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1Intercomparison of Large-Eddy Simulation Models of the 2Antarctic Boundary Layer Challenged by Very Stable 3Stratification

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10Abstract In polar regions, where the boundary layer is often stably stratified,
**11atmospheric models present large biases that are dependent upon the schemes used to
12parametrize the boundary-layer processes and the exchange of energy at the surface. This**

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13model intercomparison study focuses on very stable stratifications encountered over the
14Antarctic Plateau in 2009. Here, we analyze results from 10 large-eddy simulation (LES)
15codes, run at different spatial resolutions for 24 consecutive hours and compare them to
16observations acquired at the Concordia Research Station during summer. This is a
17challenging exercise for such simulations as they need to reproduce both the 300-m-deep
18convective boundary layer and the very thin stable boundary layer characterized by a
19strong vertical temperature gradient (10 K difference over the lowest 20 m) when the sun
20is low over the horizon. A large variability in surface fluxes among the different models
21is highlighted. The LES models correctly reproduce the convective boundary layer in
22terms of mean profiles and turbulent characteristics but display more spread during stable
23conditions, which is largely reduced with higher horizontal and vertical resolutions in
24additional simulations focusing only on the stable period. This highlights that very fine
25resolution is needed to represent such conditions. Complementary sensitivity studies are
26conducted regarding the roughness length, the subgrid-scale turbulence closure scheme as
27well as the resolution and domain size. While we find little dependence on the surface
28flux parametrization, the results indicate a pronounced sensitivity to both the surface
29roughness length and to the turbulence closure.

30**Keywords** Dome C, Antarctica • Large-eddy simulation • Parametrization • Stable
31boundary layer • Subgrid turbulence scheme

321 **Introduction**

33A stably stratified boundary layer develops in the presence of a surface colder than the
34overlying air. Such conditions are encountered frequently in polar regions, over land
35during night-time and wintertime, and during advection of warm air over a colder
36surface. Stable boundary layers (SBLs) can be classified according to the strength of the
37thermal inversion. Generally, weakly stable boundary layers with continuous turbulence
38occur when the wind speed is moderate to strong or in the presence of clouds limiting the
39surface radiative cooling. A model intercomparison for a weakly-stable boundary layer
40was conducted in the first intercomparison (GABLS1) of the GABLS (the GEWEX,
41Global Energy and Water Cycle Experiment, Atmospheric Boundary Layer Study)
42project (Beare et al. 2006). As shown in Beare et al. (2006), the turbulence under weak

43stratification, mainly mechanical turbulence forced by wind shear, is relatively well
44understood and described by similarity theory. This kind of turbulence is also correctly
45reproduced by high-resolution large-eddy simulations (LESs; Beare et al. 2006; Huang
46and Bou-Zeid, 2013; Matheou and Chung, 2014). Very stable boundary layers typically
47occur in the presence of low wind speeds and clear skies and are characterized by strong
48temperature inversions. With an increase in stratification, turbulence can become
49intermittent or decoupled from the ground (Mahrt 1999; Sun et al. 2012; Mahrt 2014). In
50such strong stratification, similarity theory becomes inapplicable (Ha et al. 2007) and it is
51a challenge to simulate the boundary layer even with high-resolution LESs. Van de Wiel
52et al. (2012) proposed a framework to predict the critical synoptic conditions for
53sustained turbulence and showed that below a minimum wind speed threshold,
54continuous turbulence is unlikely to occur. Vignon et al. (2017a) showed that the wind
55speed threshold under which the very stable regime occurs lies around 5 to 6 m s⁻¹ at
56Dome C (a meteorological and astronomical station in the high East Antarctic plateau),
57which is above the average wind speed observed at 10 m for the case study considered
58hereafter.

59 The accurate representation of the SBL is still a key issue for numerical weather
60prediction or climate models, particularly for very stable conditions. Numerical weather
61prediction models often report significant biases at night over land (Holtslag et al. 2013)
62with warm or cold biases depending on the excess of mixing or the strength of the
63decoupling with the surface. Indeed, Sandu et al. (2013) explained how enhanced
64turbulent diffusion is maintained in the European Centre for Medium-Range Weather
65Forecast (ECMWF) model besides its detrimental impact on the representation of stable
66boundary layers but due to the improved large-scale flow and near-surface temperature.
67This study emphasizes that this enhanced diffusion is needed to compensate for errors
68caused by other poorly represented processes, encouraging more studies of processes in
69stable boundary layers. Climate models also suffer from significant biases of temperature
70in the low levels, with a strong climate signal in polar regions, where the results strongly
71depend on boundary-layer parametrizations (King et al. 2001). Several intercomparison
72activities endorsed by GABLS proposed different cases in which LES and single column
73models (SCMs) are intercompared in order to evaluate parametrizations. The use of LES

74has proven to be very useful for the evaluation and development of parametrizations for
75clear and cloudy boundary layers (Randall et al. 2003; Hourdin et al. 2013). One aim of
76those GABLS investigations was also to evaluate the spread among different LES models
77in order to examine how reliable these high-resolution simulations are and to what degree
78they can be used as a guidance for the parametrization of the SBL. Three different
79GABLS intercomparisons have already been carried out, focusing on progressively more
80realistic cases.

