Quality and reliability of general-purpose finite-volume solvers for the simulation of atmospheric boundary layer flow

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Motivation and objectives

Large-Eddy Simulations (LESs) of Atmospheric Boundary Layer (ABL) flows have been historically carried out using single-domain spectrally-accurate solvers. The increasing need to include complex geometries and physics has resulted in ad-hoc modifications to such solvers, whose impact on accuracy and stability is often hard to quantify. For this reason, general-purpose Finite-Volume (FV) solvers represent an attractive alternative for LES of ABL. Here, the performance of a general-purpose FV solver (OpenFOAM®[1] framework) is assessed in Wall-Modeled Large-Eddy Simulation (WMLES) of neutrally-stratified ABL flow. Results are contrasted against those from a well-proven mixed Pseudo-Spectral Finite-Difference (PSFD) code[2]. The sensitivity of the solution to grid resolution and aspect ratio is analyzed.

Methodology

Governing equations

- Spatially-filtered incompressible Navier-Stokes equations
- Static Smagorinsky sub-grid scale (SGS) model
- Wall-model for surfaces in fully-rough aerodynamic regime, based on equilibrium logarithmic law of the wall[4]

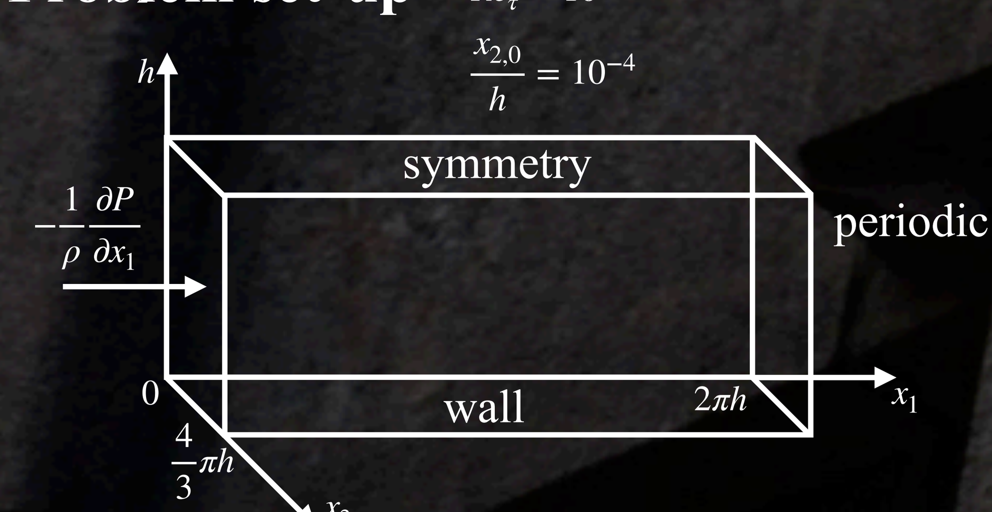
Numerical schemes

- `Gauss linear`: Gaussian integration and linear interpolation
- `pisoFoam`: PISO algorithm
- `backward`: implicit Adam-Moulton

Problem set-up

$Re_\tau = 10^7$

$\frac{x_{2,0}}{h} = 10^{-4}$



	$N_1 \times N_2 \times N_3$	$\Delta x_1/\Delta x_2$
light blue	$32 \times 32 \times 32$	2π
pink	$32 \times 64 \times 32$	4π
orange	$64 \times 64 \times 64$	2π
green	$128 \times 64 \times 128$	π
dark teal	$128 \times 128 \times 128$	2π

Table 1. Summary of the cases simulated.

