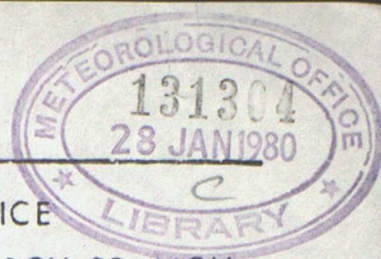


MET.O.14

METEOROLOGICAL OFFICE
BOUNDARY LAYER RESEARCH BRANCH
TURBULENCE & DIFFUSION NOTE



T.D.N. No. 114

Measurements of the flow structure around Ailsa Craig,

a steep, three dimensional, isolated hill.

by

G.J.Jenkins, P.J.Mason, W.H.Moores and R.I.Sykes

January 1980

Please note: Permission to quote from this unpublished note should be obtained from the Head of Met.O.14, Bracknell, Berks., U.K.

FH1B

Measurements of the flow structure
around Ailsa Craig, a steep, three-dimensional, isolated hill

by

G J Jenkins*, P J Mason**, W H Moores**, and R I Sykes***

* Meteorological Division, Porton Down, Wiltshire

** Meteorological Research Unit, Cardington, Bedford

*** Meteorological Office, Bracknell

Summary

Observations of neutral flow around an isolated, nearly circular hill with slopes of about 30° are presented. The flow field at 4 m above the surface shows a speed-up around the sides and over the summit, with reverse flow on the lee slope. Measurements of the mean flow in the wake obtained with an instrumented aircraft reveal a very powerful trailing vortex, with axis close to the upstream wind direction. Measurements of fluctuating quantities with a tethered balloon system experienced difficulties with the severe turbulence, but show marked distortions of the normal Reynolds stress components in the flow around the side of the hill.

1. Introduction

Despite a wide interest in the subject, our knowledge of turbulent flow over surface-mounted obstacles is extremely limited. Research on the problem has important applications in the context of atmospheric dynamics; the main requirements are the prediction of local flow changes which are necessary for the assessment of effects on buildings, forest damage, wind power studies, or pollution dispersal in hilly terrain and also information on the net effects on the boundary for use in large scale models. Most research has been concerned with neutral flow over relatively small two-dimensional ridges. Numerical studies such as Taylor and Gent (1974), Deaves (1975), Taylor (1977) have calculated the steady flow over a shallow ridge using simple closure assumptions, and the resulting velocity profiles have been compared favourably with measurements from small obstacles such as embankments. The analytic theory of Jackson and Hunt (1975) has also been compared with the numerical and observational flows, and gives reasonable results in spite of the assumption of linearity. Sykes (1980) has developed an asymptotic theory for the flow over a shallow ridge, and shown that the correct leading order mean velocity perturbations are obtained from the inviscid potential flow result, and consequently not a sensitive test of theoretical models. Thus, for the case of gentle topography, measurements of more sensitive quantities such as the Reynolds stresses are necessary to adequately test the validity of theoretical models. In the case of steep topography, when flow separation may occur, even the mean flows are very poorly understood.

The work presented here is part of a programme of research ultimately aimed at obtaining a comprehensive set of measurements of flow around simple topographic features. Our progress is limited both by inherent difficulties, such as surface irregularities in real topography and lack of control over atmospheric flow, and also by the instrumentation available to us. For these reasons, we have confined our initial work to topography steep enough to produce large flow changes which are easily measured. Our first experiment, Mason and Sykes (1979a), was conducted on the isolated, almost circular hill, Brent Knoll. This has a slope of about 1 in 5, and although flow separation does not occur, the changes in speed are large, and agreement with theories based on the assumption of gentle slopes could not be anticipated. The measurements were restricted to velocities at 2m above the surface. The results compared surprisingly well with the predictions of the three-dimensional extension of the linear theory of Jackson and Hunt (1975), indicating that the mean flow was still qualitatively similar to the potential flow field. Following this preliminary work, we have now undertaken a more ambitious study of flow over a nearly circular, isolated hill which is steep enough to produce flow separations.

The site chosen for the experiment was the island of Ailsa Craig off the coast of Ayrshire in South West Scotland. It has a relatively idealised shape, which is an almost circular bell-shape, see figure 1. The island has a base diameter of roughly 1 km, and a height of 330 m, and is situated about 20 km from the nearest coast. It can be seen that, apart from the cliffs along the Western and Southern sides, the terrain has slopes of about 30° - 45° and almost rivals a wind-tunnel model in its suitability for the study of flow around a simple isolated obstacle.

The objectives of our experiment were basically to obtain as full a picture as possible of the three-dimensional flow field under conditions of near-neutral stability. There were three types of measurement undertaken; these were fixed anemographs measuring mean wind at 4 m above the surface, turbulence probes carried on a tethered balloon system giving vertical profile information, and also the instrumented Hercules aircraft of the Meteorological Research Flight giving the capability of measuring velocities both upwind and downwind of the island.

We have exploited the near circular symmetry of the hill to give a more complete measurement of the flow using the fixed instruments. As the upstream wind direction changes, the position of a fixed site moves around on a circle relative to the incident flow. Thus if the geostrophic wind direction varies through 360° , data is obtained all around the obstacle. This technique was employed in the analysis of the Brent Knoll observations, Mason and Sykes (1979a). Although the ideal wind variation was not obtained, the results show several exciting features of the mean flow quite clearly; in particular, the mean surface flow in the downstream separated region is delineated, and a strong streamwise vortex is detected in the wake.

We are not aware of any other direct quantitative measurements of the mean flow of a turbulent boundary layer around a three-dimensional surface-mounted obstacle. Such measurements are very difficult in the wind-tunnel where the boundary layer of the correct character can usually only be obtained by the use of large roughness elements on the surface. These artificial roughness elements not only make measurements close to the surface very doubtful but also raise uncertainties in scaling to atmospheric sizes. There are further instrumental difficulties in measuring velocities in the highly turbulent separated flow region. We therefore feel that mean flow measurements in the atmosphere, where the longer time scales allow cruder instrumentations to give accurate results, are of general interest.

2. Instrumentation and data acquisition

1. Surface flow measurement

In order to delineate the windflow over the island with the number of anemographs available, and in a reasonable time, we opted for a distribution of instruments roughly equally spaced along the south-eastern radius of the island. As we have mentioned, it was our hope that an effective circular coverage of the island at each radial distance would be produced as the upstream wind direction varied around the compass during the course of the experiment. In practice, due to the absence of any significant period with winds having an easterly component, the windflow pattern was only established for the downstream half of the island - this being the most interesting sector, however. Due to this predominance of westerly winds, enough data was gathered from many sites sufficiently early in the experiment to allow us to relocate the anemographs. This improved the spatial resolution, and reduced the effects of imperfect exposure; by the end of the experiment, good data had been collected from a total of twelve sites. The plan and elevation diagrams

of the island, showing the sites, are at Figure 2.

The sites were chosen mostly on the south-eastern slopes of the island, since this is the most uniformly smooth region. There were also two sites about 50 m apart on the summit, and a further site about 100 m down the western slope. The sites were chosen to give a reasonably representative exposure, i.e. away from any obvious local sheltering or speed-up effects, and also for their accessibility.

At each site, a 4 m mast was erected perpendicular to the slope; each mast supported an anemometer and wind-vane, the latter being well balanced to minimise any gravitational effects with the vane used out of the vertical. In eight of the anemographs, the wind speed was sensed photoelectronically (Jones, 1965) and the wind-vane direction was read out on a series of relays spaced around the vane housing (Jones, 1970). Outputs from each of these sensors was recorded, with a smoothing time constant of about 1 minute, on a Rustrak recorder. Three other anemographs used the same type of anemometer, but with its output voltage fed to a sine-cosine resolving potentiometer attached to the wind vane. Outputs corresponding to the two resolved components of wind were again smoothed and logged on a chart recorder. These vector averaging wind recorders give results which are more interpretable than the speed and direction traces when the flow is very turbulent and the wind direction is varying considerably.

All wind vanes and anemometers were calibrated before and after the experiment, and accuracies are estimated to be within $\pm 10^\circ$ for direction and $\pm 0.5 \text{ ms}^{-1}$ for speed.

Subsequent analysis involved estimating the value of the mean vector wind over each period of one hour from the chart record. Any periods when

there were instrument faults or when marked synoptic features were passing through were rejected. These hourly mean winds, together with the surface geostrophic wind estimated from the British Isles hourly synoptic chart, then constitute the basis data which was then averaged into various categories of geostrophic wind speed and direction. The details of the analysis are presented in the next section with the results. It might be noted here that any random errors introduced by the subjective scaling of the chart records will be greatly reduced by the averaging process.

ii. Aircraft data

Measurements of the velocity field remote from the surface were made using the instrumented 'Hercules' aircraft of the Meteorological Research Flight. The velocity components of the airflow relative to the aircraft are measured by means of a pitot-static pressure sensor on the noseboom with directional information from balanced vanes also on the noseboom. The aircraft velocity is derived from a Doppler radar system coupled with an inertial platform. The complete system, together with instrumental accuracies, is described in detail by Nicholls (1978) and therefore will not be discussed further here.

The flight plan for the experiment is shown schematically in Figure 3. A series of tracks were flown perpendicular to the undisturbed mean wind both upstream and downstream of the island and at heights of 80m, 160m, 320m and 480m. These heights roughly correspond to $h/4$, $h/2$, h and $3h/2$ where h is the height of the island. Although flights were made at positions more remote from the island, they did not reveal features which could be definitely distinguished from the general turbulence in the boundary layer.

