NESTED MULTI-SCALE SYSTEM IN THE PALM LARGE-EDDY SIMULATION MODEL

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Abstract: Large-Eddy Simulation (LES) of atmospheric boundary layer (ABL) is becoming an important research method for urban air-quality studies. Until very recently, it was impossible to include detailed structures, such as buildings in ABL LES. Nowadays, it is possible, but such LES is still limited to a relatively small areas because typically about 1 m resolution is required. However, for several reasons an ABL LES domain should cover a large area leading to huge computational task. A means to overcome this is to concentrate resolution to the primary area of interest by means of model nesting. The idea of nesting is to simultaneously run a series of two or more LES in domains with different sizes and resolutions. In this work, two-way nesting is implemented in the parallelized LES model, PALM. The nesting system is tested for several test cases including a convective boundary layer with zero mean wind, several neutral boundary layers over both flat terrain and terrain with an array of obstacles.

Key words: Large-eddy simulation, atmospheric boundary layer, turbulence, urban air quality, urban climate, model nesting.

1 INTRODUCTION

Large-Eddy Simulation (LES) of atmospheric boundary layer (ABL) is an important research method. Until very recently, it was impossible to include detailed surface structures, such as buildings or steep complex terrain shapes in ABL LES. Nowadays, it is possible to carry out LES e.g. for complex built areas (Letzel et al., 2008). But this is still limited to a relatively small areas because of the high spatial resolution requirement. Xie and Castro (2006) have shown that at least 15 - 20 grid nodes are needed accross street canyons to satisfactorily resolve the most important turbulent structures within the canyons. This requirement typically leads to grid spacings of the order of 1 m. However, the extent of the LES domain should vertically include the whole ABL and the horizontal size should span over several ABL heights. The uncertainty related to the boundary conditions usually decreases as the domain is made larger. Therefore, even larger domains are highly recommendable.

Many numerical solution methods allow variable resolution so that the resolution can be concentrated to the area of principal interest and relaxed elsewhere. However, only unstructured grid systems allow full advantage of spatially variable resolution. Many general-purpose computational fluid dynamics packages offer unstructured grid systems, but such solvers are usually computationally much slower and somewhat less accurate than ABL-tailored LES models, such as PALM (Maronga et al., 2015), that are usually based on structured grid system with constant horizontal resolution. Model nesting approach can be exploited to further speed up ABL LES models or to allow larger domain sizes without compromizing the resolution in the area of primary interest.

The idea of nesting is to simultaneously run a series of two or more LES in model domains with different spatial extents and resolutions. The outermost model is called the root model and it is given boundary conditions on its outer boundaries similarly as in usual LES. The other models are called nest models and their domains are smaller than that of the root and they are nested completely inside the root domain. A nest model can have its own nest models and so on. A nest model obtains boundary conditions from its parent model. In one-way coupled nesting only the nests obtain information from their parents. However, one-way coupled nesting is known to be of little advantage (Clark and Hall, 1991). In two-way coupled nesting, also the parents are influenced by their nests (Clark and Farley, 1984; Clark and Hall, 1991; Sullivan et al., 1996). The latter interaction may be implemented using e.g. the post insertion (PI) approach (Clark and Hall, 1991) which means that the parent solution is replaced by the restricted nest solution in the domain of overlap. This procedure is called anterpolation. In practice, some spatial underrelaxation is necessary near the nest boundaries in order to avoid growth of unphysical perturabations near the nest boundaries (Moeng et al., 2007). An example of a two-way coupled nesting implemented in the WRF-LES model is given by (Moeng et al., 2007). However, the WRF-LES nesting is limited to horizontal directions, i.e. all the domains have equal height.

