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Coupling method of WRF-LES and LES based on scale similarity model

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ABSTRACT: The one-way coupling method is applied to connect meso-scale model WRF and micro-scale LES using the scale similarity model to get rid of numerical errors at the interface between coarse grid and fine grid. The coupling between coarse-grid WRF-LES and fine-grid LES is studied on a free convective boundary layer flow with no heat flux from the ground. We found that the connection between the coarse grid WRF-LES and the fine grid LES works well without large interpolation errors.

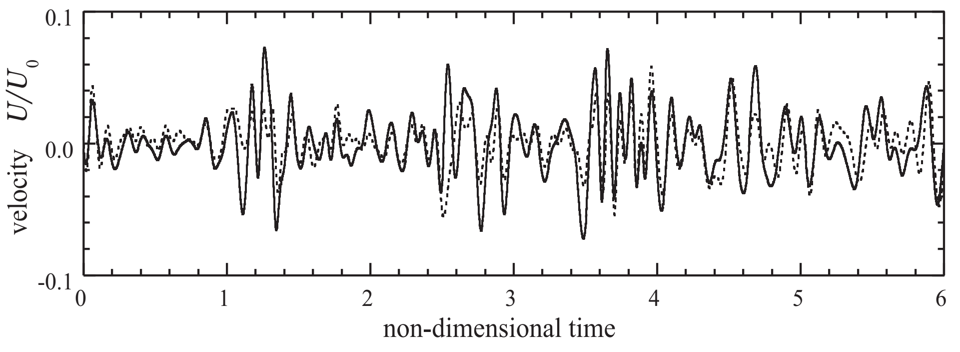
KEYWORDS: Large-Eddy-Simulation, WRF, scale similarity model, one-way coupling, immersed boundary method.

1 INTRODUCTION

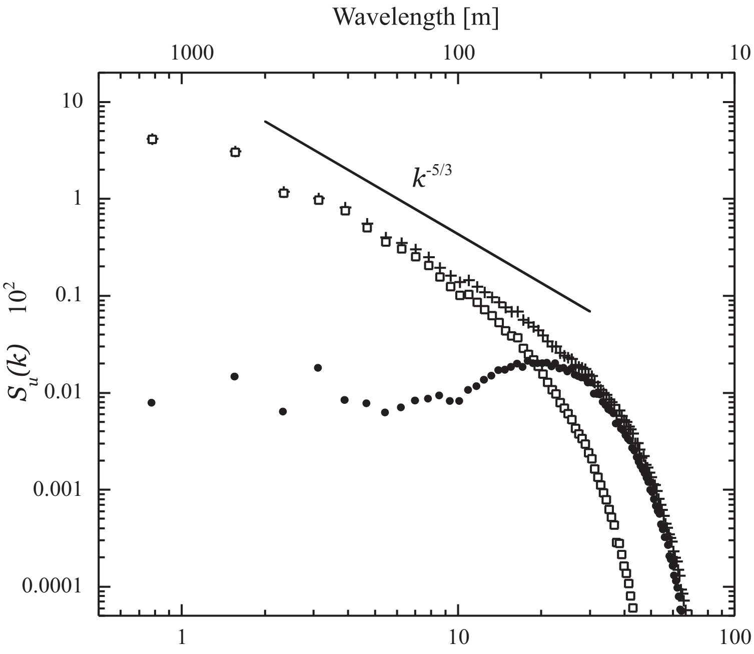
The connection between a meso-scale model and a micro-scale LES is significant to simulate the micro-scale meteorological problem such as strong wind events due to the typhoon using LES. In these problems the mean velocity profiles and the mean wind directions change with time according to the movement of the typhoons. The inflow turbulence generating technique for LES which uses turbulent boundary layer driver can't support such mean velocity transition because this technique assumes that the simulating turbulent boundary layer flow is in equilibrium. Although, a fine grid micro-scale LES could not be connected to a coarse grid meso-scale WRF directly.

