GABLS3-LES Intercomparison Study

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Abstract

Recently, a large-eddy simulation (LES) intercomparison study was organized under the auspices of the GEWEX Atmospheric Boundary Layer Study (GABLS). Eleven LES modelling groups around the world participated in this study to model a baroclinic, mid-latitude nighttime stable boundary layer utilizing several LES subgrid-scale (SGS) models. Some of the findings from this intercomparison study are unexpected, which make it quite unique. First of all, the LES-ensemble not only captures the statistics, but also the dynamical evolution of the observed variables remarkably well. Second, the diversity among the members of the ensemble is found to be surprisingly low. In other words, the simulated results (especially the first-order statistics) are not very sensitive to the LES-SGS parameterizations. Last, a relatively coarse spatial resolution of 6.25 m is shown to be adequate for representing the basic characteristics of a moderately/strongly stratified (the ratio of the boundary layer height and the Obukhov length is on the order of 5) boundary layer. In this conference paper, we discuss a subset of these findings.

1. Introduction

In comparison to the unstable and neutral boundary layers, the large-eddy simulation (LES) of stable boundary layers (SBLs) has a briefer and arguably less successful history. One of the first and comprehensive LES studies of SBLs (henceforth LES-SBL) was conducted by Mason and Derbyshire in 1990. In the following decade, only a mere handful of LES-SBL studies were reported in the literature (e.g., Brown et al. 1994; Andrén 1995; Saiki et al. 2000; Kosović and Curry 2000; Cederwall 2002). Several of these past studies reported various challenges and disappointments related to LES-SBL. For example, in the context of model initialization Mason and Derbyshire (1990) noted:

> *"Previous attempts to start directly from SBL mean profiles were failures... our first attempted simulations used as initial conditions a SBL with a mean velocity and temperature structure obtained from a 1D model (the 'direct' strategy).... To initialize the LES model, the resulting stable 1D flow was then subjected to three-dimensional random perturbations located in the expected boundary-layer region, and of a magnitude typical of the expected final turbulence level. For this 'direct' approach, two alternative domains... were used. However, in neither domain was turbulence maintained. A simulation with a much larger initial disturbance gave sustained turbulence, but the initial mean profiles were destroyed by the violent initial perturbations. The difficulty in sustaining turbulence under plausible initial conditions reflects the problems of specifying the initial mean and fluctuating fields.*

> *On the other hand, failure to sustain turbulence could be due to mismatch between the 1D and LES models..."*

Another issue, related to the lower boundary condition prescription, is illustrated in Saiki et al. (2000):

> *"The early stages of this study revealed that the two part SGS model of Sullivan et al. (1994) in its original form produced unphysical profiles in the turbulent quantities when the boundary layer was cooled by a large negative heat flux. This behaviour first manifested itself when the SGS vertical heat flux fell to zero near the surface in direct conflict with assumptions associated with large-eddy simulation of the atmosphere. This was remedied by adding a second term to the SGS vertical heat flux model in a manner similar to the model for the SGS momentum flux. While this improved SGS model alleviated these problems, the simulations were still sensitive to rapid cooling by the sudden application of large negative heat fluxes at the surface. Therefore, the boundary layer was gradually cooled by incrementally increasing the surface cooling flux."*

Other challenging issues and similar (negative) sentiments documented by the LES-SBL studies include (but are not limited to): unusual SGS model behaviour, excessive resolution sensitivity, unphysical runaway surface cooling, unexpected model crashing, etc. In order to confront these issues, during 2003-2004, the first GABLS LES intercomparison study (henceforth GABLS1-LES) took place (Beare et al., 2006; Holtslag 2006). More than ten LES modelling groups from around the world participated in this intercomparison study. They modelled a weakly stable barotropic boundary layer utilizing several LES-SGS models. This intercomparison study highlighted that LES of weakly stable boundary layers was quite feasible. However, some of the key turbulence statistics were found to be sensitive to SGS models even at relatively fine resolutions, which is not desirable.

