10.6 PARAMETERIZATION OF DRAG AND TURBULENCE FOR URBAN NEIGHBOURHOODS WITH TREES

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1. INTRODUCTION

Vegetation is common in cities worldwide, and its inclusion in models is critical for proper simulation of neighbourhood-scale (10^2-10^4 m) energy balances (Grimmond et al. 2011), street-level climate (Shashua-Bar and Hoffman, 2000), and air pollutant dispersion (Vos et al. 2013). Furthermore, it is an important design tool in urban environmental management (Oke, 1989; Bowler et al. 2010).

Trees in particular offer shade and shelter to pedestrians and buildings, and modify near-surface turbulent and radiative exchanges. Furthermore, they regulate transpiration and interception, increase absorption and deposition of pollutants, emit biogenic volatile compounds (a temperature-dependent process), and affect pollutant dispersion by exerting drag on the flow and modifying the turbulent environment. Hence, the current challenge in numerical models of the urban environment is to account for the physical and chemical effects of urban vegetation. In essence, the interactions between vegetation and the 'built' fabric (e.g., buildings, streets) in cities must be better understood and modelled to accurately simulate and forecast weather, climate, hydrology, building energy demand and pollution. These interactions are more significant, and more complex, for trees than for shorter vegetation.

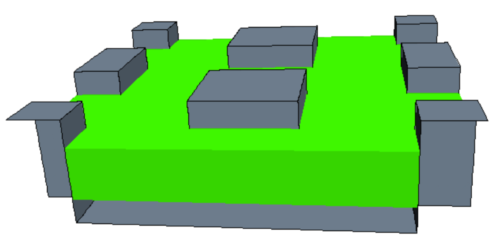

Figure 1: A scenario with tree foliage in the building canopy and building density $\lambda_P = 0.25$ (Tree2). Leaf area density varies between the following for each scenario: 0.06, 0.13, 0.25, and 0.50 m^2 m^{-3}. Foliage layer thickness is 8 m and forcing wind is from the left in all cases.

Trees are expected to interact with buildings primarily in terms of flow dynamics (e.g., sheltering) and radiation exchange (e.g., shading); the former is the focus of the present contribution. Trees and buildings shelter each other and both modify their shared turbulent and thermal environments; however, for which scenarios these effects are significant, if any, remains an open question. Trees also shade buildings and other trees, and vice versa, and exchange diffuse radiation with buildings. A neighbourhood-scale model for these interactions has recently been developed (Krayenhoff et al. 2014a).

The challenge undertaken here is to represent the combined effects of trees and buildings on the spatially-averaged mean flow with a relatively simple parameterization. To do so these effects must be assessed in the three-dimensional (3-D) flow and subsequently parameterized in one-dimension (1-D), i.e., in terms of the horizontally-averaged vertical exchanges. The scheme developed here is intended for neighbourhood-scale modelling (e.g. to be included in an urban canopy parameterization, and ultimately within a mesoscale model), and hence it is designed to predict the neighbourhood-scale average, or integrated, effect of these obstacles at each height in the canopy without resolving each obstacle. To assess these neighbourhood-scale effects on the flow for simplified geometries, the results of microscale simulations may be scaled-up, or horizontally-averaged. Here, obstacle-resolving Computational Fluid Dynamics (CFD) simulations are conducted for neutral flow through canopies of blocks (buildings) with varying distributions and densities of porous media (tree foliage; Figs. 1 and 2), and the spatial-average impacts on the flow of these building-tree combinations are assessed. A 1-D column model with *k-l* closure is parameterized based on the CFD results.

The objectives of the present work are:

A) to assess the relative importance of the (source/sink) terms added to the momentum and turbulent kinetic energy budgets in a column model to representation of the effects of urban tree foliage on flow profiles, as compared to a 3-D CFD model;

B) to determine if trees and buildings can be treated independently (i.e., they are additive),

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or if their *relative* impacts on the flow (e.g., their efficiencies as momentum sinks, that is, their drag coefficients) are affected by each other's presence;

C) to assess the resulting parameterization, which is based on those source terms found to be important to the correct reproduction of the spatially-averaged flow profiles in urban neighbourhoods with trees;

D) to determine for which subset(s) of scenarios tree foliage-related terms are of consequence, in addition to the building-related terms, to simulation of spatially-averaged flow.

