A multi-layer radiation model for urban neighbourhoods with trees

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1. Introduction

Urban development alters local climate. This has implications for the prediction of weather and air pollution dispersion, and for neighbourhood design/modification for pedestrian thermal comfort and building energy conservation. Fortunately, urban effects on local climate can be predicted by well-evaluated numerical models that incorporate the relevant urban elements and physical processes.

Numerical models of urban meteorology and climate have primarily been limited to the buildings and streets that together form the archetypal 'urban canyon' (Nunez and Oke, 1977; Masson, 2000; Kusaka *et al*. 2001; Martilli *et al*. 2002; etc). Yet, vegetation is common in many cities worldwide, and its inclusion in models is critical for the simulation of neighbourhood energy balance, street-level climate, and air pollution dispersion. Furthermore, vegetation is an important candidate for urban climate modification in many neighbourhoods. The challenge, then, is to account for the effects of urban vegetation in numerical models of urban climate and dispersion. In essence, the direct interactions between vegetation and the 'built' fabric (i.e., buildings, streets) in cities must be better understood and modelled. These interactions are more significant, and more complex, for trees than for shorter vegetation.

Trees not only provide evaporative cooling, but also offer shade and shelter to pedestrians and buildings and impact air pollution concentrations. They interact with buildings primarily in terms of flow dynamics (e.g., sheltering) and radiation exchange, the latter of which is the focus of this article. Buildings shade trees and other buildings, and trees shade buildings and other trees. Diffuse radiation is exchanged between buildings, between trees, and between buildings and trees, enhancing 'radiation trapping'. The representation of these varied and complex interactions with a simple and consistent model is a challenge.

To date, most modelling of vegetated neighbourhoods has 'tiled' urban and soil-vegetation surface models such that they may interact only indirectly via an atmospheric model. With this approach, important vegetation-building interactions are not included. Recent work has integrated vegetation into urban canopy models and accounted for vegetation-building interaction (Lee and Park, 2008; Lemonsu *et al*. 2012); however, these contributions are limited to trees in single-layer models and/or ground-level vegetation.

Multi-layer canopy models (e.g., Martilli *et al*. 2002) are well-equipped to represent vertical distributions of tree foliage and built elements and their effects on canopy-layer climates, but no model is capable of both at present. The present contribution develops a model for exchange of shortwave and longwave radiation in urban canopies that explicitly includes building-tree interaction and retains significant flexibility in terms of the layout of building and tree foliage elements. The new model discussed herein represents a significant improvement over 'tile' approaches to the inclusion of vegetation.

2. Urban canopy radiation model with integrated trees

The model builds on the two-dimensional multi-layer 'canyon' geometry with probabilistic height distribution of Martilli *et al*. (2002; Figure 1). It largely reformulates the model physics and computational methods in order to incorporate several processes, most significantly the effects of tree foliage on radiation exchange in the urban canopy. The model also addresses the weaknesses in the Martilli *et al*. (2002) formulation identified by Schubert *et al*. (2012); it incorporates sky-derived diffuse solar radiation, permits full radiative interaction of lower roofs with canyon (and foliage) elements, and fully accounts for the radiative effects of fractional building coverage at each height (i.e., it conserves energy).

