SIMULATIONS OF THE EFFECT OF CANOPY DENSITY PROFILE ON SUB-CANOPY WIND SPEED PROFILES

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ABSTRACT

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In computational simulations for weather prediction and fire simulation, forest canopies are often modelled as regions of aerodynamic drag. The magnitude of the drag term depends on the Leaf Area Density ($\boldsymbol{LAD}$) of the forest. For most forests LAD varies strongly with height; trees typically have more vegetation at the top of the canopy than at the bottom. Dupont, and Brunet (*Agricultural and forest meteorology*, 148(6), pp.976-990. 2008), simulated the flow through three very different profiles of $\boldsymbol{LAD}$ measured from three different Canadian forests, and Moon, Duff, and Tolhurst (*Fire Safety Journal*, 2016), recently measured the sub-canopy winds and $\boldsymbol{LAD}$ for seven different Australian forest types. Thus although, Large-Eddy Simulations (LES) of flow through idealised forests are now computationally tractable, a systematic study of different $\boldsymbol{LAD}$ profiles is missing, which motivates our investigation. Here we assume that the $\boldsymbol{LAD}$ can be modelled by a Gaussian profile with two parameters representing the mean and variance of the distribution of $\boldsymbol{LAD}$. The total vegetation density is maintained constant as the $\boldsymbol{LAD}$ profile changes. We present preliminary simulation results showing how the mean and variance of $\boldsymbol{LAD}$ affects the sub-canopy wind velocity, and we discuss a potential modelling approach for sub-canopy wind velocity.

INTRODUCTION

Understanding sub-canopy wind profiles is of crucial importance to parameterising the atmospheric boundary layer above a forest canopy and also estimating wind reduction factors for fire spread models. An analytic model exists for large, uniform canopy. That is, the occupied volume fraction, or leaf area density ($\boldsymbol{LAD}$) of the canopy is constant over the whole canopy. The model of Inoue [1963] is based on a balance between turbulent stresses and the drag force of the canopy assuming a uniform canopy. Harman and Finnigan [2007] significantly extended the Inoue model to include the above canopy flow and non-neutral atmospheric conditions.

In nature, there is strong variation $\boldsymbol{LAD}$ in all three spatial directions; the variation is most prominent in the vertical direction because trees typically have more vegetation at the top of the canopy than at the bottom. A limited investigation of the effect of vertical distribution of $\boldsymbol{LAD}$ on the sub-canopy wind profiles was conducted byDupont et al. 2008. Three different observed profiles of $\boldsymbol{LAD}$ from different forests were used, and the profiles were scaled to give a range of five different leaf area indices (integrated $\boldsymbol{LAD}$). Dupont et al. drew several important conclusions from this study: the gross features of the above canopy flow are unchanged by canopy profile; increasing the total $\boldsymbol{LAD}$ makes the features of the canopy flow more pronounced; finally there is considerable variation in the mean flow and turbulent profiles in the sub-canopy space. That is, close to the ground the difference in flow and turbulence profiles caused by different $\boldsymbol{LAD}$ profiles are seen more clearly.

Recently, Moon [2016] performed field measurements of sub-canopy wind speeds in Australian vegetation. The measurements of $\boldsymbol{LAD}$ by Moon et al. [2016], and similar measurements made by Amiro [1990], show considerable variability in the $\boldsymbol{LAD}$ profiles for different forest types around the world. Dupont et al. [2008] conduced simulations of canopy flow with three distinct $\boldsymbol{LAD}$ profiles similar to the spruce, pine, and aspen forests measured by Amiro [1990]. Here we parameterise forests with a Gaussian $\boldsymbol{LAD}$, systematically vary the mean and variance of the $\boldsymbol{LAD}$ distribution, and analyse the resulting sub-canopy flow with an eye towards constructing simplified models of the sub-canopy wind profile.

