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Flow over partially forested ridges

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Abstract Numerical simulations of flow over hills that are partially covered with a forest canopy are performed. This represents a much more realistic situation than previous studies that have generally concentrated on hills that are fully-forested. The results show that the flow over the hill is sensitive to where on the hill the forest is positioned. In particular, for low slopes flow separation is predominantly located within the forest on the lee slope. This has implications for the transport of scalars in the forest canopy. For large hills the results show more variability in scalar concentrations within the canopy compared to either a fully forested hill or a patch of forest over flat terrain. These results are likely to have implications for a range of applications including the siting and interpretation of flux measurements over forests in complex terrain, predicting wind damage to trees and wind-farm developments.

Calculation of the hill-induced pressure drag and canopy-plus-surface stress drag shows a strong sensitivity to the position of the forest relative to the hill. Depending on the position of the forest the individual drag terms may be strongly enhanced or reduced and may even change sign. The net impact is generally to reduce the total drag compared to an equivalent fully-forested hill, but the amount of the reduction depends strongly on the position of the forest canopy on the hill.

In many cases with large, wide hills there is a clear separation of scales between the adjustment of the canopy to a forest edge (of order $6-8L_c$, where L_c is the canopy adjustment length scale) and the width of the hill. This separation means that the hill-induced pressure and flow fields and the forest-edge induced pressure and flow fields can in some sense be considered as acting separately. This provides a means of explaining the combined effects of partial forestation and terrain. It also offers a simple method for modelling the changes in drag over a hill due to partial forest cover by considering the impact of the hill and the partial canopy separately. Scaling

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arguments based on this idea successfully collapse the modelled drag over a range of different hill widths and heights and for different canopy parameters. This offers scope for a relatively simple parametrization of the effects of partial forest cover on the drag over a hill.

Keywords Flow over a hill, Forest canopy, Forest edge, Partial forest cover, Pressure drag, Scalar transport

1 Introduction

The dynamics of airflow in and above inhomogeneous forest canopies has become a topic of interest in recent years. This has largely been motivated by an interest in understanding the advective effects in flux measurements (primarily fluxes of CO_2) over forests. There are, however, a significant number of other reasons for interest in flow over inhomogeneous canopies, for example predicting wind damage to trees and estimating potential wind energy.

Recently Belcher et al. (2008) highlighted two common examples of such inhomogeneities, namely forest edges and hills, and discussed their individual impact on transport. Studies of the impact of a forest edge on airflow date back some time, and Lee (2000) provides a good review of some of the earlier work. More recent observations include those of Morse et al. (2002). These observations have been supported by modelling studies including the large-eddy simulations of Yang et al. (2006),Dupont and Brunet (2008) and Cassiani et al. (2008). Belcher et al. (2003) developed an analytical solution to explain the adjustment of the flow to a forest edge, helping to highlight the different dominant processes in different regions of the flow. More recently Ross (2012) studied the related problem of flow within and above a canopy with a slowly changing canopy density, as opposed to the discontinuous change occurring at a forest edge, using both analytical and numerical models.

There has also been significant work on the flow over forested hills over recent years. Again, this includes analytical models (Finnigan and Belcher, 2004; Harman and Finnigan, 2010), numerical simulations (Ross and Vosper, 2005; Ross, 2008, 2011; Dupont et al., 2008; Patton and Katul, 2009) and laboratory experiments (Finnigan and Brunet, 1995; Poggi and Katul, 2007a,b,c). These studies have been largely motivated by understanding the induced flow and the transport of CO_2 and other scalars over forested hills. Ross and Vosper (2005) discussed the impact of the canopy on the pressure drag exerted by the hill on the atmosphere, an important effect that requires parametrization in weather and climate models.

These studies have helped to explain the individual effects of the flow across a canopy edge, or flow over a fully-forested hill. In reality, most hills are actually partially forested, and so these two problems cannot be considered in isolation. Using a numerical model Allen (2006) studied flow over hills of variable roughness, however this study only uses a roughness length parametrization of the vegetation rather than explicitly modelling the canopy. Similarly Inglis et al. (1995) compared observations over a partially-forested site with results from a linear model including both terrain and a variable roughness length. More recent detailed field experiments over a partially-forested ridge described in Grant (2011) show the sensitivity of the flow to partial canopy cover but do not include any systematic assessment of their importance. The present study looks at flow over partially-forested hills using a numerical model with an explicit representation of the canopy. In particular it studies the effect of different positions of a patch of forest relative to the hill. In all cases the forest covers half of the total area of the hill. Sect. 2 presents some simple scaling arguments and considers the impact of these on the drag over a partially-forested hill. Sect. 3 describes the numerical model used in this study and the setup of the simulations, and a general description of the flow over partially-forested hills is presented in Sect. 4.1 along with the impact of this flow on tracer transport. This is followed up in Sect. 4.2 by a more detailed study of the surface pressure, surface stress and canopy drag distributions across the hill and the impact these have on the total drag exerted by a partially forested hills. Finally Sect. 5 offers conclusions.

2 Theory

2.1 Scaling arguments for flow over partially-forested hills

The momentum equation for flow through a forest canopy can be written as

$$\rho \frac{D\mathbf{U}}{Dt} = -\nabla p + \nabla \cdot \tau - \rho C_d a \mathbf{U}|\mathbf{U}|, \tag{1}$$

where the final term, $-\rho C_d a \mathbf{U}|\mathbf{U}|$, is the additional drag term due to the canopy, with $\mathbf{U}$ the velocity of the flow. The canopy also modifies the turbulent fluxes in the Reynolds stress tensor, τ; the pressure is denoted by p. The key parameter for considering the adjustment of the flow to a canopy is the adjustment length $L_c = 1/(C_d a)$ where C_d is the canopy drag and a is the leaf area density (Belcher et al., 2008).

Over partially-forested hills there are two processes leading to perturbations in the flow. Both can, to leading order, be considered to be driven by inviscid pressure perturbations (Belcher et al., 2003; Finnigan and Belcher, 2004), at least for wide hills. Following Belcher et al. (2003) the pressure perturbation induced by a forest edge scales on $p \sim \rho U_0^2 h/L_C$ (where U_0 is the background velocity scale and h is the canopy depth) while the pressure perturbation induced by a hill scales on $p \sim \rho U_0^2 H/L$ (where H and L are the height and width of the hill). In terms of the induced flow patterns it is the pressure gradient dp/dx that appears in the momentum equation. For the forest edge the changes are over a distance scaling on L_c so $dp/dx \sim \rho U_0^2 h/L_c^2$. Typically the flow adjusts to a canopy edge over a distance of $4.5L_c - 6L_c$ (Belcher et al., 2012), while for a hill the changes are over the scale of the hill width, L and so $dp/dx \sim \rho U_0^2 H/L^2$. In general $L_c \ll L$ and so forest-edge induced pressure gradients are localized. The ratio of the two pressure gradient terms gives $hL^2/(HL_c^2)$, which determines the relative importance of the hill and the canopy edges in determining the pressure gradient. This separation in scales between the-canopy edge adjustment length scale and the hill width suggests that in many cases flow near the forest edge will be dominated by the relatively localized edge effects, while away from the forest edge hill effects will dominate. In Sect. 2.2 this idea of scale separation is extended to develop a scaling theory for the drag exerted by a partially-forested hill. It is also used to interpret results from numerical simulations described in Sect. 4.1.