A total of five independent flights were made when the winds were relatively steady and the boundary layer stability was near neutral.

iii. Balloon-based measurements

Details of the turbulence probe and radio telemetry system of M.R.U. Cardington have been given by Caughey (1977), so we only give a brief

outline here. The probe is essentially a windvane, pivoted at the balloon cable, with a critically-damped vertical arm at the front on which the sensors are mounted. The sensors comprise

- (1) a fine platinum wire resistance thermometer,
- (2) a hot wire head measuring the instantaneous wind inclination to the vertical,
- (3) a hot wire head measuring the instantaneous wind inclination to the windvane direction,
- (4) a small cup anemometer giving total wind speed,
- (5) a modified flux gate magnetometer giving the direction of the windvane with respect to magnetic North.

Signals from these sensors are relayed to the ground using an FM telemetry system, and the data is stored in analogue form on a multi-channel tape recorder. After being electronically low-pass filtered (~ 10 Hz) the data are digitised and stored on computer-compatible magnetic tape. Subsequent processing on the Meteorological Office COSMOS computer system gives time series of three orthogonal wind components and temperature accurate up to 10 Hz. Turbulence statistics are then generated by removing linear trends from these time series.

3. Data analysis and results

i. Surface flow

As noted in the previous section, the basic data are hourly observations of mean wind at each site, together with the appropriate surface geostrophic wind. The geostrophic wind was used as a reference velocity, defining the upstream conditions, and a table was constructed for each site giving the mean wind at that site as a function of geostrophic wind speed and direction. The directions were split into 20° sectors, and there were four speed categories between 0 and 30 ms^{-1} . In fact, all

speeds were scaled relative to the geostrophic wind, and it was found that the results were independent of wind speed provided the geostrophic wind was greater than 5 ms^{-1} . Therefore we can merge all speed categories above 5 ms^{-1} and refer all speeds to the surface geostrophic wind. The results for winds below 5 ms^{-1} are discounted as they are unreliable and erratic. Thus our surface flow results consist of a table of velocities against geostrophic wind direction for each site. These results can all be presented on one diagram if we assume that the island is circular, since then a change in geostrophic wind direction is equivalent to a change in the position of the site.

A standard deviation of the velocity component observations in each category was calculated, and this can be used to estimate the uncertainty in the average velocity. The estimate was simply the standard deviation divided by the square root of the number of observations in the category. Only data where the estimated error was less than 20% of the mean velocity were plotted on the diagram. The rejected data were almost entirely Easterly geostrophic wind directions for which very few observations were available.

Fig 4 shows the surface flow vectors with the surface geostrophic wind blowing from left to right as indicated by the unit length arrow upstream of the hill. The wind speed on the summit is about 0.9, i.e. 90% of the geostrophic wind. There is a very clear pattern to the flow; the wind around the base of the island, which is indicated by the dotted circle, follows the contours very closely and forms a region in the lee where the wind direction changes completely in a very short distance. There is a distinct region of slow reversed flow on the lee slope, and a strong local speed-up over the summit. There are also high speeds around the sides of the island. Although obscured by the close grouping of vectors, the flow on the summit was affected by local separation on some occasions;

this is the reason for having two summit sites, and also why the geostrophic wind, rather than the summit wind, is used as a reference. Apart from this, the overall consistency of the observations is very encouraging, and is a reflection of the idealised shape of the island.

In order to make the flow pattern more obvious, the observations were objectively analysed onto a rectangular grid by fitting a plane to the nearest six observations for each grid-point. A series of trajectories from a large number of starting positions were then calculated and plotted in Fig 5(a), illustrating the pattern of flow in a rectangle in the lee. The dashed line again indicates the base of the island. The pattern is very well defined, and shows two singular points, as discussed by Hunt et al (1978). There is a saddle-point just downstream of the island, and a nodal point of separation near the summit. The slight spiralling of the node appears on a number of pictures using different objective analysis schemes (i.e. - four or eight points instead of six), and seems to be a feature contained in the observations. There is a definite asymmetry in the pattern which shows more flow lines into the reversed flow region from the upper half; this may have some connection with the asymmetry in the nodal separation point. The asymmetry can also be seen in the aircraft data presented below, and is probably due to the geometric asymmetry of the island, and therefore depends on the actual positions of the measurements.

The observations of the surface flow seem sufficiently smooth for the calculation of the two-dimensional divergence field, and hence the normal velocity near the surface. Our main interest in the normal velocity centres on the saddle-point downstream of the island. It is not obvious whether this is a point of separation, as in the laminar flow situation, see eg Hunt et al (1978) or the numerical computations of Mason and Sykes (1979b), or a point of attachment. We are not aware of any direct measurements of the mean velocity in this type of flow, and the interpretation of smoke dispersion is very ambiguous, so it seems worthwhile estimating the normal

velocity from our observations. The divergence field, in dimensionless units, is shown in fig 5(b). Although the field is somewhat rough, it is negative throughout the region of interest, implying a normal velocity component away from the surface. Maximum numerical values are obtained at the nodal point of separation near the summit, indicating that the largest normal velocities occur there. However, it appears that the saddle-point is also a point of separation, although the normal velocity is smaller.

Fig 6 shows the anemograph traces from site 1 at the base of the island with a geostrophic wind of about 20 ms^{-1} which is slowly changing direction from a South-Westerly flow towards a North-Westerly flow. The wind at the site is initially constant in direction and has a speed of about 12 ms^{-1} . However, at 0640 when the geostrophic wind direction reaches about 290° , there is an abrupt change in the character of the wind at the site. The speed drops sharply to about 5 ms^{-1} , and the direction become highly variable. There is a maintained Easterly component but there are large deviations almost between Northerly and Southerly directions. The variations are not regular, but there appears to be a typical period of about 5 or 6 minutes in the trace. It must be emphasised that these oscillations are probably affected by the electrical smoothing of the signals which has a time constant of 1 minute. The oscillations are possibly indicate large-scale variations of the separated region, since the Strouhal number, $\omega L / U_0$, where ω is the frequency of the oscillation, L is a length scale, and U_0 is a velocity scale, is approximately unity if we take $L = 1 \text{ km}$ and $U_0 = 20 \text{ ms}^{-1}$. A more detailed study of the separation region would be necessary to reveal the time-dependent structure suggested here.

ii. Aircraft data

3

A series of flights were made along the sections shown in fig. 4 at heights of 80m, 160m, 320m, and 480m. These data were then used to obtain vertical sections along AA', BB', CC'. For each traverse across the flow, the velocities were normalised using the average wind from the extremities of the run where the flow is undisturbed by the island. The winds were recorded at 10 Hz, which gives a horizontal resolution of 10 m at an airspeed of 100 ms^{-1} , but each traverse effectively gives an instantaneous realisation of the turbulent velocity field. The data were averaged into 1s blocks to remove some of the small-scale fluctuations, giving a horizontal resolution of about 100 m, and several flights along each section were also combined to give a better estimate of the mean velocity. Unfortunately, the positional data from the aircraft were not sufficiently accurate to allow the objective averaging of different flights; an accuracy of better than 100 m is necessary. In the results presented below, the mean fields are calculated by adjusting the horizontal coordinate so that a particular feature such as a minimum in the streamwise velocity component or a maximum in the vertical component coincided with the origin. This procedure was necessary on each height level, therefore vertical phase information is lost since the flow pattern is forced into vertical alignment.

The results from flight H291 on 23rd October 1978 are presented in Fig 7 (a)-(c). On this occasion the geostrophic wind direction was about 210° and the speed was 10 ms^{-1} . The duration of the flight was about 4 hours, and the wind remained nearly constant throughout the period. The upstream section AA' shows a slight reduction of about 20% in the streamwise component near the surface in the centre of the box, and a deflection of streamlines both over and around the island in the secondary flow vectors. As stated above, we cannot position the island accurately relatively to these plots, but it is reasonably clear that

the airflow is diverted around the obstacle. The secondary flow vectors in Fig 7 (a) also indicate that more air passes to the left of the island.

The exact positions of sections AA' and BB' are not known due to the inaccuracy of the positional data, but the two sections are certainly between 100m and 300m of the base of the island and further refinement seems unnecessary. The downstream cross section is shown in fig 9 (b), and there are clearly very large flow perturbations here. The streamwise velocity component shows a maximum reduction of about 70%, but is still positive therefore the section is downstream of the reversed flow region. The most striking feature in the secondary flow vectors is the very powerful vortex centred between 80m and 160m. The velocities in this circulation are about 50% of the mean wind outside the wake; this represents an extremely large velocity disturbance on a length scale of about 500 m across the flow. Finally fig 7 (c) shows the results from the section CC' which is about 2 km downstream of the island. The streamwise velocity has only recovered to about 50% of its undisturbed value, and there is still evidence of a vortex although it is not as powerful and its centre has moved upwards. It is worth noting that these features were evident in each of the runs comprising the averaged cross sections. The number of runs used to obtain the average on each level is indicated on the figure.

The principal feature in these observations is clearly the large vortex downstream of the island. This may be one of the horseshoe vortices produced by stretching of vortex lines in the upstream shear flow around the face of the bluff obstacle as described in the review by Sedney (1973). In symmetric aerodynamic flows, two vortices are produced giving a downdraught in the centre of the wake as vortex lines are stretched around both sides of the obstacle. However, the island is rather elliptical with a ratio of major to minor axes of about 1.5, and a wind from 210° encounters

an asymmetric obstacle. This will certainly produce some asymmetry in the wake, but it is not clear whether the observations are consistent with this mechanism. Alternatively, the vortex may be the bound vortex associated with the transverse lift force produced by flow past an asymmetric body, as in the case of an aerofoil. A detailed discussion of this mechanism is difficult in view of the marked flow separation which occurs. The three-dimensionality of the upstream boundary layer, i.e. the turning of the wind with height, is unlikely to be of significance in this context since the streamwise vorticity in the upstream flow is very much smaller than the vorticity in the downstream eddies.

