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Numerical analysis of heat environment in central Tokyo using tree-crown-resolving large-eddy simulation considering three-dimensional radiation process

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1. Introduction

The air temperature of urban area is increasing due to the global warming and the heat island phenomena. Increase of urban green spaces is considered to be one of the countermeasures to mitigate the urban temperature increase since the cool island effect of green spaces was observed by a lot of field measurements (e.g., Jauregui 1990/91; Saito et al. 1990/91; Gomez et al. 1998; Vu et al. 1998; Hiruta & Ishikawa 2012). For the effective planning of urban green spaces, it is important to understand the mechanism of the cool spot effect and its effect on the heat environment mitigation. In order to investigate influence of urban green spaces on the heat environments, numerical simulations are one of the powerful tools. The multiscale general circulation model "MultiScale Simulator for the Geoenvironment" (MSSG) is capable of running as an urban-scale large-eddy simulation (LES) model considering the three-dimensional radiation process. However, for analyzing the influence of green spaces, it is necessary to consider the physical processes regarding trees: the friction drag force on the atmospheric flow, transpiration, sensible heat from leaves, and the scattering and absorption of radiations. Thus, this study aims to implement the physical models for a tree-crown-resolving LES into MSSG, and investigate the influence of trees on urban heat environments by performing the LES, in which the heat balance equation on the tree leaves is solved considering the transpiration, sensible heat and the three-dimensional radiation at each time step and each grid cell inside the tree crowns.

2. Model description

2.1 MSSG

"MultiScale Simulator for the Geoenvironment" (MSSG) is developed at Center for Earth Information Science and Technology, Japan Agency for Marine-Earth Science and Technology (JAMSTEC). MSSG is a multiscale atmosphere-ocean coupled general circulation model, which covers whole of global, meso- and urban scales (Baba et al. 2010; Onishi & Takahashi 2012; Takahashi et al. 2013). For urban scales, the atmospheric component of MSSG can work as a building-resolving LES model (Takahashi et al. 2013). The governing equations of the atmospheric dynamical process are the air density transport equation, the compressible Navier-Stokes equation, the pressure transport equation, and the equation of state. The pressure, density and momentums are coupled by using the fractional step method. In this study, the transport equation for water vapor density is also solved. Transport of sub-grid scale (SGS) turbulence kinetic energy is calculated for the one-equation SGS turbulence model (Deardorff 1980). The third-order Runge-Kutta method is used for temporal integration. Uniform Cartesian grids are used for spatial discretization. Buildings are resolved by the voxel method. Tree crowns are also resolved as distributions of the leaf area density a.

2.2 Three-dimensional radiation

The three-dimensional radiation process must be considered for the case of building-resolving simulation since thermal radiation from building walls influence local thermal environment on the ground surface. In the three-dimensional radiation model, surfaces of buildings and the ground are discretized in surface elements along the computational grids for atmosphere, while tree crowns are discretized in volume elements. The radiation flux on each element is calculated by the following radiosity equation:

$$S_i^* R_{\lambda,i} = S_i^* \epsilon_{\lambda,i} B\left(T_{surf,i}\right) + \alpha_{\lambda,i} \left[R_{\lambda,i}^{sky} + \sum_j A_{i\leftarrow j}^* F_{ij} R_{\lambda,i} \right]$$

where $R_{\lambda,i}$ is the radiosity, which is the radiation flux emitted from element i for the wavelength band λ. $R_{\lambda,i}^{sky}$ is the incident radiation flux from the sky including solar radiation. $\epsilon_{\lambda,i}$ and $\alpha_{\lambda,i}$ are the emissivity and reflectivity of element i, which satisfy $\epsilon_{\lambda,i} + \alpha_{\lambda,i} = 1$. $B\left(T_{surf,i}\right)$ is the thermal radiation flux from element i at the surface temperature of $T_{surf,i}$. F_{ij} is the view factor of element j viewed from element i. The view factors are calculated by the ray-tracing method, in which tree crowns are treated as semitransparent objects. The transmittance of a tree crown is given by the Beer-Lambert law. $A^*_{i\leftarrow j}$ and S^*_i are the effective projection area and effective surface area of a semitransparent volume element, respectively.

2.3 Surface flux

The heat budget on the surfaces of ground and building walls are calculated based on the following equation:

$$R_{net} - H - LE = G$$

where R_{net} is the net radiative flux absorbed by the surface, H and LE are the sensible and latent heat fluxes from the surface, and G is the heat conduction flux into the ground or the wall.

