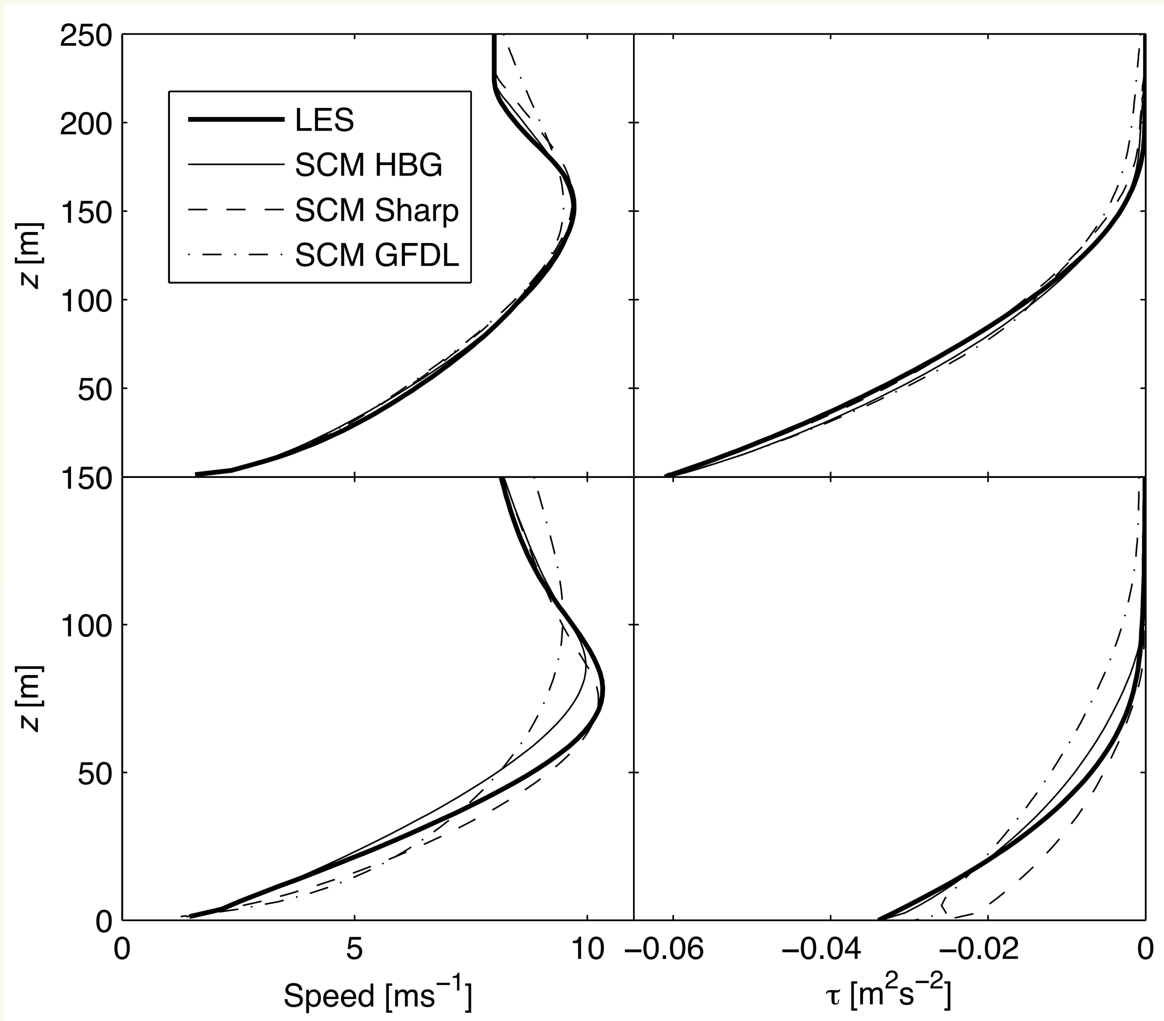

Figure 4. Vertical profiles for cases with steady forcings: (top) Case A; (bottom) Case F.

For cases with unsteady forcings:

⊙ The HBG model reproduces the near-surface temperature that is closes to LES.

⊙ For u_*, the HBG model converges to the LES results, while the other two do not.

