9th AUSTRALASIAN
FLUID MECHANICS CONFERENCE,
AUCKLAND, 8-12 DECEMBER 1986

The Evolution of Atmospheric Turbulence over a Two-Dimensional Ridge

P. A COPPIN, E. F. BRADLEY and P. C. KATEN

CSIRO Divison of Environmental Mechanics, Canberra, Australia.

ABSTRACT

Measurements of the mean wind field and turbulence statistics have been made over an isolated, two-dimensional ridge of height 100 m and characteristic length 500 m. The mean field showed a fractional speedup approaching 0.8 near the surface, but there is no evidence of equilibrium between the turbulent field and the acceleration. Curvature is shown to be the major influence on the turbulence, which followed the variations in curvature up the windward face of the ridge.

INTRODUCTION

The effects of complex terrain, such as hills and ridges, on the atmospheric boundary layer are of wide interest in such areas as

- wind loading (both static and fluctuating) on buildings and structures.
- dispersion of various kinds of matter, e.g., pollutants, insects, etc.
- aircraft flight.
- wind energy.
- suitabilty of terrain for agriculture.
- lower boundary conditions for meso- and synoptic-scale models of weather, trajectories, etc.

Some of these applications require not only knowledge of the mean wind field but also of the turbulent velocity components.

Complex terrain in its simplest form, that of a hill or an obstacle, affects the flow up to a height of the order of the object's length (Hunt, 1980). It causes a pressure perturbation, generally resulting in an increase in mean velocity at the top of the hill. Much is known from aerofoil theory about potential flow over smooth surfaces, but rough surfaces are a different matter. Modelling flow over a hill with a rough wall boundary layer requires assumptions about the behaviour of the turbulence components.

A classic model is that of Jackson and Hunt (1975), who proposed a scheme consisting of two regions or layers: an outer layer, where the turbulent length scales are larger than the length scale of the hill; and an inner layer, where turbulent length scales are shorter than the terrain scale and hence the turbulence is in equilibrium with the surface. They formulated an analytic, small perturbation model in which the behaviour of the two layers was asymptotically matched. The pressure field, calculated from a potential flow solution, drives the velocity perturbation in both layers. In the outer layer, turbulence changes have no effect on the mean field; pressure changes are balanced by acceleration only. Turbulence behaviour can be deduced from a rapid distortion calculation (e.g., Hunt, 1980). In the inner region the pressure perturbation is balanced by the flow acceleration and turbulent stress divergence, where the turbulence behaviour is calculated from conventional surface layer relations, mean flow and surface roughness.

Being a perturbation theory, the Jackson and Hunt model is valid only for hills with small aspect ratio h/L, with the matching level between the two regions typically at L/20. Here h is the height of the hill and L is the 'half length' of the hill (see Fig. 1). The fractional speedup over the hill, ΔS, is approximately 2h/L. $\Delta S = (\bar{U}_{TOP} - \bar{U}_{BOTTOM})/\bar{U}_{BOTTOM}$. For turbulence the model predicts that in the inner layer the shear stress, τ, increases with $\bar{U}^2$, as do the variances of horizontal, σ_u, and vertical, σ_w, velocity components. In the outer layer τ is unchanged and $-\Delta\sigma_u = \Delta\sigma_w \sim \Delta S$, as given by the rapid distortion calculation. Other models followed this development, not necessarily based on two layers, but certainly using conventional surface layer turbulence formulations (Taylor, 1977, 1980; Sykes, 1980). These models used second-order closure or finite difference numerical techniques to improve on the Jackson and Hunt analytical formulation, relaxing such requirements as the size of the hill and providing extension to three dimensions.

Wind tunnel and field studies showed that the mean flow over hills is fairly well understood (Bradley, 1980, 1983; Mason and Sykes, 1979; Britter et al., 1981). However, as more detailed turbulence measurements have become available, it is clear that the theoretical predictions for the turbulence behaviour are seriously in error (Finnigan and Raupach, 1985; Taylor and Teunissen, 1985).

Finnigan (1983), in his analysis of the turbulent flow equations in streamline co-ordinates, showed that in flow over a hill, extra terms due to the curvature of the flow become significant. None of the previously mentioned models explicitly incorporated curvature in their schemes. If models are formulated in terrain following co-ordinates, curvature must be included explicitly. It has been known for some time in laboratory flows that curvature has an influence on the behaviour of turbulence, concave curvature destabilizing and convex curvature stabilizing the flow. Bradshaw (1969) formalized the analogy between buoyancy and curvature by defining a curvature Richardson number, Rc, which plays the same role as the familiar gradient Richardson number, Ri. So and Mellor (1973) confirmed this analogy for a laboratory turbulent boundary layer with sections of constant convex curvature. Finnigan and Raupach (1985) in their wind tunnel study showed that the behaviour of shear stress over a model hill correlated with R_c near the surface, giving a decrease in stress at the crest rather than the increase suggested by the models.

