587: Development of Parallelized Urban Meteorological Model based on LES Model

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Abstract

A local meteorological model, which is based on LES model, is developed and tested with several basic verification tests. The results from verification tests indicate that the model is correctly developed at least with regarding to dynamics and physics. Parallel computation tests are performed on the super computer, T2K-Tsukuba. The parallelization efficiency is approximately 0.59 with 1024 processors.

Keywords: Large eddy simulation, Urban thermal environment

1. Introduction

Many weather observation points with a long-term history of observations are located in urban areas. Temperature changes recorded at these points are likely to be impacted by the urbanization process. It has been pointed out that changes in local environment (e.g., tree growth, altered land use, etc.) may contribute to the observed temperature changes. Qualitative assessment of such contribution has been done previously, but has not been described in numerical models at great details.

In this research, a large eddy simulation (LES) model capable of simulating urban areas was developed, and the degree of impact of buildings, parks, and trees on the local temperature distribution was evaluated.

In general, computational load of LES model is very large, so parallelization of the code is also performed.

2. Model Description

In this section, we briefly describe the LES model developed in this study. The governing equations utilized for the basic variables, after application of space filtering and coordinate transformation are:

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0$$

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial \overline{u_i}\,\overline{u_j}}{\partial x_j} = -c_p \Theta_0 \frac{\partial \overline{\pi'}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(-\tau_{ij} + 2\nu \overline{S_{ij}}\right) + \frac{g}{\Theta_0}\overline{\theta'}\delta_{13} + F_i$$

$$\frac{\partial \overline{\theta}}{\partial t} + \frac{\partial \overline{u_j}\,\overline{\theta}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(-\tau_{\theta j} + \kappa \frac{\partial \overline{\theta}}{\partial x_j}\right) + Q$$

$$\frac{\partial \overline{q_v}}{\partial t} + \frac{\partial \overline{u_j}\,\overline{q_v}}{\partial x_j} = -\frac{\partial \tau_{q_v j}}{\partial x_j} - (CN_{vc} - EV_{cv} - EV_{rv})$$

$$\frac{\partial \overline{q_c}}{\partial t} + \frac{\partial \overline{u_j}\,\overline{q_c}}{\partial x_j} = -\frac{\partial \tau_{q_c j}}{\partial x_j} + (CN_{vc} - EV_{cv} - AC_{cr} - CC_{cr}) + \frac{\partial}{\partial z}(\rho V_c \overline{q_c})$$

$$\frac{\partial \overline{q_r}}{\partial t} + \frac{\partial \overline{u_j}\,\overline{q_r}}{\partial x_j} = -\frac{\partial \tau_{q_r j}}{\partial x_j} + (AC_{cr} + CC_{cr} - EV_{rv}) + \frac{\partial}{\partial z}(\rho V_r \overline{q_r})$$

where u_i is the *i*th velocity component (*i*, *j* run from 1 to 3), π is the exner function, θ is potential temperature, τ_{ij} is the subgrid stress tensor, $\tau_{\theta j}$ and τ_{qj} is the subgrid turbulent flux for heat and vapor, respectivery. The overbar indicates a resolved-scale variable. The Boussinesq approximation has been applied here. The subgrid tensor and subgrid turbulent flux must be determined in order to close the basic equations. Our model adopted the Smagorinsky model and Deardorff's model (Deardorff 1980 [1]). Numerical schemes are listed in Table 1. In order to prevent refrection of gravity wave, Rayleigh damping layer set in the upper domain leyers. The dumping coefficient follows Klemp and Lilly (1978)[2].

In the radiation model, the shape factor is calculated by the Monte Carlo method. Multiple scattering between buildings can be considered.

Table 1: Model description.

Basic equations	Boussinesq approximation
Coordinate	Cartesian
Discretization approach	Finite difference method
Grid system	Arakawa-C staggered
Time integration scheme	3rd order Runge-Kutta
Spatial difference	2nd order central
Solution method for the equations	SMAC
Solution method for the poisson equation	Bi-CGStab method
SGS model	Smagorinsky or Deardorff
Shortwave Radiation	Kondo(1994) or Dudhia
Longwave radiation	Kondo(1994) or RRTM (take into consideration of multiple scattering between buildings)
Surface model	Bulk, Mascart(1995)
Vegetation model	Multi-layer
Cloud physics	Warm-rain
Building	0-1 masking method

3. Verification tests

Several model verification tests are performed to evaluate the robustness of model dynamics and physics, as well as the effects of stratification.

First, a convective thermal simulation is conducted. Vertical flow near the surface ($z = 0.2z_i$) is organized into polygonal convective elements ranging from about 700m to 1.2km in diameter (figure not shown). This result is in a good agreement with previous studies.

Second, a flow simulation with cube arrays is conducted. The simulated flow exhibits streaky structure above the cubic arrays (Figure 1). Figure 2 shows the contribution of momentum flux from resolvable and subgrid scale (SGS) components. The SGS contribution is very small except at the top of the canopy. This is because the roof surface is treated as a rigid wall. Away from the roof surface, the SGS contribution becomes small. These features are in a good agreement with previous studies [3].

Last, verification test of radiation model was conducted. For verification of the form coefficient calculated by the Monte Carlo method, we compared the simulated result with analytical solution. The result indicates that the form coefficient value converges to analytical solution when the number of trials is 200,000 times or more. It was also shown that two reflections is sufficient for resolving reflection between buildings (Figure 3). The simulated effective albedo was compared with the observations of Kanda et al.(2005)[4] and shown well comparable.

