BOUNDARY-LAYER FLOW OVER TOPOGRAPHY: IMPACTS OF THE ASKERVEIN STUDY

JOHN L. WALMSLEY
Atmospheric Environment Service, Downsview, Ontario M3H 5T4 Canada

and

PETER A. TAYLOR
Department of Earth and Atmospheric Science, York University, North York, Ontario M3J 1P3 Canada

(Received in final form 20 October, 1995)

Abstract. One of the objectives of the Askervein Hill Project was to obtain a comprehensive and accurate dataset for verification of models of flow and turbulence over low hills. In the present paper, a retrospective of the 1982 and 1983 Askervein experiments is presented. The field study is described in brief and is related to similar studies conducted in the early 1980s. Data limitations are discussed and applications of numerical and wind-tunnel models to Askervein are outlined. Problems associated with model simulations are noted and model results are compared with the field measurements.

1. Introduction

1.1. Basic Description of the Askervein Study

The Askervein Hill Project was a collaborative study of boundary-layer flow over low hills conducted under the auspices of the International Energy Agency Program of Research and Development on Wind Energy Conversion Systems. Field experiments were conducted during September and October of 1982 and 1983 on and around Askervein, a 116-m high hill on the west coast of the island of South Uist in the Outer Hebrides of Scotland (57°11′N, 7°22′W; UK Ordnance Survey grid reference: NF 754 237). For future reference in this paper, the following locations are defined with their abbreviations and grid references (in Ordnance Survey grid NF): Hilltop (HT), 75383 23737; Centrepoint (CP), 75678 23465; FRG 16-m tower (CP′), 75688 23493; reference station (RS), 74300 20980. During the experiments, more than 50 towers were deployed and instrumented for wind measurements. The majority were simple 10-m posts bearing cup anemometers, but, in the 1983 study, two 50-m towers, a 30- and a 16-m tower, and thirteen 10-m towers were instrumented for three-component turbulence measurements. Participants in the project represented the UK, Canada, Denmark, Federal Republic of Germany and New Zealand. Taylor and Teunissen (1987) presented an overview of the project, including details of the instrumentation and a summary of the data obtained. Complete data reports (Taylor and Teunissen, 1983, 1985) were prepared for the two field campaigns. Walmsley and Salmon (1985) presented early results of model

Boundary-Layer Meteorology **78:** 291–320, 1996.

calculations in comparison with 1983 data for vertical profiles and horizontal (i.e., constant height) cross-sections. Several journal papers have subsequently provided an interpretation of the experimental results.

Salmon *et al.* (1988a) presented results on the variations in mean wind speed at fixed heights above ground from linear arrays of anemometer posts and towers. Selected mean-flow data were grouped by wind direction and compared with model estimates of fractional speed-up ratio at hilltop locations and along the lines of instrumented towers. Good agreement was found in most cases.

Mickle *et al.* (1988) presented vertical profiles of mean wind and some turbulence integral statistics at upwind reference locations and at two hilltop sites. The data were obtained from sonic, Gill UVW and cup anemometers mounted on 10-, 17-, 30- and 50-m towers and from TALA kite systems. Attempts to obtain additional turbulence data using tilted Gill UVW anemometers were unsuccessful. Comparisons were made with estimates from numerical models.

Tetzlaff (1983) stressed the importance of measurements at high spatial and temporal resolution to describe the wind field over Askervein. Such resolution is required for comparisons with results of high-resolution models. The procedure for such detailed measurement was described, and results obtained were presented.

1.2. Related Studies

The Kettles Hill Project can be considered as a rehearsal for Askervein, although it did produce interesting results of its own. In preparation for this experiment, an extensive search, with the help of university geography departments, weather offices and local flying clubs, was made throughout Canada for a suitable candidate hill. The criteria for selecting the hill were a lack of trees (to avoid having to erect towers extending 3 to 10 m above treetops), lack of obstructions (e.g., buildings), horizontal scale of order 1 km, maximum slope less than about 0.3, accessibility and landowner's permission. Eventually Kettles Hill, near Pincher Creek, Alberta, Canada was selected. Salmon *et al.* (1988b) described the measurement program, conducted in February 1981 and March 1984. They also compared model calculations and wind-tunnel simulations with the field study data. Other details may be found in Mickle *et al.* (1981) and Teunissen (1983).

More or less concurrently with the Askervein study, a similar experiment was conducted at Blashaval, a 100-m high hill on the eastern side of the island of North Uist (57°37′N, 7°12′W). Mason and King (1985) provided details of the field measurements of the mean flow and turbulence statistics. The flow speed at 8 m over the summit was found to increase by a factor of 1.7 over the upwind value, and the flow direction reversed in the lee of the hill. The turbulence structure observed above the summit showed marked variations with height. The observed mean flow was compared with results from a linear model. Turbulence measurements were compared with results from available theories. Several years later, model intercomparison studies were conducted by Walmsley *et al.* (1990a) and Walmsley *et al.* (1994), both used the Blashaval field data as a reference.

Taylor *et al.* (1987) summarized these and other experiments over low hills published during the period 1979 to 1986. New experiments continue to be undertaken, though generally on a smaller logistical scale. An example is the study of mean wind flow and turbulence parameters over Cooper's Ridge, a 115-m high elongated ridge with low surface roughness, described by Coppin *et al.* (1994). Their paper presented measurements of the streamwise and vertical variations in the mean field for a variety of atmospheric stability conditions. In near-neutral conditions, the normalized speed-up over the ridge compared well with measurements from Askervein. In non-neutral conditions, the speed-up over the ridge reduced slightly in unstable conditions and increased by up to a factor of two in stable conditions.

1.3. Problems in Establishing Gridded Topographic Data

Obtaining an accurate representation of the terrain is a nontrivial yet important task. Experience gleaned from both modelling and measurements in the Kettles Hill Project revealed that wind speeds, especially within 10 m of the ground, can vary significantly from one location to another even over a smooth hill with few apparent small-scale topographic variations. Speeds were found to be dependent on the terrain slope; scarcely noticeable variations in slope caused significant variations in wind speed. To model such variations, therefore, high-quality and highly detailed topographic information is required.

For Askervein, a topographic contour map (for future reference, *Map B*) was created, from an existing stereo-photo pair, especially for deriving accurate terrain data for both numerical and wind-tunnel models. *Map B*, on a scale of 1:5 000, had contours over Askervein Hill and its immediate surroundings at vertical intervals of 2 m, with additional contours at 1-m intervals near the summit and in some of the flatter regions at the base of the hill. The horizontal grid used for reference purposes was that of the UK Ordnance Survey. All of the measurement locations were placed on *Map B* with an accuracy of about 10 m.

Originally the contours on *Map B* were digitized by manually following each contour with the crosshair of a digitizer. Position information was automatically extracted at intervals of order 3 mm (15 m full scale). Each contour was labeled with a contour number, the number of digitized points and the height above mean sea level (MSL). The contour data were quality-controlled to insert missing contours, eliminate crossed contours and to ensure that the height labels were correct.

Gridded topographic data were then generated using the *contour-to-grid* program associated with the mainframe-computer MS3DJH model of Walmsley *et al.* (1982). This program calculated the points of intersection of contours and gridlines to generate input for a cubic-spline-under-tension interpolation scheme performed on each x- and y-gridline. Care had to be taken to ensure that interpolated values fell between the heights of the two adjacent contours. Problems of overshooting that sometimes occurred near the summits of hills and crests of ridges were controlled. Gridded values in flat areas varied from slightly above to slightly below the correct value. In the case of water surfaces, these small variations were sometimes eliminated by "flooding".

Later an improved, more user-friendly master-grid generation scheme, was developed as part of the MS-Micro package described by Walmsley *et al.* (1990b). This scheme found the nearest contour point in each of the eight octants around each gridpoint. Linear interpolation was performed using the pair of points (first and fifth octant, second and sixth, *etc.*) that gave the steepest slope. Spot heights were added to the contour file to ensure good representation of summits, ridges and valleys. Gridded output was then contoured and plotted and the results compared with the original contour points. Results near the summit and crests and on the sides of the hill were improved over the 1982 scheme. Flat areas such as lakes were accurately represented as a result of the linear interpolation. Some problems still appeared near the edges of the contour information where extrapolation was required to complete the master grid.

More recently (1994–95) further improvements have been made to the grid-generation scheme. The extrapolation process has been modified to ensure a smoother transition from the interpolation region. An option to "blank" out contour information in defined regions enables a better smoothing down of terrain edges to a uniform height, analogous to matching a physical terrain model to the floor of a wind tunnel. In the same period, the complete *Map B* was redigitized by scanning with an electronic scanner and then using a semi-automatic *raster-to-vector* software package to generate contour information in the same format as before. The same process was used on the 1:50 000 scale UK Ordnance Survey map, Landranger Series, sheet 22. Here an area of about 6 km $\times$ 7 km centred on Askervein (to be referred to as *Map A*) was digitized for the purpose of investigating possible effects of nearby topographic features on the wind flow over and near Askervein.

Calculations with the new gridded topography based on the improved digital contour data and the improved *contour-to-grid* software are planned but have not yet been performed at either of the *Map A* or *Map B* scales.

2. Applications of Linear Models

Beljaars *et al.* (1987) introduced a new linear model for neutral surface-layer flow over complex terrain. The model, called MSFD, was a successor to the MS3DJH model developed by Walmsley *et al.* (1982) which was in turn based on the two-dimensional theory of Jackson and Hunt (1975) and its extension to three dimensions by Mason and Sykes (1979). This approach used a Fourier transformation in the horizontal coordinates, effectively changing each partial differential equation to a set of ordinary differential equations (ODEs) in the vertical coordinate. In MS3DJH, with its simple mixing-length closure and other simplifying assumptions, an analytic solution was obtained in Fourier mode for each of the ODEs. Wind speed results were obtained for an arbitrary distribution of surface roughness and topography at high spatial resolution with very low computing cost, relative to a three-dimensional finite-difference model of comparable resolution.

The spectral approach in the two horizontal coordinates was also utilized for the new MSFD model. Because of its higher-order closure scheme and less restrictive assumptions, however, an analytic solution of the ODEs was no longer possible. Instead, finite differencing was used in the vertical. This combination of spectral and finite-difference techniques provided the simplicity and computational efficiency of linear methods with the flexibility of improved turbulence closure schemes. Comparison between the MSFD model results and field data from Askervein were made and will be described in Section 6.

Results presented by Salmon *et al.* (1988b), Mason and King (1985), Walmsley *et al.* (1990a) and Beljaars *et al.* (1987) allow us to reach some conclusions regarding the applicability of linear models. At hilltops, wind speeds produced by linear models were found to be in excellent agreement with field data from the Kettles Hill, Blashaval and Askervein experiments, despite the fact that the linearity assumption seems to be invalid, as observed values of fractional speed-up ratio are as high as 0.9. Xu *et al.* (1994) noted that there may be compensating effects when linearity and low-order closure assumptions are combined, though Beljaars *et al.* (1987) found that MSFD results for Askervein were slightly improved when higher-order closure was implemented. For purposes of siting wind turbines, where summits of hills and crests of ridges are preferred locations, the linear models appear to provide adequate prediction of wind speed-up for hills of this scale and slope. These estimates are also appropriate for calculations of design wind speeds on hilltops for wind-loading purposes. Linear model results on the upwind sides of Kettles Hill, Blashaval and Askervein were also in very good agreement with wind-speed observations. Beljaars *et al.* (1987) showed, however, that on the lee side of Askervein, especially for flow over the steepest part of the hill, the linear model results tended to significantly overestimate the measured speeds. Evidently, flow separation had occurred or almost occurred. Perturbations of wind-speed components were of the same order of magnitude as the corresponding mean-flow component, making the linear approximation highly suspect and probably explaining the poor performance on the lee slopes.

