15.A2 CASE STUDIES FROM A FIELD CAMPAIGN TO MEASURE CANOPY AIR FLOWS OVER COMPLEX TERRAIN

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1. INTRODUCTION

The 1980's saw the publication of several studies into the properties of canopy air flows (e.g. Raupach and Thom 1981, Denmead and Bradley, 1987). The motivation behind this work was to increase our understanding of the flow dynamics between the atmosphere and the trees and also to increase our understanding of the processes involved in wind damage, snow loading, dispersion of seeds and pesticides and C02 fluxes. Most of the studies conducted at this time were mainly restricted to homogeneous canopies on level terrain. So there is now a need to get a better understanding of more complex canopy flows such as those over hilly and mountainous terrain. The incorporation of orographic drag has been shown to improve the skill of numerical weather prediction models (Belcher and Hunt 1998). Since a significant portion of the worlds mountainous terrain is forested and since a hill covered with a plant canopy will exert more drag on the atmospheric flow than a smooth hill, being able to parameterize this increased drag will hopefully help to improve the skill of these models when predicting these types of flow. Further motivation is found in wind energy. There has been a large worldwide investment into wind energy, and turbines are being sited in regions of mixed topography and forests so it would be beneficial to be able improve our quantitative understanding of the yields of these turbines.

Studies into the effect of complex terrain on canopy air flows begun at the end of the 1980's but to date literature on the subject is still fairly scarce. A wind tunnel study conducted by Finnigan and Brunet (1995) has provided the most comprehensive dataset so far. In 2004 an analytical model by Finnigan and Belcher helped to highlight the dominant dynamics of canopy airflow over complex terrain and also quantitatively explained some of the results from Finnigan and Brunet. In continuation Ross and Vosper conducted a series of numerical simulations in 2005. There is now a need to validate these latest model developments with an observational dataset. This work introduces some results from a set of measurements collected by the University of Leeds in winter 2006-07 in collaboration with the Forestry Commission, the UK Met Office and the University of Edinburgh. The measurements provide a dataset for validating some of the latest model developments and theories surrounding the problem of canopy-air flow interaction over complex terrain and will also be useful for improving numerical weather prediction models and estimating wind damage to commercial forests.

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2. SCIENTIFIC BACKGROUND

Figure 1 shows a neutrally stratified boundary layer flow within and above a canopy on flat terrain. The airflow is driven by a synoptic pressure gradient and this yields a wind above the canopy. Above the canopy the boundary layer is modeled as a neutrally stratified surface layer where the turbulent shear stress is constant with height and the mean velocity profile is logarithmic. Inside the canopy an extra term is introduced with the canopy drag. The canopy drag is balanced by the turbulent stress gradient and when solved for the mean velocity this exponential profile is produced. Since the mean wind velocity and the turbulent stress are both continuous at the top of the canopy, the shear is high here in order to match the logarithmic profile above.

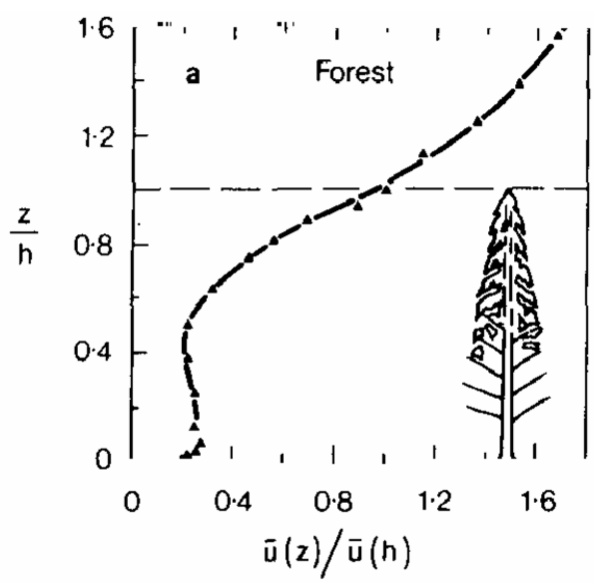

Figure 1. Vertical profile of mean wind speed within pine forest, canopy height h=16m, presented in dimensionless form with h and u(h) as normalisers. Figure taken from Raupach and Thom (1981).

