278: A multi-layer radiation model for urban neighbourhoods with trees

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Abstract

A new multi-layer urban canopy model of shortwave and longwave radiation exchange is developed that explicitly includes the radiative effects of tall vegetation (trees). The basic geometry is a two-dimensional canyon with probabilistic building height variation. Tree foliage is permitted both between and above buildings, and mutual shading and reflection between buildings and trees are included. Ray tracing determines the receipt of direct shortwave radiation by building and foliage components. View factors for longwave and shortwave diffuse radiation exchange are computed once at the start of the simulation with a Monte Carlo ray tracing approach; for subsequent model time steps, matrix inversion yields rapid solution of infinite reflections between all elements. System response simulations generate realistic results; full model evaluation is limited by the paucity of within-canyon radiation measurements in treed urban neighbourhoods. The model is designed to be portable to any neighbourhood-scale urban surface model based on the urban canyon. The new radiation model contributes to the inclusion of vegetation in neighbourhood-scale urban canopy models and to the assessment of trees as a tool to improve urban microclimates.

Keywords: Monte Carlo ray tracing, Radiation model, Thermal climate, Trees, Urban forest, Vegetation, View factors

1. Introduction

Over the past decade several process-based urban canopy models designed for coupling with atmospheric models have revolutionized our ability to understand and predict the local climate effects of urban development at the neighbourhood-scale (10^2 to 10^4 m). These models can be broadly divided into single-layer [1] and multi-layer [2] models. Multi-layer models have several vertical layers which allows for reduced parameterization of the canopy physics, inclusion of building height distributions, and more detailed prediction of the street level climate. Urban canopy models typically account for momentum absorption by the urban surface as well as the heat exchanges of horizontal (road and roof) and vertical (wall) facets via conduction, convection and radiation. Some include latent heat fluxes and urban hydrology, but very few integrate vegetation.

Vegetation is common in cities worldwide and a prime candidate for urban climate modification in many others [3,4]. Soil and vegetation store water and slow its release, moderating climate via more consistent evaporation. The latent heat flux is a critical part of the energy balance in most urban environments, yet there is evidence that it is the least well-modelled flux and that inclusion of vegetation in urban climate models significantly improves model performance [5]. Most modelling of vegetated neighbourhoods has 'tiled' urban and soil-vegetation surface models such that they interact only via the coupled atmospheric model [6]. In these approaches important vegetation-building interactions are not accounted for.

Tall vegetation elements (trees) interact with buildings primarily in terms of radiation exchange and flow dynamics. Buildings shade trees and other buildings, and trees shade buildings and other trees. Diffuse longwave and shortwave radiation is exchanged between buildings, between trees, and between buildings and trees, enhancing 'radiation trapping'.

Multi-layer canopy models are well-suited to the representation of vertical distributions of tree foliage and built elements, their interactions, and their combined impact on canopy-layer climate, but no model does so at present. A combined model will be able to include tree foliage at several heights within and above the urban canopy, and hence will have the ability to assess its effects on the canopy-layer climate. The present contribution develops a model for exchange of shortwave and longwave radiation in urban environments that explicitly includes building-tree interaction and retains significant flexibility in terms of the layout of building and tree foliage elements. The new model represents a significant advance relative to current 'tile' approaches to the inclusion of vegetation, and ultimately contributes to the full inclusion of vegetation in multi-layer urban canopy models.

2. Urban radiation model with trees

The current model builds on the two-dimensional multi-layer 'canyon' geometry of [2]. Their model is extended here by introducing trees and sky-derived diffuse solar radiation, and by fully accounting for the radiative effects of fractional building coverage at each height. Ray tracing tracks *direct* shortwave radiation as it descends through the domain, impinging on different parts of the urban system. A Monte Carlo ray tracing implementation computes view factors between surface elements for *diffuse* shortwave exchange and longwave reflection and emission. A system of linear equations is then solved to model an 'infinite' number of reflections between surface elements. As such, reflections are not computed explicitly via ray tracing.