81 The first case, GABLS1, used an idealized set-up over an icy surface with the
82development of a shear-driven stable boundary layer (Beare et al. 2006). This case was
83loosely based on observations from the Arctic and corresponded to weakly stable
84conditions. A prescribed uniform geostrophic wind of 8 m s^{-1} and a constant surface
85cooling rate of 0.25 K h^{-1} were applied and neither radiation nor surface interaction were
86taken into account. Beare et al (2006) showed relatively good agreement among the
87different LES and Cuxart et al. (2006) further used the LES results as a reference for a
88SCM intercomparison. Cuxart et al. (2006) also showed that the SCMs generally
89overestimated mixing, except for those using a prognostic turbulence kinetic energy (e)
90scheme.

91 The second case, GABLS2, was based on observations from the Cooperative
92Atmospheric Surface Exchange Study (CASES-99) field campaign and aimed at
93representing a complete diurnal cycle with SCM runs (Svensson et al. 2011). For this
94case, the models were run with a prescribed surface temperature inhibiting a possible
95ground surface--boundary layer interaction. The intercomparison focused on the
96evaluation of the turbulence schemes. However, most of the spread between models was
97attributed to differences in interaction between fluxes and stability.

98 The third case, GABLS3, was more closely based on observations from the
99Cabauw tower. Special emphasis was placed on the analysis of the coupling with the
100surface and the radiation (Bosveld et al. 2014a; 2014b). The observed near-surface
101potential temperature and moisture were prescribed so the intercomparison focused on
102the role of numerical schemes and subgrid-scale (SGS) turbulence schemes on the
103boundary-layer profiles. The different LES models were in very good agreement
104(Holtslag et al. 2013).

105 However, those three cases did not tackle very strong stable conditions and this is
106the main objective of the GABLS4 intercomparison study (Bazile et al. 2014). This case
107is based on the observations acquired on a meteorological tower at Dome C on the
108Antarctic Plateau (Genthon et al. 2013) on 11 December 2009. This site has been chosen
109because of:

110- i) the relatively large dataset acquired in the framework of the Concordiasi field
111campaign (Rabier et al. 2010)

112- ii) the flatness and homogeneity of the ground: topography and surface heterogeneities
113are significant factors of turbulence in stable conditions; even a very fine slope can
114produce drainage flows (Mahrt and Larsen 1990).

115-iii) the dryness of the air. Indeed, the occurrence of a clear and clean atmosphere with
116very small water vapour content induces a strong radiative cooling at the surface with a
117rate reaching more than 2 K h^{-1} when the sun is very low above the horizon.

118 On 11 December 2009, the boundary layer was convective when the sun was high
119above the horizon reaching a height of a few hundred metres. This is a frequent feature
120over Dome C, as highlighted by previous studies (King et al. 2006; Ricaud et al. 2012;
121Genthon et al. 2013; Casasanta et al. 2014) who showed frequent convective boundary
122layer heights of 250 m to 350 m in summer. On that day and consistently with the
123climatology, when the sun was low above the horizon, very strong vertical gradients of
124temperature were measured close to the surface at that site with values reaching more
125than 0.7 K m^{-1} . The net radiation varies throughout the 24 hours from 49 W m^{-2} at 0400
126UTC (local time = UTC + 8 h) and -44 W m^{-2} at 1600 UTC, this is typical values for
127surfaces covered by snow and summer conditions over Antarctica (King et al. 2006).

128 Three different stages were proposed for the GABLS4 intercomparison (Bazile et
129al. 2014). The first one is dedicated to the intercomparison of SCMs with an interactive
130snow surface scheme, the second one prescribes observed surface temperature
131(suppressing feedback from the surface), and the third one is an idealized case where the
132large-scale forcing and initial conditions have been simplified. In this paper, we focus on
133stage 3, which is the most idealized set-up. It includes prescribed surface temperature, no
134radiation, no specific humidity, and a constant large-scale forcing with time. This case is
135very challenging for LES models as it incorporates the full diurnal cycle with both a

136relatively deep convective boundary layer during midday and an extremely thin boundary
137layer when the sun is very low over the horizon. The objective of this work is to present
138the skill among various LES models at such stability. Indeed, at such strong stability we
139test the limit of the validity of the LES technique that has been shown to represent
140convective boundary layers satisfactorily and weakly stable boundary layer in the
141previous GABLS exercises. We expect deficiencies of LES in such very stable conditions
142because of (i) a possibly problematic estimation of the dissipation associated to the
143existence of non-isotropic subgrid turbulence (only a few subgrid turbulent schemes do
144not assume isotropy), or a misrepresentation of the buoyant destruction by the subgrid
145turbulence scheme (Bou-Zeid et al. 2010) (ii) the importance of radiative flux divergence,
146indeed in the present study as in many LES studies the radiative flux divergence is
147neglected, (iii) the weak surface turbulent fluxes, (iv) the need of very fine grid resolution
148in order to still have most of the turbulence resolved. We also want to assess what is the
149necessary resolution to resolve the main processes in such stable cases and how the
150results depend on the SGS turbulence scheme and surface parametrizations. Several
151studies have shown that it is difficult to get convergence of the results for a given model
152and that results even at high resolution still depend on the used resolution (Huang and
153Bou-Zeid 2013; Van Stratum and Stevens, 2015; Sullivan et al. 2016 and Maronga et al.
1542020, among others).

