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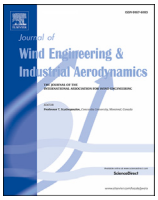

Tree-crown-resolving large-eddy simulation coupled with three-dimensional radiative transfer model

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ABSTRACT

This paper presents a tree-crown resolving large-eddy simulation (LES) coupled with a three-dimensional radiative transfer (3DRT) model. Real-time coupling of the LES and 3DRT models is achieved by using a simplified 3DRT model based on the volumetric radiosity method. The 3DRT model is validated by comparing with an observation and a Monte Carlo radiative transfer model. The sensitivity test for an ideal green space confirms that the real-time coupling is necessary for the reliable evaluation of the thermal environment in green spaces. The computational time required for the 3DRT calculation is negligibly small for performing the coupled LES. The present model is then applied to an actual urban area, which contains tree crowns along streets and in parks, covering 8000 m × 8000 m with 5-m grid mesh in order to confirm its feasibility in real applications. The error of the estimated WBGT at pedestrian level is smaller than 0.2 K when the optical thickness of a volume element is smaller than 2.5, and thus the local spatial distribution of the WBGT is predicted with an accuracy sufficient for capturing the influence of tree crowns.

1. Introduction

Urban temperatures are on the rise due to the combined influence of global warming and urban heat islands. Higher temperatures increase the risk of heat-related illness, and this risk is expected to increase in the future. Thus, mitigating summer heat in urban areas is one of the largest current social concerns. Increasing urban green space is one countermeasure employed against urban heat as it has been proved to have a cooling effect: Lower air temperatures in urban green spaces were compared with the temperature of the surrounding built-up areas (e.g., Jauregui, 1991; Saito et al., 1991; Gomez et al., 1998; Shashua-Bar and Hoffman, 2000; Vu et al., 1998). For example, Shashua-Bar and Hoffman (2000) measured 11 urban green wooded areas in Tel-Aviv during summer, and reported that the temperature difference between the points inside and outside of the green spaces ranged from 1.3 K to 4.0 K at 3:00 p.m. Vu et al. (1998) reported that the cooling effect of green areas has an economic impact as well. They carried out field measurements during hot summer days around Tama Central Park in Tokyo, and estimated that the cooling effect of the park on the surrounding city area reduces the electricity demand by 4000 kWh per hour, which corresponds to roughly US$650 of energy cost saving.

Two mechanisms explain the cooling effect of green spaces: The transpiration of plants and the shading effect of trees. Transpiration is the emission of water vapor by leaves through the stomata and moderates the leaf temperature. The presence of shade decreases direct solar radiation under the trees and suppresses the daytime ground surface temperature (Shashua-Bar and Hoffman, 2000). It should be noted that the trees have warming effect as well; e.g., tree crowns reduce the sky view factor of the ground, and thereby weaken the radiative cooling of the ground underneath. Trees also have the blocking effect of wind below the tree crowns (Gromke and Ruck, 2009, 2012): Tree crowns tend to diminish the air ventilation in street canyons, sometimes leading to warming inside the street. Thus, it is important to accurately estimate the effects of transpiration and shading on the urban thermal environment and their dependency on the three-dimensional tree crown distribution.

A three-dimensional numerical simulation can be a powerful tool for estimating the effects. Many large-eddy simulation (LES) and Reynolds-averaged Navier-Stokes (RANS) models that consider plant canopies have been developed (e.g., Shaw and Schumann, 1992; Kanda and Hino, 1994; Robitu et al., 2006; Bohrer et al., 2009; Bailey and Stoll, 2013). For a domain with a complex arrangement of obstacles, such as an urban area, the flow field obtained by RANS models is less reliable than that obtained by LES models (Walton and Cheng, 2002; Tominaga and Stathopoulos, 2011; Salim et al., 2011). However, most of the LES models do

