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Intercomparison of Large-Eddy Simulation Models of the Antarctic Boundary Layer Challenged by Very Stable Stratification

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Abstract In polar regions, where the boundary layer is often stably stratified, atmospheric models present large biases that are dependent upon the schemes used to parametrize the boundary-layer processes and the exchange of energy at the surface. This

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model intercomparison study focuses on very stable stratifications encountered over the Antarctic Plateau in 2009. Here, we analyze results from 10 large-eddy simulation (LES) codes, run at different spatial resolutions for 24 consecutive hours and compare them to observations acquired at the Concordia Research Station during summer. This is a challenging exercise for such simulations as they need to reproduce both the 300-m-deep convective boundary layer and the very thin stable boundary layer characterized by a strong vertical temperature gradient (10 K difference over the lowest 20 m) when the sun is low over the horizon. A large variability in surface fluxes among the different models is highlighted. The LES models correctly reproduce the convective boundary layer in terms of mean profiles and turbulent characteristics but display more spread during stable conditions, which is largely reduced with higher horizontal and vertical resolutions in additional simulations focusing only on the stable period. This highlights that very fine resolution is needed to represent such conditions. Complementary sensitivity studies are conducted regarding the roughness length, the subgrid-scale turbulence closure scheme as well as the resolution and domain size. While we find little dependence on the surface flux parametrization, the results indicate a pronounced sensitivity to both the surface roughness length and to the turbulence closure.

Keywords Dome C, Antarctica • Large-eddy simulation • Parametrization • Stable boundary layer • Subgrid turbulence scheme

1 Introduction

A stably stratified boundary layer develops in the presence of a surface colder than the overlying air. Such conditions are encountered frequently in polar regions, over land during night-time and wintertime, and during advection of warm air over a colder surface. Stable boundary layers (SBLs) can be classified according to the strength of the thermal inversion. Generally, weakly stable boundary layers with continuous turbulence occur when the wind speed is moderate to strong or in the presence of clouds limiting the surface radiative cooling. A model intercomparison for a weakly-stable boundary layer was conducted in the first intercomparison (GABLS1) of the GABLS (the GEWEX, Global Energy and Water Cycle Experiment, Atmospheric Boundary Layer Study) project (Beare et al. 2006). As shown in Beare et al. (2006), the turbulence under weak stratification, mainly mechanical turbulence forced by wind shear, is relatively well understood and described by similarity theory. This kind of turbulence is also correctly reproduced by high-resolution large-eddy simulations (LESs; Beare et al. 2006; Huang and Bou-Zeid, 2013; Matheou and Chung, 2014). Very stable boundary layers typically occur in the presence of low wind speeds and clear skies and are characterized by strong temperature inversions. With an increase in stratification, turbulence can become intermittent or decoupled from the ground (Mahrt 1999; Sun et al. 2012; Mahrt 2014). In such strong stratification, similarity theory becomes inapplicable (Ha et al. 2007) and it is a challenge to simulate the boundary layer even with high-resolution LESs. Van de Wiel et al. (2012) proposed a framework to predict the critical synoptic conditions for sustained turbulence and showed that below a minimum wind speed threshold, continuous turbulence is unlikely to occur. Vignon et al. (2017a) showed that the wind speed threshold under which the very stable regime occurs lies around 5 to 6 m s^{-1} at Dome C (a meteorological and astronomical station in the high East Antarctic plateau), which is above the average wind speed observed at 10 m for the case study considered hereafter.

The accurate representation of the SBL is still a key issue for numerical weather prediction or climate models, particularly for very stable conditions. Numerical weather prediction models often report significant biases at night over land (Holtslag et al. 2013) with warm or cold biases depending on the excess of mixing or the strength of the decoupling with the surface. Indeed, Sandu et al. (2013) explained how enhanced turbulent diffusion is maintained in the European Centre for Medium-Range Weather Forecast (ECMWF) model besides its detrimental impact on the representation of stable boundary layers but due to the improved large-scale flow and near-surface temperature. This study emphases that this enhanced diffusion is needed to compensate for errors caused by other poorly represented processes, encouraging more studies of processes in stable boundary layers. Climate models also suffer from significant biases of temperature in the low levels, with a strong climate signal in polar regions, where the results strongly depend on boundary-layer parametrizations (King et al. 2001). Several intercomparison activities endorsed by GABLS proposed different cases in which LES and single column models (SCMs) are intercompared in order to evaluate parametrizations. The use of LES has proven to be very useful for the evaluation and development of parametrizations for clear and cloudy boundary layers (Randall et al. 2003; Hourdin et al. 2013). One aim of those GABLS investigations was also to evaluate the spread among different LES models in order to examine how reliable these high-resolution simulations are and to what degree they can be used as a guidance for the parametrization of the SBL. Three different GABLS intercomparisons have already been carried out, focusing on progressively more realistic cases.

The first case, GABLS1, used an idealized set-up over an icy surface with the development of a shear-driven stable boundary layer (Beare et al. 2006). This case was loosely based on observations from the Arctic and corresponded to weakly stable conditions. A prescribed uniform geostrophic wind of 8 m s^{-1} and a constant surface cooling rate of 0.25 K h^{-1} were applied and neither radiation nor surface interaction were taken into account. Beare et al (2006) showed relatively good agreement among the different LES and Cuxart et al. (2006) further used the LES results as a reference for a SCM intercomparison. Cuxart et al. (2006) also showed that the SCMs generally overestimated mixing, except for those using a prognostic turbulence kinetic energy (e) scheme.

