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FLOW OVER A FORESTED HILL: CANOPY – ATMOSPHERE INTERACTIONS

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Abstract: Results from numerical simulations of neutral, turbulent flow over small forested hills using a first-order turbulence closure model are presented. The different dynamical balance within and above the canopy leads to significant vertical motion into and out of the canopy over the hill. Such a flow would not be predicted by the more common roughness length parametrization of a forest often used in atmospheric models. These differences from the roughness length model can lead to an increase in the predicted drag caused by the hill and increased flow separation. Further simulations with a passive tracer demonstrate that the flow also leads to large differences in local vertical flux of a tracer when compared to simulations over flat ground. Both advection by the mean flow and modification of the turbulent flux are important locally. When averaged over the hill the difference in total vertical flux between the hill and no hill cases is generally small. The precise sign and magnitude appear to depend on the details of the flow, in particular whether the recirculation region reaches above the canopy.

1 INTRODUCTION

Detailed studies of flow within and above a homogeneous, flat forest canopy have been conducted over the last twenty years (see Finnigan, 2000, for a summary) and we now have a reasonable picture of the mean flow and turbulence in such a canopy. Much less attention has been paid to inhomogeneous problems where there are changes in the forest canopy or the topography. A review of current research in this area is provided by Lee (2000). In recent years there has been a growing appreciation of the need to understand the interaction between forest canopies and topography, both in terms of understanding the dynamics of flow over forested hills and for applications such as the analysis and interpretation of CO_2 flux measurements made on slopes.

To date there has been little published work on flow over forested hills, with the wind tunnel experiments of Finnigan and Brunet (1995) providing perhaps the only detailed experimental study. Similarly only the numerical simulations of Kobayashi et al. (1994) and Wilson et al. (1998) have begun to represent these processes with detailed models of the canopy. More recently Finnigan and Belcher (2004) have developed a linear analytical model to predict the flow above and within the canopy over low, wide hills. This model has helped to highlight the dominant dynamics occurring with the canopy and the importance of including these effects in order to correctly model the flow above the canopy. Motivated by this, Ross and Vosper (2005) have conducted a series of numerical simulations to extend this work. These simulations demonstrated the importance of the canopy in enhancing flow separation and in increasing drag when compared to traditional roughness length parametrizations of the surface. The simulations also investigated smaller scale hills where the Finnigan and Belcher (2004) model breaks down because vertical advection at the canopy top becomes significant. Clearly this vertical motion may have important consequences for transport into and out of the canopy. Katul et al. (2006) have begun to investigate this by using the analytical results of Finnigan and Belcher (2004) to drive a CO_2 model incorporating both photosynthesis and transport processes. For gentle slopes, they observed large variations in vertical CO_2 transport due to advection effects and flow separation within the canopy which could be significant when considering how to interpret measurements made at an individual flux tower situated on a slope. When averaged over the hill however the total net change in flux by including the effect of the hill was small.

2 INDUCED FLOW OVER SMALL HILLS

Here we present results from idealised simulations of neutral flow over a series of small forest-covered hills. The canopy corresponds to that used by Finnigan and Belcher (2004) and Ross and Vosper (2005) with a canopy height of $10\,\mathrm{m}$, a leaf area density of $0.4\,\mathrm{m}^{-1}$ and the drag coefficient is taken as 0.25. This corresponds to a roughness length, $z_0 = 0.35\,\mathrm{m}$. Simulations were carried out using the BLASIUS model from the UK Met Office (see e.g. Wood and Mason, 1993). A first order turbulence closure scheme was used. Within the canopy the turbulence scheme is modified to use a fixed mixing length and an additional drag term within the canopy (see Ross and Vosper, 2005, for further details).

As shown by Finnigan and Belcher (2004), the presence of a sinusoidal hill induces a pressure perturbation which is, to leading order, an inviscid response of

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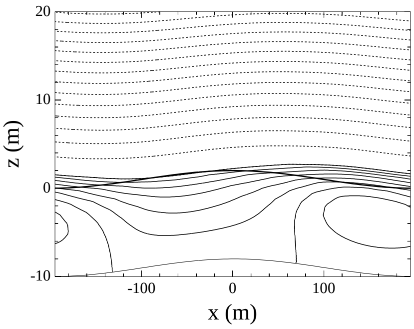


Figure 1: Streamlines of the flow over a small forest-covered hill. The canopy top is at a height of 10m.

