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RAMS sensitivity to grid spacing and grid aspect ratio in Large-Eddy Simulations of the dry neutral Atmospheric Boundary Layer

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ABSTRACT

Large Eddy Simulation (LES) is being established as a commonplace modeling tool in many areas of research interested in reproducing Atmospheric Boundary Layer (ABL) turbulence. LES results can however be highly dependent on the combination of the numerical schemes, subgrid scale model and computational grid, and their impact on simulations should be examined. The present work focuses on assessing the impact of grid spacing on LES of an idealized neutral ABL realized with the Regional Atmospheric Modeling System (RAMS), a commonly employed mesoscale model. To this aim, nine simulations with varying grid resolutions and otherwise identical setups have been performed. The grids are obtained combining three different horizontal (64, 32, 16 m) and vertical (16, 8, 4 m) spacings, covering a domain of 4096 × 4096 × 1024 m. Results are post-processed in terms of mean profiles of momentum flux, horizontal velocity and velocity variances, as well as velocity spectra and instantaneous snapshots of velocity fields. The analysis reveals that the turbulent flow can be simulated satisfactorily by employing a computational grid with a sufficiently fine horizontal spacing and an aspect ratio that alleviates potential adverse effects of the combination of RAMS numerics and subgrid model on the solution. Based on the present results, a horizontal spacing smaller than around 30 m is suggested for the examined regime, and an aspect ratio of 4 is recommended, while both larger and smaller values should be avoided. When using different aspect ratios RAMS LESs of the neutral ABL were found to be affected by an excessive dissipation of turbulence kinetic energy.

1. Introduction

Large Eddy Simulations (LESs) of the Atmospheric Boundary Layer (ABL) are increasingly applied in many areas of atmospheric research. The complex processes and physics that occur in the ABL have been investigated through LESs since the pioneering works of Deardorff [22–24], and progressively more accurate and detailed studies have been published over the years [e.g. 52,1,7,18,35,58,61,75]. LES of the ABL has also gained popularity in other fields. For instance, it has been employed to predict pollutant dispersion in urban environments [e.g. 29,40,56,69,79,80,84,89], to evaluate the impact of wind farms on the ABL [e.g. 15,44,64,65,88], as well as to improve the understanding of eddy covariance techniques for measurements of surface vertical turbulent fluxes of heat, water vapor, momentum, carbon dioxide and other gases [e.g. 6,10,37,46,72].

Depending on the aim of the study, LESs of the ABL are conducted under idealized or more realistic conditions. In the former case, homogeneous surface properties, prescribed surface fluxes and periodic lateral boundary conditions are adopted [e.g. 2,14,38,43,49,51,76]. Studies for such idealized conditions are especially useful for evaluating the performance of LES codes regarding the reproduction of ABL turbulence, since the results can be compared with previous similar LESs and theoretical expectations for turbulence statistics and flow structures.

More complex and realistic ABL flows can be simulated by considering a heterogeneous surface that includes a representation of the coupling between land and overlaying air [27,73], and by removing the simplification of lateral periodic boundary conditions. The first can be achieved by coupling the LES with a Land Surface Model (LSM) [e.g. 9,33,58,78]. The LSM includes prognostic equations for the land surface states and dynamically computes surface fluxes on the basis of the resulting land surface states and the simulated atmospheric state. The second is enabled by grid

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nesting techniques that allow defining lateral boundary conditions based on mesoscale reanalysis data [e.g. 41,42,77], although several issues arise regarding turbulence transfer from coarser to finer grids [50,54]. Numerical Weather Prediction-Limited Area Models (NWP-LAMs) offer both these capabilities, i.e. equations of motion are natively coupled with a LSM and grid nesting capabilities are implemented. As a result, they are increasingly used to perform LES of the ABL [e.g. 5,50,56,77]. It is however important to verify the ability of these codes to correctly reproduce turbulence in the ABL, since they were primarily designed to simulate atmospheric flows at the mesoscale [28,57].

The Regional Atmospheric Modeling System (RAMS) is a commonly used NWP-LAM, that is also suitable for microscale simulations [19,60,81,82]. It has mainly been employed for LES of the ABL in realistic conditions [4,5,86], or for specific purposes such as simulating wind flow in a street canyon [13,21] and assessing the impact of surface patchiness on ABL characteristics [12,31,32]. These studies have proven the general capabilities of RAMS-LES, but evaluations of the performance of the code in idealized conditions as described above would further support identifying its potentials and shortcomings. A detailed study for the performance of RAMS under an idealized convective regime has been recently presented in Ercolani et al. [25], where the impact of grid spacing was evaluated, and a comparison with simulations performed using the LES module of the Weather Research and Forecasting model [WRF, 70] was made. The study showed that both models can properly simulate a convective ABL when adequate computational grids are used. A horizontal spacing of 30 m is suggested for both RAMS and WRF in the examined conditions (free convection over a homogeneous flat surface forced by an initial temperature gradient of 5 K between the surface and the overlaying air). In addition, the RAMS results were found to be sensitive to grid aspect ratio (horizontal over vertical spacing), thereby indicating this is a relevant parameter for LESs of the convective ABL, as also shown by Nishizawa et al. [55]. An aspect ratio of 3 was identified as the optimum value, while higher ratios caused the appearance of spurious fluctuations in the flow. WRF did not show a similar dependency on the grid aspect ratio, but exhibited enhanced damping of turbulent fluctuations at the smallest scales.