Most recently, Zeman and Jensen (1986) describe a model in which the flow equations are transformed into streamline coordinates and some curvature terms included. The predictions of the model confirm that the curvature has a dominating influence on the turbulence at heights z < L, e.g. reducing shear stress at the crest. A limited set of field results were shown to agree with this model's production.

Here we examine the results of a large scale field experiment in which mean wind field and turbulence measurements were made over an isolated two-dimensional ridge. Begun in 1984, the study was originally designed to test the theory of Jackson and Hunt, but the results are also useful to examine the effect of curvature on the flow.

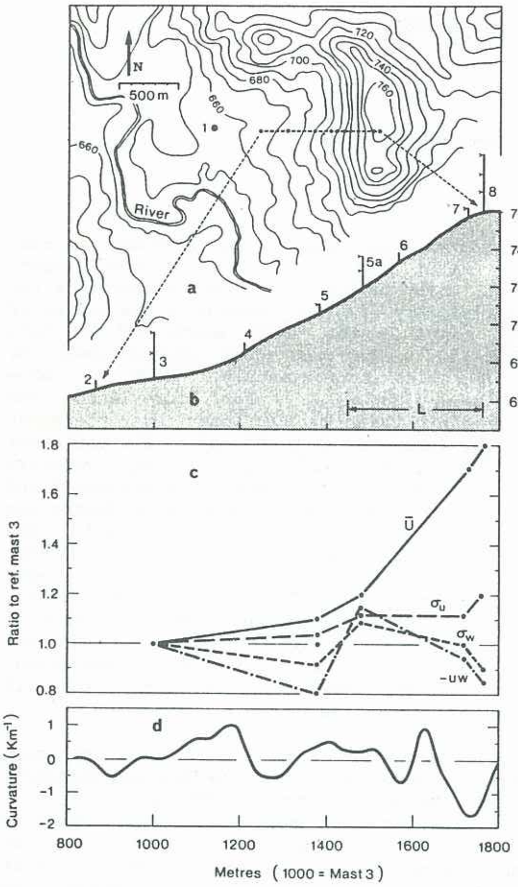

Fig. 1 (a) Contour map of the Cooper's Ridge area. Location of mast 1 is marked. (b) Cross section along mast line of ridge face with 4:1 vertical exaggeration showing tower locations. (c) Mean velocity and turbulence ratios referred to upstream values measured at $z = 2$ m on mast 3. (d) Smoothed surface of curvature along transect of 1(b). Values are of $1/R$; where R is the radius of curvature (km).

EXPERIMENTAL DETAILS

Cooper's Ridge is a north-south orientated ridge located northwest of Goulburn in New South Wales, Australia. It is about 100 m high with a half length of 400-500 m. Cooper's Ridge is located in an east-west orientated river valley that turns south at the foot of the ridge area and so exposes the ridge to a reasonably flat farmland fetch in the prevailing westerly winds. The surface in the vicinity of and on the ridge itself is essentially treeless, grassed grazing land. Figure 1a shows a contour map of the ridge environs, while Fig. 1b shows an exaggerated cross-section of the windward face of the ridge with the position of the instrumentation marked.

The experiment was conducted in two phases. In the first phase, 4 m masts were placed at positions 1 to 7 (excluding 5a). All of these masts were equipped with at least 2 cup anemometers, and sonic anemometers of the type described in Coppin and Taylor (1983) were placed at $z = 3$ m on masts 1, 3, 5 and 7, where z is the height above the ground.

In the second phase a 24 m mast was used at position 3 and a 30 m mast at position 8. Later a 16 m mast was added at position 5a. The two taller masts were equipped with profiles of cup anemometers. A total of five sonic anemometers were used in various combinations on the three masts. Although not discussed here, extensive measurements of heat flux, evaporation and other energy balance components were made.

A total of 1100 15-min. runs were taken in westerly flow conditions and the time series data recorded on magnetic tape for later processing on the Divison's VAX 11/730 computer. Aerodynamic surface conditions varied as the grass height changed, with roughness length, z_o, varying betwen 3 and 8 cm. Here we consider briefly the behaviour of the mean wind field and describe the turbulence behaviour in near-neutral conditions. Although measurements were not taken at 30 m at the upwind site, valid estimates can be made for this level using recognized flat land behaviour and checking this against the variations at lower levels.