2.2 Drag exerted by a forested hill

The drag exerted by the hill and forest on the flow is made up of three parts - the pressure drag, F_p, the surface shear stress, F_s and the canopy drag, F_c. The first two act at the surface and the third acts throughout the canopy. In two dimensions the three terms can be evaluated as,

$$F_p = -\int_{-2L}^{2L} p_{sur} \frac{dh}{dx} dx, \tag{2}$$

$$F_s = -\int_{-2L}^{2L} \tau \cdot \mathbf{n} ds, \tag{3}$$

$$F_c = -\int_{-2L}^{2L} \int_{-h}^{0} C_d |\mathbf{U}| u dz dx, \tag{4}$$

where p_{sur} is the surface pressure, τ is the surface stress tensor, $\mathbf{n}$ is the normal to the slope, s is the along-slope coordinate, $\mathbf{U}$ is the wind speed and u is the component of the wind in the x direction. Even in the absence of a hill the canopy drag and surface stress drag are significant. From the point of view of this study the interest is in assessing the change in these quantities with the inclusion of a partially-forested hill compared to the drag over flat ground. These perturbed canopy and surface stress terms are labelled ΔF_c and ΔF_s. At each location across the hill the background state used to calculate the perturbations are the drag terms over the equivalent uniform flat canopy if the location is within the canopy and the drag terms over the equivalent uniform rough surface otherwise.

Ross and Vosper (2005) investigated the drag over a fully-forested hill in detail. They showed that the pressure drag dominates over the canopy drag in many cases, and that for deep canopies the surface shear stress is negligible since the stress terms tend to zero deep in the canopy. There are two processes controlling the pressure drag over a forested hill: a) the thickening of the shear-stress layer (SSL) in the lee of the hill through the 'non-separated sheltering' mechanism of Belcher et al. (1993), which even occurs over a rough surface, and b) the enhanced thickening of the SSL due to asymmetric canopy top vertical velocities induced by flow in the canopy. Ross and Vosper (2005) used the theory of Finnigan and Belcher (2004) to estimate the importance of these two effects. For large and relatively steep hills (which are most important in terms of total drag) then the first process dominates. The total pressure drag over a forested hill in this case is very similar to the pressure drag over an equivalent rough hill (see Fig. 10 of Ross and Vosper, 2005). Belcher et al. (1993) therefore provide a useful estimate of the pressure drag

$$F_{full} = \rho u_*^2 \frac{H^2}{L^2} L \frac{1}{S^4} \frac{\pi^2}{2} \tag{5}$$

over a full forested hill where $S = U_B(h_i)/U_B(h_m)$ is a measure of the shear across the middle layer. Even for cases where the canopy-induced flow increases the asymmetry this expression provides a useful lower bound on the drag.

Over partially-forested hills the situation is more complicated. Precisely where over the hill the forest lies makes a significant difference to the pressure field and hence to the pressure drag.

The impact of a partial canopy on the pressure drag can be estimated using the scaling for the pressure induced by a canopy edge in Sect. 2.1. If the pressure change at a forest edge scales on $\rho U_0^2 h/L_c$ and this change occurs over a distance that scales on L_c then the additional drag contribution from the partial canopy will scale on

$$F_{part} = \rho U_0^2 h(H/L). \tag{6}$$

The relative change in drag over a partially-forested hill therefore scales on

$$F_{part}/F_{full} = \frac{U_0^2}{u_*^2} \frac{h}{H} S^4 \frac{2}{\pi^2}. \tag{7}$$

Interestingly this shows that the relative change in pressure drag due to a partially forested hill is independent of the wind speed (u_* scales on U_0 for a given hill and canopy). The hill width, L and the canopy adjustment length scale, L_c only enter indirectly through the dependency of the inner and middle layer heights on these parameters. The hill and canopy parameters only enter directly through the non-dimensional group h/H, although there is some implicit dependence through the middle layer shear, S. The explicit dependence on h/H suggests that deeper canopies / lower hills result in the partial canopy having a bigger impact on the pressure drag.

For partially-forested hills shear stress cannot necessarily be neglected since there are regions where there is no forest cover and so the surface shear stress is no longer small. There may also be significant variations in the canopy drag and shear stress depending whether the forest canopy is in a region where the hill-induced pressure field is accelerating or decelerating the flow. Using the idea of separation of scales one might expect that for most of the flow the surface stress and canopy drag at a point will be similar to the equivalent rough hill or canopy simulation. A reasonable first guess at the total canopy drag and shear stress terms for a partially-forested hill would be to integrate the canopy drag term from the fully-forested hill over just the part of the hill where the canopy is located, and to integrate the surface stress from the fully rough hill simulation only over the unforested part of the hill. In theory this could be done using the analytical solutions of Belcher et al. (1993) and Finnigan and Belcher (2004), however, here, we take a practical approach and do this numerically using the relevant simulations. One further point to note is that one would expect simulations with a full canopy and with a rough surface of the equivalent roughness length to agree in the rough surface limit (see discussion in Finnigan and Belcher, 2004; Ross and Vosper, 2005, for details) and so the sum of these canopy drag and shear-stress terms should vary relatively little compared to the individual variations canopy and stress terms as the location of the canopy on the hill changes. We will revisit these theoretical ideas when analyzing the results of the numerical simulations described below.

3 Model simulations

Simulations were carried out using the BLASIUS model from the UK Met Office (Wood and Mason, 1993), which solves the time-dependent Boussinesq equations in a terrain-following coordinate system. The simulations described here are conducted with a 1.5-order turbulence closure scheme with a prognostic equation for turbulent kinetic energy. The canopy is represented through a drag term in the momentum equation, and a modified mixing length in the turbulence scheme. Full details are given in Ross and Vosper (2005). The model has previously been used for studying the dynamics and scalar transport in flow over canopy-covered hills (Brown et al., 2001; Ross and Vosper, 2005; Ross, 2011) and for flow through canopies of variable density (Ross, 2012) as well as in the study by Allen (2006) of flow over hills with variable roughness.

A uniform canopy density, $a = 0.25$ or $0.4\,\mathrm{m}^{-1}$ and a fixed canopy drag coefficient ($C_d = 0.25$) were used for all simulations, giving values for the canopy adjustment length, $L_c = 1/(C_d a)$, of 16 m or 10 m respectively. These are the same values used in previous idealized studies (e.g. Finnigan and Belcher, 2004; Ross and Vosper, 2005) and are representative of values observed in real forest canopies (see e.g. Finnigan, 2000). The empirical parameter, β, which measures the ratio of the friction velocity to the mean wind speed at canopy top, is taken as 0.3, as in Ross and Vosper (2005) and consistent with observations over real forests (Finnigan, 2000) and in large-eddy simulations (Ross, 2008). This parameter controls the relationship between L_c, the canopy mixing length, $l = 2\beta^3 L_c$, and displacement height, $d = l/\kappa$, where κ is the von Karman constant, as described in Finnigan and Belcher (2004) and Ross and Vosper (2005). In the experiments described here a fixed canopy height $h = 10\,\mathrm{m}$ was used.

