A multi-layer urban canopy model for neighbourhoods with trees

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1. Introduction

Process-based numerical models of urban canopy meteorology and climate – urban canopy models, or UCMs – have been designed in recent years to predict the time-averaged effects of canopy micrometeorology and to be coupled with mesoscale atmospheric models. Some UCMs include latent heat fluxes and basic urban hydrology (e.g., Masson, 2000), but very few integrate the effects of urban vegetation.

Urban canopy models can be broadly divided into single-layer (e.g., Masson, 2000) and multi-layer (e.g. Martilli et al. 2002) models. Single-layer models have only one atmospheric layer in the urban canopy, i.e., between the buildings. Multi-layer models compute meteorological variables for several vertical layers within the canopy which allows for reduced empiricism in the canopy physics, inclusion of building (and tree foliage) height distributions, and more detailed prediction of street level climate and dispersion; however, multi-layer models are more computationally-demanding.

According to Chen et al. (2012), a primary challenge in numerical modeling of the urban climate and energy balance is the representation of vegetation-related processes in urban canopy models, instead of including them using a ‘tile’ scheme such that they may interact only indirectly, via an atmospheric model. With a tile approach, vegetation-building interactions are not included (Fig. 1). In essence, the direct interactions between vegetation and the ‘built’ fabric (e.g., buildings, streets) in cities must be better understood and modeled. These interactions are more complex, and are expected to be more significant, for trees than for shorter vegetation.

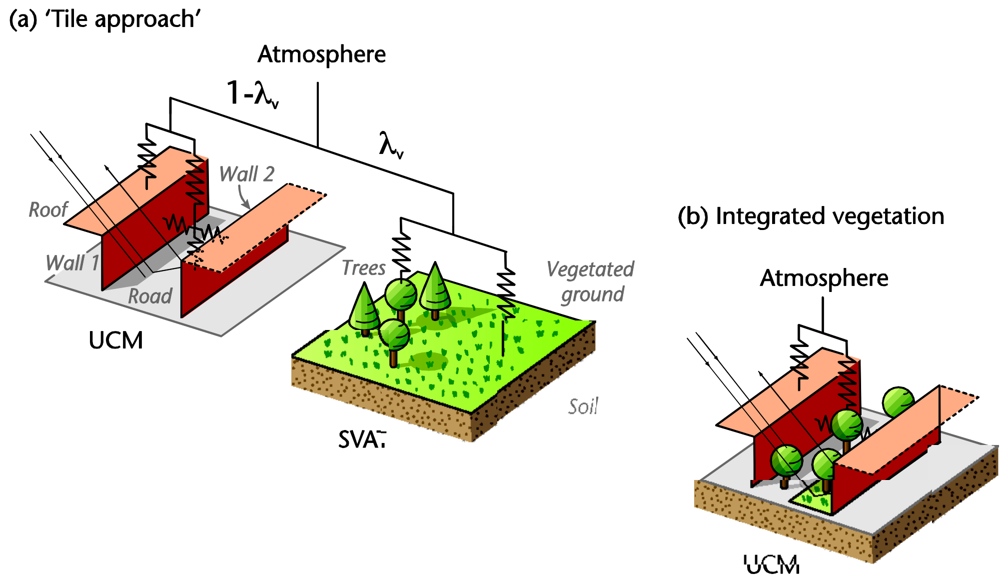

Figure 0 Indirect interaction (via the atmospheric model) with the tile approach (a) as compared to direct built-vegetation interaction with integrated urban vegetation modeling (b). UCM = Urban Climate Model. SVAT = Soil-Vegetation-Atmosphere Transfer scheme.

Vegetation is common in cities worldwide, and its inclusion in models is critical for proper simulation of the neighbourhood-scale energy balance (Grimmond et al. 2011), street-level climate (Shashua-Bar and Hoffman, 2000), and air pollutant dispersion (Vos et al. 2013). More broadly, it is an important design tool in urban environmental management (Oke, 1989). Trees in particular also offer shade and shelter to pedestrians and buildings, and modify near-surface turbulent and radiative exchanges. Furthermore, they increase deposition of pollutants and affect pollutant dispersion by reducing exchange between the canopy and above-canopy.