155 Very few studies have focused on the representation of very stable boundary
156layers in LES models. Huang and Bou-Zeid (2013) simulated a suite of GABLS1-based
157test cases by increasing the surface cooling rate up to -2.5 K h^{-1} and obtained a largely
158expanded stability range where the gradient Richardson number reached values up to
159around 1. They systematically investigated the effects of stability on the bulk dynamics,
160turbulent structure, and e budget, as well as the applicability of local similarity theory in
161the SBL, and found that i) the vertical extent of turbulent structures is reduced with
162increasing stability, ii) buoyant destruction of turbulence kinetic energy becomes more
163important than viscous dissipation under the strongest stabilities, and iii) the z-less range
164of scaling in the SBL starts at lower heights than previously anticipated. Walesby and
165Beare (2016) proposed a case derived from observations from the Halley research station
166on the Brunt iceshelf for which they ran both LES and SCM. They used the LES result as

167a reference to show that the choice of stability functions was critical for the behaviour of
168the SCM. Following Huang and Bou-Zeid (2013), Sullivan et al. (2016) modified the set-
169up of GABLS1 by imposing stronger surface cooling rate up to -1 K h^{-1} in order to obtain
170very stable conditions and conducted very high grid-resolution (down to $\Delta x = \Delta y = \Delta z =$
17139 cm) simulations run for 9 physical hours. They noted a decrease of the SBL height
172with increasing resolution and showed the existence of temperature micro-fronts in the
173simulations. Also they found that grid convergence was not reached in their simulations.
174Recently, Maronga et al. (2020) investigated whether the surface boundary conditions
175(i.e. the Monin–Obukhov Similarity Theory, MOST) are responsible for the lack of grid
176convergence observed in stable conditions. While grid convergence was significantly
177improved for surface fluxes of heat and momentum, they found, however, that the non-
178convergence of the mean profiles could not be ascribed to the boundary conditions. Very
179recently, van der Linden et al. (2019) simulated accurately winter weakly and very stable
180boundary layers observed at Dome C with very fine (cm-scale) LES. They show that a
181thermal equilibrium can be reached between subsidence (heating) and turbulence
182(cooling).

183 The main objective of this paper is to present the results of the first
184intercomparison of large-eddy simulations in very stable conditions. In the following,
185Sect. 2 details the methodology for the intercomparison, focusing on the case and model
186description but also giving information on the diagnostics and the sensitivity tests that
187have been carried out. Section 3 presents the main results with a distinction between the
188representation of the convective and stable behaviour of the boundary layer. Section 4
189presents the different sensitivity tests and the paper closes with conclusions and
190recommendations for future LES intercomparisons in very stable conditions. A
191forthcoming companion paper will present the results of the SCM intercomparison.

192 **Methodology**

193 **2.1 Case Description**

194As documented by Bazile et al. (2014), the present case is based on observations from
195Dome C (123.3E, 75.1S, 3223m above sea level) on the Antarctic Plateau (Genthon et al.
1962013). Recall that this case occurs in summer in Antarctica, so there is daylight

197throughout 24 hours although the net radiative energy at the surface is positive when the
198sun is high above the horizon and negative when the sun is low. Here, the simplest set-up
199is used in order to allow contributions to this intercomparison from many modelling
200groups. In particular, the case neglects radiation and land-surface interactions.
201Furthermore, the large-scale forcing includes only the geostrophic wind, which is
202assumed constant in time and along height. Temperature advection and subsidence are
203not included in the case set-up. The initial profiles of potential temperature, zonal wind
204and meridional wind are derived from the soundings launched at 0000 UTC (0800 local
205time; see Fig. 1 and Table 5). The initial sounding consists of a stable boundary layer
206with a relatively steep temperature gradient up to 45 m overlaid by a less stable layer.
207The wind is almost constant with height (except in the lowest part of the boundary layer)
208with a speed of around 4 m s^{-1} . The case is considered dry (note that the water vapour
209mixing ratio is very low at Dome C with typical values of 0.3 g kg^{-1} , see Genthon et al.
2102017). A spatially uniform time-dependent temperature derived from observations is
211prescribed to provide the surface boundary condition (Table 5). As shown in Fig. 1e,
212there is a warming of the surface for the first five hours of the simulation followed by a
213cooling. The largest cooling rate occurs between 1100--1600 UTC with values about 2 K
214 h^{-1} , which is a significantly larger cooling rate than the 0.25 K h^{-1} used in GABLS1
215(Beare et al. 2016) or the range of cooling rates used in Sullivan et al. (2016) that
216increases from 0.25 to 1 K h^{-1} . The roughness lengths for heat and momentum are also
217prescribed to be 10^{-2} m for momentum, z_{0m} and 10^{-3} m , z_{0h} for heat (Experiment 1). To
218better agree with observations (Vignon et al. 2017b), additional simulations with
219momentum and heat roughness lengths of 10^{-3} m and 10^{-4} m , respectively, were carried
220out. The default case is named Experiment 1 while the case with modified roughness
221lengths is called Experiment 2. The sensitivity of the LES results to roughness length is
222discussed in Sect. 4.