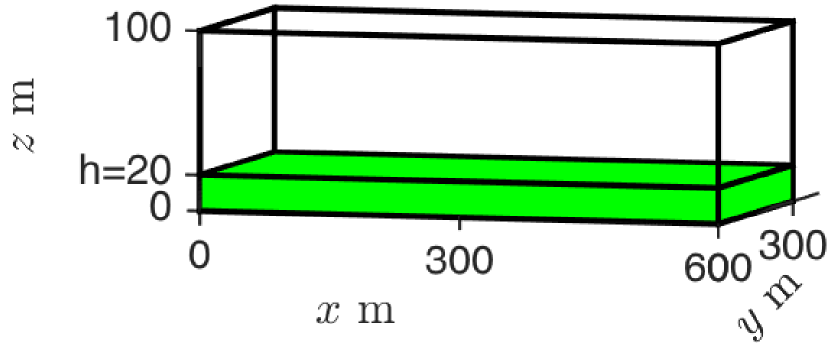

Figure 1: The simulation domain showing the canopy region, shaded in green. The boundaries in the $x-$ and $y-$directions are periodic, the top boundary is free slip and the bottom is a no-slip boundary.

NUMERICAL MODEL

We use Fire Dynamics Simulator (FDS) [McGrattan et al., 2013] to perform large eddy simulations (LES) of canopy flow. In LES, the continuity and Navier-Stokes equations are spatially filtered to retain the dynamically important large-scale structures of the flow. In FDS, the filtering operation is implicit at the grid scale. The largest eddies contain the most energy and therefore make the largest contribution to momentum transport. The diffusive effect of the unresolved small scales on the resolved large scales is non negligible. The constant Smagorinsky sub-grid-scale stress model (see, for example, Pope, 2001) is used in this work with the Smagorinsky constant set to $C = 0.1$. The flow is maintained by a pressure gradient equal to 0.005 Pa/m. The fluid is assumed to be air with density $\rho = 1.225$ kg/m^3 and viscosity $\nu = 1.8 \times 10^{-5}$ m^{2}s^{-1}.

The overall domain size is $600 \times 300 \times 100$ m $(30h \times 15h \times 5h)$, where the height of the canopy is taken as $h = 20$ m. The streamwise and spanwise boundary conditions are periodic. The bottom (ground) boundary condition is enforced using the log-law of the wall [Bou-Zeid et al., 2004]. The resolution of the simulation 5 m in the horizontal directions and 0.5 stretched to 4 m at the top of the domain. The resolution is approximately three times finer than the resolution used by Bou-Zeid et al. [2009]. A sketch of the simulation domain and the canopy location is shown in figure 1. The flow is allowed to develop to a statistically stationary state over approximately 3600 s and statistics are sampled every 2 s for 7200 s.

Following Dupont et al. [2011] the canopy of height h is modelled as an aerodynamic drag term of the form

$$F_{D,i,k}\,(x,z) = \rho c_D \chi(z; h, \mu, \sigma, A, B)\left(u_j u_j\right)^{1/2} u_i,$$

where the velocities are u_j .The value of the drag coefficient is taken to be $c_D = 0.25$ roughly consistent with the measurements of Amiro [1990] and the study of Cassiani et al. [2008]. The function $\chi(z, h, \mu, \sigma, A, B)$, defines the spatial location of the canopy. The canopy is assumed to have a constant height across the whole domain. Below the canopy height there is some LAD profile. In this study the LAD is assumed to be a Gaussian with some specified geometric mean μ and some variance σ. Physically, μ corresponds to the height at which the canopy is most dense; σ roughly measures the width of the leafiest part of the tree crowns.

The LAD profile is:

$$\chi(z; h, \mu, \sigma, A, B) = \begin{cases} \mathrm{A}\exp\left(-\dfrac{(z-\mu)^2}{\sigma^2}\right) + B\,, & z \le h \\ 0 \qquad , & z > h \end{cases},$$

We firstly assume that $h = 20$ m is constant. The Leaf Area Index (LAI), that is integral of LAD with respect to z over the canopy, is also fixed and for this report we consider only $LAI = 1$. We use this constraint to determine:

$$A = \frac{1 - Bh}{\displaystyle\int_0^h \exp\left(-\frac{(z-\mu)^2}{\sigma^2}\right) dz}.$$

Because A is considered to be positive, $B < \frac{1}{h}$. We somewhat arbitrarily assumed that B contributes approximately 10% of the LAD and therefore we fixed $\frac{B}{A} = 0.1$. This assumption was justified by fitting profiles to the measurements of Moon et al. Profiles of LAD are shown in figure 2 and the simulation cases are tabulated in table 1.