2. MODELS

a. CFD model

The CFD simulations solve the steady-state Reynolds-Averaged Navier Stokes (RANS) equations in three-dimensions with the standard k-ε model as turbulence closure. Hence, prognostic equations for both the turbulent kinetic energy (k) and its rate of dissipation (ε) are solved, and model simulations proceed until a steady-state is achieved (Santiago and Martilli, 2010).

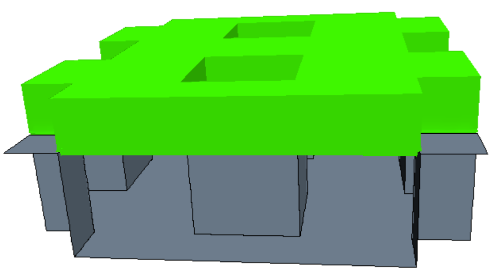

Figure 2: Same as Fig. 1, except for tree foliage above the building canopy (Tree5).

Source terms are added to the momentum, turbulent kinetic energy and turbulent kinetic energy dissipation rate equations to represent the effects of tree foliage on the 3-D flow (Santiago et al. 2013). The form drag induced by the foliage is represented with the 'porous medium approach', i.e., it is added as a sink term in the momentum equation (e.g., Raupach and Shaw 1982):

$$S_{u_i} = -L_D C_{DV} U \overline{u}_i, \qquad (1)$$

where u_i is the wind velocity in direction i, U is the 3-D wind *speed* $\left(\sqrt{u_i^2 + u_j^2 + u_k^2}\right)$, both in m s^{-1}, L_D is the leaf area density (m^2 m^{-3}), C_{DV} is the *sectional* drag coefficient for the foliage (dimensionless), and ρ is the air density (kg m^{-3}). The optimized value of C_{DV} = 0.20 determined by Katul and Albertson (1998) is chosen here. The C_{DV} coefficient acts as a blunt, covering parameter, and nuanced effects on drag such as leaf fluttering and streamlining are not explicitly included. However, within the context of neighbourhood-scale averaging this is probably a reasonable approach.

Eq. 1 represents an additional sink of momentum due to foliage-atmosphere interaction and it is added after averaging of the momentum equation. This sink of mean momentum implies a source of turbulence due to extraction of mean kinetic energy from the flow (assuming conversion of mean kinetic energy to turbulent kinetic energy only). Furthermore, despite the rapid generation of wake turbulence, the typical effect of vegetation is to reduce overall turbulence levels (Green et al. 1995), as larger turbulent eddies are chopped up by the small foliar drag elements. The representation of this 'short circuiting' of the turbulent energy cascade is not possible with a one-band model of turbulent energy (Raupach and Shaw, 1982). Nevertheless, Green (1992) proposed a parameterization of this enhanced dissipation of turbulence generated by foliage element drag (but not by buildings) with an addition to the prognostic equation for k. With this addition the source term for tree foliage in the turbulent kinetic energy equation reads:

$$S_k = L_D C_{DV} \left(\beta_p U^3 - \beta_d k U\right), \qquad (2)$$

where β_p = 1.0 (no direct conversion to heat) and β_d = 6.5 (Sanz, 2003).

Results from this 3-D RANS model with tree foliage implementation as described here, are used to parameterize the coefficients needed to represent the spatially-averaged profiles in the 1-D column model.

b. Column model

A mesoscale model requires vertical profiles of the effects of buildings and trees on the spatially-averaged mean flow. Hence, the overall objective is to accurately represent the effects of a variety of simple arrangements of buildings and trees on the spatially-averaged vertical profiles of flow properties. This requires that the interactions between buildings and trees be accounted for.

Table 1: The (source) terms investigated and the naming convention used in subsequent figures and text, and a description of each term. Terms 1-3 are sink terms in the momentum equation. Terms 4-7 are source/sink terms in the turbulent kinetic energy equation. Terms 8 and 9 affect the length scales, which directly impact both $\langle\overline{u}\rangle$ and $\langle\overline{k}\rangle$ balances. Impacts of buildings are captured by terms 1, 5, and 9, effects of tree foliage by terms 2, 6, 7, and 8, and 'interaction' between buildings and trees by terms 3, 4, and 8.

