Improving the representation of convective heat transfer in an urban canopy model

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ABSTRACT
The urban street canyon has been widely recognized as a basic surface unit in urban micrometeorological studies. Urban canopy models (UCMs), which quantify the exchange of energy and momentum between the urban surface and the overlying atmosphere, often adopt this type of street canyon representation as the fundamental surface element. Since UCMs can be coupled to regional-scale weather and climate models such as the Weather Forecast and Research Model (WRF), parametrizations of the surface momentum and scalar fluxes in UCM are of paramount importance. However, many current single-layer UCMs rely on empirical relations that were obtained over 80 years ago and often invoke the exponential wind profile derived from the existing literature for vegetation canopy. In this study, we conducted wall-modeled large-eddy simulations (LES) to study the forced (very weak buoyancy) convective heat transfer over idealized two-dimensional street canyons. It shows that the transfer efficiency computed following commonly applied resistance formulations can be one order of magnitude lower than LES results. The main reasons for the deviation include inaccurate wind speed parameterization and the use of a log-law based formulation for turbulent heat exchange between canyon air and the flow above.

KEYWORDS
Large-eddy simulation, convective heat transfer, urban canopy model

INTRODUCTION
Buildings do not exist as isolated objects. Their energy consumptions are subject to their external environment and especially the climatic factors such as wind speed, temperature and moisture (Li and Sailor, 1995). To represent this impact of urban climate on building performance, various building energy models have been implemented into urban canopy models (UCMs) (Kikegawa et al. 2003; Salamanca et al. 2010; Bueno et al. 2011). A UCM is one type of urban land-surface model that accounts for the surface heat balance using the street canyon as the prototypical element for the surface. Different UCMs of different degrees of complexity exist in the literature, e.g. (Masson, 2000; Ryu et al. 2011; Wang et al. 2013). Buildings exchange energy with the surrounding environment via conductive, radiative, and convective heat transfer processes. While the two former processes are captured relatively well by current UCMs, convective transfer poses significant challenges.
Nevertheless, accurate modelling of convective heat transfer is essential for building energy simulation (Mirsadeghi et al. 2013). For example, as summarized by Palyvos (2008), the wall convective heat transfer coefficient (CHTC), often denoted by h, could lead to errors in energy demand calculation of 20-40% if set improperly. The convective heat transfer due to turbulent air motions around the building envelopes has been parameterized in UCMs using empirical relations derived in the 1920s, such as the so-called Jürges formula (Rowley et al.

1930). One way to obtain better estimates of h is to use computational fluid dynamics (CFD) modelling to calculate the rate of convective heat transfer, with the CFD model coupled to the building energy model (Zhai et al. 2002; Zhai and Chen, 2004; Defraeye et al. 2010). However, this is not feasible for more than a few buildings and thus not applicable directly in a UCM. However, CFD results could be used to develop reduced parametrizations of convective heat transfer in UCMs, which have not been analyzed in detail. Therefore, this study conducts large-eddy simulations (LES) to assess the current formulation of convective heat transfer, as well as to propose possible reasons for its success or failure.

METHODS

LES is one type of computational fluid dynamics models, in which the large-scale fluid motions are explicitly resolved and appropriate subgrid-scale models are implemented for turbulence closure. We use a research code, which shares many commonalities with the open-source code LESGO (https://github.com/lesgo-jhu/lesgo). Details of the current LES code, validations of the turbulent quantities and convective heat transfer coefficients for two-dimensional roughness elements can be found in previous studies (Bou-Zeid et al. 2005; Chester et al. 2007; Li et al. 2016a,b). A surface of two-dimensional street canyons of various height-to-width aspect ratios H/W are considered in this study. The boundary conditions are horizontally periodic and free-slip for velocity at the top of the domain (Figure 1a). The net radiation on all surfaces (i.e., roof, wall, and road) is kept at 800 W/m^{-2}, and the wall-model is coupled to a conduction model with a constant indoor temperature at 25 ºC, similar to the setup in Li and Wang (2017). 16 points are used to represent the obstacle height H at 12.5 m. The total number of points in each direction is shown in Fig. 1a and grid resolution is the same in all three directions.