The present work is complementary to Ercolani et al. [25]. We perform an extensive assessment of RAMS-LES capabilities in simulating an idealized neutral ABL, focused on investigating the influence of the computational grid on the results. This additional study is motivated by the fact that, as ABL stability increases, LESs require finer grids in response to smaller turbulent structures, and simulation results may exhibit a larger dependency on the subgrid-scale model. The study analyzes nine simulations that share an identical setup except for the computational grid. The nine computational grids are obtained combining three different horizontal (64, 32, 16 m) and vertical (16, 8, 4 m) spacings. The domain extent is 4096 × 4096 × 1024 m, and the only turbulence forcing is geostrophic wind. Results are post-processed in terms of mean profiles of momentum flux, horizontal velocity and velocity variances, as well as velocity spectra and instantaneous snapshots of velocity fields. In order to identify the impact of grid resolution and evaluate RAMS-LES capabilities, these results are compared among the nine simulations, and in addition results from previous similar LESs are considered [2,16,45,49,77].

In contrast to Ercolani et al. [25], this study focuses on RAMS only, since WRF-LESs that use comparable computational grids and a similar setup have been discussed in previous studies [38,49,77]. For RAMS-LES some results under idealized neutral conditions can be found in Cai et al. [11], but this study did not examine the influence of the computational grid, nor did it consider any spectra, instantaneous snapshots of the flow, or velocity variance profiles. Moreover, it employed the Smagorinsky subgrid-scale model [71], while here we use Deardorff's [24]. In addition, the vertical grid spacing used in their study is non-uniform, with an expansion rate of 1.2 up to a maximum spacing of 60 m. Hence, our work is intended to contribute to the overall verification of RAMS-LES capabilities in reproducing neutral ABL turbulence. Furthermore, it can guide users regarding the selection of an appropriate grid resolution and provide a thorough evaluation of the resulting impact on turbulence statistics. It therefore represents a useful starting point for applications targeted towards more complex ABL flows, which is particularly relevant for the more widespread use of LES of the ABL in areas of research that are not traditionally linked to this LES (e.g. hydrology, renewable energy production, agro-meteorology, etc.).

The remainder of the paper is organized as follows. Section 2 presents the LES module of RAMS and describes the setup of the nine simulations performed. Results of the nine simulations are analyzed in Section 3, showing vertical profiles of mean non dimensional velocity, shear and velocity variance, and presenting velocity spectra and instantaneous snapshots of the velocity fields. Based on these results the capabilities of RAMS-LES for simulating a neutral idealized ABL, and the impact of grid spacing are discussed in Section 4. Lastly, conclusions are reported in Section 5.

2. Model description

RAMS is a Numerical Weather Prediction-Limited Area Model (NWP-LAM) developed by Colorado State University, ASTeR division of Mission Research Corporation and ATMET (ATmospheric, Meteorological and Environmental Technologies) [19,60,81]. It is primarily designed for mesoscale simulations (domain sizes from tens to hundreds of kilometers) of meteorological phenomena, but there is no lower limit to the simulated domain and to the grid cell size [85]. This characteristic, combined with the fact that it solves the equations of motion coupled with a LSM, makes it an appealing tool for LESs of the ABL. Moreover, RAMS is an open source, highly flexible code [57]. For instance, the numerical grid and boundary conditions can be modified without recompiling the code, and some customizations, such as the employment of user defined surface characterization, are already accommodated in the code. In the present work the most recent release of the code, RAMS 6.0 [82], is employed. In this section only those aspects of the model that are relevant for the present study are described, while a comprehensive description of RAMS can be found in Pielke et al. [60].

2.1. RAMS-LES

In LES, the more energetic, large-scale turbulent structures are explicitly resolved, while the effects of unresolved smaller-scale eddies are modeled. The separation between resolved and modeled turbulence is obtained by applying a low-pass spatial filter to the velocity field [62]. The filtering operation can be done explicitly or implicitly by the numerical discretization scheme, on the basis of the grid spacing [67]. In both cases, the result is the decomposition of any generic state variable x into the sum of resolved, $\overline{x}$, and subgrid scale (SGS), x', components. Filtered Navier–Stokes equations contain an unknown term, the SGS stress tensor, that originates from their non-linearity. The SGS stress tensor is responsible for the effect that the SGS turbulence has on the resolved structures, and it must be modeled to obtain the closure of the set of equations. In RAMS, the SGS stress tensor is modeled adopting the eddy viscosity approach. Specifically, RAMS employs the 1.5-order-of-closure scheme of Deardorff [24], and hence determines the eddy viscosity ν_t as follows:

$$\nu_t = C_k l \sqrt{e} \quad (1)$$