Jing Huang, Marcus Thatcher and Elie Bou-Zeid (2016) Testing the HBG model under strong stabilities of GABLS4: a SCM inter-comparison study using CCAM. The 22nd Symposium on Boundary Layers and Turbulence, The American Meteorology Society. 20-24 June 2016, Salt Lake City, USA.

Testing the HBG model under strong stabilities of GABLS4: a SCM inter-comparison study using CCAM

Jing Huang[1,*] , Marcus Thatcher[1] and Elie Bou-Zeid[2]

1 CSIRO Oceans and Atmosphere Flagship, Australia
2 Civil and Environmental Engineering, Princeton University, USA

Abstract

The difficulty in simulating and modeling the stable Atmospheric Boundary-Layer (ABL) increases with stability. The GABLS-4 project is designed to address this challenge and study the ABL under strong stability (Ri>1) through a series of inter-comparison studies of Land Surface Models (LSM), Single Column Models (SCM) and Large Eddy Simulations (LES). We have participated in the SCM inter-comparison of GALS-4 using the CSIRO's Cubic Conformal Atmospheric Model (CCAM). Three ABL parameterization schemes for stable conditions have been tested for this study: (1) the HBG model (Ri-based) proposed in Huang et al. (2013), (2) the Louis (1979) scheme and (3) a standard prognostic k-epsilon approach. The main difference of the HBG model from other Ri-based schemes is that the mixing length under stable conditions is not a corrected form based on its formulation under neutral conditions. Instead, the mixing length in the HBG model depends on Ri only under strongly stable conditions. In this paper, we will present how the HBG model is derived and parameterized based on a suite of LES runs under moderate and intermediate stabilities (Ri<=1). Then, the performance of the HBG model in CCAM will be tested, and compared with other well-known turbulence closure schemes as well as with observation under strong stabilities.

1. Introduction

The Atmospheric Boundary-Layer (ABL) becomes stably stratified when the land surface is cooler than the air above it. The Stable ABL (SABL) typically forms over polar regions and over continental land surface during night and wintertime. Consequently, it is vital to represent the SABL accurately within weather and climate models. Unfortunately, our current understanding in the detailed processes of the SABL is rather limited compared to those of the neutral and unstable ABL, thus preventing us from developing accurate models for the SABL.

[*] *Corresponding Author*: CSIRO Oceans and Atmosphere, GPO Box 3023, Canberra, ACT 2601, Australia
E-mail: jing.duke@gmail.com (Jing Huang)

The Global Energy and Water Exchanges (GEWEX) Atmospheric Boundary Layer Study (GABLS) represents an effort to better understand the SABL through inter-comparison studies of Land Surface Models (LSM), Single Column Models (SCM) and Large Eddy Simulations (LES) for specific cases. In the previous three GABLS cases, weak to moderate stabilities (Ri<1) have been studied raising the attention of operational modeling centers to examine the SABL schemes. In the GABLS4 case organized by Meteo France, the aim is to study the interaction of an SABL under strong stabilities (Ri>1) with a snow surface, which is based on a real case at the Antarctic Plateau at DomeC.

GABLS4 consists of four stages of model inter-comparisons and we have participated the latter three stages. Stage 1b involves the interaction of SCM and LSM with prescribed atmospheric forcing and initial surface and soil conditions. Stage 2 uses the same SCM and LSM as in stage 1b and further prescribes the surface temperature. Stage 3 is a rather simplified version of stage 2 with no radiation, no humidity and constant geostrophic wind.

We will briefly introduce the SCM and the LSM used in this study in Section 2. Then in Section 3, the HBG model and other benchmark models are introduced. The results are demonstrated in Section 4 and the study is summarized in Section 5.

2. Cubic Conformal Atmospheric Model (CCAM)

The Cubic Conformal Atmospheric Model (CCAM) is a global forecasting model developed by CSIRO (McGregor, 2005; McGregor & Dix, 2008). A unique feature of CCAM is that it supports a variable-resolution global grid through the use of Schmidt transformation (Schmidt, 1977). Therefore, it is able to focus on a target area with a fine grid spacing while avoiding the need for any special treatment of simulation boundaries. In this study, CCAM is run in single column mode and couples with the CSIRO Atmosphere Biosphere Land Exchange (CABLE) model, which is a land surface model developed by the CSIRO (Kowalczyk, et al., 2006).

3. The HBG model and other models for SABL

The CCAM SCM has three options for the representation of the SABL: (1) the Louis (1979) scheme; (2) a prognostic k-epsilon approach; and (3) the HBG model. To introduce the exact formulations of the three models, a few parameters need to be defined in advance.

