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Research paper

Parametric study of the influence of environmental factors and tree properties on the transpirative cooling effect of trees

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ABSTRACT

Vegetation can provide transpirative cooling in cities and is therefore being increasingly integrated as an essential part of Urban Heat Island (UHI) mitigation strategies. However, the behaviour of vegetation must be accurately understood to determine the effectiveness of vegetation based solutions. In this study, vegetation is modelled as a porous medium in a computational fluid dynamics model for flow of moist air, where a leaf energy balance model is used to determine the heat fluxes. We study the cooling effect of a single row of trees at noon with solar altitude at 90° for various environmental factors (wind speed, air temperature, relative humidity and solar radiation intensity) and tree properties (leaf size, stomatal resistance and leaf area density). Furthermore, the influence of tree height and number of tree rows on the cooling effect are studied. The Universal Thermal Climate Index (UTCI) around the trees is estimated to determine the impact of transpirative cooling on pedestrian thermal comfort. The study shows that, at low wind speeds, pedestrians would only perceive a local benefit of transpirative cooling. However, vegetation extracts overall more heat from the flow at higher wind speeds. A study on the influence of environmental conditions quantifies to which extent a single row of trees provide maximum cooling during hot and dry conditions. The shading provided by trees improves thermal comfort more that transpirative cooling of a single row of trees. Furthermore, taller trees are more beneficial as the vegetation canopy with high leaf temperatures is further away from the pedestrian level.

1. Introduction

Cities are known to experience higher temperatures than the surrounding rural areas (Oke, 1973). This Urban Heat Island (UHI) effect has detrimental effects on human health and comfort in cities (Santamouris and Asimakopoulos, 2001). Furthermore, in the future, the UHI effect will grow due to increasing urbanization, which will lead to a predicted urban population of 5 billion by 2030 and 66% of the world's population living in cities by 2050 (Seto et al., 2012; United Nations, 2015). The temperatures in urban areas will further increase due to the combined effect of climate change with a projected 2–4 °C increase in global average surface temperature by 2100 (Pachauri et al., 2014). Vegetation can provide cooling and is therefore increasingly being considered as part of UHI mitigation strategies to improve the human comfort in cities.

The effectiveness of vegetation as a UHI mitigation strategy has been verified through various field measurements including on-site survey and remote sensing studies. Bowler et al. (2010) provide an extensive review of such empirical studies summarizing the effectiveness of parks, trees, ground vegetation and green roofs on the urban climate. These studies show that vegetation prevents warming of land surfaces and the air through evapotranspiration and shading. For example, parks and trees are shown to provide a cooling on average around 0.5–3 °C to cities (Bowler et al., 2010; Chen and Wong, 2006; Kurn et al., 1994; Ng et al., 2012; Rahman et al., 2017). However, it is also seen that the cooling provided by vegetation is dependent on the local climate, vegetation species and the amount of vegetation. Numerical simulation using urban microclimate models can, therefore, be an important mean to assessing these influences. Furthermore, these studies can be used to develop effective mitigation strategies.

Urban microclimate models employed to predict the effectiveness of vegetation should accurately model the different physical interactions of vegetation and environment. Vegetation exchanges momentum, heat and mass and has thus an impact on the urban microclimate and

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comfort. Trees shelter from wind and modify the turbulence levels at the pedestrian level. They also provide shading below the crown by intercepting the solar radiation. Furthermore, transpiration extracts heat from the airflow due to phase change from liquid water to water vapour. In the literature, heat and mass exchanges of vegetation with the air are modelled using approaches with different levels of complexity. The big-leaf approach treats vegetation canopy as a single unit (Penman and Schofield, 1951; Sellers et al., 1996; Shuttleworth and Wallace, 1985). The dual-leaf model differentiates sunlight and sunshaded leaf surfaces (Dai et al., 2004). The more advanced multi-layer canopy model discretizes vegetation into multiple layers (Dolman, 1993; Krayenhoff et al., 2014; Leuning et al., 1995; Ryder et al., 2014; Wang and Jarvis, 1990). To better describe the heterogeneity of heat and mass exchanges due to the heterogeneity of the foliage, an improved discretization of vegetation is required such as resolving individual leaves (Dauzat et al., 2001) or modelling vegetation as a heterogeneous porous medium inside a computational fluid dynamics (CFD) model (Hiraoka, 2005; Liang et al., 2006; Sanz, 2003; Wilson, 1985). Such models have been used to assess the influence of vegetation in urban areas (Bruse and Fleer, 1998; Gromke et al., 2014; Kenjereš and Ter Kuile, 2013; Robitu et al., 2006) and can be used to determine the effectiveness of vegetation in providing cooling.