To visualize the transport within and above the canopy simulations include a passive tracer, which is released uniformly within the canopy at a constant rate. As in Ross (2011) a matching sink is present at the top of the domain to ensure the tracer reaches a steady-state solution. A no-slip lower boundary condition is used, with a constant roughness length equivalent to the effective roughness length of the forest canopy $z_0 = \frac{l}{\kappa} e^{-\kappa/\beta} = 0.35\,\mathrm{m}$ or $0.23\,\mathrm{m}$ used throughout the domain. This is on the large side, but it means that the effective roughness is the same everywhere across the hill so that any changes in the flow, particularly in terms of the drag, are a result of changes in displacement height and / or the canopy-induced flow rather than being a result of changes in roughness length. If anything, the use of a smaller and more realistic surface roughness length would tend to enhance the differences between the forested and unforested regions, although the work of Allen (2006) showed that roughness length changes on their own only produce a relatively small effect over a hill.

In all cases the domain is two dimensional with a horizontal resolution of between 3.125 m and 6.25 m depending on the domain and hill dimensions. This resolution is required to ensure that the adjustment region at the canopy edge, which is $\sim 6L_c$, is adequately resolved. The domain width varies depending on the hill width, but the domain depth is fixed at 5000 m. A stretched grid is used in the vertical with 80 grid points and a resolution of 0.5 m near the surface increasing gradually to 90 m at the

Table 1 Hill and canopy parameters for the model configurations used.

Configuration	H (m)	L (m)	L_c (m)
Large	160	1600	10
Small	10	100	10
Large shallow	80	1600	10
Large sparse	160	1600	16
Medium	80	800	10

domain top. The flow is forced by a constant wind speed of $10\,\mathrm{m\,s^{-1}}$ at the top of the domain. Periodic boundary conditions are used for all simulations and the flow is always assumed neutral. A periodic hill is used with $h(x) = (H/2)\cos(\pi x/(2L))$ where H is the hill height and L is the hill half width. The simulations therefore represent neutral flow over an infinite series of identical sinusoidal hills that are partially covered with forest. For most of the simulations the hill height and half width are chosen so that the slope of the hill is the same, with a maximum slope of $\pi H/(4L) = 0.079$. The only exception is the large shallow hill that has a slope of half the size.

For each model configuration a series of simulations was conducted. In all cases with partial forest cover, the forest extended over half of the hill, and simulations were conducted with the forest at eight different locations across the hill to investigate the dependence of the flow on forest position relative to the hill. For each configuration simulations with a fully-forested hill, with an unforested, rough hill and over flat ground with full, partial and no forest cover were also performed for comparison. Table 1 summarizes the model configurations used. Detailed results from the first two configurations are presented in Sect. 4.1, while results from the remainder of the configurations are used in Sect. 2.2.

For comparison, the large and small hill simulations with full canopy cover are equivalent to those presented in Ross and Vosper (2005) and Ross (2011) and the values of the canopy parameters are typical of the values observed in real forests (see e.g. the canopies presented in Finnigan, 2000).

4 Results and discussion

4.1 Mean flow and tracer concentrations over a large and small hill

Fig. 1 shows the tracer concentration and streamlines over the large hill with $L = 1600\,\mathrm{m}$ and $H = 160\,\mathrm{m}$. In this case the parameter $hL^2/(HL_c^2) = 1600$ and so the pressure gradient induced by the canopy edge is likely to be larger than the hill-induced pressure gradient, but will be localized to the vicinity of the canopy edge. The analysis of Belcher et al. (2012) suggest this occurs over a distance $\sim 6-8L_c$.

Fig. 1a shows the results for a fully-forested hill which is the same large hill and canopy used in the simulations of Ross and Vosper (2005) and Ross (2011). A region of separated flow extends over most of the lee slope and results in enhanced concentrations of tracer near the bottom of the hill, as discussed in Ross (2011). Fig. 1b shows the results with no hill, but with the forest canopy only occupying half of the domain. The streamlines show significant vertical motion as the flow impinges on the canopy. Adjustment to the presence of the canopy appears to take place over a horizontal distance of order $8L_c$ from the canopy edge. Fig. 2a shows this more clearly in a zoomed-in section around the leading edge of the canopy. While the flow above the canopy adjusts on this length scale, it takes longer for the flow within the canopy to adjust. In this canopy the adverse pressure gradient persists for greater distances downstream and so leads to flow separation at around $8L_c$ from the canopy edge and a recirculation region extending to about $26L_c$ from the canopy edge. The highest tracer concentrations are seen near the flow separation point (as in many of the simulations of Ross, 2011). Behind this recirculation region the flow descends back into the canopy (leading to lower tracer concentrations) before the canopy flow reaches a quasi-horizontally uniform state. This separation near the upwind canopy edge is not seen in all studies, however it is observed in the large-eddy simulations of Cassiani et al. (2008). We speculate that this is likely to depend on the details of the canopy structure and potentially the model turbulence scheme. At the downwind edge of the canopy there is another separation point and a region of recirculated flow in the lee of the forest extends a few L_c from the forest edge (see Fig. 2b). This leads to a very rapid decrease in the near-surface tracer concentration in the lee of the forest. This downwind separation region is much smaller than that seen at the upwind canopy edge.

Together these two figures show the individual impact of the hill and the canopy edge on the flow. Figs. 1c-f show the combined effect of hill and partial canopy for four cases with the canopy covering half of the domain, but centred on different locations. The presence of the forest edge is still the significant factor in all cases, with flow being broadly forced up over the canopy and then descending on the lee side. The details of the flow near the canopy edge though are dependent on the position relative to the hill, and hence on the large-scale hill-induced pressure gradient (see Figs. 2c-f). For the case where the forest lies entirely over the upwind or downwind slope (Fig. 1c) then the flow near the canopy edges (Fig. 2c) looks very similar to the case over flat ground, (Fig. 2a) because the hill-induced pressure gradient is small near $x/L = -2$ and $x/L = 0$ and so canopy-edge effects dominate. The negative hill-induced pressure gradient through the rest of the canopy accelerates the flow within the canopy and by continuity draws air down through the canopy top (see Fig 1c). Over the bare lee slope the adverse hill-induced pressure gradient is not strong enough to induce flow separation, even when coupled with the adverse pressure gradient in the lee of the forest. For cases where some or all of the forest canopy lies over the lee slope (Figs. 1d-f) then a greatly enhanced recirculation region is seen within the canopy compared to the partial canopy over flat ground, Fig. 1b, since the adverse pressure gradient from the hill acts to promote flow separation. The flow separation and recirculation region is entirely confined to the canopy. In the absence of the canopy, flow separation does not occur for this hill (figure not shown). This is an example of the importance of the canopy in promoting flow separation over moderate slopes (see Ross and Vosper, 2005, for details). In all these cases, in addition to the large-scale flow separation caused by the hill-induced pressure gradient, there is also a small recirculation region observed near the leading canopy edge due to the canopy-edge induced pressure gradient, as seen in Figs. 2d-f. The canopy edge re-