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not consider the radiative heat transfer, which is one of the most important processes in the evaluation of urban heat environments as the surface temperature increases due to the absorption of radiative energy. To run an LES for the analysis of an urban thermal environment while considering the effects of plants, it is necessary to use an efficient three-dimensional radiative transfer (3DRT) model that considers the effects of tree crowns. The 3DRT is also necessary in evaluating heat-related illness risks, which is done using the wet-bulb globe temperature (WBGT) (Asayama, 2009). WBGT for shade and sunlit areas ($\mathrm{WBGT_{shade}}$ and $\mathrm{WBGT_{sunlit}}$, respectively) is defined as

$$\mathrm{WBGT_{shade}} = 0.7T_{\mathrm{wetb}} + 0.3T_{\mathrm{globe}}, \tag{1}$$

$$\mathrm{WBGT_{sunlit}} = 0.7T_{\mathrm{wetb}} + 0.2T_{\mathrm{globe}} + 0.1T, \tag{2}$$

where T is the air temperature, T_{wetb} is the wet-bulb temperature, and T_{globe} is the globe temperature, which is determined from the balance of the net absorbed radiation flux and the convective heat transfer at the globe sphere. A few LES models have considered the 3DRT process: Bakkali et al. (2015) performed a building-resolving LES for an actual urban area using the Parallelized LES Model (PALM) (Maronga et al., 2015), considering the influence of the 3DRT. The 3DRT and the outdoor-indoor energy balance of the buildings were precomputed and the sensible heat flux was imposed onto the building-resolving LES model. However, the influence of tree crowns were not considered in their LES. To couple an LES model with the 3DRT while considering the effects of tree crowns, it is necessary to consider the temporal variation of radiation flux because the leaf surface temperature varies within minutes. That is, the 3DRT should be calculated repeatedly during the time integration of the LES.

The Monte Carlo ray-tracing (MCRT) method is a direct simulation method for the 3DRT. In this method, a large number of discrete photon parcels are traced stochastically, and the exact solution is obtained when tracing infinitely many photon parcels. In repetitive 3DRT calculations, the computational cost for photon propagation can be reduced by using the radiosity method, in which the geometrical relation between obstacles is represented by view factors. Thus, the radiosity method is commonly used for building-resolving 3DRT simulations to calculate the energy balance at the building surfaces (Huang et al., 2005; Bakkali et al., 2015). The radiosity is the total radiation power leaving a surface per unit area, and it includes the radiation flux that is emitted and reflected (scattered) by the surface. The method was developed based on the zonal method, developed by Hottel and Cohen (1958) to predict the radiative heat transfer in a gas-filled enclosure. Sinoquet et al. (2001) applied the radiosity method (zonal method) to the 3DRT for an isolated tree crown, represented by the voxel data of the leaf area density. In their method, surfaces of the ground and walls in the computational domain were decomposed into many surface elements, and the tree crown was decomposed into volume elements. Their model was, however, not coupled with the LES.

Thus, we present a tree-crown-resolving LES model coupled to a 3DRT model. The present 3DRT model is based on the volumetric radiosity method (VRM), in which the tree crowns are decomposed into volume elements. The present model is eventually similar to that developed by Sinoquet et al. (2001), but it adopts the simplification that the radiation flux at an element is represented by single-valued radiosity to achieve real-time (online) coupling of the LES and 3DRT models. That is, the present model calculates the 3DRT repeatedly during the time integration of the LES so that the temporal variation of the radiation flux is considered in the LES. The radiation flux obtained by the 3DRT model is used for calculating the transpiration and heat exchange processes in tree leaves. Thus, the heat flux on the leaves and the radiation flux are updated along with the time evolution of the flow, temperature, and humidity fields in the atmosphere. In this paper, we investigate three issues regarding the present coupled model: The reliability of the present 3DRT model for radiations through tree crowns is investigated first. Second, the relevance of real-time (online) coupling to the LES is investigated; i.e., the influences of temporal variation of the radiation flux on flow and temperature are investigated by running the coupled LES for an ideal green space. Third, the feasibility of the coupled model is investigated by applying it to the analysis of the thermal environment in an actual urban area around the Tokyo Bay.

2. Computational method

2.1. Governing equations for large-eddy simulation

The tree-crown-resolving LES model coupled to a 3DRT model has been developed in the framework of the Multi-Scale Simulator for the Geoenvironment (MSSG) (Onishi and Takahashi, 2012; Takahashi et al., 2013; Sasaki et al., 2016, and the references therein). MSSG is an atmosphere-ocean coupled general circulation model, developed at the Center for Earth Information Science and Technology, Japan Agency for Marine-Earth Science and Technology (JAMSTEC). MSSG can cover the entirety of the global, meso-, and urban scales. For urban scales, the atmospheric component of MSSG (i.e., MSSG-A) can work as an LES model for resolving building shapes (Baba and Takahashi, 2009; Takahashi et al., 2013). The governing equations for MSSG-A are the transport equations for compressible flow, which consist of the conservation equations for mass, momentum, energy, and water vapor:

$$\frac{\partial\overline{\rho}}{\partial t} + \nabla\cdot(\overline{\rho}\tilde{\mathbf{u}}) = \overline{S}_{\rho\mathrm{q}}, \tag{3}$$

$$\frac{\partial\overline{\rho}\tilde{\mathbf{u}}}{\partial t} + \nabla\cdot(\overline{\rho}\tilde{\mathbf{u}}\tilde{\mathbf{u}}) = -\nabla\overline{p} - \overline{\rho}\mathbf{g} + \nabla\mathbf{\Pi} - 2\overline{\rho}\mathbf{\Omega}\times\tilde{\mathbf{u}} + \overline{\mathbf{S}}_{\rho\mathbf{u}}, \tag{4}$$

$$\frac{\partial\overline{p}}{\partial t} + \tilde{\mathbf{u}}\cdot\nabla\overline{p} = -\widetilde{c^2}\overline{\rho}\nabla\cdot\tilde{\mathbf{u}} + (\gamma-1)\nabla\cdot\mathbf{j}_{\mathrm{h}} + (\gamma-1)\overline{S}_{\rho\mathrm{h}} + \gamma R_{\mathrm{v}}T\overline{S}_{\rho\mathrm{q}}, \tag{5}$$

$$\frac{\partial\overline{\rho}\widetilde{q_{\mathrm{v}}}}{\partial t} + \nabla\cdot\left(\overline{\rho}\widetilde{q_{\mathrm{v}}}\tilde{\mathbf{u}}\right) = \nabla\cdot\mathbf{j}_{\mathrm{q}} + \overline{S}_{\rho\mathrm{q}}, \tag{6}$$

where ρ is the density of the moist air, $\mathbf{u}$ is the velocity, p is the pressure, q_{v} is the specific humidity of the water vapor, $\mathbf{g}$ is the gravitational acceleration, $\mathbf{\Omega}$ is the angular velocity of the earth, c is the speed of sound, and γ is the specific heat ratio, defined as $\gamma = C_{\mathrm{p}}/C_{\mathrm{v}}$, where C_{p} and C_{v} are the specific heats at constant pressure and volume, respectively. An overbar denotes a spatially filtered value for the grid scale (GS), whereas an over-tilde denotes a Favre-filtered value, a density-weighted average defined as $\tilde{\phi} = \overline{\rho\phi}/\overline{\rho}$ for a given value ϕ. $\mathbf{S}_{\rho\mathbf{u}}$, $S_{\rho\mathrm{h}}$, and $S_{\rho\mathrm{q}}$ are the sources (both positive and negative) for the momentum, enthalpy, and water vapor density, respectively. MSSG-A uses cloud microphysics to compute the temporal evolution of the water substances; in this study, we consider clear sky conditions, and thus omit a detailed description of that component.

Let $\mathbf{\Pi}$ be the subgrid-scale (SGS) turbulent stress tensor, and let $\mathbf{j}_{\mathrm{h}}$ and $\mathbf{j}_{\mathrm{q}}$ be the SGS turbulent enthalpy and water vapor fluxes, respectively. The eddy viscosity and diffusivity are assumed for the terms related to the SGS turbulence effect; i.e., $\mathbf{\Pi}$, $\mathbf{j}_{\mathrm{h}}$, and $\mathbf{j}_{\mathrm{q}}$ are given by

$$\mathbf{\Pi} = \overline{\rho}\nu_{\mathrm{t}}\left[\nabla\tilde{\mathbf{u}} + (\nabla\tilde{\mathbf{u}})^{\mathrm{T}} - \frac{2}{3}\mathbf{I}\nabla\cdot\tilde{\mathbf{u}}\right], \tag{7}$$

$$\mathbf{j}_{\mathrm{h}} = \overline{\rho}C_{\mathrm{p}}\kappa_{\mathrm{T,t}}\nabla\tilde{T}, \tag{8}$$

$$\mathbf{j}_{\mathrm{q}} = \overline{\rho}\kappa_{\mathrm{q,t}}\nabla\widetilde{q_{\mathrm{v}}}, \tag{9}$$

where ν_{t} is the turbulent eddy viscosity, $\kappa_{\mathrm{T,t}}$ and $\kappa_{\mathrm{q,t}}$ are the turbulent eddy diffusivities for heat and moisture, respectively, T is the air temperature, and $\mathbf{I}$ is the identity tensor. The superscript T denotes the