To date, two process-based UCMs have integrated explicit building-vegetation interaction. Lemonsu et al. (2012) integrate low vegetation into a multi-layer version of the Town Energy Balance model, incorporating building-vegetation radiative interaction. An urban canyon model developed by Lee and Park (2008) also includes the effects of trees; however, it is a highly-parameterized single-layer model that permits tree foliage only in the canyon space. Dupont et al. (2004) include flow effects of both buildings and trees; however, trees and buildings do not interact radiatively in a rigorous fashion.

In the present model the radiative and dynamic model developments of Krayenhoff et al. (2014, 2015) are combined with a multi-layer urban canopy model to assess their functionality in a full simulation of neighbourhood-scale flow and exchange of heat and humidity. The combined model, called BEP-Tree, is the first multi-layer model of urban energy exchange and flow at the neighbourhood scale that includes trees and their dynamic and radiative effects on buildings.

2. BEP-Tree model design

Radiative and dynamic developments for the inclusion of urban tree foliage, presented in Krayenhoff et al. (2014) and Krayenhoff et al. (2015), respectively, are designed to integrate with most urban canopy models. They are particularly suited to multi-layer models, and the radiation model is built around the urban canyon concept. Here, these model developments are combined with the latest version of the Building Effect Parameterization (BEP), originally created by Martilli et al. (2002). BEP is a multi-layer, neighbourhood-scale, urban meteorological and dispersion model also based on the urban canyon. It has also been combined with a column model of vertical turbulent exchange in the urban atmosphere (Santiago and Martilli, 2010) that is updated here to include conservation equations for heat and humidity, and buoyant production of turbulent kinetic energy. Thermal effects on turbulent length scales, a shortwave radiation scheme that determines the diffuse fraction, and tree foliage energy balance and temperature, including leaf sensible and latent heat fluxes, are also added.

Figure 1 View from Sunset tower toward the southwest, July 23, 2008. Note that lawns are mostly dry and trees are green.

2.1 Column model for non-neutral urban surface layer

A one-dimensional column model with *k-l* turbulence closure for neutral atmospheric flow (Santiago and Martilli, 2010) forms the dynamical basis for the complete urban canopy model with trees. Equations for vertical turbulent transport of horizontal-mean, Reynolds-averaged velocity and turbulent kinetic energy are solved. Turbulent fluxes are determined with the eddy viscosity approach. Source and sink terms representing drag and turbulence for urban canopies with trees, as distinguished in Krayenhoff et al. (2015), are included, as are terms for skin drag due to roads and roofs from Martilli et al. (2002).

Length scales for calculation of dissipation and turbulent viscosity are affected by stability. This effect is observed in recent CFD simulations for arrays of cubes with ‘realistic’ distributions of sensible heat flux imposed for several times throughout the day (Santiago et al. 2014). From this CFD data, modification of length scales for neutral conditions due to thermal effects has been determined (Krayenhoff, 2015).

Equations for vertical turbulent transport of spatial- and ensemble-average potential temperature, specific humidity and a passive tracer are solved in addition to those for velocity and turbulent kinetic energy. The conservation equations of temperature, humidity and passive tracers are composed of the storage term, the vertical diffusion term, and the source/sink terms from relevant model elements: roofs, roads, walls (left and right sides of canyon), tree foliage. All elements contribute to sensible heat exchange, whereas only tree foliage elements are sources of moisture (Krayenhoff, 2015).

2.2 Temperature and water vapour source terms: built surfaces, tree foliage

Sensible heat fluxes from roofs and roads are determined by Monin-Obukhov Similarity Theory, whereas sensible heat flux from walls follows a stability-independent bulk transfer formulation that depends on wind speed (see Martilli et al. 2002, Eqs. 15 and 16).

Sources of heat and moisture from tree foliage are computed following Campbell and Norman (1998), where sensible heat flux occurs at both sides of the leaves. Tree leaves are assumed hypostomatous. All leaves are assumed to contribute equally to turbulent heat exchange, despite the fact that some are more radiatively active than others (i.e., those at the interior of foliage clumps).

2.3 Foliage and built surface energy balances and surface temperatures

The surface energy balance of each roof and wall layer, and of the roads, is identical to Martilli et al. (2002), and does not include latent heat flux. Shortwave and longwave exchange computed by the radiation scheme (Krayenhoff et al. 2014) drives the energy balance at each surface: roofs, walls, ground/road, tree foliage/leaves. For impervious surfaces, the conduction heat flux is determined by Fourier diffusion (Martilli et al., 2002; their Eq. A1), and sensible heat flux is determined as discussed in Sect. 2.2. Storage by leaves is neglected, and sensible and latent heat are calculated based on Campbell and Norman (1998). A linearized, approximate form of the leaf energy balance equation (Campbell and Norman, 1998; their Eq. 14.6) is rearranged to solve for foliage temperature at each timestep and in each layer.

