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Modelling Radiative Exchange in a Vegetated Urban Street Canyon Model

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1. Abstract

One of the key findings of the recent International Urban Energy Balance Models Comparison Project (PILPS-urban) was that models do not capture the magnitude and temporal variability of the latent heat flux relative to observations. This is despite many of the schemes including a vegetation component, which is typically represented by separate vegetation tiles or, in a limited number of models, explicitly within the urban scheme. The inability to reproduce the latent heat flux suggests that many schemes do not accurately represent urban vegetation and do not account for the impact of urban surfaces on vegetation physiology. PILPS-urban did however suggest that there was an advantage in using an integrated vegetation scheme as the range in performances of models using the separate tile was larger. This raises the following question; can we improve model accuracy of urban moisture fluxes by including vegetation explicitly within an urban land surface scheme? To address this question an integrated vegetation scheme is being developed for the Met Office – Reading Urban Surface Exchange Scheme (MORUSES) to explicitly include vegetation in the form of urban trees and natural surfaces (e.g. grass). The new vegetation scheme will be tested within a 2D infinitely long street canyon, with the aim of improving urban weather forecasts and to provide a tool to test the mitigation of extreme heat events through urban greening. This study presents the theory and initial results for the first aspect of the new scheme, radiative exchange within a vegetated urban street canyon. An analytical method was developed and applied to determine the view factors for calculation of the longwave radiation budget between the surfaces within a non-turbulent street canyon, with a range of aspect ratios, containing a representation of an urban street tree. Unlike previous methods for modelling radiative exchange, which often assume that the wall and road surface have the same equilibrium temperature, this work investigates the non-trivial radiative exchange problem of vegetated (tree and grass) and urban surfaces that are likely not to be in equilibrium due to the impact of vegetation physiology on canopy temperature.

2. Introduction

Magnitude and temporal variability of latent heat fluxes observed in urban areas are not captured well by urban land surface models (ULSMs). This was a key finding to come out of the recent International Urban Energy Balance Models Comparison Project (PILPS-urban) (Grimmond *et al.* 2010; 2011). This highlights that current ULSMs either, have insufficient moisture to be evaporated, or sufficient moisture but insufficient energy to evaporate it. Urban areas have traditionally been represented within models as virtual deserts, analogous to concrete blocks in bulk representations (e.g. Best 2005; Fortuniak 2003), or formed of impervious surfaces devoid of vegetation with limited water stores in the case of single and multi-layer models (e.g. Masson 2000; Martilli *et al.* 2002; Porson *et al.* 2010;). These model representations were relatively successful in simulating the urban sensible heat flux and net-all wave radiation in PILPS-Urban, suggesting that there is sufficient available energy but they are not partitioning this energy correctly (i.e. an inaccurate Bowen ratio). Reasons for this could be that there is either (or a combination of) insufficient moisture to be evaporated within the model, for example Best & Grimmond (2013) highlighted that inaccurate soil moisture values had a '*substantial impact*', especially for short simulation periods on the Bowen ratio; or a mechanism is missing from ULSMs that observations are capturing e.g. anthropogenic moisture and urban hydrology representation (Wang *et al.* 2013; Yang *et al.* 2015); and the representation of urban vegetation (Best & Grimmond 2014).

The majority of the ULSMs tested within PILPS-urban included a vegetation component in the form of a separate vegetation tile(s) or in a limited number of schemes in an integrated manner (Grimmond et al. 2010). While those that did include vegetation performed better relative to those that didn't and integrated models showed a narrower range in performance relative to those that used independent vegetation tiling schemes, overall all ULSMs showed significant errors relative to observations. Therefore it is possible that processes and feedbacks due to the interaction between urban and vegetated surfaces are not being represented within current ULSMs (e.g. impact of surface temperature differences on plant/tree physiology (Meier & Scherer 2012) and integrated impact of microscale processes such as advection and edge effects (Hagishima *et al.* 2007)), either due to the treatment of vegetation being independent from urban tiles or considerations/compromises made in the integration of vegetation into existing ULSM frameworks (e.g. Lee & Park 2008; Lemonsu et al. 2012).

