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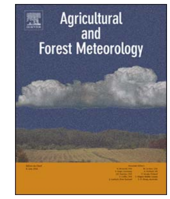

Large-eddy simulation of the impact of urban trees on momentum and heat fluxes

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A B S T R A C T

Trees in urban environment have a profound impact on the microclimate and environmental sustainability. Realistically representing them in urban models is an ongoing area of research in urban environmental study. In this paper, we develop a novel large-eddy simulation (LES) model (LES-UrbanTree) that resolves the buildings and parameterizes urban trees by accounting for their aerodynamic impact. The shading effect of trees is explicitly taken into account in LES-UrbanTree by a subsurface conduction model coupled to LES. Two-dimensional street canyons with trees in the middle of the street are used as a prototype for case studies. It is found that under moderate canyon aspect ratio (i.e. height/width being 0.5 and 1), trees taller than the mean building height leads to the strongest modification of the flow and temperature fields. Tall trees strongly impact the downward transport of high momentum (i.e. sweeping events) and therefore alter the momentum and heat fluxes most significantly through direct interaction with the strong shear layer near the roof top. Simulations of street canyons of different aspect ratios also produce physically consistent results, thus demonstrating the application potential of LES-UrbanTree. The study overall highlights the importance of representing both the aerodynamic and thermodynamic changes due to trees in urban models.

1. Introduction

Urban forestry presents an attractive urban planning strategy to practitioners and decision makers. Its impacts on land-atmosphere systems and the built environment in general include, but are not limited to, change of drag and turbulent transport (Krayenhoff et al., 2015), re-distributing surface energy balance particularly through radiative and evaporative cooling (Krayenhoff et al., 2014; Ryu et al., 2016), altering the urban water and energy budgets (Wang et al., 2011; Roy et al., 2012; Zipper et al., 2017; Litvak et al., 2017) and affecting the pollutant dispersion (Salim et al., 2011). For example, previous studies have shown that homes with shade trees in cooling dominant cities can save over 30% of residential peak cooling demand (Akbari et al., 1997; Wang et al., 2016). Several approaches have been adopted to account for the presence of trees in urban environmental studies. In particular, urban canopy models (UCMs) that are developed to capture urban land surface processes constrained by energy/water balances, incorporate the effects of trees. Lee and Park (2008) used a highly parameterized fashion by assuming the tree is an opaque medium to direct shortwave and diffusive longwave radiations. Krayenhoff et al. (2015, 2014) included the more physical radiative processes in the multi-layer UCM with a Monte Carlo ray tracing approach, such as the mutual shading between trees and built structure, emission and reflection of radiations. Ryu et al. (2016), in a single-layer urban canopy framework, not only included both the radiative processes (Wang, 2014) of trees in the street canyon but also the meteorological impacts such as evaporation and water uptake by the tree roots.

Despite the practical usefulness of UCMs, the urban flow field and momentum transport are in general parameterized in these models for them to be incorporated in mesoscale atmospheric models, such as the Weather Research and Forecasting (WRF) model. Thus, UCMs can only, at best, represent the mean statistics of atmospheric turbulence and momentum flux without resolving the detailed physics of urban flows, especially those at fine resolutions. On the other hand, from a generic point of view of environmental fluid dynamics, flows over building and vegetation canopies can be regarded as rough-wall boundary layers, where the canopy layer (below the average height of the canopy) and roughness sublayer (above the canopy but the effect of the roughness still exists) have been investigated in detail using computational fluid dynamics (CFD) models. For example, high-resolution obstacle-

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resolving large-eddy simulations (LES) model (Giometto et al., 2016), which the current study is based upon, has been developed, verified and applied in studying the flows and transport in building arrays (Tseng et al., 2006a; Chester et al., 2007; Li et al., 2016a,b). LES has also been applied over pure vegetation canopies that provides much insight of the flow details, turbulent coherent structures and scalar dispersion (Shaw and Schumann, 1992; Kanda and Hino, 1994; Patton et al., 2003; Fitzmaurice et al., 2004; Yue et al., 2007; Pan et al., 2014). For example, Krayenhoff et al. (2015) implemented Reynolds-averaged Navier–Stokes (RANS) model to model urban trees in three-dimensional building arrays but LES can capture the turbulent fluxes as shown by the comparison study (Salim et al., 2011) between RANS and LES in the context of urban trees. However, compared to the extensive literature on simulations of flows over either pure building or vegetation canopy, it is of interest and practical importance to model the combined effects, especially when the effect of trees on urban flows is concerned. Furthermore, there is a growing concern in urban sustainability using green infrastructure. Toward this end, this study primarily aims at using a high-resolution numerical model, incorporating the shading and drag of urban trees to quantify their impact on modifying surface heat and momentum fluxes (hereafter referred to as "surface fluxes" for brevity).

The topography of built terrains is represented by a two-dimensional street canyon (Nunez and Oke, 1977), which captures the essential balances of surface fluxes with reasonable accuracy and yet retains the geometric and numerical simplicity (Grimmond et al., 2010). In addition, the proposed method combines the advantage of a urban land surface model (such as a UCM) in representing the surface energy budget (especially radiation in the street canyon and heat conduction through the building envelop) and the LES model in accurate modeling of transport of momentum and temperature over a rough-wall boundary layer. Our main objective in this study is to introduce the current modeling framework (LES-UrbanTree) that was developed for vegetation canopy coexisting with the built terrain. In addition, we aim to investigate how trees modify the surface energy budget as well as the turbulent transport of momentum and temperature from a set of idealized runs with LES-UrbanTree. We also performed different numerical experiments to examine what role the morphology of trees and the street canyons plays in altering the fluxes.