Results

Mean profiles

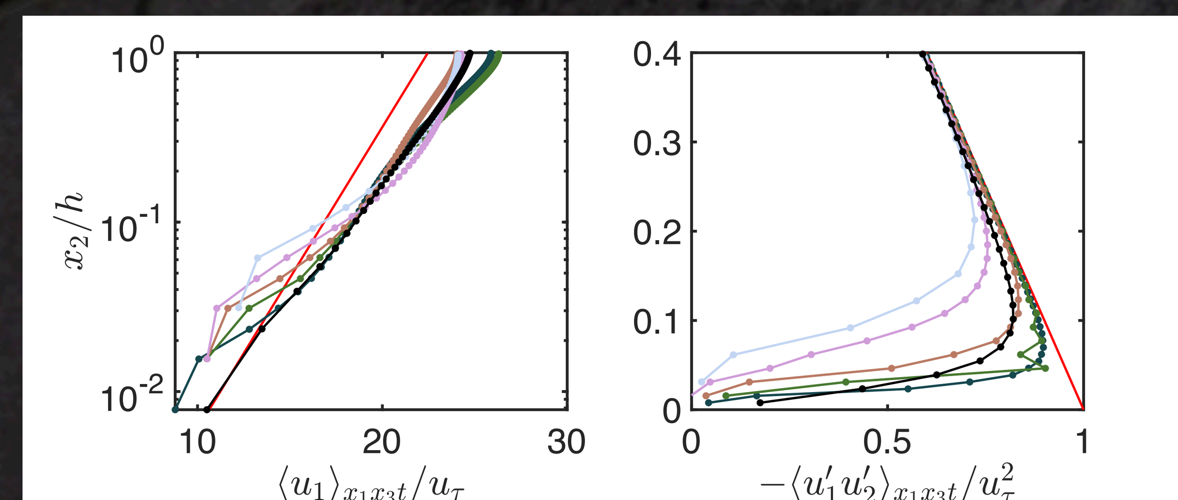


Figure 1. Wall-normal structure of streamwise velocity (left) and resolved Reynolds stress (right). Colored line-stars, see Table 1; black line-star, PSFD; solid red line, law of the wall (left) and $x_2/h = 1 - \langle u_1'u_2' \rangle_{x_1x_3t}/u_\tau^2$ (right).

- Underprediction of streamwise velocity in the near-wall region
- Overprediction of streamwise velocity in the bulk of the flow
- Increase of turbulent stress with decrease of aspect ratio

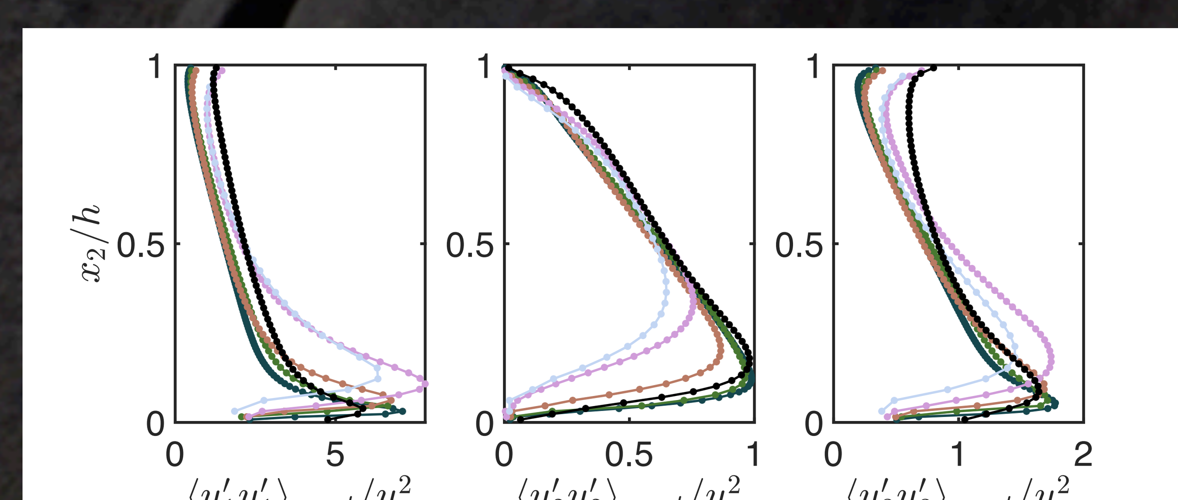


Figure 2. Wall-normal structure of resolved variances of streamwise velocity (left), vertical velocity (center) and spanwise velocity (right). Colored line-stars, see Table 1; black line-star, PSFD.

- Increase of resolved velocity variances in the near-wall region ($x_2/h < 0.05$) with grid refinement
- Overshoot of $\langle u_1'u_1' \rangle_{x_1x_3t}$ for $x_2/h > 0.1$ at low resolution
- Underestimation of $\langle u_2'u_2' \rangle_{x_1x_3t}$ and $\langle u_3'u_3' \rangle_{x_1x_3t}$ (weak pressure redistribution) at low resolution