223 Simulations of the convective part of the diurnal cycle require large computational
224domains because of the relatively large boundary-layer height compared to that
225encountered in the stable conditions. Thus, the grid resolution is constrained by the height
226of the convective layer and the stable boundary layer is only captured by the lowermost
227few model layers. In order to focus on the stable conditions and optimize grid resolution,

228 Experiment 3 was carried out, in which simulations start at 1000 UTC (instead of 0000
 229 UTC) and ensemble mean profiles of Experiment 2 are used as the initial conditions (Fig.
 2301 a-d and Table 5 for numerical values). The same large-scale forcing and surface
 231 boundary conditions of Experiment 1 and 2 are used. The roughness lengths used in
 232 Experiment 2 are used. The initial profile of potential temperature at 1000 UTC is close
 233 to neutrality.

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

246 The boundary-layer height is defined as the level of minimum turbulent vertical
 247 potential temperature flux in convective conditions and follows the definition used in
 248 Beare et al. (2006) for the stable conditions, 1./0.95 times the height where the mean
 249 stress reaches 5% of its surface value. The Obukhov length is also computed as, where U ,
 250 V are the zonal and meridional component of the wind, θ the potential temperature, $\overline{u'w'}$,
 251 $\overline{v'w'}$, $\overline{\theta'w'}$ momentum and temperature turbulent fluxes, κ , the von Kármán constant and
 252 g the gravitational constant:

253

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

254

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

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

$$K_h^{\text{eff}} = \frac{\overline{\theta'w'}}{\frac{\partial \theta}{\partial z}}, \quad (3)$$

258

259

260 2.2 Models

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

262 All the models use their own model-specific SGS turbulence parametrization and
 263 discretization in space and time as well as MOST for calculating surface fluxes (see
 264 Table 1). Most of the SGS schemes are based either on a prognostic equation for the
 265 turbulence kinetic energy, with a Deardorff (1974) length scale or on a Smagorinsky
 266 (1963) scheme with or without a dynamic component. In particular, CSIRO and
 267 MATLES use advanced scale-dependent SGS models to calculate the SGS eddy viscosity
 268 (Bou-Zeid et al. 2005; Basu and Porte-Agel 2006), which have been shown to simulate
 269 the SBL reliably even under strong stabilities (Huang and Bou-Zeid 2013). The
 270 University of Connecticut LES (UConn) uses the buoyancy adjusted stretched vortex
 271 model (Chung and Matheou 2014) and the sensitivity to the SGS turbulence scheme for
 272 this model is shown in Sect. 4. All the models use a MOST-based formulation (see
 273 Cuxart et al. 2006), using an integral formulation, to calculate surface turbulent fluxes
 274 following:

275

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

276

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

277

278with $|\vec{U}|$ being the wind speed, L the Obukhov length, u_* the friction velocity, θ_* the
279surface temperature scale and f_m and f_h functions that are often written as $1 + \beta_{m,h} z/L$ for
280stable conditions with $\beta_{m,h}$ coefficients whose values are model-specific. Note that $\beta_{m,h}$
281coefficients are not constrained in the present GABLS4 case and differ from one model to
282another (see Table 2 for more details). No moisture is included and therefore no
283microphysics parametrization is needed. Radiation is also excluded to focus on
284turbulence.

285 The domain size was set to $1000 \times 1000 \times 1000 \text{ m}^3$ with a horizontal resolution of
2865 m and a vertical resolution of 2 m at least up to 400 m for the Experiments 1 and 2 (E1
287and E2 runs). To prevent spurious reflection from the model top boundary, most models
288applied a Rayleigh damping above heights of 600-700 m where the prognostic variables
289are relaxed towards the large-scale fields. Tests with a larger horizontal domain indicate
290that the prescribed domain size is sufficient (see Sect.4). For runs starting at 1000 UTC
291(Experiment 3), the domain was restricted to $500 \times 500 \times 150 \text{ m}^3$, or even smaller
292depending on the models, with an isotropic grid of 1 m resolution. The different
293sensitivity tests performed for each model are indicated in Table 2, as well as their
294configuration (resolution, domain and roughness lengths).

295

2962.4 Sensitivity Tests

297Several models contributed to the exercise with an ensemble of simulations, which
298allowed us to analyze the sensitivity of the results to aspects of physical parameters and
299numerical configuration.