Although the poor representation of lee-slope flow may not be a concern for wind-energy applications, it is important to modelling enthusiasts and in other applications such as the dispersion of atmospheric pollutants and for calculations of form drag on topography. In the following section we consider the use of nonlinear models to address this deficiency.

3. Applications of Nonlinear Models

Raithby *et al.* (1987) described a three-dimensional nonlinear numerical model, which had been extensively used to predict environmental water flows. When applied (with a $20 \times 20 \times 19$ grid) to atmospheric boundary-layer flow over Askervein and compared with data collected during the 1983 field study, it was concluded that the model predicted the mean flow variables with good accuracy, even on the lee slope. These results were also presented by Beljaars *et al.* (1987), who concluded that nonlinear effects were probably the reason that the linear models performed poorly on the lee side. Raithby *et al.* (1987) found discrepancies between their model results and measured turbulence quantities, suggesting deficiencies either in their turbulence model or in some of the measurements, or both. It should be remarked that Askervein is a hill with a fairly simple shape and not much small-scale detail. This made it possible to obtain good results with relatively few grid nodes.

Lalas *et al.* (1995) described an application of the Hybrid AIOLOS-T model to Askervein. This model combines a mass-consistent code with the vertical momentum equation and an O'Brien (1970) K-profile. Agreement with data was better than the linear models on the lee side of Askervein, but the maxima were displaced about 100 m upwind from their observed locations near the crest of hill.

Zeman and Jensen (1987) developed a two-dimensional second-order closure model in streamline coordinates, which they ran for a cross-section through the Askervein hilltop. They adopted a boundary-layer approach in which the pressure field was determined from an inviscid outer-layer solution and the inner-layer solution, with the boundary-layer assumptions, was obtained by marching forward along the streamlines. Application of the model was limited to the upwind side of the hill. Another two-dimensional higher-order E-ϵ closure model using a version of the SIMPLE algorithm (Patankar, 1980) is being applied to Askervein at Universidade do Porto, Portugal (J. Palma, personal communication).

For an idealized, isolated three-dimensional hill of dimensions similar to those of Askervein, Weng *et al.* (1995) compared results from MSFD with its nonlinear descendant, NLMSFD, developed by Xu and Taylor (1992). In NLMSFD, all the nonlinear terms, which were neglected in MSFD, are retained and treated as additional source terms on the right-hand sides of the governing equations. Computation begins with the linear solution and is conducted in Fourier mode in an iterative manner with nonlinear terms, which are evaluated in physical space, lagged one step behind. The iteration converges very rapidly for gentle terrain slopes, but more iterations and under-relaxation are needed as the terrain slope increases. The results from NLMSFD were similar to those of MSFD on the upwind slope and at the summit of the idealized hill. On the lee slope, however, wind speeds from the nonlinear model were significantly reduced from those produced by the linear model, in good agreement with observations at Askervein. Similar results were obtained by Walmsley *et al.* (1994) in a two-dimensional application of MSFD and NLMSFD to Blashaval.

As presently formulated, the NLMSFD iteration appears to converge satisfactorily for idealized two- and three-dimensional topographies for slopes up to order 0.3 (see Xu *et al.*, 1994) but there is some dependence on L/z_0, where L is a length scale for the topography and z_0 is the surface roughness length. The convergence is better with lower-order than with higher-order closure. For a model of flow over water waves with NLMSFD (P.Y. Li, personal communication), the slope limitation is more severe and convergence can only be achieved for slopes of order 0.2. Weng *et al.* (1995) noted that they were unable to obtain convergent NLMSFD solutions for the Askervein topography. Work on the model continues and further investigation of convergence properties is planned. The Askervein study had been a major motivation for much of this modelling work and it continues to be a source of frustration that the NLMSFD model fails in this case.

4. Wind Tunnel Studies

Teunissen *et al.* (1987) described wind-tunnel simulations of flow over Askervein that were conducted at three different length scales (1:800, 1:1 200 and 1:2 500) in two wind-tunnel facilities. The wind-tunnel results were compared with each other and with full-scale data and were shown, in general, to be in good agreement. Both smooth-surfaced and rough-surfaced models were used, with the latter better able to simulate separated flow on the lee side of Askervein. More details are presented in Section 6. Further analyses and spectra are reported by Stock and Bowen (1992).

5. Data Limitations

The Askervein study provided a substantial quantity of high quality, internally consistent observational data on the topographically-induced variations in near-surface mean wind speed. There are also some data on turbulence quantities, but these are more limited. As noted earlier (Section 1.1), Mickle *et al.* (1988) presented vertical profiles of some turbulence integral statistics from upstream and hilltop locations. Profiles of σ_u or σ_h (standard deviations of the downwind and horizontal components of wind speed, respectively) are available, based on sonic, propellor and cup anemometer data. A limited amount of profile data for σ_v and σ_w (standard deviations of the crosswind and vertical components of wind speed, respectively) is also available from four sonic anemometers mounted on the hilltop towers (10 and 50 m). One case has been presented by Zeman and Jensen (1987) but additional data have not yet been published.

A serious disappointment was the failure to resolve problems with the hilltop tilted Gill propellor anemometers that the group had hoped would provide extensive turbulence profile data. There was more success with the (horizontally mounted) Gill UVW propellor anemometers on the 16-m tower at the CP′ location and selected data from these anemometers have been reported by Mickle *et al.* (1988). The σ_u and σ_h data were generally satisfactory and reference station (RS) to hilltop (HT) differences (see below and Mickle *et al.*, 1988) can be interpreted in terms of both near-surface equilibrium layer and outer-layer rapid distortion behaviours. The comparisons of data for σ_v and σ_w at RS and CP′ were a little less conclusive but do indicate a pattern. Given the effort put into the collection of these hilltop turbulence data, it is unfortunate that technical problems in the field (signal conditioning with the tilted Gill propellor anemometers and a host of problems with maintaining the sonic anemometers in a rather hostile environment) limited the amount of useful data obtained. Significant efforts were put into data recovery and analysis by Atmospheric Environment Service (AES) and Risø National Laboratory (Denmark) scientists, and work on turbulence data at HT is in progress at Risø (N.O. Jensen, personal communication).

Turbulence data were also collected from Gill UVW propellor anemometers mounted at a height of 10 m above ground along the A and AA lines through HT and CP, respectively. Mean wind data from these anemometers are reported in Section 4.3 of Salmon *et al.* (1988a). Turbulence integral statistics were included in the data reports and compared with wind-tunnel data by Teunissen *et al.* (1987). Turbulence data for flow over topography from a single height, however, are rather difficult to interpret. For Askervein, the 10-m level was often in a transition region between inner-layer equilibrium behaviour, with increased wind speed leading to increased values for σ_u *etc.*, and the outer layer, where rapid distortion and streamline curvature effects can dominate (see for example Kaimal and Finnigan, 1994, pp. 181, 196).

There is a lack of published results on turbulence spectra from the Askervein field data. Relatively low sampling rates (2 or 4 Hz) for the cup and Gill UVW anemometer data are a serious limitation for their spectral analysis and, although some gust factor analysis was planned, it has so far not been executed. Spectral analyses of some of the sonic anemometer data were carried out (Teunissen, personal communication) but have not been published. Stock and Bowen (1992), however, reported on spectra from their wind-tunnel model study for Askervein.

An omission from the field experiment was any attempt to deploy microbarographs to measure pressure differences across the topography of the hill. At the time of the experiment, this addition was considered too difficult and costly, especially since the main thrust was wind-energy applications, but with improvements in microbarograph technology and a new emphasis on the determination of form drag in flow over topography, such measurements might have added an interesting component to the study. We estimate that *dynamic* pressure differences would be $\Delta p \sim 0.5\rho U_{10}^2$, where ρ is air density and U_{10} is wind speed at a height of 10 m above ground. This estimate is based on values obtained from NLMSFD runs over idealized topography. With $U_{10} \sim 10$ m s^{-1} and $\rho \sim 1.2$ kg m^{-3}, this

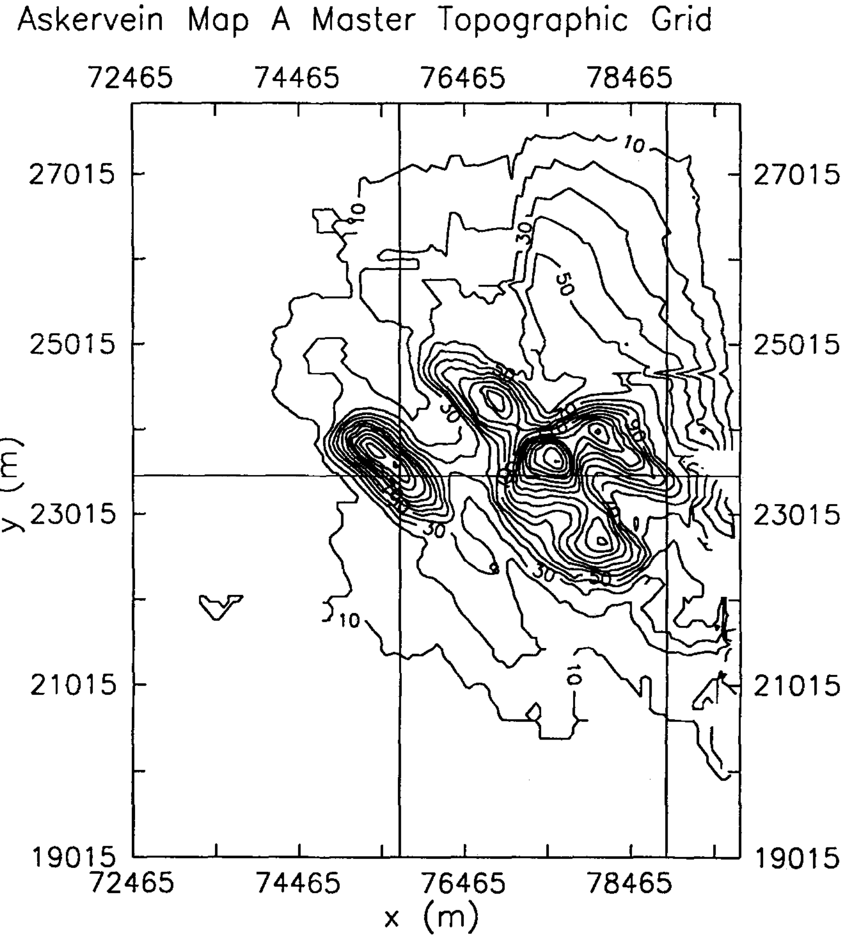


Figure 1. Contour map of Askervein and surrounding area referred to in the text as *Map A*, which was produced by digitizing UK Ordnance Survey Landranger Series Sheet 22 (scale 1:50 000), followed by gridding and re-contouring. Horizontal axes show distances in metres within grid square NF of the Ordnance Survey grid. Centre point (CP) of Askervein hill (Ordnance Survey reference: NF 75678 23465) is indicated by the overlying mesh. Grid north is approximately 5° west of true north. Heights are in metres above sea level and the contour interval is 20 m. Contours between the centrally located five hills and the edges of the map are incorrect as they are based on incomplete data in the original file of digitized contours.

means $\Delta p \sim 60$ Pa or 0.6 mbar, which should be measurable, provided *hydrostatic* pressure differences associated with differences in elevation (above sea level) are first removed.