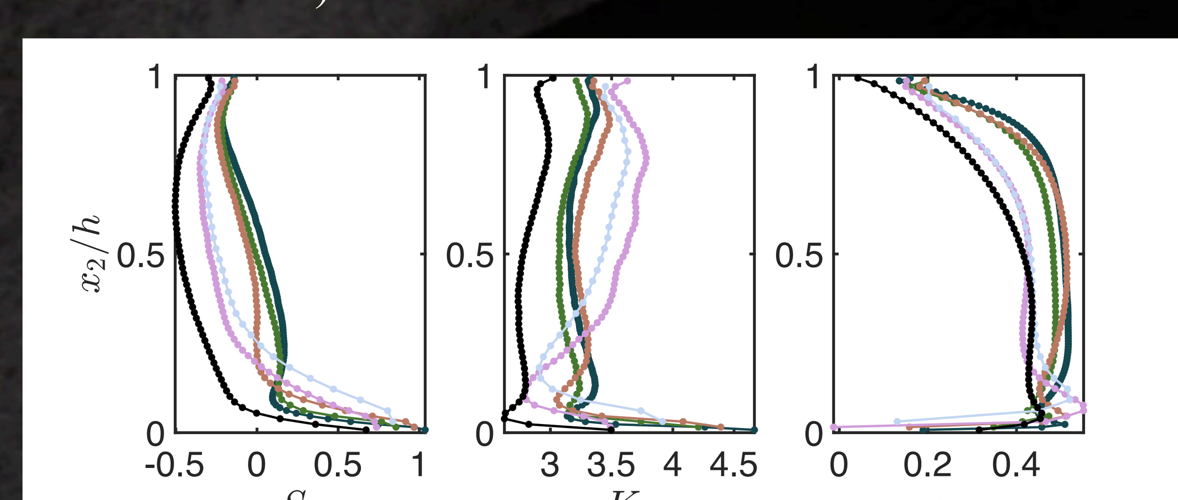


Figure 3. Wall-normal structure of skewness of streamwise velocity (left), kurtosis of streamwise velocity (center) and transfer efficiency coefficient (right). Colored line-stars, see Table 1; black line-star, PSFD.

- Overprediction of higher-order statistics

Spectra and autocorrelations

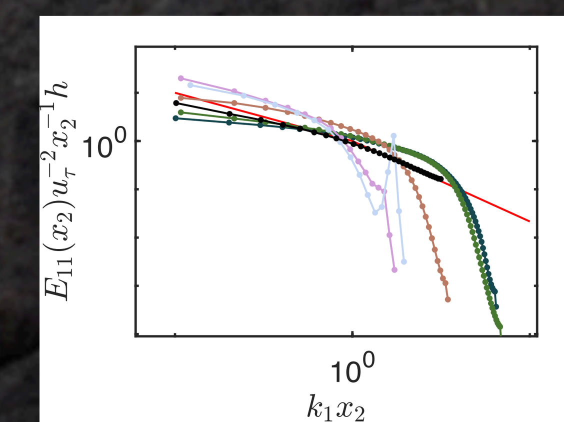


Figure 4. Normalized one-dimensional spectrum of streamwise velocity at height $x_2/h \approx 0.1$. Colored line-stars, see Table 1; black line-star, PSFD; solid red line, $(k_1x_2)^{-1}$ in the production range and $(k_1x_2)^{-5/3}$ in the inertial sub-range.

- Rapid decay of spectra at high wavenumber, with pile-up of energy on coarse mesh

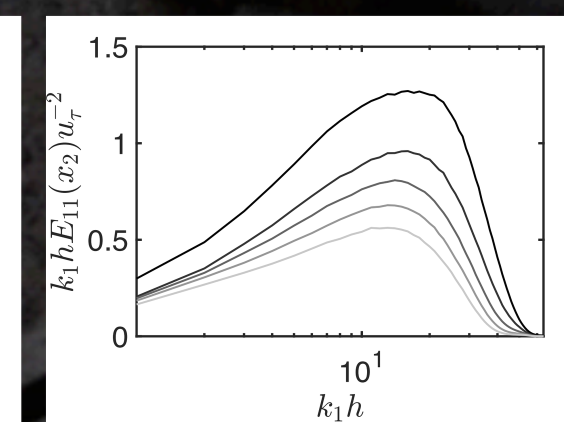


Figure 5. Premultiplied one-dimensional spectrum of streamwise velocity from the simulation F-2π. Dark to light gray lines correspond to height $x_2/h \approx 0.1$ to $x_2/h \approx 0.5$.