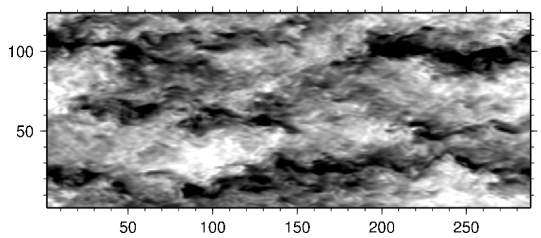

Figure 1. x-y horizontal cross-section (z=1.1h). Low speed streaks defined as the region where the stream-wise velocity fluctuation u''=U-<U> is negative.

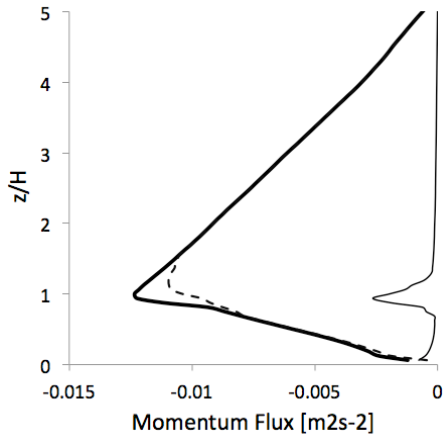

Figure 2. Vertical profiles of the horizontal mean momentum flux of the total (solid line), the resolvable scale (dashed line), and the subgrid-scale field (thin line), respectively.

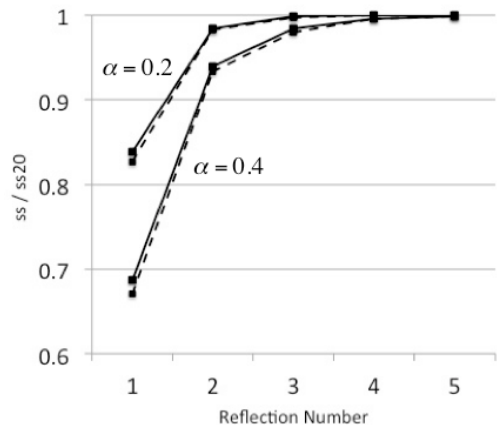

Figure 3. Reflected solar radiation divided by 20 times reflection. Solid line is uniform building arrangement, and dashed line is staggered arrangement.

4. Test case

Some numerical tests were performed under various building pattern and building height dispersion; uniformed building pattern, non-uniform building height pattern, and sparse building pattern. The results show that the air temperature in the canopy layer is the highest in the non-uniform building height pattern. This is

because turbulent transportation in the upper canopy layer becomes active.

5. Parallelization

Parallelization of the model was tested on the T2K-Tsukuba super computer. T2K-Tsukuba hosts 648 compute nodes providing 95.4 Tflops of computing capability. Each node consists of quad-socket, 2.3 GHz Quad-Core AMD Opteron Model 8356 processors whose on-chip cache sizes are 64 KBytes/core, 512 KBytes/core, 2 MB/chip for L1, L2, L3, respectively. Each processor has a direct connect memory interface to an 8 GBytes DDR2-667 memory and three hypertransport links to connected to other processors. All the nodes in the system are connected through a full-bisectional fat-tree network consisting of four interconnection links of 8 GBytes/sec/direction aggregate bandwidth with Infiniband 4xDDR.

In the parallelization, MPI was used to transfer information between the processors.

5.1 Strong scaling test

A convective boundary layer simulation was used for strong scaling test. The simulation domain has 320x320x100 grid points. The result shows that parallel efficiency is over 75% under 128 processors, and about 59% with 1024 processors. It is considered that the decrease in performance from one to sixteen processors occurs because of the increased memory access requirements.

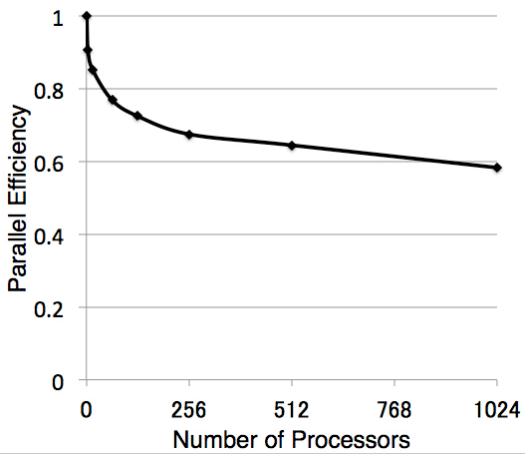

Figure 4. Strong scaling test. Parallel efficiency.

5.2 Weak scaling test

The sub-domains for this test each have 50x50x50 grid points. The result of the test shows that beyond 16 processors, the performance is nearly uniform. The 1024 processors simulation require about 10% more time than the 16 processors simulation.

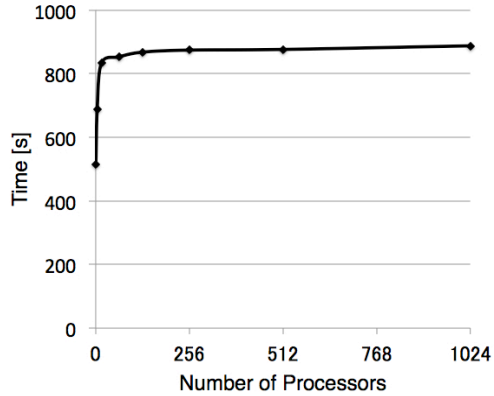

Figure 5. Weak scaling test.

6. Conclusion

We have developed a local meteorological model based on the LES model. Several verification tests were performed. Based on these numerical test results, it is concluded that at present, our model is correctly developed at least with regarding dynamics and physics.

It is shown that two reflections should be considered for reflection between buildings in radiation scheme..

Parallel computation tests are performed on the super computer, T2K-Tsukuba. The results show that parallel efficiency is over 75% under 128 processors, and about 59% with 1024 processors.

7. Acknowledgements

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8. References

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