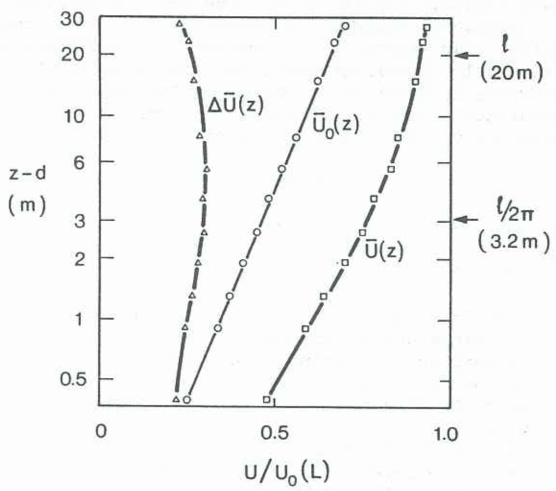

Fig. 2 Vertical cup anemometer profiles of mean wind speed at mast 3, $U_o(z)$, mast 8, $U(z)$, and the difference $\Delta U(z) = U(z) - U_o(z)$. All values are normalized with the extrapolated free stream value $U_o(L)$.

RESULTS

Results from the first phase of the experiment showed little change in any parameters between mast 1 and 3; thus, position 3 is considered a valid measure of upwind conditions. Figure 2 shows typical wind profiles obtained with cup anemometers in neutral conditions at mast 3 and at the crest of the hill, mast 8. The upstream profile is of the classic logarithmic form. The hilltop profile shows a nonlogarithmic form with the difference profile indicating a speedup at all levels with a maximum absolute speedup at about $z = 6$ m. The Jackson and Hunt theory predicts the maximum to be at the height of matching between the inner and outer regions, ℓ, which for Cooper's ridge is about 20 m. Mason and King (1985) also indicate, in their summary of model results, that some predict the maximum speedup to be in the vicinity of $\ell/2\pi$ (~ 3 m). Figure 3 shows the fractional speedup, ΔS, compared with the Jackson and Hunt prediction; the values agree well in the region $z = 2$ to 20 m. At $z = 2$ m the fractional speedup is approximately 0.7 in this example.

Figure 4 is a plot of the ratio of the wind speed at the crest (mast 8), measured by a sonic anemometer at $z = 2$ m, to the corresponding value upstream at mast 3, as a function of atmospheric stability. The neutral intercept is about 1.8.

The scatter is not unduly large for unstable conditions, typical of any measurement in the atmospheric boundary layer. There is a small decrease in speedup with instability, while in stable conditions the speedup shows a gradual increase until the flow at the bottom of the hill starts to decouple from that at the top, whereupon the speedup increases sharply.

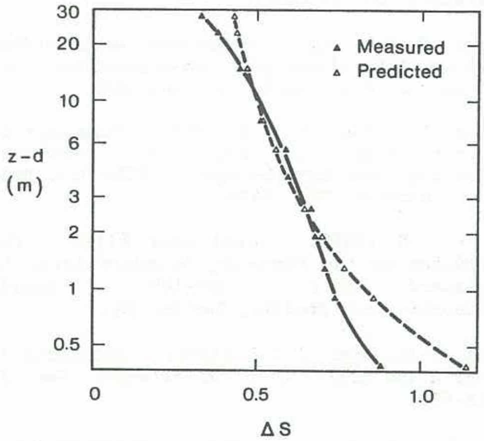

Fig. 3 Fractional speedup $\Delta S = (U(z) - U_o(z))/U_o(z)$ and the prediction for ΔS from Jackson and Hunt (1975).

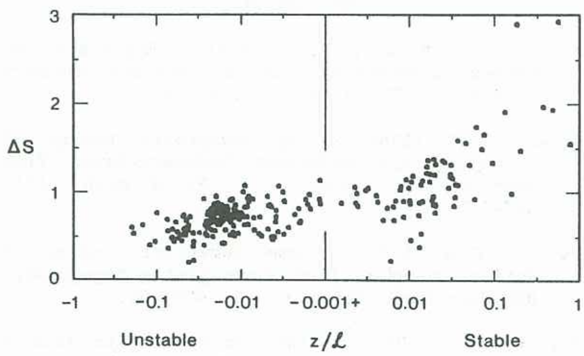

Fig. 4 Fractional speedup ΔS vs. atmospheric stability, $z/\mathcal{L}$, measured at z = 2 m with a sonic anemometer.