The findings from PILPS-urban has led to action within the urban modeling community to address the poor performance in simulating latent heat flux with a number of existing models starting to include vegetation in an integrated manner, with promising results (Krayenhoff *et al.* 2014; Lee 2011; Lemonsu *et al.* 2012; Wang *et al.* 2013). This project will attempt to address this issue in the JULES (Joint UK Land Environment Simulator)/Met Office Unified Model (MetUM) environment through the development of an integrated urban vegetation scheme TUrban (Trees in Urban areas model).

3. TUrban

TUrban aims to improve the modelling of urban moisture fluxes within JULES (Best *et al.* 2011), the land surface model utilised by the MetUM, by including an explicit representation of urban vegetation and some limited urban hydrology. In TUrban's development particular focus will be made to physically represent the impact of vegetation, on the radiation balance, on the surface exchange of heat and moisture, on canyon flow regimes within a single layer street canyon geometry. While also capturing the impact on vegetation physiology due to feedbacks with urban surfaces. There are three main urban vegetation forms that TUrban will aim to represent; a) street trees; b) suburban gardens; c) urban greening (green walls and roofs). The developed model will be evaluated relative to observations and existing urban schemes, with the aim to improve latent heat flux simulation, provide a tool to evaluate urban heat mitigation strategies and reduce error in urban weather forecasts.

The underlying model framework of TUrban is the urban tile scheme MORUSES (Met Office Reading Urban Surface Exchange Scheme) (Porson *et al* 2010) and vegetation dynamics within JULES (Clark *et al.* 2011). Within MORUSES the urban surface is represented as a single layer model with two independent tiles, a 2D street canyon and a roof. TUrban will draw strongly on the foundations of MORUSES but will have to consider a number of processes that the original model was not designed for and challenge some of its underlying assumptions (e.g. assumption of all canyon facets having the same surface temperature). The first aspect of TUrban considered was the longwave radiative exchange within a canyon containing a representation of urban trees (Figure 1).

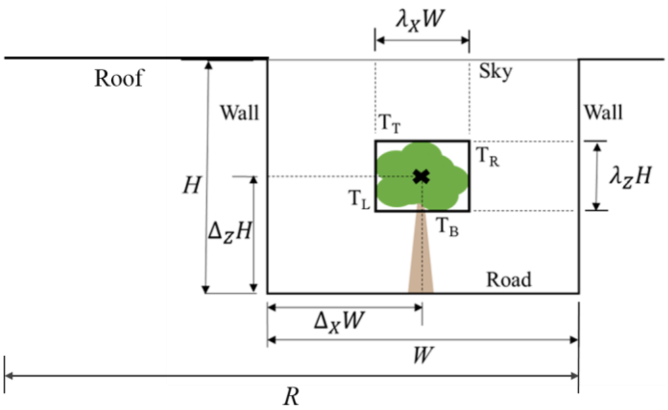

Fig. 1 Schematic of urban facets and tree representation within the TUrban model.

3. Method

3.1 Longwave Radiative Exchange within a Vegetated Urban Street Canyon

Simulating the net-radiation balance of a surface is critical in determining its energy balance, as it is this radiation that provides the energy that drives fluxes of heat and moisture at the surface. In an urban context this balance is modified (relative to a flat surface or dense canopy) as radiation is trapped within the urban canopy due to an increased number of reflections and enhanced absorption due to a greater effective surface area. This results in reduced nocturnal radiative cooling and the subsequent formation of an urban heat island (Oke 1987). However due to the nature of urban areas and surfaces being highly heterogeneous, over a wide range of scales, makes modelling of the radiation balance complicated. To address this urban modellers typically use a simplified geometry of a 2D infinitely long street canyon (Figure 1) with representative height-to-width (H/W) and street-to-roof (W/R) ratios for the urban morphology (Masson 2000; Porson *et al.* 2010). The net long and shortwave radiation balances are then solved using methods based on radiation heat transfer theory (Jones 2000), with varying degrees of complexity considered (e.g. number of reflections).