The second case, GABLS2, was based on observations from the Cooperative Atmospheric Surface Exchange Study (CASES-99) field campaign and aimed at representing a complete diurnal cycle with SCM runs (Svensson et al. 2011). For this case, the models were run with a prescribed surface temperature inhibiting a possible ground surface--boundary layer interaction. The intercomparison focused on the evaluation of the turbulence schemes. However, most of the spread between models was attributed to differences in interaction between fluxes and stability.

The third case, GABLS3, was more closely based on observations from the Cabauw tower. Special emphasis was placed on the analysis of the coupling with the surface and the radiation (Bosveld et al. 2014a; 2014b). The observed near-surface potential temperature and moisture were prescribed so the intercomparison focused on the role of numerical schemes and subgrid-scale (SGS) turbulence schemes on the boundary-layer profiles. The different LES models were in very good agreement (Holtslag et al. 2013).

However, those three cases did not tackle very strong stable conditions and this is the main objective of the GABLS4 intercomparison study (Bazile et al. 2014). This case is based on the observations acquired on a meteorological tower at Dome C on the Antarctic Plateau (Genthon et al. 2013) on 11 December 2009. This site has been chosen because of:

- i) the relatively large dataset acquired in the framework of the Concordiasi field campaign (Rabier et al. 2010)
- ii) the flatness and homogeneity of the ground: topography and surface heterogeneities are significant factors of turbulence in stable conditions; even a very fine slope can produce drainage flows (Mahrt and Larsen 1990).
- iii) the dryness of the air. Indeed, the occurrence of a clear and clean atmosphere with very small water vapour content induces a strong radiative cooling at the surface with a rate reaching more than 2 K h^{-1} when the sun is very low above the horizon.

On 11 December 2009, the boundary layer was convective when the sun was high above the horizon reaching a height of a few hundred metres. This is a frequent feature over Dome C, as highlighted by previous studies (King et al. 2006; Ricaud et al. 2012; Genthon et al. 2013; Casasanta et al. 2014) who showed frequent convective boundary layer heights of 250 m to 350 m in summer. On that day and consistently with the climatology, when the sun was low above the horizon, very strong vertical gradients of temperature were measured close to the surface at that site with values reaching more than 0.7 K m^{-1}. The net radiation varies throughout the 24 hours from 49 W m^{-2} at 0400 UTC (local time = UTC + 8 h) and -44 W m^{-2} at 1600 UTC, this is typical values for surfaces covered by snow and summer conditions over Antarctica (King et al. 2006).

Three different stages were proposed for the GABLS4 intercomparison (Bazile et al. 2014). The first one is dedicated to the intercomparison of SCMs with an interactive snow surface scheme, the second one prescribes observed surface temperature (suppressing feedback from the surface), and the third one is an idealized case where the large-scale forcing and initial conditions have been simplified. In this paper, we focus on stage 3, which is the most idealized set-up. It includes prescribed surface temperature, no radiation, no specific humidity, and a constant large-scale forcing with time. This case is very challenging for LES models as it incorporates the full diurnal cycle with both a relatively deep convective boundary layer during midday and an extremely thin boundary layer when the sun is very low over the horizon. The objective of this work is to present the skill among various LES models at such stability. Indeed, at such strong stability we test the limit of the validity of the LES technique that has been shown to represent convective boundary layers satisfactorily and weakly stable boundary layer in the previous GABLS exercises. We expect deficiencies of LES in such very stable conditions because of (i) a possibly problematic estimation of the dissipation associated to the existence of non-isotropic subgrid turbulence (only a few subgrid turbulent schemes do not assume isotropy), or a misrepresentation of the buoyant destruction by the subgrid turbulence scheme (Bou-Zeid et al. 2010) (ii) the importance of radiative flux divergence, indeed in the present study as in many LES studies the radiative flux divergence is neglected, (iii) the weak surface turbulent fluxes, (iv) the need of very fine grid resolution in order to still have most of the turbulence resolved. We also want to assess what is the necessary resolution to resolve the main processes in such stable cases and how the results depend on the SGS turbulence scheme and surface parametrizations. Several studies have shown that it is difficult to get convergence of the results for a given model and that results even at high resolution still depend on the used resolution (Huang and Bou-Zeid 2013;Van Stratum and Stevens, 2015; Sullivan et al. 2016 and Maronga et al. 2020, among others).

Very few studies have focused on the representation of very stable boundary layers in LES models. Huang and Bou-Zeid (2013) simulated a suite of GABLS1-based test cases by increasing the surface cooling rate up to -2.5 K h^{-1} and obtained a largely expanded stability range where the gradient Richardson number reached values up to around 1. They systematically investigated the effects of stability on the bulk dynamics, turbulent structure, and e budget, as well as the applicability of local similarity theory in the SBL, and found that i) the vertical extent of turbulent structures is reduced with increasing stability, ii) buoyant destruction of turbulence kinetic energy becomes more important than viscous dissipation under the strongest stabilities, and iii) the z-less range of scaling in the SBL starts at lower heights than previously anticipated. Walesby and Beare (2016) proposed a case derived from observations from the Halley research station on the Brunt iceshelf for which they ran both LES and SCM. They used the LES result as a reference to show that the choice of stability functions was critical for the behaviour of the SCM. Following Huang and Bou-Zeid (2013), Sullivan et al. (2016) modified the set-up of GABLS1 by imposing stronger surface cooling rate up to -1 K h^{-1} in order to obtain very stable conditions and conducted very high grid-resolution (down to $\Delta x = \Delta y = \Delta z = 39$ cm) simulations run for 9 physical hours. They noted a decrease of the SBL height with increasing resolution and showed the existence of temperature micro-fronts in the simulations. Also they found that grid convergence was not reached in their simulations. Recently, Maronga et al. (2020) investigated whether the surface boundary conditions (i.e. the Monin–Obukhov Similarity Theory, MOST) are responsible for the lack of grid convergence observed in stable conditions. While grid convergence was significantly improved for surface fluxes of heat and momentum, they found, however, that the non-convergence of the mean profiles could not be ascribed to the boundary conditions. Very recently, van der Linden et al. (2019) simulated accurately winter weakly and very stable boundary layers observed at Dome C with very fine (cm-scale) LES. They show that a thermal equilibrium can be reached between subsidence (heating) and turbulence (cooling).