Results from the other flights give some support to the hypothesis that the geometric asymmetry is responsible for the dominance of one vortex. Of the five flights, the wind direction on four occasions was between 210° and 250° and these four flights all give a clockwise rotating vortex. The fifth flight, H300, was executed on the 7th November when the geostrophic wind was 15 ms^{-1} from 140° . The cross-section through BB' from this flight is shown in fig. 8, and the vortex in this case is rotating in the opposite sense to the other four flights. The geometric asymmetry of the island is also reversed relative to the other occasions, therefore we have some further evidence that the single vortex is a consequence of the asymmetry of the island.

It is quite possible that the trailing vortex system which has been observed here is not a steady phenomenon, but may oscillate from side to side in some manner as suggested by the oscillations in the surface velocity in

the lee reported in the previous section. Owing to this possibility, it should be noted that the phase-averaging, as effectively carried out here, is necessary for the analysis of a small number of realisations widely separated in time, otherwise any movement of the flow pattern would 'smear out' the results over a wide area.

The general character of the flow described above is similar to that observed in the wind-tunnel model study of flow around the Rock of Gibraltar by Cook et al (1978). They also observed powerful horizontal roll-vortices generated by the topography which they suggested were due to the lifting body mechanism. The structure was very dependent on the incident wind direction due to the relatively complex shape of the topography. Two flow visualisation techniques were employed in their study, namely soap bubble tracers and oil film on the surface, and these give some qualitative information about the mean flow. Also, some mean velocities and turbulence energy levels measured with hot wire anemometry are presented. but as the authors point out, these values are not reliable

in regions of highly disturbed flow since the response of the hot-wires only accounts for a $\pm 40^\circ$ variation in the flow direction. Cook et al definitely observed downward motion downstream of the obstacle, but this does not necessarily conflict with the view expressed in the previous section that the vertical component is upward from the saddle-point immediately downstream of Ailsa Craig. There is a strong downward motion in the vortices measured by the aircraft, so flow is eventually brought towards the surface, and this is possibly what was observed by Cook et al. In the wind-tunnel study, it was not possible to accurately measure velocities very close to surface in the reversed flow region.

iii. Balloon-based measurements

Our initial intention was to fly the balloon system as frequently as possible and to obtain turbulence statistics for all wind directions. However, once on the island, it quickly became apparent that when the upstream wind was in a sector roughly between SW and NW, the turbulence in the lee of the island was of sufficient scale and intensity as to make balloon-flying dangerous. Consequently, useful data was only gathered on three occasions, and the mean flow data for these cases are summarised in fig. 9. It can be seen that all three cases give data from the flow almost directly to the side of the island. The direction measured by the balloon system is not very different from the geostrophic wind direction, and there was no consistent mean wind shear with height in these results. Furthermore, the magnitude of the measured heat flux never exceeded 20 W m^{-2} in any of the three measurement periods, which coupled with the mean wind speeds indicates the existence of a near-neutral boundary layer. Estimates of the Monin-Obukhov length are of the order of several kilometres. During daylight hours, the 1 m temperatures measured on the island never varied much from the sea-surface temperature, both usually in the range 10° - 12°C , providing further evidence of the neutral boundary layer.

With regard to the errors involved in the balloon system measurements, Readings and Butler (1972) have shown that when the turbulence probe was mounted on a fixed support, the mean quantities, variances, and covariances agreed well with those obtained using sonic anemometry. Further measurements were made by Haugen et al (1975) to determine the effects of balloon cable motion on the derived turbulence statistics. Their conclusions were that the horizontal velocity variances derived from a balloon-mounted probe were 30% too large while the vertical velocity variance was 10% low. Their results were obtained using a large (1300 m^3) balloon; for the small balloon used in this study (150 m^3) the errors could be slightly worse.

A further anomaly, probably due to the relatively high turbulence levels, became apparent upon analysing the data gathered at Ailsa Craig; this is best discussed in relation to the spectra. Fig. 10(a) shows typical spectral analysis of the velocity components obtained on the 20th October. With the possible exception of small spurious peaks around 1 Hz, the spectra all show well-defined shapes. Fig. 10(b) gives similar data obtained on the 6th November when the wind speed was $10-12 \text{ ms}^{-1}$, roughly twice that on the 20th October. There are pronounced peaks at 0.2 and 1 Hz. The higher frequency peak is probably due to oscillations of the front arm which holds the sensors, while the origin of the lower frequency peak is still uncertain. This latter peak is most obvious in high wind speed cases, and has been noted before even over flat terrain and with large balloons. It has been estimated that these two peaks contribute 5, 25 and 30% of the u, v and w variances respectively, and all the turbulence statistics presented below for high wind speed cases have been reduced by this amount. The results still contain errors of uncertain magnitude due to balloon motion, but the effects to be discussed are so pronounced that errors much larger than those already described would not invalidate the conclusions.

For the purposes of analysis, each time series was divided into 6.8 minute periods (corresponding to 8192 points at 20 Hz) from which a linear trend was removed to leave the fluctuating quantity. Since the usual length of a run is about 30 minutes at each height, this procedure will normally generate four or five estimates for any statistic. On the graphs presented below, the mean of these estimates is plotted, together with a bar indicating the extreme values which give an indication of statistical reliability. It should be emphasized that due to the limited amount of data collected, we have not plotted the results as a function of geostrophic wind direction, but have grouped together data corresponding to a spread of about 40° in wind direction. Much of the scatter on the graphs may thus be a consequence of the angular variation of mean quantities. For comparison purposes, data obtained over the sea by Pennel & LeMone (1974) and Nicholls (1978) is also shown.

Although the Ailsa Craig data are scattered, the turbulence levels in the flow around the side of the hill, as measured by the velocity variances normalised with the geostrophic wind, are greater than the corresponding values measured by Pennel and LeMone, and Nicholls. The difference is very marked in the v (across-wind) component variance, as can be seen in Fig. 11(a) which gives the ratio of across-wind to along-wind variances $\overline{v'^2}/\overline{u'^2}$. The increase in the ratio at mid-levels is due mainly to additional energy in the across-wind component. Such an increase in energy is consistent with a 'rapid-distortion' of the turbulence as described by Britter et al (1979). They have shown that in a two-dimensional flow over a ridge, the vertical component of the turbulence energy is increased, while the streamwise component is decreased; in our three-dimensional flow, we would expect an increase in the cross-wind component around the side of the hill. Unfortunately, we do not have estimates of the upstream turbulence levels with which to test this hypothesis. Another possible explanation is that the instruments were in a region affected by the strong secondary flow.

The vertical variations of $\overline{u'^2}/u_g^2$ and $\overline{w'^2}/\overline{u'^2}$, shown in figs 11(b) and (c), also suggest an increased amount of turbulence energy, but the differences from the data in homogeneous conditions is less marked. The scatter in the $\overline{u'^2}$ profile makes it difficult to draw any firm conclusions, but it is clear that $\overline{u'^2}$ is not increased nearly as much as $\overline{v'^2}$.

One final feature of the turbulence measurements which deserves comment is the occasional absence of the usual $2/3$ power fall off at high frequencies.

The effect does not appear to be instrumental, and may be related to the distortion of the turbulence by the hill. Similar qualitative effects have been observed in highly distorted flows in the wind-tunnel by Bearman (1972).

Conclusions

Observations of the flow around a steep, isolated, three-dimensional hill have been presented. Several interesting features of the separated flow are apparent in the results, and have been reliably measured. The mean velocity near the surface, as measured with cup anemometers and wind vanes, produces a coherent picture of the flow around the obstacle and the reversed flow and separation on the downstream side. The tangential velocity field was sufficiently well-defined to permit the surface divergence field to be derived, which gives an indication of the normal velocity component near the surface. These results suggest that both singularities in the surface flow field are separation points, as in the case of laminar three-dimensional separation at moderate Reynolds number.

Aircraft observations revealed a very powerful trailing vortex downstream of the obstacle, with its axis oriented along the upstream wind direction, and circulation velocities of the same order of magnitude as the undisturbed horizontal speed. In all our observations there is only one vortex in the wake; this appears to be due to the asymmetry of the shape of the island.

Finally, although we were only able to gather turbulence data from the flow around the side of the island, the balloon system results have indicated that the turbulence structure is highly distorted from the equilibrium situation. In the flow around the side of the hill, the cross-wind component of turbulence energy is greatly increased.

There were many problems encountered during the course of the experiment on Ailsa Craig, and the data collected were not as complete as originally hoped. However, the experiment has been of great value not only from the point of view of the encouraging and interesting flow field measurements obtained but also as a source of experience with the difficulties associated with such measurements. This experience will be valuable in the planning of future experiments, and will undoubtedly lead to more accurate and comprehensive data sets. It is clear that with a suitable choice of topography, atmospheric observations are not only of interest in themselves but are capable of throwing a great deal of light on the general problem of flow over obstacles.

