Development of Urban Meteorological LES model for thermal environment at city scale

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1. Introduction

Recently, the temperature increase in urban areas has become significant due to urbanization and global warming. With the degradation of urban thermal environment, there is a concern that health risks in residents, such as heatstroke, could increase. As a result, a number of heat-island mitigation strategies have been proposed and tested, such as dry-misters installation, and street-side tree plantation. In order to evaluate the effectiveness of such heat-island mitigation strategies, we need a model that can resolve processes at the city scale (10^3 m) to the scale of areas around buildings (10^1 m). In order to simulate at these wide range of scales in a numerical model, buildings need to be explicitly resolved, and the effects of street trees also need to be considered in the model.

In this research, a large eddy simulation (LES) model capable of simulating urban areas is developed, by which the impacts of buildings, roadside trees and dry-misters on the local temperature distribution are evaluated.

In general, computational cost of LES model is very high, 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 dynamics part of our model is based on Non-hydrostatic Boussinesq approximation equations. Numerical and physical schemes in the LES model are listed in Table1.

The main features of the LES model include (i)Building resolving, (ii)Roadside trees resolving in 3-dimensional space, (iii) resolving shadows from buildings and trees, (iv) treatment of multiple reflections of short- and long-wave radiation between buildings and trees by radiosity method, and (v) incorporation of cloud physics and atmospheric radiation models (e.g., RRTM).

The radiative environment within an urban canopy layer is an important factor in determining local- or micro-scale temperature distribution. In order to investigate the impact of urban 3-D structure (i.e., buildings and trees) on the urban thermal environment, we have developed an urban radiation model. Our urban radiation model is capable of treating multiple reflections between buildings or trees. Short- and long-wave radiations are calculated by radiosity method (Aoyagi and Takahashi, 2012). In our tree model, each individual tree is represented as a porous board constituted by many layers of leaves, and each board is characterized by its Leaf Area Index (Figure 1). The Leaf Area Index is determined by the leaf density of each grid box. Optical parameters are leaf transmittance and reflectance. The intensity of direct solar radiation decreases as it passes through the porous boards. Reflected solar radiation is calculated by the radiosity method.

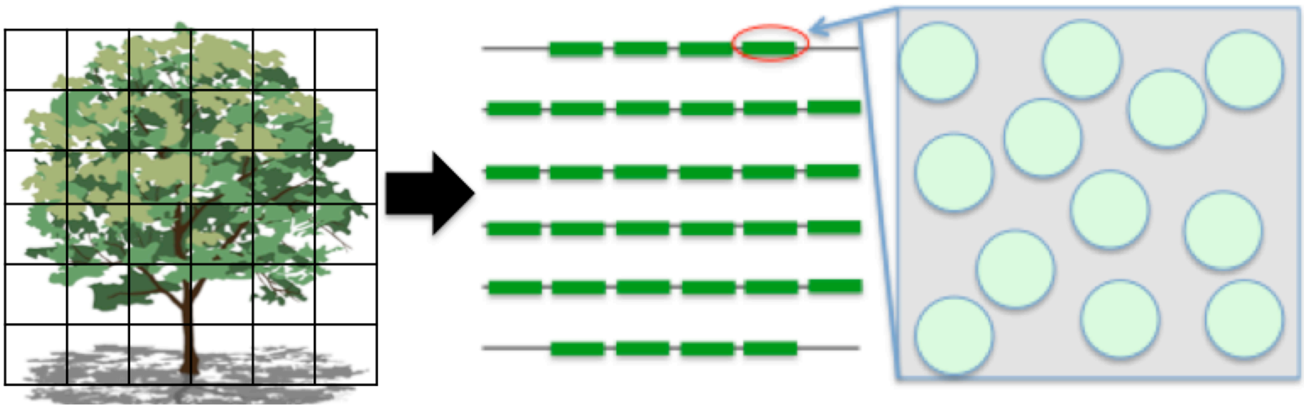

Figure 1. Schematic illustration of the tree model.

Table 1: Model description.

Basic equations	Non-hydrostatic Boussinesq approximation equations
Coordinate	Cartesian
Discretization approach	Finite difference method
Grid system	Arakawa-C staggered
Time integration scheme	Three-stage Runge-Kutta method (Wicker and Skamarock 2002)
Spatial difference	2nd order central (Option: 4th and 6th order central, 3rd and 5th order upwind scheme, monotonic limiter scheme (Wang et al. 2009))
Algorithm	SMAC method
Solution method for the poisson equation	Bi-CGStab method
SGS model	Smagorinsky or Deardorff(1980)
Shortwave Radiation	Kondo(1994) or Dudhia simple (Dudhia 1989)
Longwave radiation	Kondo(1994) or RRTM (Mlawer et al. 1997)
Radiation within urban canopy layer	Radiosity method
Surface model	Mascart(1995) Building: Jurges's formula
Cloud physics	Warm-rain or Bin type Warm-rain (Lulin et al. 2012) (use only for fog simulation and fair weather cumulus simulation)
Building	Building resolving (Δx < 10m) Multi-layer Urban Canopy model (Δx ~ 100m)
Programing language	Fortran 90 with MPI and PGI CUDA Fortran

Several model verification tests are performed to evaluate the robustness of model dynamics and physics, and radiation. The verification outcomes indicated that our code development has been successful in correctly simulating the dynamical, physical, and radiative processes.