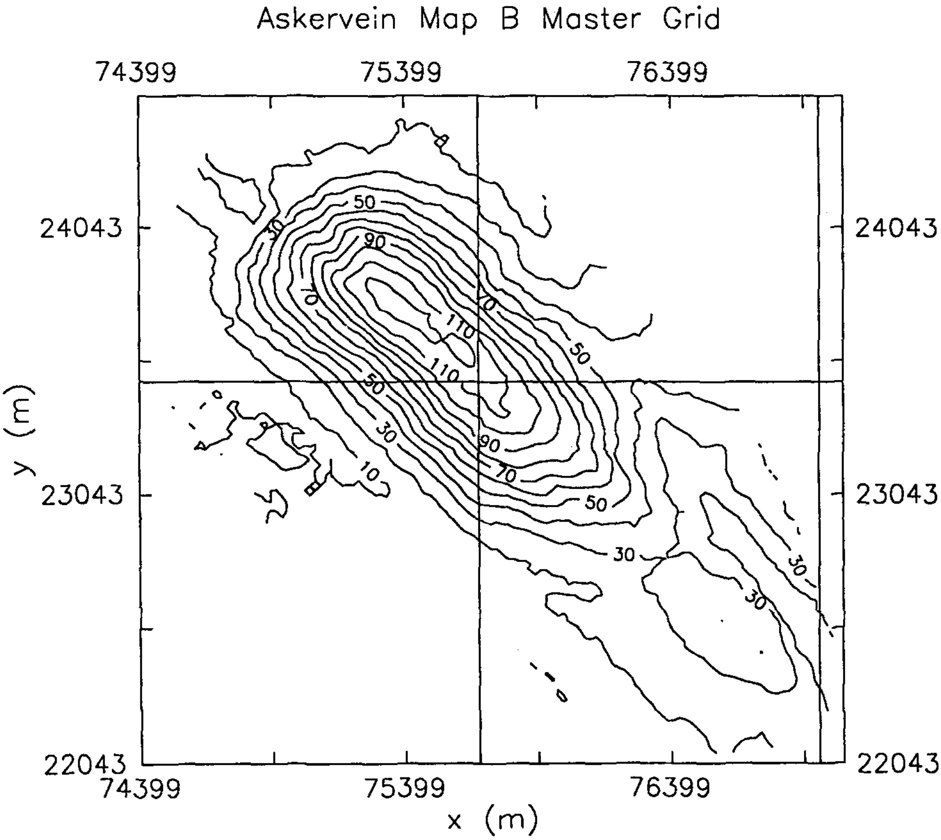


Figure 2. Same as Figure 1 except the area covered is referred to in the text as *Map B* and the original contour map was specially prepared for the Askervein study at a scale of 1:5 000; see text for further details. Heights are in metres above sea level and the contour interval is 10 m. Topographic features to the north and east of Askervein have been blanked out as they were incomplete on the original map.

6. Comparison of Model and Wind-Tunnel Results with Field Data

For reference purposes, Figure 3 shows the Askervein topography on which the tower lines and measurement locations are overlaid. We will discuss results from the mean flow and turbulence runs denoted as MF03-D and TU03-B collected during 1400-1700 British Summer Time on 3 October 1983. Wind direction and 10-m wind speed at the upwind reference site were 210° (i.e., $-13°$ from the 223° orientation of lines A and AA, which are perpendicular to the ridge) and 8.9 m s^{-1}, respectively. Further details of these runs appear in Taylor and Teunissen (1987) and Teunissen *et al.* (1987). The following two sub-sections compare model results with field observations along tower lines A and AA and as vertical profiles at point HT.

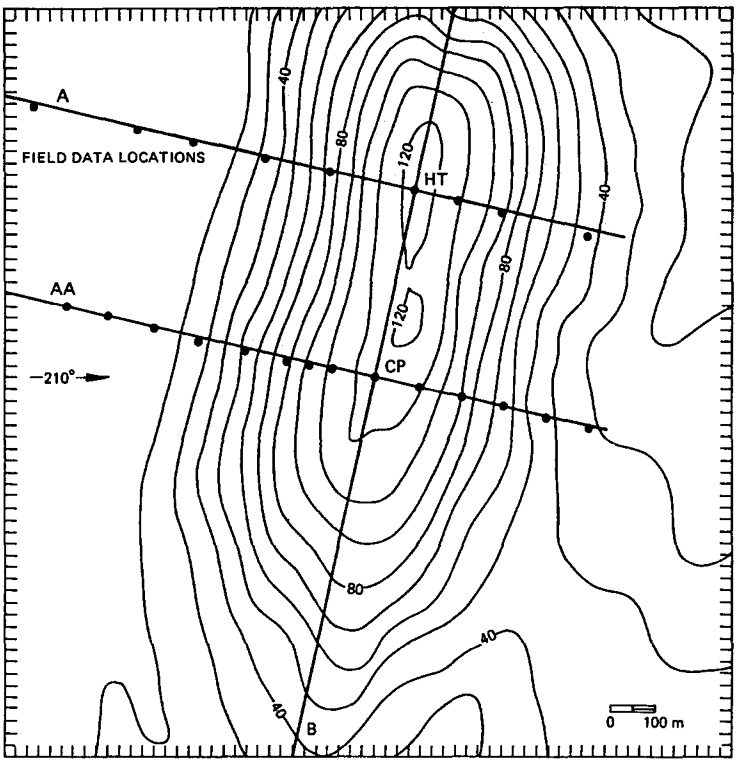
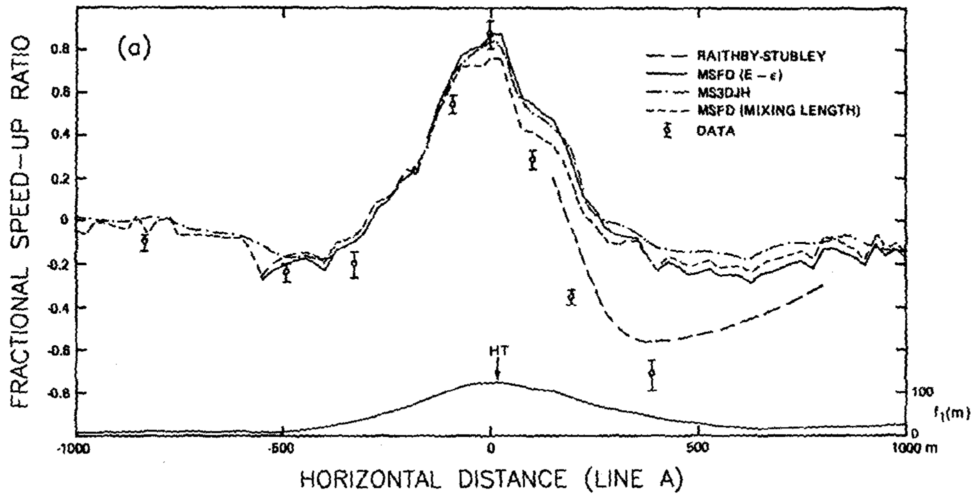


Figure 3. Contour map of Askervein showing full-scale experiment tower lines and data positions. Contour interval is 10 m. Map is oriented so that 210° (the wind direction for the case shown in Figures 4–10) is towards the left. The orientation of the tower lines A and AA is 223–043° and line B is perpendicular (133-313°). Centre point of the hill (CP) and the hilltop (HT) locations are shown. MSFD grid spacing (25 m) is shown by tick marks on the perimeter. Area shown is the central portion (64 × 64 grid points or 1575 × 1575 m) of a 256 × 256 gridpoint periodic domain (6400 × 6400 m). Source: Mickle *et al.* (1988).

6.1. Mean Flow

Beljaars *et al.* (1987) published model results of fractional speed-up ratio at 10 m for upwind flow from 210°, reproduced here in Figure 4. They concluded that for the mean flow, the differences between the linear models, MS3DJH and MSFD, were small. Agreement with upwind-slope and summit measurements was excellent, with the higher-order closure scheme in MSFD giving slightly better results than those obtained with mixing-length closure. (This good agreement with observations was obtained in spite of the fact that the linear approximation would appear to be invalid, as perturbations were of order 0.6, i.e., not small relative to unity.) Small-scale variations in wind speed, both modelled and measured, were related to small-scale changes in terrain slope. In Figures 4a and 4b, the maximum speed calculated by the models and suggested by the data occurs near the maximum



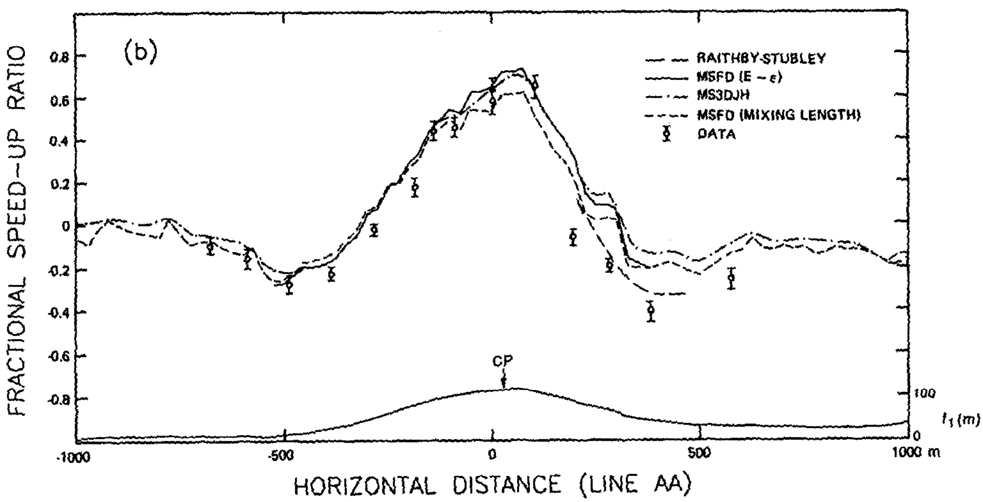


Figure 4. Fractional speed-up ratios for flow over Askervein (see Figure 3) at a height of 10 m above terrain. Comparison of different model results and experimental data. Wind direction is 210°; roughness length is 0.03 m. Topographic cross-sections (f_1) are also shown, without vertical exaggeration. Data are from runs TU25, TU03-A and TU03-B of the 1983 Askervein experiment. (a) Cross-section along line A. (b) Cross-section along line AA. Source: Mickle *et al.* (1988).

height of lines A and AA (i.e., at HT and about 25 m downwind of CP, respectively). On the lee slopes, the linear models overestimated the wind speed. Observed values of fractional speed-up ratio at positions about 400 m downwind from points HT and CP were −0.7 and −0.4, respectively, whereas model calculations produced values of about −0.2 at both locations.

The nonlinear finite-difference model of Raithby *et al.* (1987) gave results close to those of the linear models on the upwind slopes and crests of lines A and AA, but much lower speeds on the lee slopes (Figures 4a and 4b, respectively). Fractional speed-up values from the nonlinear model were about −0.35 and −0.6 at locations 400 m from CP and HT, respectively. Corresponding measured values were, as mentioned above, −0.4 and −0.7, respectively.

Similarly, in a two-dimensional application of MSFD and NLMSFD to Blashaval, Walmsley *et al.* (1994) found that values of lee-slope fractional speed-up ratio were about −0.18 with a higher-order closure version of MSFD, whereas NLMSFD gave results of −0.25 and −0.57, respectively, with low-order and higher-order closure forms of NLMSFD.

Various wind-tunnel results were compared with the field data by Teunissen *et al.* (1987), reproduced here in Figure 5. Interestingly, the two smooth-surfaced models (AES and NZS) gave the best agreement with the full-scale data (FS) on the upwind side and at the summit, whereas the rough-surfaced model (NZR) results agreed better than those of the smooth models on the lee side. The NZR results for fractional speed-up ratio at 400 m were about −0.43 and −0.72 on lines AA (Figure 5b) and A (Figure 5a), respectively, compared with field measurements of −0.4 and −0.65, respectively. (It should be noted that the full-scale value of −0.65 in Figure 5a is different from the value of −0.7 plotted in Figure 4a because the former was the result of one run in the 1983 experiment, whereas the latter was an average over three runs.)