2 METHODS

2.1 NUMERICAL METHODS

In this work two-way coupled nesting is implemented in the parallelized LES model, PALM (Maronga et al., 2015). PALM is based on the non-hydrostatic, filtered, incompressible Navier-Stokes equations together with a subgrid-scale model according to Deardorff (1980). PALM solves the transport equations in staggered Arakawa C grid with horizontally constant grid spacing. The vertical grid spacing may be stretched. The solution method is a projection method in which a provisional velocity field is first integrated from the momentum equations without the pressure gradient term using three-step Runge-Kutta scheme. Then perturbation pressure is solved from a Poisson equation and the provisional velocity is projected to solenoidal field using pressure gradient. Parallelization of PALM is based on MPI and two-dimensional (horizontal) domain decomposition.

Our nesting approach is a variant of the PI method. In the present implementation, the inter-model communication including interpolations and anterpolations is carried out on each Runge-Kutta substep before the pressure-projection step. This way the mass conservation is enforced in the anterpolated solution. Interpolation scheme is trilinear and the anterpolation is based on top-hat filtering.

2.2 IMPLEMENTATION

The nested model system is implemented using two levels of MPI communicators. The inter-model communication is handled by a global communicator using the one-sided communication pattern. The intra-model communication is two-sided and it is handled using a 2-D communicator that has different color for each model. The mapping between each parent and nest model domain decompositions is determined in the initialization phase so that the communication during the time-stepping is straightforward and efficient. Each model inputs and outputs in the same way. The i/o-files are separated from each other by model tags added to their names.

3 TEST RESULTS

3.1 BASIC FUNCTIONAL TESTING

First, the nested model system was functionally tested in a very simple case with neutral boundary layer over flat ground with no buildings. In this case the system was tested up to three models. First a root model including two parallel nests, and second a root with two cascading nests. The model interfaces are continuous and smooth, and the mean profiles in each model domain are consistent with each other. No results from these tests are shown here owing to the space limitation.

3.2 CONVECTIVE BOUNDARY LAYER WITHOUT MEAN WIND

Next, the system was tested in a convective boundary layer with zero mean wind. Also in this case, the ground is flat with no obstacles. The horizontal size of the root domain is 10.24 km X 10.24 km, and its height is 1.92 km. The resolution is 20 m in all directions. The nest domain size is 5.12 km X 5.12 km X 0.96 km with 10 m resolution. Constant kinematic heat flux of 0.15 K m s^{-1} is set on the ground surface and there is a capping inversion starting at height of 1250 m. This test case is described in more detail by Hellsten and Zilitinkevich, (2013). Instantaneous vertical velocity component *w* in an *x*,*z*-plane is shown in Figure 1. The figure shows that the solutions are continuous over the nest boundaries. Also vertical profiles are continuous and smooth over the nest top boundary.

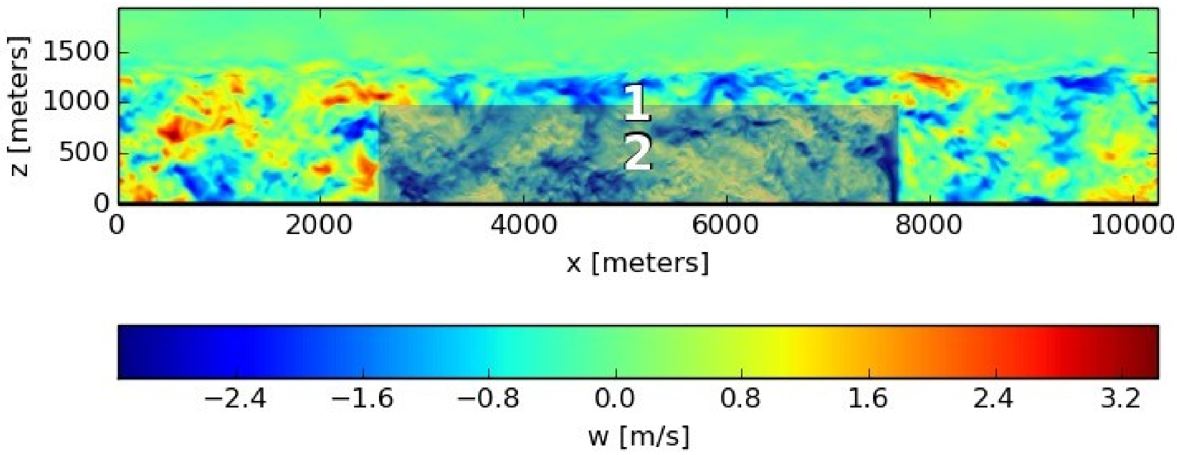

Figure 1. Instantaneous vertical velocity component *w* in a vertical cut plane through convective boundary layer. Different colormap and transparency is used for the nest solution in order to make the nest boundaries visible.