300 The sensitivity to the roughness length is first tested. Most models (MesoNH,
301PALM, UConn, MATLES, MONC, ELMM and CSIRO) contributed with one simulation
302with $z_{0m}=10^{-2} \text{ m}$ and $z_{0h}=10^{-3} \text{ m}$ (Experiment 1) and an additional one with $z_{0m}=10^{-3} \text{ m}$ and
303 $z_{0h}=10^{-4} \text{ m}$ (Experiment 2). Sensitivity to the subgrid turbulence parameterization is
304addressed with one model. UConn was run with the exactly same configuration for runs
305of Experiment 2 with varying grid resolution from 5m to 1m (see Table 3) but with either
306a Smagorinsky subgrid turbulence scheme or a newly developed turbulence scheme
307based on buoyancy adjusted stretched vortex model (Chung and Matheou, 2014). Three
308models investigated the sensitivity to the surface turbulent flux parameterization.

309MesoNH, PALM and UConn carried out a simulation for Experiment 3 with a prescribed
310formula to compute surface turbulent fluxes from the differences between the first level
311information and the surface temperature following equations (1 and 2) with values of
312 $\beta_m=4.8$ and $\beta_h=7.8$.

313 The sensitivity to grid-resolution has also been addressed. PALM and UConn
314performed additional simulations with a range of horizontal and vertical resolutions
315between 5 m and 0.5 m for Experiment 2 (see Table 3). For Experiment 3, MesoNH and
316UConn also performed simulations with different horizontal and vertical resolutions.
317Note that those simulations were run on a smaller domain (see Table 3 and iii).
318Sensitivity to the size of the domain has been documented with two models. Several
319domain sizes were used ranging from $2.5 \times 2.5 \times 1 \text{ km}^3$ down to $0.25 \times 0.25 \times 0.075 \text{ km}^3$.
320In particular, PALM provided a simulation with a $2.5 \times 2.5 \times 1 \text{ km}^3$ domain and a $1 \times 1 \times$
3211 km^3 for Experiment 2, the simulations with MicroHH were provided with a $3 \times 3 \times 0.5$
322 km^3 domain for Experiment 1 and MesoNH provided two simulations with $0.5 \times 0.5 \times$
3230.15 km^3 and $0.25 \times 0.25 \times 0.075 \text{ km}^3$ domains for Experiment 3. Eventually, sensitivity
324to the starting time has been analyzed. MesoNH and MicroHH were run starting either
325from the profile prescribed for Experiment 3 (ensemble mean at 1000 UTC) or from the
326initial profiles at 0000 UTC in order to assess the sensitivity to the different
327initializations.

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

3293 Results

3303.1 Diurnal Cycle

331Figure 2 presents the time-evolution of the vertical structure of potential temperature for
332Experiment 1 (nine models). All models represent the convective boundary layer
333developing during the first seven hours of the simulations with a boundary-layer height,
334defined as the height of the minimum of vertical turbulent heat flux, reaching 300 m to
335400 m. This is consistent with the range of summer convective boundary-layer heights
336observed at Dome C as reported, for example, by sodar observations (Cassasanta et al.
3372014).

338 Figure 3a, b show the relatively good agreement between models in representing
339the convective boundary layer, although SAM displays stronger convection with a
340warmer (0.5 K) and higher boundary layer, consistent with its larger sensible heat flux
341and larger turbulence kinetic energy (Fig. 4). Focusing on the models that use a 10^{-2} m
342roughness length (shown in full lines), the spread between the other models is no larger
343than 0.3 K for the boundary-layer potential temperature and 20 m for the boundary-layer
344height. A further evaluation of the horizontal structures, distribution of temperature
345fluctuations and turbulence spectra in the boundary layer indicates good agreement
346between observations and simulations for the convective period (not shown). The data
347reveal more spread during stable conditions, however. Indeed, after the 10th hour, a SBL
348develops with a height that varies between models with the highest values for CSIRO and
349MATLES, which have the lowest spatial resolution (see Fig. 2). This is also evident when
350looking at the vertical profiles at 17 hours of simulations (Fig. 3c, d) with a relatively
351large spread of the peak of the low-level nocturnal jet, of the boundary-layer height and
352of the stratification observed at the top of the boundary layer. Part of the differences
353between observations and LES may be due to the definition of the forcing, which have
354been simplified in the studied case.

355 Figure 4a shows the surface sensible heat fluxes as computed by the individual
356models (only the surface temperature is prescribed). The spread during convective
357conditions reaches about 10 W m^{-2} , which is of the same order of magnitude as the
358ensemble mean that reaches a maximum of 20 W m^{-2} ; during stable conditions the spread
359still reaches 10 W m^{-2} , which is equal, in absolute value, to the ensemble mean. The
360simulated fluxes agree more or less with observations given the uncertainties of in-situ
361turbulence measurements (and the fact that the observations correspond to flux estimate
362at either 1.5 m for gradient estimate or 7 m for turbulence measurements) but issues with
363the applicability of MOST in such stable conditions may also explains some departure
364(Mahrt, 2008; 2010). The momentum flux at 7 m (Fig. 4b and Table 3) in Experiment 1
365varies from $-0.09 \text{ m}^2 \text{ s}^{-2}$ to close to $0 \text{ m}^2 \text{ s}^{-2}$ depending on the model with a mean value
366during convective conditions of $-0.065 \text{ m}^2 \text{ s}^{-2}$ and a very small spread apart from two
367departing models; this is larger than the observed value of $-0.025 \text{ m}^2 \text{ s}^{-2}$. The total
368(resolved plus subgrid) turbulence kinetic energy (Fig. 4c) at 30 m reaches 0.2 to 0.35 m^2

