BOUNDARY-LAYER FLOW OVER LOW HILLS

*(A Review)**

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Abstract. In 1975 Jackson and Hunt observed that there had, until that time, been few attempts to relate measurements of wind velocity on hills to the local topography. The succeeding ten years have seen substantial research effort aimed at rectifying this omission. The field measurements, in conjunction with theoretical, numerical and wind tunnel studies now provide a good basis for a preliminary description of neutrally stratified boundary-layer flow over low hills. There are still gaps in the description and understanding of the flow but many more data are now available. The present review attempts to summarize recent field experiments that have been conducted on boundary-layer flow over low hills and to review what we have learnt from them.

1. Introduction

There has been considerable theoretical and applied interest in the study of boundary-layer flow over low hills in the last ten years. Together with flow above roughness changes and changes in surface thermal properties, the flow over hills or valleys is one of the basic components of boundary-layer flow in 'complex terrain'. The present review will attempt to summarize our present knowledge of these flows, especially that derived from recent field studies, and to identify a few gaps. Several of the field studies discussed have not yet been fully reported in the open literature but results of these should be published very soon. We shall concentrate on flows with near-neutral thermal stratification since most of the data are for this situation. The hills to be considered will typically have lengths ~ 1 km and heights ~ 100 m, i.e., they are hills rather than mountains.

* The original idea for this review started with the IAMAP-sponsored symposium on 'The Atmospheric Boundary-Layer over Complex Terrain' at the 1981 IUGG Congress in Hamburg. One of us (EFB) convened the session while another (PJM) presented the keynote review paper. The idea was elaborated when PAT and PJM visited CSIRO early in 1984 and is now published as the second in a series of reviews at the invitation of Working Group A of the IAMAP Commission on Dynamic Meteorology. A condensed version of this review was presented at the 1985 American Meteorological Society, 7th Symposium on Turbulence and Diffusion, Boulder, Colo.

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2. Theoretical Considerations and Model Studies

In this section we shall consider some basic ideas concerning neutrally stratified boundary-layer flow over a low hill. Many of the theoretical and model studies formally assume that the flow perturbations caused by the hill, Δu, are small compared to the upstream flow, $u_0(z)$. In practice we often have to relax this assumption. Several analyses are based on Jackson and Hunt's (1975) division of the flow into inner and outer layers – the JH theory. The outer layer is assumed to be essentially inviscid while turbulent transfer processes are dynamically significant only within the inner layer of depth l. For a hill with (uniform) surface roughness, z_0, and characteristic horizontal length, L (defined here, following Jackson and Hunt, 1975, p. 947 as 'the distance from the hilltop to the upstream point where the elevation is half its maximum' – see Figure 1), Jackson and Hunt's equation for l is

$$\frac{l}{L} \ln(l/z_0) = 2\kappa^2 \tag{1}$$

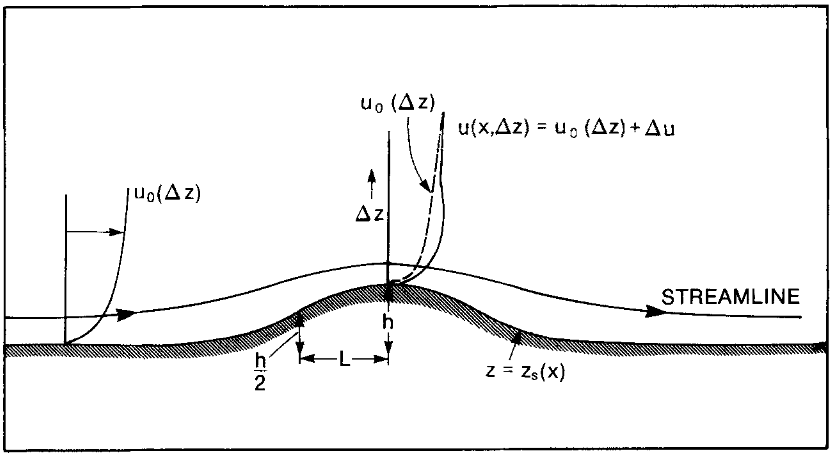

Fig. 1. Definitions of h, L, Δu, u_0, Δz, and z_s.

where κ is von Karmán's constant (0.4) and an undisturbed, upstream profile of the usual logarithmic form is assumed. Note that the equation does not involve the height of the hill, which we shall designate by h, since it is based on the assumption of small-amplitude perturbations for low hills with no significant mean flow separation. Figure 2 shows this relationship between l/L and L/z_0. For a typical case with $L = 500$ m and $z_0 = 0.05$ m, we find $l/L \simeq 0.05$ ($l \simeq 25$ m). We shall use the definition of L given above throughout the present review since it is convenient and may easily be obtained from contour maps. From a theoretical point of view, there would perhaps be more merit to an inverse wavenumber scale or scales based on a spectral analysis

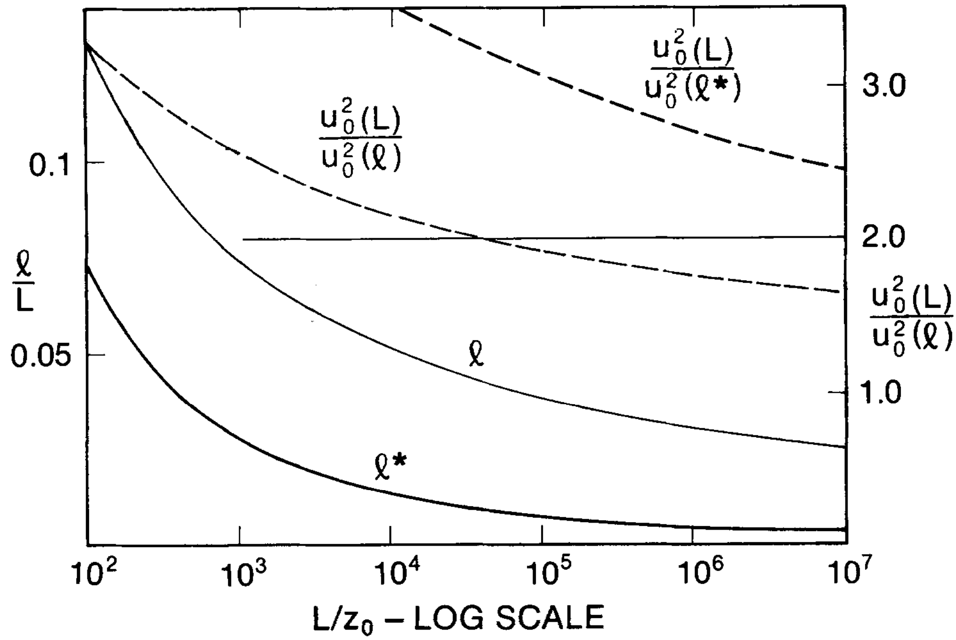

Fig. 2. Graphs of l/L, l^*/L, and $u_0^2(L)/u_0^2(l)$ as functions of L/z_0.

of the terrain but this would be rather less practical. Note that some of the works cited have used different conventions.

Equation (1) is based on an order-of-magnitude balance of the nonlinear advection term with the stress divergence term in the equation of motion, i.e.,

$$u_0(l)\,\frac{\Delta u}{L} \sim \frac{\Delta\tau}{l}\,.$$

Note that there is nothing sacred about the numerical coefficient and that the scale depends upon the use of a mixing-length parameterization of the stress tensor. More general forms of the relationship can be obtained by relaxing the assumption that the upstream profile, $u_0(z)$, is logarithmic. As it stands, Equation (1) is equivalent to

$$l = \frac{2\kappa u_*}{u_0(l)}\,L = 2\kappa C_D^{1/2} L \tag{2}$$

with C_D defined as $u_*^2/u_0^2(l)$. This is the form preferred by Mason and King (1985). Since $2\kappa \simeq 0.8$, it is conveniently written as $l \sim C_D^{1/2}L$.

In his estimate of the inner-layer stress divergence term, $\partial\tau/\partial z$, Hunt (1980, p. 113) assumes that the stress perturbation is given by

$$\Delta\tau = 2\kappa u_*\Delta z\; \partial\Delta u/\partial\Delta z \sim 2\kappa u_*\Delta u\,.$$

It can, however, be argued that, *if* the inner layer is in approximate local equilibrium, $\Delta u \propto \ln(\Delta z/z_0)$ and so $\partial \Delta u/\partial \Delta z = \Delta u/(\Delta z \ln(\Delta z/z_0))$. With this assumption, $\Delta\tau \sim 2\kappa u_* \Delta u/\ln(\Delta z/z_0)$ and the equation for the inner-layer thickness becomes

$$\frac{l}{L}\ln^2(l/z_0) = 2\kappa^2 . \qquad (3)$$

We shall denote the solution to this equation as l^*. Several researchers have used Equation (3) or similar expressions; Jensen (1983, unpublished discussions at Auckland meeting of the International Association for Wind Engineering and Jensen *et al.*, 1984) appears to be the originator. The assumption of a logarithmic variation for Δu is certainly appealing and, as we shall see, the shallower depths predicted for the inner layer (see Figure 2) are in better agreeement with observations than the values given by Equation (1). We anticipate that Equation (3) may be used more widely in future.

The JH theory formally considers the situation with $z_0 \to 0$ and $l/L \to 0$. In this asymptotic limit, there is no velocity shear in the flow interior i.e., $u_0(L) \sim u_0(l)$. However, in most practical flows, z_0 is not small enough and there is a significant difference between $u_0(L)$ and $u_0(l)$. Recent applications of the Jackson and Hunt theory (see below) have been based on a physical understanding of the dynamics to try to allow for such effects. In particular, they recognize that the pressure field is largely determined by the velocity $u_0(L)$ characterizing the inviscid flow region whilst $u_0(l)$ is a typical advection velocity in the inner layer.