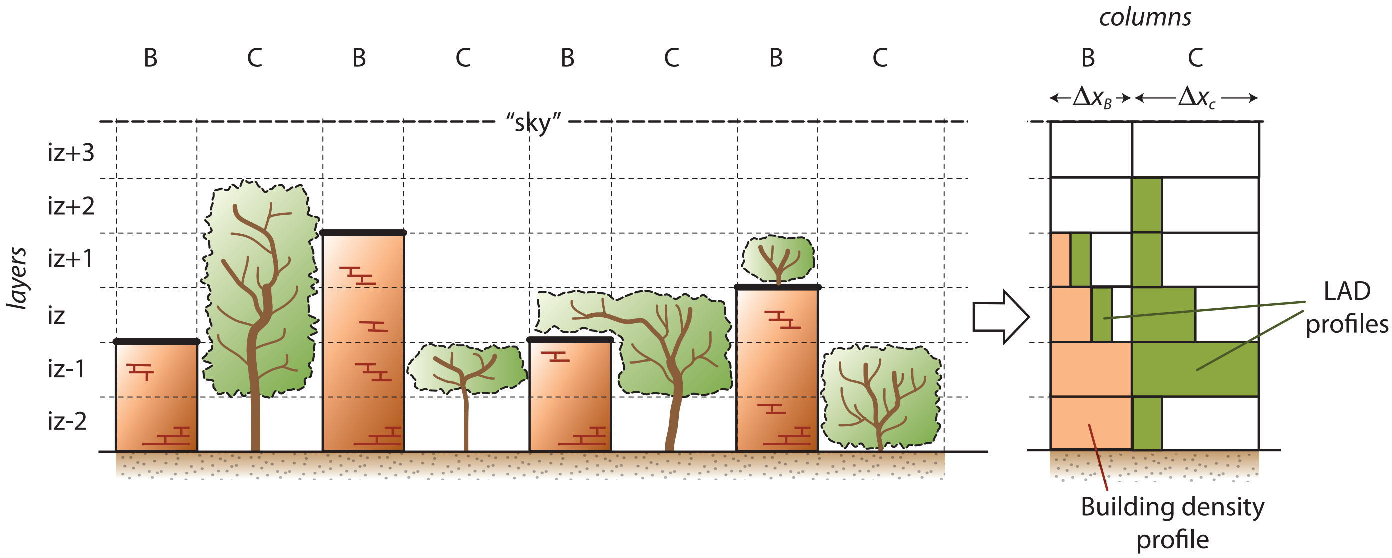

Figure 1. A two-dimensional view of the conceptualization of the urban surface that underlies the model geometry: equal width and equally-spaced buildings with a height frequency distribution, randomly ordered in the horizontal. Foliage layers of different densities are present above and between buildings and at random horizontal locations. An example urban height distribution, building order, and foliage distribution is shown. B = building column; C = canyon column.

A range of computational methods are exploited in order to permit urban configurations of variable complexity while optimizing both accuracy and computation time. Ray tracing tracks direct shortwave radiation as it descends through the domain, impinging on different elements of the urban system. A Monte Carlo ray tracing implementation computes view factors between building and tree foliage elements for *diffuse* shortwave and longwave reflection and emission (i.e., this calculation is performed only once at the beginning of a model run). A system of linear equations is then solved at each timestep to simulate an 'infinite' number of reflections between these elements.

While the radiation model operates in two dimensions, it accounts for the three-dimensional path length of each ray as it travels through layers containing foliage. Foliage layers are characterized by their leaf area density (LAD, in $m^2\,m^{-3}$) and clumping index (Ω), and may be present in the building column above rooftops and in the canyon column at any height (Figure 1). The Bouguer-Lambert-Beer law is used to model radiation interception by layers of foliage, assuming a spherical leaf angle distribution. All elements are assumed to be Lambertian and hence emit and reflect radiation diffusely.

The model is designed for both shortwave (≈0.4-3.0 μm) and longwave (≈3.0-100 μm) radiation wavelength bands. The subsequent discussion assumes that shortwave and longwave are 'broadband', that is, they encompass the ranges as defined above; however, provided wavelength-specific reflection/scattering coefficients the model can be applied to scenarios with narrower bands (e.g., photosynthetically-active radiation vs. near-infrared radiation).

3. Model testing and application

System response tests are performed to demonstrate modelled distributions of radiation exchange for different arrangements of building and foliage elements. Further model testing is discussed in Krayenhoff *et al*. (2013).

Shortwave radiation: Zenith angle, tree foliage location and density

Incident direct and diffuse shortwave irradiance and subsequent reflections are modelled to determine the vertical distribution of absorbed shortwave radiation in each case. Figure 2 and Table 1 outline the geometrical parameters for all scenarios. The following also apply to all scenarios: diffuse is 15% of incoming shortwave; roof, ground and wall albedos are 0.15, 0.15 and 0.25, respectively; tree foliage reflection and transmission coefficients are both 0.25.