Legends

- Figure 1 Areal photograph of Ailsa Craig looking towards the North-East
- Figure 2 Schematic illustration of surface site positions; (a) plan view, (b) elevation.
- Figure 3 The flight plan for aircraft measurements; runs made along the three tracks perpendicular to the main wind at four different heights
- Figure 4 Mean dimensionless surface flow vectors from anemometers at 4 m. The dashed circle denotes the base of the hill, and the unit vector on the left represents the geostrophic wind which is the reference velocity for the observations.
- Figure 5(a) Objectively-analysed flow pattern from the central area of the results shown in fig.5.
- (b) Divergence of the objectively-analysed velocity field in arbitrary units.
- Figure 6 Wind speed and direction traces from the anemograph at site 1 on the 24th October.
- Figure 7 Mean velocity fields in vertical sections from aircraft observations. on 23rd October. The three sections (a) AA', (b) BB', (c) CC' are defined in fig 4. In each figure, the upper field is a contour plot of the dimensionless streamwise velocity component, i.e. normal to the section. The contour interval is 0.1, and dashed contours denote values less than 1. The lower field shows the secondary flow vectors in the transverse section, and the length of the arrow is proportional to the velocity. The arrow at the top of the box shows the length of the arrow corresponding to unit speed, i.e. the mean streamwise wind speed remote from the hill. The numbers to the right of the box indicate the number of runs used to obtain the average, and the heights are on the left. Tick marks on the bottom of the box indicated a horizontal spacing of roughly 100m
- Figure 8 The section along BB' of fig. 4 from aircraft observations on 7th November. Details of the figure are as in fig. 7.
- Figure 9 Summary of occasions when turbulence data was gathered by the balloon-based system.
- Figure 10 Velocity spectra from (a) 20th October, (b) 6th November.
- Figure 11(a) Vertical profile of $\sqrt{v'^2} / \bar{u}^2$ from balloon-based measurements. The solid line represents the observations of Pennel and LeMone, and circled crosses are values obtained by Nicholls (1978).

- (b) Vertical profile of $\overline{u'^2} / u_g^2$, where u_g is the geostrophic wind.
- (c) Vertical profile of $\overline{w'^2} / \overline{u'^2}$.

References

- Bearman, P.W. (1972) 'Some measurements of the distribution of turbulence approaching a two-dimensional body.' *J.Fluid.Mech.* 53, 457-468.
- Britter, R.E., Hunt, J.C.R., and Richards, K.J. (1979) 'Airflow over a two-dimensional hill: studies of velocity speed-up, roughness effects and turbulence.' Submitted to *Quart.J.Roy.Met. Soc.*
- Caughey, S.J. (1977) 'The Cardington turbulence instrumentation.' Unpublished Meteorological Office, Turbulence and Diffusion Note No.62.
- Cook, N.J., Coulson, B.H., and McKay, W. (1978) 'Wind conditions around the Rock of Gibraltar.' *J.Ind.Aerodynamics*, 2, 289-309.
- Deaves, D.M. (1975) 'Wind over the hills: a numerical approach.' *J.Ind.Aerodynamics*, 1, 371-391.
- Haugen, D.A., Kaimal, J.C., Readings, C.J. and Rayment, R. (1975) 'A comparison of balloon-borne and tower mounted instrumentation for probing the atmospheric boundary layer.' *J.Appl.Met.* 14, 540-545.
- Hunt, J.C.R., Abell, C.J., Peterka, J.A. and Woo, M. (1978) 'Kinematical studies of the flows around free or surface-mounted obstacles; applying topology to flow visualisation.' *J.Fluid.Mech.* 86, 179-200.
- Jackson, P.S. and Hunt, J.C.R. (1975) 'Turbulent wind flow over a low hill.' *Quart.J.Roy.Met.Soc.* 101, 929-935.
- Jones, J.I.P. (1965) 'A portable sensitive anemometer with proportional D.C. output and a matching wind velocity component resolver.' *J.Sci.Inst.* 42, 414-417.
- (1970) 'A new recording wind vane.' *J.Phys.E.* 3, 414-417.
- Mason, P.J. and Sykes, R.I. (1979a) 'Flow over an isolated hill of moderate slope.' *Quart.J.Roy.Met.Soc.* 105, 383-395.
- (1979b) 'Three-dimensional numerical integrations of the Navier-Stokes equations for flow over a surface-mounted obstacle.' *J.Fluid Mech.*, 91, 433-450.

- Nicholls, S. (1978) 'Measurements of turbulence by an instrumented aircraft in a convective atmospheric boundary layer over the sea.' Quart J. Roy. Met. Soc. 104, 653-676.
- Pennell, W.T. and LeMone, M.A. (1974) 'An experimental study of turbulence structure in the fair weather trade wind boundary layer.' J. Atmos. Sci. 31, 1308-1323.
- Readings, C.J. and Butler, H.E. (1972) 'The measurement of atmospheric turbulence from a captive balloon.' Met. Mag. 101, 286-298.
- Sedney, R. (1973) 'A survey of the effects of small protuberances on boundary layer flows.' AIAA Journal 11, 782-792.
- Sykes, R.I. (1980) 'An asymptotic theory of incompressible turbulent boundary layer flow over a small hump.' Submitted to J. Fluid Mech.
- Taylor, P.A. (1977) 'Numerical studies of neutrally stratified planetary boundary layer flow above gently topography. I: two-dimensional case.' Boundary-Layer Met. 12, 37-60.
- Taylor, P.A. and Gent, P.R. (1974) 'A model atmospheric boundary layer flow above an isolated two-dimensional hill: an example of flow above gentle topography.' Boundary-Layer Met. 7, 349-362.

Acknowledgements

The experiment was made possible through the joint efforts of many people and, while we acknowledge some contributions specifically, we would like to take this opportunity to thank everyone involved.

We must first acknowledge the kind permission of the Marquis of Ailsa to work on the Island. H.M.S. Gannet, Prestwick and the Joint Air Transport Establishment, Brize Norton undertook the responsibility for airlifting both inexperienced personnel and many awkward loads to and from the Island. Without their enthusiastic support the experiment would not have been possible. While on the Island the light house keepers and the Northern Light House Board provided us with help, facilities and encouragement. The Met. Research Flight and MOD Procurement Executive, Cardington (who manned and flew the balloon system) must be commended for working in what can only be described as dangerous levels of turbulence.

We must also express our appreciation for help received from many branches of the Meteorological Office. In particular staff from the Meteorology Division, Forton and the Meteorological Research Unit, Cardington prepared the instrumentation and expended much energy in keeping it serviceable and calibrated. Finally our special thanks are due to Miss P Ward who bore the burden of the data processing involved in the surface and aircraft observations.

