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Integrated vegetation model for studying the cooling potential of trees in urban street canyons

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ABSTRACT
Vegetation in cities provides natural cooling of the climate and is therefore increasingly integrated as an essential part of Urban Heat Island (UHI) mitigation strategies. In the present study, the influence of trees on the local climate in a street canyon is studied using an integrated vegetation model in OpenFOAM. Vegetation is modeled as porous medium providing the necessary source terms for the heat, mass and momentum fluxes. Additionally, a radiation model is developed to model the short-wave and long-wave radiative heat flux exchanges between vegetation and the surroundings. The study investigates the influence of transpirative and shaded cooling due to vegetation on the pedestrian comfort inside a street canyon. The study shows that both shading and transpiration have a direct positive influence on the temperatures measured in the street canyon. Moreover, the cooling due to shading is seen to be larger than the transpirative cooling, especially under the tree.

KEYWORDS
CFD, transpirative cooling, shading, vegetation, UHI

INTRODUCTION
Vegetation in urban environments has a natural cooling effect on the urban climate and can mitigate Urban Heat Islands (UHI). The natural cooling is provided through heat extraction during transpiration and through shading from vegetation on the surrounding buildings and the ground below. However, trees can also negatively influence the ventilation characteristics in cities as the foliage obstructs air movement. This effect can further deteriorate the airflow characteristics at the pedestrian level and may reduce pedestrian thermal comfort. Thus, vegetation can have non-trivial impact on the comfort in cities and numerical models are needed to assess the influence of vegetation in cities.

The interaction between vegetation and the environment is a multi-physical phenomenon. Vegetation exchanges momentum, heat and mass with the air and undergoes radiative exchanges. A computational fluid dynamics (CFD) approach (Hiraoka, 2005; Liang et al., 2006; Boulard et al., 2008) can be used to identify the interactions between vegetation and environment, where the vegetation is modeled using a porous medium approach. Such an approach is shown to provide a good estimation of the thermal impact of vegetation and was used to study the influence of vegetation in urban areas (Bruse and Fleer, 1998; Gromke et al., 2014; Robitu et al., 2006). An urban microclimate model that can model the airflow and radiation in an integrated approach provides the means to accurately assess the environmental impact of vegetation for a given complex urban topology.

In the present study, the influence of vegetation, namely trees, on the microclimate of a street canyon is studied using a CFD model in OpenFOAM. Vegetation is modeled as a porous medium, providing the source/sink terms for heat, mass and momentum fluxes. A radiation model is developed to model the short-wave and long-wave radiative heat fluxes between the leaf surfaces and the surrounding environment. The radiation model enables to model the impact of the diurnal variations of solar intensity and direction, and the long-wave radiative fluxes between vegetation and nearby urban surfaces. Using the developed model, we investigate the cooling potential of vegetation on the microclimate of a street canyon exposed to a moderate wind in June. The influence of transpirative cooling and shading due to vegetation on pedestrian thermal comfort inside a street canyon is studied. The thermal comfort for pedestrians is evaluated using the Universal Thermal Climate Index (UTCI) (Fiala et al., 2001).

MATERIALS AND METHODS

Numerical method

The mean flow field in the street canyon with vegetation is modeled using the Reynolds-Averaged Navier-Stokes (RANS) equations,

$$\frac{\partial \rho \bar{u}_j}{\partial x_j} = 0, \tag{1}$$

$$\frac{\partial \rho \bar{u}_i \bar{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left[-\tilde{p}\delta_{ij} + \mu_{eff}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} - \frac{2}{3}\frac{\partial \bar{u}_k}{\partial x_k}\delta_{ij}\right)\right] + \rho g_i + s_{u_i}, \tag{2}$$

$$\frac{\partial \rho \bar{e}\, \bar{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(k_{eff}\frac{\partial \bar{T}}{\partial x_j}\right) + s_h, \tag{3}$$

$$\frac{\partial \rho k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\rho D_k \frac{\partial k}{\partial x_j}\right) + \rho G - \frac{2}{3}\rho\frac{\partial \bar{u}_k}{\partial x_k}k - \rho\varepsilon + s_k, \tag{4}$$

$$\frac{\partial \rho \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\rho D_\varepsilon \frac{\partial \varepsilon}{\partial x_j}\right) + C_{1,\varepsilon}\left|S_{ij}\right|\varepsilon - C_{2,\varepsilon}\rho\frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} + s_\varepsilon, \tag{5}$$

$$\frac{\partial \bar{w}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(D_{eff}\frac{\partial \bar{w}}{\partial x_j}\right) + s_w, \tag{6}$$

where $s_{u_i}, s_h, s_k, s_\varepsilon, s_w$ are the source terms of vegetation for momentum, energy, turbulent kinetic energy (TKE), TKE dissipation rate and humidity ratio (Manickathan et al., 2018a). The Reynolds stresses are closed using Boussinesq eddy-viscosity hypothesis where the eddy-viscosity is determined from the realizable $k - \varepsilon$ model. The air domain is coupled with the ground and building facades to model the transport of heat and moisture therein, to take in account of dynamics of the thermal and hygric storage in the street canyon (Kubilay et al. 2017).