2.4 Tree-crown-resolving tree model

Tree crowns influence the atmospheric flow field and the temperature and water vapor distributions. Winds are attenuated by passing through tree crowns. The drag force F_i is given as

$$F_i = -C_d \rho a U^2 \frac{u_i}{U}$$

where C_d is the drag coefficient, ρ the air density, u_i the ith component of flow velocity and U the magnitude of the flow velocity. The volume fraction of leaves, brunches and trunks is assumed to be negligibly small. Influence of tree crowns on the SGS turbulent kinetic energy is also considered (Kanda & Hino 1994). The following heat balance equation on the tree leaves is solved considering the transpiration, sensible heat and the net radiation flux (Yoshida et al. 2000).

$$R_{p,net} - H_p - LE_p = 0$$

where $R_{p,net}$ is the net radiative flux absorbed by the leaves, H_p and LE_p are the sensible and latent heat fluxes from the leaves. H_p and LE_p are given by the following equations:

$$H_p = -\alpha_h \left(T_{air} - T_{leaf}\right)$$

$$LE_p = -L\beta_p \alpha_m \left\{e - e_{sat}\left(T_{leaf}\right)\right\}$$

where α_h and α_m are the convective heat and mass transfer coefficient, respectively. T_{air} is the air temperature, T_{leaf} the leaf surface temperature, e the water vapor pressure and $e_{sat}\left(T_{leaf}\right)$ the saturated water vapor pressure at T_{leaf}. β_p is the evaporation efficiency, which depends on the plant physiological conditions. Since the heat capacity of leaves is assumed to be negligibly small, the leaf surface temperature T_{leaf} is determined to satisfy the heat balance equation. The heat balance equation is solved at each time step and each grid cell inside the tree crowns. This study has confirmed that the model can predict the leaf temperature and heat flux distributions inside the tree crowns by conducting the heat environment simulation for an ideal green space.

3. Application to an actual urban area in Tokyo

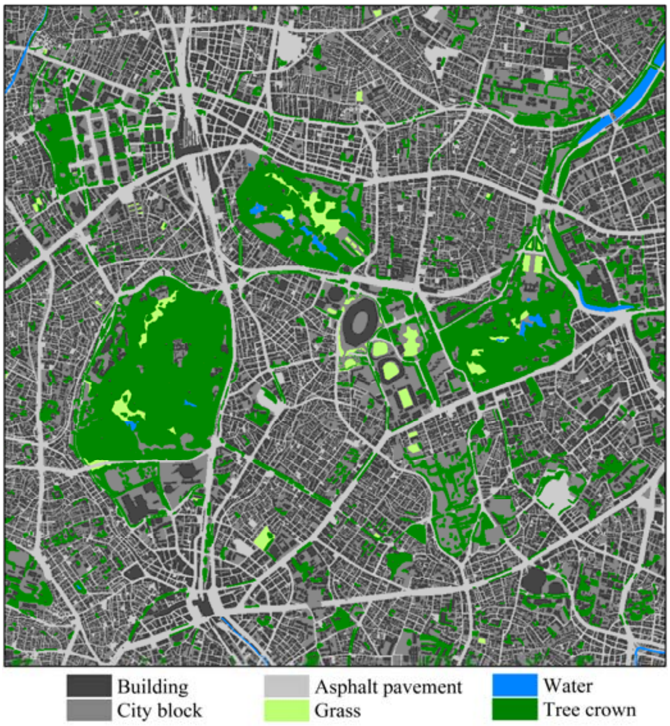
3.1 Computational conditions

The model is applied to the case of an urban area around the New National Stadium Japan, which will be constructed for the 2020 Tokyo Olympics. The Japan Sports Council (JSC) plans to build the stadium on a huge artificial ground. In this plan (current JSC plan), there are only a few shadow areas on the artificial ground. Since the Olympic Games are held in the hottest season in a year: from 24 July to 9 August, concerns about serious heat environment on the artificial ground are growing. Taking account of the fact that this area is designated as a landscape area, increase of trees is considered to be a potential candidate of mitigating the heat environment. Thus, a modified JSC plan, in which the artificial ground is removed and a lot of trees are planted around the stadium, has been proposed. In this study, the influence of increasing trees on the heat environment is investigated by comparing the cases of the current and modified JSC plans.