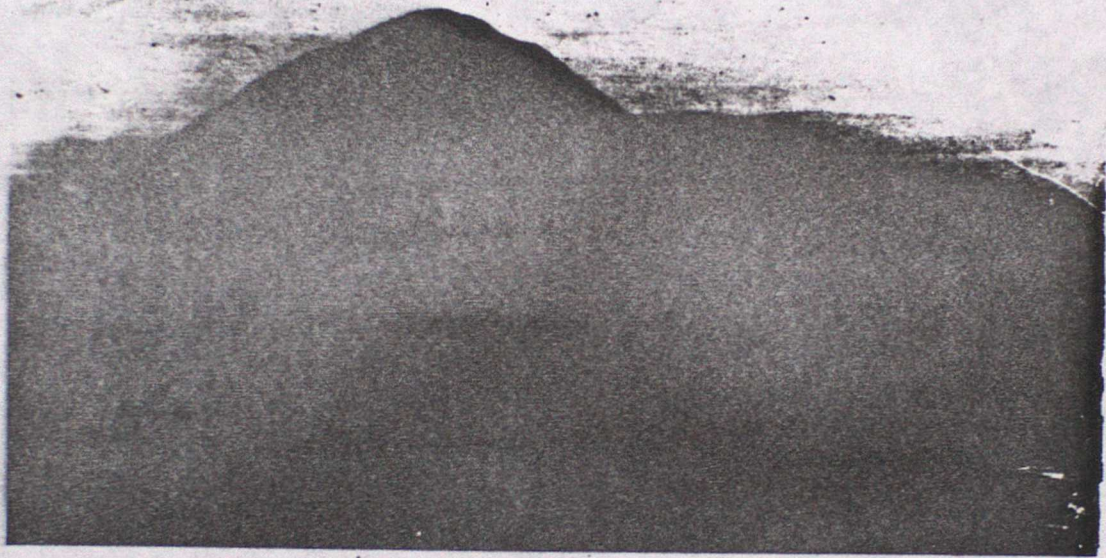


Fig. 1

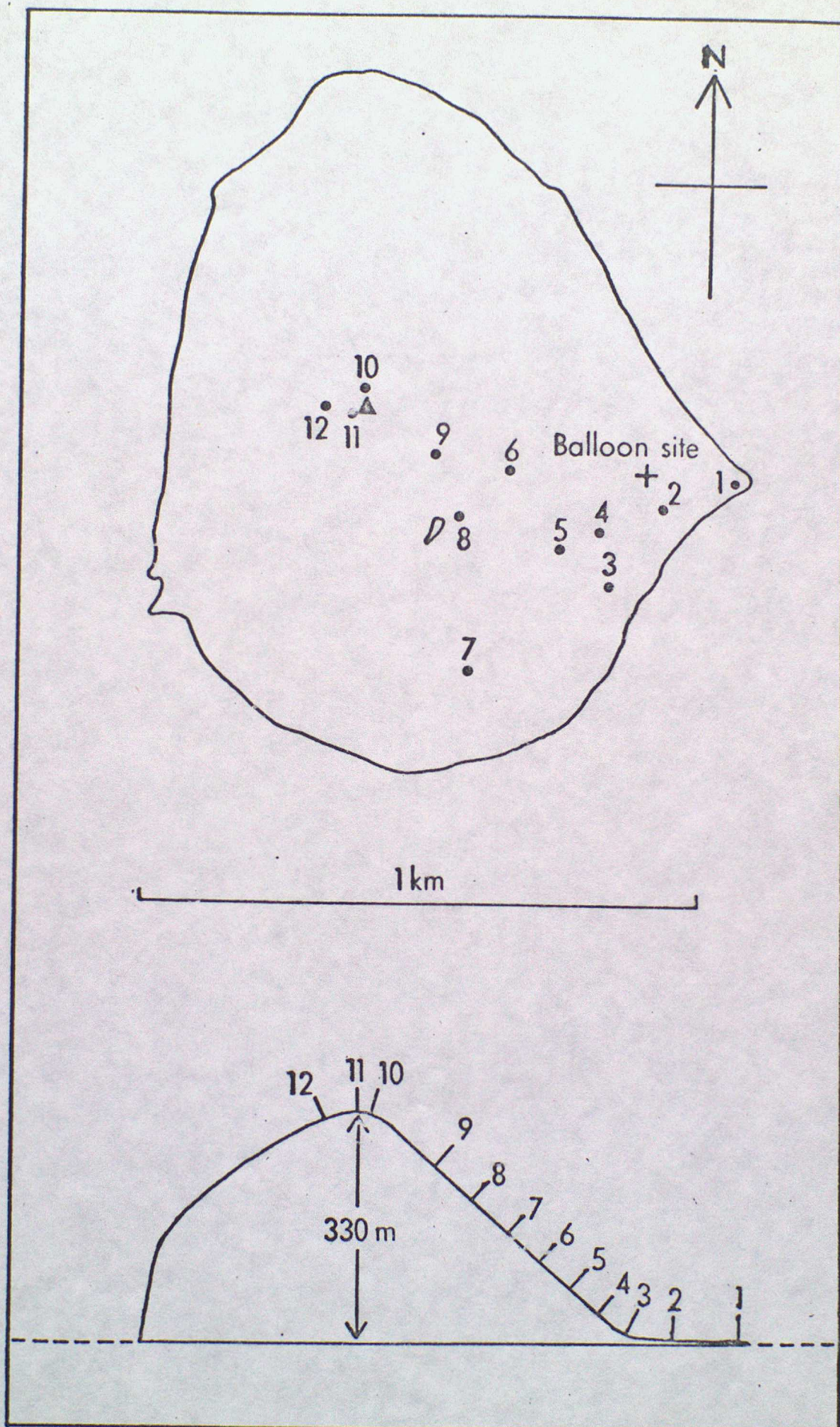


Fig. 2

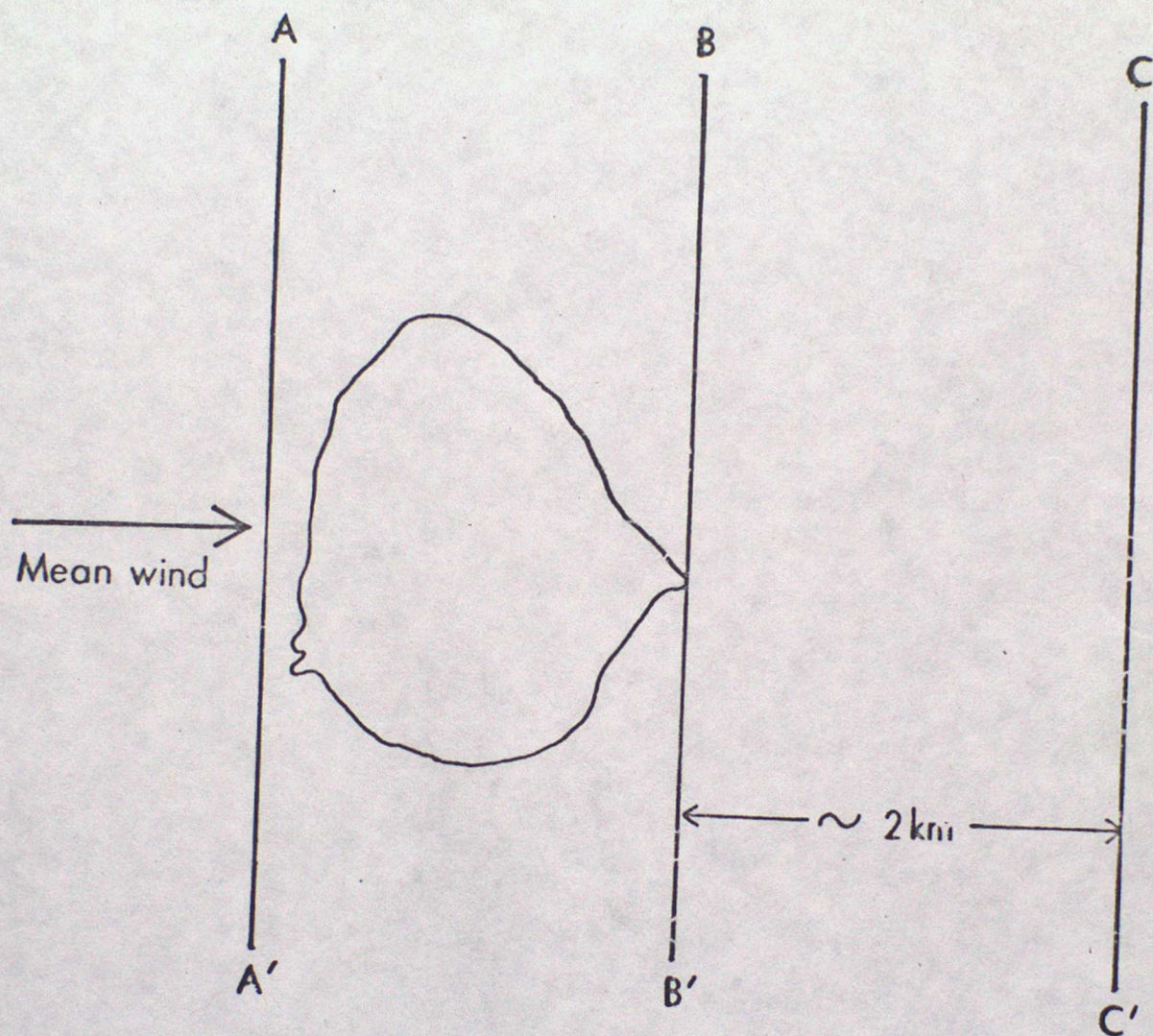


Fig 3

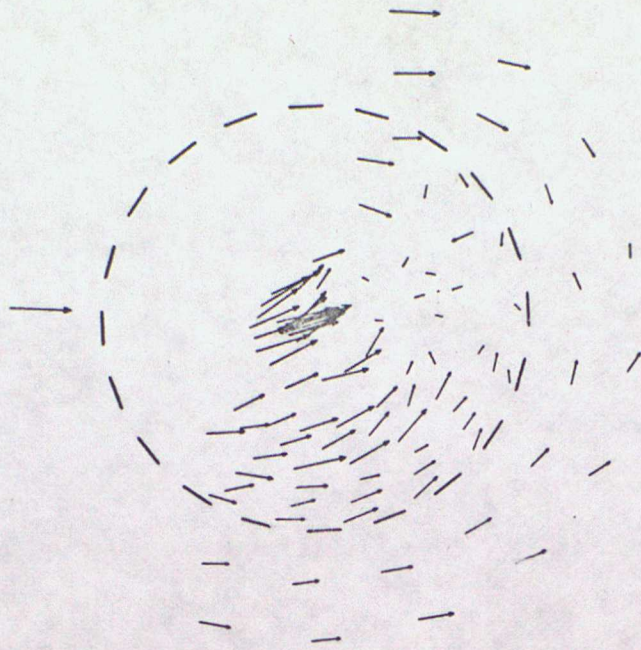


Fig 4

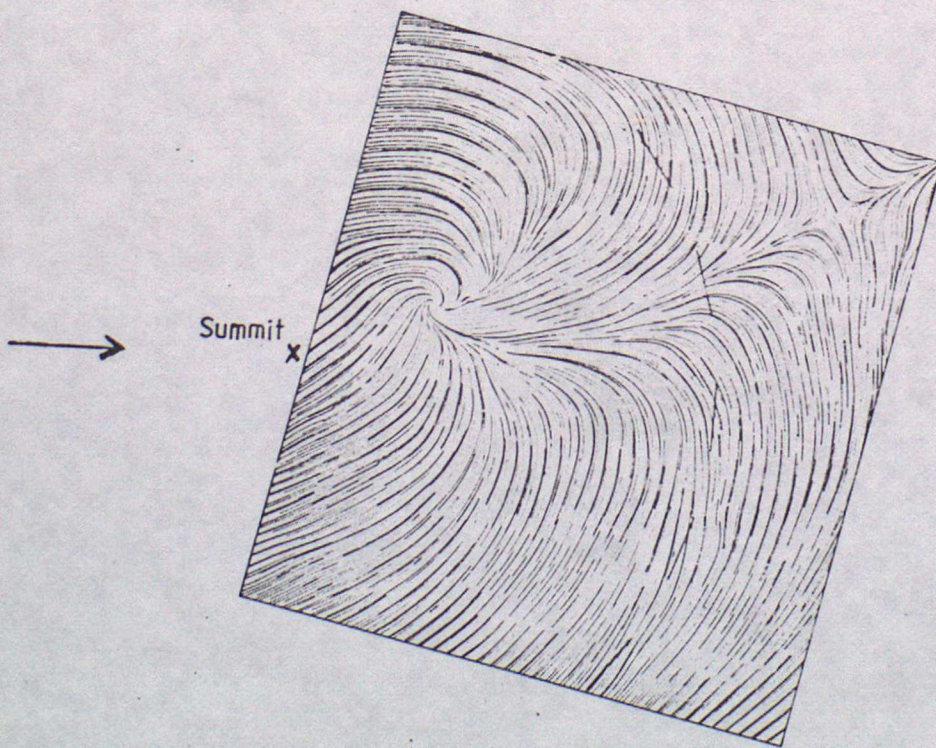


Fig. 5(a)