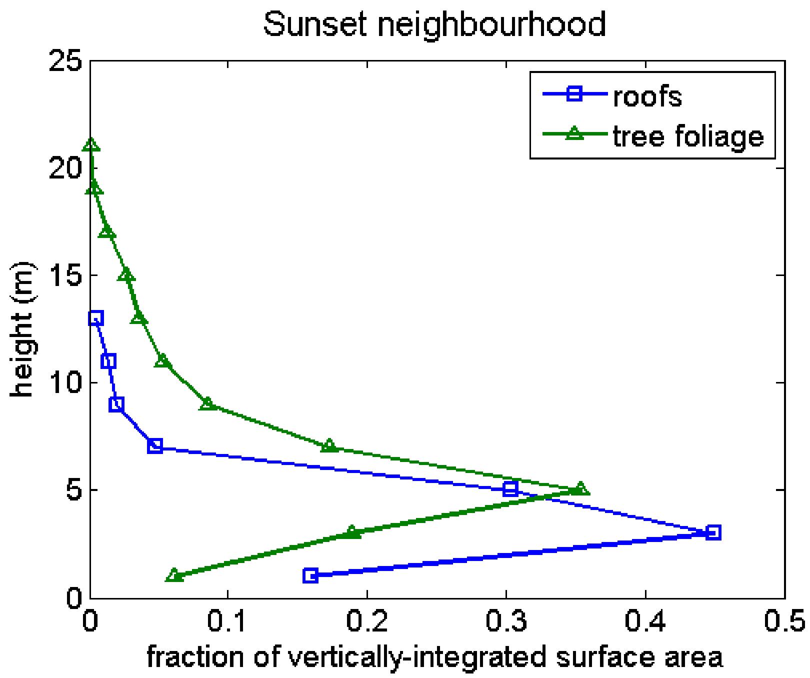

Figure 1 Profiles of fractional building (i.e., roof) area and foliage (leaf) area as a function of height within 500 m of the Vancouver Sunset tower, as determined by LiDAR. Data pre-processed by Drs. R. Tooke and N. Coops (UBC) and by van der Laan et al. (2012).

3. Model evaluation: Sunset neighbourhood

Measurements on a 28.8 m tower (49.2261 °N, 123.0784 °W, WGS-84; Fluxnet Site Code: “Ca-VSu”; Christen et al. 2011, Crawford and Christen, 2014) in the Sunset neighbourhood of Vancouver, BC, Canada, during the measurement campaign of the Environmental Prediction in Canadian Cities Network (EPiCC) are used to evaluate the model. Sunset is a residential neighbourhood with north-south and east-west gridded streets, and it is classified as ‘Open Low-rise’ in the Local Climate Zone scheme of Stewart and Oke (2012). It is chosen because it has a significant leaf area index (*LAI* = 0.39 $m^2 m^{-2}$; Liss et al. 2010), about half of which is located above the mean building height ($H \approx 5$ m) – hence, trees are expected to be impactful. Moreover, LiDAR mapping of the area has generated detailed information about the vertical distributions of built volume (van der Laan et al. 2011) and tree foliage (R. Tooke, personal communication).

3.1 Simulation development

July 19-21, 2008, a period with high solar insolation and hot, dry conditions—so dry that the grass contributes negligible evaporative heat flux—is chosen as the test simulation (Fig. 2). The first 24 hours is a model spinup period, and the subsequent 24 hours is used for model-observation comparison. There had not been any rain for more than two full days, and the duration of the period of simulation is characterized by fair weather. Simulations begin at 0400 Local Solar Time (LST) on July 19, just prior to sunrise, and finish at 0500 LST July 21, just after sunrise.

The plan area fractions of land cover in the Sunset neighbourhood comprise 29% buildings, 34% vegetation, and 37% impervious within a 500 m radius from the micrometeorological tower (Liss et al. 2010). About 12% of plan area of vegetation is tree crowns, and a further 22% is low vegetation, e.g. grass. Total leaf area index (*LAI*) for leaf-on conditions was determined to be 0.39 m^2 m^{-2}. Profiles of leaf area density and building (i.e., roof) fraction (van der Laan et al. 2012) for input to the model are determined based on LiDAR, and plotted in Fig. 3. To account for the clustered distribution of tree crowns, foliage clumping is estimated at 0.34 (Krayenhoff, 2015).

