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Acoustic sounding of the atmospheric boundary layer at Halley, Antarctica

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Abstract: The records obtained from a monostatic acoustic sounder run at Halley, Antarctica, have been analysed with the use of data from instruments on a 32 m mast and from radiosonde ascents. Echoes representing ground-based layers, waves, and shallow gravity currents are discussed. The spiky ground-based echo is related to a westerly surface wind, whilst a layered wavy flow is related to surface easterlies. Such relationships are consistent with the sloped inversion wind regime at Halley.

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Introduction

During 1986 the British Antarctic Survey ran the Stable Antarctic Boundary Layer Experiment (STABLE) at Halley. Antarctica (75°36'S, 26°40'W) with the aim of studying turbulence and waves in the stably stratified surface layer. Halley is situated on the relatively uniform Brunt Ice Shelf, 40 km north-west of the nearest irregular terrain as shown in Fig. 1. Strong stable stratification of the boundary layer persists at Halley throughout the winter months, and so it is a good site for such an experiment. However, the slight slope of the Brunt Ice Shelf, which is discussed in the next section, and the proximity of the Weddell Sea coast of the ice shelf, only 10 km to the west, introduce some complexity into the wind and temperature regime at Halley which is apparent in the results discussed below. Part of the instrumentation installed for STABLE was a monostatic acoustic sounder (SODAR). In this paper the output from the SODAR is discussed. Results from other aspects of STABLE can be found in King *et al.* (1987), Rees & Mobbs (1988), King *et al.* (in press) and Mobbs & Rees (1989).

SODAR has been used extensively as a method of investigating atmospheric structure since the late 1960s. The technique involves sending a relatively narrow pulse of sound up into the atmosphere at regular intervals. The sound is scattered by centimetric scale temperature inhomogeneities associated with past or present turbulence, fronts, inversion lids, etc. and the backscattered soundwaves are detected by a receiver at the ground and displayed as a time-height record. In this way a picture of the evolution of thermal structure is built up pulse by pulse. An introduction to acoustic sounding of the atmosphere is given by Holmes *et al.* (1976).

The Halley SODAR was manufactured by Sensitron and operated at a peak electrical power of 120 W and a frequency of 2300 Hz with a pulse length of either 30 or 120 ms. The majority of the output from the SODAR was in the form of facsimile charts which display echoes from a vertical range of 500 or 1000 m depending on the stylus sweep speed selected. The pulse rate was about one every 9 s but with a paper advance speed of only 30 mm per hour the records are very compacted in time and some structure is inevitably lost.

A fault with the SODAR meant that throughout STABLE the lowest 30 to 40 m of the facsimile charts were completely blacked out. The fault was rectified towards the end of 1986 and the SODAR remained operational at Halley for another

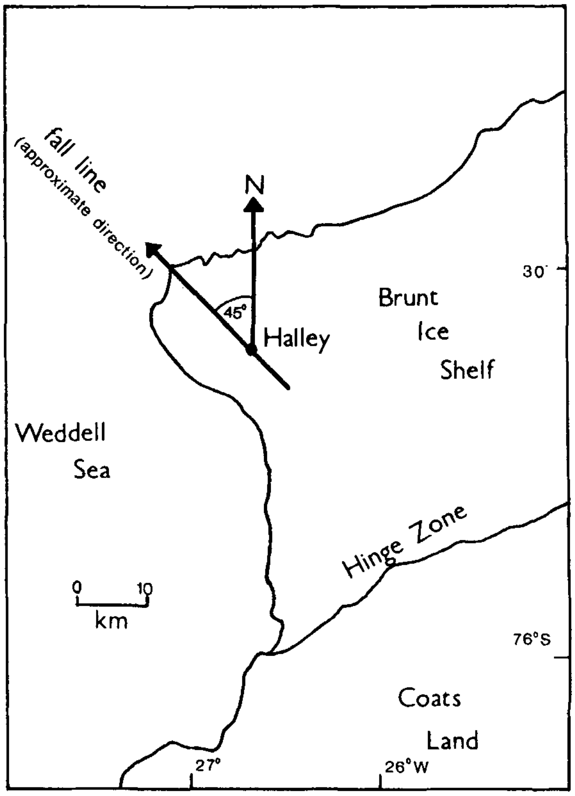


Fig. 1. A sketch map showing the location of Halley station on the slightly sloping Brunt Ice Shelf. The Hinge Zone is the nearest irregular terrain to Halley.

year although the rest of the STABLE instrumentation was removed. The 1987 records have been included in this study despite the lack of corresponding conventional data.