Figure 1 shows definitions for the velocity perturbation, Δu, at a height, Δz, above the local terrain, z_s, relative to the upstream profile, $u_0(\Delta z)$. The ratio $\Delta u/u_0$ is frequently used and referred to as the fractional speed-up ratio, ΔS. In the asymptotic limit with $u_0(l) \sim u_0(L)$ then, for heights, Δz, of $0(l)$, ΔS will be the same as it would be for inviscid, irrotational flow. This is represented by $(h/L)\sigma(x, \Delta z)$. As noted by Jackson and Hunt (1975) and Hunt (1980), and considered in more detail by Taylor *et al.* (1983a) and Mason and King (1985), allowance for differences between $u_0(l)$ and $u_0(L)$ leads, for the inner layer, to

$$\Delta S \sim (u_0^2(L)/u_0^2(l))\,(h/L)\sigma . \qquad (4)$$

For typical values of L, z_0, and l, the ratio $(u_0^2(L)/u_0^2(l)) \simeq 2$ (see Figure 2) while for many 2D hills, $\sigma \simeq 1$ near the surface above the summit. Thus, in this location, $\Delta S_{\max} \simeq 2h/L$. Taylor and Lee (1984) make use of these ideas in formulating simple guidelines for estimating wind speed variations caused by small-scale topographic features. They suggest $\Delta S_{\max} \simeq 1.6h/L$ for 3D axially-symmetric hills. If we use Equation (3) to determine l, we find that the ratio $(u_0^2(L)/u_0^2(l^*))$ is slightly increased ($\simeq 3$ for $10^4 \leq L/z_0 \leq 10^6$) and that slightly higher estimates could be appropriate for fractional speed-up ratio estimates very close to the surface. Jensen (1983) notes that the Jackson–Hunt inviscid irrotational outer layer solution leads to $\Delta S \sim (u_0(L)/u_0(z))\,(h/L)\sigma$ for $\Delta z > l$ and the inner and outer layer solutions do not match. This form is also recommended by Jensen *et al.* (1984). It is our view, however, that $\Delta S \sim (u_0(L)/u_0(\Delta z))^2(h/L)\sigma$ better represents the effects of velocity shear in the outer layer and will provide more reliable ΔS estimates.

Jackson and Hunt's linear theory for terrain-induced mean flow perturbations above 2D low hills was extended to 3D terrain features by Mason and Sykes (1979b) and has formed the basis for a series of models developed by Walmsley *et al.* (1982, 1986), Taylor *et al.* (1983a) and Mason and King (1984b). The latter two references introduce terrain wavenumber dependency modifications which are particularly useful for real terrain applications. We shall refer to this as the 'modified Jackson–Hunt (JH) theory'. Within this theory, the outer layer is still assumed irrotational. However, Hunt *et al.* (1987a) have recently proposed a division of an inviscid, outer region into an upper irrotational layer and a middle, inviscid shear layer. With this extra modification, the JH theory can be extended to include upstream approach flows with significant shear. Note that the JH theory is linearized in terms of the slope (h/L) but still appears to give reasonably good results on the hilltop and upstream for $h/L \leq 0.4$.

For two-dimensional topography ($z_s = z_s(x)$), Taylor (1977), and Deaves (1976, 1980) have presented numerical, finite difference, calculations of flow over idealized terrain features. Although these avoid the necessity of division of the flow into two layers and are not linearized, they still use relatively simple closure hypotheses, based on the use of the turbulent kinetic energy equation. The mean flow results are similar to those predicted by JH theory while the value of turbulence results is limited by the closure hypotheses. Recent developments include a linearised, 3D, mixed spectral-finite difference model using $k - \varepsilon$ closure (Beljaars *et al.*, 1987), 2D and 3D finite difference models using $k - \varepsilon$ closure (Detering, 1985; Raithby, 1985, personal communication) and a 2D higher order closure model (Zeman and Jensen, 1985).

Some theoretical predictions of the modifications to the turbulence field in flow over low hills have been discussed by Britter *et al.* (1981) and Hunt (1980) based on the application of rapid distortion theory in the outer layer and the assumption of equilibrium conditions close to the ground. (Rapid distortion theory assumes that the 'eddies' are distorted by the flow sufficiently rapidly that the turbulence is not significantly modified by the change in strain rate (i.e., by the production terms) but is modified by the stretching or compressing of the individual vortex elements.) A more detailed approach to predicting the turbulence modifications for flow over idealized 2D terrain using higher order closure was attempted by Sykes (1980) but we now note that although we believe the analysis is correct, the numerical plots given in the paper appear to be subject to coding errors. Recently, Newley (1985) has extended the type of finite-difference model previously used by Taylor (1977) to include a full second-order closure model. His results will be discussed in more detail below. In the asymptotic limit considered by Sykes, the turbulence stresses only influence the mean flow on the scale $C_D L$, which is closer to the ground than l ($\sim l^*$ in fact). The scale l still appears but as a scale important in the turbulence dynamics. In flow for realistic parameters, and not in the asymptotic limit $z_0 \rightarrow 0$, the finite-difference calculations show a mean flow close to that anticipated from the Jackson and Hunt theory. In most practical applications, we are concerned with flow at least a few metres from the surface and this is dominated by the inviscid dynamics. The subtleties of the turbulence model are of importance to the turbulence structure but appear to have little influence on the mean flow.

3. Field Experiments

Jackson and Hunt (1975) noted that 'measurements of the wind velocity distribution for specific sites on hills are not uncommon, but there have been few attempts to relate them to topographic features...'. Since then, there have been several field experiments designed specifically to do this.

Among the more significant studies are those on Brent Knoll (Mason and Sykes, 1979b), Black Mountain (Bradley, 1980), Ailsa Craig (Jenkins *et al.*, 1981), Kettles Hill (Taylor *et al.*, 1983b; Mickle *et al.*, 1984), Blashaval (Mason and King, 1985), Bungendore ridge (Bradley, 1983), Askervein (Taylor and Teunissen, 1983, 1985) and Nyland Hill (Mason, 1986). Although final results or publications are still awaited from several of these studies, it is clear that there is now a substantial body of field data available and that the situation is much better than it was in 1975.

We should perhaps stress that the present review is based exclusively on the 'Western literature'. Theoretical and experimental work in the Soviet Union related to atmospheric diffusion in non-uniform terrain is reviewed by Berlyand (1975, Sections 6 and 9.8). A study of particular interest in the present context is a 1969 stereo-photogrammetric investigation of the air flow over a hill. This is also discussed by Eliseev (1973). The hill studied was about 100 m high with $L \sim 150$ m. Wind speeds at heights from 5 to 70 m above the terrain were determined from the analysis of photographs of 'vertical' smoke traces. They display ΔS values of $0(1)$ near the surface above the hilltop. We are not aware of any more recent work along these lines but we hope that this review might prompt a companion article from authors more familiar with the Russian language literature.

Here we shall endeavour to categorize recent experiments in terms of hill length (L/z_0) and steepness (h/L) and to summarize some of the results. In all cases, the hills studied have a well-defined shape and a distinct 'spectral gap' between the topography and the roughness elements contributing to a local z_0. Almost all of the data available are for near-neutral thermal stratification so this may be assumed unless otherwise stated. There is clearly a need for additional field data in non-neutral situations, a point that we shall discuss later.

Figure 3 attempts to indicate those parts of the $(L/z_0,\, h/L)$ parameter-space which have so far been explored by field studies. For approximately axially-symmetric hills, a single point is shown, while for elongated hills a short line is drawn covering the range of values of L for which data were obtained. For Bungendore ridge, the line corresponds to variations in z_0 during the course of the study. The experiments are cross-referenced in Table I which attempts to summarize the data that are, or should become, available. It is clear from Figure 3 that many of the field studies are clustered together in the range $6 \times 10^3 < L/z_0 < 6 \times 10^4$. The Black Mountain and Worms Embankment studies

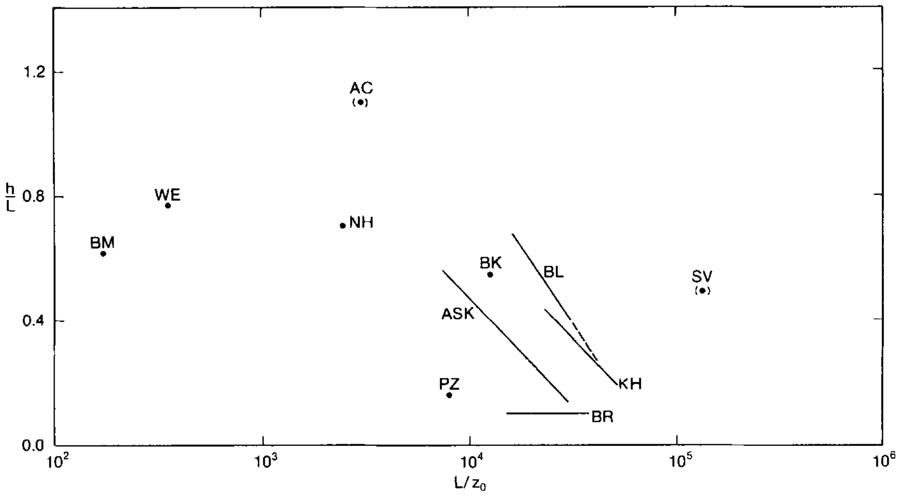

Fig. 3. Parameter space diagram – field studies of boundary-layer flow over hills. See Table I for additional details.

TABLE I

Field studies of boundary-layer flow over low hills

Code	Hill	Reference	Experiment details: Mean flow data	Experiment details: Turbulence instrumentation
BK	Brent Knoll	Mason and Sykes (1979b)	2 m wind speed at about 20 sites.	None
PZ	Pouzauges Hill	Sacré (1979)	3 25 m masts.	Gill UVW anemometers at 10, 15, 20, and 25 m levels on three masts.
BM	Black Mountain	Bradley (1980)	Cup anemometers at 9 levels up to 124 m on hilltop tower and 7 levels to 25 m on upwind reference tower.	Gill UVW and Sonic anemometers at various levels.
(AC)	Ailsa Craig	Jenkins *et al.* (1981)	4 m wind speed at 12 sites plus aircraft data.	Tethered balloon-borne measurements.
KH	Kettles Hill[a] (1981)	Taylor *et al.* (1983b)	3, 6, and 10 m wind speed on 8 3 m posts and 10 10 m towers. Direction at 10 m levels only.	10 Gill UVW anemometers at 10 m along hill axis + 10 m Sonic at hilltop. (Turbulence data not yet published.)