Building geometric and material properties are derived from several sources, including van der Laan et al. (2012), the Open Lowrise Local Climate Zone by Stewart et al. (2014), and a detailed analysis of a similar Open Lowrise neighbourhood by Krayenhoff and Voogt (2010). North-south and east-west canyons are simulated, and their interactions with the canopy atmosphere are equally-weighted.

Broadband shortwave is calculated for simplicity, instead of splitting into PAR and NIR bands, because no model for stomatal conductance is included. The model timestep is 60 s, and the direct solar ray tracing scheme is run every 5 minutes. All forcing and evaluation data are converted to Local Solar Time.

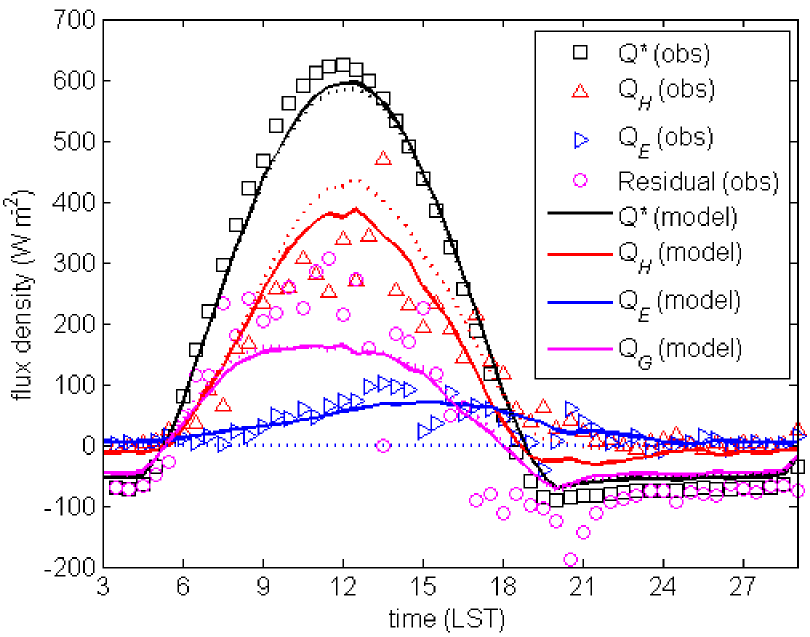

Figure 4 Observed and modeled energy balance at Vancouver Sunset tower, 0300 July 20 – 0500 July 21, 2008. Dotted lines are from the corresponding simulation without trees.

3.2 Model-observation comparison

Reported model results are based on the best *a priori* estimate of the physics (processes) and associated parameters required. There are two exceptions: turbulent Prandtl number *Pr* is reduced to 0.25 to vent sufficient heat from the canopy (Krayenhoff, 2015); and low vegetation (grass) is not included in the model.

Measurements at the top of Sunset tower available for model comparison include: turbulent fluxes of heat, humidity and momentum, upward fluxes of longwave and shortwave radiation, wind speed and direction, and air temperature and specific humidity. Unfortunately there are few measurements in the urban canopy.

Model-observation agreement in terms of overall energy exchange between the urban surface and the atmosphere is remarkably good, considering all parameters are decided *a priori* (Fig. 4, Table 1). Modeled sensible heat flux (Q_H) is too large at midday and too negative at night, by an average of 41.6 W m^{-2} (Table 1). Daytime results improve with addition of trees (Fig. 4). Total conduction heat flux (Q_G) for all built facets appears to follow the residual of the observed energy balance (Fig. 4), yet the residual may not be a reliable estimate of Q_G. Net radiation (Q^*) is generally well-reproduced by the model, and addition of trees to the model improves daytime results (Fig. 4).

