FOREST CANOPY – ATMOSPHERE INTERACTIONS OVER COMPLEX TERRAIN

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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 presence of the hill drives a strong mean flow into and out of the forest canopy. Such a flow would not be predicted by the more common roughness length parametrization of a forest. This can lead to an increase in the predicted drag caused by the hill, increased flow separation and increased transport of gases and other tracers between the forest canopy and the atmosphere. Preliminary results for large-eddy simulations (LES) show very similar features. The use of LES however allows a more detailed study of the turbulence within and above the canopy and are useful in validating the first-order closure scheme.

Keywords - Forest canopy, hill, large-eddy simulation

1 INTRODUCTION

Detailed studies of flow within and above a homogenous, 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. Very little attention however has been paid to inhomogeneous canopies, due either to changes in forest cover or to the underlying topography. Lee (2000) reviews current research in this area. Many hilly or mountainous areas are also at least partially forested areas and so an understanding of the role and importance of the forest canopy is needed. To date there has been little published work on flow over forested hills, with the wind tunnel experiments of Finnigan and Brunet (1995) 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.

For mesoscale numerical simulations a common approach to modelling a forest is to ignore the details of the flow within the forest canopy and simply represent the effect of the canopy through a relatively large roughness length value. Recent theoretical work by Finnigan and Belcher (2004) using a linear analystical model has shown that the roughness length parametrization may not be appropriate. Further numerical simulations by Ross and Vosper (2005) back this up.

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 hills are 400 m wide with a height of 10 m. The forest canopy is 20 m deep with a leaf area density of $0.25\,\mathrm{m}^{-1}$ and the drag coefficient is taken as 0.15. This corresponds to a roughness length, $z_0 = 0.95\,\mathrm{m}$. 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 with a fixed mixing length and an additional drag term within the canopy.

The presence of a sinusoidal hill induces a pressure perturbation which is, to leading order, an inviscid response of the flow to the presence of the hill and is 180° out of phase with the orography (Finnigan and Belcher, 2004). 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 (this leads to the usual speed up near the summit of the hills). Within the canopy the dominant terms are the drag ($-2C_d U\Delta U$)

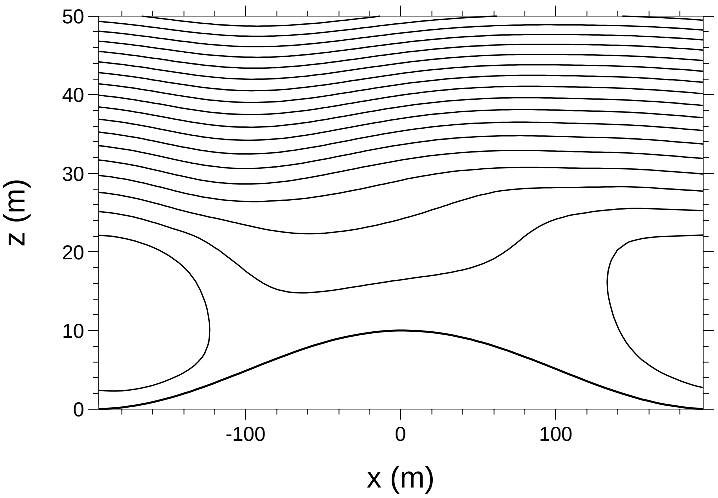

Figure 1: Streamlines of the flow over a small forest-covered hill. The canopy top is at a height of 20m.

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 feeds back on the pressure field above the canopy meaning that the minimum pressure is actually located over the downwind slope rather than near the summit. The induced vertical flow can clearly be seen from the streamlines in figure 1. 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.

Despite the relatively shallow hill (maximum slope of 0.08) a large recirculation region is observed over the valley. This region stretches above the canopy. Simulations using a roughness length parametrization require a much steeper slope for the onset of flow separation. This enhanced flow separation is another common feature 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 will always lead to flow reversal within the canopy. Consideration of the analytical solutions and more systematic numerical simulations both show that the separation region will extend 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. Comparison of the results with a simulation using a roughness length parametrization of the canopy shows an increase by a factor of 2.6 in the pressure drag as a result of include the effect of the flow within the canopy. 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 differences in flow are also greatest. Since these small hills produce a small fraction of the pressure drag over a real mountain range the total change in drag will be less dramatic than this example suggests, but may still be significant.

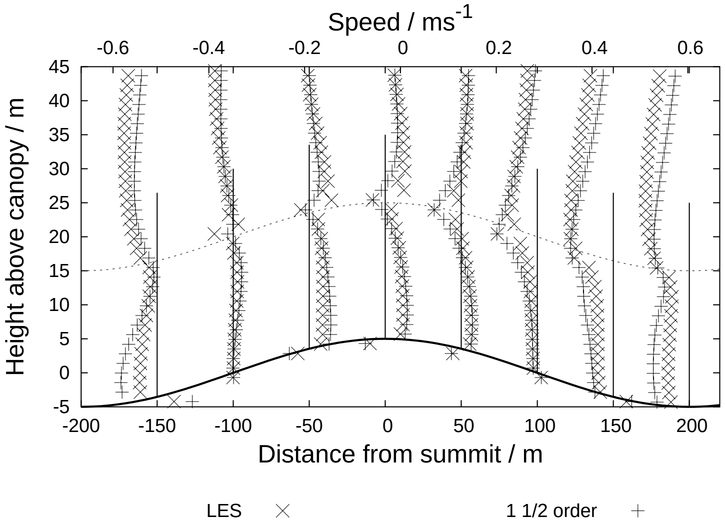

Figure 2: Profiles of velocity perturbation across a small forest-covered hill

3 LARGE-EDDY SIMULATIONS

Although the first order turbulence closure results are important in understanding the dynamical interaction between the boundary layer and a forest canopy over complex terrain there are still unanswered question about the turbulent structure in such flows and whether the simple closure schemes are adequate to describe the turbulence. In flat, homogeneous canopies large-eddy simulations (LES) have been used for some time to investigate the canopy dynamics, mostly building on the work of Shaw and Schumann (1992). Possibly the only study to date to use LES over a canopy covered hill is that of Brown et al. (2001), which used a canopy to improve the lower boundary condition in LES simulations of a series of wind tunnel experiments.

The preliminary simulation describe here is for a larger scale hill (as described in §2) of width 400 m and height 10 m. A $288 \times 192 \times 96$ grid is used, with a uniform grid resolution of about 1.4 m. This gives a domain depth of about 133 m, which is small, but still twice the middle layer depth for this hill. Simulations were run for 5000s and statistics were collected from 1000s, giving an averaging period of approximately 10 hill advection times. Figure 2 shows profiles of the velocity perturbation across the hill from both the first-order closure model and the LES results. While there are some small quantitative differences between the schemes related to slightly different treatment of the upper boundary, both schemes show qualitative very similar behaviour over the hill.

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. 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.

In the absence of experimental measurements, the large-eddy simulations provide a means of studying the effect of complex terrain on the turbulence within a forest canopy. This is important for validating current mixing length closure models and in the future enhancing them where necessary.

Clearly there is scope for further modelling studies to assess the impact of forest canopy dynamics over more realistic complex terrain. Of practical interest to forecasters is an assessment on the impact of forest canopies on parametrized drag in numerical weather prediction models. Similarly, the inclusion of more realistic dynamics should improve the accuracy of flux measurements from a single tower and assist in scaling these measurements up to give forest wide fluxes of, for example, CO_2 - an important part of the global carbon budget. There is also an urgent need for experimental measurements to validate these recent theoretical and modelling developments.

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