- Shift of the Large-Scale Motion (LSM) peak to higher wavenumber[3]

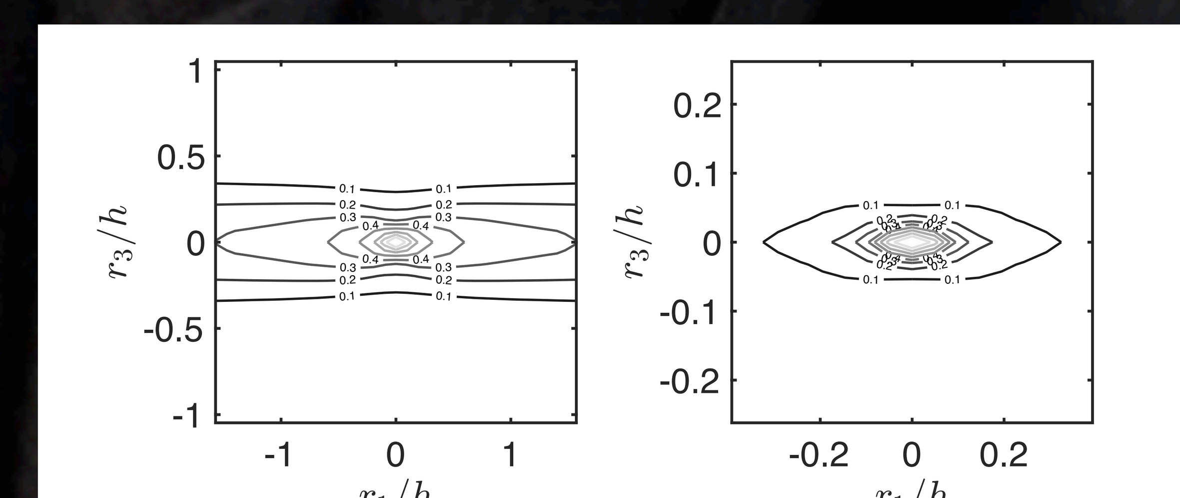


Figure 6. Contours of two-dimensional spatial autocorrelation of streamwise velocity from the simulation F-2π, at height $x_2/h \approx 0.1$. PSFD (left); FV (right). Dark to light gray lines correspond to contour levels from 0.1 to 0.9 with increments of 0.1.

- Less streamwise elongation and more isotropy in the contours of two-dimensional autocorrelation, when compared to PSFD results

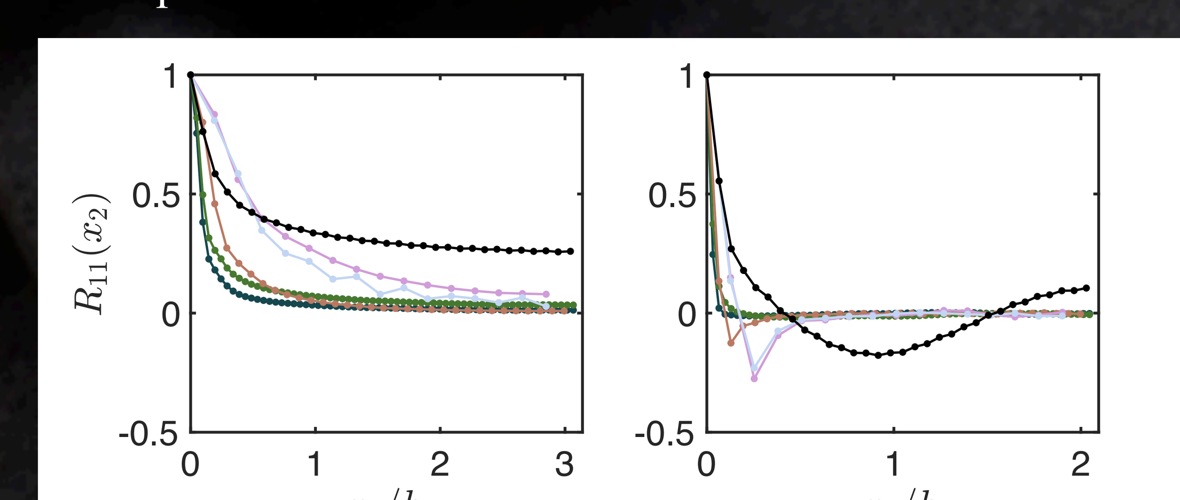


Figure 7. One-dimensional spatial autocorrelation of streamwise velocity at height $x_2/h \approx 0.1$, along streamwise direction (left) and along spanwise direction (right). Colored line-stars, see Table 1; black line-star, PSFD.