In LES when the grid is suddenly refined at the interface of nested grids which is normal to the mean advection the resolved shear stresses decrease due to the interpolation errors and the delay of the generation of smaller scale turbulence that can be resolved on the finer mesh [1]. The adjustment region is required to regenerate the high wavenumber part in the energy spectrum of the fluctuating velocity. In the grid nesting approach for LES the commutation errors are thought to be very significant near the nest inflow interfaces.

Nozawa and Tamura [2] proposed the method which could get rid of these numerical errors at the interface between coarse grid and fine grid by applying the one-way coupling method using the scale similarity model [3]. In the method the mean velocity component of the fine grid is equal to the velocity of the coarse grid and the averaged fluctuating velocity component of the fine grid is zero. Meanwhile the high wavenumber fluctuating velocity component of the fine grid which is implicitly estimated as subgrid-scale turbulence in the coarse grid is reproduced explicitly in the fine grid near the nest inflow interface. The fluctuating components of the fine grid velocity could be estimated solving the momentum equations which could be derived by subtracting coarse grid filtered Navier-Stokes equations from fine grid filtered Navier-Stokes equations. In order to validate the approach an apriori test was carried out. The LES of a turbulent boundary layer flow over rough surface was conducted using the fine grid and the fluctuating component of the fine grid velocity was reproduced introducing the low-pass filtered finely resolved velocity data into the momentum equations. The reproduced fluctuating velocity component agreed well with the true value which was derived by subtracting the generated low-pass filtered velocity data from the finely resolved LES velocity data (Figure 1). The kinetic energy spectrum of total velocity by summing up the reproduced fluctuating velocity component and low-pass filtered velocity fitted well to the -5/3 power law for the inertial subrange (Figure 2).



Fgure 1. Time history of streamwise fluctuating velocity component for the apriori test conducted by Nozawa and Tamura [2], solid line: reproduced fluctuating component, dashed line: true value.



Fgure 2. Streamwise kinetic energy spectra for the apriori test conducted by Nozawa and Tamura [2], •: reproduced fluctuating component, □: low-pass filtered velocity, +: true value.

In this paper the method is introduced to nest meso-scale WRF [4] and micro-scale LES. The low-pass filtered velocity component of the micro-scale LES should be equal to the velocity of the meso-scale WRF and the averaged fluctuating velocity component of the micro-scale LES must be almost zero. Meanwhile the fluctuating velocity component of the micro-scale LES is implicitly estimated as subgrid-scale turbulence in the meso-scale WRF. So the grid-scale turbulence in the micro-scale LES must be reproduced explicitly at the connection with the meso-scale WRF flow. This grid-scale turbulence in the micro-scale LES could be estimated using the scale similarity model when the filter width of the meso-scale WRF is in the range of inertial subrange of an energy spectrum. So in this study we carry out an idealized free convective boundary layer flow using WRF-LES mode [4-6]. The velocity data simulated in the WRF-LES is imposed to a fine-grid LES and the grid-scale fluctuating velocity of the fine-grid LES would be reproduced using the proposed one-way coupling method.

2 ONE-WAY COUPLING METHOD

The Navier-Stokes equations which are filtered with the LES grid filter width ($\overline{\Delta}$) are written as below:

$$\frac{\partial \overline{U}_i}{\partial t} + \frac{\partial \overline{U}_i \overline{U}_j}{\partial x_j} = -\frac{\partial \overline{P}}{\partial x_i} - \frac{\partial \overline{\tau}_{ij}}{\partial x_j} \tag{1}$$

where $\overline{U}_i$= velocity in *i*th-direction filtered with LES grid filter; $\overline{P}$=filtered pressure; and $\overline{\tau}_{ij}$=subgrid scale Reynolds stresses. In this filtered Navier-Stokes equations, the diffusion terms is neglected because of high Reynolds number. The filtered Navier-Stokes equations for coarser grid system which are filtered with filter width $\widetilde{\Delta}$ are written as below:

$$\frac{\partial \widetilde{U}_i}{\partial t} + \frac{\partial \widetilde{U}_i \widetilde{U}_j}{\partial x_j} = -\frac{\partial \widetilde{P}}{\partial x_i} - \frac{\partial \widetilde{\tau}_{ij}}{\partial x_j} \tag{2}$$

where $\widetilde{U}_i$=filtered velocity in *i*th-direction; $\widetilde{P}$=filtered pressure; and $\widetilde{\tau}_{ij}$=subgrid scale Reynolds stresses. We assume the filter width $\widetilde{\Delta}$ is much larger than that of the LES grid filter $\overline{\Delta}$. The filtered velocity $\overline{U}_i$ can be decomposed into $\widetilde{\overline{U}}_i$ and u_i as below:

$$\overline{U}_i = \widetilde{\overline{U}}_i + u_i . \tag{3}$$

The velocity $\widetilde{\overline{U}}$ is fluctuating very slowly due to the filter width, $\widetilde{\overline{\Delta}}\left(= \sqrt{\widetilde{\Delta}^2 + \overline{\Delta}^2}\right)$. The velocity u_i is a fluctuation component which consists with subgrid scale turbulence of the coarser grid system. If the difference between the two filter widths is large enough we can obtain the equation:

$$u_i \approx \overline{U}_i - \widetilde{U}_i . \tag{4}$$

By using this relation, we can extract the equations of motion for fluctuation velocity components u_i by subtracting equation (2) from equation (1).

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{U}_i \overline{U}_j - \widetilde{U}_i \widetilde{U}_j\right) = -\frac{\partial}{\partial x_i}\left(\overline{P} - \widetilde{P}\right) - \frac{\partial}{\partial x_j}\left(\overline{\tau}_{ij} - \widetilde{\tau}_{ij}\right) \tag{5}$$

Figure 3 indicates that we only have to obtain the difference between the finer grid grid-scale (GS) turbulence and the coarser grid GS turbulence to reproduce the fluctuation velocity components u_i of the equations (5). In the equations there two subgrid-scale stress terms, $\overline{\tau}_{ij}$ is for energy cascade from finer grid GS turbulence to SGS turbulence, and $\widetilde{\tau}_{ij}$ is the production term which cascade turbulence energy form coarser grid to finer grid.

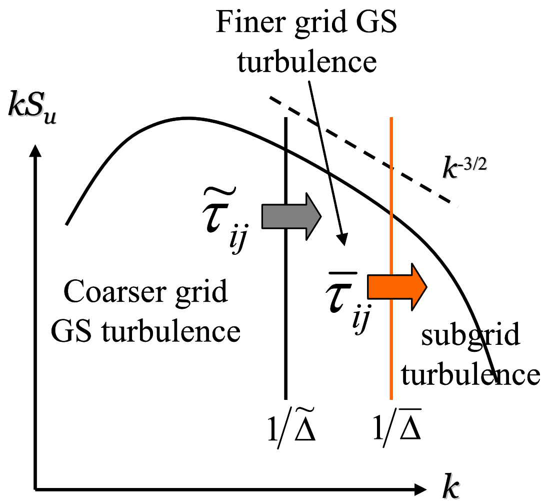


Figure 3. Schematic representation of the energy spectrum of turbulence.

These equations could be solved in the same manner to solve the Navier-Stokes equations by adding an equation of continuity for the fluctuation velocity. Additional restriction that time-space average of fluctuation velocity components u_i is zero will make averaged $\bar{U}_i$ follow the mean value of $\tilde{U}_i$. The technique for the immersed boundary method proposed by Goldstein et al [7] is applied to force the averaged fluctuating velocity component to zero. Goldstein et al proposed the method to determine the velocity at particular point to the desired value in an unsteady viscous flow. The body force f_i which is controlled by the feedback system is imposed to the equation (5):

$$f_i(t, x_i) = \alpha \int_0^t err(\tau, x_i) d\tau + \beta \cdot err(t, x_i). \tag{6}$$

The quantities α and β are negative constants and $err(t, x_i)$ is a residual error between the simulated velocity and the determined velocity. The error being feed back is the velocity integral and the velocity itself. In this study we applied this feedback system to control u_i to zero. The quantities are α=-2000 and β=-30 in this study.