the flow to the presence of the hill and is 180° out of phase with the orography. This pressure perturbation drives the flow within and just above the canopy. Scaling analysis shows that above the canopy this pressure perturbation term ($-d\Delta p/dx$) balances the advection term ($Ud\Delta U/dx$) and so the pressure and velocity perturbations are 180° out of phase. As in roughness length models, this leads to a speed up near the summit of the hill. Deep within the canopy the dominant terms are the drag ($-C_d\Delta U^2$) and the pressure gradient ($-d\Delta p/dx$) and so the pressure and velocity perturbations are only 90° out of the phase. The maximum speedup is on the upwind slopes with flow convergence near the summits and flow divergence in the valleys. By analysing the linear solutions of Finnigan and Belcher (2004) and through a series of numerical simulations Ross and Vosper (2005) have shown that for narrower hills this flow convergence and divergence within the canopy can lead to a strong induced vertical flow into the canopy over the upwind slope and out of the canopy over the lee slope. This feedback between the canopy and the atmosphere above means that the pressure field is no longer solely determined by the inviscid flow well above the hill. The minimum pressure is actually observed to be located over the downwind slope rather than near the summit. Figure 1 shows the streamlines for a small hill of width 400m and height 2m. The induced vertical flow can clearly be seen near the canopy top. These vertical velocities and the related shift in the observed pressure perturbation over the hill cannot be modelled using a roughness length parametrization since such a parametrization constrains the vertical velocity to be zero near the canopy top.

Figure 1 also shows that despite the hill only having a maximum slope of 0.016 there is a large recirculation within and above the canopy over the lee slope. Simulations using a roughness length parametrization do not exhibit flow separation for this hill. Enhanced flow separation is another consistent feature of these simulations of flow over a forested hill. Within a deep canopy the background windspeed is always low and so the adverse pressure gradient over the lee slope always lead to flow reversal within the canopy. Consideration of the analytical solutions of Finnigan and Belcher (2004) and numerical simulations both show that the separation region extends above the canopy top for much lower slopes than suggested by more traditional roughness length models.

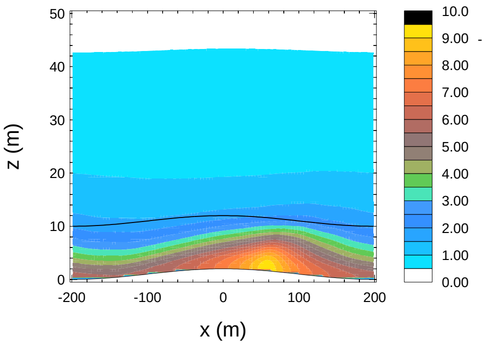
The change in the pressure perturbation over the hill has implications for the pressure drag exerted by the hill on the atmosphere. Ross and Vosper (2005) have shown how the size of the drag can be estimated using the linear theory of Finnigan and Belcher (2004). The relative increase in drag compared to the roughness length parametrization is greatest for narrow hills where the vertical advection is most significant and so there are larger shifts in the pressure minimum. Since these small hills produce a relatively small fraction of the total pressure drag over a real mountain range the overall change in drag including these canopy effects will be less dramatic than this example suggests, but may still be significant.

3 Tracer experiments over a forested hill

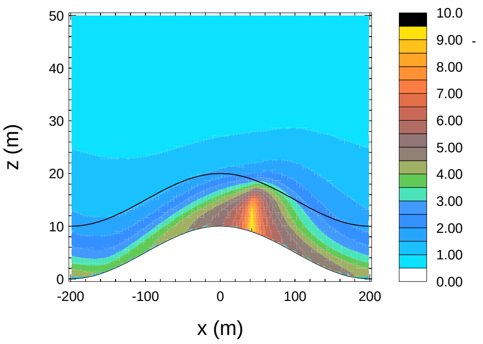
To further investigate the importance of these terrain effects on transport into and out of a canopy additional simulations have been conducted with a constant distributed source of a passive tracer released within the canopy. Katul et al. (2006) showed that advection is the dominant process, and so rather than using a more complicated CO_2 model we initial just use a passive tracer to study the transport processes.

Figure 2 shows the tracer field after 1000s both over the hill used in figure 1 (a) and over flat ground (b). Comparing the two figures shows that the presence of the hill leads to enhanced tracer levels deep within the canopy just in the lee of the summit. This is due to the trapping of the tracer within the recirculation region caused by flow separation. Qualitatively this is similar to the calculations of Katul et al. (2006), except that the location of the maximum is displaced downstream here as a result of the recirculation region being displaced when the effect of vertical advection at the canopy top is included.