There is generally a very low background noise level at Halley, and the charts usually show well-defined echoes against a very clean background. Wind noise, however, is a problem and wind speeds of over 8 ms^{-1} at the 8 m level generated enough noise to blacken the facsimile record completely. Consequently the SODAR was not operated during such periods. Between May and September 1986, the period when most of the STABLE measurements were made, the SODAR was not operating for about 40% of the time because of high wind speeds.

During the analysis of the SODAR records use was made of continuous paper chart records of 8 m wind speed and direction and 16–32 m temperature difference obtained from instruments on a 32 m mast. For some periods 10 min average data from the same instruments were available, and limited use was made of data recorded at 0.1 Hz. The routine radiosonde ascents carried out daily at Halley at 1200 Z, and some slow radiosonde ascents carried out especially for STABLE were also used in the interpretation of the SODAR records. A full description of all the STABLE instrumentation, its installation and its performance, can be found in King & Anderson (1988).

The sloped inversion wind

The Brunt Ice Shelf has a slope of about 1:500 (Thomas 1973) with the fall line making an angle of about 90° to the Hinge Line (Fig. 1). When a strong temperature inversion develops over such an extensive slope a horizontal pressure gradient develops. The effect of such a 'slope pressure gradient force' when balanced with friction, the Coriolis force, and the synoptic scale pressure gradient force is to constrain the surface wind to being easterly (Schwerdtfeger 1984, chapter 3) and to create a maximum, or low-level jet, in the wind profile. Westerlies cannot occur at the surface during strongly stably stratified conditions unless the geostrophic wind is westerly and large enough to dominate the slope pressure gradient force.

The importance of the sloped inversion wind is confirmed by observations made at Halley. Fig. 2 shows a plot of surface wind direction against 16–32 m temperature difference. It is apparent that there are two dominant wind directions, east and south-west to west. As stability increases, however, the wind direction becomes confined to a narrow band around 80°. King (1989) analysed the daily radiosonde ascents made at Halley throughout 1985. He found that, on average, the westerlies were colder and more stable than the easterlies, in contrast to the results for 1986 which have been discussed here. It should be stressed, however, that King's profiles were averages of several radiosonde flights, and that both easterlies and westerlies actually occur over a considerable range of surface temperatures. A study of individual temperature profiles obtained from radiosonde flights shows that is perfectly possible for an easterly flow to be both colder and more stable than a westerly. In spite of this fact there may be a real difference between the two years, perhaps due to variations in the amount of ice-cover in the Weddell Sea. An analysis of the 1986 radiosonde data should be carried out to investigate the problem further.

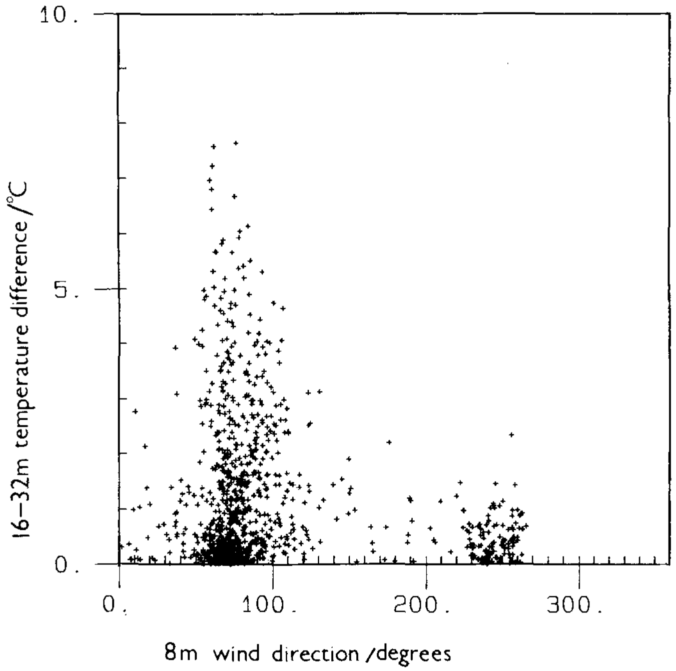


Fig. 2. Scatter plot of 16–32 m temperature difference against 8 m wind direction.

A survey of echo types seen on the Halley records

A typical 24-hour portion of the Halley SODAR charts reveals that the structure of temperature inhomogeneities in the stably stratified boundary layer at Halley is often very complex. There are often many reflecting layers displayed from ground level right up to the 1000 m maximum range of the SODAR. There may be rising and descending layers, some displaying waves, others having no apparent structure. Despite this complexity, a survey of the 1986 and 1987 charts reveals some echo types which are readily identifiable, and which appear relatively frequently. Some particularly clear examples of each of these types are discussed below.