The eddy diffusivity for momentum K_m in the ABL is expressed as:

$$K_m = {l_m}^2 \left[\left(\frac{\partial \mathrm{U}}{\partial z}\right)^2 + \left(\frac{\partial \mathrm{V}}{\partial z}\right)^2 \right]^{1/2}, \qquad (1)$$

where l_m is the mixing length, U and V are the mean streamwise velocity and mean spanwise velocity, respectively, and z is the vertical direction.

The gradient Richardson number is defined as:

$$Ri_g = \frac{g}{\Theta}\frac{\partial\Theta}{\partial z}\left[\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2\right]^{-1}, \tag{2}$$

where Θ are the mean potential temperature, and g is the gravitational acceleration.

Louis (1979) proposed that the mixing length l_m under stable conditions can be obtained from its form under neutral conditions l_N by adding a multiplicative factor f_m, i.e.:

$$l_m{}^2 = l_N{}^2 f_m(Ri_g), \tag{3}$$

where f_m takes the following form:

$$f_m(Ri_g) = (1 + 4.7Ri_g)^{-2}. \tag{4}$$

The classical form suggested by Blackadar (1962) for l_N is used:

$$\frac{1}{l_N} = \frac{1}{\kappa z} + \frac{1}{l_\infty} \tag{5}$$

where κ is the von Karman constant, and l_∞ is a constant representing a turbulence mixing length far above the land surface. Louis (1979) also set l_∞ = 100 m.

Huang et al. (2013) studied the parameterization of the SABL based on a suite of LES runs and found that the concept of introducing a stability correction function f_m as a multiplicative factor into the mixing length used under neutral conditions is problematic because f_m computed a priori from LES tends not to be a universal function of stability. Instead, Huang et al. (2013) proposed the HBG model for the mixing length under stable conditions:

$$\frac{1}{l_m} = \frac{1}{\kappa z} + \frac{1}{l_\infty} + \frac{Ri_g}{\lambda} \tag{6}$$

λ is a constant length scale under stable conditions, which was set to be 0.45 m by Huang et al. (2013). Huang et al. (2013) also determined that the appropriate value for l_∞ would be 9 m based on their fine-resolution LES results. This formulation makes sense because in the neutral limit where $Ri_g = 0$, Equation (6) reduces to the classical form of Equation (5). In the stable limit where the first two terms in the RHS of Equation (6) become negligible, the mixing length becomes inversely proportional to stability, which was demonstrated by Huang and Bou-Zeid (2013) and Huang et al. (2013).

Being aware of the sensitivity of l_∞, we also construct a modified Louis (1979) scheme with l_∞ set to be the same as in the HBG model (i.e. l_∞ = 9 m).

4. Results

We first examine the time series of surface temperature and ABL height for Stage 1b as shown in Figure 1. The Louis scheme overestimates the turbulent diffusivities of the SABL as evidenced by a spurious deep boundary layer, which is mainly attributed to the unrealistic high value of l_∞. The overestimation also leads to a generally hotter surface compared to the observation. Conversely, the k-eps scheme underestimates the turbulent diffusivities of the SABL, which in turn causes a colder surface particularly during the night period. The results of surface temperature coincide for the HBG model and the modified Louis model with l_∞ = 9 m (hereafter the Louis 9m model), which confirms the importance of l_∞.

However, the ABL depth of the HBG model is considerably lower than the Louis 9m model during partial period of the diurnal cycle.

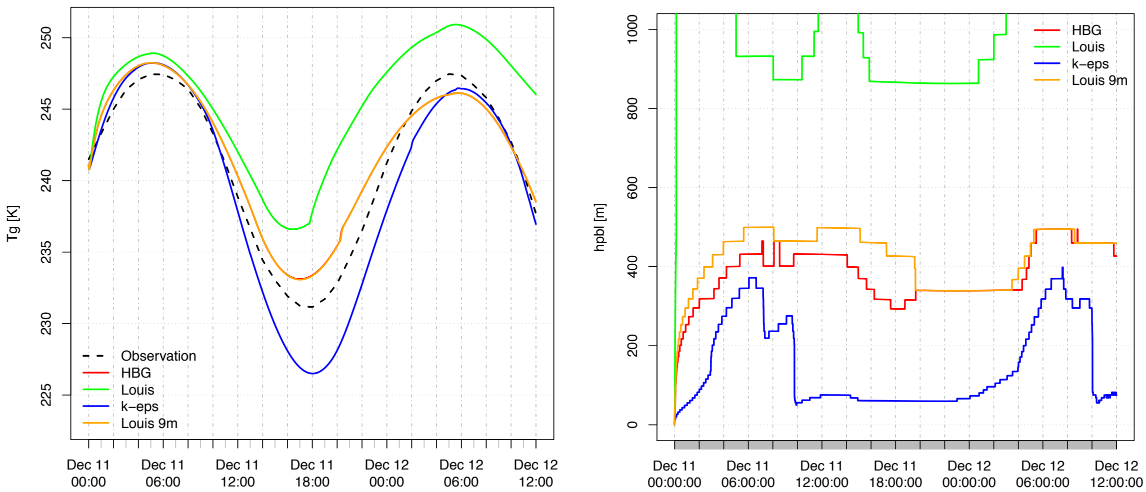

Figure 1. (Left) Surface temperature and (right) ABL height of GABLS4 stage 1b for four SABL schemes.