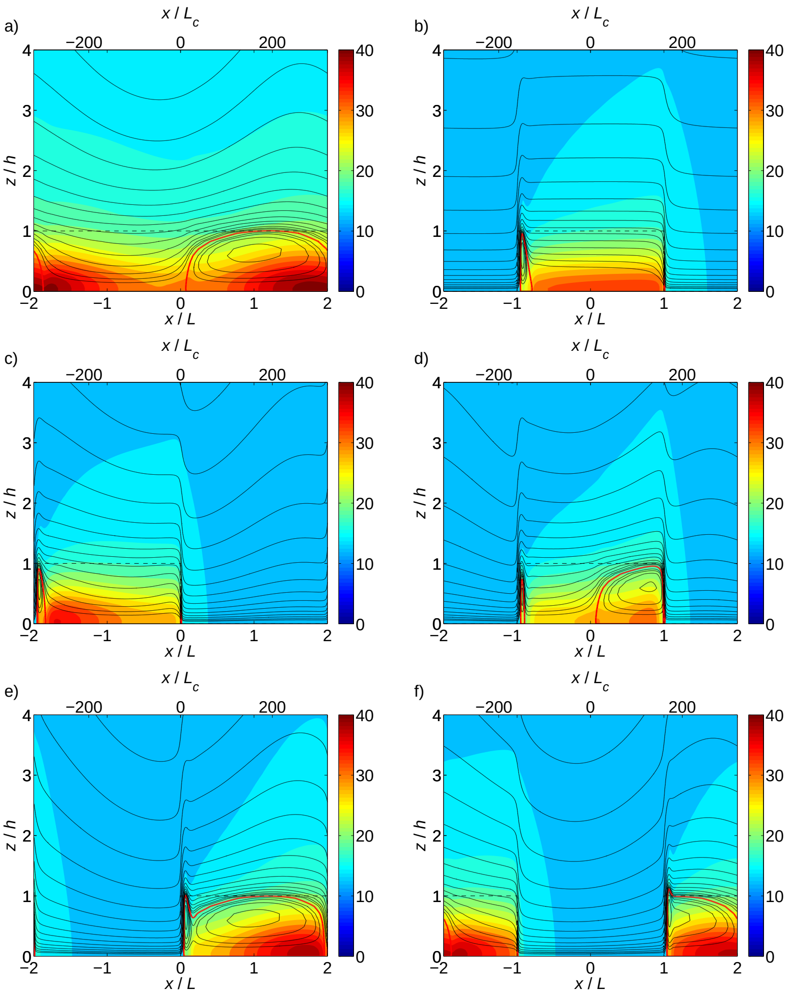

Fig. 1 Tracer concentration (shading) and streamfunction (lines) plotted over a partially-forested large hill. The spacing of the streamfunction contours is logarithmic for clarity both in and above the canopy. The bold red line marks the dividing streamline of the separation region. The forest canopy is marked with a dashed line. In each case the domain width is 6400 m ($L = 1600$ m), the hill height, $H = 160$ m. Results are plotted in a coordinate system with z as the height above the surface to make comparison easier between cases with and without a hill. Results are shown for (a) fully-forested hill, (b) no hill, (c) forest from $x/L = -2$ to 0, (d) forest from $x/L = -1$ to 1, (e) forest from $x/L = 0$ to 2 and (f) forest from $x/L = 1$ to -1.

circulation region in Fig. 2e, with the forest canopy entirely over the lee slope, again looks very similar to the recirculation region over flat ground since the hill-induced pressure gradient is small at the hill top where the canopy edge is located.

Fig. 3 shows the tracer concentration and streamlines over a smaller scale hill with $L = 100$ m and $H = 10$ m, with the slope the same as the larger hill. In this

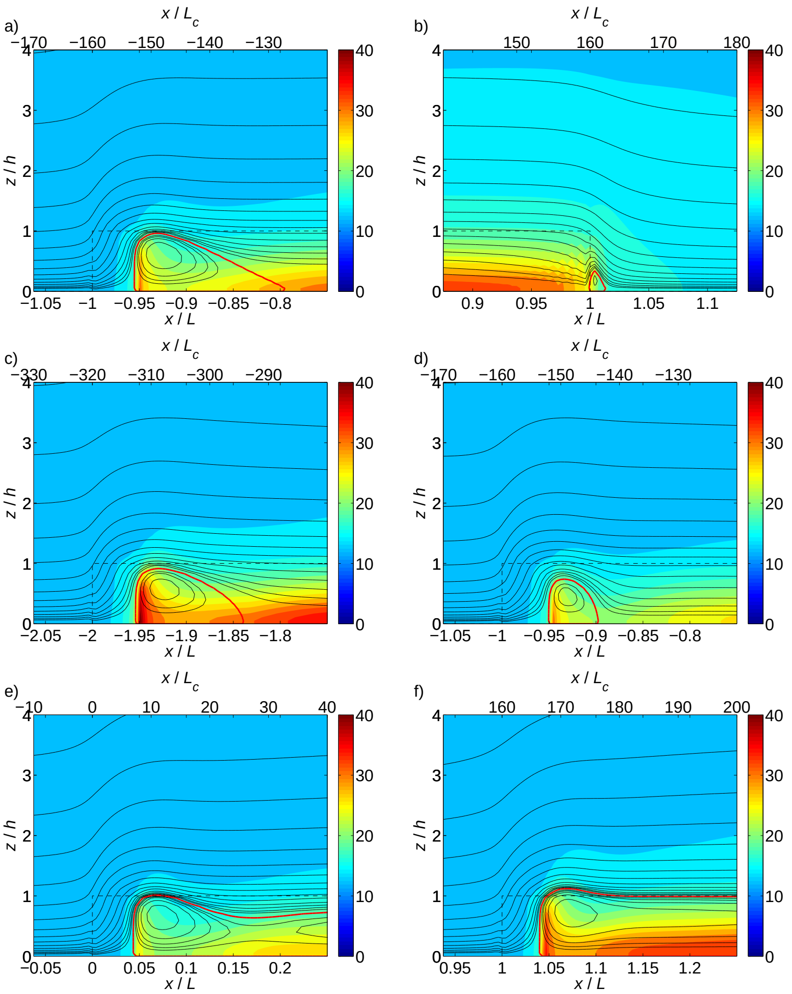

Fig. 2 As in Fig 1 for the large hill with $L = 1600\,\text{m}$ and hill height, $H = 160\,\text{m}$, but for a zoomed-in section around the canopy edge. (a) and (b) shows the results over a partial forest on flat ground at the leading and trailing edge of the forest. (c)-(f) correspond to the partially-forested hills in Fig 1c-f, but focusing around the leading edge of the canopy.

case the parameter $hL^2/(HL_c^2) = 100$ and so the pressure gradient induced by the canopy edge is still likely to be larger than the hill-induced pressure gradient, but the differences will be less. In this case, unlike the larger hill, the hill width scale $L = 100\,\text{m}$ and the canopy edge adjustment length scale $8L_c = 80\,\text{m}$ are very similar in size and so one might expect a stronger interaction between the hill-induced flow and the canopy-edge induced flow.