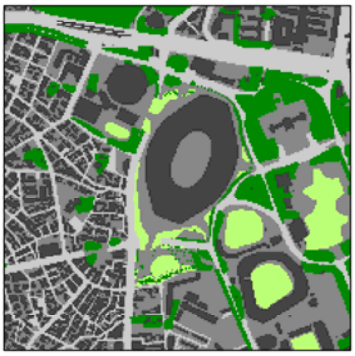
The computational domain was set to cover 5km x 5km horizontal area, which was discretized by 5m-resolution computational grids. The vertical height of the domain was set to 400m. Building and tree distributions in the current and modified JSC plans were converted to 5m-resolution three-dimensional data. Figure 1 shows the horizontal distributions of the land-use and tree crowns. Tree height and tree crown bottom height in large green spaces were set to 15m and 5m, respectively, while those in otherwise area were set to 10m and 5m, respectively. The anthropogenic sensible and latent heats were considered. The initial and side-boundary atmospheric conditions were set based on the reanalysis data provided by the Japan Meteorological Agency. The time integration was started at 12:00 JST (Japan Standard Time) on 11 August, 2007, when Tokyo was covered with clear sky and a typical meteorological condition of the heat island was observed around Tokyo.

3.2 Results and discussion

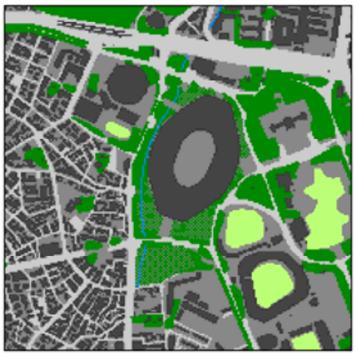
Figure 2 shows the three-dimensional visualization of the instantaneous potential temperature distribution for the modified JSC plan case at 12:30. Buildings and tree crowns are visualized in gray surfaces and green boxes, respectively. The isosurfaces of potential temperature at 305.9, 307.5 and 309.0 K are shown in blue, yellow and red. Wind is blown from the right-hand side (east side) of the figure. Thermal plumes develop above the built-up areas. Relatively cool air is observed in and above the large green spaces. These features are also observed for the current JSC plan case.



(a) 5km-square horizontal domain (current JSC plan)



(b) Current JSC plan



(c) Modified JSC plan

Fig. 1 Land-use and tree crown distributions in the target domain.

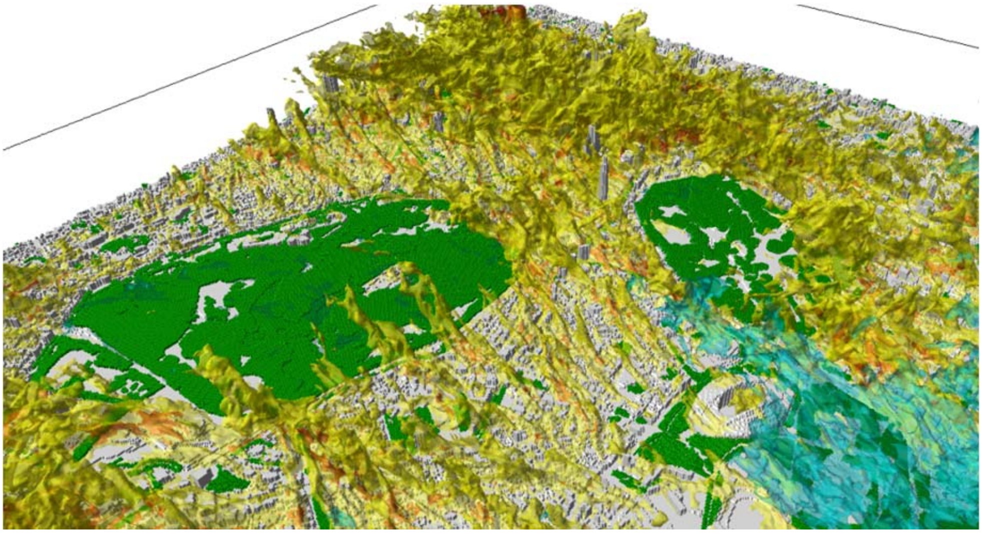


Fig. 2 Isosurfaces of potential temperature in the urban area and large green spaces in Tokyo. The New National Stadium Japan is located based on the modified JSC plan.