While the radiation model operates in two dimensions, it accounts for three dimensionality in two ways. First, the actual three-dimensional paths of rays are mapped onto the two-dimensional model domain, and second, the ratio of three-dimensional to two-dimensional path lengths is accounted for when rays travel through layers with foliage. The Beer-Bouguer-Lambert law is used to model radiation interception by foliage layers, and foliar clumping is included in the formulation. All surfaces are assumed to be Lambertian and hence emit and reflect radiation diffusely.

2.1 Two-dimensional urban geometry

Urban areas are conceptualized as very long urban canyons with equally-spaced buildings of equal width, randomly-ordered and present according to a building height probability distribution (Fig. 1). The current model geometry is then derived from this conceptualization, and consists of layers divided by levels in the vertical, and alternating 'building' and 'canyon' columns in the horizontal (Fig. 2). Five types of 'surfaces' or 'layers' interact radiatively in the model: roof, wall, canyon floor (or road or street), tree foliage, and 'sky'.

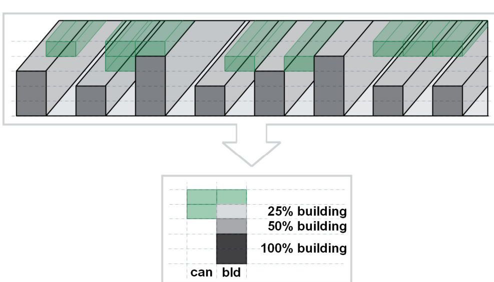

Fig 1. The conceptualization of the urban surface that provides the foundation of the model geometry for an example neighbourhood, and its reduction to the 2-D model geometry with canyon (can) and building (bld) columns.

The spatially-averaged building height distribution for a neighbourhood is represented as partial building opacity in the two-dimensional model [2]. Canyon column layers contain tree foliage according to an input profile of leaf area density (LAD) in the canyon space. Likewise, layers in the building column with opacity less than 1.0 contain tree foliage according to a different input LAD profile.

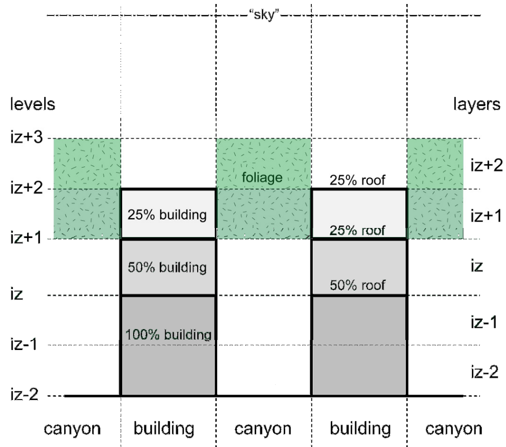

Fig. 2. Two-dimensional model geometry for an example urban neighbourhood with trees.

Tree foliage is treated as a 'surface' that is divided into small pieces (e.g., leaves) of different orientation angles and dispersed throughout a layer. A spherical leaf angle distribution is chosen because it eliminates directionality and it is a reasonable approximation to real tree canopies. Unlike previous urban vegetation models [7] tree foliage may be present in the building column above rooftops and in both columns above the tallest buildings.

3. System response simulations

Evaluation of the new model over the range of realistic scenarios is a significant challenge. Moreover, given the highly complex nature of real geometries, in particular those that include trees, appropriate observational data sets are not currently available to the authors' knowledge. Therefore, the following three tests were performed on the model: a) energy conservation tests on all model components (not shown); b) sensitivity tests to determine model parameters (e.g. numbers of rays) that yield sufficient accuracy while minimizing computation time (not shown); and c) system response tests to demonstrate modelled distributions of radiation absorption and exchange for different arrangements of built and foliage elements and radiation characteristics.

3.1 Absorbed direct solar after reflections

Three system response tests are performed to evaluate direct shortwave receipt and reflection, and the vertical profiles and partitioning of absorbed radiation are analyzed. For all three tests the solar beam is perpendicular to the canyon(s). Albedos of roofs & roads, walls, and foliage (reflection + transmission) for the first two tests are 0.20, 0.35, and 0.50, respectively.