The main objective of this paper is to present the results of the first intercomparison of large-eddy simulations in very stable conditions. In the following, Sect. 2 details the methodology for the intercomparison, focusing on the case and model description but also giving information on the diagnostics and the sensitivity tests that have been carried out. Section 3 presents the main results with a distinction between the representation of the convective and stable behaviour of the boundary layer. Section 4 presents the different sensitivity tests and the paper closes with conclusions and recommendations for future LES intercomparisons in very stable conditions. A forthcoming companion paper will present the results of the SCM intercomparison.

2 Methodology

2.1 Case Description

As documented by Bazile et al. (2014), the present case is based on observations from Dome C (123.3E, 75.1S, 3223m above sea level) on the Antarctic Plateau (Genthon et al. 2013). Recall that this case occurs in summer in Antarctica, so there is daylight throughout 24 hours although the net radiative energy at the surface is positive when the sun is high above the horizon and negative when the sun is low. Here, the simplest set-up is used in order to allow contributions to this intercomparison from many modelling groups. In particular, the case neglects radiation and land-surface interactions. Furthermore, the large-scale forcing includes only the geostrophic wind, which is assumed constant in time and along height. Temperature advection and subsidence are not included in the case set-up. The initial profiles of potential temperature, zonal wind and meridional wind are derived from the soundings launched at 0000 UTC (0800 local time; see Fig. 1 and Table 5). The initial sounding consists of a stable boundary layer with a relatively steep temperature gradient up to 45 m overlaid by a less stable layer. The wind is almost constant with height (except in the lowest part of the boundary layer) with a speed of around 4 m s^{-1}. The case is considered dry (note that the water vapour mixing ratio is very low at Dome C with typical values of 0.3 g kg^{-1}, see Genthon et al. 2017). A spatially uniform time-dependent temperature derived from observations is prescribed to provide the surface boundary condition (Table 5). As shown in Fig. 1e, there is a warming of the surface for the first five hours of the simulation followed by a cooling. The largest cooling rate occurs between 1100--1600 UTC with values about 2 K h^{-1}, which is a significantly larger cooling rate than the 0.25 K h^{-1} used in GABLS1 (Beare et al. 2016) or the range of cooling rates used in Sullivan et al. (2016) that increases from 0.25 to 1 K h^{-1}. The roughness lengths for heat and momentum are also prescribed to be 10^{-2} m for momentum, z_{0m} and 10^{-3} m, z_{0h} for heat (Experiment 1). To better agree with observations (Vignon et al. 2017b), additional simulations with momentum and heat roughness lengths of 10^{-3} m and 10^{-4} m, respectively, were carried out. The default case is named Experiment 1 while the case with modified roughness lengths is called Experiment 2. The sensitivity of the LES results to roughness length is discussed in Sect. 4.

Simulations of the convective part of the diurnal cycle require large computational domains because of the relatively large boundary-layer height compared to that encountered in the stable conditions. Thus, the grid resolution is constrained by the height of the convective layer and the stable boundary layer is only captured by the lowermost few model layers. In order to focus on the stable conditions and optimize grid resolution, Experiment 3 was carried out, in which simulations start at 1000 UTC (instead of 0000 UTC) and ensemble mean profiles of Experiment 2 are used as the initial conditions (Fig. 1 a-d and Table 5 for numerical values). The same large-scale forcing and surface boundary conditions of Experiment 1 and 2 are used. The roughness lengths used in Experiment 2 are used. The initial profile of potential temperature at 1000 UTC is close to neutrality.

Although the set-up is idealized from the real conditions that occurred on 11 December 2009, when possible we always add the observations in the following graphs in order to illustrate the expected behaviour. In particular, observations from a 45-m meteorological tower with six levels (3 m, 9 m, 18 m, 25 m, 33 m, 42 m) of wind and temperature measurements, as well as four levels (7 m, 23 m, 30 m, 38 m) of turbulent flux measurements are shown. The turbulent quantities are measured by sonic thermo-anemometers that sample at 10 Hz. Because of the very cold conditions encountered, the instruments alternate a period of measurements for 8 min with heating periods of 12 min. Turbulent quantities were computed over a 60-minute period corresponding to 24 minutes (3 × 8 min) of effective measurements. We refer to Vignon et al. (2017a) for more information on the complete derivation of these turbulent quantities and to Genthon et al. (2013) for details of the temperature and wind measurements.