Unlike many previous studies that have implicitly included vegetation within their ULSMs (e.g. Lee & Park 2008; Lemonsu et al. 2012), TUrban will include a representation of urban trees directly within the canyon itself. This decision was taken as we don't only want to simulate the canyon net-radiation balance but also the radiative exchange between vegetation and surrounding urban surfaces to represent the urban impacts on plant physiology. The radiation scheme is based upon the exact solution (using matrix inversion) of Harman *et al.* (2004) in which all reflections are modelled under the assumption of Lambertian reflection, no interaction with canyon air and uniform surface temperature. With an initial focus on the longwave radiative balance (although also applicable to shortwave radiation). The total amount of longwave radiation transmitted from one surface, or facet (A), to another (B) in a system of n facets is determined by their relative surface temperature, emissivity and the view factor. The view factor is a weighting dependent on the relative visible surface areas of facets A and B and the distance between them, with the sum of all view factors from A to all other facets (including B) equal to unity. The addition of a tree within the radiation scheme was far from a trivial task relative to the four facet system presented by Harman *et al*. (2004). This was due to the need to calculate additional view factors for partially occluded facets (e.g. road-to-sky) due to the presence of the tree. This was achieved using an analytical method, Hottel's crossed string construction (Hottel, 1954), as opposed to the few studies that have considered trees implicitly within/above the canyon that utilised Monte Carlo ray tracing (Krayenhoff *et al,* 2014; Wang 2014).

The tree representation used within TUrban is a 2D rectangle which like the canyon is infinitely long. The size of the rectangle is either defined as fraction of the canyon width (λ_x) and height (λ_z) or a specified length, with the midpoint of the rectangle located at the centre of the canyon. The Hottel crossed strings construction (Hottel 1954) enables a great degree of flexibility when considering tree shape as there are multitude of different tree geometries (e.g. Troxel *et al.* 2013, considered 10 different shapes in a study of urban crown sizes). In this study a rectangle was chosen as it has a degree of flexibility to contain any shaped tree desired, under the assumption that the rectangle acts as a convex hull. The tree is confined by the boundaries of the canyon and the trunk is treated as transparent as the crown is assumed to be more radiatively active (Wang, 2014).

4. Results

4.1 View Factor Calculations

View factors were calculated between each canyon and tree facet over a range of H/W (0.01 to 10) and tree sizes ($0 \le \lambda_x \le 0.9$; $0 \le \lambda_z \le 0.9$), as a fraction of H and W, using Hottel's crossed string construction (Hottel, 1954) and analytical relations within an online view factor catalogue based upon the former (Howell 2010). The resultant view factors for a treed canyon (Figure 2) were then compared with those for a no tree case as presented by Harman et al. (2004). As would be expected the inclusion of tree led to a reduction in the magnitude of the view factors between urban facets with increasing tree size. Even a small tree representation ($\lambda_x = 0.1$; $\lambda_z = 0.1$) led to a reduction in the view factor (as observed by Wang 2014 over a smaller range of H/W) of up to 10 %, with the magnitude varying non-linearly with respect to canyon H/W.