Section 2 describes the details of LES-UrbanTree; Section 3 describes one of the scenarios that we focus on to analyze the differences in processes and mechanisms that are brought about by trees of different physiological parameters; the last section summaries our findings and propose future directions to examine the physical mechanisms more in depth using LES-UrbanTree.

2. Numerical setup

2.1. Modeling the aerodynamic and shading effects of trees in LES

The large-eddy simulations applied to complex canopy have been developed and validated in previous studies (Tseng et al., 2006a; Chester et al., 2007; Li et al., 2016a,b). Here we give details on representing urban trees in the model. Since the pioneer work by Shaw and Schumann (1992), LES as a useful tool have been applied to study the vegetation canopy (Shaw and Schumann, 1992; Kanda and Hino, 1994; Patton et al., 2003; Pan et al., 2014). In the current LES model, the buildings/obstacles are resolved and the urban trees are parameterized. For neutral condition, the filtered momentum and temperature equations (Pan et al., 2014) are given by

$$\frac{\partial u_i}{\partial t} + u_j\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right) = -\frac{1}{\rho_0}\frac{\partial p}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + F_i + B_i + d_i, \quad (1)$$

$$\frac{\partial \theta}{\partial t} + u_i\frac{\partial \theta}{\partial x_i} = -\frac{\partial \pi_i}{\partial x_i} \quad (2)$$

where t denotes time; u_i is the resolved velocity vector; p is the modified pressure; τ_{ij} is the deviatoric part of the subgrid stress tensor; F_i is the body force driving the flow (here simply a homogeneous steady horizontal pressure gradient along the streamwise direction); B_i is the immersed boundary force representing the action of the obstacles (buildings) on the fluid; and d_i is the drag exerted by the trees, θ is the resolved temperature; π_i is the subgrid scale heat flux. Note that θ is treated as a passive scalar here and thus we start with neutral stability as the first step in the model development. The density ρ_0 of air is assumed to be unity without loss of generality. d_i is parameterized using the same approach as in Shaw and Schumann (1992) and Pan et al. (2014):

$$d_i = -C_d P_i a(z)|u|u_i, \quad (3)$$

where C_d is the drag coefficient, $a(z)$ is the leaf area density (m^2/m^3) and P_i is the projection coefficients. C_d is 0.40 in all the simulations considered in this study based on laboratory experiment (Gillies et al., 2002). $a(z)P_i$ gives the effective leaf area density facing the ith direction. For simplicity, we adopted P_i in well-documented maize canopy, where $P_x = P_y = 0.28$ and $P_z = 0.44$ (Wilson, 1988; Bouvet et al., 2007; Pan et al., 2014). We further assumed that the vegetation canopy is horizontally homogeneous such that P_i and $a(z)$ are functions of height (z) only. An empirical relation found by Lalic and Mihailovic (2004) in Eq. (4) for the leaf area density a is implemented here. The model is shown to be applicable for vegetation canopy of a wide range of leaf-area-index (2–20).

$$a(z) = a_m\left(\frac{h - z_m}{h - z}\right)^n \exp\left[n\left(1 - \frac{h - z_m}{h - z}\right)\right], \quad (4)$$

where $n = 6$ for $0 \le z \le z_m$; $n = 1/2$ for $z_m \le z \le h$. $a(z)$ depends on three parameters, which are the tree height h, maximum value of leaf-area density a_m at corresponding height z_m. The physiological characters of different types of vegetation are found to be well described by these three parameters (Law et al., 2001; Lalic and Mihailovic, 2004). Note that Eq. (3) does not represent the unique way to parameterize the drag. Other approaches include (plant-scale models (Yue et al., 2007)) and accounting for reconfiguration of plants (Vogel, 1984) by modifying C_d as function of velocity. As a first step in simulating trees in urban areas, we adopt the widely used approach described above. Note that the parameter C_d depends on the specific kinds of trees, how $a(z)$ is measured and Reynolds number (Gillies et al., 2002). The analytical expression chosen for $a(z)$ is for investigating the impact of tree morphology in subsequent case studies. P_i in the simulations may not represent any particular type of urban trees but it is a physically reasonable value. Thus, for the purpose of presenting the numerical framework, we will proceed with these parameters.

To verify that the current LES code can reproduce results of a horizontally homogeneous vegetation canopy, we first conducted a validation run by comparing to the experimental and LES results in Pan et al. (2014) using exactly the same parameters for modeling F_i. The results of predicted mean velocity and Reynolds stress are shown in Fig. 1. The reasonably good result of comparison gives confidence in the current LES code to model dynamics of the vegetation. In addition to the aerodynamic effect of vegetation canopy, we consider shading of trees in altering the surface energy balance and therefore modifying the boundary condition for temperature on the building walls. For an impervious and dry urban surface (e.g. a pavement or a building surface), a more realistic boundary condition is to consider the energy budget in Fig. 2,

$$\mathrm{Rn} = G + \mathrm{Hs}, \quad (5)$$

where the net radiation Rn is balanced by G, the ground (conductive) surface energy flux and the sensible heat flux, Hs. In reality, the indoor temperature T_b in urban buildings is usually set as invariant by the functioning of heating, ventilation, and air conditioning (HVAC) systems inside buildings. Given the outside air temperature θ, Rn, T_b and