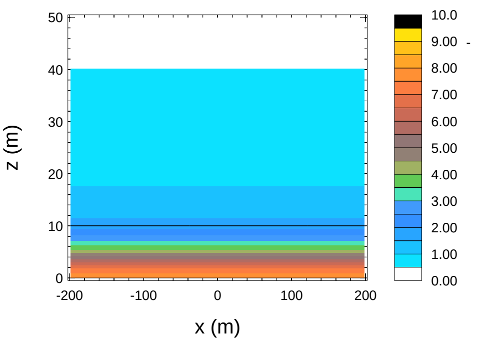
At canopy top there is a significant variation in the tracer concentration from -15% to +35% over the shallow hill and -20% to +90% over the steeper hill when compared to the values over flat ground. The very large increases over the steeper hill are where the canopy top is within the recirculation region where the tracer is trapped. Figure 3 shows the vertical tracer flux at canopy top. Both mean vertical advection and the perturbation in vertical turbulent flux compared to the flat ground case are significant. The pattern of positive and negative tracer flux due to mean advection closely follows the mean vertical velocities at canopy top. In contrast the turbulent fluxes are reduced over much of the upstream slope, due to decreased gradients of tracer concentration in these regions. The maximum turbulent



(a) Hill, height 2m

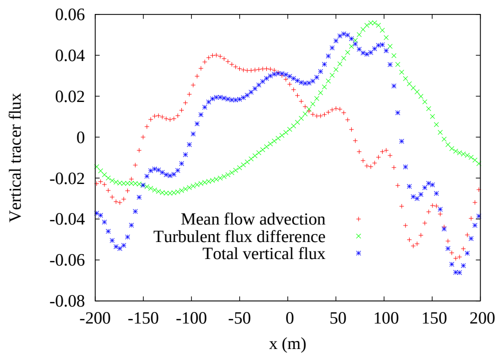


(b) Hill, height 10m

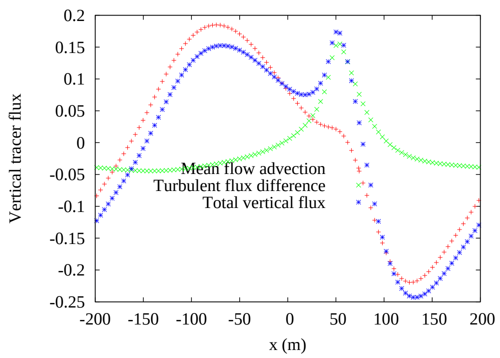


(c) Flat ground

Figure 2: Tracer concentrations above a small hill of height (a) 2m, (b) 10m and (c) over flat ground. Tracer is continuously released from a distributed source within the canopy.



(a) Hill, 2m high



(b) Hill, 10m high

Figure 3: Vertical tracer flux at canopy top over a hill showing the contribution from vertical advection by the mean flow and from the alteration in the turbulent transport compared to the flat ground case.

fluxes occur just downwind of the summit, above the recirculation region. Here the turbulent flux increases by more than 50% compared to the flat case, even over the 2m high hill. Over the 10m hill the increase is more like 250%. This is principally due to an increased gradient in the tracer concentration in this region rather than as a result of large changes in the eddy viscosity. At any point the vertical flux variations may be large compared to the flat ground case. However, if we look at the values averaged over the hill then the net effect is small, as shown by the figure in table 1. The sign of the flux changes are different between the two hills. The principal difference appears to be that the recirculation region is entirely within the canopy for the lower hill, while it extends above the canopy in the higher hill case.

4 Conclusions

The results presented here show than in some circumstances the dynamic interaction between a forest canopy and the atmosphere can be important. Modelling with a roughness length parametrization may not be sufficient to capture the behaviour above the canopy.

Hill height (m)	Mean advection (%)	Turbulent transport (%)	Total flux (%)
2	-1.8	2.7	0.8
10	4.3	-9.4	-5.1

Table 1: Percentage change in mean vertical tracer fluxes over a hill compared with simulations over flat ground. The mean advection and the turbulent contributions to the fluxes are shown along with the total flux.

This may be particularly important for applications such as calculating the pressure drag or for predicting the transport of gases, aerosols or other tracers out of the forest canopy.

Simulations with a passive tracer released within the canopy show how the canopy-atmosphere interactions can alter transport into and out of the canopy. As observed by Katul et al. (2006), the presence of a hill can lead to large local variations in the tracer concentrations and fluxes when compared to simulations over flat ground. Both mean flow advection and turbulent transport are significant terms. When averaged over the hill however there is only a small net change in the total vertical transport at canopy top, even for cases where vertical advection at canopy top is significant in altering the dynamics of the flow. These results are from a small number of case studies and there is clearly scope for a more systematic investigation of these effects. This may be of particular importance to those interested in interpreting measurements from single flux towers and scaling them up to estimate fluxes of CO_2 and other gases from forests.

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