3. Evaluation of heat island countermeasures using the LES model

Using our LES model, we examined the effectiveness of dry-misters installation and street-side trees plantation as heat island mitigation strategies.

Figure 2a shows the building distribution of the target area (the center of Tajimi city, Japan). The domain size is 1280m x 1280m x 1200m and the spatial resolution is 2 m. The simulation is targeted for a typical calm clear summer day. Simulations are repeated with and without each of the mitigation strategies. For street-side tree plantation strategy, trees with 4-m-wide crown and 10-m-height are placed along the side walk. For dry-mister installation strategy, misters are placed around the station square at 3 m above the ground, each separated by 4 m and spraying mist at 50 ml/min rate. (Figure 2b).

We evaluated the effects of the above two types of mitigation strategies (street trees and dry-misters) on the moist thermal environment within urban canopy. For heat index, we used Wet Bulb Globe Temperature (WBGT), which is one of the major heat-stress risk indices.

Figure 3 shows the simulated surface air temperature distribution, and Figure 4 shows the simulated WBGT distribution at 13LT. The simulation with street-side trees shows 0.5 °C reduction of the surface air temperature, and about 2 °C reduction of WBGT around the tree plantation area. The simulation with dry-misters shows 2 °C reduction in temperature, but only about 0.5 °C reduction in WBGT around the dry-misters installation area. The areas of high density installation of misters shows a 4 °C reduction in temperature.

Street-side trees are effective in lowering temperature due to transpiration and shading effect. Lowering effectiveness is more prominent in WBGT, as trees act to block direct sunlight and lowers the black bulb temperature via reduction of ground surface temperature from 15 to 20 °C in the shades. On the other hand, while dry misters act to lower the temperature, they cannot block the sunlight, thus, the WBGT lowering effect is smaller than trees.

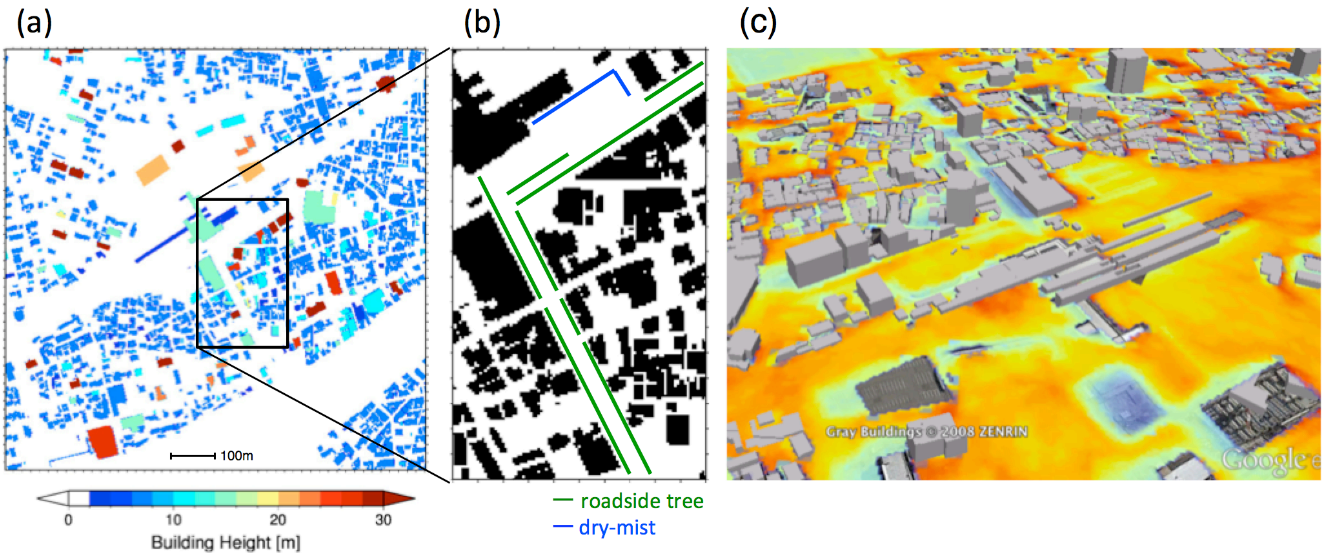

Figure 2. (a) Building distribution of computational domain. (b) Planting place of roadside tree and installing place of dry-mist. (c) Output image of surface air temperature calculated by the model.