Table I (continued)

Code	Hill	Reference	Experiment details	
			Mean flow data	Turbulence instrumentation
KH	Kettles Hill (1984)	Mickle *et al.* (1984)	2.5, 5, and 10 m wind speed on 4 10 m posts plus TALA kite profiles at hilltop and reference sites.	None
WE	Worms Embankment	Hauf and Neumann-Hauf (1982)	Two 18 m masts upstream of embankment with 6 cup anemometers on each.	One 3-component Sonic anemometer on boom or small mast above embankment.
BR	Bungendore Ridge	Bradley (1983)	3 27 m towers with cup anemometers.	2 Sonic and 4 Gill UVW anemometers at 2.2, 4, and 8 m levels on 2 towers.
(SV)	Sirhowy Valley	Mason and King (1984)	8 m wind speed at 12 sites.	One Sonic anemometer at 16 m in valley and hot film up to 16 m on summit. Tethered balloon and aircraft measurements.
BL	Blashaval	Mason and King (1985)	11 8 m towers with 2 component propeller anemometers + cup anemometer profile to 16 m at upwind reference site and TALA kite profiles.	Hot film and Gill propeller anemometers on 16 m towers at reference and summit sites.
ASK	Askervein[a] (1982)	Taylor and Teunissen (1983)	35 10 m posts plus profiles to 50 m at hilltop (HT) and upwind reference site (RS).	6 Sonic anemometers (2 at RS, 4 at HT) on 50 m towers plus Gill UVW anemometers at 10 m (RS and HT). Cup anemometer variances also available from 50 m towers.
ASK	Askervein[a] (1983)	Taylor and Teunissen (1985)	As above plus TALA kite profiles to ~ 150 m at HT and RS.	As above, plus Gill UVW anemometers on 50 m towers, on 30 m tower just upwind of hill, on 17 m tower at second hilltop location and on 13 10 m towers at other locations.
NH	Nyland Hill	Mason (1986)	Hilltop and upwind measurements to 16 m + 2 lines of 8 m towers down hill sides (10 sites).	Hot film, Sonic, and Gill propeller anemometers on 16 m towers at hilltop and upwind reference sites.

[a] Parallel wind tunnel studies also undertaken.

stand out at the 'rough surface' end of the range but neither is entirely satisfactory. At Black Mountain, there are good mean wind speed and turbulence data on the hilltop for $9 \text{ m} < \Delta z - d < 89 \text{ m}$, where d is displacement height but at the upstream location, the tower only gave profiles up to $\Delta z - d = 18$ m and extrapolation was necessary to compare profiles above that level. The Worms Embankment study has severe limitations due to the relatively low wind speeds ($\sim 2 \text{ m s}^{-1}$) encountered during the observation period and the limited data available. The study with the highest value of L/z_0 is Mason and King's (1984) work in the Sirhowy Valley. As the name suggests, it is not an isolated hill and the measurements were made over one of a series of rolling ridges and valleys. The studies at Ailsa Craig cannot be regarded as characteristic of low hills. The flow definitely separates very vigorously due to the steepness. Also the study by Sacré (1979) near Pouzauges was conducted in generally complex terrain and it is hard to isolate the effect of a single hill.

Thus the studies at Brent Knoll, Kettles Hill, Bungendore Ridge, Blashaval, Askervein, and Nyland Hill are the ones most capable of providing comprehensive and reliable data on flow over isolated, relatively low hills at the present time. These studies cover a reasonable range of h/L values (0.1 to 0.7) but have quite similar values of L/z_0 (0.8×10^4 to 5×10^4 except for Nyland Hill with $L/z_0 \sim 2.5 \times 10^3$). We might suggest that if additional field studies are to be undertaken, it would be desirable that sites be chosen to extend this L/z_0 range. Field studies with $L/z_0 \sim 10^3$ are of particular interest as many hills are tree-covered and fall into this area of parameter space ($L \sim 300$ m, $z_0 \sim 0.3$ m). Such large roughness elements generate local flows on their own scale and measurements are difficult as they must be made well above the height of the roughness elements. As in Bradley's (1980) Black Mountain work, it may be possible to make use of existing tall towers for these studies if suitable sites can be found. At the other end of the scale, it would be highly desirable from a basic theoretical viewpoint to conduct a field study with $L/z_0 \sim 5 \times 10^5$. In this range it would be relatively easy to make inner layer measurements well above the roughness elements since $l/z_0 \sim 2 \times 10^4$. Note, however, that as L increases, thermal, slope wind effects can begin to dominate (see Taylor and Gent, 1980) and directional shear in the upstream profile may become important. For these and other reasons, it would probably be best to aim for a low z_0 surface (sand or snow with $z_0 \sim 10^{-4}$–10^{-3} m) rather than a very long hill.

Another factor which should be considered in planning any future field studies is that almost all of the existing data for low hills are for near neutral stratification (Bungendore Ridge is the main exception). Mason and Sykes (1979a) carried out numerical simulations of laminar (or constant eddy viscosity) stratified flow over 2D idealized hills; other recent work by Carruthers and Choularton (1982) and Hunt *et al.* (1987b) has included the effects of elevated inversions and thermal stratification on atmospheric boundary-layer flows over hills. It would now seem to be appropriate to be collecting some field data for comparisons against these theoretical predictions. There have been a number of excellent studies of dispersion in complex terrain, for example the US EPA experiments at Cinder Cone Butte and Hogback Ridge (see Lavery *et al.*, 1983), which have investigated stably stratified flow over hills. These experiments have included flow visualization and some wind measurements but have not provided flow data with the spatial resolution that we believe is necessary for quantitative testing of models of stably stratified flow in complex terrain.

4. What Have We Learned?

Based on the field data collected in the experiments described in Section 3 coupled with additional insights based on theoretical considerations, wind tunnel simulation and numerical modelling work, we now have at least a provisional picture of the influence of low hills on boundary-layer flow. We attempt to sketch it below.

4.1. Inner Layer Depths

Mean flow perturbations are primarily governed by inviscid flow considerations except for a layer close to the ground and, for $h/L \gtrsim 0.3$, on the downwind side of the hill. The velocity shear in the upstream flow is, however, an important factor and, as discussed above, leads to near-surface, hilltop, fractional speed-up ratios, ΔS, which are much higher (approximately double) than would be expected from a direct application of inviscid irrotational flow theory.

Jackson and Hunt's l is probably best considered as a scale height for the inner layer

TABLE II

Inner-layer estimates and the height of Δu_{max} at the hilltop for several field experiments

Field experiment[a]	Run No. or date	Wind direction (deg)	z_0 (m)	Hill height h, m	Jackson–Hunt L, m	Jackson–Hunt l, m	Jensen l^*, m	Height (m) of Δu_{max}
Black Mountain	All neutral data	290 ± 15	1.14	170	275	28	14	27[b]
Askervein (82)	2.27	165	0.03	116	380	19	4.7	5
	2.28	175		116	300	15	4.0	3
	2.29b	235		116	220	12	3.2	2.5
Askervein (83)	TU01B	180	0.03	116	280	14	3.8	5
	TU03B	210		116	215	12	3.2	3
Kettles Hill (84)	1, 6, 7	260 ± 10	0.01	100	520	22	4.5	5[1]
Bungendore Ridge	Sample, near-neutral data	280 ± 20	0.002–0.005	7.5	75	3.4	0.8	5[1]
Nyland Hill	Selected	~180	~0.04	70	100	6.3	2.0	3

[1] Very broad maxima, not clearly defined for Bungendore profiles.
[a] See Table I for reference to data source.
[b] Relative to displacement height.

rather than the height at which something specific occurs. It is, however, only natural to ask how l could be determined from observational data. Following Jackson and Hunt (1975, p. 944) and Bradley (1980, p. 103), we could estimate l as the local height above a hilltop of the Δu maximum. Table II includes comparisons between the computed Jackson–Hunt l and this height for several field studies. For Black Mountain, Δu_{max} was at about 27 m while $l \sim 28$ m, indicating good agreement between the two estimates; in the Bungendore ridge data, Δu appears to be almost constant with height from the surface to about 8 m. For Kettles Hill and Askervein, however, the maxima appear to occur much lower than $\Delta z = l$ and we suspect that the JH l overestimates the depth of the layer in which turbulent momentum transfers are important in determining the terrain-induced mean velocity perturbations, especially for relatively smooth hills. Jensen's l^* is generally a better estimate of the height of the Δu_{max}.

4.2. Mean flow perturbations

Walmsley and Salmon (1984) have recently undertaken some initial comparisons between hilltop velocity profile data from Askervein '83 and computations made using MS3DJH/3 – the modified JH theory model developed by Taylor *et al.* (1983) – see discussion in Section 2. They find good agreement in the outer layer but the model under-predicts the speed-up, Δu, near the surface as shown in Figure 4b. This is perhaps partially associated with the neglect of velocity shear and the term $\Delta w\, \partial u_0/\partial z$ in the u momentum equation but it should also be remarked that the observed values of ΔS for the particular Askervein '83 run considered do seem high in comparison with other Askervein cases. Apart from these discrepancies in the hilltop profiles, we find that the modified Jackson–Hunt theory predicts mean flow velocity perturbations very well on the upwind side of hills. This is well illustrated in Figure 5, again taken from Walmsley and Salmon's (1984) Askervein comparisons, which shows predicted and observed normalized, 10 m, wind speeds (U/U_{RS}, where U_{RS} is the wind speed at an upwind reference site) along two lines across the hill. The theory does not always do as well in the lee where observations show larger wind speed reductions than are predicted. This may be partially a result of nonlinear effects. Mason and King (1985) show that nonlinear finite-difference models with simple closure tend to exhibit the same weakness but Raithby's (1985, personal communication) Askervein simulations with a nonlinear, 3D $k - \varepsilon$ finite-difference model show better agreement with observations than comparable linear models on the lee side of that hill.

