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Turbulent Wind Structure Above Very Rugged Terrain

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ABSTRACT

Results from an experiment conducted in very rugged, heavily wooded terrain at Wyong on the New South Wales coast are presented. Wind measurements were made with cup and sonic anemometers mounted on four 60 m masts spaced between one and 4 km apart. Deflection of the mean flow by specific terrain features is established. Wind characteristics just above the crest of the 200 m coastal escarpment include the combined effects of acceleration up the slope and an increase in surface roughness, reducing speedup and increasing turbulence levels. At 60 m height, momentum transport *away* from the surface is attributed to the structure of the sea breeze.

INTRODUCTION

The first attempts to predict the effect of topography on the near-surface wind field took as their model the simplest possible feature, an infinitely long ridge normal to the flow. Subsequent field experiments also sought sites with simple geometry, either ridges or isolated three-dimensional hills; and theoretical models will continue to require validating experiments on simple geometry in both field and wind tunnel. However, such features are still far removed from the "complex terrain" associated with most practical problems of the real world. Understandably, there have been few attempts to study details of mean, let alone turbulent, wind structure over more complicated topography. One disincentive, apart from the inevitable logistic problems, may be the suspicion that variability of surface conditions and of the wind regime may combine to produce so much scatter in the data that unequivocal conclusions may not be possible.

Nevertheless, Panofsky et al. (1982) compared data from various sources and came to the conclusion that one effect of large-scale surface undulations was to add energy to the low-frequency end of velocity spectra. This was confirmed by Mason and King (1984), who studied wind flow across the floor of one of a succession of valleys, about 1.5 km wide by 200 m deep. They observed separation of flow on the lee slope and describe the complicated recirculating trajectory followed by balloons released from the valley floor. For winds blowing directly across the valley, wind speeds above the valley floor even to a height of 150 m were only 0.2-0.4 times those recorded at the ridge crests.

The range of applications for a proper description of turbulent transfer in the vicinity of such terrain is wide: prediction of the microclimate of crops and forests; evaporation estimates for catchment hydrology; parameterisation of surface conditions in climate models; turbulent dispersion of pollutants, aerosols and particulates. It was in the context of the last example that the present study of mean and turbulent wind flow took place over very complicated terrain.

EXPERIMENTAL CONDITIONS

The experimental site was about 6 km WSW of Wyong (NSW), a small town about 80 km from Sydney on the coastal highway. The topography is typical of the Central Coast region, consisting of a coastal plain of variable width, rising fairly sharply over an escarpment to a forested region of hills and valleys extending to the west. At Wyong the coastal plain extends about 10 km from the sea, successively settlement, lake, partly cleared land and forest; the escarpment rises from about 20 m to 200 m above sea level, the ensuing valleys descending again to around 30-50 m with a typical spacing of 2 km, all densely covered with eucalypt forest averaging 20 m in height.

A simplified topographic map (Fig. 1) shows that the experimental region consists of three N-S ridges connected at their northern ends by a ridge running E-W. Short spurs extend from the main ridges. The map indicates the position of four 60 m high instrument masts coded by letters signifying some nearby object. One is about 300 m east of the foot of the escarpment (BS-Black Stump); two along the first ridge (FT-Fire Tower and WB-White car Body); and the fourth on the second ridge (OB-Orange car Body).

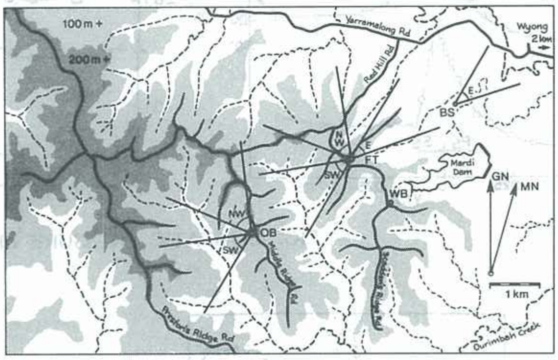

Fig. 1. Map of site in Ourimbah State Forest, Wyong. Positions of four 60 m masts and principal wind directions are indicated.

Each mast was equipped to carry three-dimensional sonic anemometers (Coppin and Taylor, 1983) at two levels, 60 m and at about 10 m above the surrounding trees; viz 33 m at WB, 30 m at OB, 24 m at both FT and BS. We refer to the lowest level on FT, for example, as FT24. Only 5 sonics were available so that positions were interchanged as adequate data were collected for a particular disposition of instruments. Sonic data were transmitted by modem along twin cable from each mast to the data-collecting caravan at FT. FT carried a permanent profile of 9 cup anemometers, while a second array of 6-8 anemometers was moved in turn to each of the other masts.