Figure 3 shows the 10-minutes-averaged air temperature distributions in the stadium premises. The air temperature around the stadium decreases more than 0.5 °C for large portion of the premises by increasing trees. For evaluating the influence of trees on the people, the discomfort index (DI) and the Wet-Bulb Globe Temperature (WBGT) index are calculated from the temperature, relative humidity, wind velocity, and three-dimensional radiation flux data. Figure 4 and 5 show the 10-minutes-averaged DI and WBGT index distributions, respectively. DI tends to decreases by increasing trees but the difference is smaller than roughly 1.0. The small influence on DI is caused by the relative humidity increase, which is due to increase of latent heat from trees and temperature dependency of the saturated water vapor pressure. On the other hand, WBGT index decreases significantly. The difference of WBGT index is approximately 1.0 °C in average and 4.6 °C in maximum. The significant decrease of WBGT index is caused by the attenuation of the direct solar radiation by the tree shadows, which decrease the globe temperature. Since the WBGT index is an indicator of the heat attack risk, this results indicates that the heat environment can be mitigated by increasing trees.

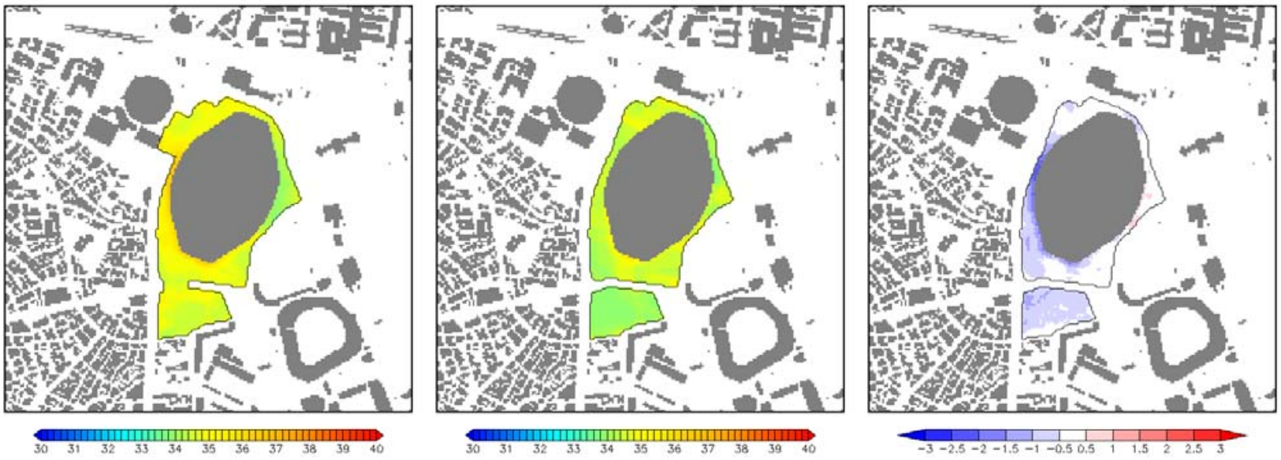


Fig. 3 Air temperature (°C) averaged during 12:20-12:30 at 2.5m above the ground for (left) current JSC plan case, (center) modified JSC plan case, and (right) difference of the modified plan case from the current plan case