Term	Name	Description
1	Bdrag-u	Drag due to buildings.
2	Vdrag-u	Drag due to tree foliage.
3	Bdragv-u	Modification to building drag due to presence of tree foliage.
4	Bprodv-k	Modification to production of turbulence by building drag due to presence of tree foliage.
5	Bprod-k	Production of turbulence by building drag.
6	Vprod-k	Production of turbulence by tree foliage drag.
7	Vdiss-k	Enhanced dissipation of turbulence due to the small (wake) scales produced by the presence of tree foliage.
8	Blengthv-u,k	Modification to length scales for case building-only case due to the presence of tree foliage.
9	Blength-u,k	Modification to length scales due to the presence of buildings.

The prognostic equations for momentum and turbulent kinetic energy are as in Santiago and Martilli (2010). Their parameterization is expanded here to include and parameterize foliage-related terms. In the momentum equation, the drag due to buildings and tree foliage is parameterized as follows (Foudhil et al. 2005; Santiago and Martilli, 2010):

$$\underbrace{\frac{1}{\rho}\left\langle\frac{\partial\tilde{p}}{\partial x_i}\right\rangle}_{V} = -\left(\overbrace{\overline{B_D C_{DBv}}}^{1} + \overbrace{\frac{\overline{L_D\,C_{DV}}}{v_L}}^{2}\right)\left\langle\overline{U}\right\rangle\left\langle\overline{u}\right\rangle, \qquad (3)$$

where B_D is sectional building area density (m^2 of area facing the wind per m^3 of air volume), L_D is the foliage leaf area density (m^2 of one-sided leaf area per m^3 of air volume), v_L is the fraction of canopy volume not occupied by building, U is the three-dimensional wind *speed*, C_{DV} is the drag coefficient for tree foliage (=0.2, as in the CFD model), and overbars denote the time mean and angle brackets the spatial mean. Note that L_D is a property of the foliage, whereas B_D is a neighbourhood property and as such already implicitly includes canopy air volume reduction (v_L). C_{DBv} is the *sectional* drag coefficient for buildings when foliage is present:

$$C_{DBv} = \overbrace{\omega}^{3,4} C_{DB}, \qquad (4)$$

where C_{DB} is the sectional drag coefficient for buildings without any tree foliage in the domain, and ω represents the effect of the foliage on the building drag coefficient for a particular building and foliage configuration. Hence, interaction between buildings and trees is accounted for in the building drag coefficient, because the foliage drag coefficient is fixed. This interaction between buildings and trees is a *relative* effect. That is, simply by including sink terms to represent the drag by buildings and trees, they each impact the *absolute* effect the other has on the flow. However, they do not impact *each other's* drag coefficient, or drag 'efficiency'. The question investigated here is whether the presence of tree foliage impacts the drag *coefficient* of buildings, that is, the drag force that they exert relative to the mean kinetic energy in the same atmospheric layer.

As in the CFD model, the loss of momentum (i.e. mean kinetic energy) due to building and foliage drag implies a reciprocal production of turbulent kinetic energy. Furthermore, the more rapid dissipation of the fine 'wake' scale turbulence produced by tree foliage that is incorporated in the CFD (Eq. 2) must also be included in the 1-D column model. Therefore, added source terms in the k-equation are:

$$\underbrace{\left\langle\overline{u_i'u_j'}\frac{\partial\tilde{u}_i}{\partial x_j}\right\rangle}_{VII} + \underbrace{S_k}_{VIII} = \left(\overbrace{\overline{B_D\,C_{DBv}}}^{5} + \overbrace{\frac{\overline{L_D\,C_{DV}}}{v_L}}^{6}\right)\left\langle\overline{U}\right\rangle^3 - \overbrace{\frac{\overline{L_D\,C_{DV}}}{v_L}\left\langle\overline{k}\right\rangle\left\langle\overline{U}\right\rangle}^{7} \qquad (5)$$

Finally, the turbulent length scale is derived from the dissipation length scale ($l_{\varepsilon bv}$) following Santiago and Martilli (2010), here:

$$\frac{l_{\varepsilon bv}}{C_\varepsilon} = \frac{l_\varepsilon}{C_\varepsilon} \overbrace{\nu}^{9} \overbrace{\upsilon}^{8}, \qquad (6)$$

where $l_\varepsilon / C_\varepsilon$ is output by the CFD, or parameterized, for the equivalent case without buildings or tree foliage, ν represents the effect of buildings on the length scale for a particular configuration, and υ represents the effect of the foliage on the length scale for a particular building and foliage configuration.

