

The JHU Turbulence Databases (*JHTDB*)

STABLY-STRATIFIED ATMOSPHERIC BOUNDARY-LAYER TURBULENCE ON A 2048³ GRID

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The data is from an atmospheric large-eddy simulation (LES) of the GABLS1 intercomparison case originally described by Holtslag (2006) and Beare et al. (2006). The problem design provides an excellent test-bed to study stratified turbulence in a high-Reynolds-number boundary-layer flow using large-eddy simulation (LES).

The first GABLS1 intercomparison used LES models with coarse and fine meshes of $N = 128^3$ and 200^3 gridpoints (Beare et al., 2006; Huang and Bou-Zeid, 2013), suitable for the computational capabilities at that time; flow was forced by specifying a geostrophic windspeed $U_g = 8 \text{ m s}^{-1}$ and a surface cooling rate $C_r = 0.25 \text{ K h}^{-1}$. Although there was qualitative agreement amongst the LES models, there are hints that an increased resolution resulted in shallower SBLs inducing a change in the surface friction velocity u_* and surface cooling flux Q_* . This motivated further study and Sullivan et al. (2016) explored the LES solution sensitivity using meshes of $N = (200^3, 512^3, 1024^3)$ gridpoints along with four different cooling rates $C_r = (0.25, 0.375, 0.5, 1.0) \text{ K h}^{-1}$. Here we advance the work presented in Sullivan et al. (2016) by providing data from LES of the GABLS1 configuration for a cooling rate of $C_r = 0.25 \text{ K h}^{-1}$ using $N = 2048^3$ gridpoints.

Governing equations: The model equations for large-eddy simulation of a stably-stratified atmospheric boundary layer (SBL) under the Boussinesq approximation with system rotation and with a flat bottom boundary are:

$$\frac{\partial \bar{\mathbf{u}}}{\partial t} + \bar{\mathbf{u}} \cdot \nabla \bar{\mathbf{u}} = -\mathbf{f} \times (\bar{\mathbf{u}} - \mathbf{U}_g) - \nabla \bar{\pi} + \hat{\mathbf{z}} \beta (\bar{\theta} - \theta_{ref}) - \nabla \cdot \mathbf{T} \quad (1a)$$

$$\frac{\partial \bar{\theta}}{\partial t} + \bar{\mathbf{u}} \cdot \nabla \bar{\theta} = -\nabla \cdot \mathbf{B} \quad (1b)$$

$$\frac{\partial e}{\partial t} + \bar{\mathbf{u}} \cdot \nabla e = \mathcal{P} + \mathcal{B} + \mathcal{D} - \mathcal{E} \quad (1c)$$

$$\nabla \cdot \bar{\mathbf{u}} = 0. \quad (1d)$$

The equation set includes transport equations for: momentum $\rho \bar{\mathbf{u}}$ (1a); virtual potential temperature $\bar{\theta}$ (1b); and subfilter-scale (SFS) turbulent kinetic energy e (1c). The divergence-free (incompressible) condition (1d) determines the elliptic pressure variable $\bar{\pi}$. The variables that appear in (1) are: velocity

components $\bar{\mathbf{u}} \equiv \bar{u}_i = (\bar{u}, \bar{v}, \bar{w})$, geostrophic winds $\mathbf{U}_g = (U_g, V_g)$, rotation vector $\mathbf{f} = (0, 0, f)$ with Coriolis parameter f , unit vector $\hat{\mathbf{z}}$ in the vertical direction, and buoyancy parameter $\beta = g/\theta_{ref}$, where g is gravity and θ_{ref} is a reference temperature. Pressure \bar{p} and air density ρ do not appear explicitly in (1). The terms on the right-hand side of (1c) for e are shear production \mathcal{P} , buoyancy production–destruction \mathcal{B} , diffusion \mathcal{D} , and dissipation \mathcal{E} . The modeling of these terms is described in Moeng and Sullivan (2015). The overbar notation $\bar{(\)}$ denotes a spatially filtered quantity.

The LES equations are formally derived by applying a spatial filter term-by-term to the governing equations of motion. This operation introduces the unknown SFS kinematic momentum and temperature fluxes

$$\mathbf{T} \equiv \tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j \quad ; \quad \mathbf{B} \equiv B_i = \overline{u_i \theta} - \bar{u}_i \bar{\theta} \quad (2)$$

For the SBL we adopt the two-part SFS model proposed by Sullivan et al. (1994), which utilizes the transport equation (1c) and an eddy viscosity approach to parameterize the SFS fluxes given by (2). This parameterization is specifically tailored to a high-Reynolds-number LES that uses rough-wall surface boundary conditions based on Monin–Obukhov (MO) similarity theory. In the eddy viscosity prescription $\nu_t = C_e \gamma \sqrt{e} \ell$, the isotropy factor $\gamma = S' / (\langle S \rangle + S')$ where $(\langle S \rangle, S')$ are the resolved strain rate average and fluctuation, respectively; the strain rate average is over an x – y plane. The isotropy factor essentially reduces the length scale ℓ as the wall is approached depending on the magnitude of the resolved turbulence fluctuations. The boundary conditions, solution algorithm, and further details are provided in Sullivan et al. (2016).