There are no measuring positions in the valleys, where the wind structure is likely to be at least as complicated as found by Mason and King (1984) with little chance of comprehensible data analysis. On the other hand, enough is known about conditions at the summit of hills and ridges to enable us to recognize terrain-induced phenomena in the wind structure. In this initial analysis we concentrate on the effect of flow up the escarpment and evidence of flow distortion caused by local terrain features.

RESULTS

Two expeditions were made to the site. The first, in May/June 1985, coincided with a period of very wet weather with usable winds almost exclusively from the west. We have selected for analysis two periods of differing wind conditions: 84 15-min runs in the sector 280° - 340° magnetic from 16-18 June which we call NW and 77 runs in the sector 200 - 250° magnetic from 22-23 June which we call SW. (see Fig. 1). The second was undertaken in Feb/March 1986 to obtain easterly wind directions and convective conditions. We have analysed winds in the narrow sector 40-80° magnetic which we term E. These occurred on various days throughout the period due to a very consistent afternoon sea breeze, which resulted in about 55 hours of data. For all directions we excluded variable or transient conditions by requiring mean wind speeds greater than 3 m s^{-1} and a standard deviation in azimuth less than 20°.

MEAN FLOW CHARACTERISTICS: EASTERLY WINDS

For easterly winds we expect acceleration of the flow up the escarpment from BS to FT. For the near surface region Jackson and Hunt (1975) provide a "rule-of-thumb" for the fractional speedup at the crest of an isolated ridge, $\Delta s = \Delta u/u_o \approx 2h/L$, where Δu is the increase in speed at a particular level, z, above the surface relative to its upstream value u_o. h and L are respectively the height and characteristic length (roughly half the physical length) of the hill. Experiments over various natural ridges have shown this expression to be a reasonable approximation to the speedup.

According to Fig. 2 h ≈ 200 m and L ≈ 1000 m for the leading ridge at Wyong, whence $\Delta s \approx 0.4$. Both sonic and cup anemometers indicate a smaller speedup than this, around 0.1 at 24 m and 0.25 at 60 m, as illustrated by the neutral profiles of Fig. 3a. One reason for this may be an effective asymmetry of the ridge which reduces the shape factor involved in the derivation of Δs, as discussed by Bradley (1983). In fact, other geometrical parameters relevant to Jackson and Hunt's analysis, L, h, z_o, are poorly determined for this escarpment so that further examination of this point does not seem profitable.

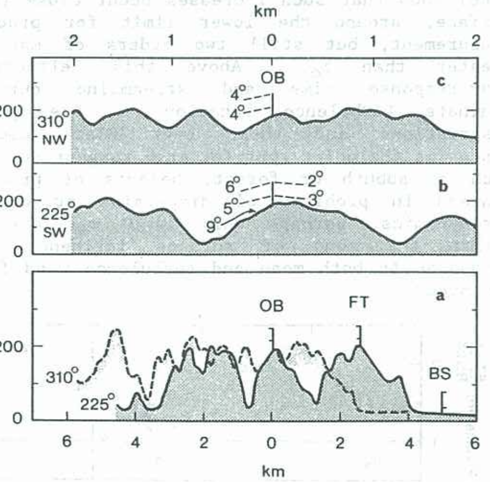

Fig. 2. Transects through Wyong site along bisectors of NW and SW sectors: (a) 225° passes almost directly through OB, FT and BS; (b) SW expanded showing slope and vertical inclination of flow at OB; (c) same for NW.

Of more significance are the unusual differences between the upwind and hill-top profiles: the considerable variation of Δs with height, and the deceleration close to the surface at FT. Near-neutral values of u_* derived from logarithmic profiles at BS are between 0.57 and 0.68 of those measured by the 24 m and 60 m sonics. Such anomalous flux-gradient relationships have been discussed by Garratt (1980) and Raupach (1979) in what Raupach terms the "roughness sublayer" above very rough tree vegetation. This sublayer extends over a height z_s which has been found to vary with surface roughness density in a way which is not yet understood. For wind tunnel data, Raupach found z_s about equal to his model vegetation height, whereas for savannah with tree spacing about 20 m Garratt found z_s about eight tree heights, or 60 m. The fetch at BS consists of trees about 10 m high, singly and in groups with cleared areas in between - rather inhomogenous with a poorly defined mean tree separation somewhat greater than for Garratt's savannah. It is therefore probable that the entire 60 m profile at BS lies within the roughness sublayer, accounting for the reduced shear relative to the measured shear stress.