If this boundary layer flow is deflected over a hill, the resulting vertical motion leads to a disturbance in the pressure field and we see a pressure minimum at the crest of the hill. This pressure gradient accelerates the flow on the windward slope and decelerates the flow on the lee slope.

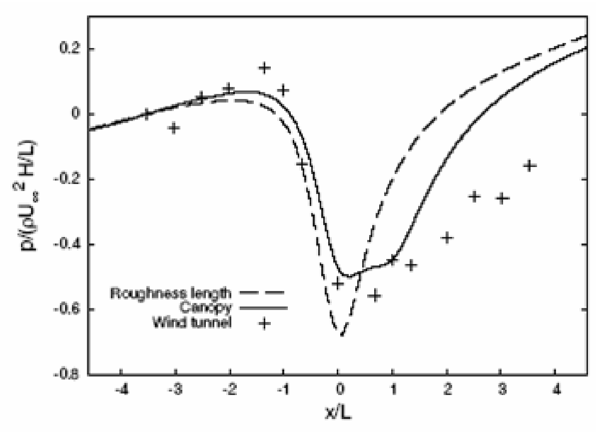

Figure 2. Non-dimensional surface pressure perturbation over the 'Furry Hill' described in Finnigan and Brunet (1995). Figure taken from Ross and Vosper (2005).

Figure 2 shows the non-dimensional surface pressure perturbations over a hill. The data comes from the wind tunnel study of Finnigan and Brunet (++) and from the numerical simulations from Ross and Vosper (--, —). All three profiles show the pressure minima over the crest very clearly but the canopy numerical simulation also shows an additional feature with the flattened peak. This represents a region of flow separation. As indicated by figure 1, the mean wind speed towards the bottom of the canopy is very low and is maintained only by the turbulent transfer of momentum from the faster moving air in the upper canopy. If this canopy is placed on a hill then the flow over the lee slope is decelerated and this downward transport of momentum to the bottom of the canopy diminishes. As a result the flow here drops to zero and then to negative resulting in reversed flow and a separation region. The appearance of a separation region has the effect of increasing the width of the hill from the perspective of the pressure perturbation and since the pressure perturbation over the hill is inversely proportional to the width of the hill, this separation region decreases the pressure perturbation, resulting in this flattened peak.

Figure 3 shows the variation of the mean velocity profile over a symmetrical 2-dimensional hill. The hill is marked with a solid line and the canopy top with a dashed line. The data is taken from the same source as from the previous figure. At the crest of the hill the point of inflexion is more pronounced than for a canopy on flat terrain. The velocity perturbation within the canopy tends to drop below that of a flat canopy on either side of the crest. On the lee slope the flow reversal is clearly indicated with the velocity dropping to below zero.

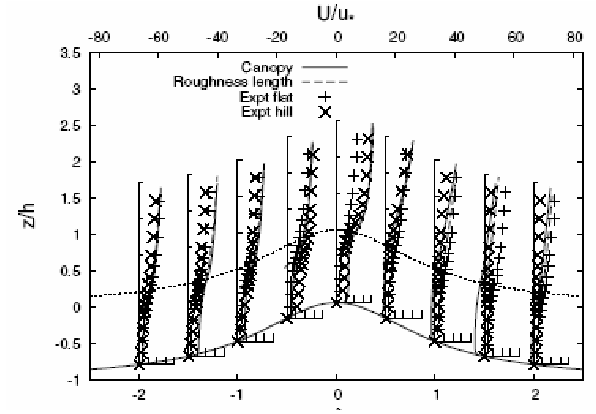

Figure 3. Vertical profile of mean wind speeds over the 'Furry Hill' described in Finnigan and Brunet (1995), presented in dimensionless form with h and u* and L as normalisers. Figure taken from Ross and Vosper (2005).