Quite a few novel SGS models have been proposed in the ABL literature in the recent past (e.g., Chow et al. 2005; Basu and Porté-Agel 2006). The existing SGS models have also been improved during this period. The GABLS community agreed that the time was opportune for another LES intercomparison in order to re-evaluate the capabilities of the SGS models - in the context of stably stratified flows. As a result, the GABLS3-LES intercomparison study was organized in 2008-2009.

2. Expectations for the GABLS3-LES Case

The GABLS1-LES case was idealized in the sense that the (simulated) stable boundary layer was driven by a constant geostrophic wind and a constant surface cooling rate. Even though we gained valuable insights from this intercomparison study (Beare et al., 2006), the lack of observational data for direct validation of the simulated results was unsatisfactory.

The main expectation for the GABLS3 case was to simulate a truly realistic scenario. The GABLS community also wanted to confront their models with a more challenging moderately/strongly stratified case. In order to fulfill both these expectations, researchers at the Royal Netherlands Meteorological Institute and Wageningen University spent several months to identify a 'golden' case (see Baas et al., 2008) from an extensive multi-year observational database (van Ulden and Wieringa, 1996; Beljaars and Bosveld, 1997; Verkaik and Holtslag, 2007; Baas et al., 2009). They selected a low- level jet (LLJ)[1] event observed on July 1st-2nd, 2006 over Cabauw, the Netherlands. This observed case was first simulated by several SCMs (GABLS3-SCM). To resemble reality as faithfully as possible, single column modelers were asked to utilize land-surface and radiation schemes in their simulations in conjunction with various boundary layer parameterizations. Quite a few contemporary LES modelling groups neither have a land-surface scheme, nor a radiation parameterization option in their codes. Thus, in order to enhance the participation of LES modelling groups in the GABLS3-LES study, we decided to make certain simplifications of the GABLS3-SCM case, as detailed below.

3. Setup of the Case Study

The GABLS3-LES case involves a total simulation period of nine hours (00 UTC - 09 UTC, July 2, 2006). This period essentially encompasses: (a) the development of a moderately/strongly stratified, baroclinic, mid-latitude nighttime boundary layer; and (b) its transition (after sunrise) into daytime convective boundary layer.

The initial conditions at 00 UTC were created by synthetically merging the observed 200 m Cabauw tower data, wind profiler data, and a high-resolution sounding from DeBilt. Time-height-dependent geostrophic wind forcings were derived from a network of surface pressure stations in the Netherlands combined with the analysis of a mesoscale weather forecasting model. In a similar fashion, time-height-dependent advection terms (for momentum, heat, and moisture) were also obtained from modeled mesoscale forecasts and observed trends at the 200 m level during nighttime.

To avoid using land-surface and radiation schemes, observed (extrapolated) near-surface (0.25 m above ground level - AGL) potential temperature and specific humidity were prescribed as lower boundary conditions2. An aerodynamic roughness length of 0.15 m was used.

Eleven LES modeling groups from different parts of the world simulated this GABLS3-LES case. They were required to use a domain size of 800 m $\times$ 800 m $\times$ 800 m and to run their simulations at a common isotropic resolution of 6.25 m. Some groups ran additional simulations using higher resolutions (up to 1 m).

4. Post-Processing of Data

Before elaborating on the results, we would like to briefly describe our data post-processing and plotting strategy. The GABLS3-LES database contains planar-averaged mean, variance, and flux profiles of relevant variables at a temporal resolution of 5 min. For further analysis and visualization, each of these individual profiles is linearly interpolated to the vertical levels ranging from 10 m to 800 m (with an increment of 10 m). Thus, for every hour duration, there is a total of 132 data samples (=

[1] LLJs are wind maxima typically centered around 100 m to 1000 m AGL, which are frequently observed during nighttime hours (stably stratified conditions).