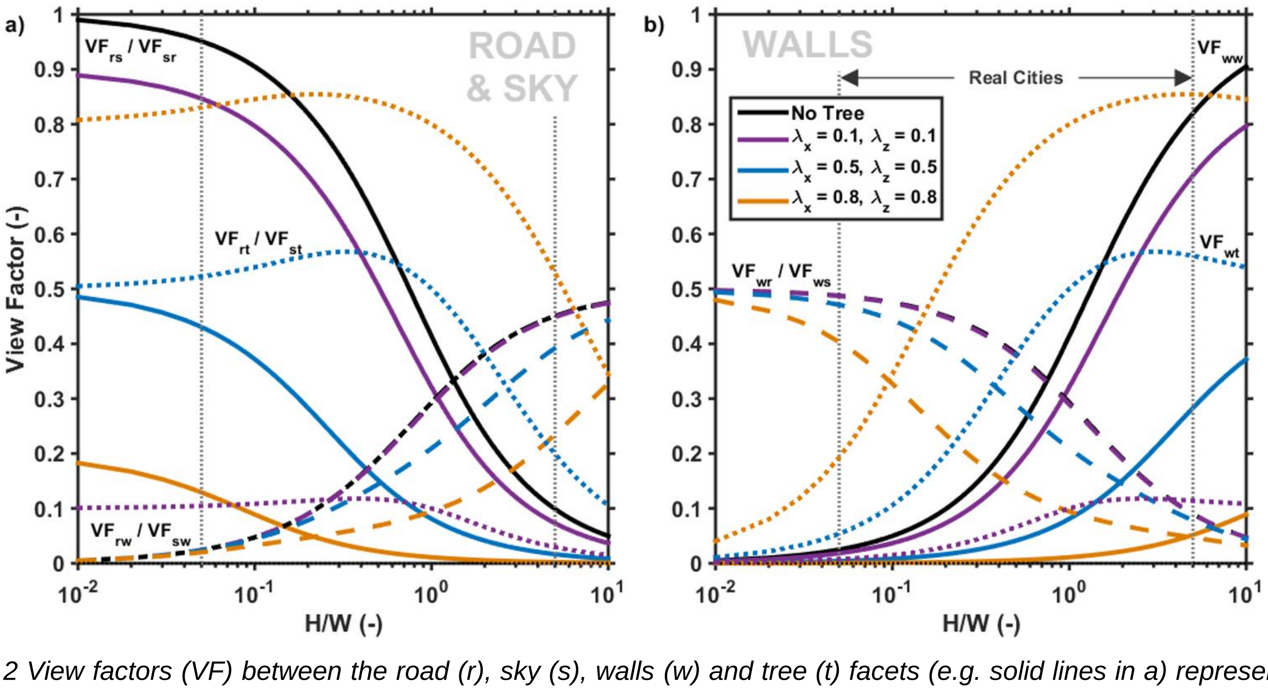

Fig. 2 View factors (VF) between the road (r), sky (s), walls (w) and tree (t) facets (e.g. solid lines in a) represent road-to-sky VF and sky-to-road VF and in b) wall-to-wall VF) for different sized trees (λ_x = 0.1, 0.5, 0.8; λ_z = 0.1, 0.5 and 0.8) over a range of aspect ratios. a) View factors from the road and sky to other facets. b) View factors from the walls to other facets. Vertical grey dotted lines represent the range of aspect ratios observed in real cities (after Harman et al. 2004).

4.2 Idealised Simulations

A number of idealised simulations were undertaken to look at the impact that the inclusion of a tree representation would have on top of canyon longwave radiation balance and effective canyon emissivity (ε_{eff}). This was achieved by first calculating an area weighted net longwave radiative flux density of the urban and vegetated facets using the previously calculated view factors, assigning a surface material emissivity, ε_{mat}, and an initial surface temperature (after Harman *et al.* 2004). In these simulations the surface temperature of all facets was set to 295 K, with all having the same surface emissivity (tested over the range, $0 \leq \varepsilon \leq 1$) apart from the sky that was fixed at $\varepsilon = 1$, and sky downwelling longwave radiation of 275 W m^{-2}. ε_{eff} was calculated by taking the net longwave radiative flux density at the top of the canyon and normalising by the equivalent net longwave radiative flux density of a horizontal surface of equivalent temperature emitting as a black body.