Table 1: Simulation LAD parameters for all cases.

LAI	μ	σ^2	A	B/A
1.000	0.700	0.050	0.104	0.100
1.000	0.700	0.142	0.075	0.100
1.000	0.700	0.233	0.065	0.100
1.000	0.000	0.325	0.084	0.100
1.000	0.233	0.325	0.064	0.100
1.000	0.467	0.325	0.057	0.100
1.000	0.700	0.325	0.061	0.100

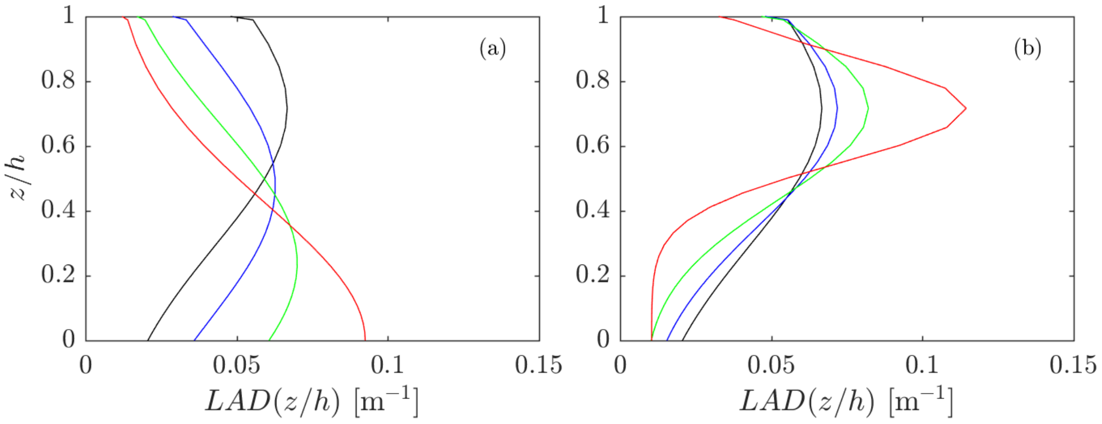

Figure 2: LAD profiles used in this study. In (a) σ^2=0.325 is held constant and μ= 0.00 (red), 0.233 (green), 0.467 (blue), and 0.700 (black). In (b) μ=0.70 is constant and σ^2=0.325 (black – the same curve as in (a)), 0.233 (blue), 0.142 (green), and 0.050 (red).

RESULTS AND DISCUSSION

The simulated mean wind profiles are shown in figure 3. The profiles are all normalized by the value of the wind speed at the top of the canopy at $z/h = 1$. In figure 3(b) there is a significant local maximum at approximately $z/h = 0.3$ for the profile with $\mu = 0.7$, $\sigma^2 = 0.05$ (red). The local maximum of velocity is likely to be a consequence of using an imposed pressure gradient to drive the mean flow through the domain.
The Harman and Finnigan [2007] model for neutral flow over a canopy with known LAI and drag coefficient relies on three parameters: β the ratio of friction velocity to $u(z = h)$ –velocity at the canopy top, z_0 the equivalent roughness length of the canopy, and d the displacement height of the canopy (defined below). These three parameters may be measured from our simulations. The computed β are shown in figure 4, d in figure 5, and z_0 in figure 6 all plotted against the canopy parameters μ and σ^2. β shows weak linear growth with is approximately constant with μ, and β is approximately constant with σ^2. The observations of Harman and Finnigan [2007] suggest that β is constant independent of the canopy LAD distribution. The β values