[2] In the past, numerous SBL modeling studies used sensible heat flux as a lower boundary condition (Brown et al. 1994; Saiki et al. 2000; Jiménez and Cuxart 2005; to name a few). In Basu et al. (2008), the fundamental shortcomings of such sensible heat flux-based lower boundary conditions was discussed. Based on analytical and numerical results, it was shown that if the surface sensible heat flux is prescribed as a boundary condition, only the near-neutral to weakly stable regime will be captured. In order to represent the moderate to very stable regime in a simulation, surface temperature prescription or prediction is required. For this reason, we used surface temperature as a lower boundary condition.

11 runs × 12 data samples per hour) corresponding to each vertical level. From these data points, we calculate and plot the 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles. The Cabauw meteorological tower data are only available every 10 min. Since there are only 6 data samples per hour, we only report the 50^{th} percentile (median) in conjunction with the minimum and maximum values. Last, the wind profiler provides data at a very coarse output frequency of 30 min. Therefore, only hourly averaged values are utilized for comparison.

5. Results

In this conference paper, we only discuss the results from the time-frame of 3-4 UTC. During this period, the observed and simulated boundary layers are found to be moderately/strongly stratified (the ratio of the boundary layer height and the Obukhov length is on the order of 5). Figures 1-3 show the observed and simulated mean, variance, and flux profiles, respectively. Based on these figures, the following statements can be made:

- Overall, the diversity among different LES runs is surprisingly small. This finding is quite unexpected and somewhat disagrees with the GABLS1-LES results.
- All the LES runs capture the height and the strength of the observed LLJ quite accurately.
- In contrast to the LES-ensemble, the high-resolution (Δ = 1 m) simulation generates less mixing, more boundary layer decoupling, and in turn leads to a stronger LLJ.
- The wind observations from the Cabauw tower show strong temporal variations at the heights near and above the LLJ peak. This is due to the presence of the so-called sub-meso motions. The LES runs do not capture these motions.
- The performance of the LES-ensemble to reproduce the near-surface wind shear is not satisfactory. This finding is in line with the existing literature.
- Extensive wind directional shear (between the surface and the LLJ peak) is adequately reproduced by all the LES runs, which is very encouraging.
- The (marginal) convexity of the observed potential temperature profile signifies the dominance of the turbulent mixing over the longwave radiational cooling process. For this reason, all the LES models, in the absence of any radiation scheme, more-or-less successfully reproduce the observed potential temperature profile.
- Qualitatively, the simulated variance profiles agree with the observations as they all decrease (almost) linearly with height (from the surface to ~100 m AGL). Since the simulated variances do not include the SGS contributions, they are expected to be lower in magnitude than the observed ones.
- Around 150 m AGL, some (not all) of the LES-SGS models do not dissipate enough energy and lead to spurious pile-up of energy. The pile-up of energy above 300 m AGL is an artifact of the Rayleigh damping layer.
- The high observed variance at 180 m AGL is due to a ‘bursting’ event (see Figure 4). None of the LES-SGS models captures this event.

- As noted before, the high-resolution (Δ = 1 m) simulation generates less mixing (less variance) than the LES-ensemble.

- The simulated flux profiles agree very well with the observations. Except very close to the surface, the resolved fluxes are larger than their subgrid-scale counter-parts. In other words, the spatial resolution of 6.25 m seems to be appropriate for this moderately/strongly stratified case.

Currently, we are performing further analyses and interpretation of the wealth of data generated by the GABLS3-LES intercomparison study. These results will be reported in an upcoming peer-reviewed journal publication.