369s⁻² depending on the model, also overestimated compared to observations. Using a
370reduced prescribed roughness length of 10⁻³ m (Experiment 2 and Table 3) reduces
371surface sensible heat fluxes, friction velocity at 7m and turbulence kinetic energy at 30m
372mainly during convective conditions, with values closer to observations (not shown). It is
373worth remembering that the mean estimated roughness length derived from observations
374was also close to 10⁻³ m (Vignon et al. 2017b). In the following, we will focus on the
375analysis of runs using this value of roughness length (Experiments 2 and 3). The spread
376among simulations is reduced during convective conditions but not during stable
377conditions.

3783.2 Stable Period

379In the rest of the paper, we concentrate on the analysis of the stable conditions, i.e. the
380period when the sun is very low above the horizon and the boundary layer is stably
381stratified. According to the literature, 5-m horizontal grid spacing is not fine enough to
382correctly represent the very shallow boundary layer during the stable conditions (see
383Beare et al. 2006; Sullivan et al. 2016 among others). Indeed, Fig. 2-4 evidence an
384absence of convergence between LES for the stable period that may partly be explained
385by too coarse a resolution in the simulations.

386 Figure 5 presents the vertical profiles of potential temperature and wind speed for
387the models that did run both experiments 2 and 3 (which differ in resolution and initial
388profiles). The spread among the simulations is clearly reduced from Experiment 2 ($\Delta x=5$
389m, $\Delta z=2$ m) to Experiment 3 ($\Delta x=\Delta z=1$ m) both in terms of intensity and height of the
390low-level jet as well as regarding the height of the maximum positive gradient of
391potential temperature. For example, the standard deviation at 20m reduces from 0.52 m s⁻¹
392¹ to 0.28 m s⁻¹) for the wind speed and from 2.53 K to 1.88 K for the potential
393temperature. The spread is also reduced for the turbulent sensible heat flux from slightly
394more than 10 W m⁻² to 5 W m⁻². Table 4 also a reduction of spread in the main turbulent
395characteristics (boundary-layer height, friction velocity, Obukhov length) for those two
396experiments. The reduction of spreads is caused by the increased resolution rather than by
397the initial conditions. Indeed, further sensitivity tests revealed that the reduction of the
398spread is not explained by different initial conditions (not shown). Figure 6 presents a
399time evolution of the vertical profiles of the potential temperature below $z = 42$ m. As an

400 illustration, the time-evolution of the observations collected from the tower at Dome C is
401 also shown. This figure clearly shows that the stable boundary layer tends to be thinner
402 and to have a stronger inversion at the top for simulations with higher resolution (it is
403 slightly less evident for Uconn and PALM), which is in agreement with previous results
404 from the literature (Sullivan et al. 2016; van Stratum and Stevens 2015 among others).
405 Also the models overestimate the boundary-layer height compared to observations but
406 this may be caused by the absence of subsidence in the simulations (Vignon et al. 2017c).
407 The spread in model results is larger when focusing on variances and covariances for
408 both experiments as illustrated by the turbulence kinetic energy and the turbulent heat
409 flux (Fig. 7), although there is also a clear reduction of the spread in higher resolution
410 simulations. Dotted lines in Fig. 7 show the subgrid component of the turbulence kinetic
411 energy and indicates a strong decrease of its contribution to the total turbulence kinetic
412 energy in higher resolution simulations. For the turbulence kinetic energy, two
413 estimations are available from observations, either from turbulence data with a high-pass
414 filter at 200 s^{-1} or from raw turbulence data. The difference between the two estimations
415 may reveal the existence of waves, large eddies or sub-mesoscale eddies that contribute
416 significantly to the turbulence kinetic energy. Figure 7 also shows the evolution of the
417 wind velocity components with height. The vertical variation of wind from simulations
418 with a resolution of 1 m show closer agreement than those from more coarsely resolution
419 simulations. However, some differences persist, with Meso-NH having the weakest
420 winds and PALM the strongest ones. Figure 8 presents the evolution through time of the
421 wind at 41m with again a better agreement between the simulations of Experiment 3 than
422 those of Experiment 2. As shown in Vignon et al. (2017c, their Fig. 8), observations
423 clearly indicate an inertial oscillation after the turbulence decay in the evening transition
424 with a frequency of the order of 12 hours as expected from the theory and the latitude of
425 75°S of Dome C. The simulations agree with the observations for the inertial oscillation
426 and the period (the geostrophic wind used in the forcing is indicated by the grey square).
427 The reduction of spread for Experiment 3 is probably due to the use of the same
428 initialization just at the moment of turbulence decay in opposition to Experiment 2 where

321

this is the classical cut-off frequency used for flux computation, and, using ogive computation, it was checked

33 that this was appropriate for turbulence measurement in this situation

429the different convective boundary layers have led to different profiles of wind speed.
430Figure 9 presents the effective momentum and heat diffusivities normalized by the
431boundary-layer height and the friction velocity and shows that the spread is also reduced
432for such diagnostics between Experiment 2 runs and Experiment 3 runs. The profiles
433differ significantly from those of the GABLS1 experiment (Beare et al. 2006). Shapes of
434the profiles are quite different than those shown in Beare et al. (2006) for momentum due
435in particular to an almost null vertical gradient of wind.