The boundary-layer height is defined as the level of minimum turbulent vertical potential temperature flux in convective conditions and follows the definition used in Beare et al. (2006) for the stable conditions, 1./0.95 times the height where the mean stress reaches 5% of its surface value. The Obukhov length is also computed as, where U, V are the zonal and meridional component of the wind, θ the potential temperature, $\overline{u'w'}$, $\overline{v'w'}$, $\overline{\theta'w'}$ momentum and temperature turbulent fluxes, κ, the von Kármán constant and g the gravitational constant:

$$L = \frac{-\left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{(3/4)}}{\kappa \frac{g}{\theta} \overline{\theta'w'}}, \qquad (1)$$

Effective diffusivities of momentum (K_m^{eff}) and heat (K_h^{eff}) were calculated from the total momentum and heat fluxes and the mean wind and potential temperature profiles following Beare et al. (2006):

$$K_m^{eff} = \frac{\left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/2}}{\left(\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2\right)^{1/2}}, \tag{2}$$

$$K_h^{eff} = \frac{\overline{\theta'w'}}{\frac{\partial \theta}{\partial z}}, \tag{3}$$

2.2 Models

In total, 10 different LES models contributed to this exercise (see Table 1 and Table 2).

All the models use their own model-specific SGS turbulence parametrization and discretization in space and time as well as MOST for calculating surface fluxes (see Table 1). Most of the SGS schemes are based either on a prognostic equation for the turbulence kinetic energy, with a Deardorff (1974) length scale or on a Smagorinsky (1963) scheme with or without a dynamic component. In particular, CSIRO and MATLES use advanced scale-dependent SGS models to calculate the SGS eddy viscosity (Bou-Zeid et al. 2005; Basu and Porte-Agel 2006), which have been shown to simulate the SBL reliably even under strong stabilities (Huang and Bou-Zeid 2013). The University of Connecticut LES (UConn) uses the buoyancy adjusted stretched vortex model (Chung and Matheou 2014) and the sensitivity to the SGS turbulence scheme for this model is shown in Sect. 4. All the models use a MOST-based formulation (see Cuxart et al. 2006), using an integral formulation, to calculate surface turbulent fluxes following:

$$\frac{\partial |\vec{U}|}{\partial z} = \frac{u_*}{\kappa z} f_m\left(\frac{z}{L}\right), \tag{4}$$

$$\frac{\partial \theta}{\partial z} = \frac{\theta_*}{\kappa z} f_h\left(\frac{z}{L}\right), \tag{5}$$

with $\left|\vec{U}\right|$ being the wind speed, L the Obukhov length, u_* the friction velocity, θ_* the surface temperature scale and f_m and f_h functions that are often written as $1 + \beta_{m,h}\, z/L$ for stable conditions with $\beta_{m,h}$ coefficients whose values are model-specific. Note that $\beta_{m,h}$ coefficients are not constrained in the present GABLS4 case and differ from one model to another (see Table 2 for more details). No moisture is included and therefore no microphysics parametrization is needed. Radiation is also excluded to focus on turbulence.

The domain size was set to 1000 × 1000 × 1000 m^3 with a horizontal resolution of 5 m and a vertical resolution of 2 m at least up to 400 m for the Experiments 1 and 2 (E1 and E2 runs). To prevent spurious reflection from the model top boundary, most models applied a Rayleigh damping above heights of 600-700 m where the prognostic variables are relaxed towards the large-scale fields. Tests with a larger horizontal domain indicate that the prescribed domain size is sufficient (see Sect.4). For runs starting at 1000 UTC (Experiment 3), the domain was restricted to 500 × 500 × 150 m^3, or even smaller depending on the models, with an isotropic grid of 1 m resolution. The different sensitivity tests performed for each model are indicated in Table 2, as well as their configuration (resolution, domain and roughness lengths).

2.4 Sensitivity Tests

Several models contributed to the exercise with an ensemble of simulations, which allowed us to analyze the sensitivity of the results to aspects of physical parameters and numerical configuration.

The sensitivity to the roughness length is first tested. Most models (MesoNH, PALM, UConn, MATLES, MONC, ELMM and CSIRO) contributed with one simulation with $z_{0m}=10^{-2}$ m and $z_{0h}=10^{-3}$ m (Experiment 1) and an additional one with $z_{0m}=10^{-3}$ m and $z_{0h}=10^{-4}$ m (Experiment 2). Sensitivity to the subgrid turbulence parameterization is addressed with one model. UConn was run with the exactly same configuration for runs of Experiment 2 with varying grid resolution from 5m to 1m (see Table 3) but with either a Smagorinsky subgrid turbulence scheme or a newly developed turbulence scheme based on buoyancy adjusted stretched vortex model (Chung and Matheou, 2014). Three models investigated the sensitivity to the surface turbulent flux parameterization.

MesoNH, PALM and UConn carried out a simulation for Experiment 3 with a prescribed formula to compute surface turbulent fluxes from the differences between the first level information and the surface temperature following equations (1 and 2) with values of $\beta m=4.8$ and $\beta h=7.8$.

The sensitivity to grid-resolution has also been addressed. PALM and UConn performed additional simulations with a range of horizontal and vertical resolutions between 5 m and 0.5 m for Experiment 2 (see Table 3). For Experiment 3, MesoNH and UConn also performed simulations with different horizontal and vertical resolutions. Note that those simulations were run on a smaller domain (see Table 3 and iii). Sensitivity to the size of the domain has been documented with two models. Several domain sizes were used ranging from 2.5 × 2.5 × 1 km^3 down to 0.25 × 0.25 × 0.075 km^3. In particular, PALM provided a simulation with a 2.5 × 2.5 × 1 km^3 domain and a 1 × 1 × 1 km^3 for Experiment 2, the simulations with MicroHH were provided with a 3 × 3 × 0.5 km^3 domain for Experiment 1 and MesoNH provided two simulations with 0.5 × 0.5 × 0.15 km^3 and 0.25 × 0.25 × 0.075 km^3 domains for Experiment 3. Eventually, sensitivity to the starting time has been analyzed. MesoNH and MicroHH were run starting either from the profile prescribed for Experiment 3 (ensemble mean at 1000 UTC) or from the initial profiles at 0000 UTC in order to assess the sensitivity to the different initializations.