In the majority of the field studies discussed, either the observed or the assumed upstream velocity profile was approximately logarithmic up to heights of $0(L)$. This is also assumed in most applications of the JH theory although it is not essential. Two field studies where distinctly non-logarithmic upstream profiles were observed were Bungendore Ridge and Kettles Hill '84. Some Askervein '83 upstream profiles also suggest departures from a logarithmic form above about 50 m. At Bungendore, Bradley (1983) observed the variation of hilltop ΔS at height l ($= 3$ m) as a function of stability ($\zeta = l/L_M$ where L_M is the Monin–Obukhov length). The data (see Figure 6) show ΔS increasing with ζ and also with z_0, which varied from 0.002–0.005 m during the course

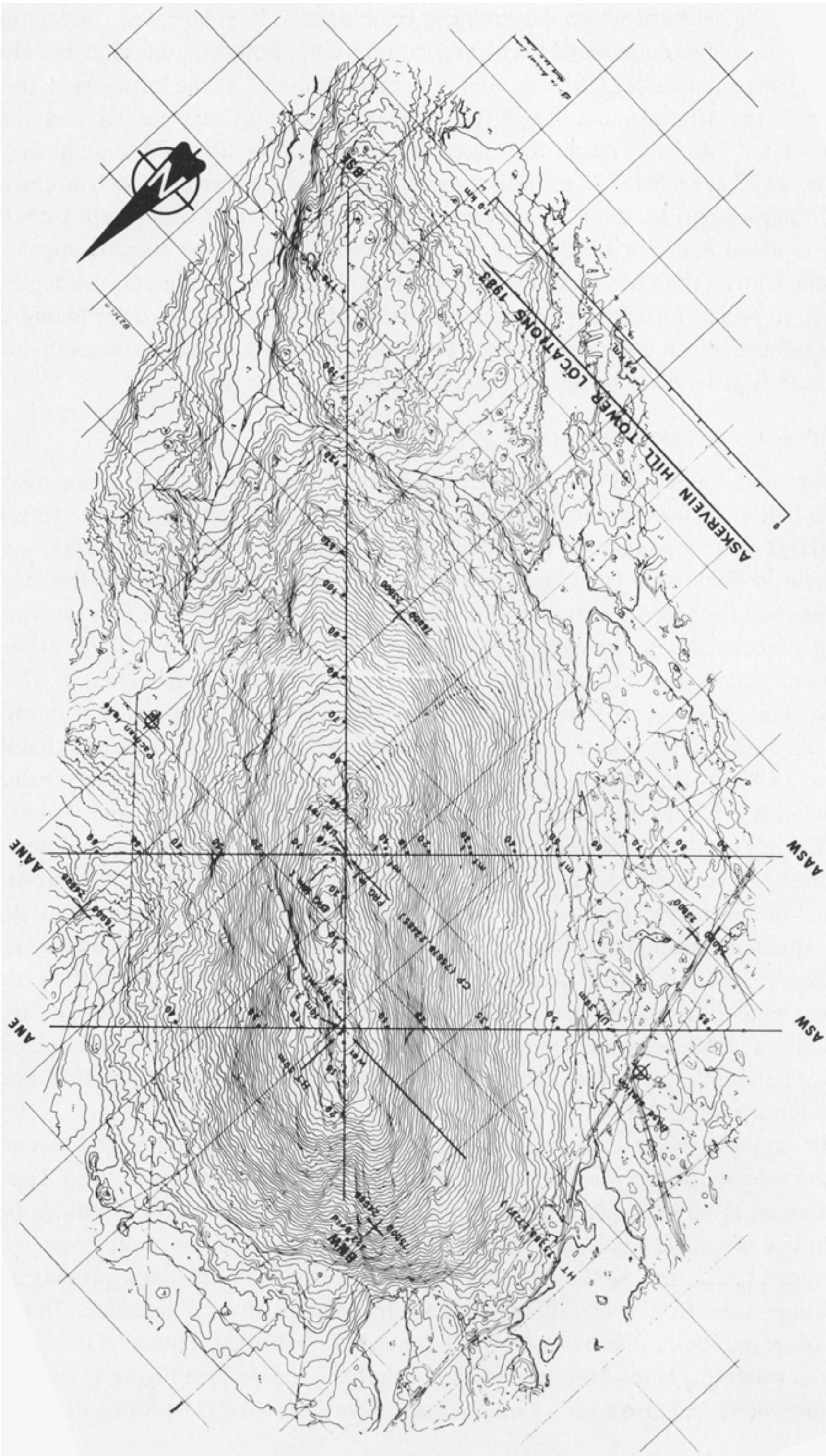

Fig. 4a. Askervein contour map showing tower locations used during 1983 experiment. Contour interval 2 m.

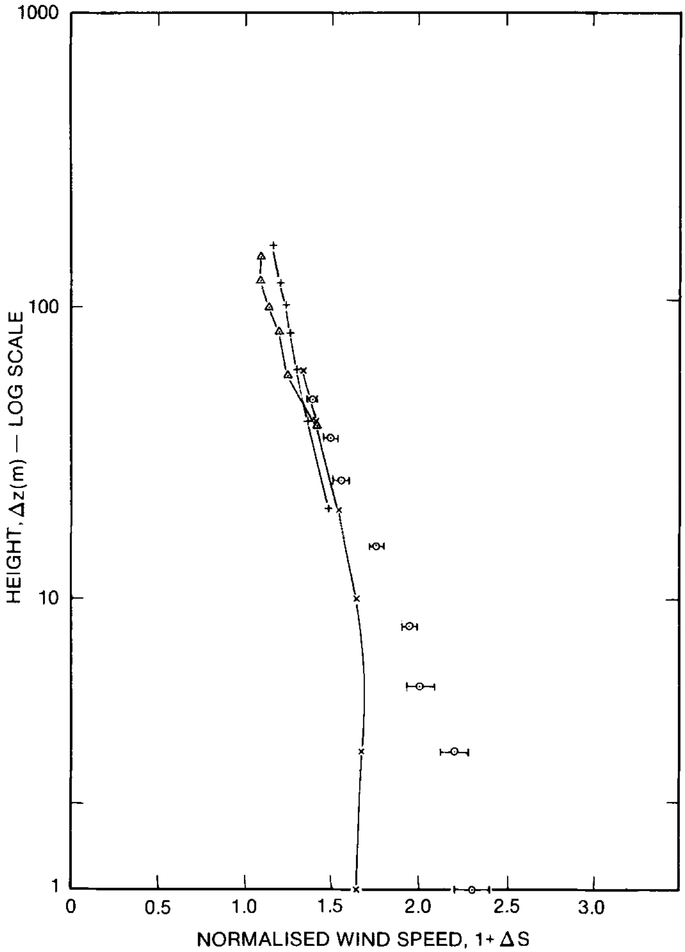

Fig. 4b. ΔS values from the MS3DJH/3 model and field data from Askervein '83. Wind direction, $\phi = 180°$. ⊢⊖⊣ Cup anemometer data (mean + standard deviation) from HT towers. –×–×– MS3DJH/3 results at HT. –Δ–Δ– TALA kite data at location mid-way between HT and CP. –+–+– MS3DJH/3 results at point mid-way between HT and CP (after Walmsley and Salmon (1984)).

of the experiment. Typically ΔS varied by a factor 2 between the most unstable ($\zeta \sim -0.1$) and the most stable ($\zeta \sim +0.1$–0.3) cases. On the unstable side, modification to the JH theory to allow for a non-logarithmic, non-neutral, upstream velocity profile gave good agreement with the data. On the other hand, assuming a log-linear stable flow profile for $\zeta > 0$ led to large overestimates of the hilltop ΔS. We should, however, remark that profiles were only measured to $\Delta z = 27$ m and could not confirm that the log-linear profile,

$$u_0 = \frac{u_*}{\kappa}\left(\ln \frac{\Delta z}{z_0} + 5\,\frac{\Delta z}{L_M}\right)$$

would hold up to height $\Delta z = L$ (75 m).

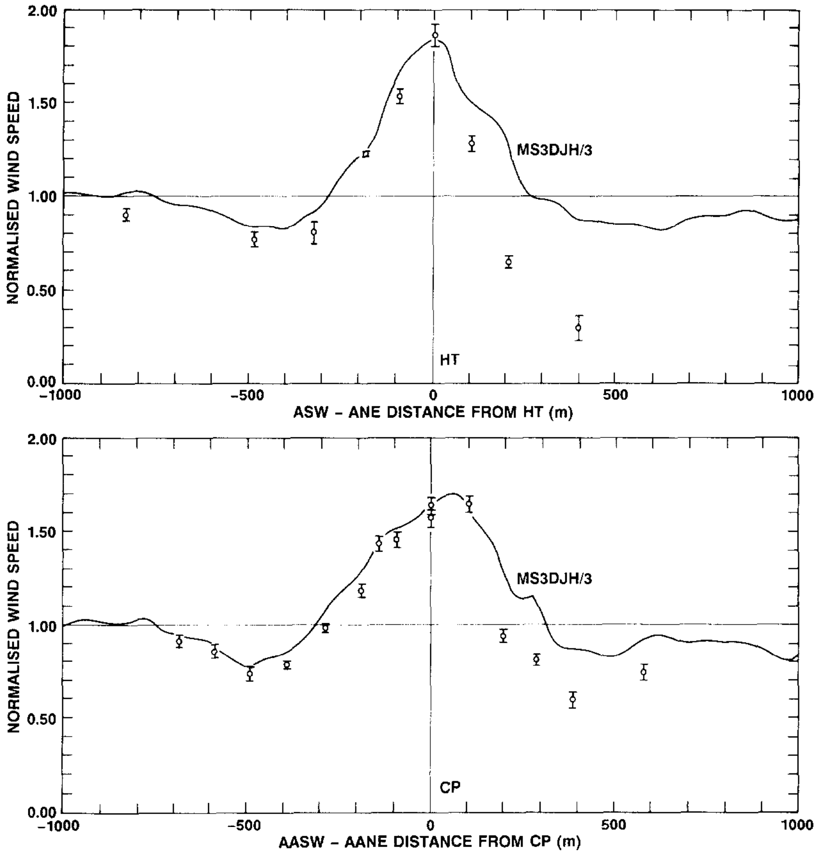

Fig. 5. Normalized wind speeds at $\Delta z = 10$ m above Askervein. Data (mean, o, and standard deviation) from Askervein '83 along tower lines A and AA as shown in Figure 4a. Wind direction $\phi = 210°$. Model predictions (———) obtained using MS3DJH/3 (after Walmsley and Salmon, 1984).

During their 1984 field study at Kettles Hill, Mickle *et al.* (1984) observed upstream profiles with a combination of a 10 m tower, TALA kite and tethersonde profiling and AIRsonde tracking. Figure 7 shows upstream and hilltop profiles for two of their runs with similar surface wind speeds and directions. The substantial differences in the shape of the upstream profiles lead to widely different near-surface fractional speed-up ratios. According to JH theory, the near-surface ΔS should scale with $[u_0(L)/u_0(l)]^2$ and the difference in this factor between the two runs is significant (1.2 and 3.9). The ratio of these values is quantitatively larger than the ratio of the observed ΔS values (0.27 and 0.6) but is clearly the major factor accounting for differences between the two runs.