Simulation configuration and methods:

GABLS1 is a canonical high-latitude SBL driven by constant geostrophic winds $U_g = 8 \text{ m s}^{-1}$ with Coriolis parameter $f = 1.39 \times 10^{-4} \text{ s}^{-1}$ above a horizontally homogeneous rough surface $z_o = 0.1 \text{ m}$. The simulations are initiated from a neutral state with an overlying stable inversion $\partial_z \theta = 0.01 \text{ K m}^{-1}$ imposed at an initial height $z = 100 \text{ m}$. The computational domain size is $(400 \times 400 \times 400) \text{ m}$. A constant rate of surface cooling $C_r = 0.25 \text{ K h}^{-1}$ is applied starting at $t = 0$ to generate stably stratified turbulence. The specification of surface temperature fully couples the momentum and temperature relations in the Monin–Obukhov bottom boundary conditions, which is a more demanding test for LES compared to a specified temperature flux: further description of the simulation design is given in Sullivan et al. (2016). Previous LESs find a quasi-steady SBL featuring a low-level jet with wind profile veering in the SBL after 8 hours of simulation; the SBL depth $h \approx 200 \text{ m}$, the surface temperature flux $Q_* \approx -9 \text{ K m s}^{-1}$, and friction velocity $u_* \approx 0.25 \text{ m s}^{-1}$, which vary with the mesh resolution (Sullivan et al., 2016). The GABLS1 SBL is weakly stable with continuous turbulence and the boundary-layer stability metric is $h/L_{mo} \sim 1.7$, where $L_{mo} \approx 118 \text{ m}$ is the Monin–Obukhov length; see Table 1.

The present work expands on Sullivan et al. (2016) using an unprecedented resolution of $\Delta = 0.2 \text{ m}$ in all three directions with a mesh of $N = 2048^3$. Because of the computational cost a two-step recipe is used to perform the LES. First, a seed simulation with $N = (512 \times 512 \times 2048)$ is run from scratch for 8 hrs. The grid in this seed simulation is anisotropic but has the advantage that the wind and temperature profiles vary smoothly in the vertical direction. Next, the last volume from the seed simulation is archived and the field

Table 1: Bulk simulation properties, with entries: LES case, mesh points N , cooling rate C_r , mesh spacing Δ , friction velocity u_* , temperature flux Q_* , boundary layer height h , Monin-Obukhov stability length $L_{mo} = -u_*^3/\kappa\beta Q_*$, boundary layer stability h/L_{mo} .

Case	N	C_r (K hr ⁻¹)	Δ (m)	u_* (m s ⁻¹)	$Q_* \times 10^3$ (K m s ⁻¹)	h (m)	L_{mo} (m)	h/L_{mo}
C2	2048 ³	0.25	0.20	0.249	-8.83	187.2	118.6	1.56

variables are interpolated in the horizontal x - y directions using zero padded Fourier transforms to generate a restart volume with $N = 2048^3$ points. The fine mesh solution is then started and run for an additional 0.5 hr.

Data available

The available data include the three LES-resolved velocity components $\bar{u}(x, y, z, t)$, $\bar{v}(x, y, z, t)$, $\bar{w}(x, y, z, t)$ pressure $\bar{p}(x, y, z, t)$, virtual potential temperature $\bar{\theta}(x, y, z, t)$, and subgrid-scale kinetic energy $e(x, y, z, t)$.

Two classes of data are available: time-resolved during a relatively short period of time consisting of 100 time-steps (high-frequency dataset name = “sable2048high”), and 20 statistically independent snapshots (low-frequency dataset name = “sable2048low”).

The stored data are provided in SI units.

Flow statistics

Profiles of various quantities are provided in McWilliams et al. (2023). Specifically, mean velocity and temperature vertical profiles are provided in Fig. 2 (red lines) of McWilliams et al. (2023), profiles of average Richardson number and average shear and buoyancy frequency squared are provided in Fig. 3 of McWilliams et al. (2023) (red lines), while second order statistics profiles are shown in Figs. 4 and 5 of this reference. Fig. 6 shows profile of mean SGS kinetic energy (red line).

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⁽¹⁾ *Note:* The divergence-free condition in the simulation is enforced based on the spectral representation of the derivatives on horizontal planes. The JHTDB analysis tools for gradients are based on finite differencing of various orders. Therefore, when evaluating the divergence using these spatially more localized derivative operators, a non-negligible error in the divergence is obtained, as expected.

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