With the forest canopy fully covering the hill, Fig. 3a, the smaller hill demonstrates a much larger and deeper region of flow separation, with the flow into and

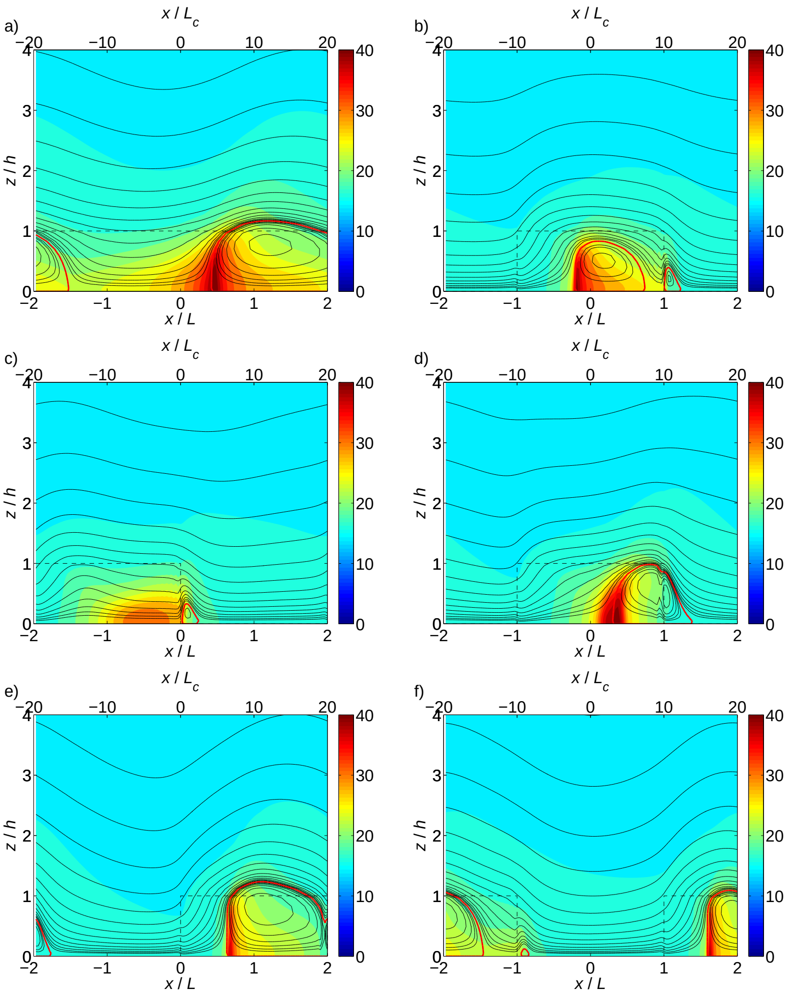

Fig. 3 Tracer concentration (shading) and streamfunction (lines) plotted over a partially-forested small hill. The spacing of the streamfunction contours is logarithmic for clarity both in and above the canopy. The bold red line marks the dividing streamline of the separation region. The forest canopy is marked with a dashed line. In each case the domain width is 400 m ($L = 100$ m), the hill height, $H = 10$ m. Results are plotted in a coordinate system with z as the height above the surface to make comparison easier between cases with and without a hill. Results are shown for (a) fully-forested hill, (b) no hill, (c) forest from $x/L = -2$ to 0, (d) forest from $x/L = -1$ to 1, (e) forest from $x/L = 0$ to 2 and (f) forest from $x/L = 1$ to -1.

out of the canopy being more significant compared to the large hill case (note the steeper streamlines). As explained in Ross and Vosper (2005), this is a result of the increased pressure gradient over a smaller scale hill leading to a larger induced flow and stronger convergence / divergence in the canopy. With the partial forest over flat ground, Fig. 3b, the smaller horizontal extent of the forested region means that the canopy adjustment occupies a much greater fraction of the forest canopy, and in fact the separation region induced by the upwind edge of the canopy extends almost to the downwind canopy edge. The flow and tracer concentrations in the interior of the canopy never reach a horizontally uniform state. Similarly the flow separation region in the lee of the downwind forest edge extends over half way back towards the upwind edge of the next patch of forest. The fact that, for the small hill, the hill width and the length scale over which the canopy adjusts to a forest edge are similar means that there is a much greater interaction between the two processes in this case. Figs. 3c-f show results for four different positions of the canopy over the small hill. The flow patterns are qualitatively similar to those over the large hill in terms of the effect of the forest location on the flow. The similarity in horizontal scale of the hill-induced changes and the forest-edge induced changes means that the two effects are not separate, but interact more strongly than over the large hill. As an example of this, it is not possible to identify a difference between the deflection of the streamlines at the canopy edge and the deflections due to the hill. One significant example occurs for Fig. 3c where the forest is over the upstream slope. Over the large hill the strong adverse pressure gradient at the windward edge of the forest occurs close to the bottom of the hill where the pressure gradient induced by the hill is close to zero and so flow separation occurred near the canopy edge. In contrast, over the small hill, because of the lack of separation of scales the canopy-edge pressure gradient is present over much of the upwind slope. Over this distance there is a significant positive pressure gradient induced by the hill. This positive pressure gradient prevents flow separation occurring at the forest edge over the small hill. The stronger vertical flow induced in the canopy over the small hill leads to more efficient transport of tracer out of the canopy and hence larger differences in concentration within the canopy. Higher concentrations are observed in the separation region of the flow within the canopy, with much lower concentrations elsewhere in the canopy. This is broadly consistent with that observed over the large hill. If anything, the differences in tracer concentration are enhanced for partially-forested hills compared to the fully-forested hill due to the horizontal transport into and out of the canopy at the forest edges (see in particular Fig. 3d).

4.2 Surface pressure and drag

To further test the idea that the contribution of the canopy edge and the hill can be looked at separately, the surface pressure is plotted in Fig. 4 for the large hill with the forest canopy placed in a number of different locations across the hill. In each case the pressure over an equivalent fully-forested hill and a partially-forested flat surface are plotted, along with the sum of these two. The figures suggest that the net surface pressure over a large partially-forested hill can be represented relatively well by a sum of the surface pressure fields observed over an equivalent fully-forested hill and the partial forest on flat ground. This is due to the scale separation between the canopy adjustment length scale (which controls the scale of the pressure perturbation near the forest edge) and the hill width. The error in the surface pressure field using this simple relation is less than 20% near the canopy edge, depending on the canopy position. Over most of the hill the error is substantially less ($< 1\%$).

Figure 5 shows the sum of the local canopy drag and surface-stress terms as a function of position across the large hill for four different canopy positions. For all positions of the canopy the sum of these terms varies smoothly over most of the hill. Further, the partially-forested hill cases are very similar to the fully-forested hill and rough hill cases. This supports the hypothesis in Sect. 2.2 that flow above the canopy on a partially-forested hill would be similar to flow over a rough hill with the same effective roughness length. Only near the canopy edges are large deviations seen. These occur just inside the canopy where higher velocities are observed due to the higher velocity flow from outside the canopy penetrating some distance into the canopy. These higher velocities lead to a large increase in the canopy drag at the forest edges. As might be expected, this effect is localized to the canopy edges in the same way as the canopy-edge induced pressure perturbations are localized near the canopy edge. The magnitude of this effect varies depending on the location of the canopy over the hill. The largest spike is observed when the upwind edge is located at the top of the canopy as this is where the wind speeds outside the canopy are greatest and so the canopy edge induces the largest change in flow speed. The total canopy drag plus surface stress over a partially-forested hill is again well represented by the sum of the contributions from a fully-forested hill and a partially-forested flat ground case.

Over the small hill, Fig. 6 shows that the pressure field is more complicated because the two processes interact, but nevertheless the sum of the individual surface pressure fields is close to the pressure field over the partially-forested hill. A similar result is seen with the combined canopy drag and surface stress terms (not shown). Understanding the pressure field is important because this pressure field is what drives the flow within the canopy. Further, this decomposition allows the pressure drag and canopy drag / surface stress over a partially-forested hill to be calculated as a contribution from a fully-forested hill (which is constant), plus a contribution from a patch of partial forest over flat ground. The latter contribution will vary sinusoidally depending on the location of the forest, and hence the location of the pressure changes induced by the canopy edges, relative to the hill.

