1 Response to reviewer 1

We thank the reviewer for his/her time and for the constructive comments, which helped improve the quality of the manuscript. We address each comment below.

1.1 Major comments

Reviewer statement 1: *The study described in the reviewed paper definitely makes sense, as it provides valuable insights regarding capabilities of a class of numerical schemes broadly used for simulations of atmospheric boundary-layer flows. It should be specifically mentioned (so far, it is not clear from the title) that techniques specifics are considered only for dynamic part of the problem (that includes Navier–Stokes and continuity equations for incompressible fluid). The study is reported in sufficient detail, and the results are analyzed quite comprehensively and candidly.*

Response: We thank the reviewer for this comment. In the Abstract it is now explicitly stated that a neutrally-stratified ABL flow without Coriolis effects is considered.

Reviewer statement 2: *The only major issue I have with the study is associated with desperation that the reader feels when—guided by the authors—she/he goes through the figures showing the results and their interpretations, and comes (together with the authors) to a conclusion that the whole situation with application of considered second-order-accurate FV schemes for LES of ABL flows in even basic setup is rather bleak (at resolutions investigated), which brings in question the entire feasibility of such schemes. The authors make some comments on what one may expect from the employed scheme with respect to its ability to reproduce particular features of the ABL turbulent flow. In my view, to make sense out of the paper findings, this discussion needs to be significantly expanded in order to provide the reader with a clear guidance regarding performance of the scheme and explain how its specific deficiencies are associated with its properties.*

Response: We thank the reviewer for this critical input. If the reviewer refers to a detailed, applied-math type analysis focusing on the impact of discretization and modeling errors on the solution, one would then need to introduce strong simplifications to make such an analysis possible (see e.g. [1] and [2]) and findings might not then be directly transferrable to the ABL flow system. The aim of this work is a different one, namely to analyze the performance of a class of general-purpose FV solvers in the *full-fledged* setup for the study of ABL flows, with a focus on their capabilities to predict physical quantities that are of interest for the ABL community without necessarily ascribing limitations thereof to specific properties of the numerical scheme. This type of analysis is within the aim and scope of this journal, which lists "[...]full evaluations of previously published models" as one of the manuscripts' categories (see `https://www.geoscientific-model-development.net/about/manuscript_types.html`). In an efford to address the comment from the reviewer while keeping the analysis limited to the physics of the system, we identified an important limitation of the considered class of FV-solvers, which sheds light on some of the observed discrepancies and variability in flow statistics. Specifically, this class of FV solvers is not able to correctly capture the dominant momentum transport mechanism in the ABL, namely the sweep and ejection pairs, at the considered resolutions (see discussion in §3.3 as well as related comments in the Abstract and Conclusions sections of the revised manuscript, which we also report below).

> "(Abstract) At the considered resolutions, the considered class of FV-based solvers yields a poorly correlated flow field and is not able to accurately capture the dominant mechanisms responsible for momentum transport in the ABL, especially when using linear interpolation schemes for the discretization of non-linear terms. The latter consist of sweeps and ejection pairs organized side by side along the cross-stream direction, representative of a streamwise roll mode. This shortcoming leads to a misprediction of flow statistics that are relevant for ABL applications and to an enhanced sensitivity of the solution to variations in grid resolution, calling for future research aimed at reducing the impact of modeling and discretization errors."

> "(Section 3.3) As apparent from Fig. 9, the PSFD conditionally-averaged velocity field exhibits counter-rotating patterns associated with positive and negative streamwise velocity fluctuations (corresponding to the aforementioned streaks). The roll modes feature a diameters ($d \approx h$) throughout the ABL, which is consistent with findings from the literature, and positive an negative velocity fluctuations are approximately of the same magnitude ($\approx u_\tau$). From Fig. 10, it is also apparent how the considered isosurfaces extend in the streamwise direction for about $4h$. Quite surprisingly, the FV-based solver is not able to predict the roll modes, irrespective of the interpolation scheme or resolution, and the magnitude of the low-momentum streaks is also severely underpredicted across the considered cases. Further, Figs. 1 and 8 both depict a FV conditionally-averaged flow field that is poorly correlated in the cross-stream and streamwise directions, resulting in significantly smaller momentum-carrying structures. This supports previous findings from the two-point correlation maps (Fig. 4). The lack of roll modes implies that these solvers are not able to capture the fundamental mechanism supporting momentum transfer in the ABL, at least at the considered grid resolutions. This limitation can also be identified as the root cause of several of the observed problematics with the FV solutions, including the relatively high (low) streamwise-velocity skewness when using using linear (QUICK) schemes (see Fig. 2,a) and the inbalance between sweeps and ejections (Fig. 1

and Fig. 8).”

“(Conclusions) To summarize, the considered class of FV-based solvers overall predicts a flow field that is less correlated in space when compared that of the PSFD solver and is not able to capture the salient features responsible for momentum transfer in the ABL, at least at the considered grid resolutions. These limitations appear to be the root cause of many of the observed discrepancies between FV flow statistics and the reference PSFD or experimental ones, including the mispredicted streamwise-velocity skewness (Fig. 2,a), the inbalance between sweeps and ejections (Fig. 1 and Fig. 8), and the overall sensitivity of flow statistics to variations in the grid resolution.”