The subgrid scale Reynolds stresses implemented in coarser grid Navier-Stokes equation (2) is the production term in equation (5). In this method the scale similarity model [3] is applied to the subgrid scale stresses: $\tilde{\tau}_{ij}$ and the Smagorinsky model is applied to the subgrid scale stresses: $\bar{\tau}_{ij}$. The filter width of the coarse grid has to be in the inertial subrange of energy spectrum to predict the production terms in equation (5) properly.

3 NUMERICAL METHOD

3.1 *WRF-LES*

The advanced research WRF[4] is widely used mesoscale meteorological model and in this study we carry out a single domain idealized free convective boundary layer flow using WRF-LES mode with the periodic boundary condition in horizontal plane. WRF-LES eddy viscosity is predicted using 1.5-order, level 2.5 Mellor-Yamada-Janjic (MYJ), TKE (turbulence kinetic energy) equation with local kinetic energy vertical mixing. The MYJ planet boundary layer scheme predicts the generation and redistribution of TKE in the boundary layer, uses the value of TKE to compute a spatially varying eddy viscosity, and then diffuses simulated quantities vertically in the boundary layer. In this study the heat flux from the ground is zero. The geostropic wind speed is 10m/s in east-west direction. The Coriolis parameter is 10^{-4}/s.

In this study, the computational region of the WRF-LES is 13km in east-west direction, 6.5km in north-west direction and 2km in vertical direction. The horizontal grid space is 50m. The size of stretched vertical grid is from 40m to 60m (figure 4).

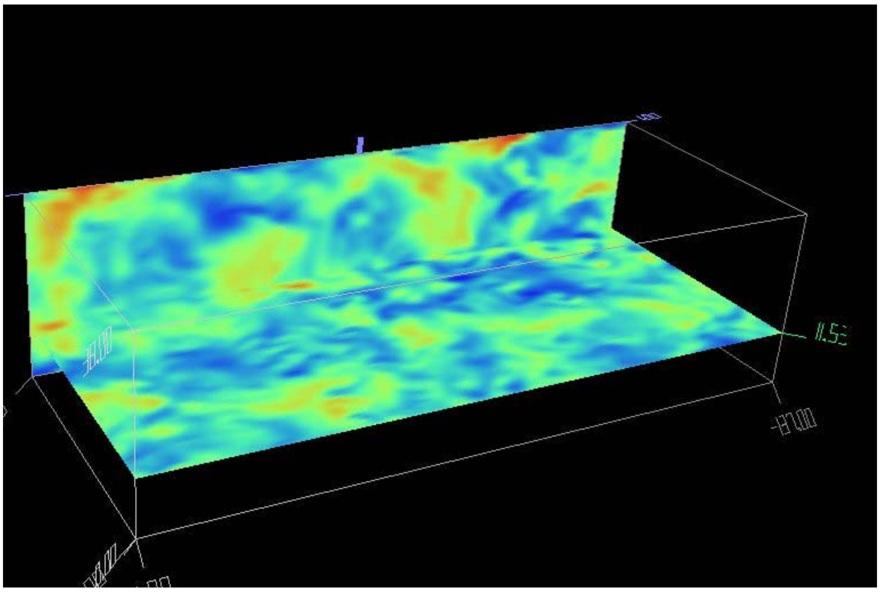


Figure 4. Distribution of east-west wind velocity using WRF-LES (red: high speed, blue: low speed).

3.2 *Micro scale LES*

The micro scale incompressible LES is simulated using the equation (5). Fourth-order central differencing scheme is used as spatial discretization and second-order time accurate explicit Adams-Bashforth differencing scheme is used for the convective terms and SGS turbulent diffusion terms. There is no thermal effect to the fine-grid LES. The WRF-LES velocity data is interpolated to the filtered ($\tilde{\Delta}$) variables in equation (5).

The LES horizontal grid space is 25m. The LES computational region is 6.5km in east-west direction, 2.7km in north-west direction and 1km in vertical direction.