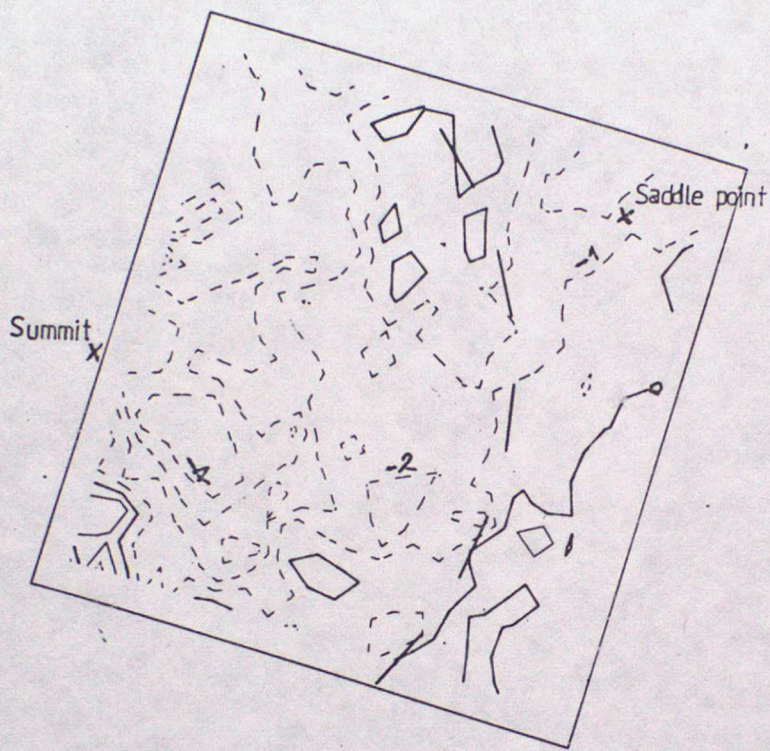


Fig. 5(b)

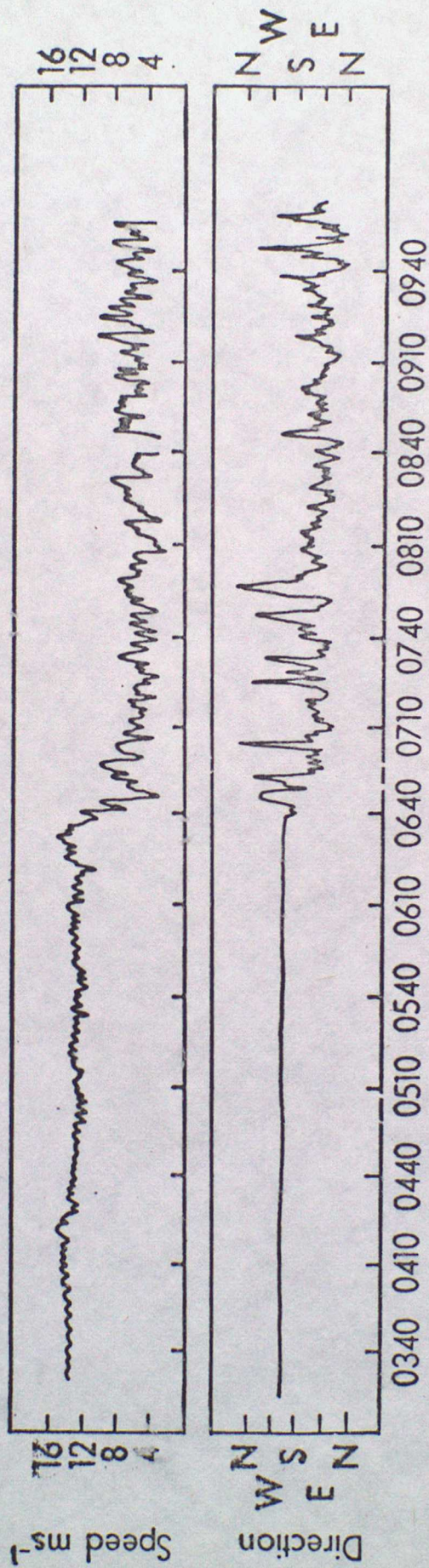
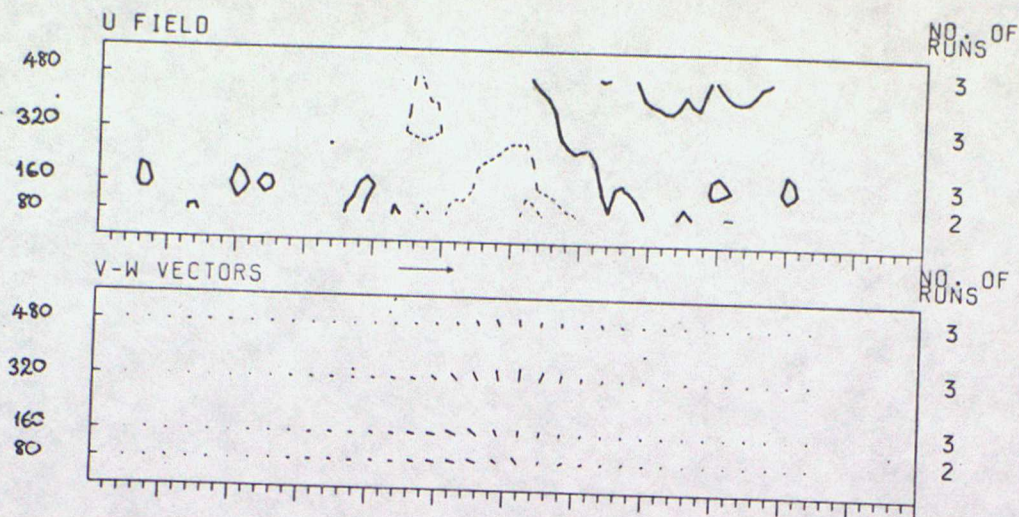
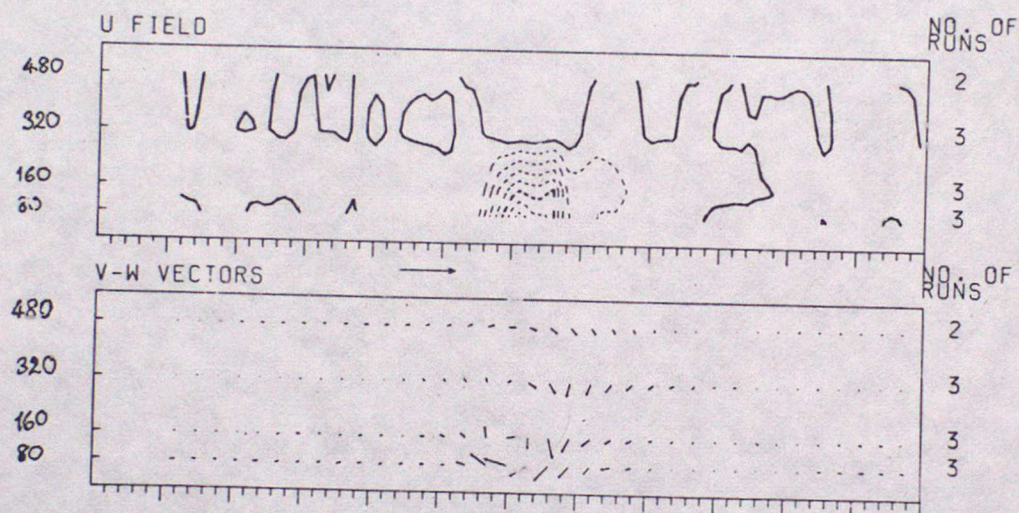


Fig. 6

a)



b)



c)