The results of these sensitivity tests are described in Sect. 4.

3 Results

3.1 Diurnal Cycle

Figure 2 presents the time-evolution of the vertical structure of potential temperature for Experiment 1 (nine models). All models represent the convective boundary layer developing during the first seven hours of the simulations with a boundary-layer height, defined as the height of the minimum of vertical turbulent heat flux, reaching 300 m to 400 m. This is consistent with the range of summer convective boundary-layer heights observed at Dome C as reported, for example, by sodar observations (Cassasanta et al. 2014).

Figure 3a, b show the relatively good agreement between models in representing the convective boundary layer, although SAM displays stronger convection with a warmer (0.5 K) and higher boundary layer, consistent with its larger sensible heat flux and larger turbulence kinetic energy (Fig. 4). Focusing on the models that use a 10^{-2} m roughness length (shown in full lines), the spread between the other models is no larger than 0.3 K for the boundary-layer potential temperature and 20 m for the boundary-layer height. A further evaluation of the horizontal structures, distribution of temperature fluctuations and turbulence spectra in the boundary layer indicates good agreement between observations and simulations for the convective period (not shown). The data reveal more spread during stable conditions, however. Indeed, after the 10th hour, a SBL develops with a height that varies between models with the highest values for CSIRO and MATLES, which have the lowest spatial resolution (see Fig. 2). This is also evident when looking at the vertical profiles at 17 hours of simulations (Fig. 3c, d) with a relatively large spread of the peak of the low-level nocturnal jet, of the boundary-layer height and of the stratification observed at the top of the boundary layer. Part of the differences between observations and LES may be due to the definition of the forcing, which have been simplified in the studied case.

Figure 4a shows the surface sensible heat fluxes as computed by the individual models (only the surface temperature is prescribed). The spread during convective conditions reaches about 10 W m^{-2}, which is of the same order of magnitude as the ensemble mean that reaches a maximum of 20 W m^{-2}; during stable conditions the spread still reaches 10 W m^{-2}, which is equal, in absolute value, to the ensemble mean. The simulated fluxes agree more or less with observations given the uncertainties of in-situ turbulence measurements (and the fact that the observations correspond to flux estimate at either 1.5 m for gradient estimate or 7 m for turbulence measurements) but issues with the applicability of MOST in such stable conditions may also explains some departure (Mahrt, 2008; 2010). The momentum flux at 7 m (Fig. 4b and Table 3) in Experiment 1 varies from -0.09 m^{2} s^{-2} to close to 0 m^{2} s^{-2} depending on the model with a mean value during convective conditions of -0.065 m^{2} s^{-2} and a very small spread apart from two departing models; this is larger than the observed value of -0.025 m s^{-1}. The total (resolved plus subgrid) turbulence kinetic energy (Fig. 4c) at 30 m reaches 0.2 to 0.35 m^{2}

s^{-2} depending on the model, also overestimated compared to observations. Using a reduced prescribed roughness length of 10^{-3} m (Experiment 2 and Table 3) reduces surface sensible heat fluxes, friction velocity at 7m and turbulence kinetic energy at 30m mainly during convective conditions, with values closer to observations (not shown). It is worth remembering that the mean estimated roughness length derived from observations was also close to 10^{-3} m (Vignon et al. 2017b). In the following, we will focus on the analysis of runs using this value of roughness length (Experiments 2 and 3). The spread among simulations is reduced during convective conditions but not during stable conditions.

3.2 Stable Period

In the rest of the paper, we concentrate on the analysis of the stable conditions, i.e. the period when the sun is very low above the horizon and the boundary layer is stably stratified. According to the literature, 5-m horizontal grid spacing is not fine enough to correctly represent the very shallow boundary layer during the stable conditions (see Beare et al. 2006; Sullivan et al. 2016 among others). Indeed, Fig. 2-4 evidence an absence of convergence between LES for the stable period that may partly be explained by too coarse a resolution in the simulations.