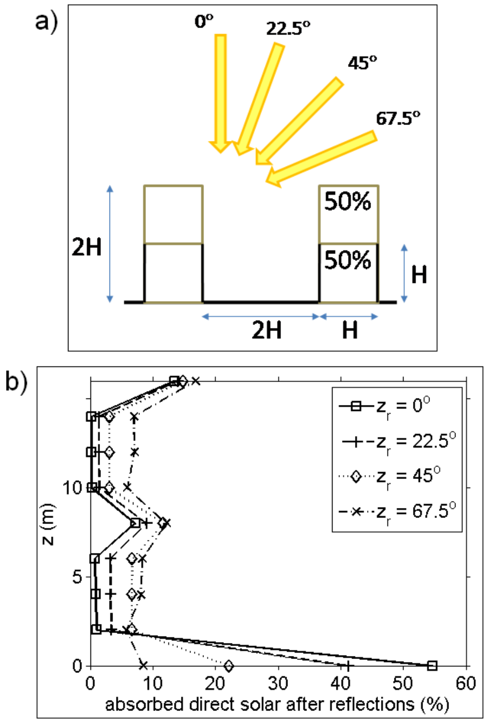

Fig. 3. Vertical profiles of absorbed direct shortwave radiation after reflections for four solar zenith angles (z_r). Half of buildings have height "H" (=8 m) and half "2H"; canyon width is 2H and building width is H. There is no tree foliage.

First, solar zenith angle (z_r) is varied for simple non-vegetated canyons of two heights (Fig. 3a). Percent of total direct shortwave radiation absorbed by each 2 m vertical interval is plotted in Fig. 3b (sky-derived diffuse is ignored). As z_r increases the walls absorb a greater fraction of the total incoming direct solar at the expense of the canyon floor (z = 0 m).

Secondly, vegetation height is varied while keeping solar zenith angle constant at 22.5° (Fig. 4a). LAD is chosen to yield a neighbourhood-average leaf area index (LAI) of 1.0. Percent of total direct shortwave radiation absorbed by each 2 m vertical interval is plotted in Fig. 4b (again, no sky-derived diffuse). The impact of tree foliage absorption is significant, and largely at the expense of canyon floor absorption. Interestingly, the latter depends only weakly on vegetation foliage height.

Finally, foliage area density (LAD) is varied for a constant solar zenith angle of 45° (Fig. 5a). For this case we take a simple canyon with H/W = 0.5 and roof, road and wall albedos of 0.13, 0.14, and 0.25, respectively; foliage albedo remains at 0.50 but clumping is now included (clumping coefficient Ω = 0.7, where Ω = 1.0 represents a fully random spatial distribution).

Total absorbed direct shortwave radiation after reflections is now plotted for each 0.5 m vertical interval in Fig. 5b (again, no diffuse). As foliage is progressively added above the canyon (i.e., LAI = 0.5, 2.0) the main site of solar absorption shifts above the canyon at the expense of all built surfaces (roofs, walls and roads). When the vegetation foliage is evenly distributed over both roofs and canyons ("All"), roofs and roads in particular absorb even less. Of particular interest is the overall neighbourhood albedo (α) computed for each case: it increases with increasing LAI and also when foliage is spread out evenly in the horizontal. This type of phenomenon cannot be captured with a tile approach.

3.2 Net longwave radiation after reflections

Finally, road net longwave loss (L^*_{road}) is computed as a function of canyon height-to-width ratio (Fig. 6). Diffuse emission from the sky is 320 W m^{-2} and isotropic, and all surfaces have temperatures 28 °C and emissivities of 0.95. This represents an early summer evening cooling scenario when urban heat islands form rapidly. As expected, L^*_{road} increases with H/W, and does so more rapidly for small H/W.