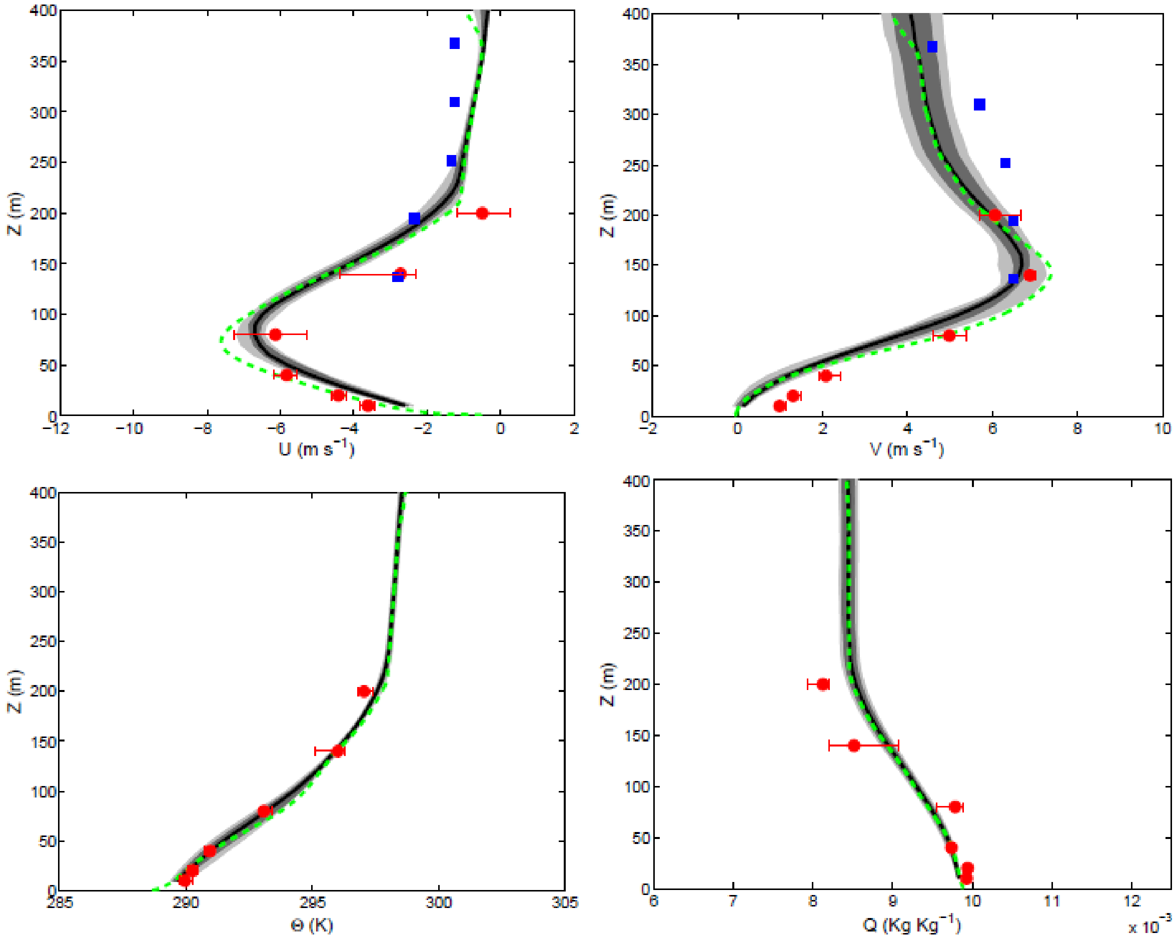

Figure 1: Plots of the longitudinal velocity component (top-left panel), lateral velocity component (top-right panel), potential temperature (bottom-left panel), and specific humidity (bottom-right panel) profiles corresponding to 3-4 UTC. The red dots with whiskers represent median and min-max values of the observations from the Cabauw meteorological tower. Data from a wind profiler are depicted by blue squares. The solid black lines, dark grey shaded areas, and the light grey areas correspond to the medians, 25th-75th percentile ranges, and 10th -90th percentile ranges of the LES ensemble-generated output data, respectively. The simulated profiles from a very high-resolution LES run (Δ = 1 m) are denoted by the green dashed lines.