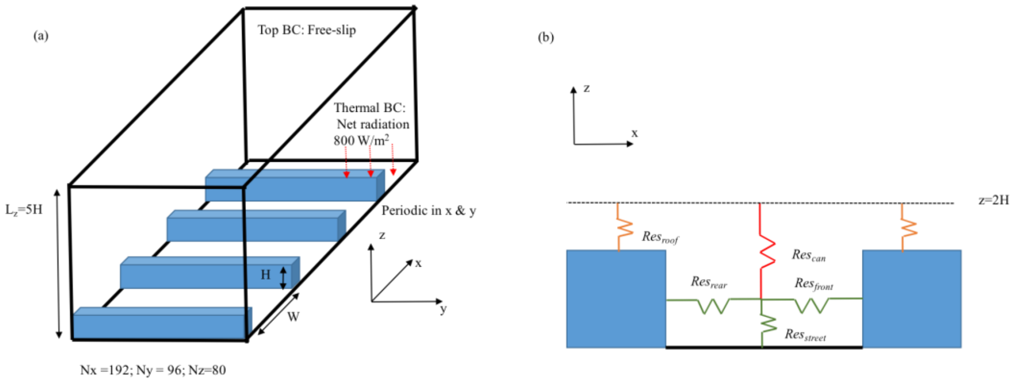

Figure 1. Sketch showing domain setup of LES in (a) for H/W=1/2 and (b) schematic diagram of resistance, the dotted line denotes the 'reference height' at $z=2H$, which is not shown to scale.

RESULTS

The exchange of energy between building facets with canyon air and canyon air with the flow above is often conceptualized as a resistance network (Fig. 1b), such as in previous UCMs and those coupled with EnergyPlus (Bueno et al. 2011). Resistance is related to h by $R = (h/\rho Cp)^{-1}$, where ρCp is the volumetric heat capacity. Since h is the heat flux divided by the wall-fluid temperature difference, the normalized canyon resistance is computed as

$$R_{can} = \frac{\langle T_{can} - T(z=2H) \rangle}{\langle Q_H \rangle / \rho Cp}, \tag{1}$$

where $\langle\ \rangle$ denotes averaging over the canyon width for all canyons in the computational domain; T_{can} is the air temperature averaged over the entire canyon; $T(z=2H)$ denotes air temperature at $z=2H$; Q_H is the sensible heat flux from the resolved and subgrid-scale contributions. Values of the canyon resistance span almost two orders of magnitude for the five different cases of canyon aspect ratios considered in this study (Fig. 2).

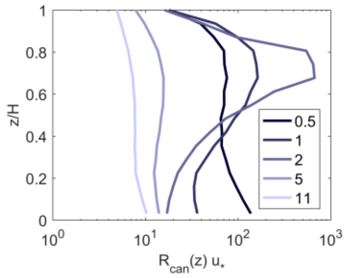

Figure 2. The canyon resistance R_{can} normalized by u_*, the friction velocity, for different values of W/H indicated by the legend.

Figure 3 shows the height averaged canyons resistance, $\langle Res_{can}\rangle_z$ plotted as a function of the difference between U_a, the horizontally averaged mean streamwise velocity at $z=2H$, and U_{can}, which is defined as the average magnitude of the vector sum of the horizontal and vertical components of velocity averaged over all non-solid grids for $z \leqslant H$ (Fig. 3a). All velocities in subsequent analyses are normalized by u_*. The square symbols denote modelled values based on the log-law and constant momentum and heat roughness lengths (e.g. Masson 2000). $\langle Res_{can}\rangle_z$ is also plotted as a function of the streamwise velocity averaged over the canyon space, $\langle U \rangle_z$, in Fig. 3b.