436 In the following, we focus only on the results of Experiment 3 that show much
437closer agreement between the different models. Figure 10 shows the vertical profiles of
438(a) turbulent heat flux and (c) horizontal momentum flux and the respective fluxes
439normalized by their surface values (b and d). From these figures, it is evident that the
440remaining spread can be to a great extent explained by differences in surface fluxes since,
441when normalized, the curves almost converge. Also, one can note close to linear profiles.
442In particular, MONC produces a particularly low wind stress at the surface, which is also
443visible in Fig. 4b, but the model has a similar transport of momentum compared to the
444other LES in normalized sense. Figure 10e, f also show the contribution to the turbulence
445kinetic energy of the variance of horizontal wind and the variance of vertical wind. As
446expected in stable conditions, the contribution of horizontal wind is stronger than the
447contribution of vertical wind, which is consistent with findings of Huang and Bou-Zeid
448(2013), who found that turbulence is much more energetic horizontally than vertically
449under very stable conditions, causing ‘sandwiched’ coherent structures (Chung and
450Matheou 2012; Matheou and Chung 2012). Note, however, a large spread among models
451in the intensity of wind variances.

452 Although, we have just shown that the spread among LES was reduced for the
453Experiment 3 set-up, there are still some discrepancies in terms of horizontal variability.
454This was in particular investigated by comparing the distribution of the potential
455temperature anomalies for five different vertical levels ranging from 7 m to 38 m above
456the surface but this is also true for the anomalies of the three wind components (not
457shown). Observations indicate that horizontal variability is large only at 7 m and strongly
458reduced at 23 m. Unfortunately, no information from the observations is provided

459between 7 m and 23 m. CSIRO and DALES present the largest variability at all levels
460except 38 m. MesoNH, MONC and UConn models show the largest horizontal variability
461at 14 m. For the horizontal variability of horizontal wind components the maximum is
462simulated close to the surface for all the models (not shown). The disagreement with
463observations is consistent with LES predicting higher boundary layers than observed.

4644 Sensitivity Tests

465This section summarizes the main conclusions of the different sensitivity tests that have
466been carried out in this intercomparison. We first investigate the sensitivity to the
467numerical configuration (time of initialization, size of the domain or resolution) and
468secondly we assess the sensitivity to the physical parameters (roughness length,
469turbulence parametrization and surface flux parametrization).

4704.1 Initial Profile

471Starting a simulation from 0000 UTC (0800 LT) or from 1000 UTC (1800 LT) had very
472little impact on the representation of the SBL for both MesoNH and UConn runs (not
473shown), which may be counter-intuitive as we may think that the way the convective
474boundary layer is reproduced (especially just before the convective-stable transition)
475matters for the rest of the period with stable conditions. However, this may also be
476explained by the fact that there is not much spread among the different LES models after
47710 hours and therefore the initial conditions at 1000 UTC do not differ much from the
478thermodynamic conditions encountered in any LES runs.

479

4804.2 Grid Resolution

481PALM and UConn ran Experiment 2 with increasing resolution from 5 m to 1 m (see
482Table 2) and MesoNH and UConn ran Experiment 3 with increasing resolution from 1 m
483to 0.25 m (see Table 2). PALM simulations show relatively little sensitivity to the
484resolution and results are similar from E2 to E3, UConn simulations show more
485differences among the different resolution tests in E2. Figure 11 shows the resulting
486vertical profiles at 1700 UTC for the runs of Experiment 3 focusing on the stable
487conditions. Convergence of the simulations, according to the mean profiles, is obtained

488for 0.5m for both Uconn and MesoNH. For MesoNH, running the simulation with a
489higher resolution leads to a shallower stable boundary layer and low-level jet, and weaker
490surface sensible heat fluxes, similar to Sullivan et al. (2016). It is worth noting that, for
491MesoNH, the change in vertical resolution from 1 m to 0.5 m has more impact than
492changing the horizontal resolution from 1 m to 0.5 m, possibly because a higher vertical
493resolution improves the representation of vertical gradients that are rather strong under
494stable conditions and of the turbulent structures that become anisotropic and, thus,
495vertically flattened by buoyancy effects. Looking at second order moments (Fig. 12), the
496convergence has been obtained at 0.5 m for Uconn as the 0.25 m has exactly the same
497results but not yet for MesoNH. This shows that grid convergence is model-specific.
498Note, moreover, that the results of Sullivan et al. (2016), Maronga et al. (2020) and van
499der Linden et al. (2019) indicated that grid convergence is not reached at grid spacings of
5000.33 m and 0.5 m for a strongly-stable and weakly-stable boundary layer, respectively.
501We must thus assume that under strongly-stable boundary-layer conditions as in the
502present intercomparison, even finer grid spacings might still alter the results.