3.3 NEUTRAL BOUNDARY LAYER OVER AN ARRAY OF OBSTACLES

The next test case is a neutral boundary layer over a uniform non-staggered array of 14 X 8 rectangular obstacles mounted on flat ground. The obstacle size is 32 m X 32 m X 24 m and their spacing is 32 m in both directions. The ABL height is about 250 m and the root domain size is 2.048 km X 0.512 km X 0.512 km and resolution is 2 m. The nest domain size is 512 m X 256 m X 128 m and resolution is 1 m. Figure 2 shows that the solution is again continuous over the nest boundaries. Also vertical profiles are continuous and smooth over the nest top boundary.

4 CONCLUSIONS

Model nesting functionality based on two-way coupling using post insertion approach is implemented in the parallelized LES model, PALM. The implementation is based on two-level parallelism including inter-model and intra-model parallelization by MPI. The nesting system is shown to work well in the test cases considered so far. The next step is to validate the system against measurement data in a realistic urban ABL test case.

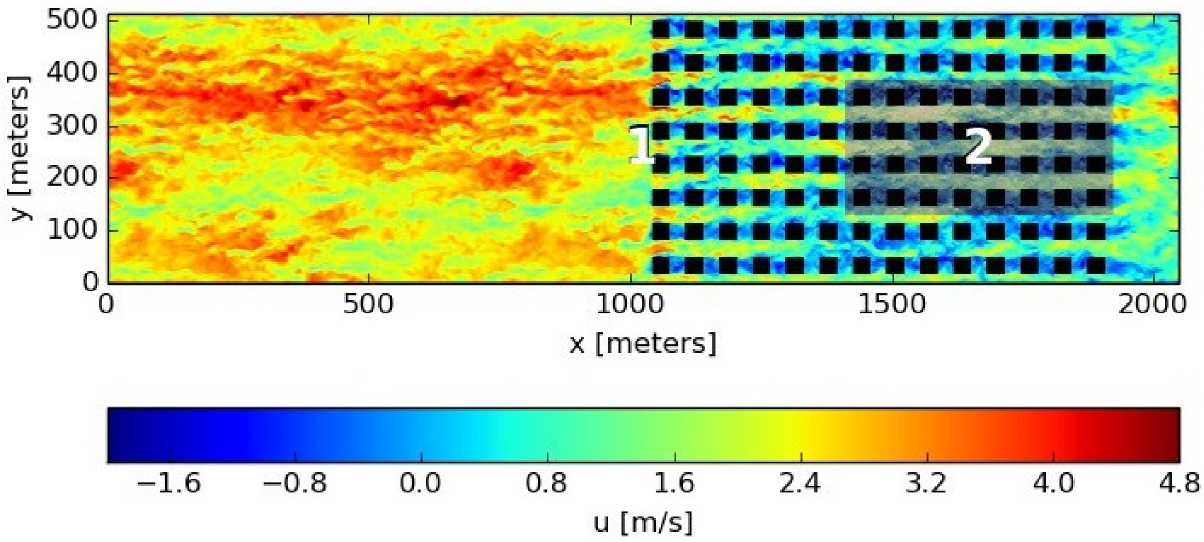

Figure 2. Instantaneous horizontal velocity component *u* in a horizontal cut plane through the surface layer of a neutral boundary layer over an array of obstacles. Again, different colormap and transparency is used for the nest solution in order to make the nest boundaries visible.

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