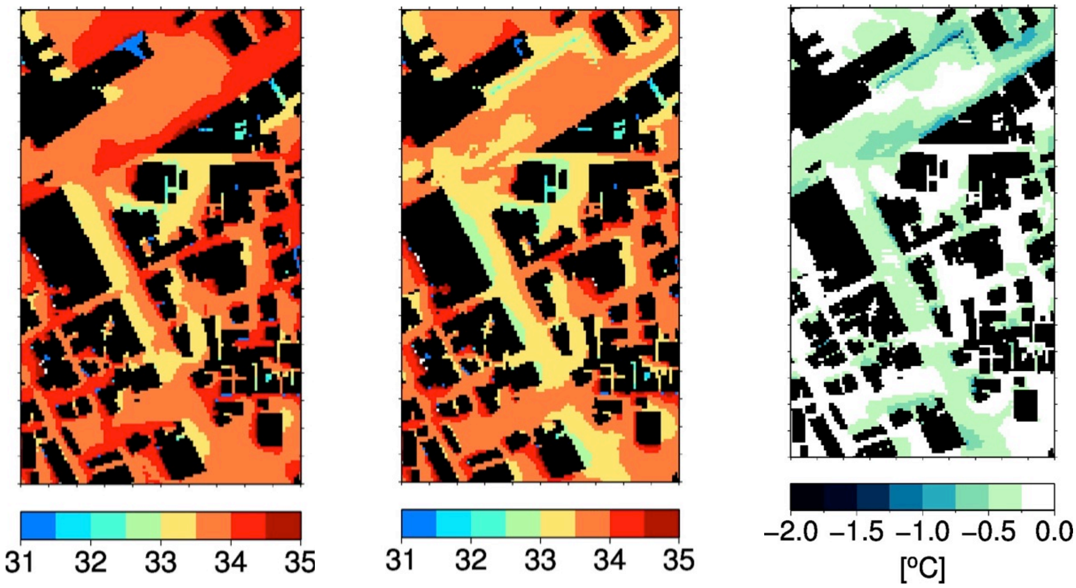

Figure 3. Surface air temperature distribution at the height of 2 m above the ground level (13LT, 10-minute average). The left figure shows non-countermeasure case. The middle figure shows the case with countermeasures. The right figure shows the difference between two cases.

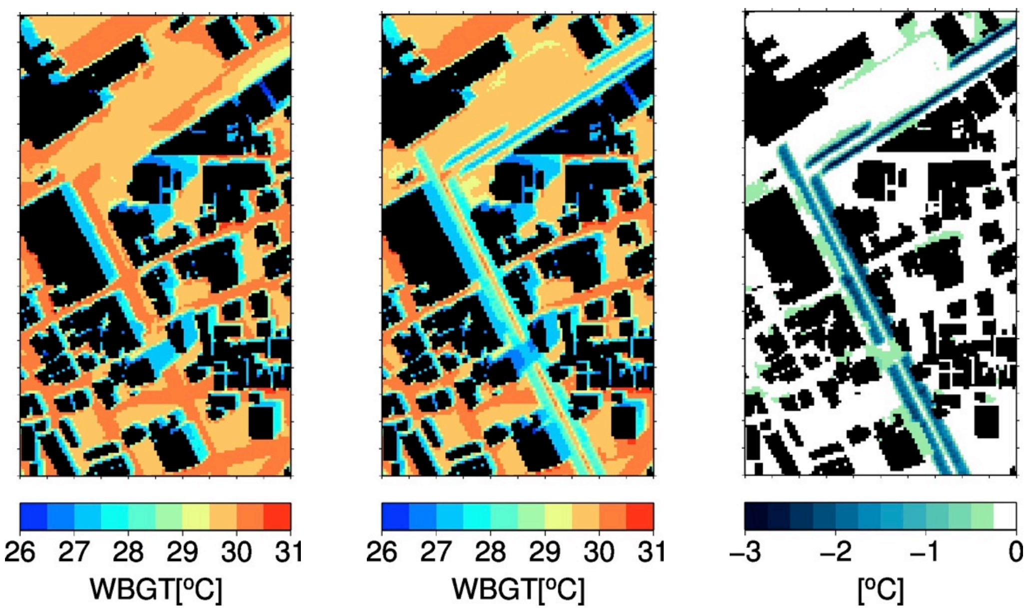

Figure 4. Wet Bulb Globe Temperature (WBGT) distribution at the height of 2 m above the ground level (13LT). The left figure shows non-countermeasure case. The middle figure shows the case with countermeasures. The right figure shows the difference between two cases.