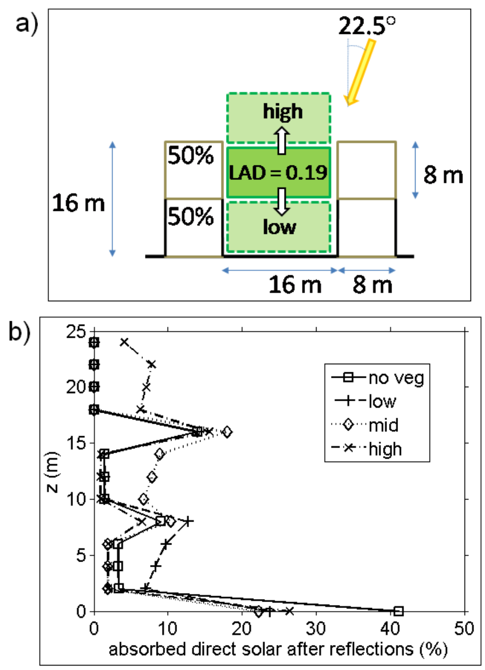

Fig. 4. Vertical profiles of absorbed direct shortwave radiation after reflections without vegetation, and with an 8 m thick tree canopy (LAD = 0.19) at three different heights. Half of buildings are 8 m tall and half are 16 m; canyon width is 16 m and building width is 8 m. Solar zenith angle is 22.5°.

4. Conclusion

A multi-layer urban radiation model with trees is developed that explicitly computes building-tree interaction using commonly accepted radiative transfer theory: (Monte Carlo) ray tracing for direct shortwave and view factor determination, matrix inversion for reflections, and the Beer-Bouguer-Lambert law for attenuation by tree foliage layers. The model is flexible—any tree heights and thicknesses, foliage densities, and building heights and height frequency distributions (provided they sum to 1.0) 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 simulation.

The outputs generated by the vegetated multi-layer urban radiation model are incident and absorbed shortwave, and incident and net longwave radiation, on all surfaces and layers. The model is intended for use at the local scale, and model outputs represent neighbourhood averages. Model simulations were conducted to demonstrate appropriate system responses to varying model geometries, leaf area densities, and incident radiation.

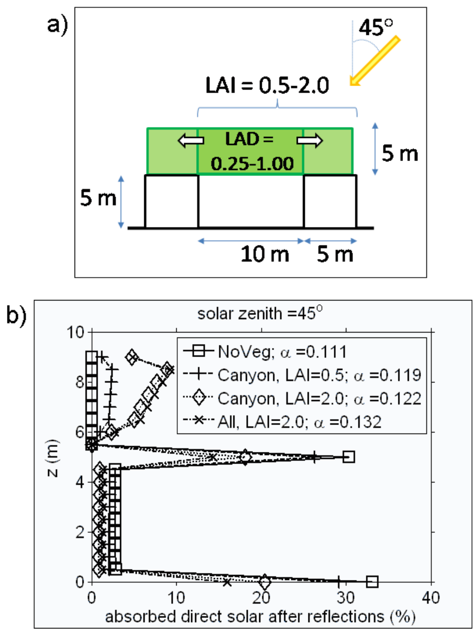

Fig. 5. Vertical profiles of absorbed direct shortwave radiation after reflections without vegetation and with an 5 m thick tree canopy of varying LAD and horizontal distribution. "Canyon" refers to vegetation layer above canyon only. "All" refers to vegetation evenly distributed in the horizontal over roofs and canyons. "α" is overall neighbourhood albedo.

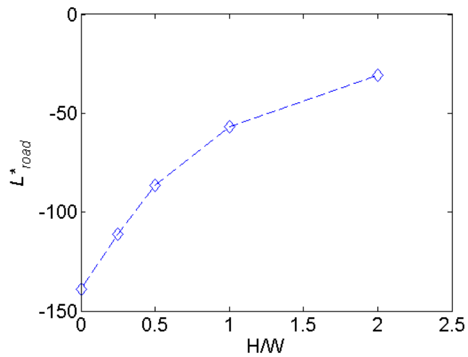

Fig. 6. Canyon floor (road) net longwave as a function of canyon height-to-width ratio (H/W) for simple non-vegetated canyons.

5. Acknowledgements

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6. References

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