3. SOURCE TERMS FOR NEW PARAMETERIZATION

Terms/parameters 1 to 9 in Eqs. 3 to 6 in the column model (Table 1) are investigated individually in terms of their relative importance in reproducing the spatially-averaged flow from the CFD model. Krayenhoff et al. (2014b) find that only four terms in Table 1 are required to parameterize the effects of buildings and foliage on the flow:

A) Bdrag-u in the momentum equation:

$$\overbrace{B_D\, C_{DBv} \langle \overline{U} \rangle \langle \overline{u} \rangle}^{1};$$

B) Vdrag-u in the momentum equation:

$$\overbrace{v_L L_D\, C_{DV} \langle \overline{U} \rangle \langle \overline{u} \rangle}^{2};$$

C) Vdiss-k in the turbulent kinetic energy equation:

$$\overbrace{L_D\, C_{DV} \langle \overline{k} \rangle \langle \overline{U} \rangle}^{7}; \text{ and}$$

D) And Blength-u,k, with consequences for both momentum and turbulent kinetic energy equations:

$$\frac{l_{\varepsilon bv}}{C_\varepsilon} = \overbrace{\frac{l_\varepsilon}{C_\varepsilon}}^{9} \omega .$$

Additionally, two other terms are of marginal importance but are implied by the corresponding drag terms in the momentum equation (Raupach and Shaw, 1982), and so are included in the turbulent kinetic energy equation in order to conserve energy:

E) Bprod-k in the turbulent kinetic energy equation:

$$\overbrace{B_D\, C_{DBv} \langle \overline{U} \rangle^3}^{5} \text{ ; and}$$

F) And Vprod-k in the turbulent kinetic energy equation:

$$\overbrace{\frac{L_D\, C_{DV}}{v_L} \langle \overline{U} \rangle^3}^{6}.$$

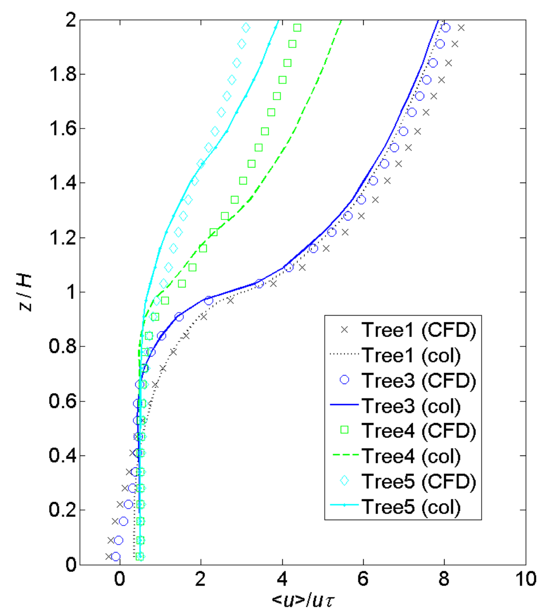

Figure 3: Profiles of normalized $\langle \overline{u} \rangle$ from CFD and column (col) models with the new parameterization, for several foliage heights with leaf area density L_D = 0.25 m^2 m^{-3}. Foliage is present at z = 0 – 8 m for Tree1, 8 – 16 m for Tree3, 12 – 20 m for Tree4, and 16 – 24 m for Tree5. Building height H is 16 m.

Overall, the important effects due to buildings and tree foliage, represented in the model as source terms, are: slowing of the mean wind by both buildings and trees (via drag terms), enhanced dissipation of turbulence by buildings (via l_ε reduction) and tree foliage (via Vdiss-k short-circuit term), and the reduction of vertical turbulent transport in and immediately above the building canopy (via l_k reduction). Impacts of foliage on length scales are ignored here but are of moderate importance for select scenarios: i.e., those with higher foliage amounts, and which are either unaccompanied by buildings or whose foliage tops are coincident with building height for low building densities.