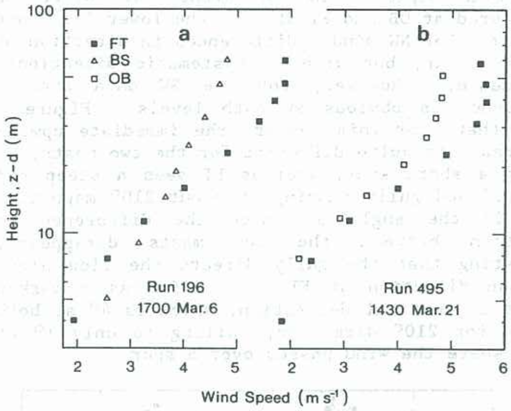

Fig. 3. Neutral velocity profiles at BS, FT and OB for easterly winds (sea breeze). Displacement plane estimated from density of vegetation surrounding each mast, i.e. d = 1 m (BS), 4 m (FT), 14 m (OB).

Thus the S-shaped profile at FT results from the separate effects of pressure-induced acceleration over the escarpment at the upper and middle levels and deceleration at the surface because the forest becomes much more dense and rough than at BS. Figure 3b indicates about 10% reduction of speed at OB relative to FT over the sonic height interval. The curved section at the top of both profiles is discussed below.

Figure 4 shows that easterly winds are deflected by up to 20° towards the north at both FT and OB. The ridge and gully running NE from FT must play a major role at this location. At OB, northerly as well as easterly winds tend to be deflected towards the direction 60° magnetic; i.e. perpendicular to the ridge as discussed by Bradley (1983). This is also the predominant direction of the spurs between OB and FT and the main ridge to the north (see Fig. 1), so that there may also exist a regional topographic influence on the flow direction.

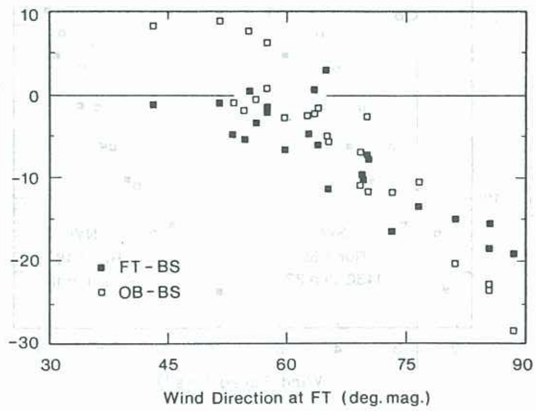

Fig. 4. Difference in wind directions at BS, FT and OB; easterly winds.

The contour map also shows that FT and OB are on opposite sides of their respective ridges. For easterly winds, this has a marked effect on the vertical inclination of streamlines, flow at both levels on FT being directed upwards at about 10°, conforming roughly to the slope of the escarpment for about 800 m upwind. This is very similar to the inclinations observed by Bradley (1980) for flow over a ridge of equivalent height. The transect through OB is expanded in Fig. 2b to illustrate the relative influence of near and more distant parts of the terrain on vertical inclination at the two levels.

MEAN FLOW CHARACTERISTICS: WESTERLY WINDS

The range of wind directions is illustrated in Fig. 5, which depicts the *difference* in direction registered at OB and FT at both the lower level and at 60 m. For NW winds, differences in direction up to 20° occur, but with no systematic directional dependence. However, for the SW data such a dependence is obvious at both levels. Figure 1 shows that, for this sector, the immediate upwind topography is quite different for the two masts, OB facing a short spur, whereas FT sees a steep and well-defined gully running at about 210° magnetic. This is the angle at which the difference in direction between the two masts disappears, indicating that the gully directs the flow along its own direction at FT. It also has a marked effect on vertical deflection, which is 4° at both levels for 210° direction, falling to only 1° at 240°, where the wind passes over a spur.