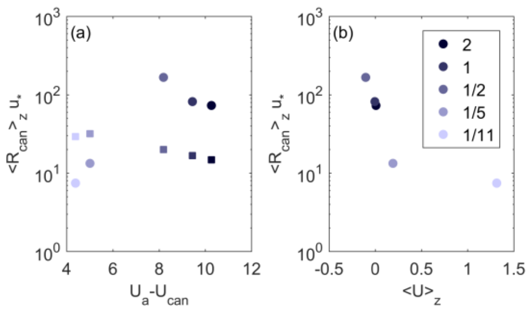

Figure 3. The averaged canyons resistance plotted as a function of $U_{can}{}^2$ in (a) and $\langle U \rangle$ in (b). Square: model in (Masson 2000), where $Res_{can} \sim log(z/z_{0m})log(z/z_{0h})/ (U_a - U_{can})$; circles are LES results.

The wall resistance R_{facet} is computed as the average over the facet of

$$R_{facet} = \frac{T_{facet} - T_{canyon}}{\langle Q_{H\,wall}\rangle / \rho Cp} \ (rear,\ street\ and\ front\ facets),\ R_{roof} = \frac{T_{roof} - T(z=2H)}{\langle Q_{H\,wall}\rangle / \rho Cp} \quad , \qquad (2)$$

where T_{air} is the air temperature at the closest grid to the wall surface; T_{canyon} is the air temperature averaged over the canyon space (for all rear, front and street facets) or T_{air} at $z=2H$; $\langle Q_{Hwall}\rangle$ is the facet-averaged sensible heat flux computed from the wall model in LES. Figure 4 shows the spatial variability of $u_*(h/\rho Cp)^{-1}$ for different facets of the two-dimensional obstacles, where h is the CHTC computed from the LES wall-model averaged over y. Cases with $H/W = 2$ and 1 have similar roof resistances (Fig 4a), but a wider street canyon, especially W/H =5, has approximately 25% higher resistances than those in H/W=2,1 and 1/2. It is also interesting to note that the rear surface resistance is higher for smaller aspect ratio (i.e. H/W<1/2), which could lead to overall smaller average wall resistance as demonstrated in Figure 5. The wall resistance averaged over different facets as a function

$U_{can}{}^2$ and comparisons to some of the convective heat transfer formulations defined as $\rho Cp(11.8{+}4.2Ucan^2)^{-1}$ (Rowley et al. 1930) in UCMs are plotted in Fig. 5.

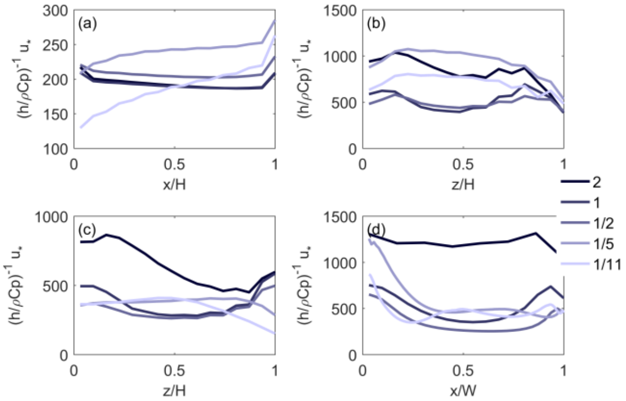

Figure 4. The wall resistance normalized by u_* for different facets of the street canyon for *W/H* indicated by the legend. a) roof, b) rear surface, c) front surface, d) ground.

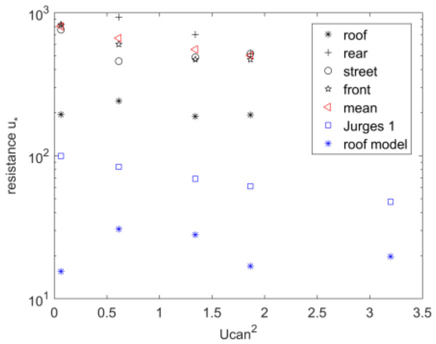

Figure 5. Res_{facet} averaged over different facets as a function of $U_{can}{}^2$. The mean of Res_{facet} is the average over rear, ground and front surfaces. From low to high $U_{can}{}^2$ corresponds to H/W = 2, 1/5, 1/11, 1 and 1/2 respectively.