The results for surface sensible heat flux generally reinforce the conclusion obtained from interpreting Figure 1. Note that the observation for sensible heat flux is for z = 7m, which is not an ideal reference for surface sensible hat flux. The Louis scheme produces too much flux at the surface during nighttime by overestimating the turbulent diffusivities in the SABL. And the k-eps scheme produces the least flux among the four schemes. The HBG scheme and the Louis 9m scheme share very similar results.

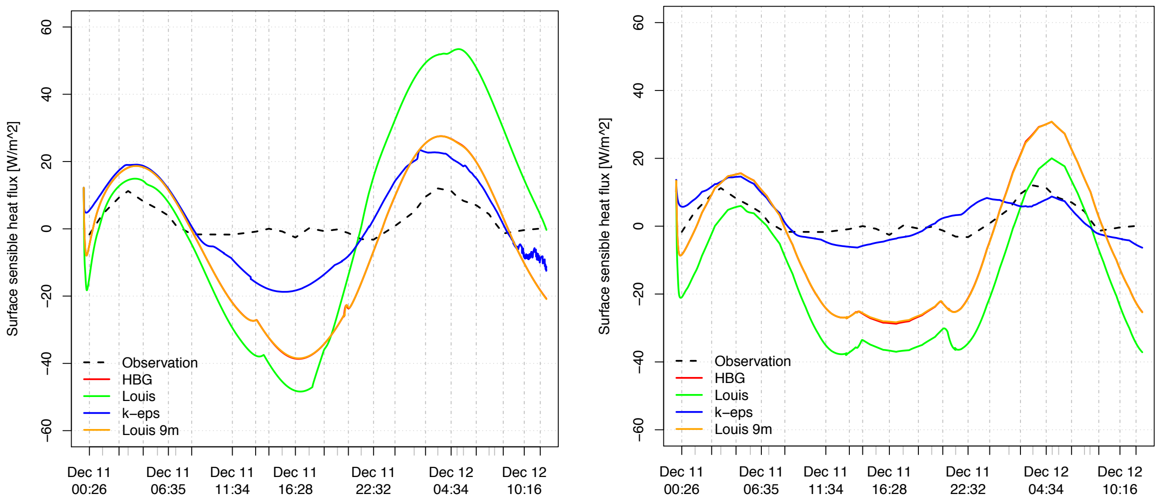

Figure 2. Surface sensible heat flux of GABLS4 Stage 1b (left) and Stage 3 (right). The observation time series is actually for z = 7m.

The updated (after presentation) result of temperature at 42 m again demonstrate that the HBG scheme and the Louis 9m scheme are the best compared to the original Louis scheme and the k-eps scheme. At Stage 1b, the k-eps scheme results in lower temperature during night with a maximum deviation of about 8 degrees. At Stage 3, the k-eps scheme even gives a constant temperature during night due to a spurious shallow SABL. The original Louis scheme overestimates the temperature at 42m significantly.