1.2 Minor comments

Reviewer statement 1: *Page 1: It should be directly indicated in the title, or at least, in the Abstract and Introduction, that only dynamic subset of ABL governing equations is considered, so that the reader will not have hopes for seeing applications of these solvers for heat and scalar transfer equations.*

Response: Please see the response to the statement 1 in the Major comments section.

Reviewer statement 2: *Line 96: “proposed” is a wrong word here.*

Response: The sentence was edited as “Results are shown in §3 . . . ”

Reviewer statement 3: *Line 105: Such constancy of density is usually associated with the Boussinesq approximation, which should probably be mentioned directly.*

Response: This comment was addressed as follows: “. . . ρ is the (constant, under the Boussinesq approximation) fluid density, . . . ”

Reviewer statement 4: *Line 122: replace “observation” with “assumption”.*

Response: The sentence now reads: “This conjecture is supported by the results of Majander and Siikonen (2002).”

Reviewer statement 5: *Line 138: "approximation". This is more correctly called the Boussinesq hypothesis or analogy (to distinguish from the Boussinesq approximation that refers to the density constancy).*

Response: "... (Boussinesq approximation)..." was replaced by "... (Boussinesq hypothesis)..."

Reviewer statement 6: *Line 199: replace "herein proposed" to "presented herein".*

Response: The paragraph has been rearranged and the sentence that was at line 199 does not appear anymore.

Reviewer statement 7: *Line 288: replace "statements" by "findings".*

Response: This comment was addressed and the sentence reads: "The one-dimensional spatial autocorrelation (R_{uu}), shown in Fig. 5 along the streamwise and cross-stream directions, further corroborates the above findings"

Reviewer statement 8: *Line 333: you need to specify correspondence between the* u, v, w *notation for velocity components and your standard* u_1, u_2, u_3 *notation (also in other places, where needed).*

Response: Instead of specifying a correspondence between u, v, w and u_1, u_2, u_3, the notation was unified consistently with the rest of the paper (where the subscripts x, y, z are used to denote streamwise, cross-stream, vertical directions, respectively, and correspondent vectorial components, and $(u, v, w) = (u_x, u_y, u_z)$).

Reviewer statement 9: *Figure 8: reduce font size of tick labels in* x_2 *direction.*

Response: The font size was reduced.

Reviewer statement 10: *Line 360: speaking of "solvers"; actually, it was a single solver that was investigated.*

Response: The "numerical framework" is indeed a single one, namely OpenFOAM®. Within this single framework, different *numerical procedures* have been considered, varying the pressure-velocity coupling method (PISO vs fractional step method), the time stepping scheme (Adam-Moulton vs Runge Kutta), and the linear interpolation scheme for the non-linear terms (linear vs QUICK). We regarded each of these procedures as "solvers", which is why we referred to "solvers". This is also standard terminology in the OpenFOAM community. Note that in the revised version of the manuscript the main analysis has now been extended to additional "solvers", and is not anymore predominantly focused on the PISO algorithm with linear interpolation scheme. We have also relaxed the terminology and we now refer to "[. . .]an important class of general-purpose, second order accurate FV solvers."

Reviewer statement 11: *Line 383: the verdict regarding FV-solvers; sounds too general... maybe still not all of them (a grain of optimism)?*

Response: We thank the reviewer for this comment and totally agree with it. We have tested only one specific class of FV solvers, and alternative ones such as those based on staggered grid setups or higher order discretization schemes have been shown to feature improved conservation properties and behaviors for high Reynolds number flows. We now made an effort to point out that findings proposed herein only pertain to the specific class of FV solvers that was considered (see below). We also mentioned that approaches based on a staggered grid setup might be required to improve the quality of predictions.

Abstract: "The present work assesses the quality and reliability of an important class of general-purpose, second-order accurate finite-volume (FV) solvers in the large-eddy simulation of a neutrally-stratified atmospheric boundary layer (ABL) flow."

Conclusions: "This work provides insight on the quality and reliability of an important class of general-purpose, second-order accurate FV-based solvers in wall-modeled LES of neutrally-stratified ABL flow. The FV solvers are part of the OpenFOAM® framework, make use of the divergence form of the nonlinear term, and are based on a colocated arrangement for the evaluation of the unknowns."

Conclusions: "To summarize, the considered class of FV-based solvers overall predicts a flow field that is less correlated in space when compared that of the PSFD solver and is not able to capture the salient features responsible for momentum transfer in the ABL, at least at the considered grid resolutions."

References

[1] S. Ghosal. An Analysis of Numerical Errors in Large-Eddy Simulations of Turbulence. *Journal of Computational Physics*, 125(1):187–206, apr 1996.

[2] J. Meyers, P. Sagaut, and B. J. Geurts. Optimal model parameters for multi-objective large-eddy simulations. *Physics of Fluids*, (9), 2006.