The impact of solar zenith angle on the vertical distribution of shortwave absorption in the canopy is first demonstrated for a canyon with two building heights (Scenarios 1 and 2, Fig. 3). Cumulative percent of total incoming solar radiation absorbed is plotted in 1 m increments; hence, the slope is an indication of absorption at each level. Most obvious is the large absorption at 0 m, 6 m and 12 m for both cases, corresponding to the ground and the two roofs, respectively. As the sun moves lower in the sky (i.e., to $\phi = 45°$/Scenario 2), the wall absorption increases as indicated by the greater slope in the cumulative absorption curves below 12 m. As a result, the street-level absorption drops and the overall neighbourhood albedo increases moderately, according to expectation.

In Scenario 3, solar zenith angle remains at 45° and a layer of tree foliage with leaf area density 0.375 m^2 m^{-3} and considerable clumping ($\Omega = 0.5$) is added between 7 m and 11 m in the canyon, corresponding to a neighbourhood-average leaf area index (LAI) of 1.0 (Fig. 3). This layer absorbs significant solar radiation at the expense of the roads and the lower walls and roofs. Furthermore, the overall albedo increases by ≈0.01. Subsequently, this same layer of foliage is moved up to 13-17 m (Scenario 4). The elevated tree foliage now absorbs about 20% of the total incoming solar radiation and reduces the absorption by all roofs, walls, and the street. Interestingly, the neighbourhood albedo changes inconsequentially.

If the foliage layer is retained above the canyon but its density increased to 1.125 m^2 m^{-3}, the neighbourhood-average LAI becomes 3.0 (Scenario 5). More than 40% of the total incoming shortwave radiation, and almost half the total absorbed radiation, is now absorbed by the foliage (Fig. 3). Notably, the overall albedo does not change significantly. Extending this same total amount of foliage over both columns preserves the LAI but reduces the leaf area density to 0.750 m^2 m^{-3} (Scenario 6). The foliage layer

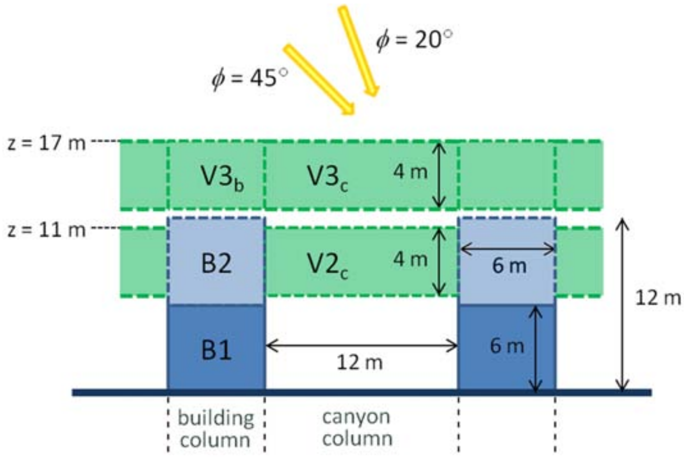

Figure 2. Model geometries and solar zenith angles for shortwave radiation system response tests. "B" = building, "V" = vegetation foliage, numbers refer to vertical layer, and subscripts refer to building (e.g. "$V3_b$") or canyon (e.g. "$V3_c$") columns. Vertical resolution is 1 m and solar azimuth is perpendicular to the canyon orientation for all simulations.

now absorbs slightly more solar radiation. Perhaps most intriguing, however, is the 0.013 increase in overall neighbourhood albedo that results from this change in the horizontal distribution of the foliage.

The model results in Figure 3 indicate that tree foliage shifts shortwave absorption away from built surfaces, and does so to a larger extent for greater foliage density and horizontal distribution. For the particular scenarios modelled here, added horizontal coverage of foliage significantly increases the overall albedo, whereas foliage height and density matter less. Furthermore, the mean height of radiation absorption increases consistently through the scenarios, from 4.0 m in Scenario 1 to 10.6 m in Scenario 6. Such effects are unlikely to be accurately represented without a flexible, consistent urban radiation scheme with integrated tree foliage. The tile approach would not account for any of these effects.

Table 1. Solar and tree foliage characteristics for the six shortwave scenarios.