The effect of the position of the canopy on the components of the domain integrated drag is illustrated in Fig. 7. Fig. 7a shows the pressure drag over the large partially-forested hill normalized on the pressure over the equivalent fully-forested hill as a function of the position of the centre of the canopy relative to the hill (x_c/L). Results are shown for the two cases in Sect. 3 (large and small hills) as well as additional simulations given in Table 1: the large shallow hill ($H = 80\,\mathrm{m}$, $L = 1600\,\mathrm{m}$), the large hill with a sparse canopy ($L_c = 16\,\mathrm{m}$) and the medium hill ($H = 80\,\mathrm{m}$, $L = 800\,\mathrm{m}$). What is immediately clear is that, for all the different configurations considered, the position of the partial canopy has a very large impact on the observed pressure drag, with the pressure drag varying between 0 and over 200% of the value over a fully-forested hill depending on where the canopy is located, and even changing sign in some cases. Even though the pressure field induced at the forest edge is relatively small in magnitude compared to the hill-induced pressure field, the fact that it can be completely out of phase with the hill means that it can have a relatively large

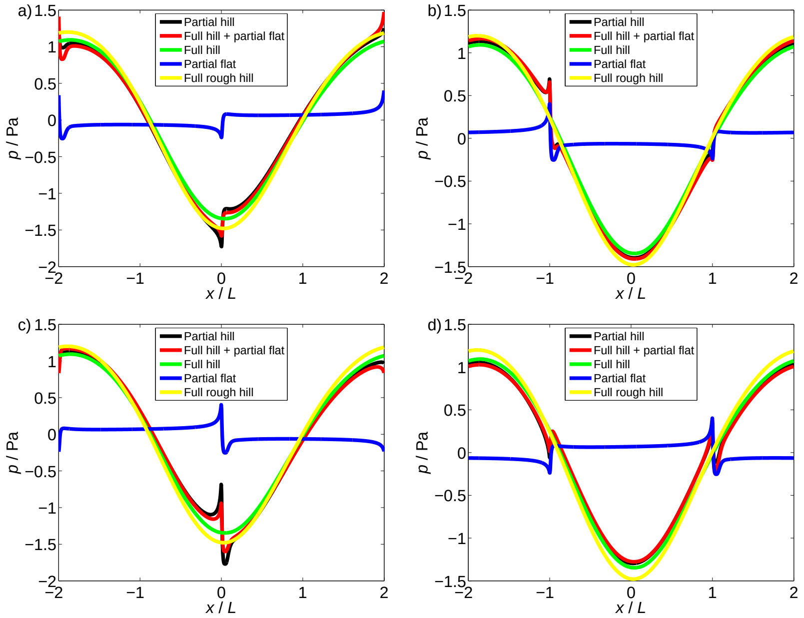

Fig. 4 Surface pressure over the large partially forested hill ($H = 160\,\mathrm{m}$, $L = 1600\,\mathrm{m}$) for different locations of the forest. Also shown for each case is the sum of the surface pressures over the fully-forested hill and for the partial forest on flat ground. Results are shown for (a) a forest from $x/L = -2$ to 0, (b) forest from $x/L = -1$ to 1, (c) forest from $x/L = 0$ to 2 and (d) forest from $x/L = 1$ to -1.

impact on the pressure drag. The position and magnitude of the drag variations are generally consistent between the different configurations despite the large differences in the scale separation and the induced flow between the different cases. Covering the foot of the hill and the lower parts of the upwind slope with trees tends to strongly reduce the drag while a forest over the summit and the upper parts of the lee slope leads to significant increases in the drag. This is entirely consistent with the variations in the position and size of the separation region depending on the positioning of the canopy that were observed in Sect. 4.1 and also with the surface pressure field induced by the forest edge over flat ground.

The curves in Fig. 7a show the drag calculated assuming that the pressure field over a partially-forested hill can be obtained by summing the contributions from the pressure field over a fully-forested hill and the pressure field from a patch of forest on flat ground. As seen in the previous section, this is a reasonably good assumption for the large hill, and even for the small hill it generally gives the right magnitude and variation in the surface pressure field. Since the drag is an integral quantity some of the discrepancy in pressure over the smaller hill is averaged out. The agreement between the drag calculated using this simple assumption and the actual drag observed in the model is reasonable in most cases. For all the hill and canopy combinations given in Table 1 the pressure drag is at a maximum when the canopy is situated over the lee slope. The presence of the canopy promotes flow separation over the lee slope

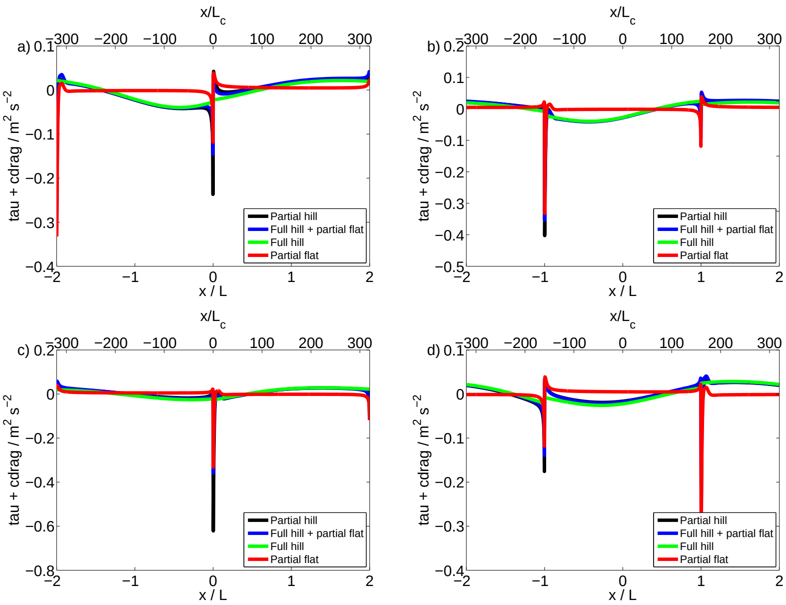

Fig. 5 Sum of the surface stress and canopy drag perturbations over the large partially forested hill ($H = 160\,\mathrm{m}$, $L = 1600\,\mathrm{m}$) for different locations of the forest. Also shown for each case is the sum of the surface stress and canopy drag terms for the partially forested hill over flat ground and for a uniformly covered hill (forested hill inside the canopy / rough hill outside the canopy). Results are shown for (a) a forest from $x/L = -2$ to 0, (b) forest from $x/L = -1$ to 1, (c) forest from $x/L = 0$ to 2 and (d) forest from $x/L = 1$ to -1.

and hence leads to a downwind shift in the pressure minimum, as over a fully-forested hill. The increased asymmetry in the pressure field relative to the hill causes an increase in the pressure drag on the hill.

Fig. 7b similarly shows the sum of the canopy drag and shear-stress perturbations normalized on the drag over a fully-forested hill. As for the pressure drag, there are significant variations in the calculated canopy drag and surface stress depending on the position of the partial canopy over the hill. Although the magnitude of the variations is similar, the phase is different with the maximum canopy drag and surface stress occurring when the canopy is situated over the upwind slope. As in Fig. 7a the lines show the predicted drag based on the drag over an equivalent fully-forested hill and a partially-forested region over flat ground. Again these are mostly in good agreement with the actual drag calculated from the model. This supports the hypothesis that the idea of separation of scales works for the velocity field (which controls the canopy drag and surface stress) as well as the pressure field, at least when averaged over the domain. At least qualitatively this conclusion can also be drawn from the streamline patterns in Fig. 1.