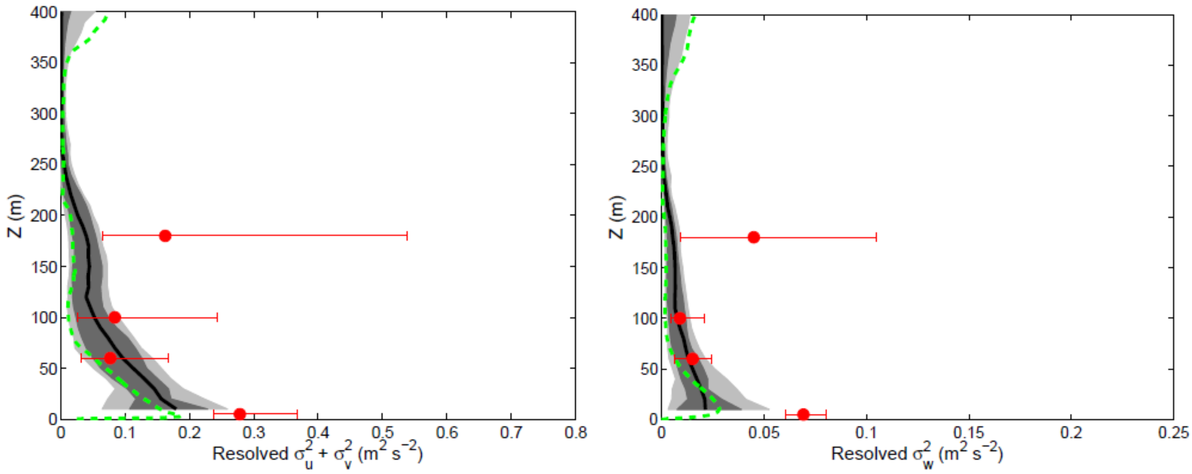

Figure 2: Plots of the horizontal (left panel) and vertical (right panel) velocity variance profiles corresponding to 3-4 UTC. The lines, shadings, and symbols have the same meaning as in Figure 1. Please note that the simulated results represent resolved variances, whereas the observed data correspond to total variances.