(approximately $\beta = 0.2$) simulated here are lower than typically observed for these flows; nonetheless, the values observed here are consistent with those observed $\beta = 0.3$ by Harman and Finnigan [2007] and Mueller et al. [2014] observe simulated values close to $\beta = 0.3$. The reason for the lower values observed here may be due to Reynolds number effects. The canopy top velocities (of the order 2 ms^{-1}) simulated here are approximately twice the canopy top velocities simulated by Mueller et al. Further work is required to explore the possible Reynolds number dependence of $\beta = 0.3$. The displacement length d by is estimated using the centroid of drag force [Garratt,1992]

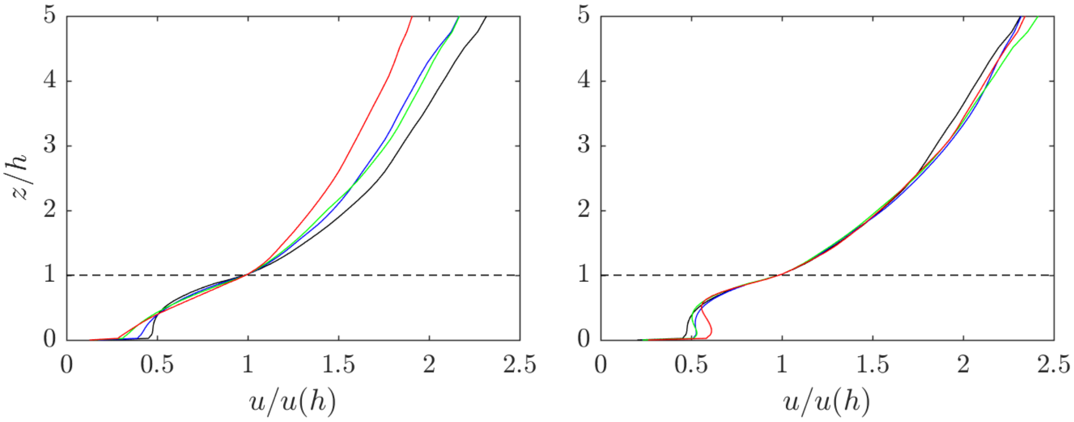

Figure 3: Mean u-velocity profiles normalised by the canopy top value. In (a) σ^2=0.325 is held constant and μ= 0.00 (red), 0.233 (green), 0.467 (blue), and 0.700 (black). In (b) μ=0.70 is constant and σ^2=0.325 (black – the same curve as in (a)), 0.233 (blue), 0.142 (green), and 0.050 (red).

$$d = \frac{\int_0^h \left(z\,\mathrm{Aexp}\left(-\frac{(z-\mu)^2}{\sigma^2}\right) + B \right) u^2\,dz}{\int_0^h \left(\mathrm{Aexp}\left(-\frac{(z-\mu)^2}{\sigma^2}\right) + B \right)\ u^2\,dz}$$

The values of simulated displacement length are of the same order as experimentally observed [Dolman, 1986]. The displacement length exhibits strong linear variation with canopy parameters μ and σ^2. The displacement length increases with increasing μ as LAD becomes concentrated at greater heights, similarly the displacement length decreases with increasing σ^2 as the LAD is distributed over a larger range of heights. The roughness length z_0 was determined from a least-squares regression fit to the average velocity data above the canopy.

The functional form of velocity profile that was fitted was a standard log-law [Zhu et al. 2016]

$$u = \frac{u_*}{\kappa} \log \frac{z-d}{z_0},$$

where $\kappa = 0.38$ is von Karmann's constant. The fitted values for z_0 are in agreement with the observations of Dolman [1986] and the values obtained for z_0 do not exhibit