4.3. Flow Separation

The occurrence of flow separation in the lee of hills sometimes gives reversed flow and high turbulence intensities which can be of importance in dispersion studies. As might

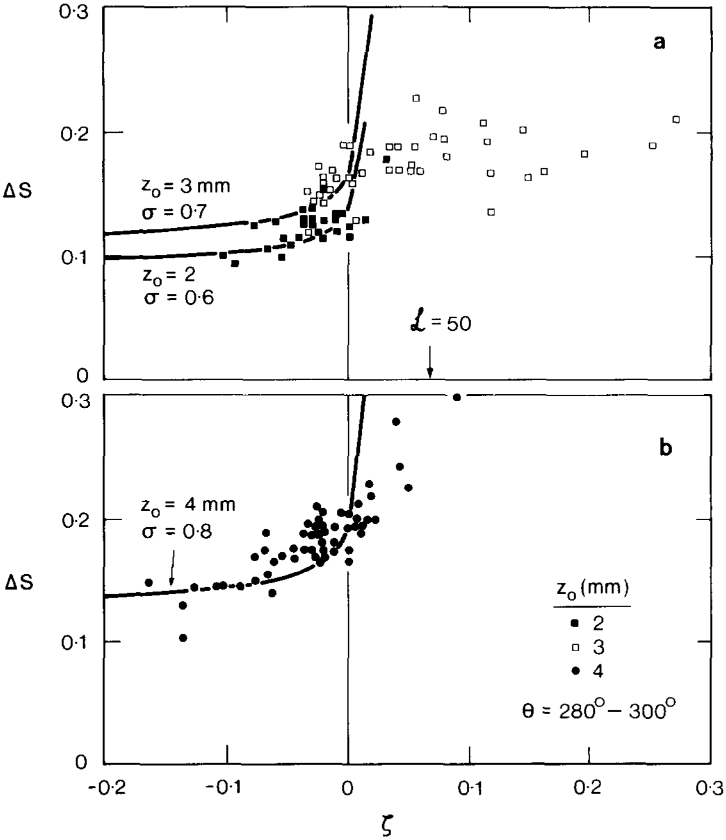

Fig. 6. Variation of ΔS with stability and roughness at height $\Delta z = l = 3$ m above the crest of an approximately two-dimensional ridge. Solid lines are the predictions of JH theory with non-neutral velocity profiles. $\zeta = \Delta z/L_M$ and σ values are chosen to fit data at $\zeta = 0$. (After Bradley, 1983, published with permission, Journal of Wind Engineering and Industrial Aerodynamics.)

be anticipated, given the theoretical underestimate of the wind reduction in the lee, separation is correspondingly poorly predicted by linear theories. From theoretical considerations and wind tunnel studies, it is clear that separation should depend on L/z_0. For a three-dimensional hill and $L/z_0 = 10^4$–10^5, observations at Blashaval (Mason and King, 1985) suggest that separation occurs at slopes $> 20°$ ($h/L \gtrsim 0.35$). At Askervein, which has an elongated plan form (see Figure 4), Taylor and Teunissen (1983, 1985) found significantly reduced mean winds and high turbulence levels in the lee of the hill for some wind directions (200–220°, with corresponding $h/L \gtrsim 0.45$). Although a weak, near-surface, reversed flow was observed for short periods, the average 10 m wind direction over half-hour blocks was always in approximately the same direction ($\pm 20°$) as the upstream flow. Mean flow separation over three-dimensional hills is not necessarily accompanied by recirculating flow with closed streamlines (cf. Hunt *et al.*, 1978), and is hard to identify positively without a complete

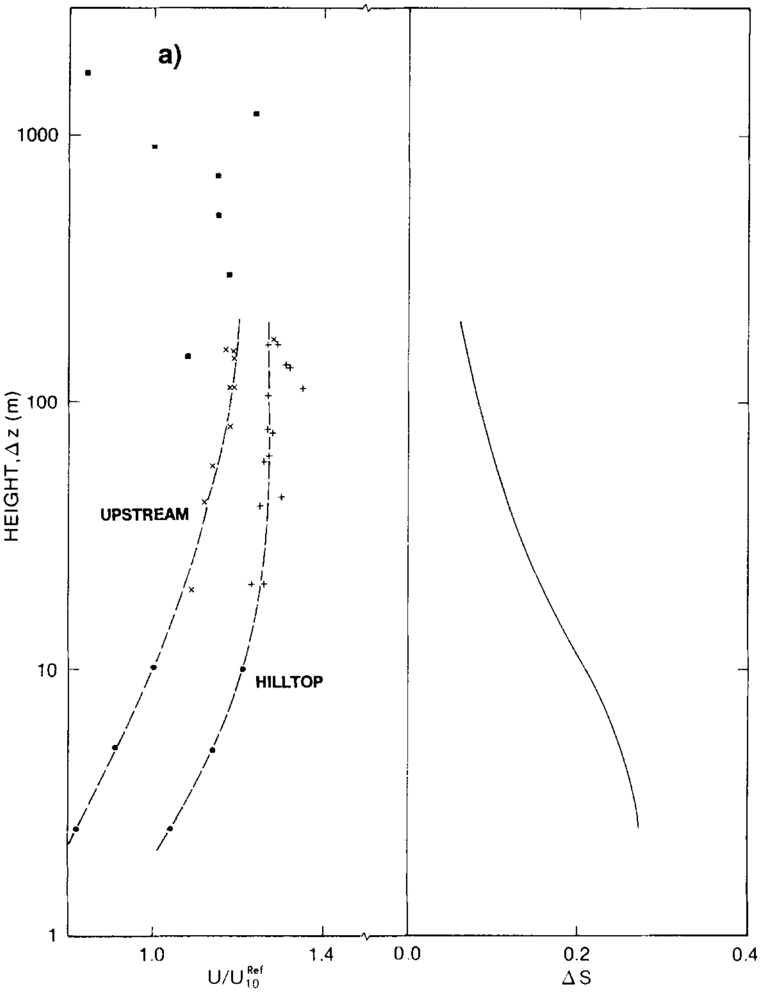

Fig. 7. Velocity and ΔS profiles above Kettles Hill and upstream for two runs with similar flow directions ($\simeq 270°$) but different upstream profiles (after Mickle *et al.*, 1984). ● Cup anemometer data, at hilltop and upstream sites. + TALA kite data above hilltop. × TALA kite data at upstream reference site. ■ AIRsonde profile (visually tracked balloon ascent); flights originated at reference site. ——— ΔS profile calculated from subjectively drawn velocity profiles.

picture of the 3D flow. From the studies at Blashaval and Askervein, the main near-surface characteristics identifying what we assume to be 'separated' flow are much reduced mean wind speeds ($\lesssim 0.5 \times$ upstream) and large ($\gtrsim 2.0 \times$ upstream) increases in σ_u, σ_v, and σ_w.

4.4. Modification of Turbulence by Hills

The turbulence structure of the planetary boundary layer over level terrain is still not completely understood and the boundary-layer response to strong distortion in flow

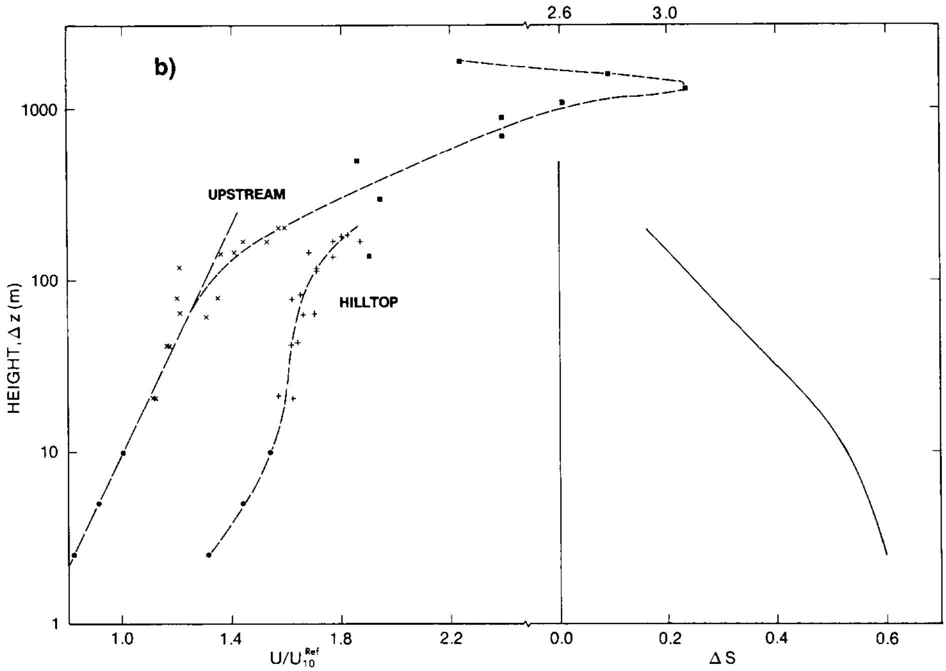

Fig. 7 (cont.)

over a hill is particularly complex. The height scale l is again of significance as it is the height at which the characteristic time-scale for turbulent adjustment is comparable with the time for fluid to pass over the hill. At heights greater than l, the ideas embodied in rapid distortion theory (Townsend, 1976) are of relevance. In spite of the anisotropy of the upstream turbulence, simple calculations based on the rapid distortion of homogeneous turbulence (Britter *et al.*, 1981) often seem successful. These predict that, for small values of distortion, the changes in the total turbulent kinetic energy above the hilltop are small and the main effect is an adjustment between the $\overline{u'^2}$, $\overline{v'^2}$, and $\overline{w'^2}$ components (defined along and normal to the streamlines). With a two-dimensional ridge, the dominant change is an increase in $\overline{w'^2}$ and reduction in $\overline{u'^2}$. In contrast, over the summit of an axially symmetric hill, $\overline{w'^2}$ is increased with relatively minor changes in the other components. The more general, but approximate, parameterizations of rapid distortion which are employed in second-order closure techniques allow estimates of changes in shear stress components but have not been verified. For many practical considerations it is important to note that the changes in turbulence are less than those in the mean flow and the turbulence intensities σ_u/u, etc., will all significantly reduced.