For a wind direction of 235° (i.e., +12° from the orientation of lines A and AA), results of Teunissen *et al.* (1987) show that the rough-surfaced model, NZR, gave the best comparison with full-scale data at upwind, summit and downwind locations along line AA. This contrast with Figure 5b may be due to the steeper ascent towards CP for a 235° wind compared to one from 210° (see Figure 3). Teunissen *et al.* (1987) reported that the full-scale flow separation on the lee side "tended to be three-dimensional in nature (i.e., low-speed, highly turbulent flow) rather than displaying the reverse flow at the surface which is typical of two-dimensional separation." They concluded that "the rough-surfaced models tend to produce good simulations whether or not the [full-scale] flow is separated, while the smooth-surfaced models produce generally less separation ... and, hence, match the [full-scale] flow only when it displays little behaviour of this type." The increased roughness caused an increased loss in energy and a greater tendency for the flow to separate.

Figure 6 shows vertical profiles of fractional speed-up ratio at HT for the same case as in Figures 4 and 5. As noted by Beljaars *et al.* (1987), the higher-order closure results show better agreement with observations than do those of the MSFD or MS3DJH mixing-length closures. Below about 5 m, the nonlinear higher-order closure model results are best, suggesting that nonlinear effects may be important close to the ground.

Figure 7 shows the corresponding vertical profiles of fractional speed-up ratio at HT from the wind-tunnel measurements. Teunissen *et al.* (1987) felt that the decrease in the NZR profile below about 8 m (full scale) was not correct and may have resulted from the effect of a local roughness element. Due to experimental

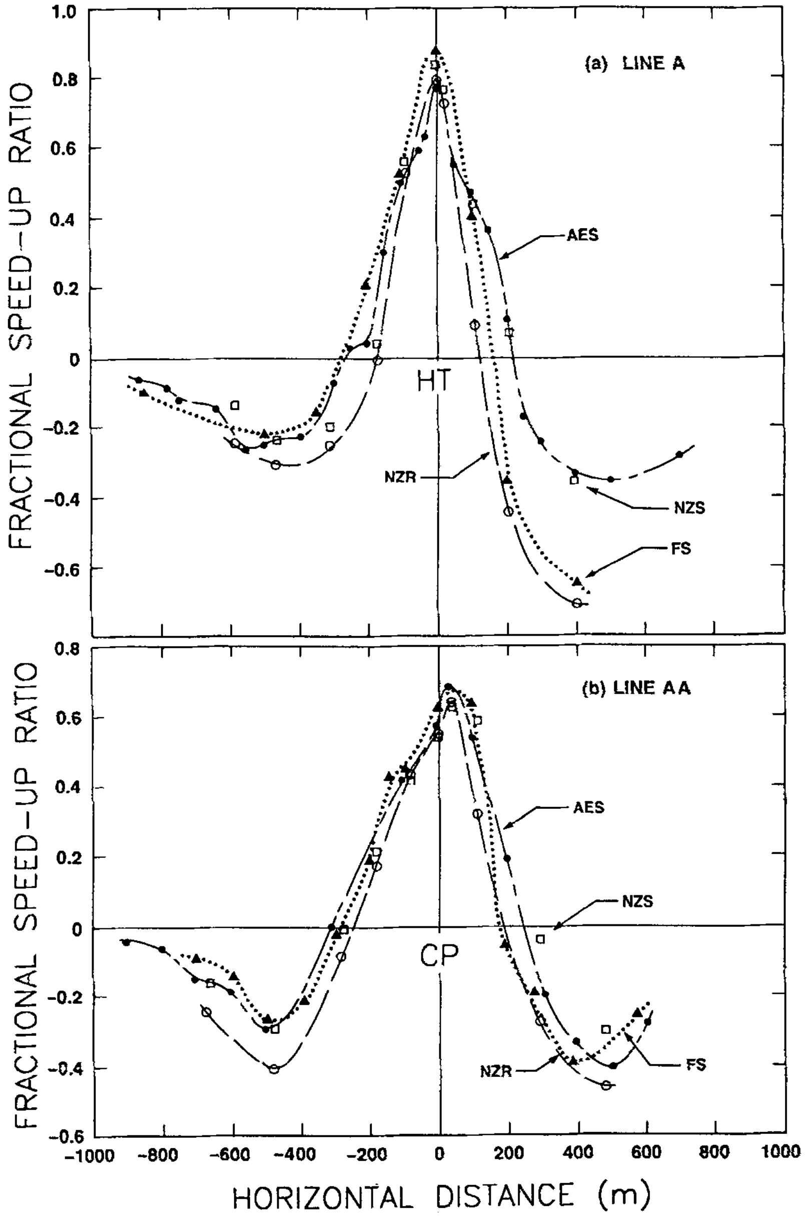


Figure 5. Same as Figure 4, except wind-tunnel results (AES, NZR, NZS) are compared with full-scale data (FS). (a) Cross-section along line A. Full-scale data are from Run TU03-B of the 1983 Askervein experiment. (b) Cross-section along line AA. Full-scale data are from Run MF03-D of the 1983 Askervein experiment. Source: Teunissen *et al.* (1987).

errors, especially height errors, that became significant in measurements within 2 mm (actual height) of the model surfaces, the wind-tunnel results only extend

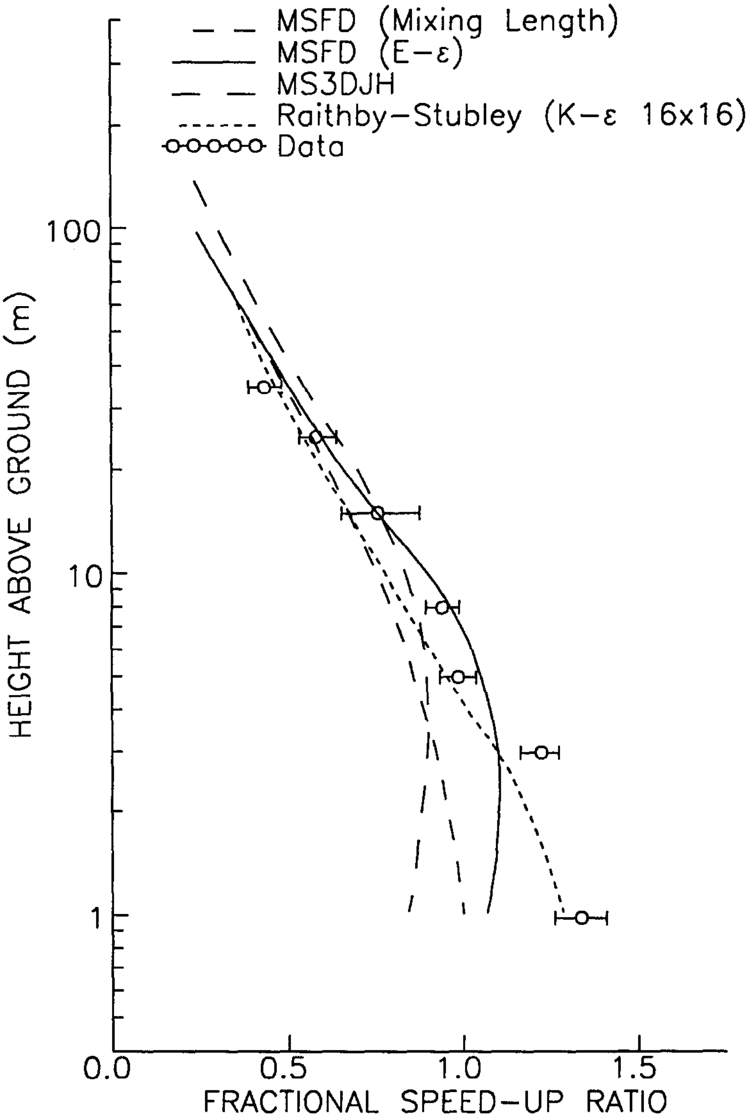


Figure 6. Vertical profile of fractional speed-up ratio at the top (point HT) of Askervein hill (see Figure 3). Comparison of different model results and experimental data. Same case as Figure 4b. Source: Mickle *et al.* (1988).

down to full-scale equivalent heights of 5 and 2 m for the NZ (1:2 500 scale) and AES (1:1 200 scale) models, respectively.

Salmon *et al.* (1988a) displayed measured values of normalized wind speed, i.e., the ratio between wind speed at 10 m above ground at locations HT or CP (Figure 3) to wind speed at the same height at the upwind reference station. These were compared with "Guidelines" estimates for a range of incident wind directions. The

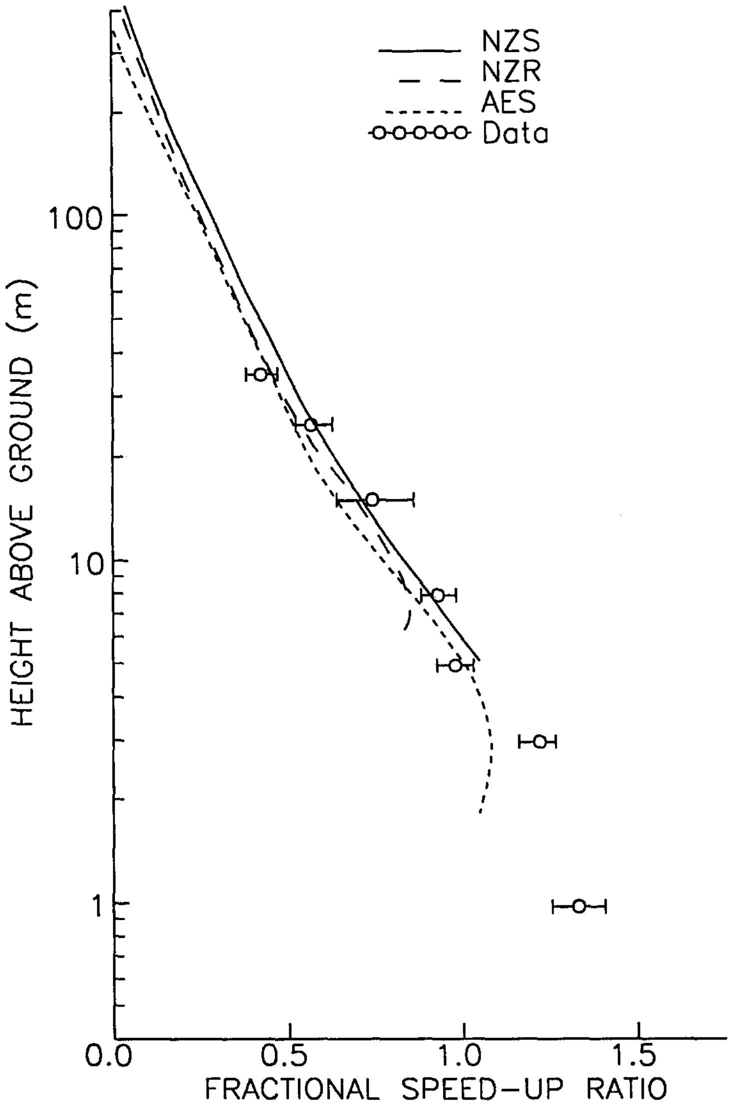


Figure 7. Same as Figure 6, except wind-tunnel results (AES, NZR, NZS) are compared with full-scale data (FS). Source: Teunissen *et al.* (1987).