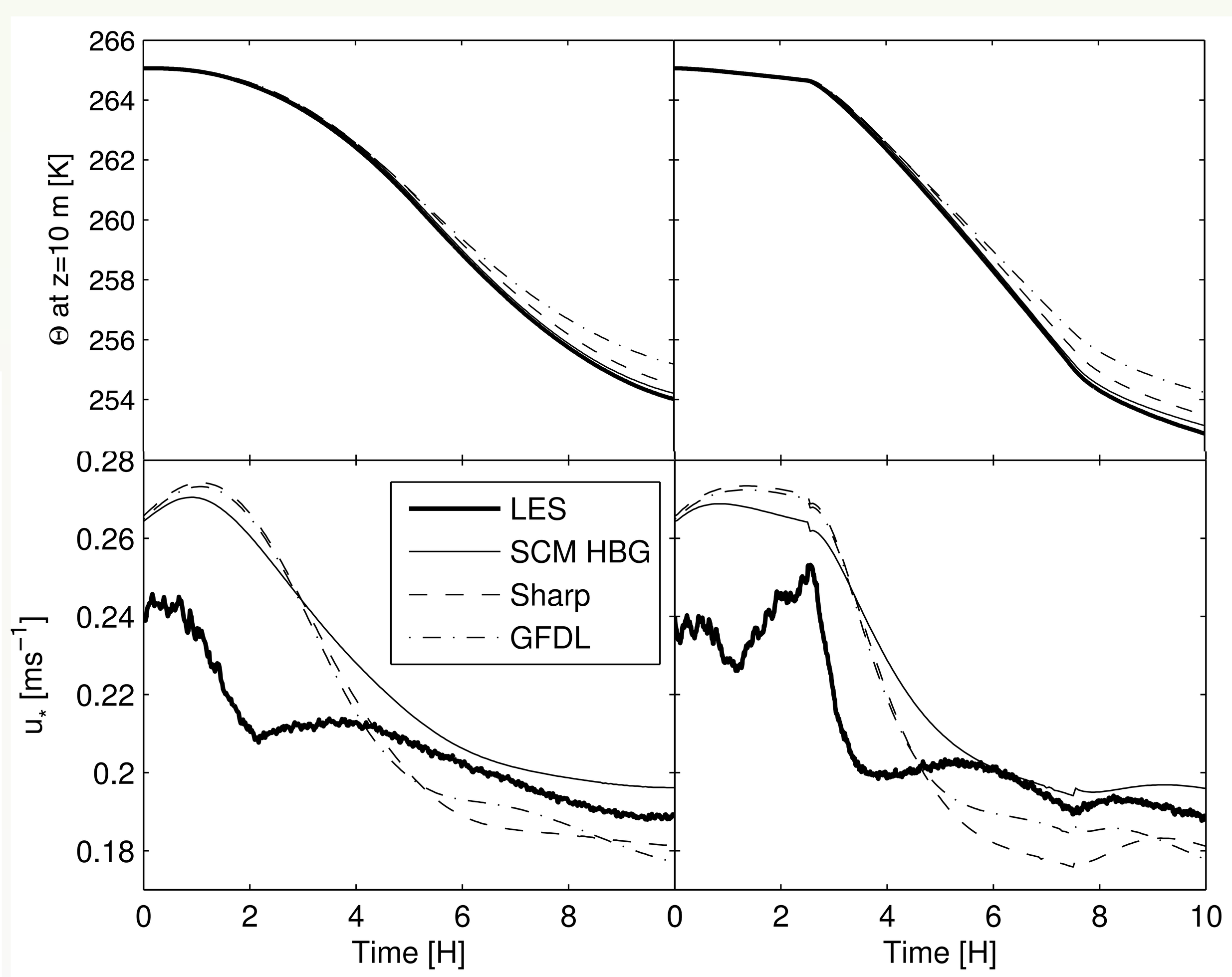

Figure 5. Time history for cases with unsteady forcings: (left) HAT; (right) STEP.

Conclusion

We developed a new first-order turbulence mixing model for the stable atmospheric boundary-layer. This model was tested using the GFDL single-column model by comparing to fine resolution large-eddy simulations. Using test cases with both steady and unsteady surface cooling rates, we found that:

⊙ The traditional parameterizations based on the concept of a stability correction function do not work under strong stabilities.

⊙ Instead, the performance of our new model (HBG) is rather stability-insensitive (tested till Ri_g of ~ 1).

⊙ The HBG model also performs better when stability forcings are unsteady.

⊙ With increasing stability: 1) angle between stress and strain decreases, 2) turbulent structures become more pancake-like, 3) buoyant destruction becomes ~ viscous dissipation.

References

1. Beare, RJ et al., An intercomparison of large-eddy simulations of the stable boundary-layer. *Boundary-Layer Meteorol.* **118**:247-272.

2. Cuxart, J et al., Single-column model intercomparison for a stably stratified atmospheric boundary-layer. *Boundary-Layer Meteorol.* **118**:273-303.

Acknowledgements

This work is funded by NSF under AGS-1026636 and by the Energy Grand Challenges Program - Princeton. The simulations were performed on the supercomputers of the National Center for Atmospheric Research.