At heights very much less than l, a surface local equilibrium layer is expected whilst for heights of order l a match between the equilibrium and rapid distortion regions should occur. An example of the expected behaviour is provided in Figure 8 which shows theoretical predictions of the $\overline{u'w'}$ and $\overline{u'^2}$ perturbations for flow over sinusoidal terrain. These numerical results illustrate the various flow regimes. The wavelength of the terrain is 2 km and local equilibrium occurs below a height of about 1 m. The stress changes in the local equilibrium region are close to those predicted by simple mixing-length models such as the numerical results of Taylor (1977) or the theory of Jackson and Hunt (1975). Rapid distortion is well established at 40 m; above that height, the main influence is a decay corresponding with the vertical decay of the flow perturbation.

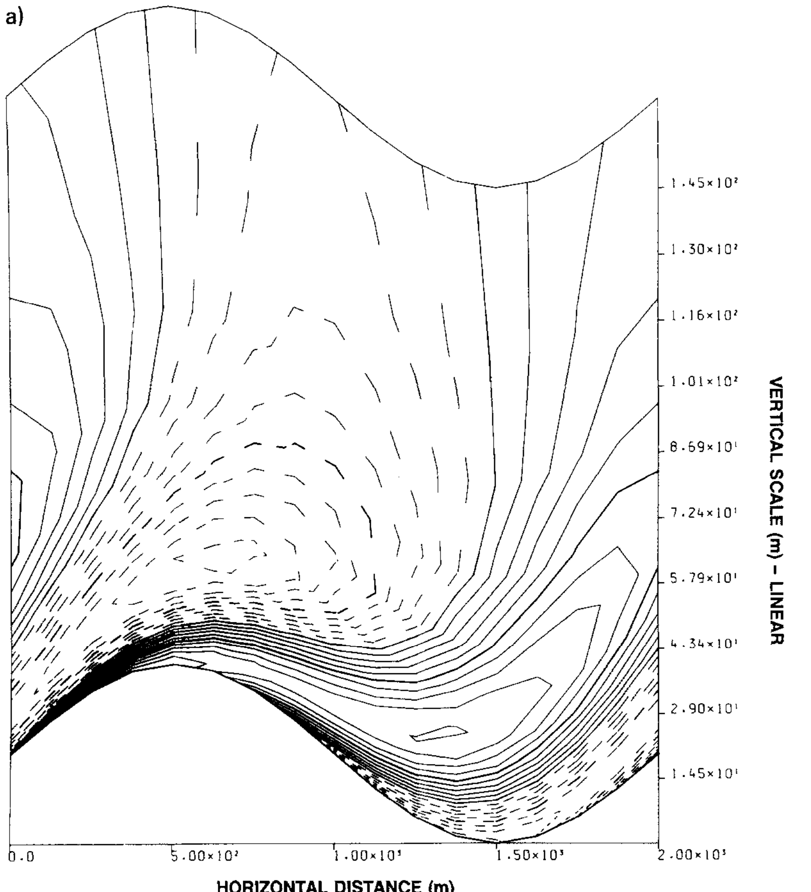

Fig. 8. Results obtained with a finite-difference model of turbulent flow over a two-dimensional sinusoidal surface (Newley, T.N. private communication). The second-order closure model of Launder *et al.* (1975) has been used to derive the turbulent stresses. Figure 8a shows contours of the perturbation to the shear stress $-\overline{u'w'}$ whilst Figure 8b shows contours of the perturbation to $-\overline{u'^2}$, where u is in the horizontal x-direction. A linear height scale has been used and heights above the lowest point of the terrain are marked on the axis. The results are for planetary boundary-layer flow over the surface $h = a\cos(2\pi x/L)$ where $L = 2000$ m and $a = 20$ m. The value of z_0 is 0.1 m and the geostrophic wind is 10 m s^{-1}. For flow over level terrain, the closure model gives a value of surface shear stress $u_*^2 = 0.18$ m^2 s^{-2}. The contour interval in Figure 8a is $0.33u_*^2\,\theta_0$ and that in Figure 8b is $0.42(\overline{u'^2})_0\theta_0$ where $\theta_0 = 2\pi a/L$ and $(\overline{u'^2})_0$ is the surface value of $\overline{u'^2}$ in the undisturbed boundary layer. The contour interval is one tenth of the maximum in the field; negative values are denoted by dashed lines.

Observations of real flows are still somewhat limited and differ from results in Figure 8 in that they are for 3-D flows without periodicity. From the field studies discussed earlier, there is some evidence of an increase in $\overline{u'^2}$, $\overline{v'^2}$, $\overline{w'^2}$, and $-\overline{u'w'}$ close to the ground above hilltops, as one would expect if a near-surface equilibrium layer existed. It would appear, however, that the layer is often very shallow (say $\sim 0.05l$ or about 1 m in a typical case); at these levels, it is hard to isolate the effects of the hill as a whole from the effects of small-scale terrain irregularities. Taylor and Teunissen

b)

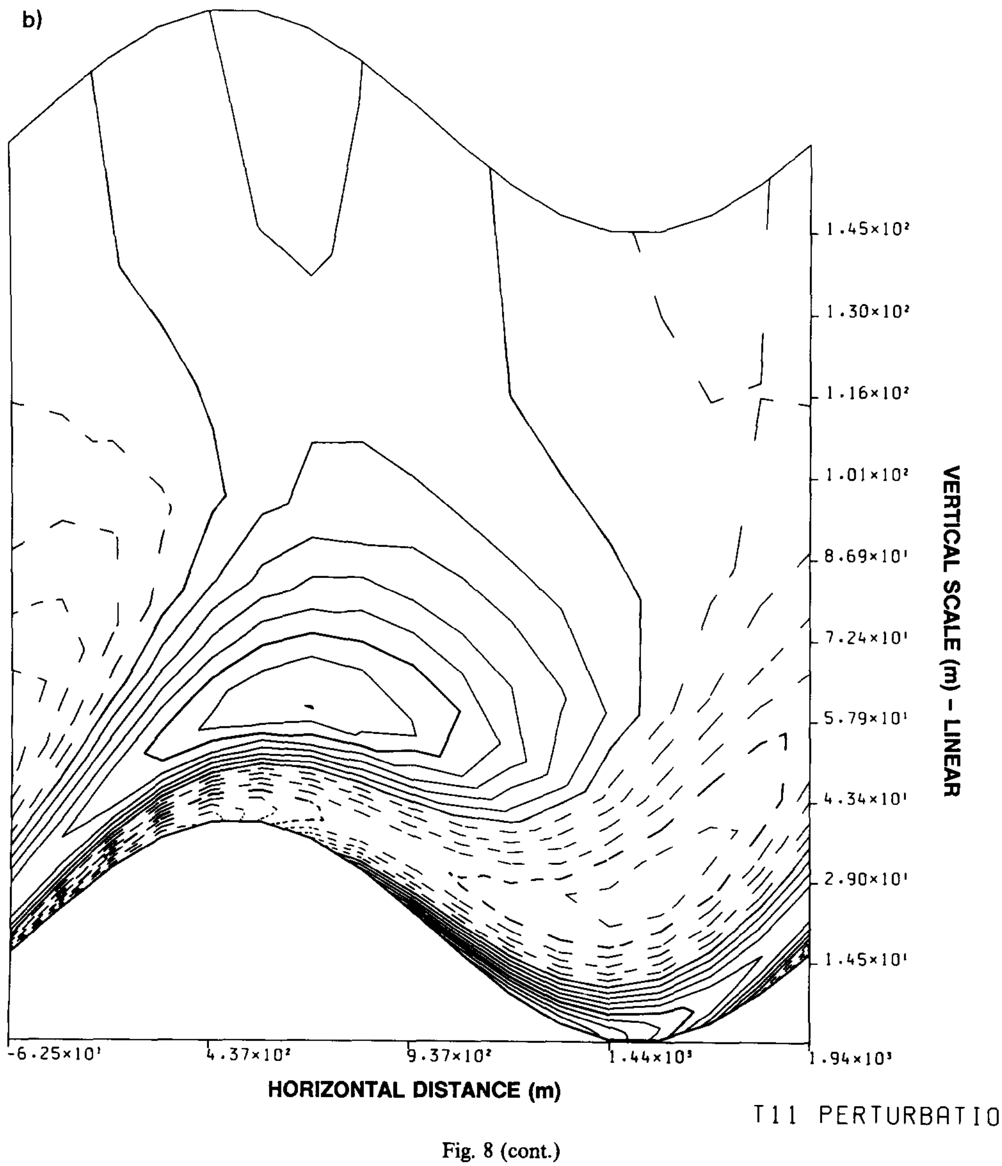

Fig. 8 (cont.)

(1983) show profiles of $\sigma_h(\simeq \sigma_u)$ above the hilltop at Askervein to a height of 50 m based on cup anemometer variances. These data show only small changes in σ_u between their reference and hilltop sites over the range $2\text{ m} < \Delta z < 50\text{ m}$ with an indication that σ_u is reduced, by about 10%, above the inner layer. Figure 9 shows some typical results. Similar data were obtained during Askervein '83 (see Taylor and Teunissen, 1985). Preliminary turbulence data from hilltop sonic anemometers combined with Gill UVW anemometer data from a second site on the summit ridge for one of the Askervein '83 runs (TU03B, $\phi = 210°$) are discussed by Zeman and Jensen (1985). These confirm that the near-surface layer within which σ_u, σ_v, σ_w, and $-\overline{u'w'}$ increase is shallow (~ 2 m for σ_u) and that above this, σ_u, σ_w, and $-\overline{u'w'}$ are reduced relative to their upstream values over quite a deep layer. Zeman and Jensen argue that the σ_w and $-\overline{u'w'}$ reductions may be associated with streamline currature effects.