Guidelines for wind flow and turbulence estimates in complex terrain are simple formulae developed by Taylor and Lee (1984) and later extended by Walmsley *et al.* (1989). (The formulae apply downwind of changes in surface roughness or at the top of hills, ridges and escarpments.) The estimates "are generally in fair to good agreement with the observations", according to Salmon *et al.* (1988a), especially for the 10-m data at HT. For the 210° wind direction case discussed above, the Guidelines give a fractional speed-up ratio of 0.85 at 10 m at HT, whereas the measured value is about 0.87.

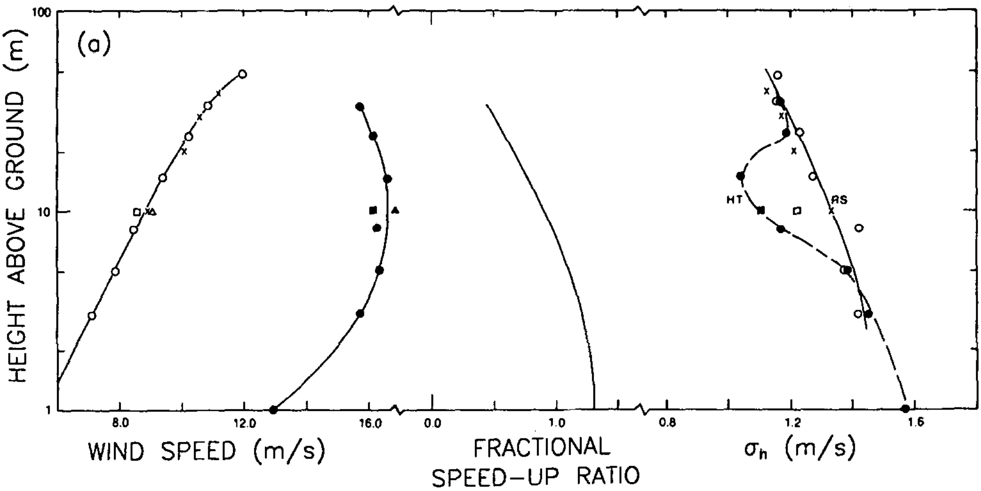


Figure 8a. Mean wind speed, fractional speed-up ratio and σ_h profiles at the reference site, RS (open symbols and $\times$) and the hilltop, HT (closed symbols) for the 1983 Askervein experiment, Run TU03-B (upwind wind direction $\approx 210°$). Source: Mickle *et al.* (1988).

6.2. Turbulence

Mickle *et al.* (1988) presented HT profile data for wind speed, U, and σ_u (or σ_h), reproduced here as Figure 8a. The most striking features are that, although the low-level (3 m) winds at HT are approximately double those at RS, the values of σ_u have not increased. Thus the turbulence intensity (σ_u/U) has decreased from 16% at RS to 9% at HT. At the 10-m level there is a significant reduction in σ_u at HT relative to RS which can be attributed to rapid-distortion and streamline-curvature effects. Corresponding changes in turbulence intensity are from 15 to 7%. Reductions in turbulent stress were also observed (Figure 8b).

Data on all three components of σ (i.e., $\sigma_u, \sigma_v, \sigma_w$) are available for Run TU03-B from the CP′ location at heights of 5, 10 and 16 m, and are shown in Figure 8c. As with the HT data, we see reductions in σ_u relative to the RS profile, although they are smaller for this location. The σ_v values may be slightly higher than those at RS and the σ_w values slightly lower, but the differences are small. Mickle *et al.* (1988) provided further discussion on these data.

Beljaars *et al.* (1987) displayed vertical profiles of dimensionless shear-stress perturbation obtained from the MSFD model with various turbulence-closure schemes in comparison with a single set of Askervein field measurements reported by Zeman and Jensen (1985, 1987). The model-derived inner-layer depth was too large in comparison with the data. Beljaars *et al.* (1987) attributed this discrepancy to the assumed roughness length of 0.03 m being too large. This question is discussed in more detail in Section 6.3. Regarding the outer-layer model results, only the E-ϵ-τ closure scheme produced good agreement with the observations.

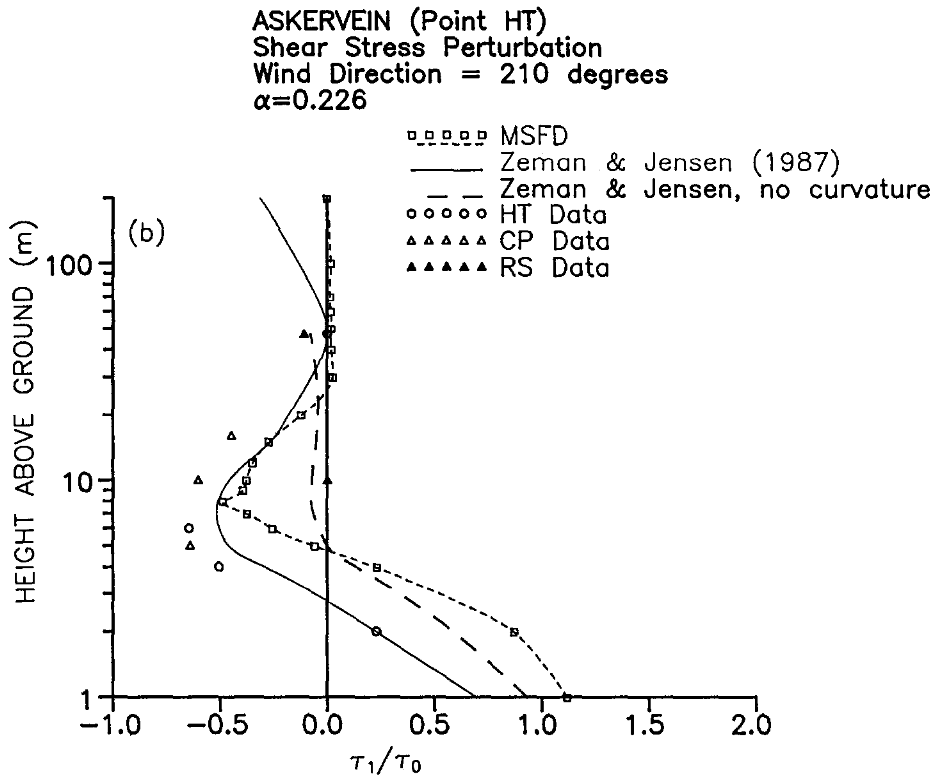


Figure 8b. Vertical profiles of dimensionless shear-stress perturbation at the top (point HT) of Askervein hill (see Figure 3). MSFD model results for E-ϵ-τ closure compared with data and model results of Zeman and Jensen (1987). τ_1 is the the shear-stress perturbation in the direction of the model-computed wind at HT. τ_0 is the magnitude of the stress at the upwind location. Experimental data points at 5, 10 and 16 m were measured at the centre point (CP′) of Askervein hill. Data points at other levels were measured at HT. Data from the reference station (RS) are also shown. Source: Walmsley and Padro (1990).

Later, Walmsley and Padro (1990) discovered that a factor, α, had been omitted from the algebraic-stress equations in the E-ϵ-τ closure scheme in the model code, as well as in Beljaars *et al.* (1987) and Karpik (1988). Walmsley and Padro (1990) corrected this oversight and recomputed the vertical profiles of stress at HT,

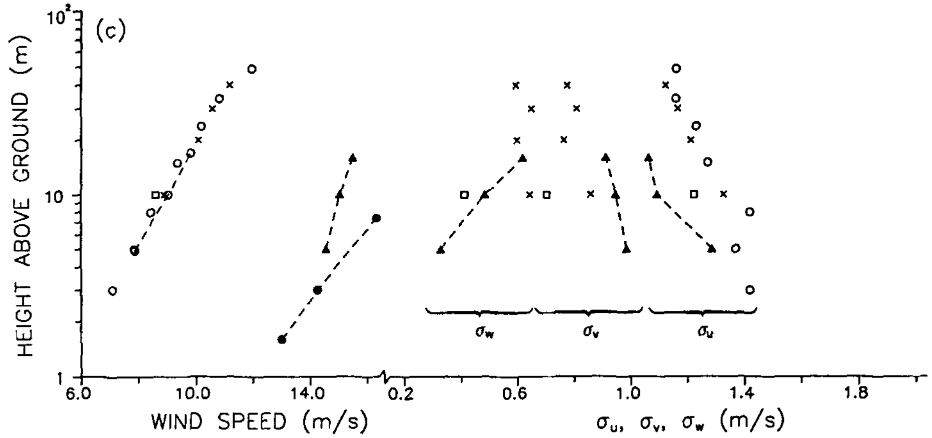


Figure 8c. Mean wind-speed and σ profiles at RS (open symbols and $\times$) and CP′ (closed symbols) for the 1983 Askervein experiment, Run TU03-B (upwind wind direction $\approx 210°$). - - - - - Data from University of Hannover towers for 1425–1700 only. Source: Mickle *et al.* (1988).

experimenting with values of α of 0.18, derived from Panofsky and Dutton (1984); 0.21, derived from Askervein run TU03-B of Mickle *et al.* (1988); and 0.226, as used by Zeman and Jensen (1987). We note that the value of α advocated by Xu and Taylor (1995) and adopted by Karpik *et al.* (1995) in the latest version of the MSFD model is 0.25. Vertical profiles at HT for $\alpha = 0.226$ are presented in Figure 8b from the MSFD and Zeman-Jensen models in comparison with data. Agreement between the MSFD results and the observations is considerably improved by including the formerly missing α, although the model-derived inner-layer depth, if taken as the height at which the profile reaches a minimum value, still seems too large. The Zeman-Jensen model simulates the low-level data somewhat better than MSFD, but only if streamline curvature effects are incorporated. This raises another question to be discussed in Section 6.3.

Teunissen *et al.* (1987) measured vertical profiles of σ_u in their wind-tunnel simulations. The corresponding reference value in the undisturbed flow, σ_{uR}, was then subtracted to give the perturbation, $\Delta\sigma_u$, which was then divided by σ_{uR} to produce the dimensionless perturbations displayed in Figure 9. It should be noted that there are differences in scaled boundary-layer depth between the full-scale and wind-tunnel simulations. This is one reason for presenting these data comparisons in terms of relative changes. Teunissen *et al.* (1987) observed that there was more variability among the different wind-tunnel results than there was for the fractional speed-up ratio profiles in Figure 7. In addition, they suspected that the NZR profile overestimated the height of the zero-crossing due to measurement difficulties near the surface associated with the small scale (1:2 500) of the NZR model, as mentioned above. The AES and NZS results agree well with the full-scale results in the 10–20 m layer, but appear rather different above and below. The

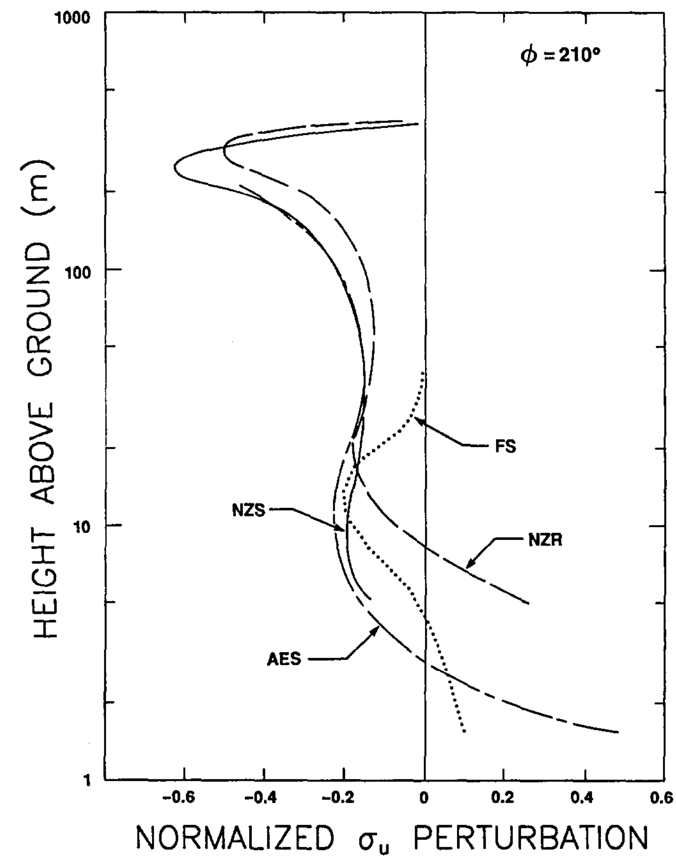


Figure 9. Vertical profiles of normalized σ_u perturbation at the top (point HT) of Askervein hill for the same case as in Figure 8b. Wind-tunnel results (AES, NZR, NZS, OXR) are compared with full-scale data (FS). Source: Teunissen *et al.* (1987).