Fig. 7c shows the total drag (the sum of the pressure drag, canopy drag and surface stress) normalized on the total drag over a fully-forested hill as a function of the position of the forest canopy across the hill. The drag terms plotted in Fig. 7a

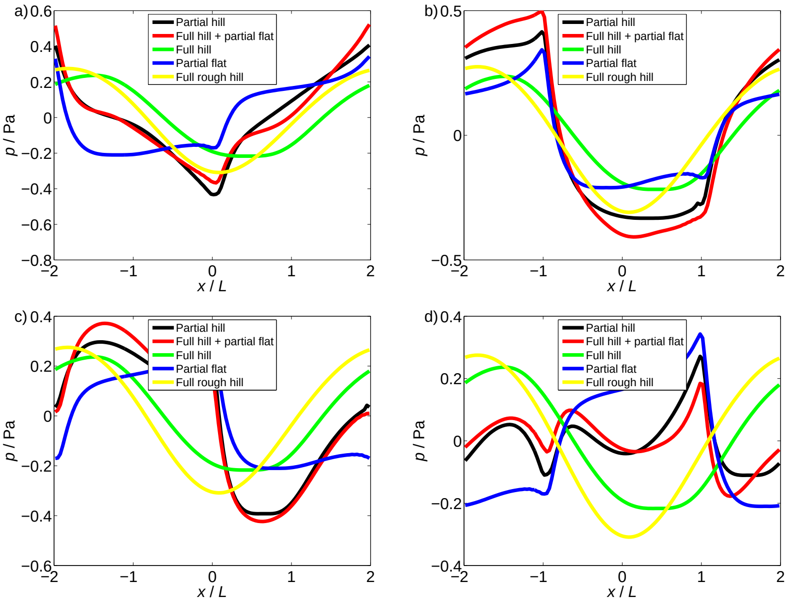

Fig. 6 Surface pressure over the small partially forested hill ($H = 10\,\mathrm{m}$, $L = 100\,\mathrm{m}$) for different locations of the forest. Also shown for each case is the sum of the surface pressures over the fully-forested hill and for the partial forest on flat ground. Results are shown for (a) a forest from $x/L = -2$ to 0, (b) forest from $x/L = -1$ to 1, (c) forest from $x/L = 0$ to 2 and (d) forest from $x/L = 1$ to -1.

and b are almost 180° out of phase and so the variation in total drag as the position of the forest canopy is changed is rather less than the individual variations in the pressure drag and the canopy drag plus surface stress. The positioning of the maximum drag also differs, with the largest increase in drag being observed when the forest canopy is centred near the summit of the hill, with very little change in the drag observed when the forest canopy was situated at the foot of the hills. This shows the importance of considering both contributions when considering the drag exerted by partially-forested hills. This is different to the conclusion of previous studies that consider fully-forested (Ross and Vosper, 2005) or uniform roughness hills (Belcher et al., 1993) where the contribution from the pressure drag dominates. The normalized change in the total drag is generally less than 1, even with the forest canopy near the summit. This means that the increase in drag due to a partially-forested hill is less than the increase in drag due to the equivalent fully-forested hill.

5 Conclusions

The results from out study show that flow and scalar transport over a partially-forested hill can be quite different from that over a fully-forested hill. Since most real world hills are not fully-forested, this is clearly a limitation of the majority of the existing idealized studies of flow over forested hills. In particular, the results show a sensitiv-

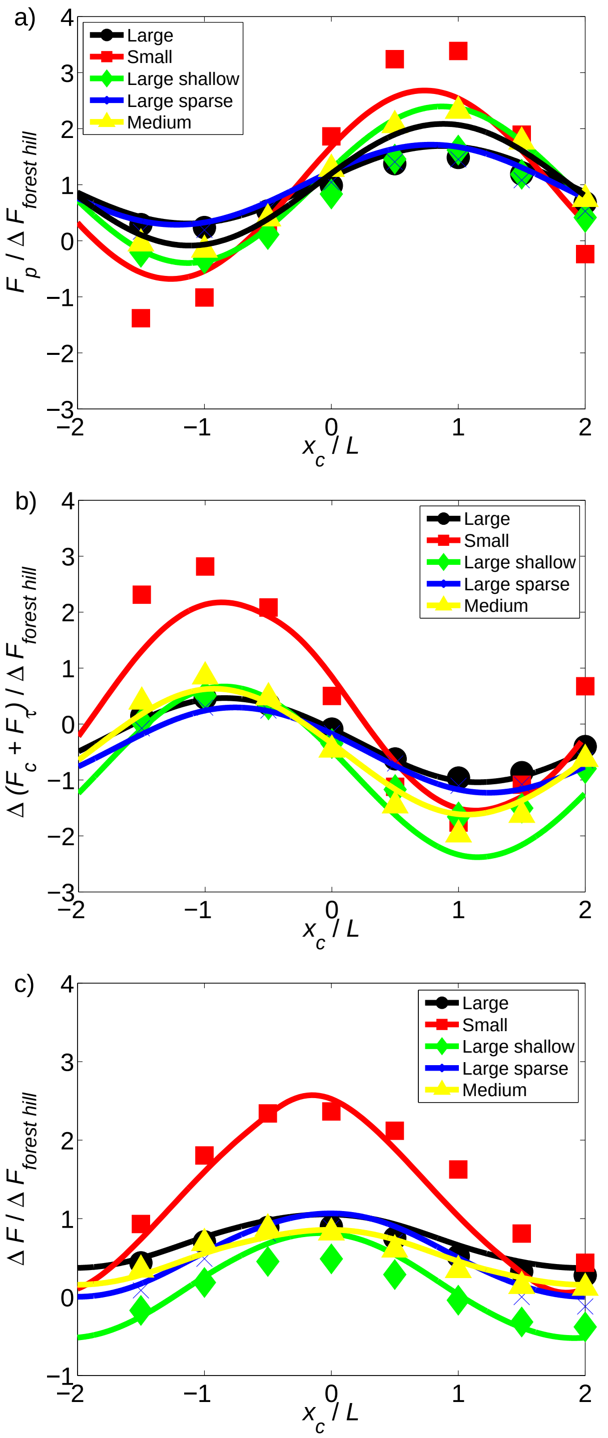

Fig. 7 (a) Pressure drag relative to the drag over a fully-forested hill plotted as a function of the centre position of the canopy relative to the hill x_c/L. Each symbol denotes the drag for a particular simulation. The different symbols correspond to the different sets of simulations detailed in Table 1. The lines are the drag calculated based on the pressure field simulated over a flat partially-forested region and over a fully-forested hill. (b) The sum of the canopy and surface stress drag normalized by the drag over a fully-forested hill plotted as a function of the centre position of the canopy relative to the hill. (c) The total drag normalized by the drag over a fully-forested hill plotted as a function of the centre position of the canopy relative to the hill.

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ity of the flow to the positioning of the forest with respect to the hill summit. Flow separation, even over hills of low slope angle, is a ubiquitous feature of flow over forested hills (see e.g. Finnigan and Belcher, 2004; Ross and Vosper, 2005). The positioning of the forest is critical in deciding if and where the flow separation occurs for the partially-forested hill case. At least for low slopes, the flow separation is almost invariably confined in the horizontal to the forested region. It is also predominantly limited to the lee slope where the hill induces an adverse pressure gradient. The differences in flow separation in turn have a large impact on scalar transport and the trapping of scalars in the canopy. Over large, partially-forested, hills there appears to be larger variability in the scalar concentrations within the canopy compared both to fully-forested hills and to partial canopies over flat ground. This is likely to have implications for the siting and interpretation of flux measurements (e.g. Ross, 2011) over forests in complex terrain.