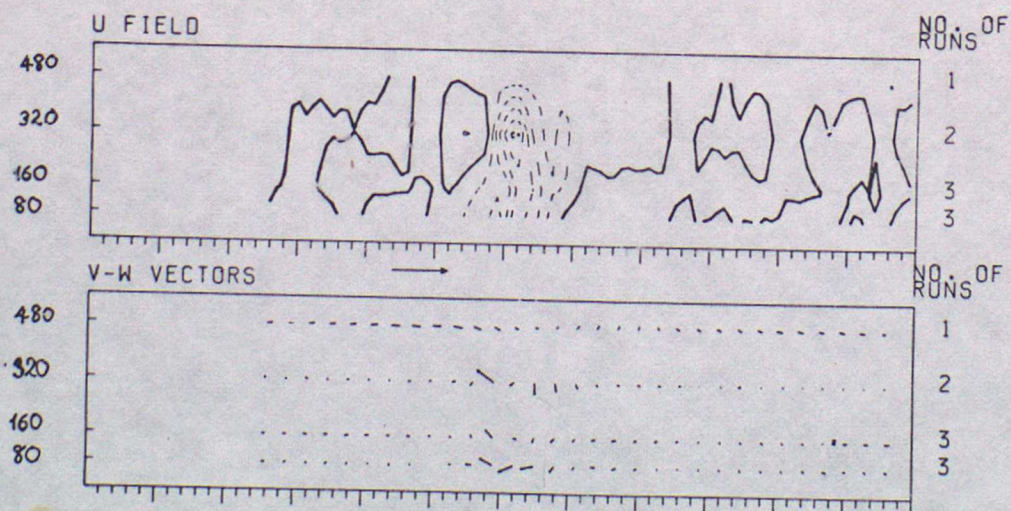


Fig 7

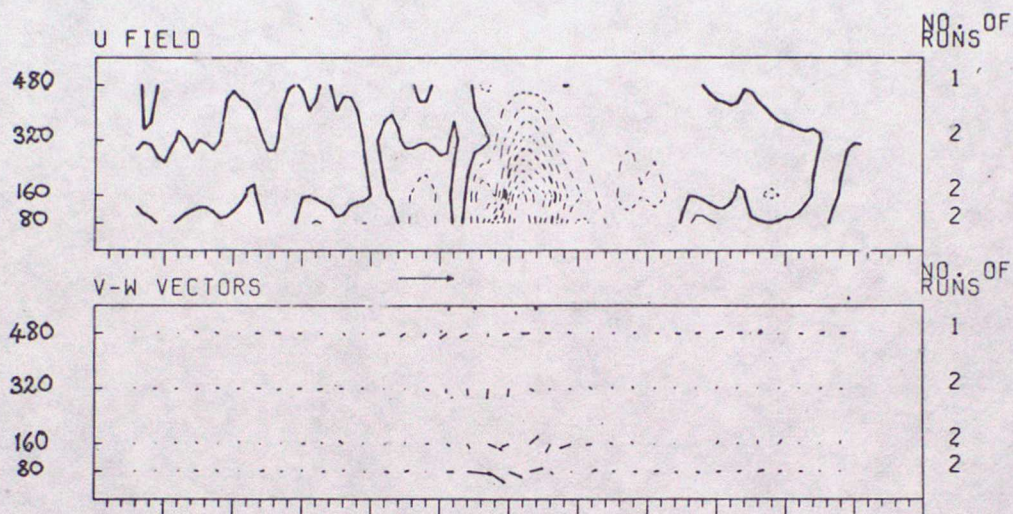


Fig. 8

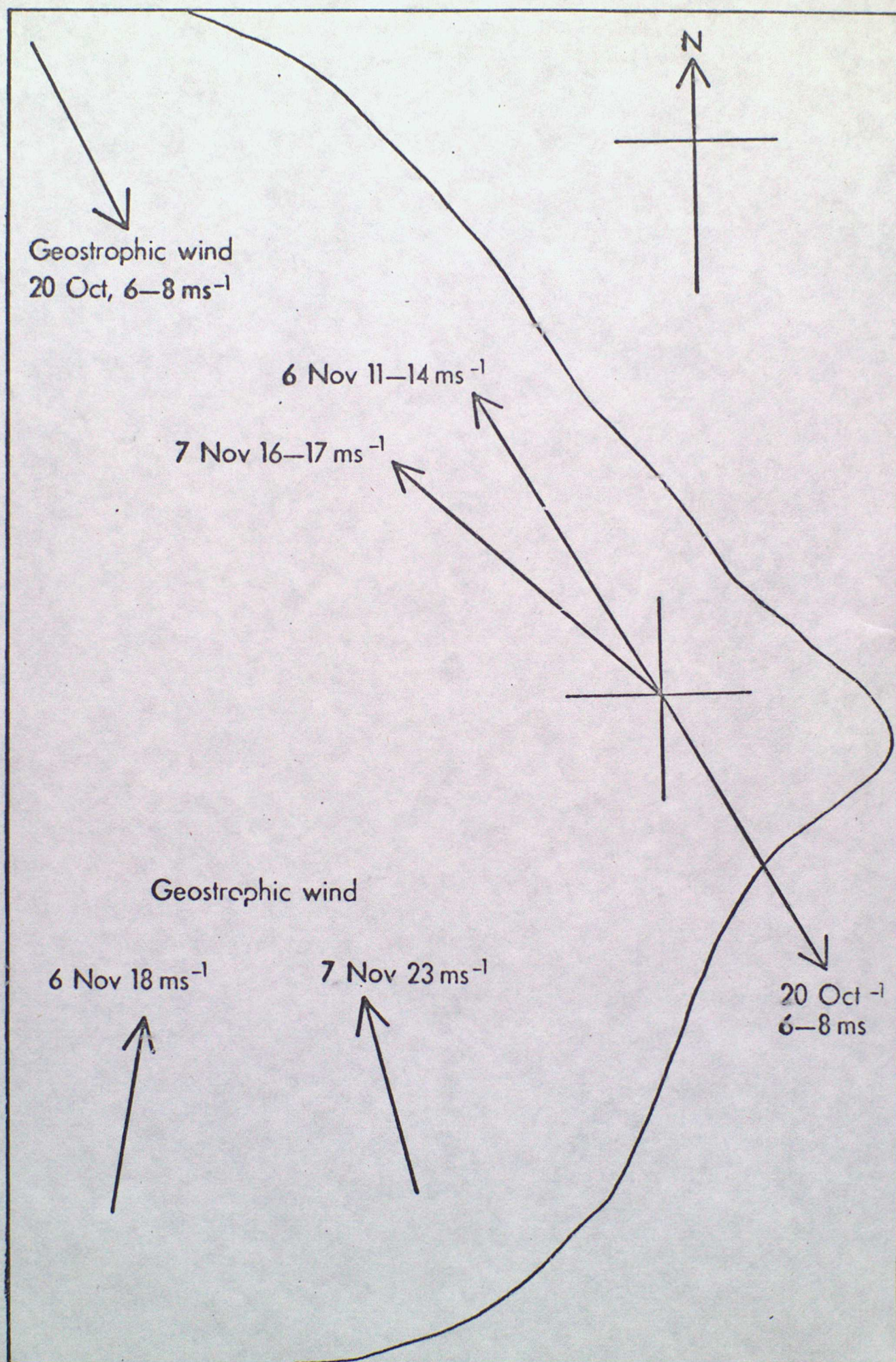
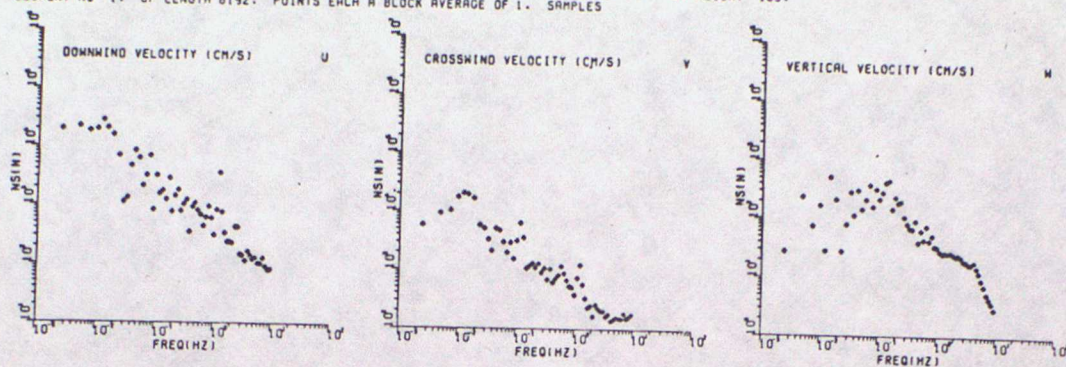


Fig. 9

(a)

AILSA CRAIG 20TH OCT RUN F
SEGMENT NO 1. OF LENGTH 8192. POINTS EACH A BLOCK AVERAGE OF 1. SAMPLES

PROBE NO 1. AT HEIGHT 185.



(b)

AILSA CRAIG 6TH NOV RUN G
SEGMENT NO 1. OF LENGTH 8192. POINTS EACH A BLOCK AVERAGE OF 1. SAMPLES

PROBE NO 1. AT HEIGHT 1.