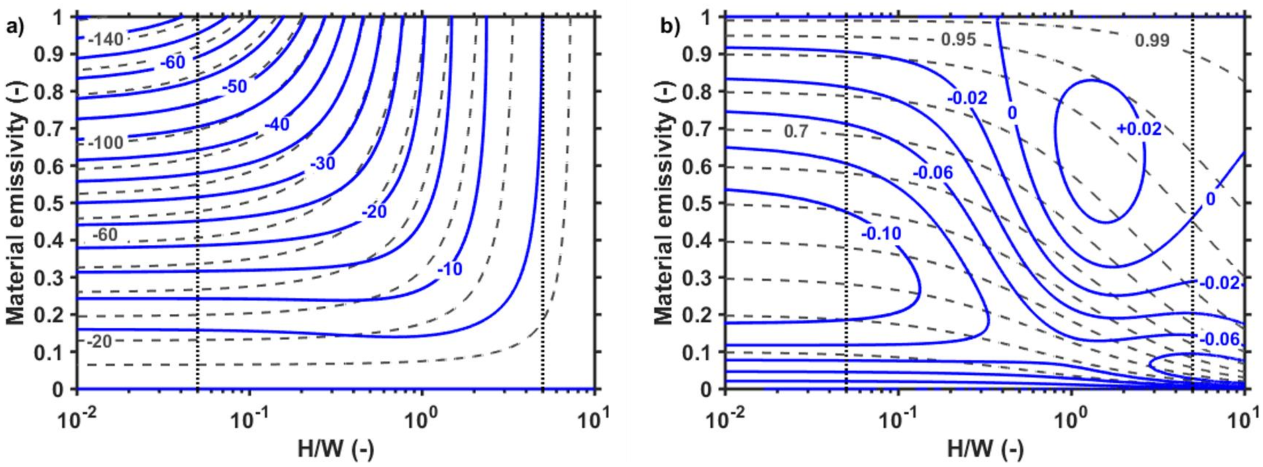

Fig. 3 a) Contour plot showing the difference in modelled top of canyon net longwave radiative flux density (weighted by surface area), W m^{-2}, with a centred tree of dimension $\lambda_x = 0.5$, $\lambda_z = 0.5$ (blue contours and labels) relative to a canyon with no tree (grey dashed contours and values), for a range of ε_{mat} and H/W. Note that negative values for a treeless canyon totals indicate upwelling longwave radiation. b) Contour plot showing the difference between effective canyon emissivity (blue contours and labels) of a canyon containing the tree geometry described in a) relative to that without a tree (grey dashed contours and labels). Vertical grey dotted lines again represent the range of H/W observed in real cities (after Harman et al. 2004).

Using the exact method (infinite reflections) with the inclusion of a tree representation results in a reduction in top of canyon net longwave radiative flux density for all values of ε_{mat} and H/W (Figure 3 a). This is expected due to the impact of the tree intercepting longwave radiation. A consequence of this is a reduction in the effective canyon temperature. The greatest difference occurs for lower H/W (up to 70 W m^{-2} for real H/W and the tree geometry presented) while the impact is much reduced for higher H/W values (all ε_{mat}) due to an effectively reduced surface area (Harman *et al.* 2004).

The impact of the inclusion of a tree on ε_{eff} is shown to be strongly dependent on material emissivity, aspect ratio and tree size relative to a treeless canyon (Figure 3 b). There is an increase in ε_{eff} when H/W ≥ 1 and material $\varepsilon > 0.5$ (typical of non-natural surfaces) of in excess of 2% in the example shown (> 8% for tree of dimension $\lambda_x = 0.7$, $\lambda_z = 0.7$ (not shown)), this is particularly significant as it lies within the range of real city H/W. While for H/W < 1 there is a reduction in ε_{eff} for all ε_{mat}, with values of the order -10% for $\varepsilon_{mat} < 0.5$. It is postulated that the increased ε_{eff} for H/W ≥ 1 is due to the tree representation effectively simulating the effect of two street canyons while the decreased ε_{eff} for H/W < 1 is due to the top of the tree acting like a flat surface while the bottom is intercepting a greater fraction of the radiation, for the tree and canyon geometries tested.

5. Conclusion

This work presents the first aspect, longwave radiative exchange within a vegetated urban street canyon, addressed within the TUrban model which is looking to improve simulation of latent heat flux through the representation of urban vegetation processes and feedbacks. Results from the calculation of view factors using analytical relations are presented along with those from idealised simulations undertaken to investigate the impact of a tree on top of canyon net longwave radiation flux density and effective canyon albedo due to material emissivity and H/W. It was shown that for even a small tree ($\lambda_x = 0.1$; $\lambda_z = 0.1$) there an impact on radiative exchange due to a reduction in view factor between each of the other facets in the canyon and radiation interception impacting on the canyon net-longwave radiation balance.

4. Future Work

The next stage of this work is to consider the impact of the differences between vegetation and urban facet temperature, surface emissivity, and different tree geometries on surface and canyon longwave radiation balance. Beyond that future development of the TUrban model will focus on the impact of including urban vegetation within a street canyon on shortwave radiation exchange (which builds on this work), the impact on flow, surface exchange, and modifications to plant physiology in urban areas. The model is currently being developed in a stand alone format to enable testing and comparison of a number of different schemes and against urban observations (both near surface air temperature and flux observations), before being implemented within JULES.

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