DISCUSSION

The spatial variation of canyon resistance demonstrates some commonalities for canyons of different aspect ratios. The most pronounced peak in Res_{can} is observed for *H/W* =1/2 at around *z/H* = 0.6 - 0.8 in Fig 2. Although other cases also show similar peaks, the pronounced peak is associated with street canyons that are categorized as 'wake interference' flow regime (Oke 1987), where the recirculation regions behind the two-dimensional obstacles impinge on the obstacle downstream. For regions *z/H* < 0.5, R_{can} decreases with aspect ratio as shown in Fig. 2. Street canyons with *H/W <1/2* have a smaller resistance, leading to higher turbulent heat fluxes given a constant temperature difference between the canyon air temperature and surface temperature. However, the canyon averaged R_{can} as shown in Fig. 3 is predominantly affected by the maximum values of R_{can}. The recirculation region, where the mean streamwise velocity becomes negative, is evident for *H/W* > 1/2. The case of *H/W* = 1/2 features the most negative canyon averaged streamwise velocity and the highest $\langle R_{can}\rangle_z$, which is the R_{can} averaged over the entire street canyon. $\langle R_{can}\rangle_z$ decreases monotonically with the canyon averaged wind speed. Notice that the simulations only consider the canyon axis perpendicular to the streamwise direction, which facilitates the formation of strong recirculation bubble. The ubiquitously adopted exponential wind profile for the canopy layer in UCMs (Masson 2006; Ryu et al. 2011; Wang et al. 2013) are usually considered as an average over all wind directions. Future studies of variable wind directions can be included in LES and investigate how the canyon wind speed can be used as the key dependent variable for parameterization of the canyon resistance.

The canyon wall resistance is important to quantify the turbulent heat transfer between individual facet and the canyon air for the rear, front and ground faces in particular. The Jürges formula (Rowley et al. 1930) applied with the canyon wind speed computed from LES (Jürges 2) has almost one order of magnitude difference compared to the LES results, although the decreasing trend with higher U_{can} is consistent. Results using the parameterized canyon wind speed according to Masson (2000) (not shown here) show over prediction of the canyon wind speed. This demonstrates that the importance of improving the accuracy of the canyon wind speed when the Jürges formulation is invoked, such as using a CFD model to parameterize U_{can} for different wind directions as propose by Ryu et al. (2011). The empirical Jürges formula in the form of $(a+bU_{can}^2)^{-1}$, where a and b are both tuneable parameters, could still be a valid formulation.

On the other hand, the roof resistance in Fig. 4 shows both inconsistent trend and large bias in magnitude compared to the formulation based on the log-law wind profile over a rough surface. Alternative parameterization of the roof resistance assuming the flow is a free shear layer (Harman et al. 2004) gives rise to $R_{roof}=(U_{ref}-U_{roof})/u_*^2$. We also tested plotting R_{roof} as a function of $\Delta U=U(z=2H)-U_{roof}$, where U_{roof} is taken as the velocity at $z=1.06H$ averaged over points directly above the roof surfaces (not shown here). A monotonic change in R_{roof} with ΔU suggests that the free shear layer could be a more appropriate conceptual model to parameterize the roof resistance, instead of using the parameterization based on log-law, which assumes that the boundary layer is in equilibrium with the roof surface. More investigations of how the free shear layer impacts the roof resistance will be carried out.

CONCLUSIONS

We applied the LES model to study the convective heat transfer coefficient for idealized two-dimensional street canyons of different aspect ratios. The canyon and surface resistance were computed and compared with the Jürges formula (for rear, front and ground surfaces) and log-law based formulation (for canyon and roof surface). It was found that the current formulation, on average, predicts resistances one order of magnitude smaller than results from LES. Although the Jürges formula appears capable of capturing the trend of surface resistance as a function of the canyon wind speed, it is essential to obtain more accurate estimates of the canyon wind speed. Canyon wind speed computed from the exponential relation has been shown by Castro (2017) to be inappropriate for roughness canopy and alternative wind speed parameterizations need to be formulated for better representation of forced convective heat transfer. Our preliminary results also show that the canyon and roof resistances could be improved by considering a free shear surface and using the difference in mean velocity as the dependent variable. Future work includes simulations of multiple wind directions, expanding the range of canyon aspect ratio and testing the resistance parameterizations in UCMs.

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