4. Large-scale parallel computation

4.1 Parallelization with MPI

Parallelization of the LES model was tested on the COMA(PACS-IX) super computer, University of Tsukuba. COMA hosts 393 compute nodes providing 1.001 PFLOPS (CPU: 157TFLOPS, MIC: 844 TFLOPS) of computing capability. Each node consists of two Intel Xeon Processors E5-2670 v2 with 10 cores per CPU and two Intel Xeon Phi coprocessors 7110P with 61 cores. All the nodes in the system are connected by a mutual high-speed network (InfiniBand FDR). In this study, we use CPU only mode.
The simulation domain has 320x320x100 grid points. A convective boundary layer simulation was used for strong and weak scaling tests. The results of strong scaling test shows parallel efficiency of over 75% under 8 nodes, and about 49% with 64 nodes. It is considered that the decrease in performance from one to sixteen processors occurs because of the increased memory access requirements. We also performed a weak scaling test. The sub-domains for this test each have 50x50x50 grid points. The result shows that 64 nodes (1024 CPU-core) simulation requires about 10% more time than the 1 node (16 CPU-core) simulation.

4.2 Parallelization with GPU

LES-GPU code was tested on the HA-PACS super computer, University of Tsukuba. The node of HA-PACS consists of two Intel E5-2670(SandyBridge-EP) with 8 cores per CPU and four NVIDIA M2090 GPU. The peak performance is 2.99 TFLOPS per node.
Each of the model core's subroutines (i.e. sgs model, surface model, radiation model etc.) is parallelized by PGI CUDA Fortran for GPU performance evaluation. The simulation domain has 512x512x128 grid points and 4 nodes of HA-PACS are used for the performance evaluation.
Figure 5 shows the calculation time of each subroutines. The calculation time using 4GPU-core/node is 1.6 – 55.2 times faster than using 4CPU-core/node. The calculation time using 4GPU-core/node is 0.4 – 25.2 times faster than using 16 CPU-core/node.

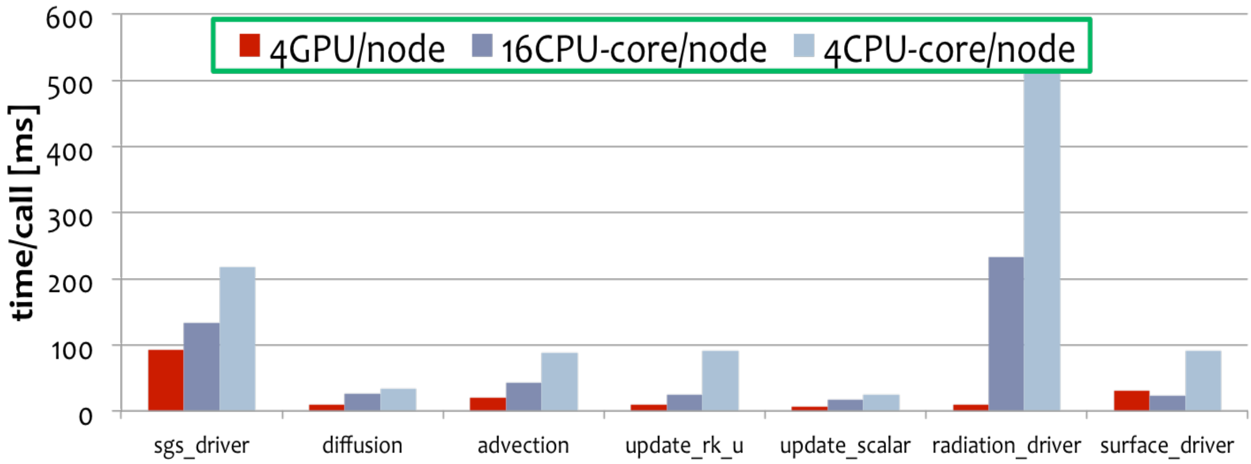

Figure 5. Calculation time of each of the model core's subroutines. Red bar indicates the calculation time of using 4GPU/node, Bule bar indicates 16CPU-core/node, and Gray bar indicates 4CPU-core/node.

5. Conclusion

We have developed a micro-scale 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 code development has been successful in correctly simulating the dynamical, physical, and radiative processes.
Using our LES model, we conducted simulations to evaluate the effects of dry-misters installation and street-side tree plantation. Results showed that street-side trees planting is effective to lower temperature due to transpiration and shades. Furthermore, we found that trees are more effective in lowering WBGT. On the other hand, although mist spray lowers the temperature, it cannot block the sunlight, thus, the WBGT lowering effect was smaller than trees.

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