Simulation setup

The simulations are performed for a street canyon with a vegetation zone of $2 \times 10 \times 4$ m^3, representing a row of trees which are surrounded by two buildings of $10 \times 50 \times 10$ m^3 ($x \times y \times z$), as shown in Figure 1. This vegetation zone has a foliage height of 4 m (with $z_{min} =$ 4 m), leaf area density $LAD =$ 10 m^2 m^{-3}, leaf drag coefficient $c_d = 0.2$ and leaf size $l = 0.1$ m. The meteorological data are based on a typical meteorological year and the total solar radiation intensity is for a clear sky on the 21st of June in the city of Zurich, Switzerland (Kubilay et al. 2017). The wind speed at the building height is $U_{ref} = 5$ m s^{-1}, the ambient temperature varies between 11°C and 19 °C with solar noon at 13:28 and the relative humidity varies between 62% and 86% RH. These are the boundary conditions applied at the inlet. A slip, symmetry and pressure outlet boundary conditions are applied at the top wall, side walls, and at the outlet, respectively. The ground outside the street canyon is defined to be adiabatic. Whereas, the wall temperatures inside the street-canyon is determined from the heat and moisture transport equations.

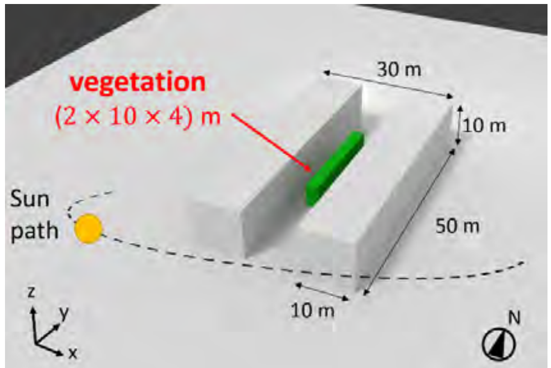
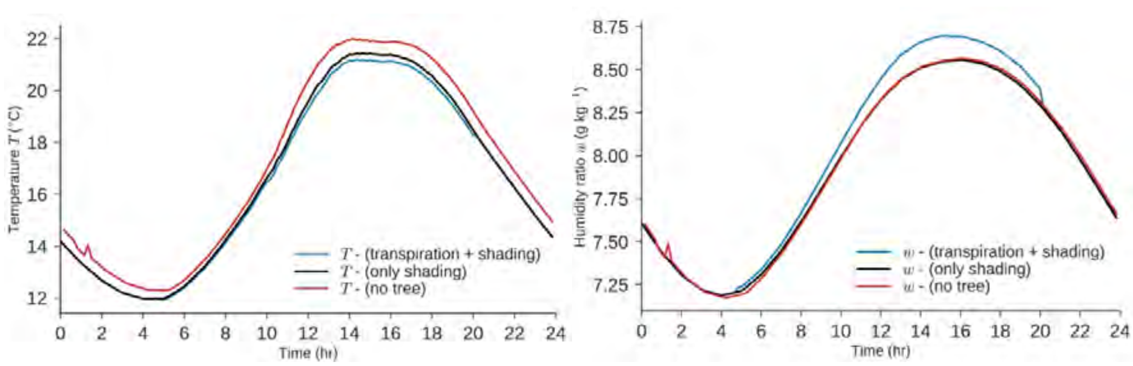


Figure 1. Simulation setup of a street canyon composed of two buildings with a vegetation band in the middle, representing a row of trees (Manickathan et al. 2018b).

RESULTS AND DISCUSSION

The cooling potential of trees in the street canyon is quantified by studying the diurnal variations of air temperature and humidity for three distinctly different configurations: street canyon without tree, street canyon with trees but only providing shading and, finally, street canyon with trees providing both transpirative cooling and cooling due to shading. The configuration of trees that only provide shading in the street canyon is achieved by artificially closing the stomata in the model. Figure 2 shows the diurnal variation of air temperature and humidity ratio below the tree at $z = 2$ m (point at the middle of the street canyon) for these three configurations. The figure shows that, without the trees, the air temperature is quantifiably higher throughout both day and night. However, once the trees are present, both shading and transpiration provide cooling in the street canyon, with an average decrease of 0.5°C in presence of shading and of an additional 0.2°C, when transpiration is added to shading. The cooling due to shading is seen to be higher than the cooling provided from transpiration. The study on the diurnal variation of humidity ratio inside the street canyon, Figure 2b, shows that the humidity in the street canyon is increased when the trees transpire. This could potentially negatively affect the pedestrian comfort below the tree.



a) Air temperature T (°C) b) humidity ratio w (g kg^{-1})

Figure 2. Diurnal variation of a) air temperature T (°C) b) humidity ratio w (g kg^{-1}) below the tree at ($z = 2$ m) for three configurations: no tree, with shading and with transpiration and shading.