The observations at Blashaval (Mason and King, 1985) tend to confirm the type of structure seen in the theoretical studies. The scale l is somewhat ambiguous as many scales are involved in describing flow over a real hill. A value of $l \simeq 11$ m is estimated from an average L for the hill. At 16 m the observations show agreement with rapid distortion theory while below 1 m there is tendency to local equilibrium. In accord with the form of results shown in Figure 8, at 5 m there is reduction in shear stress. Turbulence data from the Nyland Hill study are somewhat complicated by upstream conditions, which lead to increases in σ_w and $-\overline{u'w'}$ with height in the upwind flow. Comparisons between hilltop and upstream profiles confirm that increases in σ_w^2 and $-\overline{u'w'}$ are confined to a relatively shallow near-surface layer (1–2 m deep at Nyland Hill). Hilltop values of σ_u^2 and σ_v^2 are, however, substantially increased relative to the

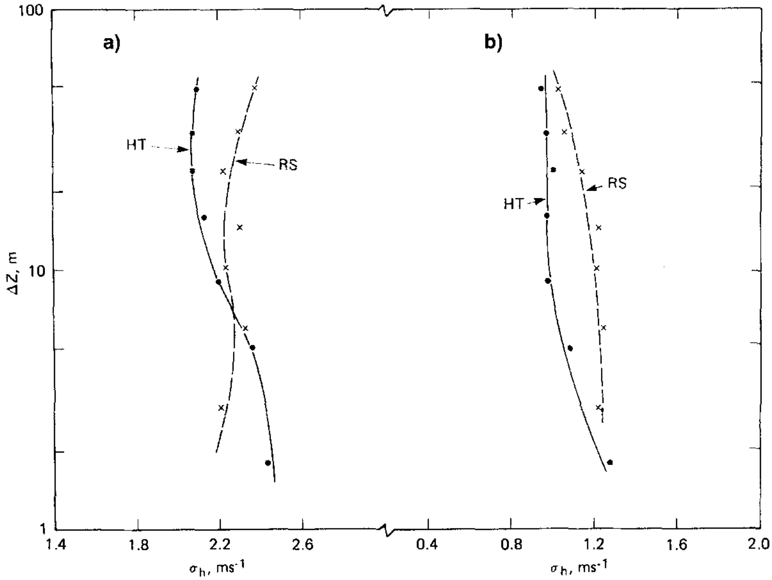

Fig. 9. Profiles of σ_h to 50 m above the Askervein hilltop and at an upwind reference location for two wind directions (after Taylor and Teunissen, 1983). (a) Run S7, $\phi = 161°$, (b) Run MF2.29b, $\phi = 236°$.

upstream profiles at all measured heights (0.3 m < Δz < 16 m). Division of the contributions to σ_u^2, etc. into 'short' and 'long' wavelength components shows that the short wavelength components (< 200 m) are responsible for this increase for $0 < \Delta z < 2$ m while the long wavelength components cause increases above this level. The behaviour of the short wavelength components at $\Delta z = 16$ m are in broad agreement with rapid distortion theory but the non-isotropic nature of the turbulence in the upstream flow should be considered.

For the Black Mountain study, Bradley (1980) reported turbulence measurements at heights up to 87 m above the hilltop and from the 23 m level at an upstream location (see Figure 10). At heights of 9 and 25 m above the hilltop, there are increases in σ_u, σ_v, and σ_w relative to their upstream values (at 23 m) while at 87 m, σ_u and σ_v are essentially the same as the upstream value but σ_w is increased by about 60%. Since $l \simeq 28$ m and there is a displacement height of 7 m, these results are consistent with the view that the lower levels have an inner layer response and the upper level behaves in qualitative accord with rapid distortion theory. It should, however, be noted that there appears to be no reduction in σ_u or σ_v to compensate for the σ_w increase. The Black Mountain results clearly differ from the observations at Askervein, Blashaval, and Nyland Hill in that the inner layer is much deeper and the observed increases in turbulence energy within it are large. These differences are presumed to be primarily due

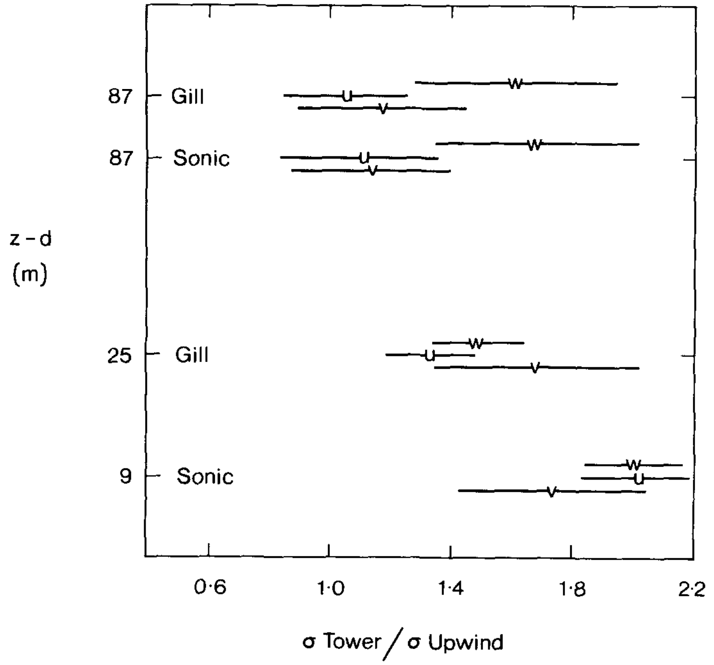

Fig. 10. Turbulence measurements, σ_u, σ_v, σ_w, above the hilltop at Black Mountain relative to upstream values (after Bradley, 1980). Published with permission, Quarterly Journal of the Royal Meteorological Society.

to the different L/z_0 values. The hilltop turbulence profile observations from different field studies fail to provide a simple universal pattern of behaviour and it is clear that additional efforts and analysis are needed to improve our understanding. It begins to look as if consideration of the integral statistics (σ_u^2, etc.) alone may not be adequate and that we may need to understand the way in which different spectral components of the turbulence react to the flow distortion caused by a hill. The relatively simple division into short and long wavelengths, relative to the hill length, carried out by Mason (1986) on the Nyland Hill data clearly illustrates this and it would be interesting to see what a similar approach would give if applied to other data sets.

So far, most of the turbulence data to appear have been restricted to hilltop and upwind reference site profiles. Data were, however, measured at 10 m along an E–W line through the hilltop during the 1981 Kettles Hill experiment, at a number of positions on Blashaval (Mason and King, 1985), and at 10 m along two lines during the '83 Askervein study. The Askervein '83 data show relatively small and slow changes in σ_u, σ_v, and σ_w on the upstream face of the hill with a tendency for σ_v and σ_w to increase and σ_u to decrease towards the hilltop. The 10 m shear stress ($-\overline{u'w'}$), relative to local streamline coordinates, has a tendency to increase on the face of the hill and then decrease so that the hilltop value (at 10 m) is a little lower than the upstream value. Detailed analyses of these data should appear shortly.

5. Applications

In his review of wind over hills, Hunt (1980) noted that studies of boundary-layer flow over hills have meteorological implications for boundary-layer parameterisation in large-scale numerical weather prediction models and for studies of local weather and climate. They also have important practical applications for the determination of wind loads on structures, the wind energy potential of hilltop windmill sites and dispersion of pollutants in complex terrain. There are many other applications where a knowledge of winds or the behaviour of the boundary layer in the presence of hills may be important; see, for example, Taylor and Lee (1984). However, the applications given above are probably the most significant.

The major influence of hills and steeper topography within numerical weather prediction and atmospheric general circulation models is through orographically excited gravity waves. Neglect of the drag associated with these waves can lead to systematic mid-latitude errors in NWP and GC models and several attempts have been made recently to improve the parameterisations used (see, for example, Chouinard *et al.*, 1986). These processes are, however, not intended to form part of our present review, which has concentrated on neutrally stratified flows and low hills. An improved understanding of boundary-layer flow over such hills and other moderately complex terrain will certainly be a help in improving the parameterisation of the boundary layer in larger-scale models but we know of no direct applications at the present time.

Turning to local weather and climate applications, an ongoing concern for climatologists in the 'representativeness' of data from a particular climate station for other locations in the same area (see, for example, Wieringa, 1986). Roughness variations are usually the major concern in the representativeness of wind data, but Walmsley *et al.* (1986) describe an interesting application of our knowledge of wind speeds over hills to a case where both topographically-induced and roughness-induced wind speed changes have to be taken into account. Their particular application was to an assessment of the representativeness of wind data from a climate station on top of a small hill on Grindstone Island for application over the surrounding waters of the Gulf of St. Lawrence, Canada. Topographic 'speed-up' ($\sim 30\%$) and roughness 'slow-down' ($\sim -20\%$) were both of similar magnitude with a net result that average winds recorded at the site were estimated to be about 10% higher than corresponding 10 m winds over the surrounding area. Ship data confirmed these estimates.

Simple guidelines for estimating design wind speeds for engineering purposes above low hills and other topography have been presented by Taylor and Teunissen (1984) and are presently being used by the Canadian Climate Centre. In the U.K., BRE (1984) provides similar guidelines. Applications to hilltop sites for microwave tower installations occur frequently. Since available wind energy varies as U^3, an accurate assessment of the wind climatology is an important step in site selection and evaluation for medium- and large-scale wind turbines. Taylor *et al.* (1985) have described an application of guidelines and models to the estimation of wind speeds at candidate WECS (wind energy conversion systems) sites in the Iles de la Madeleine. Their work was part of a study undertaken by Hydro-Quebec with a view to the possible installation of a number of wind turbines in the area.

The U.S. Environmental Protection Agency study of dispersion in complex terrain and their Complex Terrain Model Development program (see Lavery *et al.*, 1983) probably provide the best current examples of this type of work. For pollutant dispersal studies, stably stratified situations are often the most critical and the US EPA study has concentrated on these. The studies we have reviewed have, in the main, concentrated on high wind speed, near-neutral stratification but some of the data (e.g., Bradley, 1985) pertain to stable cases and some models, e.g., Carruthers and Choularton (1982); Hunt *et al.* (1987a, b), are appropriate for the stably stratified situation. We anticipate increased exchange of ideas between these two slightly separate fields in the future.

6. Conclusions

This brief review of boundary-layer flow over low hills has attempted to summarize the results derived from recent field experiments. It is clear that much progress has been made in the past ten years but that there is still work to be done to expand the parameter range (L/z_0, stability) of field observations and to improve our understanding of turbulence modifications. There is also a need for comparable data on flow over escarpments, valleys and hollows – plenty to keep us busy for the next ten years!