3. FIELD CAMPAIGN

The field campaign took place on the Isle of Arran, approximately 14miles off the south west coast of Scotland. The site was a ridge (Leac Gharbh) on the north east coast of the island. It is approximately 225m in height and 1.5km long with north-south orientation. The southern end of the ridge is forested with a majority of coniferous tress while the northern end is unforested allowing a direct comparison between between the flow over the forested ridge and the flow over the unforested ridge. Leac Gharbh was chosen specifically because the area is accessible, with suitable sites for the erection of vertical profile towers. Furthermore it can be considered to be 2-dimensional, making analysis easier. The campaign ran from October 2006 to May 2007 with an intensive data collection period taking place between February and May. These winter and spring months were chosen for the stronger winds which will hopefully provide clearer indications of the flow dynamics.

3.1. Vertical profiles within and above the forest canopy

Three vertical profile towers of 18m, 18m and 22m were erected at sites T1-T3 respectively, shown in figure 4. The canopy heights at each of these sites varied between 8 and 12m leaving the towers about 10m proud of the canopy at each site. The purpose of the towers was to provide vertical velocity and temperature profiles within and above the canopy. Each tower was mounted with four 3-dimensional sonic anemometers for collecting turbulence information as well as six temperature sensors and six cup anemometers for characterizing the mean flow. Data was logged at a frequency of 10Hz providing continuous velocity and temperature profiles within and above the canopy. Site 3 was located at approximately 90m above sea level with direct exposure to the undisturbed easterly flows coming up off the sea. Site 2 was on the summit of the ridge and site 1 was on the south-west corner of the ridge, just below the summit with exposure to uphill flows from the south and west. These sites were located in a transect over the ridge with the intent of providing information regarding how the flows interact with the ridge and the canopy.

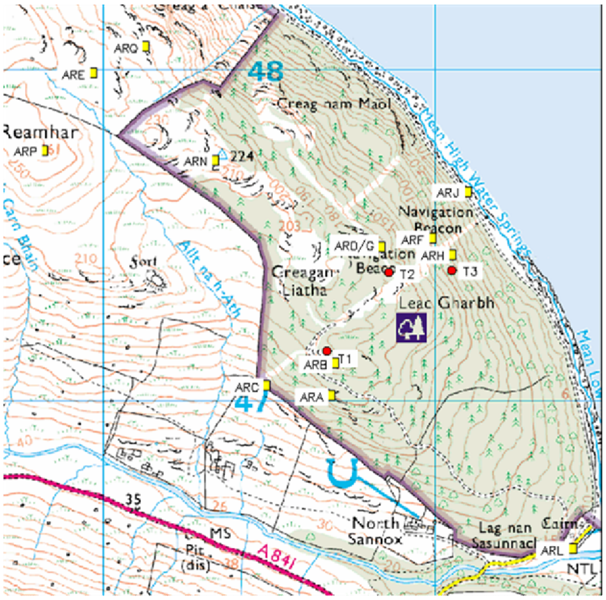

Figure 4. Map of Leac Gharbh, showing the locations of the vertical profile towers (●) and the automatic weather stations(■). © Crown Copyright/database right 2005. An Ordnance Survey EDINA supplied service.