Figure 5 presents the vertical profiles of potential temperature and wind speed for the models that did run both experiments 2 and 3 (which differ in resolution and initial profiles). The spread among the simulations is clearly reduced from Experiment 2 (Δx=5 m, Δz=2 m) to Experiment 3 (Δx=Δz=1 m) both in terms of intensity and height of the low-level jet as well as regarding the height of the maximum positive gradient of potential temperature. For example, the standard deviation at 20m reduces from 0.52 m s^{-1} to 0.28 m s^{-1}) for the wind speed and from 2.53 K to 1.88 K for the potential temperature. The spread is also reduced for the turbulent sensible heat flux from slightly more than 10 W m^{-2} to 5 W m^{-2}. Table 4 also a reduction of spread in the main turbulent characteristics (boundary-layer height, friction velocity, Obukhov length) for those two experiments. The reduction of spreads is caused by the increased resolution rather than by the initial conditions. Indeed, further sensitivity tests revealed that the reduction of the spread is not explained by different initial conditions (not shown). Figure 6 presents a time evolution of the vertical profiles of the potential temperature below z = 42 m. As an illustration, the time-evolution of the observations collected from the tower at Dome C is also shown. This figure clearly shows that the stable boundary layer tends to be thinner and to have a stronger inversion at the top for simulations with higher resolution (it is slightly less evident for Uconn and PALM), which is in agreement with previous results from the literature (Sullivan et al. 2016; van Stratum and Stevens 2015 among others). Also the models overestimate the boundary-layer height compared to observations but this may be caused by the absence of subsidence in the simulations (Vignon et al. 2017c). The spread in model results is larger when focusing on variances and covariances for both experiments as illustrated by the turbulence kinetic energy and the turbulent heat flux (Fig. 7), although there is also a clear reduction of the spread in higher resolution simulations. Dotted lines in Fig. 7 show the subgrid component of the turbulence kinetic energy and indicates a strong decrease of its contribution to the total turbulence kinetic energy in higher resolution simulations. For the turbulence kinetic energy, two estimations are available from observations, either from turbulence data with a high-pass filter at 200 s[1] or from raw turbulence data. The difference between the two estimations may reveal the existence of waves, large eddies or sub-mesoscale eddies that contribute significantly to the turbulence kinetic energy. Figure 7 also shows the evolution of the wind velocity components with height. The vertical variation of wind from simulations with a resolution of 1 m show closer agreement than those from more coarsely resolution simulations. However, some differences persist, with Meso-NH having the weakest winds and PALM the strongest ones. Figure 8 presents the evolution through time of the wind at 41m with again a better agreement between the simulations of Experiment 3 than those of Experiment 2. As shown in Vignon et al. (2017c, their Fig. 8), observations clearly indicate an inertial oscillation after the turbulence decay in the evening transition with a frequency of the order of 12 hours as expected from the theory and the latitude of 75°S of Dome C. The simulations agree with the observations for the inertial oscillation and the period (the geostrophic wind used in the forcing is indicated by the grey square). The reduction of spread for Experiment 3 is probably due to the use of the same initialization just at the moment of turbulence decay in opposition to Experiment 2 where

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[1] this is the classical cut-off frequency used for flux computation, and, using ogive computation, it was checked that this was appropriate for turbulence measurement in this situation

the different convective boundary layers have led to different profiles of wind speed. Figure 9 presents the effective momentum and heat diffusivities normalized by the boundary-layer height and the friction velocity and shows that the spread is also reduced for such diagnostics between Experiment 2 runs and Experiment 3 runs. The profiles differ significantly from those of the GABLS1 experiment (Beare et al. 2006). Shapes of the profiles are quite different than those shown in Beare et al. (2006) for momentum due in particular to an almost null vertical gradient of wind.

In the following, we focus only on the results of Experiment 3 that show much closer agreement between the different models. Figure 10 shows the vertical profiles of (a) turbulent heat flux and (c) horizontal momentum flux and the respective fluxes normalized by their surface values (b and d). From these figures, it is evident that the remaining spread can be to a great extent explained by differences in surface fluxes since, when normalized, the curves almost converge. Also, one can note close to linear profiles. In particular, MONC produces a particularly low wind stress at the surface, which is also visible in Fig. 4b, but the model has a similar transport of momentum compared to the other LES in normalized sense. Figure 10e, f also show the contribution to the turbulence kinetic energy of the variance of horizontal wind and the variance of vertical wind. As expected in stable conditions, the contribution of horizontal wind is stronger than the contribution of vertical wind, which is consistent with findings of Huang and Bou-Zeid (2013), who found that turbulence is much more energetic horizontally than vertically under very stable conditions, causing ‘sandwiched’ coherent structures (Chung and Matheou 2012; Matheou and Chung 2012). Note, however, a large spread among models in the intensity of wind variances.

Although, we have just shown that the spread among LES was reduced for the Experiment 3 set-up, there are still some discrepancies in terms of horizontal variability. This was in particular investigated by comparing the distribution of the potential temperature anomalies for five different vertical levels ranging from 7 m to 38 m above the surface but this is also true for the anomalies of the three wind components (not shown). Observations indicate that horizontal variability is large only at 7 m and strongly reduced at 23 m. Unfortunately, no information from the observations is provided between 7 m and 23 m. CSIRO and DALES present the largest variability at all levels except 38 m. MesoNH, MONC and UConn models show the largest horizontal variability at 14 m. For the horizontal variability of horizontal wind components the maximum is simulated close to the surface for all the models (not shown). The disagreement with observations is consistent with LES predicting higher boundary layers than observed.

4 Sensitivity Tests

This section summarizes the main conclusions of the different sensitivity tests that have been carried out in this intercomparison. We first investigate the sensitivity to the numerical configuration (time of initialization, size of the domain or resolution) and secondly we assess the sensitivity to the physical parameters (roughness length, turbulence parametrization and surface flux parametrization).

4.1 Initial Profile

Starting a simulation from 0000 UTC (0800 LT) or from 1000 UTC (1800 LT) had very little impact on the representation of the SBL for both MesoNH and UConn runs (not shown), which may be counter-intuitive as we may think that the way the convective boundary layer is reproduced (especially just before the convective-stable transition) matters for the rest of the period with stable conditions. However, this may also be explained by the fact that there is not much spread among the different LES models after 10 hours and therefore the initial conditions at 1000 UTC do not differ much from the thermodynamic conditions encountered in any LES runs.