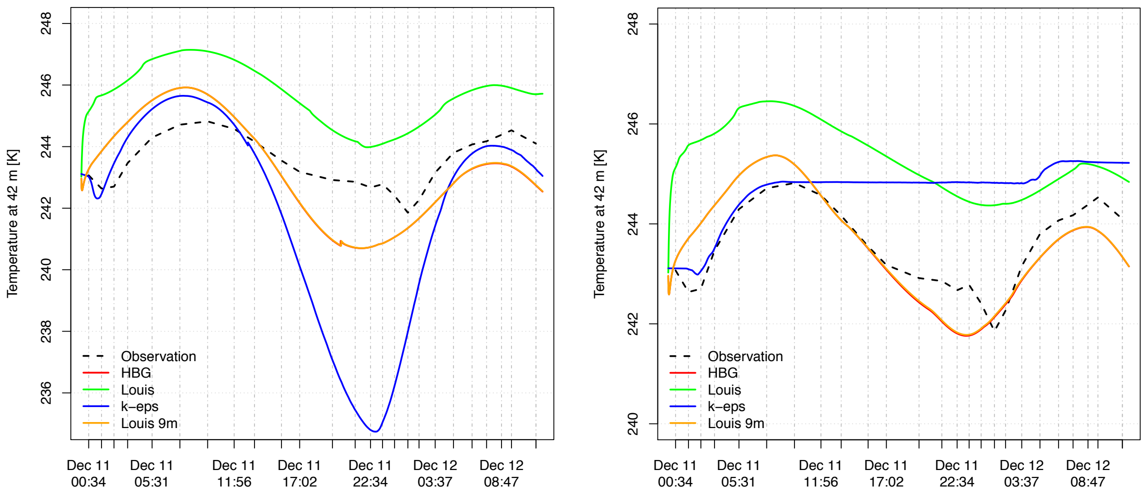

Figure 3. Temperature at 42 m for GABLS4 Stage 1b (left) and Stage 3 (right). The results have been updated after the presentation.

All the results shown above do not reveal the difference of the HBG scheme and the Louis 9m scheme. However, it is shown in the result of wind speed profile (Figure 4). While the HBG scheme produces a low-level jet (LLJ) which is typical for the SABL, albeit elevated by about 200 m, the Louis 9m scheme has none. The LLJ produced by the k-eps scheme matches relatively well with the LES result.

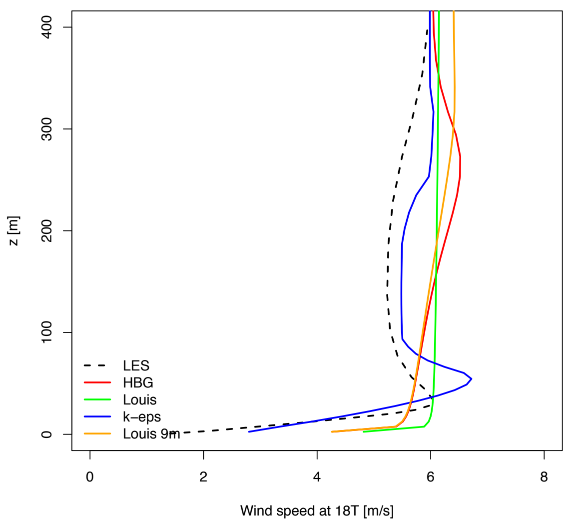

Figure 4. Wind speed profiles at 18T for GABLS4 Stage1b.

5. Summary

In this study, we have tested the performance of the HBG model under strongly stable conditions and unsteady forcing of GABLS4 using CSIRO-developed SCM and LSM. The HBG scheme is compared against the Louis (1979) scheme and a standard prognostic k-eps scheme. It is found that the HBG scheme gives the best overall result under strongly stable conditions, behaving very robustly. The Louis scheme, however, gives rise to a spurious deep SABL and a hot surface by overestimating the turbulent diffusivities in the SABL. On the contrary, the k-eps scheme leads to a spurious shallow SABL and a cold surface by underestimating the turbulent diffusivities in the SABL. The role of the asymptotic mixing length scale l_∞ is very important such that a modified Louis scheme with reduced l_∞ performs similarly as the HBG scheme. However, the modified Louis scheme does not produce LLJ, which is typical in a SABL.

References

Huang, J. & Bou-Zeid, E., 2013. Turbulence and vertical fluxes in the stable atmospheric boundary layer. Part I: A large-eddy simulation study. *Journal of Atmospheric Sciences,* Volume 70, pp. 1513-1527.

Huang, J., Bou-Zeid, E. & Golaz, J.-C., 2013. Turbulence and Vertical Fluxes in the Stable Atmospheric Boundary Layer. Part II: A Novel Mixing-Length Model. *Journal of Atmospheric Sciences,* Volume 70, pp. 1528-1542.

Kowalczyk, E. et al., 2006. *The CSIRO Atmosphere Biosphere Land Exchange (CABLE) model for use in climate models and as an offline model,* Aspendale, VIC: CSIRO Marine and Atmospheric Research.

Louis, J.-F., 1979. A parametric model of vertical eddy fluxes in the atmosphere. *Boundary Layer Meteorology,* Volume 17, pp. 187-202.

McGregor, J. L., 2005. *CCAM: Geometric aspects and dynamical formulation,* s.l.: CSIRO Marine and Atmospheric Research.

McGregor, J. L. & Dix, M. R., 2008. An updated description of the conformal-cubic atmospheric model. In: K. Hamilton & W. Ohfuchi, eds. *High-resolution simulation of the atmosphere and ocean.* s.l.:Springer, pp. 51-76.

Schmidt, F., 1977. Variable fine mesh in spectral global models. *Beitr. Phys. Atmos.,* Volume 50, pp. 211-217.