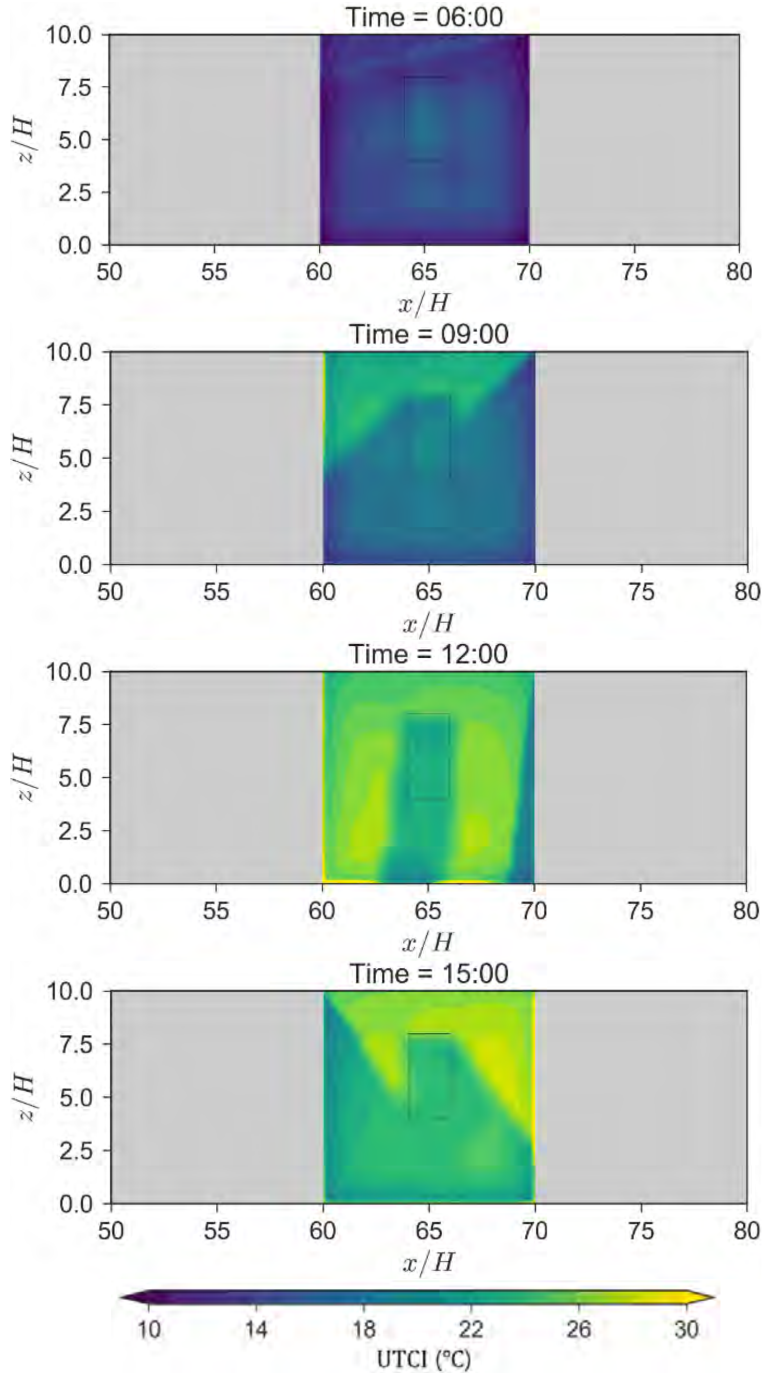


Figure 3. Spatial distribution of the universal thermal climate index (UTCI) (°C) at the vertical centre-plane of the street canyon with vegetation at 06:00, 09:00, 12:00 and 15:00 local time. The buildings are indicated by the grey zones and the vegetation inside the street canyon is indicated by the outlined rectangle.

The universal thermal climate index (UTCI) is employed to study the influence of vegetation on pedestrian comfort inside the street canyon. Figure 3 shows UTCI distribution at the vertical centre-plane of the street canyon at four distinct local times: 06:00, 09:00, 12:00 and 15:00. It is apparent that the pedestrian comfort is significantly compromised due to the exposure to solar radiation at noon. However, inside the shaded zone of the trees, the thermal comfort is substantially improved, as indicated by the reduced UTCI values. In contrast, the impact of humidity generated from the trees is not discernible in the UTCI distribution. This means the transpiration of the trees does not negatively affect pedestrian comfort in the case studied, although an increase in relative humidity could reduce the thermal comfort.

CONCLUSIONS

The integrated model is used to study the influence of transpirative cooling and cooling due to shading of trees inside a street canyon. From this case study, both transpirative cooling and cooling through shading are seen to reduce the temperatures. Furthermore, the transpiration from the vegetation is seen to increase the humidity inside the street canyon. Although, this additional humidity is seen not to have a significant impact on pedestrian comfort, measured through universal thermal climate index (UTCI), as the comfort provided by the tree shading is substantially higher and counters the negative impacts of increased humidity. However, factors such as leaf area density (LAD), vegetation position, vegetation size, ambient conditions, etc. can have an influence on the outcome. Therefore, the influence of these parameters should be investigated to accurately estimate the impact of the vegetation in urban area.

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