Scenario	Solar zenith angle (ϕ)	Leaf Area Index (LAI)*	Foliage layer height	Foliage layer column
1	20	0.0	–	–
2	45	0.0	–	–
3	45	1.0	V2 (7-11 m)	c (canyon)
4	45	1.0	V3 (13-17 m)	c (canyon)
5	45	3.0	V3 (13-17 m)	c (canyon)
6	45	3.0	V3 (13-17 m)	c, b (canyon, building)

*Neighbourhood-average LAI.

Longwave exchange: net ground and canyon fluxes

This section explores the impacts of sky view reductions due to buildings and trees on the rate of energy loss from canyon surfaces. Specifically, net longwave flux density (L^*) is computed for the canyon floor alone, and for the complete canyon system, for a range of scenarios. All surface, foliage and air temperatures are 28°C and downwelling longwave is 320 W m^{-2}, representing an early evening cooling scenario during midlatitude summer. Surface and foliage emissivities are 0.95. Canyon width is 12 m and vertical resolution is 1 m for all simulations. Simulation results represent a "snapshot" in time with imposed surface temperatures.

Greater canyon height-to-width ratio (H/W) decreases sky view factor of the canyon floor (streets), reducing net longwave magnitude and leading to warmer nocturnal street surface temperatures (Oke, 1981; Oke *et al.* 1991), and this relation is reproduced here by both the TUF2D model (Krayenhoff and Voogt, 2007) and the new model (Figure 4). This phenomenon has been postulated as a leading cause of the nocturnal canopy-layer urban heat island. However, this relation does not apply to urban neighbourhoods (or canyons) as a whole. While the canyon floor and walls each individually have reduced L^* losses, together they exhibit L^* (per unit horizontal area) of similar or greater magnitude to a flat surface ('canyon' in Fig. 4). Given that building walls and streets tend to remain warmer than flat 'rural' surfaces (as opposed to being equal in temperature, as modelled here), it is apparent that canyon L^* magnitude will typically exceed that of more rural areas. Hence, only a sufficient coverage of low emissivity and/or low thermal admittance materials (e.g., roofs), not the urban geometry, is capable of reducing the magnitude of urban L^* below rural L^*.

The introduction of a tree foliage layer with leaf area density 0.19 $m^2\,m^{-3}$ between 3 m and 7 m above the street reduces canyon floor longwave losses by ≈34% for all H/W ('LAI = 0.5' in Fig. 4). Hence, the presence of trees reduces the cooling rate of the canyon floor, as expected, an effect that is more pronounced in an absolute sense for lower H/W. For the particular conditions considered here, the addition of a moderate neighbourhood-average foliage density of LAI = 0.5 has an impact equivalent to an increase in H/W of 0.50-0.75. Finally, the total L^* of the whole canyon, including tree foliage, varies little with H/W (as for the non-vegetated cases; not shown).

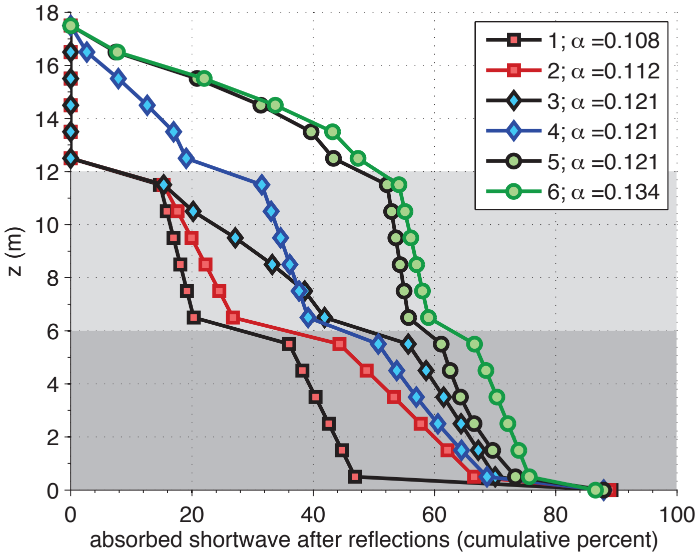

Figure 3. Cumulative percent (from top) of total incoming shortwave radiation absorbed after reflections as a function of solar zenith angle (ϕ), tree foliage location, and foliage density (Table 1, Fig. 2). The neighbourhood geometry includes 50% B1 buildings (6 m height) and 50% B2 buildings (12 m height) and tree foliage. Scenario number (see Table 1) and corresponding neighbourhood albedo (α) appear in the legend.