Furthermore, to the authors' knowledge, few rigorous studies have been performed to investigate the cooling effect of individual trees. Alexandri and Jones (2008) investigates vegetated surfaces and studies the influence of climate conditions on the cooling potential of green roofs and green walls at various climate conditions. They find that green walls have a stronger cooling effect than green roofs in an urban canyon. Furthermore, the study shows that vegetated surfaces mitigate the UHI regardless of a specific climate. Bruse and Fleer (1998) show that small modifications to urban geometries, such as introducing small parks, can result in a quantifiable improvement of the microclimate. Gromke et al. (2014) use a CFD case study of a recorded heat wave in Arnhem to quantify the impact of vegetation on the UHI. They show that transpirative cooling by avenue-trees provides a cooling effect up to 1.6 °C at pedestrian height and that green facades provide only a cooling of up to 0.3 °C. Hiraoka (2005) investigates the heat and mass exchange of a single tree and evaluates the impact of a few environmental factors such as relative humidity and air temperature. He finds that leaves absorb a substantial amount of short-wave radiation during the evapotranspiration process. In all above studies, the influence of tree properties, the size of the tree, nor the influence of cooling by vegetation on the thermal comfort is studied. There is still a need for better understanding of how these factors directly influence the pedestrian comfort and which parameters play a dominant role. At a smaller scale, CFD parametric studies have been used to investigate the influence of leaf properties on the transpiration from leaf surfaces. Defraeye et al. (2013) and Defraeye et al. (2014) show the importance of stomatal opening on the transpiration rate from the leaf surfaces. These studies demonstrate that CFD can be a useful tool to better understand the influence of various UHI mitigation strategies using vegetation and to quantify the impact of vegetation parameters on the microclimate.

In this paper, a parametric study of the influence of environmental factors and tree properties on the transpirative cooling effect of a single row of trees is presented. The environmental factors investigated are wind speed, relative humidity, air temperature and solar radiation. The tree properties investigated are stomatal resistance, leaf size and leaf area density. In addition, the influence of vegetation size in the domain is studied by varying tree height and number of tree rows. The study aims at answering the following key questions: How does the climate influence the transpirative cooling effect of a single row of trees? Which features of the trees improve its cooling performance? Does increasing the size of the vegetated volume consistently improve the cooling of the environment? These findings can then assist in developing specific guidelines for effective UHI mitigation measures.

The flow of moist air through vegetation is modelled with a computational fluid dynamics (CFD) approach where vegetation is modelled as a porous medium, where the heat and mass exchanges are determined from a leaf energy balance model (Section 2.1). The numerical model is validated against numerical and experimental study of impatiens (jewelweed) plants in a greenhouse (Section 2.3). Thereafter, the model is used to study the transpirative cooling effect of trees in Section 3. The thermal comfort for a pedestrian is assessed using the Universal Thermal Climate Index (UTCI) (Fiala et al., 2001). Furthermore, the transpirative cooling is identified by comparing the UTCI at transpiring (when the leaves can transpire) and non-transpiring (when the leaves do not transpire) conditions.

2. Materials and methods

2.1. Mathematical formulation

A computation fluid dynamics (CFD) model is used to determine the interaction between the environment and vegetation. The mean flow of moist air is modelled using the Reynolds-averaged Navier-Stokes (RANS) equations, where vegetation is modelled as porous media (Section 2.1.1). The source terms for vegetation are described in Section 2.1.2 where the heat and mass fluxes from vegetation are determined from a leaf energy balance model (Section 2.1.2). The radiation model, used to solve the leaf energy balance model, is detailed in Section 2.1.4.