In this method the scale similarity model which parameterizes the subgrid-scale stress terms requires the grid scale filter ($\tilde{\Delta}$) of the WRF-LES in the fine-grid LES. Although the grid size ratio ($\tilde{\Delta}/\bar{\Delta}$) is 2 in this study, high wavenumber turbulence has decline due to the numerical filter (damping) in WRF-LES. The numerical filter width ($\tilde{\Delta}^*$) is estimated about 8.5 times as large as the grid size ($\bar{\Delta}$) in fine-grid LES. So in this study the explicit filter width ($\tilde{\Delta}^*$) of the scale similarity model is set to $8.5\bar{\Delta}$.

4 RESULTS

The WRF-LES was run for 10 hours and statistical data were estimated with averaging over the horizontal plain. Figure 5 shows the time history of east-west direction velocities at height 740m.

The mean velocity of the WRF-LES simulation is 10m/s and its standard deviation is 1.3m/s. While the time averaged velocity of the fine-grid LES is 0.005m/s and its standard deviation is 0.71m/s. This meant that technique for the immersed boundary method worked well to force the averaged fluctuating velocity component to zero. The high frequency oscillation still occured in the fluctuating component of the fine-grid LES while the WRF-LES velocity has only lower frequency oscillation compared to that in the fluctuating component of the fine-grid LES. The high frequency turbulence is reproduced rapidly as soon as the coupling method is applied. The streamwise velocity contours at the horizontal section at z=800m are shown in figure 6. We could find the large scale turbulence structures in the WRF-LES contour, while the large scale turbulence is not generated in the fluctuating component of the fine-grid LES contour.

Figure 7 shows the kinetic energy spectra for east-west velocity fluctuations at height 740m. The inertial subrange of the kinetic energy spectrum of the coarse grid WRF-LES is limited up to wavenumber 2km^{-1}. We could find the fluctuating component of the fine-grid LES has extended the high wavenumber region of the inertial subrange. The results indicate that the coarse-grid WRF-LES and the fine-grid LES could be smoothly connected by using the proposed method.

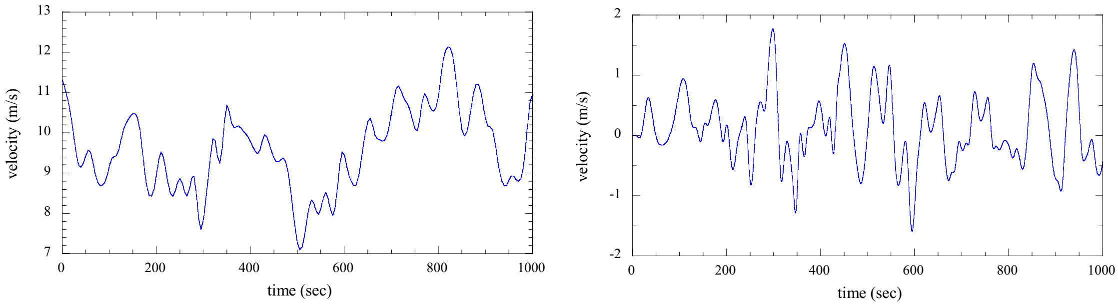
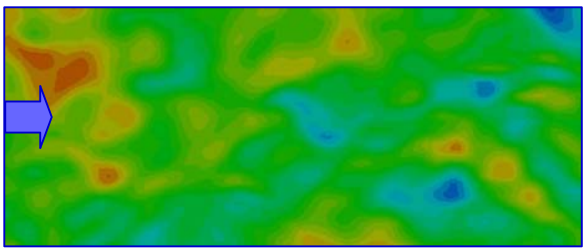
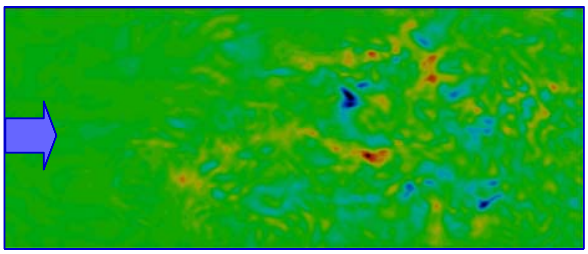