In reality most hills are not fully-forested so the results presented in Sect. 4.2 are clearly of some importance for the parametrization of drag in weather and climate models, particularly since a partial canopy also potentially introduces an asymmetry with the drag depending on the direction of the wind with respect to the canopy position. Treating the hill and canopy edge contributions separately offers a simple way to parametrize drag in such cases without resorting to high resolution numerical simulations to explicitly resolve the processes. Due to the separation of scales between the hill width and the flow adjustment length scale at a canopy edge, this approach is particularly successful for the larger scale hills that make the largest contribution to the overall drag. Further, the simple scaling arguments presented here give a good estimate of the drag, and how this varies with forest position, for a range of different hills and canopies. To produce a general parametrization, further work would be needed to study the effects of different hill shapes, and also forests that cover a different fraction of the hill, however this is a simple extension of the present study. The scaling arguments based on the separation of scales should continue to work provided that the canopy-edge adjustment length is small compared with the hill width (i.e. $L_c \ll L$) and also that the forest patches are large compared to the canopy edge adjustment length scale (such that the flow over the canopy has chance to adjust to a quasi-horizontally uniform state). This idea of scale separation may also be important for other applications with heterogeneous land use, for example in calculating heat, water vapour or CO_2 fluxes over heterogeneous terrain. Treating the effects of terrain and surface heterogeneity separately may allow for simpler or more efficient parametrizations.

Our results offers a first attempt to study the effects of partial forest cover in complex terrain, and there are clearly more questions to address. In particular the lack of field or laboratory observations of this type of flow makes it difficult to assess the validity of the results from modelling studies such as this one.

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References

Allen T (2006) Flow over hills with variable roughness. Boundary-Layer Meteorol 121(3):475–490, DOI 10.1007/s10546-006-9086-0

Belcher SE, Newley TMJ, Hunt JCR (1993) The drag on an undulating surface induced by the flow of a turbulent boundary layer. J Fluid Mech 249:557–596, DOI 10.1017/S0022112093001296

Belcher SE, Jerram N, Hunt JCR (2003) Adjustment of a turbulent boundary layer to a canopy of roughness elements. J Fluid Mech 488:369–398, DOI 10.1017/S0022112003005019

Belcher SE, Finnigan JJ, Harman IN (2008) Flows through forest canopies in complex terrain. Ecol Apps 18:1436–1453, DOI 10.1890/06-1894.1

Belcher SE, Harman IN, Finnigan JJ (2012) The wind in the willows: Flows in forest canopies in complex terrain. Annu Rev Fluid Mech 44:479–504, DOI 10.1146/annurev-fluid-120710-101036

Brown AR, Hobson JM, Wood N (2001) Large-eddy simulation of neutral turbulent flow over rough sinusoidal ridges. Boundary-Layer Meteorol 98:411–441, DOI 10.1023/A:1018703209408

Cassiani M, Katul GG, Albertson JD (2008) The effects of canopy leaf area density on airflow across forest edges: Large-eddy simulation and analytical results. Boundary-Layer Meteorol 126:433–460, DOI 10.1007/s10546-007-9242-1

Dupont S, Brunet Y (2008) Edge flow and canopy structure: A large-eddy simulation study. Boundary-Layer Meteorol 126:51–71, DOI 10.1007/s10546-007-9216-3

Dupont S, Brunet Y, Finnigan JJ (2008) Large-eddy simulation of turbulent flow over a forested hill: Validation and coherent structure identification. Q J R Meteorol Soc 134:1911–1929, DOI 10.1002/qj.328

Finnigan JJ (2000) Turbulence in plant canopies. Annu Rev Fluid Mech 32:519–571, DOI 10.1146/annurev.fluid.32.1.519

Finnigan JJ, Belcher SE (2004) Flow over a hill covered with a plant canopy. Q J R Meteorol Soc 130:1–29, DOI 10.1256/qj.02.177

Finnigan JJ, Brunet Y (1995) Turbulent airflow in forests on flat and hilly terrain. In: Coutts MP, Grace J (eds) Wind and trees, Cambridge University Press, pp 3–40

Grant ER (2011) Canopy-atmosphere interactions over complex terrain. PhD thesis, University of Leeds, UK

Harman IN, Finnigan JJ (2010) Flow over hills covered by a plant canopy: Extension to generalised two-dimensional topography. Boundary-Layer Meteorol 135(1):51–65, DOI 10.1007/s10546-009-9458-3

Inglis DWF, Choularton TW, Stromberg IMF, Gardiner BA, Hill M (1995) Testing of a linear airflow model for flow over complex terrain and subject to stable, structured stratification. In: Coutts MP, Grace J (eds) Wind and trees, Cambridge University Press, pp 88–112

Lee X (2000) Air motion within and above forest vegetation in non-ideal conditions. Forest Ecology and Management 135:3–18, DOI 10.1016/S0378-1127(00)00294-2

Morse AP, Gardiner BA, Marshall BJ (2002) Mechanisms controlling turbulence development across a forest edge. Boundary-Layer Meteorol 103:227–251, DOI

10.1023/A:1014507727784

Patton EG, Katul GG (2009) Turbulent pressure and velocity perturbations induced by gentle hills covered with sparse and dense canopies. Boundary-Layer Meteorol 133:189–217, DOI 10.1007/s10546-009-9427-x

Poggi D, Katul GG (2007a) The ejection-sweep cycle over bare and forested gentle hills: a laboratory experiment. Boundary-Layer Meteorol 122:493–515, DOI 10.1007/s10546-006-9117-x

Poggi D, Katul GG (2007b) An experimental investigation of the mean momentum budget inside dense canopies on narrow gentle hilly terrain. Agric For Meteorol 144:1–13, DOI 10.1016/j.agrformet.2007.01.009

Poggi D, Katul GG (2007c) Turbulent flows on forested hilly terrain: the recirculation region. Q J R Meteorol Soc 133:1027–1039, DOI 10.1002/qj.73

Ross AN (2008) Large eddy simulations of flow over forested ridges. Boundary-Layer Meteorol 128:59–76, DOI 10.1007/s10546-008-9278-x

Ross AN (2011) Scalar transport over forested hills. Boundary-Layer Meteorol 141:179–199, DOI 10.1007/s10546-011-9628-y

Ross AN (2012) Boundary-layer flow within and above a forest canopy of variable density. Q J R Meteorol Soc 138:1259–1272, DOI 10.1002/qj.989

Ross AN, Vosper SB (2005) Neutral turbulent flow over forested hills. Q J R Meteorol Soc 131:1841–1862, DOI 10.1256/qj.04.129

Wood N, Mason PJ (1993) The pressure force induced by neutral, turbulent flow over hills. Q J R Meteorol Soc 119:1233–1267, DOI 10.1002/qj.49711951402

Yang B, Raupach MR, Shaw RH, Tha K, Paw U KT, Morse AP (2006) Large-eddy simulation of turbulent flow across a forest edge. Part 1: Flow statistics. Boundary-Layer Meteorol 120(3):377–412, DOI 10.1007/s10546-006-9057-5