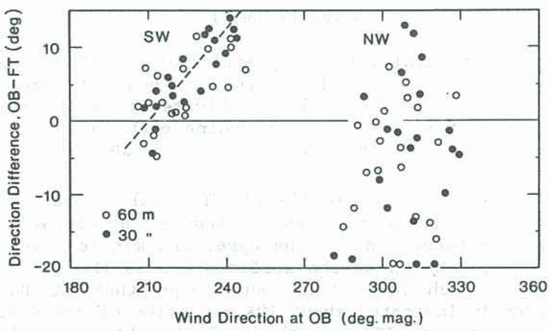

Fig. 5. Difference in wind directions at OB and FT; westerly winds.

At OB, SW winds produce a streamline tilt of 6° and NW winds 4° relative to an immediate surface slope of about 9° in each direction. The difference is obviously due to the proximity of the next upwind ridge. It is surprising to find no decrease in inclination with height. At some height detailed influence of the terrain must become insignificant, but that height is clearly much greater than 60 m.

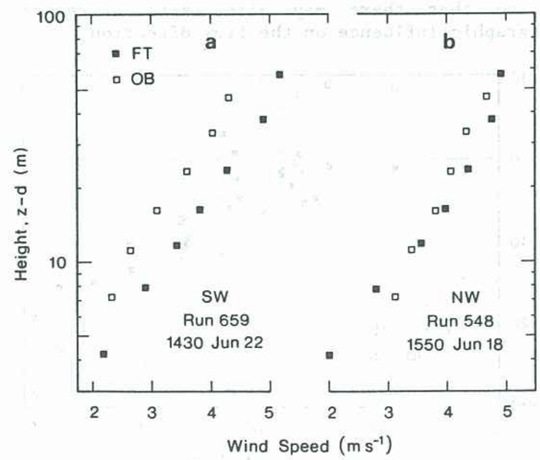

Fig. 6. Comparison of neutral velocity profiles at OB and FT: (a) from SW sector; (b) from NW sector.

The comparison of neutral wind speed profiles at OB and FT, Fig. 6, shows little difference for NW winds whereas from the SW a 20% difference exists over the whole profile. The preservation of wind gradient observed here is a feature of pressure-driven acceleration at the crest of ridges, as illustrated by Bradley (1983) and Coppin et al. (1986). This again suggests that, despite being embedded in a region of similar hills, mean flow characteristics at each hilltop are dominated by the local environment. In view of the modest increase of speed up the escarpment to FT, however, a difference of 20% between apparently similar SW exposures is very surprising. Figure 2 shows that each mast faces a valley about 2 km wide and 160 m deep. We must presume that the funneling effect of the gully at FT is responsible for the additional speedup.

TURBULENCE CHARACTERISTICS

The easterly wind at BS exhibits turbulence behaviour which is well established as characteristic of a properly developed boundary layer over a rough surface. At 24 m the stress ratios σ_u/u_*, σ_v/u_* and σ_w/u_* take conventional values (2.0, 1.7, 1.3) at neutral stability and obey Monin-Obukhov similarity scaling. σ_u, σ_v and σ_w are independent of height for all measured stability and the u_* divergence data, while very scattered, exhibit no systematic departure from unity. The few runs very close to neutral stability show that BS60 and BS24 agree to within about 20% in u_*.

Figure 7 follows the individual turbulence parameters as the wind blows up the escarpment from BS to FT at the 24 m level. Only the lateral component, v, is unchanged. The u and w components increase by an average of 30%, while u_* increases by around 50% near-neutral and rather more in the unstable regime. This is very similar to Bradley's (1980) observations over Black Mountain, which was, however, at least twice as steep and had no apparent change in surface roughness, which must in part contribute to the increase in turbulence levels here. In seeking to determine the limits of an "inner layer" of surface influence, experiments over smoother ridges (e.g. Bradley 1983; Mason and King 1985; Zeman and Jensen 1986; Coppin et al 1986) show that such increases occur close to the surface, around the lower limit for practical measurement, but still two orders of magnitude greater than z_o. Above this, effects of eddy-response time and streamline curvature dominate turbulence behaviour. The present observations and those over Black Mountain emphasize the point that for much rougher surfaces, such as suburb or forest, heights of practical concern in problems of dispersion or building aerodynamics, perhaps only 10-20 z_o, are well within the zone of surface influence where increases to both mean and turbulence wind fields can occur.