4.2 Grid Resolution

PALM and UConn ran Experiment 2 with increasing resolution from 5 m to 1 m (see Table 2) and MesoNH and UConn ran Experiment 3 with increasing resolution from 1 m to 0.25 m (see Table 2). PALM simulations show relatively little sensitivity to the resolution and results are similar from E2 to E3, UConn simulations show more differences among the different resolution tests in E2. Figure 11 shows the resulting vertical profiles at 1700 UTC for the runs of Experiment 3 focusing on the stable conditions. Convergence of the simulations, according to the mean profiles, is obtained for 0.5m for both Uconn and MesoNH. For MesoNH, running the simulation with a higher resolution leads to a shallower stable boundary layer and low-level jet, and weaker surface sensible heat fluxes, similar to Sullivan et al. (2016). It is worth noting that, for MesoNH, the change in vertical resolution from 1 m to 0.5 m has more impact than changing the horizontal resolution from 1 m to 0.5 m, possibly because a higher vertical resolution improves the representation of vertical gradients that are rather strong under stable conditions and of the turbulent structures that become anisotropic and, thus, vertically flattened by buoyancy effects. Looking at second order moments (Fig. 12), the convergence has been obtained at 0.5 m for Uconn as the 0.25 m has exactly the same results but not yet for MesoNH. This shows that grid convergence is model-specific. Note, moreover, that the results of Sullivan et al. (2016), Maronga et al. (2020) and van der Linden et al. (2019) indicated that grid convergence is not reached at grid spacings of 0.33 m and 0.5 m for a strongly-stable and weakly-stable boundary layer, respectively. We must thus assume that under strongly-stable boundary-layer conditions as in the present intercomparison, even finer grid spacings might still alter the results.

4.3 Domain Size

The sensitivity test to the size of the domain performed either for Experiment 2 with PALM or for Experiment 3 with Meso-NH shows very little change (not shown) and indicates that the domains chosen for the experiments were large enough. This is expected as the size of eddies is expected to be smaller than the scale of the boundary-layer height. During the convective period the boundary-layer height reaches a maximum of 300 m and 1000 m wide domain correspond to three times this value. During the stable period the boundary-layer height is less than 50 m and a 250 m-wide domain already corresponds to 5 times the size of the largest eddies. A 500 m-wide domain is therefore more than sufficient. This is consistent with the results of Sullivan et al. (2016) for a set-up similar to GABLS1.

4.4 Roughness Length

The simulated turbulence closed to the surface depends on the prescribed roughness length (Zilitinkevich et al. 2006). Miller and Stoll (2013) analyzed how the results of

GABLS1 depend on the momentum/heat roughness length. They showed a decrease of surface friction velocity, the boundary-layer height and the Obukhov length with lower roughness lengths. Here we have tested how the results, for this more stable case, depends on prescribed values of roughness length. Five models did run with the two sets of roughness lengths, namely 10^{-2} m for momentum and 10^{-3} m for heat for the Experiment 1 simulations and 10^{-3} m for momentum and 10^{-4} m for heat for the Experiment 2 simulations. As expected, weaker turbulence and shallower boundary layer are simulated for the low roughness simulations and the sensitivity is particularly high during the day (Fig. 3 and Table 3). Less sensitivity is seen during stable conditions. Indeed, during this later period there is a competition between the decrease in shear production associated to the decrease of momentum roughness length and the decrease in buoyancy destruction associated to the decrease of momentum heat roughness length. However, a second test performed with MesoNH for stable conditions, in which, for a momentum roughness length of 10^{-3} m, the heat roughness length was set either to 10^{-3} m or to 10^{-4} m, reveals very little sensitivity to this change (not shown).

4.5 Subgrid Turbulence Scheme

The UConn model performed simulations using two different subgrid turbulence schemes as detailed in Table 1. The reference parametrization is the buoyancy adjusted stretched vortex model (Chung and Matheou, 2014), a structural turbulence closure where the subgrid-scale flow is composed of a collection of vortical structures, which are asymptotic exact solutions of the equations of motion. The additional simulations use the classical subgrid turbulence closure of Smagorinsky (1963) and Lilly (1962, 1966). The turbulence closure constant value of Cs = 0.2 and a turbulent Prandtl number Pr= 0.33 are used based on the findings of Matheou (2016). A comparison of the performance of the two closures for the GABLS1 case is presented in Matheou and Chung (2014). Further sensitivity aspects of the Smagorinsky model for the GABLS1 case are discussed in Matheou (2016). There is very little difference between the two runs in convective conditions but a large sensitivity is revealed in stable conditions, as shown in Fig. 13 for the three resolutions (5 m, 2 m, 1 m). The Smagorinsky turbulence closure model produces a deeper and less stratified stable boundary layer, as well as larger negative sensible heat fluxes. Analysis of the distribution of the anomalies of potential temperature indicates that the distribution from the simulation with the Smagorinsky closure is slightly narrower than the one from the observations, while the distribution of the simulation with the vortex model is slightly broader at 7 m above ground level. The largest difference between the two simulations is shown at 14 m above ground level, where no observation is available. Although further exploring the difference between the Smagorinsky and the streched vortex schemes is beyond the scope of the present paper, the comparison highlights the strong sensitivity to the choice of the subgrid turbulence scheme.

4.6 Surface Parametrization

To assess the impact of the surface flux parametrization, three models (MesoNH, PALM and UConn) provided additional runs with a prescribed surface flux formulation based on MOST and derived from equation 1 and 2 with β_m=4.8 and β_h=7.8. The results with the prescribed parametrization were similar to the original formulation, thus confirming that (a) small variations in the MOST empirical fitting coefficients and (b) the implementation of the parametrization do not have a significant impact on the present results. Indeed, the surface Richardson number remains in a still weakly-stable range where the different stability functions do not significantly diverge.