The new model suggests that both urban geometry and tree foliage can substantially decrease the magnitude of net longwave exchange of individual facets such as the canyon floor. However, the net longwave exchange of canyons or urban neighbourhoods as a whole does not vary significantly with H/W or added foliage for the isothermal conditions modelled here.

4. Summary

A multi-layer urban radiation model with trees is developed that explicitly computes building-tree interaction and represents a substantial improvement over the 'tile' approach to urban vegetation simulation. The model is flexible—any tree heights and thicknesses, foliage densities and clumping, and building heights and height frequency distributions are permitted. The use of ray tracing renders the model quasi-independent of the complexity of the geometry, while the initial calculation of inter-element view factors permits a computationally speedier matrix solution to diffuse exchange for the remainder of a mesoscale or urban canopy model simulation.

Simulations with the new model demonstrate appropriate system responses to varying geometries, foliage characteristics, and solar zenith angle. Both the vertical distribution of shortwave radiation absorption and its partitioning between buildings, vegetation and ground are demonstrated. Denser foliage layers absorb more shortwave at the expense of building and ground surfaces, and the horizontal distribution of foliage can significantly modify overall neighbourhood albedo.

System response scenarios in the longwave spectrum focus on the net exchange. Simulated canyon floor (street) and whole canyon net longwave flux density (L^*) as a function of canyon H/W are in agreement with the independent radiation model TUF2D. The magnitude of ground-level L^* is shown to decrease with deeper canyons and with the addition of canyon foliage. For the isothermal conditions modelled here the L^* of the whole canyon system does not vary significantly with canyon H/W.

The new 'treed' urban radiation model is intended for use at the local scale. Furthermore, it is designed to simulate any combination of shortwave and longwave radiation bands, and to be portable to any urban surface model based on the urban canyon. Further details will be available in a forthcoming publication (Krayenhoff *et al*. 2013).

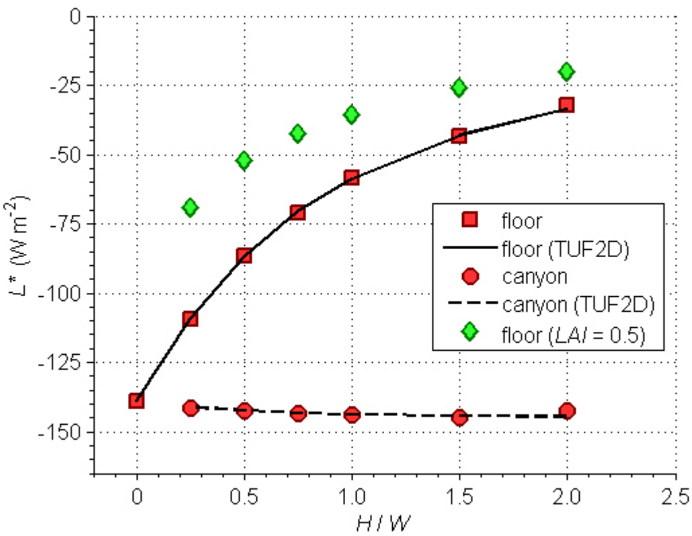

Figure 4. Net longwave flux (L^*) per m2 horizontal (plan) area of the canyon as a whole, and of the canyon floor only, as a function of canyon height to width ratio (H/W). Results are from the current model and from the TUF2D model (where indicated).

Acknowledgements

Thanks are due to Andy Black (UBC) for helpful discussions and to Iain Stewart (UBC) for comments on this article. This work was funded by the National Sciences and Engineering Research Council of Canada (Scott Krayenhoff: Canada Graduate Scholarship, Tim Oke: Discovery Grant).

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