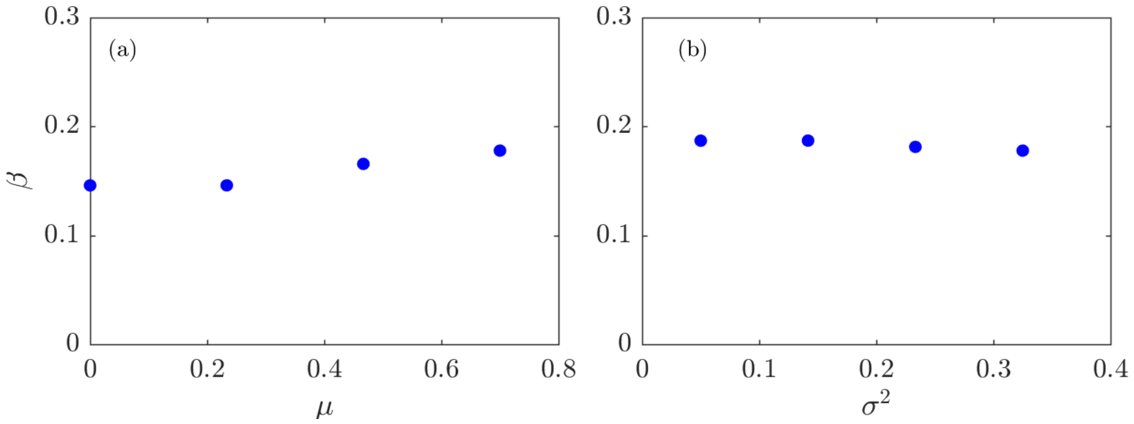

Figure 4: β displacement length variation with (a) μ, and (b) σ^2

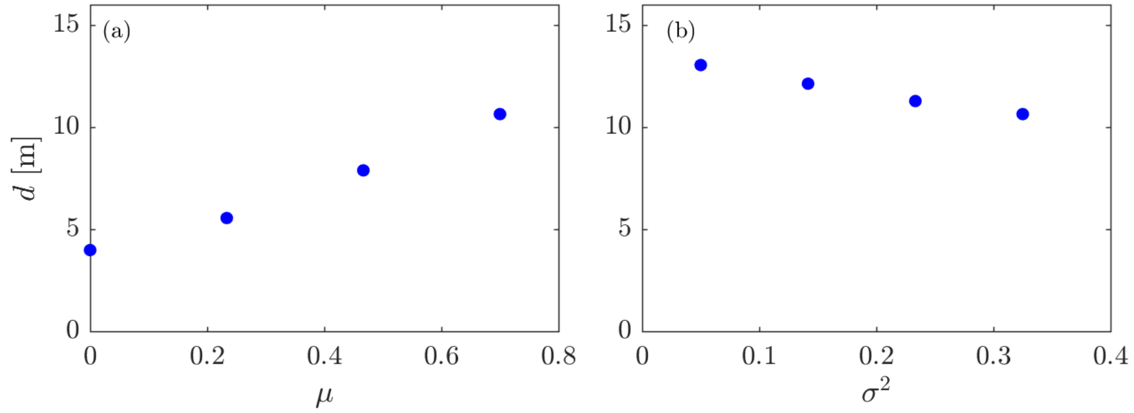

Figure 5: d displacement length variation with (a) μ, and (b) σ^2

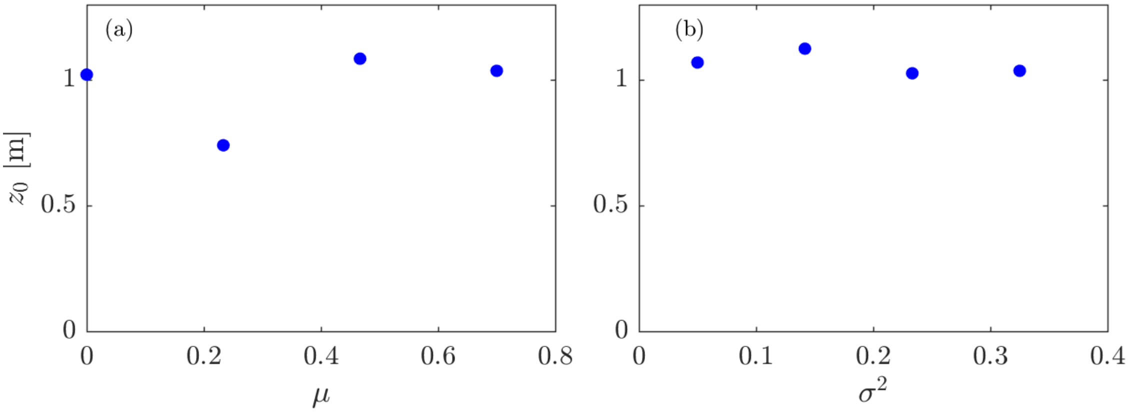

Figure 6: z_0 roughness length variation with (a) μ, and (b) σ^2

strong variation with the canopy parameters. These results suggest that μ, the geometric mean of LAD, is the only parameter that significantly influences the above-canopy flow through the displacement length.

Inoue [1963] developed a momentum-balance model to determine the sub-canopy wind profiles deep within a canopy. The Navier-Stokes equations may be averaged in time and in space for a LAD that is constant in the $x-$, $y-$, and $z-$directions. The canopy is thought of as infinitely deep. The pressure gradient term is also assumed to be negligible relative to the turbulent stress term $\tau_{x,z}$ and the drag term. The momentum balance is then

$$\frac{\partial \tau_{x,z}}{\partial z} + F_{D,x} = 0 \,.$$

The turbulent stress term may then be modelled using the mixing length approximation. The drag term is modeled as before, however, we assume that the canopy has uniform leaf area index. This gives the following ordinary differential equation

$$\frac{\partial}{\partial z}\left(l \frac{\partial u}{\partial z}\right)^2 + c_D LAI u^2 = 0 \;,$$

Boundary conditions are that the velocity derivative vanishes as $z \to -\infty$ and the canopy top velocity U_h is known. The equation has solution:

$$u = U_h \exp \frac{\beta(z-h)}{l} \,,$$

Scaling arguments which depend on a constant LAD profile show that the mixing length $l = 2\beta^3/c_d LAI$. Harman and Finnigan [2007] that the exponential profile agrees sufficiently well with observed sub-canopy profiles. The most commonly violated assumption of the Inoue model is the canopy has finite depth. In practical terms, the