AES results slightly underestimate the zero-crossing at about 5 m in the full-scale data.

Teunissen *et al.* (1987) also compared cross-sections of normalized σ_u perturbation from wind-tunnel measurements and full-scale data at a full-scale height of 10 m above ground. These are reproduced in Figure 10. The shape of the cross-sections were all in agreement: the perturbation increased as the flow approached the hill (i.e., at the upwind hill foot), decreased on the upwind slope, reached a minimum about 50–100 m upwind of the summit, increased sharply to reach a maximum 100–300 m downwind of the summit and finally decreased on approaching the downwind foot of the hill. All three wind-tunnel model results reproduced the full-scale values remarkably well on the upwind slope and near the summit, with the rough-surfaced model (NZR) performing better than the two smooth-surfaced models. On the lee slope, all models underestimated the maximum, with NZR achieving the highest value of the three but at a position 100 m upwind of the

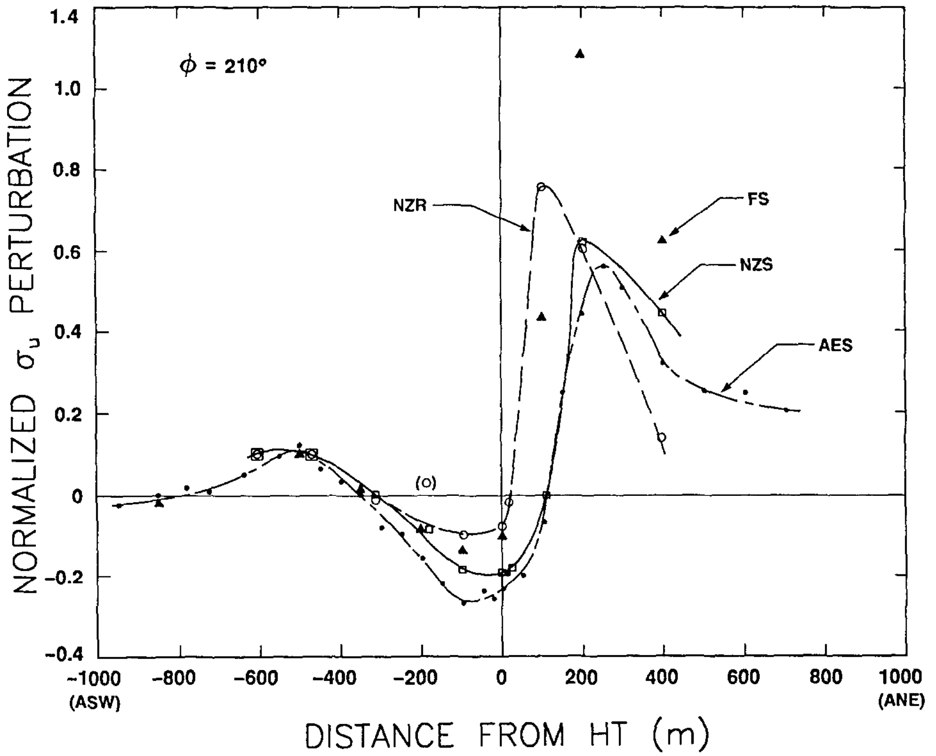


Figure 10. Same as Figure 9, except SW-NE cross-sections along line A at a height of 10 m above ground. Source: Teunissen *et al.* (1987).

correct location. The two smooth-surfaced models had lower maxima, but close to the right position. As noted earlier (Section 5), there are a number of processes affecting the turbulence at the 10-m level (rapid distortion, streamline curvature, changed production rates) and interpretation of the results is difficult. As pointed out by Kaimal and Finnigan (1994), it is sometimes better to do this in streamline coordinates.

Zeman and Jensen (1987) included both rapid-distortion and streamline-curvature effects in their two-dimensional model. The latter were demonstrated to improve their simulation of hilltop profiles of shear stress throughout the 2–20 m layer. Walmsley and Padro (1990), on the other hand, obtained results from MSFD, without streamline curvature effects, in the 8–20 m layer that were similar to those of Zeman and Jensen (1987) with streamline curvature (see Figure 8b). We can perhaps infer that streamline-curvature effects are significant for turbulence calculations between 2 and 8 m at Askervein. Between 8 and 20 m, the modelling evidence is contradictory. Above 20 m, streamline-curvature effects seem unimportant.

Kaimal and Finnigan (1994) and Ayotte *et al.* (1994) discussed the roles of rapid distortion and streamline curvature in modifying the turbulence statistics in flow over hills. The basic conclusion was that rapid distortion is the dominant process in the outer part of the outer layer, while effects of streamline curvature are significant in the inner portion of the outer layer. Identifying these effects in vertical profiles or horizontal (i.e., constant height above ground) cross-sections based on the Askervein data is a highly speculative occupation. It should be noted, nevertheless, that models with higher-order closure schemes may produce results in better agreement with field data if they incorporate rapid-distortion and streamline-curvature effects.

6.3. Outstanding Problems

6.3.1. *Nature of Hilltop Velocity Profiles*

Mickle *et al.* (1988; p. 166), reported on velocity profiles observed in the 0.5–10 m layer along the summit ridge at Askervein. They were surprised to find that, although these were essentially logarithmic in shape, the apparent roughness length was much lower (0.001 m) than that at RS (0.03 m). Mickle *et al.* (1988; p. 165), did not correct the data for possible cup overspeeding. At most these might be 8%, 5% and 1% at heights of 0.5, 1, and 3 m, respectively (see Coppin (1982) or Walmsley (1988), Figure 5). If such adjustments are made, calculated roughness lengths are still ~0.005 m. In our view, even this adjusted roughness length is far too low to be consistent with the expected value for this type of surface.

Zeman and Jensen (1987) argued that the roughness of the Askervein hilltop was less than that at RS. Their model included a roughness length that varied with distance, approaching a minimum value near 0.01 m at the hilltop. This variable roughness produced a slightly better agreement between model results and observations of wind speeds in the 1–4 m layer. It appears that an even larger decrease in the minimum z_0 (e.g., to about 0.001 m) would be needed for their model to simulate the wind speeds in that layer. We are not convinced that there were significant variations in roughness length and believe that some other explanation for the anomalous low-level wind profiles must be sought.

Ayotte *et al.* (1994) found non-logarithmic profiles from their model calculations and speculated on the causes. They, and Kaimal and Finnigan (1994), argued that the streamline-curvature effect is too small to account for these anomalies, in contrast to the speculation of Mickle *et al.* (1988; p. 166). Ayotte *et al.* (1994) were studying flow over periodic sinusoidal topography and appealed to vertical variations in the horizontal phase shifts of velocity perturbations at fixed height above ground, but their results appeared to show the opposite effect (an increase in apparent roughness length) to that discovered at Askervein.

The basic problem can be thought of as almost an uncoupling of the near-surface flow from the surface itself, with weak shear over the hilltop except, presumably, very close to the surface. Gong *et al.* (1996) and Taylor *et al.* (1995) report similar features in their wind-tunnel study of boundary-layer flow over sinusoidal terrain and find that two-dimensional flow models are sometimes unable to predict with sufficient accuracy the velocity profiles over the crests. Large eddy simulation

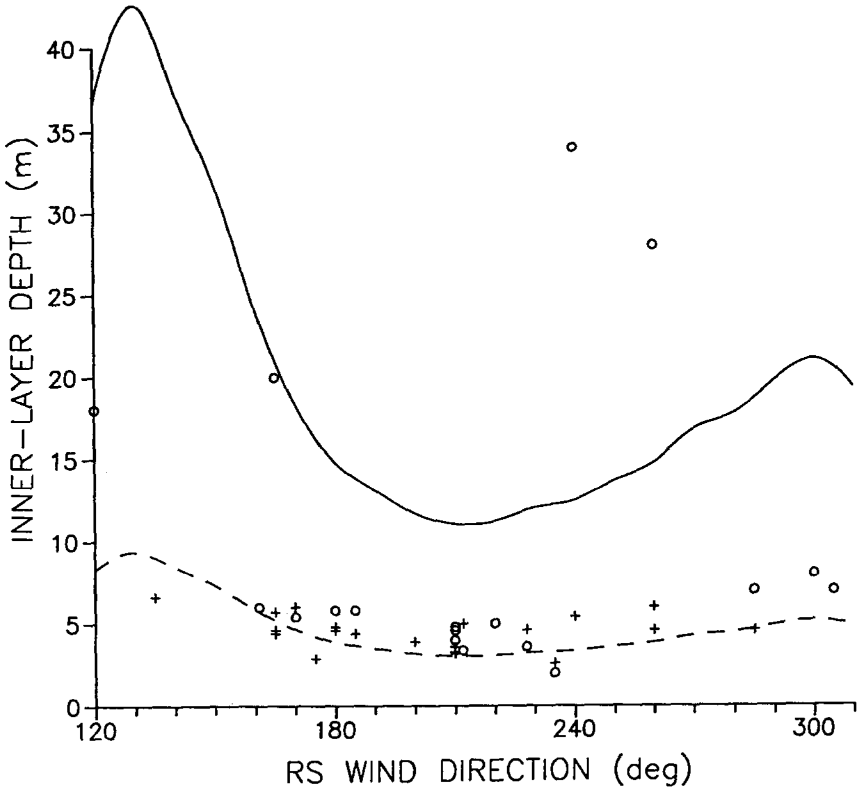


Figure 11. Estimates and observations of inner-layer depth as functions of wind direction at reference site (RS). Askervein hilltop (HT), + observed height of maximum wind-speed perturbation; o observed height of zero-crossing of σ_u perturbation; —— Jackson-Hunt estimate; - - - - - Jensen estimate. Source: Mickle *et al.* (1988).

(LES; see Gong *et al.*, 1996) does a rather better job and appears to support the contention that organized secondary flows caused by the topography are sometimes a factor. In our view we still lack a satisfactory explanation for the near-surface wind speed profiles at the Askervein hilltop.

6.3.2. *Inner-Layer Depth*

Taylor *et al.* (1987) discussed the apparent underestimation of the theoretical values obtained from Jackson and Hunt (1975), hereafter **JH**, for the inner-layer depth in comparison with the values derived from Askervein measured wind profiles. The formulation presented by Jensen *et al.* (1984), hereafter **JEN**, gives better agreement with the data, as shown in Figure 11.

An alternative formulation for the inner-layer depth, advanced by Britter *et al.* (1981), is based on the zero-crossing of the $\Delta\sigma_u$ profile. Figure 11 shows that most of the time the Britter *et al.* (1981) scale was close to the **JEN** estimate.