2.1.1. Mean flow through porous vegetation

The mean flow of humid air (i.e. binary mixture of water vapour and dry air) through and around vegetation is modelled using Reynolds-averaged Navier-Stokes (RANS) equations with the realizable k–ε turbulence closure model. Wilson and Shaw (1977) developed a mathematical model for turbulent airflow around tree canopies with closure for mean momentum, turbulent kinetic energy (TKE) and turbulent dissipation rate (TDR). Using this approach, vegetation is modelled as a porous medium, where the impact of vegetation on airflow is modelled using source terms in the conservation equations. The buoyancy force is also taken into account where the Boussinesq approximation is used for air density variations. The equations consist of conservation of mass, momentum, temperature, humidity and the turbulence model, Eqs. (1)–(6), respectively:

$$\nabla\cdot\overline{\boldsymbol{u}} = s_\rho \tag{1}$$

$$\frac{\partial\overline{\boldsymbol{u}}}{\partial t} + \overline{\boldsymbol{u}}\cdot\nabla\overline{\boldsymbol{u}} = -\frac{1}{\rho}\nabla\overline{P} + \nabla\cdot[2(\nu+\nu_t)\mathbf{S}] - \frac{2}{3}\nabla k - \mathbf{g}\beta(\overline{T}-\overline{T}_0) + \frac{1}{\rho}\boldsymbol{s}_u \tag{2}$$

$$\frac{\partial\overline{T}}{\partial t} + \overline{\boldsymbol{u}}\cdot\nabla\overline{T} = \nabla\cdot\left[\left(\frac{\nu}{\mathrm{Pr}} + \frac{\nu_t}{\mathrm{Pr}_t}\right)\nabla\overline{T}\right] + s_T \tag{3}$$

$$\frac{\partial\overline{w}}{\partial t} + \overline{\boldsymbol{u}}\cdot\nabla\overline{w} = \nabla\cdot\left[\left(\frac{\nu}{\sigma_\nu} + \frac{\nu_t}{\sigma_{\nu_t}}\right)\nabla\overline{w}\right] + s_w \tag{4}$$

$$\frac{\partial k}{\partial t} + \overline{\boldsymbol{u}}\cdot\nabla k = \nabla\cdot\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\nabla k\right] + P_k - \varepsilon + \frac{1}{\rho}s_k \tag{5}$$

$$\frac{\partial\varepsilon}{\partial t} + \overline{\boldsymbol{u}}\cdot\nabla\varepsilon = \nabla\cdot\left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right] + C_{1\varepsilon}P_k\frac{\varepsilon}{k} - C_{2\varepsilon}\frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}} + \frac{1}{\rho}s_\varepsilon \tag{6}$$

where $\overline{\boldsymbol{u}}$ [$\mathrm{m\,s^{-1}}$] is the mean velocity vector, $\overline{P}$ [Pa] the mean hydrostatic pressure, $\overline{T}$ [K] the mean air temperature, $\overline{w}$ [$\mathrm{kg\,kg^{-1}}$] the mean humidity ratio (i.e. the ratio of water vapour mass to dry air mass), k [$\mathrm{m^2\,s^{-2}}$] the turbulent kinetic energy (TKE) and ε [$\mathrm{m^2\,s^{-3}}$] the TKE dissipation rate (TDR). In the RANS model, $\nu_t = C_\mu k^2/\varepsilon$ is the turbulent viscosity, $\mathrm{S} = 1/2(\nabla\overline{\boldsymbol{u}} + \nabla\overline{\boldsymbol{u}}^\mathrm{T})$ is the mean strain-rate and $P_k = 2\nu_t\,|\mathrm{S}|^2$ is the TKE production rate. The environmental constants are the density of air $\rho = 1.225\ \mathrm{kg\,m^{-3}}$, the kinematic viscosity of air