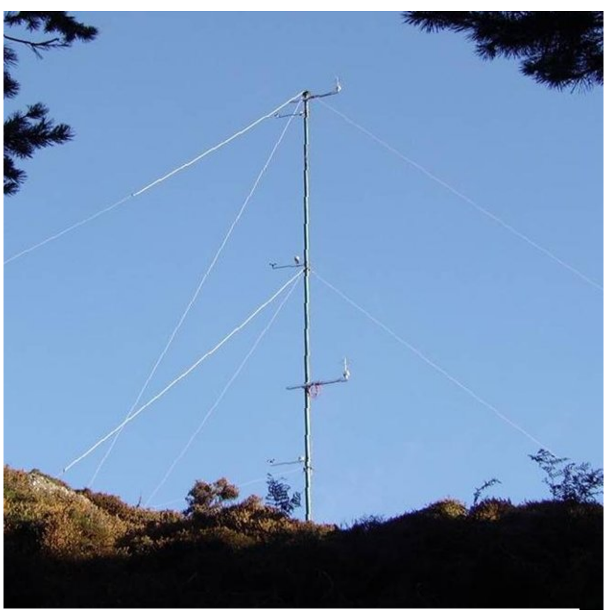

Figure 5. Photo of vertical profile tower at site T1, showing the top two sonic anemometer booms (right) and the top three mean booms (left).

Figure 6. Photo of an AWS at site ARJ showing (from top to bottom) wind vane (left), cup anemometer (right), temperature sensor aspirator, solar panel, logger box, blue lead to pressure sensor and 12v battery.

3.2. Surface measurements

Surface measurements were made using 12 automatic weather stations (AWS), located at sites ARA-ARQ in figure 4. Each AWS measured wind speed and direction at 2m, temperature, relative humidity and pressure. All instruments were measuring continuously and data was logged at a 3second sampling interval, using custom build dataloggers. An AWS station was erected close to each profile tower to provide a direct comparison. The remaining AWS were erected in areas that were thought to provide interesting data with regard to the air flow and its interaction with the canopy and topography. Four more AWS were placed on the transect to provide as much information about the flows in that area as possible. Three more AWS were set up in second transect from east to west, well out of the forest canopy to provide data for a comparison between surface flows within the canopy and surface flows outside the canopy.