Variable	Units	MAE	MBE	RMSE
Q^*	W m^{-2}	23.6 (-8%)	3.0	26.4 (-9%)
Q_H	W m^{-2}	41.6 (-3%)	-3.0	53.0 (-14%)
Q_E	W m^{-2}	15.1 (-53%)	2.3	21.5 (-51%)
Q_G	W m^{-2}	58.7 (+4%)	3.9	70.5 (+2%)
K↑	W m^{-2}	3.3 (-9%)	-1.0	4.7 (-10%)
L↑	W m^{-2}	16.3 (-22%)	-4.1	17.6 (-23%)

*Table 1 Mean Absolute Error (MAE), Mean Bias Error (MBE) and Root Mean Square Error (RMSE) of several variables measured and modeled half-hourly at Vancouver Sunset for 0430 LST July 20 – 0400 LST July 21, 2008 (*n *= 48).Percentage change in MAE and RMSE from simulation without trees is in brackets.*

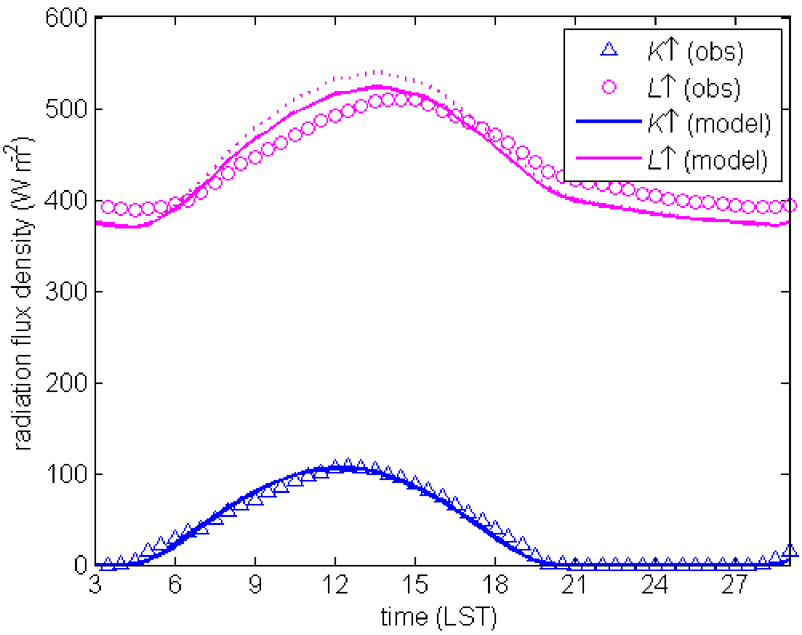

Figure 0 Observed and modeled upward radiation fluxes at the tower "Vancouver Sunset", July 20, 2008. Dotted lines are from the corresponding simulation without trees.

Latent heat flux (Q_E) is remarkably well-reproduced (Fig. 4), with mean absolute error less than 16 W m^{-2} (Table 1). Note the correct timing of the peak of all fluxes in Fig. 4. Modelled leaf energy balance on both dates (not shown) indicates Q_E from trees in this afternoon period becomes driven as much by negative Q_H due to hot urban air temperatures, as by Q^*. Hence, urban micrometeorology and thermal state impacts energy exchange at the leaf surfaces. Overall, addition of trees improves all modelled fluxes during the daytime.

Total reflected shortwave K↑ is well-predicted (3.3 W m^{-2} mean absolute error), while upward longwave L↑ is slightly overestimated (underestimated) during daytime (nighttime; Fig. 5) and its error is reduced by 20% with addition of trees (Table 1), in particular during daytime. Overall, the new multi-layer model with integrated trees performs well compared to measurements in the Sunset neighbourhood for a hot dry mid-summer period.

5. Summary and conclusions

A multi-layer urban canopy model with integrated trees, BEP-Tree, is created by combining a column model for vertical diffusion (Santiago and Martilli, 2010), the BEP urban canopy model (Martilli et al., 2002), and recently-developed radiation and drag and turbulence modules (Krayenhoff et al. 2014, 2015). Additional features such as vertical turbulent transport of heat and humidity, buoyant effects on turbulence, the foliage energy balance, and a solar scheme that includes sky-derived diffuse, are added. BEP-Tree is the first multi-layer urban canopy model to integrate trees and account for radiative and dynamic interactions between trees and built surfaces.

The new model is evaluated against measured fluxes of radiation and turbulent exchange in the inertial sublayer. It performs well overall for a hot, dry summer case. Overall, the model suggests trees are relatively important in terms of the overall energy balance. Measurements in (not only above) urban canopies with trees are required to evaluate the ability of BEP-Tree to predict canopy layer climate, which is the primary goal for its design.

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