5 Conclusion

This paper summarizes the results of the fourth GABLS intercomparison for LES focusing on very stable boundary layers. This is a challenge if one wants at the same time to reproduce the convective boundary layer that can be encountered even in extreme polar conditions in summer and the very stable boundary layer. Indeed, it is only recent that the very high resolution needed for such simulations has become affordable. This is a case of idealized stable boundary layer although the set-up was inspired by observations. However, it was simplified compared to real observations with no subsidence, no contribution of radiation, no moisture and no time variation of large-scale forcing. We thus could not expect agreement between the LES experiments and in-situ observations.

It was demonstrated that the simulation of very stable conditions requires very high spatial resolution: the spread of variables averaged over the horizontal domain was strongly reduced on increasing the horizontal and vertical resolutions from 5 m and 2 m to 1 m and 1 m. As in previous published studies, in the majority of the models, thinner stable boundary layers with stronger inversions are reproduced when using higher resolution. We show that the grid length of at least 1 m is necessary to reproduce such cases. Indeed, a relative convergence of the mean profiles simulated by the different models is observed at such a resolution suggesting that LES is becoming mature to tackle extreme stable situations. However, even at this resolution, the models diverge for some quantities such as the distribution of horizontal anomalies or second-order moments. For some of the models, sensitivity tests were performed to i) the resolution (horizontal and vertical), ii) the size of the domain, iii) the subgrid turbulence scheme, iv) the thermodynamical profile used for initialization and v) the formulation used to compute surface fluxes. The results show no sensitivity to the size of the domain or the thermodynamical profile used for initialization, suggesting that the set-up has been well-defined. In addition, little sensitivity to the formulation used to compute surface fluxes is revealed. However, strong sensitivity to the horizontal and vertical resolution as well as to the choice of the subgrid scheme is highlighted, suggesting that at such high stability the accuracy and skill of current LES models is significantly challenged. This also suggests that more work is needed on the dependence of the LES results to the choice of subgrid turbulence parametrization and on what it is better to use in such high stable conditions. This study highlights the fact that LES should not be taken as absolute references in such stable conditions, however they can still provide interesting guideline for the development of parametrizations.

Here, a simplified set-up has been used for the simulations neglecting subsidence and radiation and further studies need to document the different interplay between turbulence, radiation and eventually subsidence from observations and whether or not this partitioning is correctly reproduced by LES, in line with Edwards 2009, Edwards et al. 2014, van der Linden et al. 2019 for instance. Preliminary tests from a more realistic case suggest that similar turbulent behaviour is obtained with or without radiation if the water vapour content is set to 0, but this may hide some compensating errors and different thermodynamical equilibria. For future intercomparisons that aim to focus on turbulence in very stable conditions, we recommend using a common simplified surface scheme and radiation scheme for all the models in order to allow interactions between these processes without bringing in additional sources of variability by new parametrizations.

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Appendix 1: Initial conditions

Initial conditions and forcing for the Experiment 1, 2 and 3 of the GABLS4 case Stage3 are provided in Table 5.

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Fig. 1 Vertical profiles of initial conditions: (a)/(c) potential temperature, (b)/(d) wind speed at 0000 UTC for the 24-hour runs/ the 10-hour runs (in red). Panels c and d show a zoom over the lowest 150 m; this upper bound is materialized with dashed line in a and c. (e) time-series of the prescribed surface temperature. Observations from Dome C are overplotted with symbols

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Table 1 The different models with the parametrization of subgrid turbulence, the derivation of surface fluxes (βm and βh from Eq 1 and 2 are indicated only for stable conditions), the numerical schemes for advection and for time derivatives. Colors are used to indicate similarities among models concerning subgrid turbulence scheme, theory used for the surface flux computation or temporal scheme

Table 2 List of the different runs realized by each LES model with information on the horizontal and vertical resolution, condition at the domain top, domain size and roughness lengths used for the 24h runs (in black) and the 10h runs (in grey). Each simulation is labelled MxEyRwDz with x the number of the model, y the number of the experiment, w a change of the resolution relative to the reference, z a change of the domain relative to the reference. MOST/Sf indicates a sensitivity to the surface flux formulation and Sm/Vo indicates a sensitivity to the turbulence scheme (see text for details). Colors indicate changes relative to the previous experiment. Experiment 1 and 2 correspond to a large domain 1000 m X 1000 m X 1000 m, with a horizontal resolution of 5 m and a vertical resolution of 2 m at least below 500 m, initialization at 0000 UTC and with different roughness lengths prescribed for the two experiments. Experiment 3 corresponds to a smaller domain with a finer resolution initialization at 1000 UTC

Table 3 Main characteristics of the convective boundary layer at 0500 UTC and the stable boundary layer at 1700 UTC (averaged over an hour) for the different runs of Experiments 1 (or Experiments 2 if not participating to Experiments 1) : the boundary-layer height, h, defined as the minimum of buoyancy flux in convective conditions or 1./0.95 times the height where the mean stress reaches 5 % of its surface value in stable conditions, the Obukhov length, L, the friction velocity, u_* and the surface heat flux, H

Table 4 Main characteristics of the stable boundary layer at 1700 UTC (averaged over an hour) for the differents runs of Experiments 2 and 3: the boundary-layer height, h, defined as 1./0.95 times the height where the mean stress reaches 5 % of its surface value, the Obukhov length, L, the friction velocity, u_*, the surface heat flux, H and the temperature scale, θ_*

Table 5 Description of the initial profiles and forcing for the runs initialized at 0000 UTC or at 1000 UTC as well as the time serie of the prescribed surface temperature