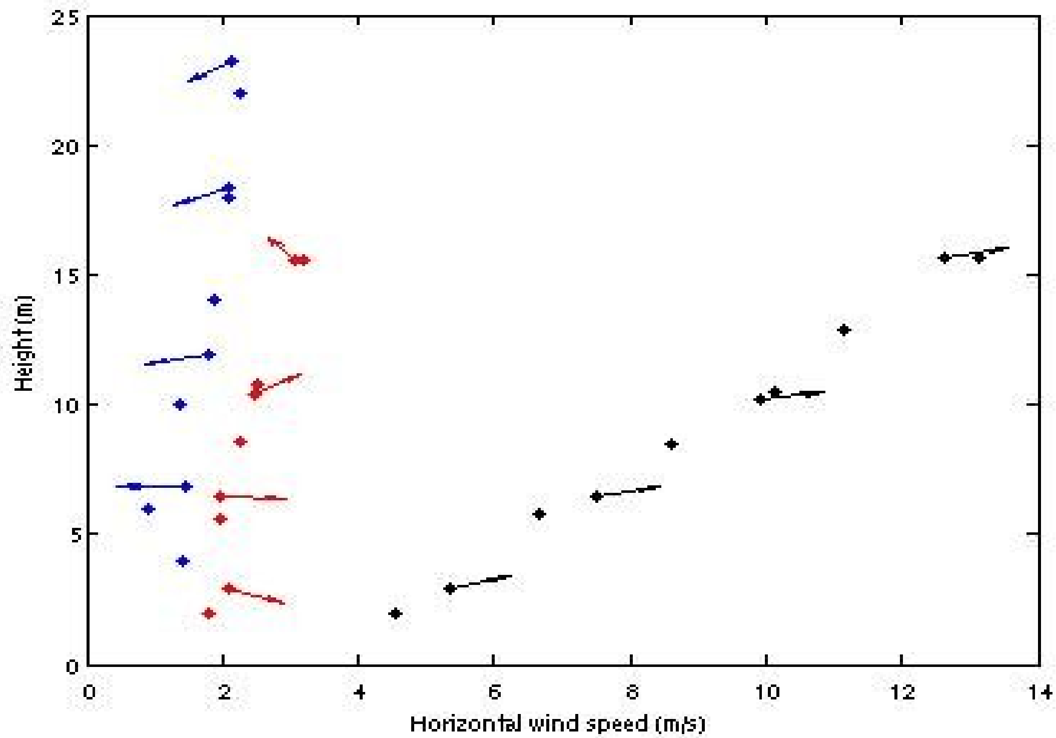

Figure 7. Vertical profiles of horizontal wind speed for each tower (tower 1- black, tower 2- red, tower 3- blue). Data from sonic anemometers include wind direction as indicated with an arrow. Data averaged over a 15 minute period from 05:00 on 06.05.07.

4. DATA

Figure 7 shows the variation in horizontal wind speed measured by the sonic anemometers and cup anemometers mounted on the vertical profile towers against the height at which they were mounted. The data is taken from a 15 minute period from 05:00 on 6th May 2007. The synoptic wind was a strong easterly wind, as shown from the profile of tower 1. With the wind coming from the west, tower 1 is unaffected by the presence of the canopy due to a clearing to the west of the tower. Towers 2 and 3 present more typical canopy profiles with tower 3 in particular showing a slight increase in wind speed around the trunks and then an increase in wind speed above the canopy (~12m at tower 3). The abrupt change in wind direction displayed on tower 3 can be attributed to a region of flow reversal on the lee slope, as expected. The slope is steep here accounting for the height of this separation region. This flow separation is a ubiquitous feature of both numerical and analytical results for forested hills and is observed for both easterly and westerly winds, as will be shown in figure 8.The wind direction measured by the top sonic on tower 2 is a recurrent feature but can not yet be explained.

Figure 8 shows wind vectors from the seven transect AWS (ARA, ARB, ARC, ARD, ARF, ARH and ARJ) averaged over a one hour period. On the east slope the winds are predominantly easterly, aligned with the synoptic flow of that day. On the western leeward slope flow separation is indicated by the abrupt change in direction, directly below the ridge summit. The AWS on the coast (ARJ) shows a south-westerly flow, which is not aligned with the synoptic flow. This feature has been seen in several cases and is thought to be due to a second region of flow separation at the foot of the ridge where the slope rises very steeply.

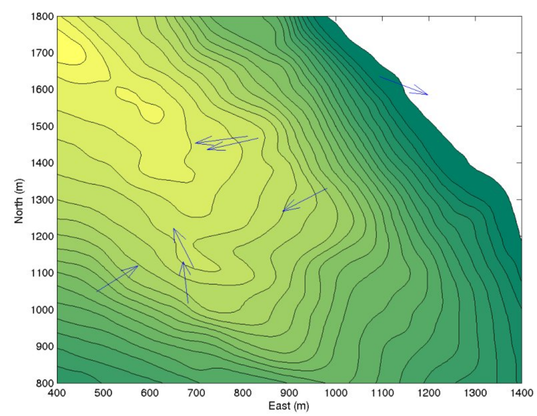

Figure 8. Wind vectors from 7 AWS sites over the southern, forested end of the ridge, plotted on height contours. Measurements are averaged over 14:00-15:00 on 27.04.07.

5. SUMMARY

A field campaign to investigate canopy airflows over a ridge is described. Case studies from the field campaign are introduced with reference to model results. At this early stage the observational dataset has shown to display some of the key features associated with canopy flow over complex terrain, in particular flow separation over the lee slope within the canopy. Future work will see the AWS data used to characterize the mean flows over the ridge and identify some of the larger scale features of the flow. The data from the sonic anemometers will be used to look more specifically at the turbulent flows within and above the canopy, with particular regard to any variation over the ridge. Data from the profile towers will also be used to see how the flow separation processes vary with height. It is also hoped that the AWS data can be used to look at night-time drainage flows.

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