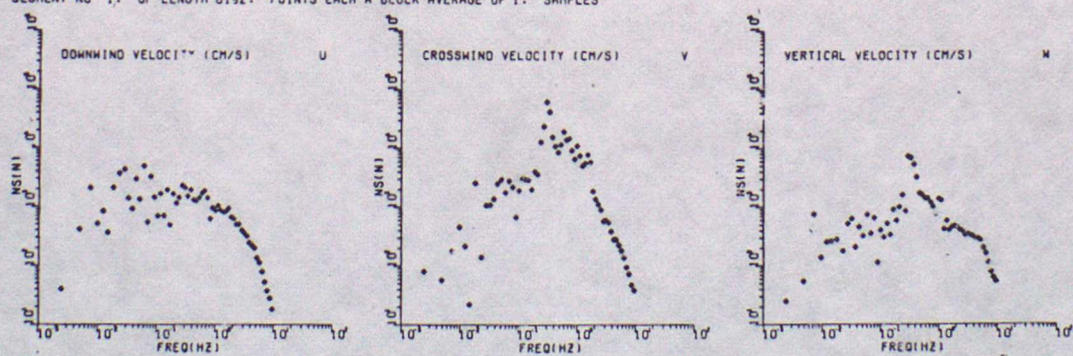


Fig 10

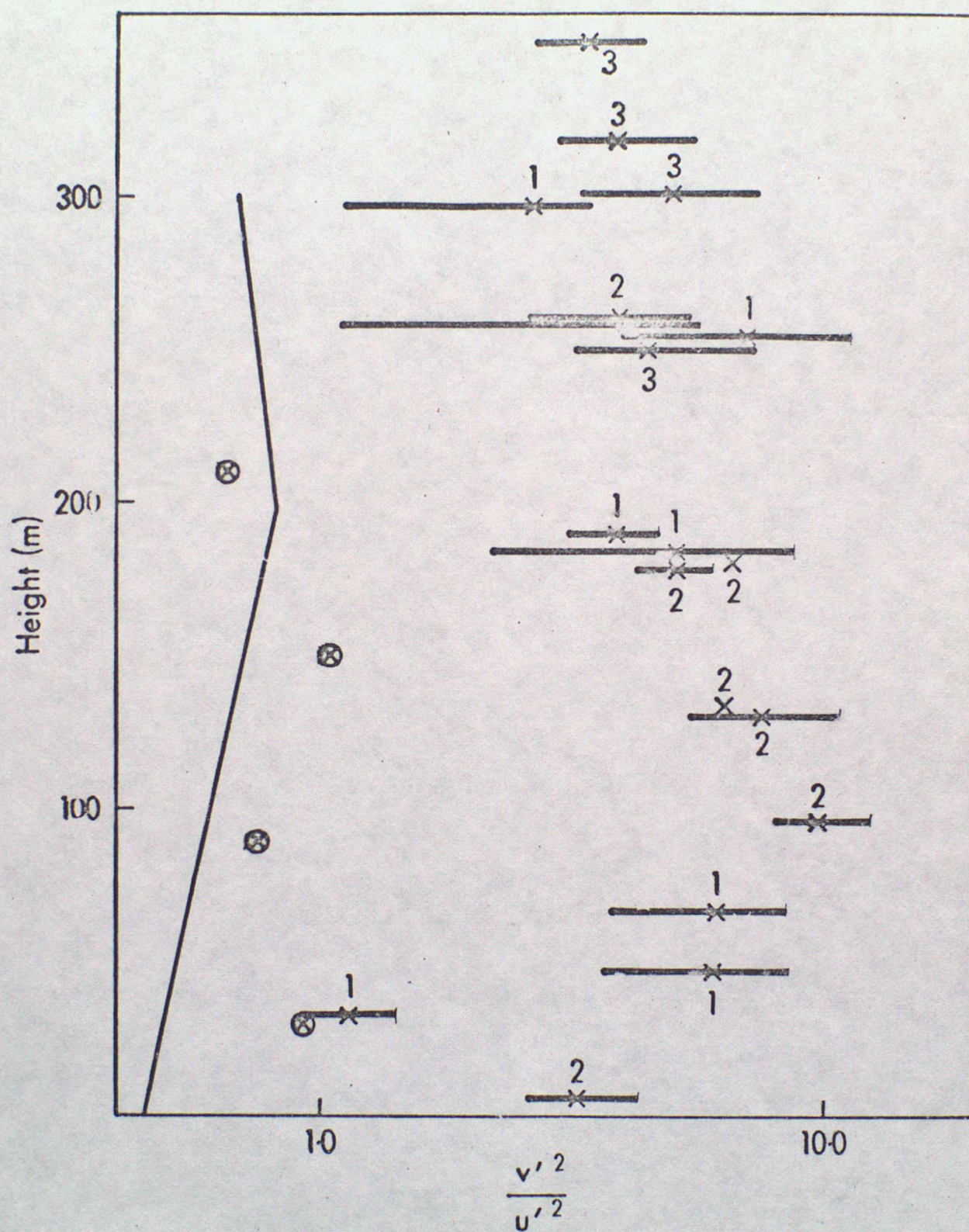


Fig. 11(a)

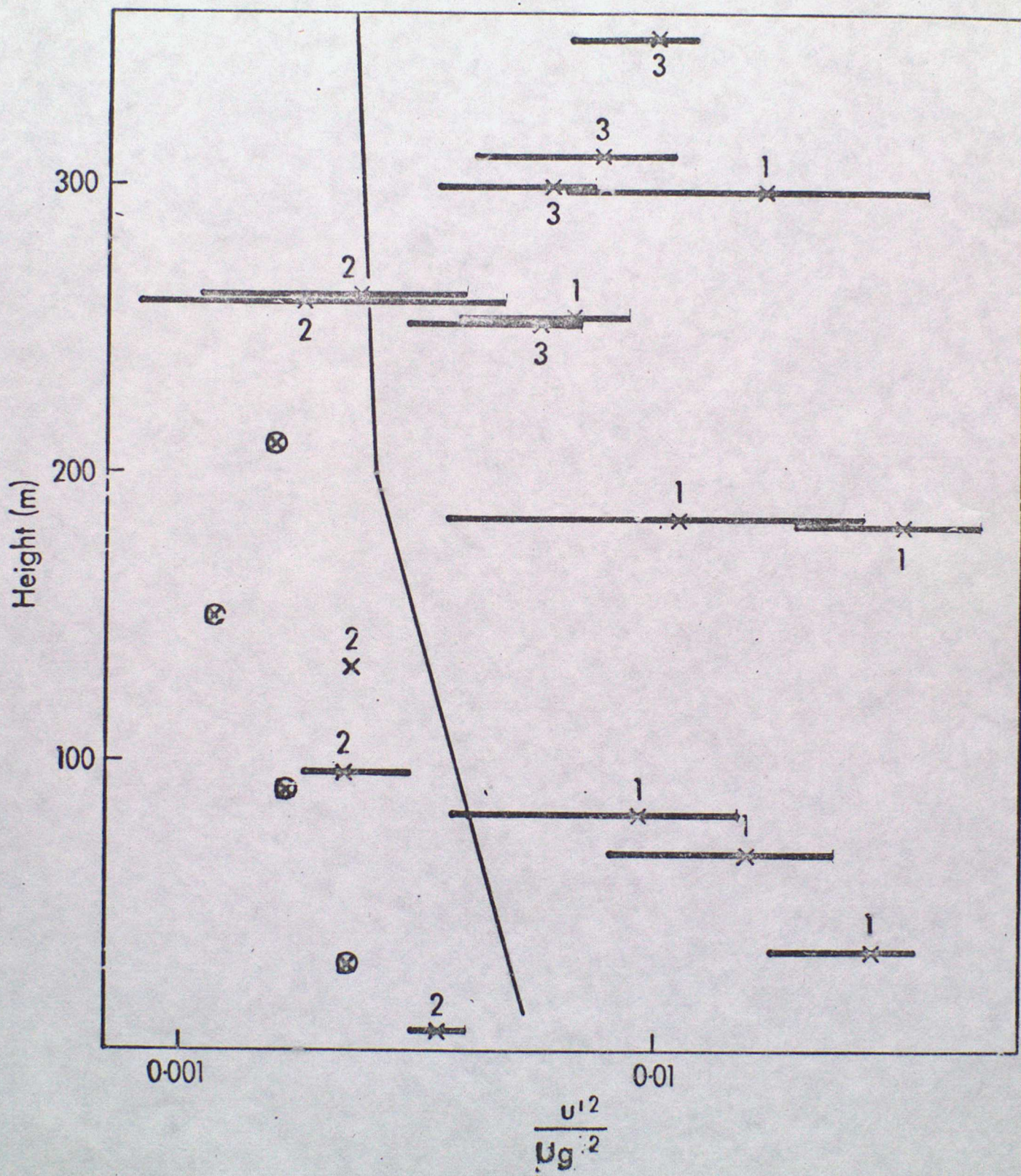


Fig. 11 (b)

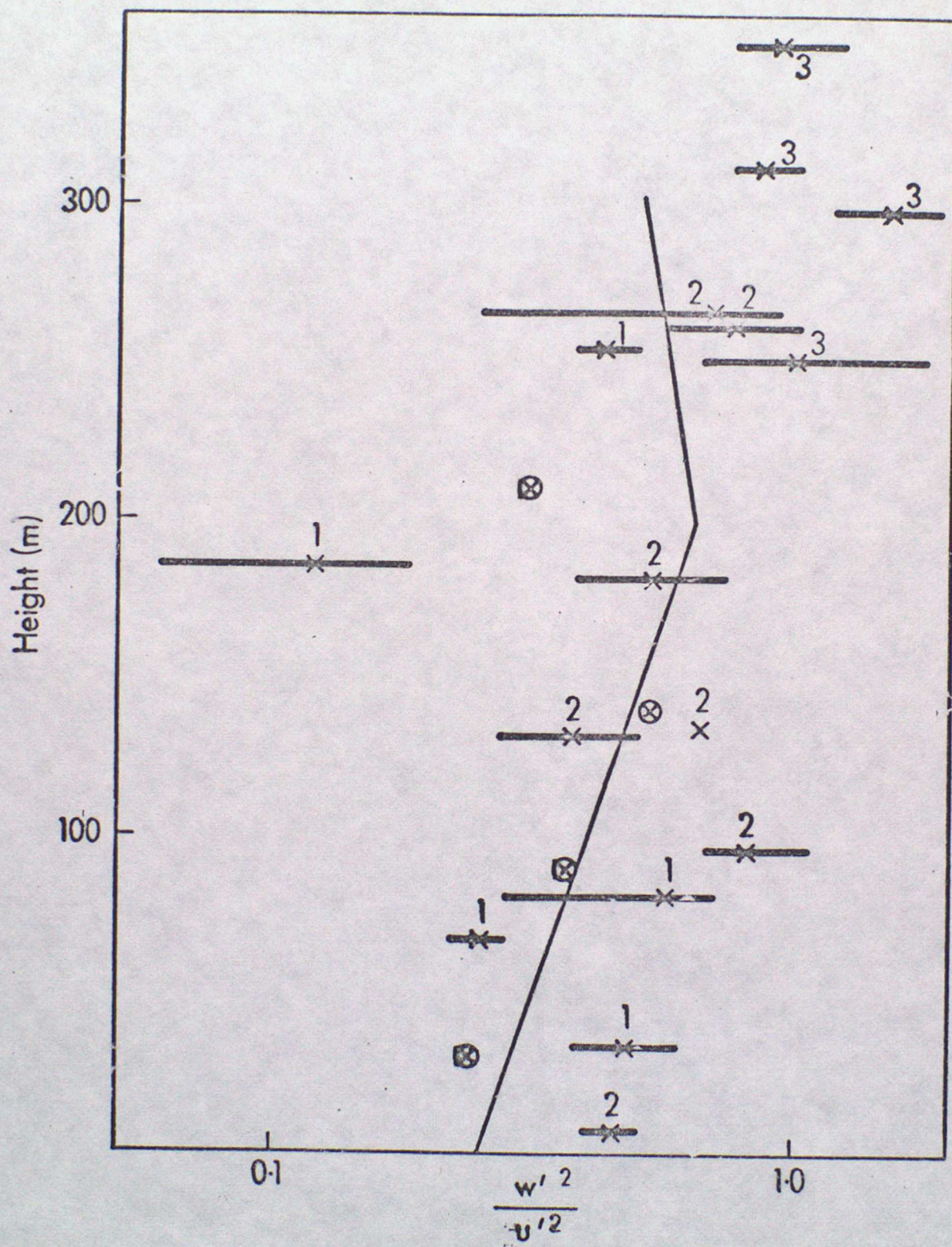


Fig. 11(c)