Teunissen *et al.* (1987) found from their wind-tunnel studies that the inner-layer depth was about 2–4 m, similar to the value predicted by **JEN**. They concluded, however, that "whether this is an indication of the superiority of [**JEN**'s] relationship or simply an indication that the order-of-magnitude constant in [**JH**'s] should be adjusted remains to be seen."

Taylor *et al.* (1987) concluded that the **JH** value "is probably best considered as a scale height for the inner layer rather than the height at which something specific occurs", e.g., the local height above a hilltop of the maximum wind-speed perturbation. They anticipated that the formulation of **JEN** "may be used more widely in future."

Claussen (1988), hereafter **CL**, pointed out that the form of the **JH** equation for the inner-layer depth was derived from a formal perturbation expansion and "does not depend on any closure assumption"; only the constant was obtained from mixing-length closure. By determining the inner-layer constant from the experimental data, **CL** found that the **JH** formula fitted the Askervein data almost as well as did the formula of **JEN**. **CL** concluded that "more data are needed to settle the question of what is the best definition of an inner-layer scale height and whether there really exists an *inner-layer constant*."

The formulae to be considered (**JH**, **JEN** and **CL**, respectively) are:

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

$$(\ell/L)\ln^2(\ell/z_0) = 2\kappa^2, \tag{2}$$

$$(\ell/L)\ln(\ell/z_0) = \text{constant}. \tag{3}$$

Here L is the horizontal scale (distance in the upwind direction from HT to the point where the elevation is half the height of the hill), z_0 is the roughness length, ℓ is the inner-layer depth and $\kappa = 0.4$ is von Karman's constant. In Table I, we present results from applying the **JH**, **JEN** and **CL** formulae to the Askervein 210° wind direction case, for which $L = 215$ m; $z_0 = 0.03$ m; and $\ell = 4$ m. Results in Table I appear in bold font; input values are in normal font. **JH** and **JEN** both use a constant of $2\kappa^2$, whereas **CL** uses the **JH** formula to compute the constant. When the **JH** formula is used to compute ℓ, the result of 11.6 m is considerably larger than the observed value of about 4 m given in Mickle *et al.* (1988). On the other hand, when the **JH** formula is used to compute z_0, an unreasonably low value results. **JEN**'s formula returns $\ell = 3.2$ m, quite close to the observed value. By changing the constant to 0.09, as suggested by **CL**, the **JH** formula is satisfied when the observed values of L, z_0 and ℓ are inserted, at least for this one wind direction (210°).

Beljaars *et al.* (1987) observed that "it seems as if the predicted inner-layer thickness is too thick, which might be due to a wrong estimate of the surface roughness." This suggestion, however, is not supported by the calculations in Table I, which show that values of z_0 would have to be extremely low ($\sim 10^{-7}$ m) for the **JH** formula to return a value of $\ell \sim 4$ m. Either **JEN**'s formula or **CL**'s

TABLE I

Calculations with inner-layer depth formulae (JH = Jackson-Hunt; JEN = Jensen *et al.*; CL = Claussen).

Formula	ℓ (m)	L (m)	z_0 (m)	Constant
JH	**11.6**	215	0.03	0.32
JEN	**3.2**	215	0.03	0.32
CL	4.0	215	0.03	**0.09**
JH	4.0	215	$\mathbf{1.3{\times}10^{-7}}$	0.32
JEN	4.0	215	**0.06**	0.32

approach of adjusting the inner-layer constant, on the other hand, is capable of producing values of ℓ close to observed values with z_0 = 0.03 m.

The formulae of **JEN** and **CL** were used in Figure 12 to plot ℓ/z_0 as a function of L/z_0. Since the **CL** formula was calibrated for the 210° wind-direction case ($L/z_0 = 7\,167$), it therefore agrees better than the **JEN** formulation for the smaller values plotted here ($L/z_0 < 12\,000$ and $\ell/z_0 < 200$). The **JEN** equation performs better than that of **CL** at the single large observed value of L/z_0 (i.e., $\phi = 300°$) available for Askervein. Data from more hills, giving a wider range of L/z_0, are needed before a final judgment is given.

Beljaars and Taylor (1989) took a different approach to the problem. They used the MSFD model, which does not assume an inner layer, to calculate inner-layer depths, defined in three different ways, for small-amplitude two- and three-dimensional sinusoidal hills over a wide range of ℓ/z_0 ratios. By generalizing (1)–(3) to the following form:

$$(\ell/L)\ln^n(\ell/z_0) = c, \tag{4}$$

Beljaars and Taylor (1989) found that the MSFD model produced parameter combinations (n, c) of approximately (1.6, 0.55) and (1.4, 0.26) for mixing-length and higher-order closure, respectively. Available experimental data, on the other hand, suggest $n \approx 3$, although this result must still be regarded as tentative.

This discussion of the inner-layer depth may be summarized as follows:

1. The inner-layer depth is lower than predicted with the Jackson-Hunt (**JH**) formula.
2. The roughness length cannot be adjusted within a reasonable range of values to make the **JH** formula fit the observations.
3. The Claussen (**CL**) formula gives better agreement with observations than that of Jensen *et al.* (**JEN**) at the low end of the range of L/z_0, i.e., near

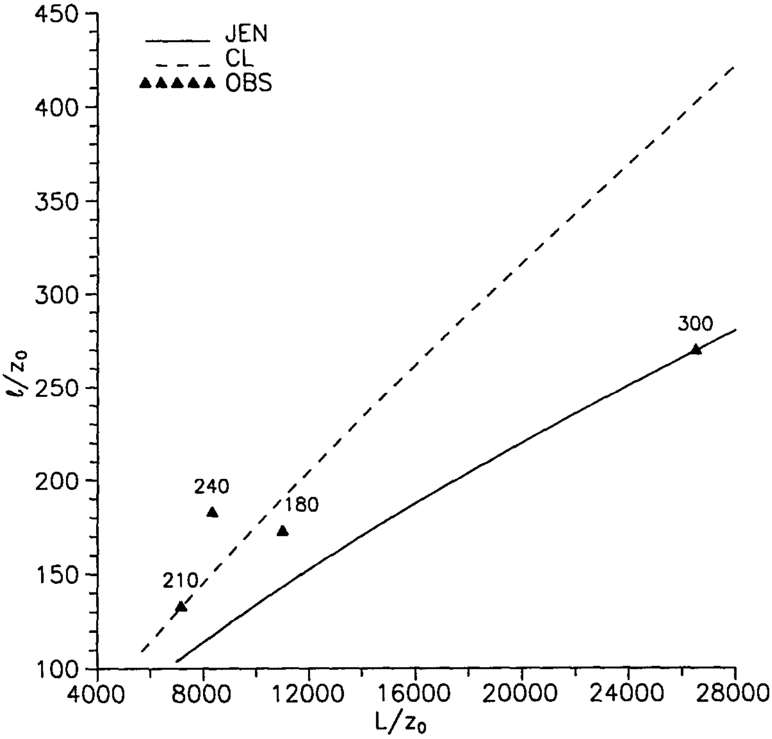


Figure 12. Theoretical curves of Jensen *et al.* (1984) and Claussen (1988) compared with observations (wind direction indicated above symbols). **JEN:** Eq. (2); **CL:** Eq. (3), constant = 0.09; **OBS:** observed values from Mickle *et al.* (1988).

where the former was calibrated. This suggests that the **JH** formula may not be completely discredited, only that the inner-layer constant needs to be adjusted. For the single large value of L/z_0, on the other hand, the **JEN** formula performs better than that of **CL**. More results, covering a wider range of L/z_0, are needed to resolve this issue.

4. Model calculations produce a power, n, in (4) between 1 (used by **JH** and **CL**) and 2 (used by **JEN**).
5. Available observations tentatively suggest $n \approx 3$, but more data are required to confirm this finding. At present, only the values $n = 1$ and 2 are supported by theory.

6.3.3. *Sensitivity to Model Constants*

Since the MSFD-derived vertical profiles of shear stress were found by Walmsley and Padro (1990) to be sensitive to the parameter α, it would be worthwhile recomputing them with the new set of model constants recently adopted by Karpik *et al.* (1995). The inner-layer depth only explicitly appears in MSFD for determining the scale-dependent vertical computational grid. It would seem, therefore, that the value of the inner-layer constant will only affect the heights of grid levels. It would be wise, nevertheless, to test the model's sensitivity to the value of this constant.

6.3.4. *Flow Distortion: Effect of Neighbouring Hills*

It seems from comparing mean-flow results from the linear and nonlinear models, that nonlinear effects are significant on the lee side of Askervein. It is possible, nevertheless, that downwind hills (Figure 1) cause some upwind blockage to the flow that contributes to the discrepancy between mean-flow model results and field measurements. As reported by Mickle *et al.* (1988), these hills were included in the nonlinear finite-difference calculations, but not in those of the linear models (Figure 4). Further numerical tests should help to resolve this question. Calculations with the Figure 1 topography should be compared with those from the same domain but with all features except Askervein Hill blanked out.

7. Summary and Conclusions

The Askervein Hill Project of 1982 and 1983 provided an extensive full-scale dataset for studies of wind flow and turbulence over low hills in near-neutral stratification using numerical and wind-tunnel models. Since no experiment of comparable logistical scale has been conducted since Askervein, the data still represent a benchmark for such studies.

Several detailed wind-tunnel studies of flow over Askervein produced good agreement with full-scale measurements. With the smaller-scale models, however, measurements were only possible down to a full-scale equivalent height of about 8 m. The smooth-surfaced models seemed to give the best agreement with full-scale data on the upwind side and at the summit, whereas the rough-surfaced model gave better results on the lee side.

Linear numerical models produced excellent agreement with mean-flow observations on the upwind slopes and at the crest of the hill, despite an apparent violation of the linearity assumption. They performed less well on the lee slopes where they underestimated the magnitude of the negative values of fractional speed-up ratio, especially for flow perpendicular to the ridge line over the summit. Mean-flow results were slightly improved by use of a higher-order turbulence closure scheme. Nonlinear models gave mean-flow results close to those of the linear models on the upwind slopes and at the crest, and showed significant improvement over the lee slopes. Computational effort, however, was much greater and problems of convergence of the NLMSFD model have still not been resolved.

Vertical profiles of turbulence over the Askervein summit were well simulated in wind-tunnel studies in the full-scale equivalent 10–20 m layer. Above that layer, magnitudes of the negative perturbations of σ_u were overestimated by the wind-tunnel measurements. Horizontal cross-sections of σ_u perturbations at full-scale equivalent height of 10 m were well reproduced in the wind tunnel both on the upwind slopes and at the summit. Magnitudes of the perturbations, however, were underestimated over the lee slopes.

Numerical-model results of shear-stress perturbation were sensitive to the turbulence-closure scheme and to values of the model constants. There was also an indication that streamline curvature effects are present. Vertical profiles at the summit, nevertheless, showed acceptable agreement with observations when the E-ϵ-τ closure scheme was used with MSFD.

The main limitation of the Askervein dataset at the time of writing is the lack of more extensive published turbulence data for hilltop locations. Work is presently in hand at Risø to rectify this limitation. It would be interesting to run a third experiment at the site to obtain additional turbulence data, and perhaps to add surface pressure measurements.

The Askervein experiment also left several unresolved questions. First, why do wind-speed profiles in the bottom few metres above the hilltop suggest very low roughness lengths? Second, what is the best way to estimate the depth of the inner layer? Third, how accurately do model constants have to be specified for accurate simulation of turbulence quantities? Fourth, what are the effects, if any, of flow distortion by neighbouring hills? In this paper, we have made preliminary attempts to answer these questions and have offered suggestions regarding the approaches needed to obtain more definitive answers.