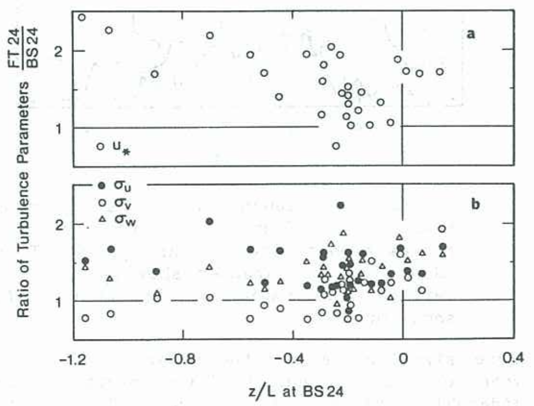

Fig. 7. Change of (a) turbulent velocity components σ_u, σ_v, σ_w and (b) u_*; expressed as the ratio FT/BS at 24 m, as function of stability measured at BS.

At 60 m height the separate u, v and w components are virtually unchanged as the easterly wind blows from BS to FT and on to OB. This implies a significant divergence of all components up FT. At 87 m above Black Mountain also, σ_u and σ_v reduced to about their upstream value, but σ_w behaved differently, remaining fairly high. However, the comparison is complicated in an unexpected way at Wyong because all easterly winds were generated by the sea breeze, as discussed below.

Figure 8b shows the kinematic stress components $\overline{uw}$ and $\overline{vw}$ at FT60 plotted against the heat flux $\overline{w\theta}$, to distinguish between stable and unstable cases. Clearly the data, over the entire range of heat flux, is "contaminated" by a large proportion of runs where the correlation between u and w is positive. Such events in uniform boundary layer measurements are usually associated with non-stationary conditions or an inadequate sampling period. Almost invariably the lateral stress component $\overline{vw}$ takes significant values under these circumstances, as is the case here. A "well-ordered" boundary layer flow returns the stress components as in Fig. 8a, which shows measurements at FT24.

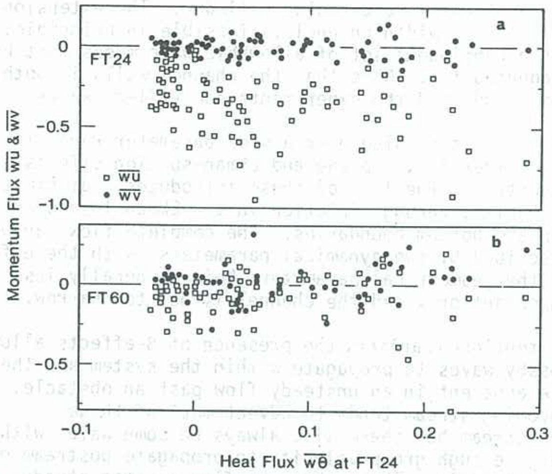

Fig. 8. Shearing stress components $\overline{uw}$ and $\overline{vw}$ at 60 m and 24 m on FT during sea breeze.

In fact, these positive $\overline{uw}$ correlations appear to indicate genuine momentum transport, at this level, away from the surface, which could occur if the sea breeze is a relatively shallow wedge with slower (or reverse) flow aloft. This proposition is supported by the following observations. During periods containing a number of 15-min positive $\overline{uw}$ values at FT60, the intervening values, while remaining negative, are generally much smaller than at FT24. These are also periods with very pronounced reversal of the mean velocity gradient at the upper levels on FT, and also on OB (Fig. 3b). Finally, these are periods of strong heat flux divergence; for one or two runs the heat flux at FT60 actually changes sign, indicating transfer downwards into the layer between the surface and 60 m. Acoustic radar measurements, not yet analysed, should provide information about the wind field at higher levels and help to complete this picture of the sea breeze structure.

SUMMARY

Measurements of the mean and turbulent wind flow over a region of hilly forest have identified several terrain-induced effects. The form of the mean velocity profile at the crest of a coastal escarpment can be interpreted as the result of three separate influences: a change in surface roughness, acceleration up the slope and the structure of the sea breeze. Turbulence and shearing stress levels are enhanced near the surface while at 60 m height upward momentum transport is observed. The latter is associated with a sea breeze surface jet and persists for at least 3 km inland from the escarpment.

Local terrain features, slopes and gulleys have been found to deflect the mean flow substantially but uniformly to at least 60 m above the highest points in country where valleys are from 400-2500 m wide and 160 m deep. This is the regional scale within which three-dimensional models are needed in such areas as forestry and hydrology for the prediction of local microclimate, evaporation and the dispersion of material. The close and quantified association between cause and effect described here is a step towards the incorporation of terrain features in such models.

ACKNOWLEDGEMENTS

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