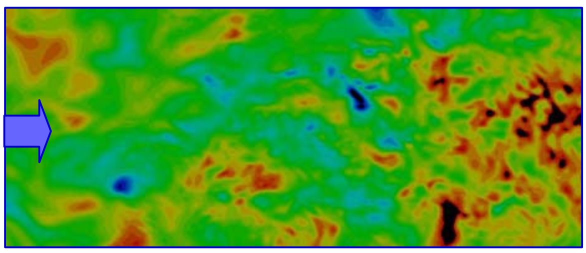
Figure 5. Time history of east-west velocity at z=740m. Left: WRF-LES, Right: fluctuating component of the fine-grid LES.



(a) WRF-LES



(b) fluctuating component of the fine-grid LES.



(c) WRF-LES + fluctuating component of the fine grid LES.

Figure 6. East-west velocity contours at horizontal section at z=800m.

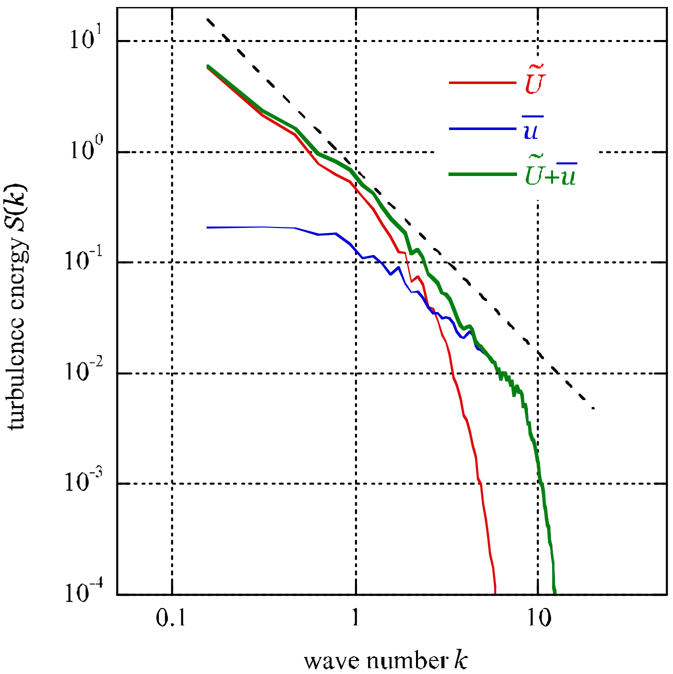


Figure 7. Kinetic energy spectra of the fluctuating velocities at z=740m. ($\tilde{U}$: WRF-LES, $\overline{u}$: fluctuating component of fine-grid LES)

5 CONCLUSIONS

The one-way coupling method is applied to connect meso-scale model WRF and micro-scale LES using the scale similarity model. The coupling between WRF and LES is studied on a free convective boundary layer flow with no heat flux from the ground nesting coarse grid WRF-LES and fine grid LES.

The time history and the instantaneous contours of the east-west direction velocity showed that the high frequency oscillation was generated in the fluctuating component of the fine-grid LES while the WRF-LES velocity had only lower frequency oscillation compared to that in the fluctuating component of the fine-grid LES. The kinetic energy spectra for the east-west velocity fluctuations of the fine-grid LES had power in the high wavenumber region where energy by WRF-LES turbulence decreased due to the artificial damping. The results indicate that the coarse mesh and the fine mesh could be smoothly connected by using the proposed method.

In this study the time series of WRF-LES velocity data were interpolated to a whole domain of the fine-grid LES and the time-averaged velocity distribution coincide with the distribution of coarse-grid WRF-LES velocity. So to connect WRF-LES and LES against the flow over complex terrain the coupling method should be modified that time-averaged velocity distribution near the surface is determined by the local effect of the terrain.

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