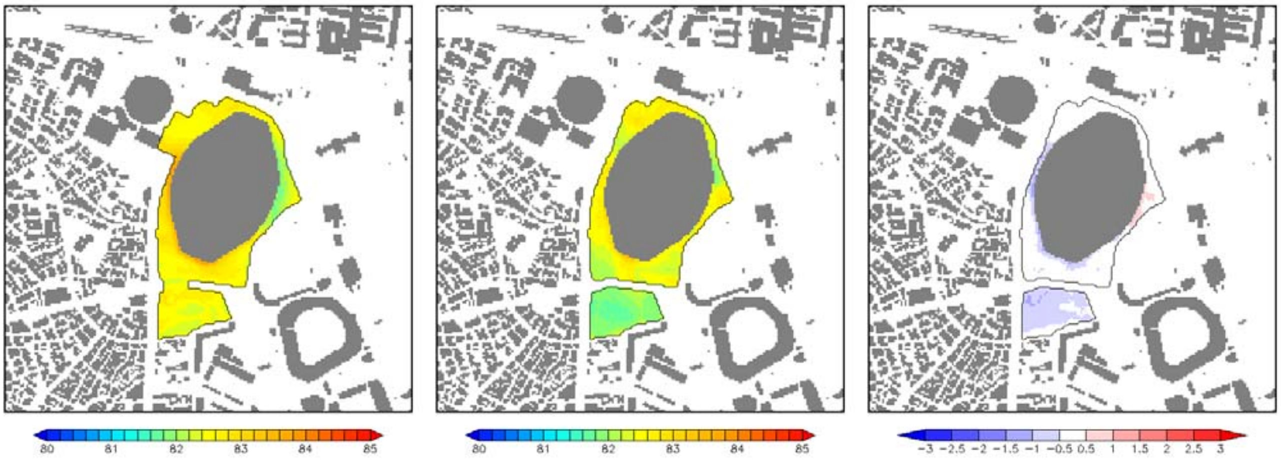


Fig. 4 Discomfort index (°F) averaged during 12:20-12:30 at 2.5m above the ground for (left) current JSC plan case, (center) modified JSC plan case, and (right) difference of the modified plan case from the current plan case

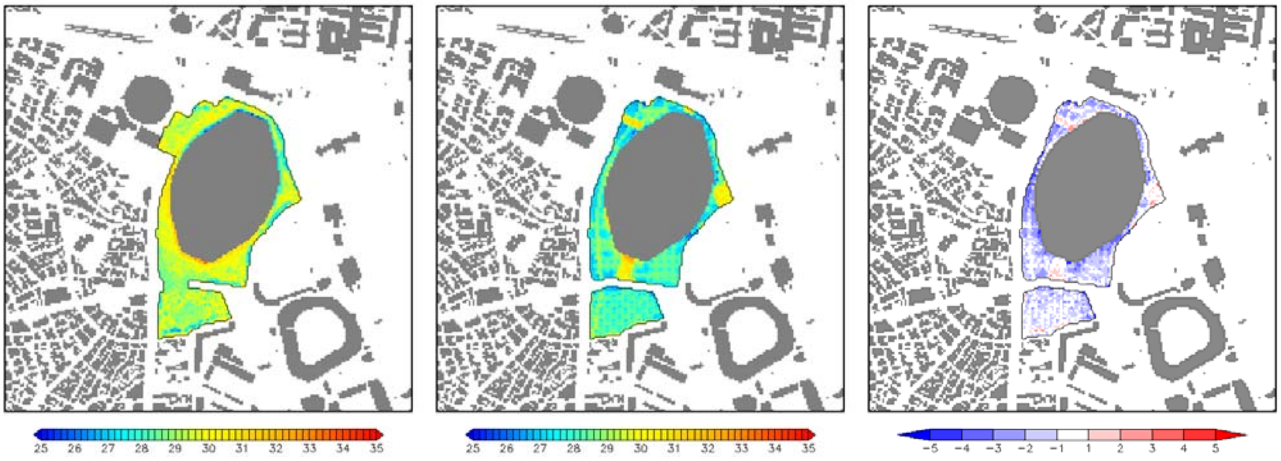


Fig. 5 Wet-Bulb Globe Temperature index (°C) averaged during 12:20-12:30 at 1.1m above the ground for (left) current JSC plan case, (center) modified JSC plan case, and (right) difference of the modified plan case from the current plan case

Conclusions

This study has investigated the influence of trees on the urban heat environment by using the "MultiScale Simulator for the Geoenvironment" (MSSG), which is capable of running as a building-resolving large-eddy simulation model. The tree-crown-resolving heat exchange model implemented in the MSSG solves the heat balance equation on the tree leaves considering the transpiration, sensible heat and the three-dimensional radiation at each time step and each grid cell inside the tree crowns. This model can predict the leaf temperature and heat flux distributions inside the tree crowns. The model is applied to the case of an actual urban area in Tokyo with the New National Stadium Japan, which will be constructed for the 2020 Tokyo Olympics. The computational domain covers 5km x 5km horizontal area, which is discretized with grid spacing of 5m. The initial and boundary conditions have been set based on the reanalysis data at noon on a summer-time clear-sky day, on which a typical meteorological condition of the heat island was observed around Tokyo. The results show that the air temperature around the stadium decreases by increasing trees in the stadium premises. The influence of increasing trees on the discomfort index is smaller than that on air temperature since the relative humidity increases. The Wet-Bulb Globe Temperature (WBGT) is, on the other hand, decreases remarkably. This is because the tree shadows attenuate the direct solar radiation and decrease the globe temperature. This indicates that the heat environment can be mitigated by increasing trees.

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