- Rapid decay of one-dimensional spatial autocorrelation

Instantaneous horizontal contours

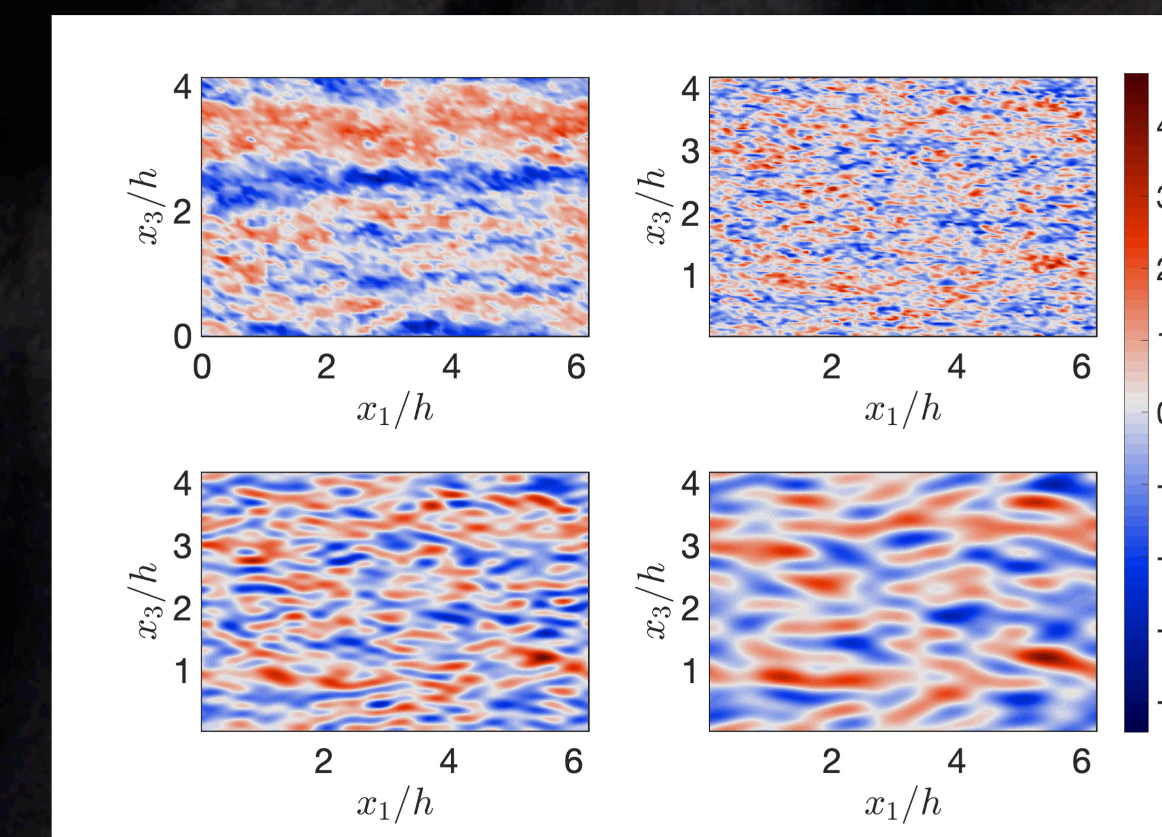


Figure 8. Instantaneous snapshots of streamwise velocity fluctuations, normalized by root-mean-square velocity, at height $x_2/h \approx 0.1$. PSFD (top-left); FV from the simulation F-2π (top-right); FV from the simulation F-2π spatially filtered with support $[0,3x_2/h] \times [0,x_2/h]$ (bottom-left); FV from the simulation F-2π spatially filtered with support $[0,6x_2/h] \times [0,2x_2/h]$ (bottom-right).

- Lack of large-scale coherent structures in the FV snapshot

Conclusions

The performances of OpenFOAM® were assessed in WMLES of ABL flows. First- and second-order statistics show a good agreement with the results from a well-proven PSFD code, provided a twice as fine grid stencil is used in the horizontal directions in the FV code (Fig. 1 and 2). Higher-order statistics, however, are severely mispredicted, spectra lack an apparent inertial sub-range, and spatial autocorrelations decay rapidly (Fig. 6 and 7). In line with these findings, no LSMs are observed in the instantaneous velocity field (Fig. 8). Findings suggest that general-purpose second-order accurate FV solvers not suitable for capturing spectral energy dynamics and turbulence topology in WMLES of ABL flows.

Acknowledgments

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References

[1]https://www.openfoam.com
[2]Albertson and Parlange, 1999
[3]Kim and Adrian, 1999
[4]Vuorinen et al., 2015