The upstream turbulence statistics, measured at mast 3, show typical surface layer behaviour with σ_u/u_*, σ_v/u_*, σ_w/u_* giving neutral stability values of 2.5, 2.2 and 1.15 respectively at z = 2 m. The shear stress, τ, showed a constant flux layer at mast 3.

Figure 5 shows the ratio of the turbulence components in near-neutral conditions at various heights at the crest of the hill compared to their upstream values. The most obvious feature is that near the ground ($z < \ell$) the values do not increase as if the turbulence were in equilibrium with the mean field. The ratio is close to unity except at the lowest level, 2 m, where it has a value of 1.2. The σ_w ratio is less than unity near the ground with an increase at height, while σ_v ratios show little change. There is little evidence for a significant trend to the rapid distortion predictions at the 30 m level. The $\overline{uw}$ ratio is less than one near the ground, with a value of 0.85 at z = 2 m, and decreases to a value of 0.5 at z = 30 m.

The small changes in standard deviations of velocity components combined with the mean field speedup result in reductions in turbulence intensities for all components. The ratios range from approximately 0.5 near the ground to 0.7 at z = 30 m. This is an important result for wind engineering applications.

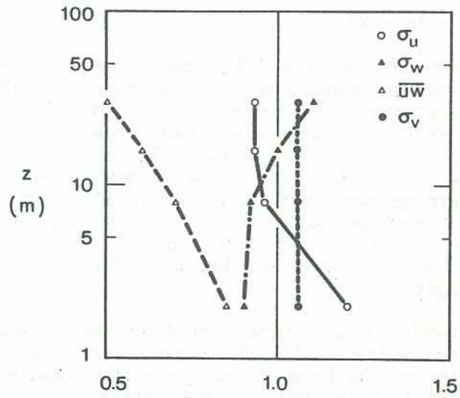

Fig. 5 Ratios of turbulence components and shear stress, (values at mast 8)/(values at mast 3), as a function of height.

The model of Zeman and Jensen (1986) is a valuable aid to the interpretation of these results. Their calculations are for a hill of similar height and roughness but greater steepness (L = 250 m). They tested their model with and without curvature terms. With curvature terms included, the model predictions for σ_u/σ_{u_o} are very similar to our results with an increase below 5 m and a decrease above, reaching a minimum of 0.8 at about 8 m. The σ_w/σ_{w_o} predictions with curvature are also very similar, even in magnitude, to our measurements above z = 5 m; however, our results do not confirm a predicted increase below z = 5 m. For $\overline{uw}/\overline{uw}_o$ the model with curvature predicts a significant minimum of < 0.3 at about z = 6 m increasing toward the ground to values > 1 below z = 3.5 m and also increasing to 1 at about z = 50 m. Our measurements do not follow this form, but rather decrease monotonically with height.

Although differing in detail, these results confirm the Zeman and Jensen prediction that at the crest of a hill curvature has a significant effect on the behaviour of the turbulence components and shear stress at heights of the order ℓ and below and that there is no true equilibrium layer close to the ground, as proposed by Jackson and Hunt.

To investigate this connection further, we examine our results for the development of the turbulence on the windward face of the ridge and relate it to the curvature. Over real terrain the curvature is constantly changing. Figure 1d shows a plot of the hill curvature along the same transect as displayed in Fig. 1b. Although smoothed somewhat to remove minor irregularities, the profile still shows the 'staircase' nature of the hill. Above, in Fig. 1c, we plot the ratios for the turbulence components taken at z = 2 or 3 m compared to the values at mast 3. The flow structure at a particular measuring point is not coupled to the surface curvature directly beneath, but reflects the combined effects of the small scale terrain variations for some distance upwind. An order of magnitude estimate of this effect can be made as follows. We assume that at a given height, z, the turbulence will integrate a length of terrain (ℓ_c) approximately equal to its own eddy length scale (ℓ_T): $\ell_c \sim O(\ell_T)$.

$$\ell_T = T_L \overline{U}$$

where T_L ($= q^2/\epsilon$) is the Lagrangian timescale, with q^2 twice the turbulent kinetic energy and ϵ the dissipation rate of turbulent kinetic energy.

$$T_L \approx \frac{q^2}{u_*^2} \frac{\partial \bar{U}}{\partial z} \approx \frac{q^2}{u_*^2} \frac{u_*}{kz}$$