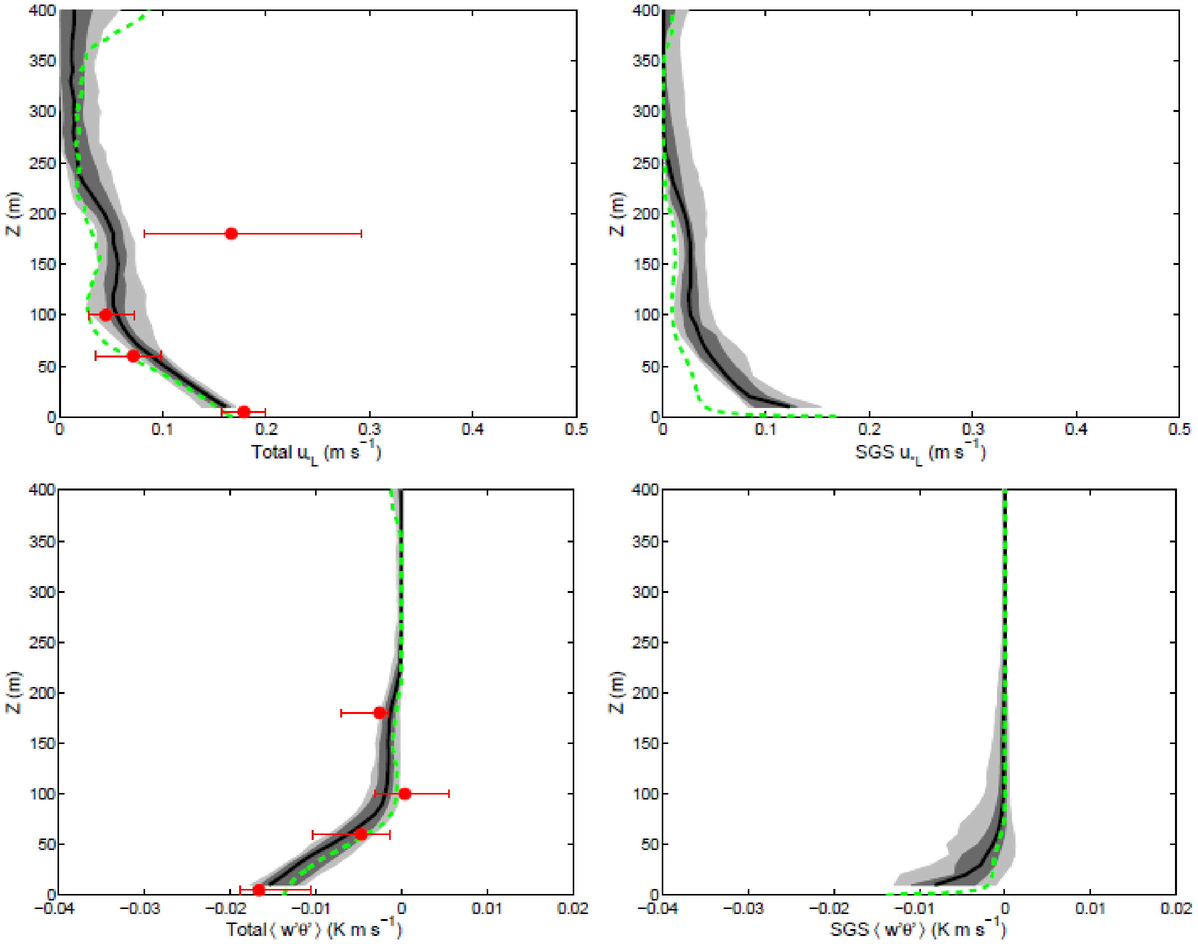

Figure 3: Plots of the local friction velocity (top) and sensible heat flux (bottom) profiles corresponding to 3-4 UTC. The left and right panels denote total (i.e., resolved plus subgrid-scale) and subgrid-scale components, respectively. The lines, shadings, and symbols have the same meaning as in Figure 1.

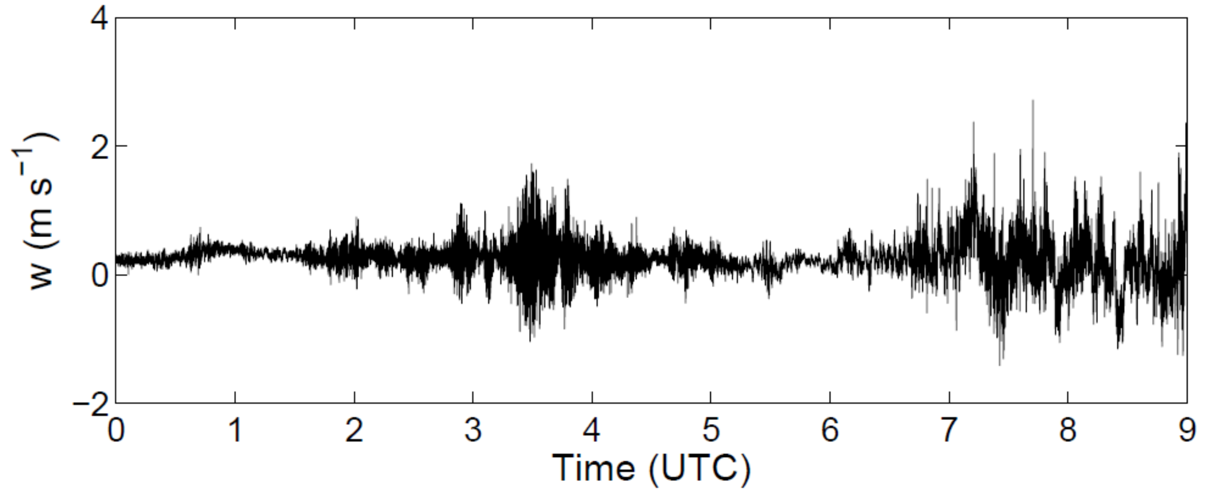

Figure 4: Time-series of the vertical velocity component measured by a sonic anemometer located on the Cabauw meteorological tower (180 m AGL). A 'bursting' event during 3-4 UTC is clearly noticeable.

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