Inoue model works for the top part of the canopy and progressively makes poor predictions near the ground. In these simulations there is the presence of a driving pressure gradient and LAD is not constant in the $z-$direction. Hence we expect that the model of Inoue [1963] will give poor agreement through the canopy.

The model of Inoue is tested by comparing the simulated sub-canopy velocity profiles with the modelled profiles using the firstly the simulated values of β (figure 4) and the value β=0.3 observed by Harman and Finnigan [2007]. The comparison between the simulated and modelled profiles are shown in figure 7(a) and (b). The modelled profiles with the simulated value of β do not agree well with the simulated profiles. However, using the value of β=0.3 observed by Harman and Finnigan [2007] improves the agreement in the top half of the canopy. To reduce the discrepancy between the modelled and simulated profiles we attempt to address the assumption of a constant LAD profile. Because the displacement length is the only quantity that varies significantly with the canopy parameters, it is hypothesised that d is a more relevant length scale than the constant canopy height h. Therefore we define the displacement length Leaf Area Index ($dLAI$) as

$$dLAI = \int_0^d \mathrm{A} \exp\left(-\frac{(z-\mu)^2}{\sigma^2}\right) + B \, dz \,,$$

that is, the leaf area index computed from $z = 0$ to $z = d$ instead of $z = h$. The $dLAI$ is then used in place of LAI in the Inoue model. The modified model predictions, using the simulated values of β, are compared to the simulated profiles in figure 7(c) and (d). Agreement between the modeled and simulated profiles in the top half of the canopy is significant but far from perfect. The modelled profiles do not agree with the simulated in the bottom half of the canopy and further work is required to improve the Inoue model in the near ground region.