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References

Beljaars, A. C. M., Walmsley, J. L., and Taylor, P. A.: 1987, 'A Mixed Spectral, Finite Difference Model for Neutrally Stratified Boundary-Layer Flow over Roughness Changes and Topography', *Boundary-Layer Meteorol.* (in press).

Berlyand, M. E.: 1975, *Contemporary Problems of Atmsopheric Diffusion and Pollution of the Atmosphere*, Gidrometeoizdat, Leningrad, 448 pp. (in Russian).

Bradley, E. F.: 1980, 'An Experimental Study of the Profiles of Wind Speed, Shearing Stress and Turbulence at the Crest of a Large Hill', *Quart. J. Roy. 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. and Indust. Aerodyn.* **15**, 231–242.

BRE: 1984, *The Assessment of Wind Speed over Topography*, Building Research Establishment, Digest 283, HMSO, London.

Britter, R. E., Hunt, J. C. R., and Richards, K. J.: 1981, 'Airflow over a Two-Dimensional Hill: Studies of Velocity Speed-Up, Roughness Effects and Turbulence', *Quart. J. Roy. Meteorol. Soc.* **107**, 91–110.

Carruthers, D. J. and Choularton, T. W.: 1982, 'Airflow over Hills of Moderate Slope', *Quart. J. Roy. Meteorol. Soc.* **108**, 603–624.

Chouinard, C., Béland, M., and McFarlane, N.: 1986, 'A Simple Gravity Wave Drag Parameterization for Use in Medium-Range Weather Forecast Models', *Atmosphere-Ocean* **24**, 91–110.

Deaves, D. M.: 1976, 'Wind over Hills: A Numerical Approach', *J. Industr. Aerodynamics* **1**, 371–391.

Deaves, D. M.: 1980, 'Computations of Wind Flow over Two-Dimensional Hills and Embankments', *J. Wind Eng. and Indust. Aerodyn.* **6**, 89–111.

Detering, H. W.: 1985, 'Mischungsweg and Turbulenter Diffusionskoeffizient in Atmosphärishen Simulationsmodellen', No. 25, Berichte des Instituts für Meteorologie und Klimatologie der Universität Hannover.

Eliseev, V. S.: 1973, 'Stereophotogrammetric Investigation of the Air Flow in the Boundary-Layer of the Atmosphere Above a Hill', in M. E. Berlyand (ed.), *Air Pollution and Atmospheric Diffusion*, Wiley, New York, pp. 95–108 (translated from 1971 Russian language edition).

Hauf, T. and Neumann-Hauf, G.: 1982, The Turbulent Wind over an Embankment', *Boundary-Layer Meteorol.* **24**, 357–370.

Hunt, J. C. R.: 1980, 'Wind over Hills', in J. C. Wyngaard (ed.), *Workshop on the Planetary Boundary Layer*, AMS publication, Boston, pp. 107–144.

Hunt, J. C. R., Abell, C. J., Peterka, J. A., and Woo, H.: 1978, 'Kinematical Studies of the Flows Around Free or Surface-Mounted Obstacles; Applying Topology to Flow Visualization', *J. Fluid. Mech.* **86**, 179–200.

Hunt, J. C. R., Leibovich, S., and Richards, K. J.: 1987a, *Stratified Shear Flow over Low Hills*, I. *Effects of Upwind Shear* (to appear).

Hunt, J. C. R., Richards, K. J., and Brighton, P. M. W.: 1987b, *Stratified Shear Flow over Low Hills*, II. *Stratification Effects in the Outer Flow Region* (to appear).

Jackson, P. S. and Hunt, J. C. R.: 1975,'Turbulent Wind Flow over a Low Hill', *Quart. J. Roy. Meteorol. Soc.* **101**, 929–955.

Jenkins, G. J., Mason, P. J., Moores, W. H., and Sykes, R. I.: 1981, 'Measurements of the Flow Structure Around Ailsa Craig, a Steep, Three-Dimensional, Isolated Hill', *Quart. J. Roy. Meteorol. Soc.* **107**, 833–851.

Jensen, N. O.: 1983, 'In Discussion of Session 21 papers at Sixth International Conference on Wind Engineering, Session 21, Rapporteur, A. J. Bowen', *J. Wind Eng. and Indust. Aerodynam.* **15**, 253–255.

Jensen, N. O., Petersen, E. L., and Troen, I.: 1984, *Extrapolation of Mean Wind Statistics with Special Regard to Wind Energy Applications*, Report WCP-86, World Meteorological Organisation, Geneva 85 pp.
Launder, B. E., Reece, G. J., and Rodi, W.: 1975, 'Progress in the Development of a Reynolds-stress Turbulence Closure', *J. Fluid Mech.* **68**, 537–566.
Lavery, T. F., Greene, B. R., Egan, B. A., and Schiermeier, F. A.: 1983, *The EPA Complex Terrain Model Development Program, Extended Abstracts*, 6th Symposium on Turbulence and Diffusion, AMS, Boston, pp. 126–130.
Mason, P. J.: 1986, 'Flow over the Summit of an Isolated Hill', *Boundary-Layer Meteorology* **37**, 385–405.
Mason, P. J. and King, J. C.: 1984, 'Atmospheric Flow over a Succession of Nearly Two-Dimensional Ridges and Valleys', *Quart. J. Roy. Meteorol. Soc.* **110**, 821–845.
Mason, P. J. and King, J. C.: 1985, 'Measurements and Predictions of Flow and Turbulence over an Isolated Hill of Moderate Slope', *Quart. J. Roy. Meteorol. Soc.* **111**, 617–640.
Mason, P. J. and Sykes, R. I.: 1979a, 'Separation Effects in Ekman-layer Flow over Ridges', *Quart. J. Roy. Meteorol. Soc.* **105**, 129–146.
Mason, P. J. and Sykes, R. I.: 1979b, Flow over an Isolated Hill of Moderate Slope', *Quart. J. Roy. Meteorol. Soc.* **105**, 383–395.
Mickle, R. E., Salmon, J. R., and Taylor, P. A.: 1984, Kettles Hill '84: 'Velocity Profile Measurements over a Low Hill', Internal Report, AQRB–84–012–L, Atmos. Environ. Service., Downsview, Ont.
Newley, T. M. J.: 1985, 'Turbulent Air Flow over Hills', Ph.D. thesis, University of Cambridge, Cambridge.
Sacré, C.: 1979, 'An Experimental Study of the Airflow Over a Hill in the Atmospheric Boundary Layer', *Boundary-Layer Meteorol.* **17**, 381–401.
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-Layer Flow Above Gentle Topography', *Boundary-Layer Meteorol.* **11**, 439–465.
Taylor, P. A. and Gent, P. R.: 1980, *Modification of the Boundary-Layer by Orography*, in R. Hide and P. W. White (eds.), *Orographic Effects in Planetary Flows*, ICSU/WMO, GARP Publication Series No. 23, pp. 145–165.
Taylor, P. A. and Lee, R. J.:: 1984, 'Simple Guidelines for Estimating Wind Speed Variations Due to Small Scale Topographic Features', *Climatological Bulletin* **18** (2), 3–32.
Taylor, P. A. and Teunissen, H. W.: 1983, 'Askervein '82: An Initial Report on the September/October 1982 Experiment to Study Boundary-Layer Flow over Askervein, South Uist, Scotland', Internal Report MSRB–83–8. Atmos. Environ. Service, Downsview, Ont.
Taylor, P. A. and Teunissen, H. W.: 1985, 'The Askervein Hill Project; Report on the September/October 1983 Main Field Experiment', Internal Report MSRB–84–6, Atmos. Environ. Service, Downsview, Ont.
Taylor, P. A., Walmsley, J. L., and Salmon, J. R.: 1983a, 'A Simple Model of Neutrally Stratified Boundary-Layer Flow over Real Terrain Incorporating Wavenumber-Dependent Scaling', *Boundary-Layer Meteorol.* **26**, 169–189.
Taylor, P. A., Mickle, R. E., Salmon, J. R., and Teunissen, H. W.: 1983b, 'The Kettles Hill experiment – Site Description and Mean Flow Results', Internal Report AQRB–83–002–L, Atmos. Environ. Service, Downsview, Ont.
Taylor, P. A., Walmsley, J. L., and Salmon, J. R.: 1985, *Guidelines and Models for Estimating Wind Speeds at WECS Sites in Complex Terrain*, Proc. Intersol '85, Montreal, International Solar Energy Society.
Townsend, A. A.: 1976, *The Structure of Turbulent Shear Flow* (2nd ed.), Cambridge University Press, Cambridge, 429 pp.
Walmsley, J. L. and Salmon, J. R.: Cambridge, *A Boundary-Layer Model for Wind Flow over Hills: Comparison of Model Results with Askervein '83 Data*, Proc. European Wind Energy Conference and Exhibition, Hamburg, October 1984.
Walmsley, J. L., Salmon, J. R., and Taylor, P. A.: 1982, 'On the Application of a Model of Boundary-Layer Flow over Low Hills to Real Terrain', *Boundary-Layer Meteorol.* **23**, 17–46.
Walmsley, J. L., Taylor, P. A., and Keith, T.: 1986, 'A Simple Model of Neutrally Stratified Boundary Layer Flow over Complex Terrain with Surface Roughness Modulations (MS3DJH/3R)', *Boundary-Layer Meteorol.* **36**, 157–186.
Walmsley, J. L., Taylor, P. A., and Salmon, J. R.: 1985, *Boundary-Layer Studies of Winds over Islands with Applications to Surface Wind Data from Grindstone Island (Iles de la Madeleine) and Sable Island*, Proc. Intnl.

Workshop on Offshore Winds and Icing, T. A. Agnew and V. R. Swail (eds.), Environment Canada, Downsview, pp. 165–174.

Wieringa, J.: 1986, 'Roughness Dependent Geographical Interpolation of Surface Wind Speed Averages', *Quart. J. Roy. Meteorol. Soc.* (in press).

Zeman, O. and Jensen, N. O.: 1985, *Response of the Reynolds Stress Tensor to the Mean Flow Distortion over a Two-Dimensional Hill*, Extended Abstracts, 7th Symposium on Turbulence and Diffusion, pp. 292–295, American Meteorological Society, Boston.