503

5044.3 Domain Size

505The sensitivity test to the size of the domain performed either for Experiment 2 with
506PALM or for Experiment 3 with Meso-NH shows very little change (not shown) and
507indicates that the domains chosen for the experiments were large enough. This is
508expected as the size of eddies is expected to be smaller than the scale of the boundary-
509layer height. During the convective period the boundary-layer height reaches a maximum
510of 300 m and 1000 m wide domain correspond to three times this value. During the stable
511period the boundary-layer height is less than 50 m and a 250 m-wide domain already
512corresponds to 5 times the size of the largest eddies. A 500 m-wide domain is therefore
513more than sufficient. This is consistent with the results of Sullivan et al. (2016) for a set-
514up similar to GABLS1.

515

5164.4 Roughness Length

517The simulated turbulence closed to the surface depends on the prescribed roughness
518length (Zilitinkevich et al. 2006). Miller and Stoll (2013) analyzed how the results of

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

534

535 4.5 Subgrid Turbulence Scheme

536 The UConn model performed simulations using two different subgrid turbulence schemes
537 as detailed in Table 1. The reference parametrization is the buoyancy adjusted stretched
538 vortex model (Chung and Matheou, 2014), a structural turbulence closure where the
539 subgrid-scale flow is composed of a collection of vortical structures, which are
540 asymptotic exact solutions of the equations of motion. The additional simulations use the
541 classical subgrid turbulence closure of Smagorinsky (1963) and Lilly (1962, 1966). The
542 turbulence closure constant value of $C_s = 0.2$ and a turbulent Prandtl number $Pr = 0.33$ are
543 used based on the findings of Matheou (2016). A comparison of the performance of the
544 two closures for the GABLS1 case is presented in Matheou and Chung (2014). Further
545 sensitivity aspects of the Smagorinsky model for the GABLS1 case are discussed in
546 Matheou (2016). There is very little difference between the two runs in convective
547 conditions but a large sensitivity is revealed in stable conditions, as shown in Fig. 13 for
548 the three resolutions (5 m, 2 m, 1 m). The Smagorinsky turbulence closure model
549 produces a deeper and less stratified stable boundary layer, as well as larger negative

550sensible heat fluxes. Analysis of the distribution of the anomalies of potential temperature
551indicates that the distribution from the simulation with the Smagorinsky closure is
552slightly narrower than the one from the observations, while the distribution of the
553simulation with the vortex model is slightly broader at 7 m above ground level. The
554largest difference between the two simulations is shown at 14 m above ground level,
555where no observation is available. Although further exploring the difference between the
556Smagorinsky and the stretched vortex schemes is beyond the scope of the present paper,
557the comparison highlights the strong sensitivity to the choice of the subgrid turbulence
558scheme.

559

5604.6 Surface Parametrization

561To assess the impact of the surface flux parametrization, three models (MesoNH, PALM
562and UConn) provided additional runs with a prescribed surface flux formulation based on
563MOST and derived from equation 1 and 2 with $\beta_m=4.8$ and $\beta_h=7.8$. The results with the
564prescribed parametrization were similar to the original formulation, thus confirming that
565(a) small variations in the MOST empirical fitting coefficients and (b) the implementation
566of the parametrization do not have a significant impact on the present results. Indeed, the
567surface Richardson number remains in a still weakly-stable range where the different
568stability functions do not significantly diverge.

569

5705 Conclusion

571This paper summarizes the results of the fourth GABLS intercomparison for LES
572focusing on very stable boundary layers. This is a challenge if one wants at the same time
573to reproduce the convective boundary layer that can be encountered even in extreme
574polar conditions in summer and the very stable boundary layer. Indeed, it is only recent
575that the very high resolution needed for such simulations has become affordable. This is a
576case of idealized stable boundary layer although the set-up was inspired by observations.
577However, it was simplified compared to real observations with no subsidence, no
578contribution of radiation, no moisture and no time variation of large-scale forcing. We
579thus could not expect agreement between the LES experiments and in-situ observations.

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

604 Here, a simplified set-up has been used for the simulations neglecting subsidence
605 and radiation and further studies need to document the different interplay between
606 turbulence, radiation and eventually subsidence from observations and whether or not this
607 partitioning is correctly reproduced by LES, in line with Edwards 2009, Edwards et al.
608 2014, van der Linden et al. 2019 for instance. Preliminary tests from a more realistic case
609 suggest that similar turbulent behaviour is obtained with or without radiation if the water
610 vapour content is set to 0, but this may hide some compensating errors and different

611thermodynamical equilibria. For future intercomparisons that aim to focus on turbulence
612in very stable conditions, we recommend using a common simplified surface scheme and
613radiation scheme for all the models in order to allow interactions between these processes
614without bringing in additional sources of variability by new parametrizations.

615

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621

622**Appendix 1: Initial conditions**

623Initial conditions and forcing for the Experiment 1, 2 and 3 of the GABLS4 case Stage3
624are provided in Table 5.

625

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