Acknowledgements

We thank Drs. Al Lo and Robert Mickle for reviewing the manuscript; also the referees for their comments. John Walmsley was partially supported by the Government of Canada's Panel on Energy Research and Development (PERD). Peter Taylor's work is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Atmospheric Environment Service (AES).

References

Ayotte, K. W., Xu, D., and Taylor, P. A.: 1994, 'The Impact of Turbulence Closure Schemes on Predictions of the Mixed Spectral Finite-Difference Model for Flow Over Topography', *Boundary-Layer Meteorol.* **68**, 1–33.

Beljaars, A. C. M. and Taylor, P. A.: 1989, 'On the Inner-Layer Scale Height of Boundary-Layer Flow Over Low Hills', *Boundary-Layer Meteorol.* **49**, 433–438.

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.* **38**, 273–303.

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

Claussen, M.: 1988, 'On the Inner Layer Scale Height of Boundary Layer Flow Over Low Hills', *Boundary-Layer Meteorol.* **44**, 411–413.

Coppin, P. A.: 1982, 'An Examination of Cup Anemometer Overspeeding', *Meteorol. Res.* **35**, 1–11.

Coppin, P. A., Bradley, E. F., and Finnigan, J. J.: 1994, 'Measurements of Flow Over an Elongated Ridge and its Thermal Stability Dependence: The Mean Field', *Boundary-Layer Meteorol.* **69**, 173–199.

Gong, W., Taylor, P. A., and Dornbrack, A.: 1996, 'Turbulent Boundary-Layer Flow Over Fixed, Aerodynamically Rough, 2D Sinusoidal Waves (Wind tunnel and LES Model Studies)', *J. Fluid Mech.* (In press).

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

Jensen, N. O., Petersen, E. L., and Troen, I.: 1984, 'Extrapolation of Mean Wind Statistics with Special Regard to Wind Energy Applications', Rep. WCP-86, World Meteorol. Organ., Geneva, 85 pp.

Kaimal, J. C. and Finnigan, J. J.: 1994, *Atmospheric Boundary Layer Flows — Their Structure and Measurement*, Oxford University Press, Oxford, 289 pp.

Karpik, S. R.: 1988, 'An Improved Method for Integrating the Mixed Spectral Finite Difference (MSFD) Model Equations', *Boundary-Layer Meteorol.* **43**, 273–286.

Karpik, S. R., Walmsley, J. L., and Weng, W.: 1995, 'The Mixed Spectral Finite-Difference (MSFD) Model: Improved Upper Boundary Conditions', *Boundary-Layer Meteorol.* **75**, 353–380.

Lalas, D. P., Panagiotidis, T. C., and Tryfonopoulos, D. A.: 1995, 'A Hybrid Micrositing Model for Wind Flow Simulations Over Complex Topographies', in J. L. Tsipouridis (ed.), *Proc., 5th European Wind Energy Assoc. Conf.*, 10–14 October 1994, Thessaloniki, Greece, **1**, pp. 285–290.

Mason, P. J. and King, J. C.: 1985, 'Measurements and Predictions of Flow and Turbulence Over an Isolated Hill of Moderate Slope', *Quart. J. R. Meteorol. Soc.* **111**, 617–640.

Mason, P. J. and Sykes, R. I.: 1979, 'Flow Over an Isolated Hill of Moderate Slope', *Quart. J. R. Meteorol. Soc.* **105**, 383–395.

Mickle, R. E., Salmon, J. R., Taylor, P. A., Teunissen, H. W., and Walmsley, J. L.: 1981, 'Boundary-Layer Flow Over Kettles Hill, Alberta', in *Proc., 5th Amer. Meteorol. Soc. Symp. on Turbulence, Diffusion and Air Pollution, Atlanta*, Amer. Meteorol. Soc., Boston, pp. 228–229.

Mickle, R. E., Cook, N. J., Hoff, A. M., Jensen, N. O., Salmon, J. R., Taylor, P. A., Tetzlaff, G., and Teunissen, H. W.: 1988, 'The Askervein Hill Project: Vertical Profiles of Wind and Turbulence', *Boundary-Layer Meteorol.* **43**, 143–169.

O'Brien, J. J.: 1970, 'A Note on the Vertical Structure of the Eddy Exchange Coefficient in the Planetary Boundary Layer', *J. Atmos. Sci.* **27**, 1213–1215.

Panofsky, H. A. and Dutton, J. A.: 1984, *Atmospheric Turbulence: Models and Methods for Engineering Applications*, John Wiley & Sons, New York, 397 pp.

Patankar, S. V.: 1980, *Numerical Heat Transfer and Fluid Flow*, Hemisphere Publ. Corp., New York, 197 pp.

Raithby, G. D., Stubley, G. D., and Taylor, P. A.: 1987, 'Askervein Hill Project: A Finite Control Volume Prediction of Three-Dimensional Flows Over the Hill', *Boundary-Layer Meteorol.* **39**, 247–267.

Salmon, J. R., Bowen, A. J., Hoff, A. M., Johnson, R., Mickle, R. E., Taylor, P. A., Tetzlaff, G., and Walmsley, J. L.: 1988a, 'The Askervein Hill Experiment: Mean Wind Variations at Fixed Heights Above the Ground', *Boundary-Layer Meteorol.* **43**, 247–271.

Salmon, J. R., Teunissen, H. W., Mickle, R. E., and Taylor, P. A.: 1988b, 'The Kettles Hill Project: Field Observations, Wind-Tunnel Simulations and Numerical Model Predictions for Flow Over a Low Hill', *Boundary-Layer Meteorol.* **43**, 309–343.

Stock, D. E. and Bowen, A. J.: 1992, 'Wind Tunnel Measurements of the Turbulence Structure of Wind Flow Over Askervein Hill', in *Proc., 10th Amer. Meteorol. Soc. Symp. on Turbulence and Diffusion*, Amer. Meteorol. Soc., Boston, pp. J73–J75.

Taylor, P. A. and Lee, R. J.: 1984, 'Simple Guidelines for Estimating Windspeed Variations due to Small-Scale Topographic Features', *Climatol. Bull.* **18**(2), 3–32.

Taylor, P. A. and Teunissen, H. W.: 1983, 'Askervein '82: Report on the September/October 1982 Experiment to Study Boundary-Layer Flow Over Askervein, South Uist', Rep. MSRB-83-8, Atmospheric Environment Service, Downsview, Ontario, Canada.

Taylor, P. A. and Teunissen, H. W.: 1985, 'The Askervein Hill Project: Report on the September/October 1983, Main Field Experiment', Rep. MSRB-84-6, Atmospheric Environment Service, Downsview, Ontario, Canada, 48 pp. plus tables and figures.

Taylor, P. A. and Teunissen, H. W.: 1987, 'Askervein Hill Project: Overview and Background Data', *Boundary-Layer Meteorol.* **39**, 15–39.

Taylor, P. A., Mason, P. J., and Bradley, E. F.: 1987, 'Boundary-Layer Flow Over Low Hills', *Boundary-Layer Meteorol.* **39**, 107–132.

Taylor, P. A., Xu, D., Gong, W., and Ayotte, K. W.: 1995, 'Modelling Turbulent Boundary-Layer Flow over 2D Sinusoidal Waves', in *Proc., Internat. Symp. on the Air-Sea Interface, Marseilles*, Univ. of Toronto Press, Toronto (In press).

Tetzlaff, G.: 1983, 'Untersuchung zur Beschreibung des Windfeldes an Hugeln (Investigation for describing the wind field on hills)', *Ann. Meteorol.* **20**, 43–44.

Teunissen, H. W.: 1983, 'Wind-Tunnel and Full-Scale Comparisons of Mean Wind Flow Over an Isolated Low Hill', *J. Wind Engin. Indust. Aerodyn.* **15**, 271–286.

Teunissen, H. W., Shokr, M. E., Bowen, A. J., Wood, C. J., and Green, D. W. R.: 1987, 'Askervein Hill Project: Wind-Tunnel Simulations at Three Length Scales', *Boundary-Layer Meteorol.* **40**, 1–29.

Walmsley, J. L.: 1988, 'On Theoretical Wind Speed and Temperature Profiles Over the Sea with Applications to Data from Sable Island, Nova Scotia', *ATMOS.-OCEAN* **26**, 203–233.

Walmsley, J. L. and Padro, J.: 1990, 'Shear Stress Results from a Mixed Spectral Finite-Difference Model: Application to the Askervein Hill Project Data', *Boundary-Layer Meteorol.* **51**, 169–177.

Walmsley, J. L. and Salmon, J. R.: 1985, 'A Boundary-Layer Model for Wind Flow Over Hills: Comparison of Model Results with Askervein 1983 Data', in *Proc., European Wind Energy Assoc. Conf., October 1984, Hamburg, Germany*, pp. 81–90.

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 Salmon, J. R.: 1989, 'Simple Guidelines for Estimating Wind Speed Variations Due to Small-Scale Topographic Features – An Update', *Climatol. Bull.* **23**(1), 3–14.

Walmsley, J. L., Troen, I., Lalas, D. P., and Mason, P. J.: 1990a, 'Surface-Layer Flow in Complex Terrain: Comparison of Models and Full-Scale Observations', *Boundary-Layer Meteorol.* **52**, 259–281.

Walmsley, J. L., Woolridge, D., and Salmon, J. R.: 1990b, 'MS-Micro/3 User's Guide', Rep. ARD-90-008, Atmospheric Environment Service, Downsview, Ontario, Canada, 88 pp.

Walmsley, J. L., Weng, W., Karpik, S. R., Xu, D., and Taylor, P. A.: 1994, 'Applications of the Mixed Spectral Finite-Difference (MSFD) Model and its Nonlinear Extension (NLMSFD) to Wind Flow over Blashaval Hill', in S.-E. Gryning and M. M. Millan (eds.), *Air Pollution Modeling and Its Application*, **10**, Plenum Press, New York, pp. 263–271.

Weng, W., Walmsley, J. L., Karpik, S. R., Xu, D., Taylor, P. A., Ayotte, K., and Salmon, J. R.: 1995, 'Applications of the MSFD and NLMSFD Models to Airflow Over Askervein Hill', in J. L. Tsipouridis (ed.), *Proc., 5th European Wind Energy Assoc. Conf.*, 10–14 October 1994, Thessaloniki, Greece, **3**, pp. 79–84.

Xu, D. and Taylor, P. A.: 1992, 'A Non-Linear Extension of the Mixed Spectral Finite Difference Model for Neutrally Stratified Boundary-Layer Flow Over Topography', *Boundary-Layer Meteorol.* **59**, 177–186.

Xu, D. and Taylor, P. A.: 1995, 'A Note on the Constants Used in E-ϵ-τ Turbulence Closure', *Boundary-Layer Meteorol.* **72**, 205–211.

Xu, D., Ayotte, K. W., and Taylor, P. A.: 1994, 'Development of a Non-Linear Mixed Spectral Finite Difference Model for Turbulent Boundary-Layer Flow Over Topography', *Boundary-Layer Meteorol.* **70**, 341–367.

Zeman, O. and Jensen, N. O.: 1985, 'Response of the Reynolds Stress Tensor to the Mean Flow Distortion Over a Two-Dimensional Hill', in *Proc., 7th Amer. Meteorol. Soc. Symp. on Turbulence and Diffusion, November 1985, Boulder CO*, Amer. Meteorol. Soc., Boston, pp. 292–295.

Zeman, O. and Jensen, N. O.: 1987, 'Modification of Turbulence Characteristics in Flow Over Hills', *Quart. J. R. Meteorol. Soc.* **113**, 55–80.