Most importantly, perhaps, the terms that represent the interactions between buildings and trees in the current formulation, Bdragv-u and Bprodv-k, are unimportant across all scenarios simulated here (Krayenhoff et al. 2014b). Hence, buildings and trees may be treated independently in terms of their effects on the *spatially-averaged* flow; for example, while drag force due to buildings will be affected by the presence of tree foliage (because the mean wind is slowed by the foliage), the building drag coefficient need not be modified due to the presence of tree foliage. This greatly simplifies the parameterization of the effects of urban neighbourhoods with trees on flow.

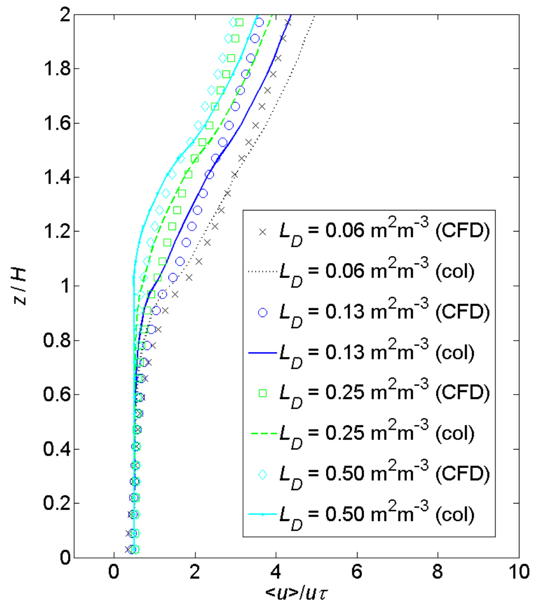

Figure 4: Profiles of normalized $\langle \overline{u} \rangle$ from CFD and column (col) models with the new parameterization, for several foliage densities with the foliage layer above the building canopy (from z/H = 1.0 – 1.5; Tree5).

4. PARAMETERIZATION OF TREE FOLIAGE AND BUILDING IMPACTS ON FLOW

This section presents testing of the new parameterization of building and tree impacts on spatially-averaged flow. It also includes an evaluation of the relative importance of the tree foliage-related terms across a range of scenarios; that is, when is the current parameterization required over and above the parameterization of Santiago and Martilli (2010) for building-only scenarios? Only the six source terms identified in Sect. 3 (terms 1, 2, 5, 6, 7 and 9 in Table 1) are included to represent the effects of buildings and tree foliage; that is, the building-tree interaction terms (terms 3 & 4 in Table 1) and the effects of trees on the length scales (term 8) are not included. These six source terms comprise the proposed parameterization which is evaluated against CFD results. Building impacts on drag and length scales are parameterized as in Santiago and Martilli (2010), with updates according to Krayenhoff et al. (2014b).

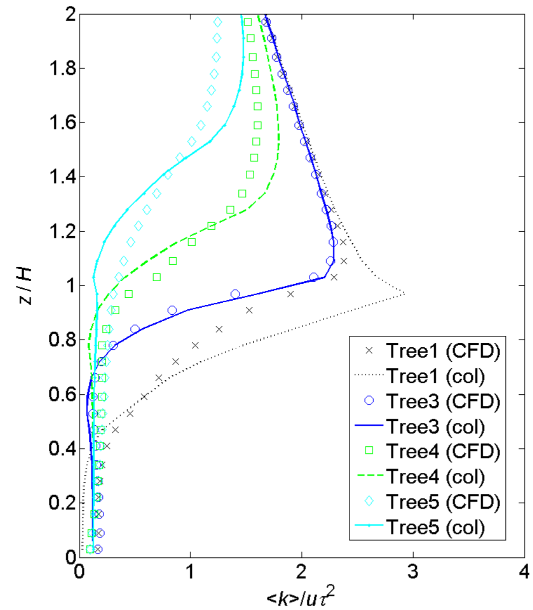

Figure 5: Same as Fig. 3, except for $\langle \overline{k} \rangle$.