CONCLUSIONS

The effect of LAD distribution on flow over a tree canopy was investigated using LES. The geometric mean μ and variance σ^2 of the LAD distribution were varied independently. The sub-canopy mean flow profile was found to be sensitive to both μ and σ^2, with the emergence of a prominent sub-canopy peak of u −velocity. The parameters of the above canopy flow, namely β the ratio of shear stress to u −velocity at the canopy top and z_0 the equivalent roughness length of the canopy, and d the displacement length, were found to be largely independent of σ^2. β exhibits a weak dependence on μ but z_0 appears to be independent of both μ and σ^2. The displacement length exhibits strong linear dependence μ and a weaker linear dependence on σ^2. Finally the sub-canopy u −velocity model of Inoue [1963] was improved by including the displacement length.

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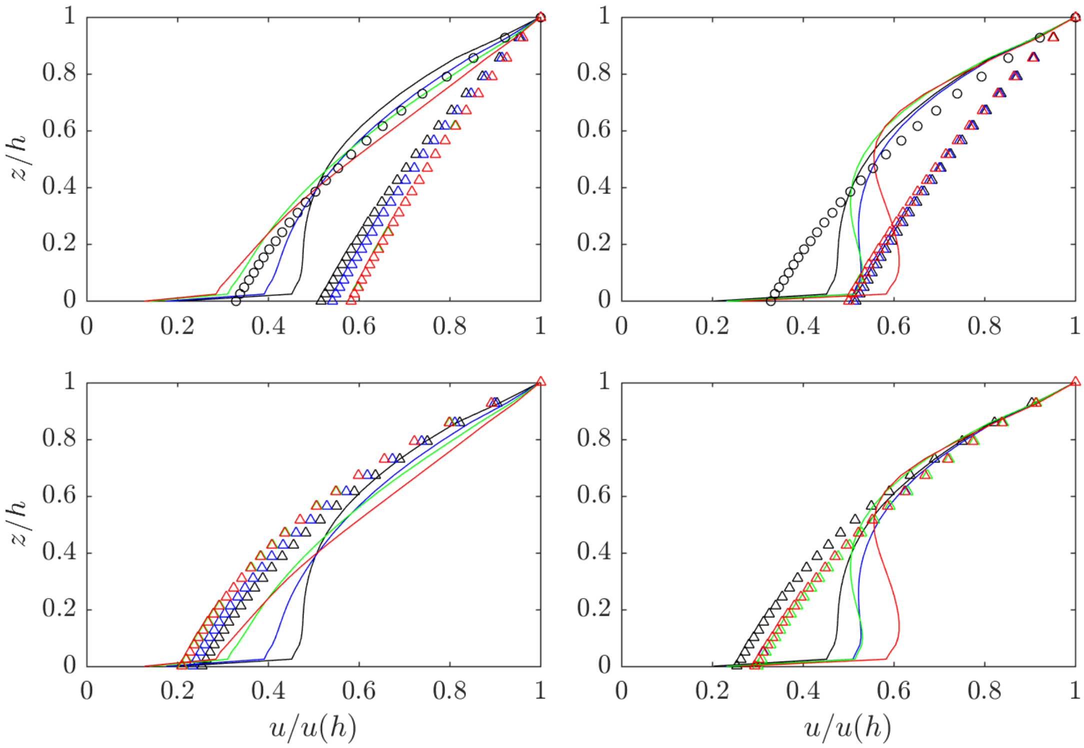

Figure 7 Modelled and simulated sub-canopy u –velocity profiles. (a and b) contain the modelled profiles using the simulated β (triangle symbols) and the observed β (circle symbol) of Harman and Finnigan [2007] and a constant mixing length based on LAI. The modelled profiles in (c and d) use the simulated β and $dLAI$.

(a) σ^2=0.325 is held constant and μ= 0.00 (red), 0.233 (green), 0.467 (blue), and 0.700 (black). In (b) μ=0.70 is constant and σ^2=0.325 (black – the same curve as in (a)), 0.233 (blue), 0.142 (green), and 0.050 (red). (c) and (d) are the same curves as (a) and (b) respectively.