Since $q^2/u_*^2 \sim 0.1$ and $u_*/U \sim 0.1$ upstream,

$$T_L U = \ell_C \sim 40\ z$$

Thus, measured at z = 2-3 m the turbulence will "see" the curvature of the surface for about 100 m upstream. The measurements of σ_w and $\overline{uw}$ plotted in Fig. 1c show a decrease at mast 5 after a region of negative, stabilizing curvature; an increase at mast 5a after some positive, destabilizing curvature; near unity values at mast 7; and a decrease at mast 8 after the signific negative, stabilizing curvature at the crest of th. hill. The curvature has little effect on σ_u at this height.

These results qualitatively confirm the curvature stability analogy, with the turbulence apparently responding to the local curvature rather than being in equilibrium with the mean wind field.

SUMMARY

The results confirm that the surface curvature has a significant effect on the turbulent boundary layer near the ground. Prior to Zeman and Jensen (1986), the effect on the turbulent flow equations of the curvature of the streamlines had been a neglected area. Nevertheless, most models describe the mean field reasonably well because the potential flow solution for the pressure perturbation includes the streamline curvature implicitly.

The local effect of the curvature is evident in the measurements on the face of the ridge and points to the need for laboratory investigations of fully developed rough wall boundary layers with constant surface curvature and of the curvature "memory" of the turbulence.

REFERENCES

Bradley, E F (1980): An experimental study of the profiles of wind speed, shearing stress and turbulent intensities at the crest of a large hill. *Q. J. R. Meteorol. Soc. 106*, 101-124.

Bradley, E F (1983): The influence of thermal stability and angle of incidence on the acceleration of wind up a slope. *J. Wind Eng. & Ind. Aerodyn. 15*, 231-242.

Bradshaw, P (1969): The analogy between streamline curvature and buoyancy in turbulent shear flow. *J. Fluid Mech. 36*, 177-192.

Britter, R E; Hunt, J C R; Richards, K J (1981): Air flow over a two-dimensional hill: studies of velocity speed-up, roughness effects and turbulence. *Q. J. R. Meteorol. Soc. 107*, 91-110.

Coppin, P A; Taylor, K J (1983): A three-component sonic anemometer/thermometer system for general micrometeorological research. *Boundary-Layer Meteorol. 27*, 27-42.

Finnigan, J J (1983): A streamline co-ordinate system for distorted, two-dimensional shear flows. *J. Fluid Mech. 130*, 241-258.

Finnigan, J J; Raupach, M R (1985): Turbulent flow over two-dimensional ridges. *Proc. Workshop on Wind Eng. and Ind. Aerodyn.* CSIRO Div. Build. Res., Highett, Vic, 1985.

Hunt, J C R (1980): Wind over hills. *Proc. Workshop on the Planetary Boundary Layer* (J C Wyngaard, Ed.) 107-149. American Meteorological Society, Boston, MA.

Jackson, P S; Hunt, J C R (1975): Turbulent flow over a low hill. *Q. J. R. Meteorol. Soc. 101*, 929-955.

Mason, P J; King, J C (1985): Measurements and predictions of flow and turbulence over an isolated hill of moderate slope. *Q. J. R. Meteorol. Soc. 111*, 617-640.

Mason, P J; Sykes, R I (1979): Flow over an isolated hill of moderate slope. *Q. J. R. Meteorol. Soc. 105*, 383-395.

So, R M C; Mellor, G L (1973): Experiment on convex curvature effects in turbulent boundary layers. *J. Fluid Mech. 60*, 43-62.

Sykes, R I (1980): An asymptotic theory of incompressible turbulent boundary-layer flow over a small hump. *J. Fluid Mech. 101*, 647-670.

Taylor, P A (1977): Some numerical studies of surface boundary flow above gentle topography. *Boundary-Layer Meteorol. 11*, 439-465.

Taylor, P A (1980): Some recent results from a numerical model of surface boundary layer flow over hills. *Proc. Workshop on the Planetary Boundary Layer* (J C Wyngaard, Ed.) 150-157. American Meteorological Society, Boston, MA.

Taylor, P A; Teunissen, H W (1985): The Askervein Hill Project: Report on the Sept/Oct 1983 Main Field Experiment. Report No. MSRB-84-6, Atmospheric Environment Service, Canada.

Zeman, O; Jensen, N O (1986): Modification of turbulence characteristics in flow over hills, *Q. J. R. Meteorol. Soc.* (in press).