Foliage height has a large impact on flow profiles (Figs. 3 and 5). For the range of scenarios considered here, $\langle \overline{u} \rangle$ and $\langle \overline{k} \rangle$ vary more with foliage height than with foliage density, and this is reproduced by the parameterization (Figs. 3-6). Largest errors for both $\langle \overline{u} \rangle$ and $\langle \overline{k} \rangle$ tend to appear in the building shear zone (i.e., $z \approx H$) or well above the canopy.

5. CONCLUSIONS AND DISCUSSION

Urban canopy parameterizations designed to be coupled with mesoscale models must predict the neighbourhood-scale average effect of obstacles on the flow at each height in and above the canopy without resolving the obstacles. To assess these neighbourhood-scale effects on the flow for simplified geometries, the results of microscale simulations may be horizontally-averaged. Here, obstacle-resolving

Computational Fluid Dynamics (CFD) simulations of neutral flow through canopies of blocks (buildings) with varying distributions and densities of porous media (tree foliage) are conducted, and the spatially-averaged impacts on the flow of these building-tree combinations are assessed.

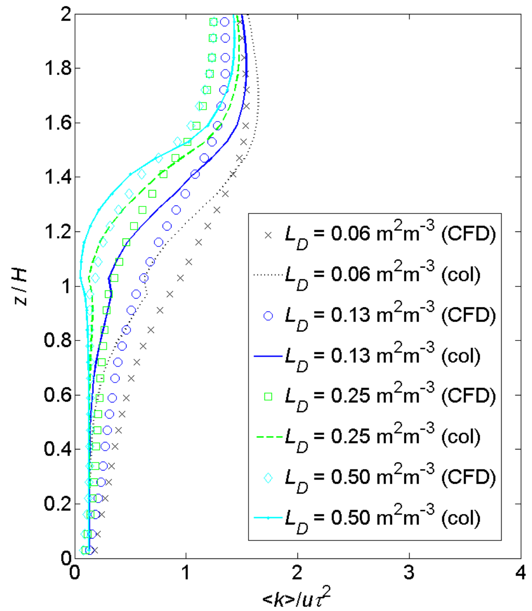

Figure 6: Same as Fig. 4, except for $\langle k \rangle$.

This work presents a methodology for determining the source/sink terms required in the momentum and turbulent kinetic energy equations to represent the spatial-average impacts of tree foliage on the flow. It builds on the work of Santiago and Martilli (2010) for neighbourhoods without trees. Considering the effects of both buildings and trees on flow, source terms deemed important and included in the new parameterization are the drag terms due to buildings and tree foliage in the momentum equation (and, although much less important, corresponding production terms in the turbulent kinetic energy equation for energy conservation), enhanced dissipation of turbulent kinetic energy by the small tree foliage wakes in the turbulent kinetic energy equation, and the modification of length scales due to buildings. The most notable finding is that interactions between buildings and trees in terms of drag and turbulent kinetic energy production are of little import for the prediction of the spatially-averaged flow profiles. As such, the impacts of trees and buildings on the spatially-averaged flow can be treated independently, or in other words, the *relative* impact of buildings on the flow, as represented by the building drag coefficient, is not affected by the presence of tree foliage. Note that the presence of trees will significantly affect the *absolute* value of the drag force exerted by buildings, and vice versa.

Impacts of tree foliage on length scales are also neglected in the parameterization, which causes significant errors for select cases, namely, for scenarios with dense foliage that is vertically coincident with sparse buildings. Hence, this is one limitation of the new parameterization, and resolution of this matter is left as future work. Overall, results indicate that tree foliage significantly impacts the mean and/or turbulent flow for a wide range of building densities if foliage protrudes above buildings, even for low leaf area density. Tree foliage also significantly impacts the flow when foliage tops are below roof height for lower building densities and with foliage of sufficient density. As such, the new parameterization of tree foliage impacts on the flow should be included for these scenarios in addition to the Santiago and Martilli (2010) parameterization for building-only neighbourhoods.

The new parameterization is a critical step in the development of a comprehensive urban canopy model for urban neighbourhoods with trees. Implementation of the new parameterization for drag and turbulent kinetic energy in a *k-l* column model is a simple way to capture the principal impacts of trees and buildings on neighbourhood-average flow and turbulence.

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