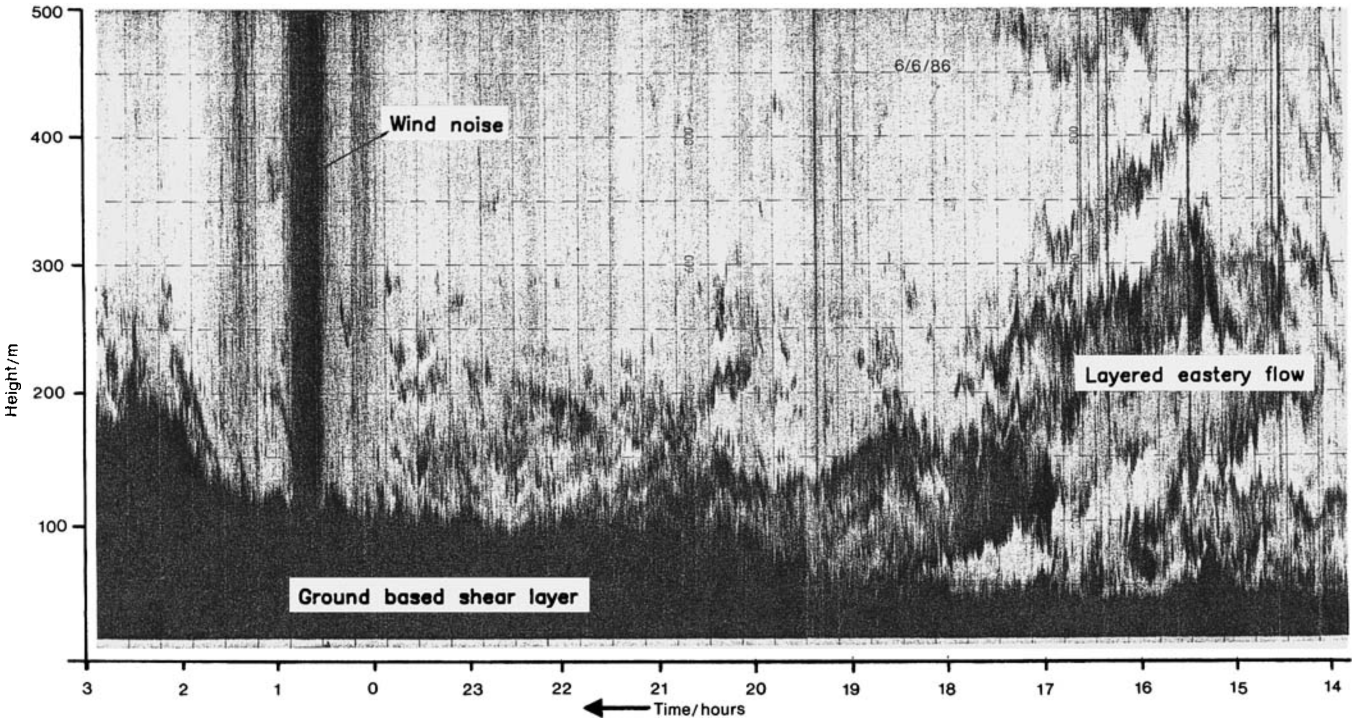
The ground-based shear layer

A criterion for the generation of turbulence is the size of the Richardson number (Ri) defined as

$$\mathrm{Ri} = \frac{g\,\frac{d\Theta}{dz}}{\Theta\,|\frac{dU}{dz}|^2}$$

where potential temperature Θ and wind U are measured as functions of height *z*. If the value of Ri falls below 0.25 laminar flow becomes unstable to wave formation and the onset of turbulence. Such turbulence can be maintained as long as the value of Ri remains smaller than 1. If turbulence is to be generated in strongly stably stratified conditions (i.e. large $d\Theta/dz$) the wind shear (dU/dz) must be large. This is typically the case close to the ground, and the echo then recorded by the SODAR is known as the ground-based shear layer. Neff & Hall (1976) found the ground-based shear layer to be the typical echo at the South Pole, and they identified within the layer a characteristic herring bone pattern. Such persistent patterns are rarely seen at Halley and, because the SODAR was operated at high gain and with a slow paper advance speed, even when the ground-based shear layer does occur, it is not possible to see the herring-bone structure.

The increasing depth of the ground-based shear layer with increasing wind speed can sometimes be seen. Fig. 3a shows the ground-based shear layer increasing in depth from about 40 m to about 200 m as the 8 m wind speed, plotted in Fig. 3b, increases. The vertical bands on the SODAR chart are due to the wind noise discussed in the introduction. The ground-based shear layer may typically reach a depth of about 200 m before the chart blacks out entirely due to wind noise. It is interesting to note that in Fig. 3b the minimum in the wind speed trace occurs at the same time as the drop in stability and the change of wind direction from east to west (note that in this case the wind vane has jammed between 1500 Z and 1600 Z). Such a relationship is typical of the



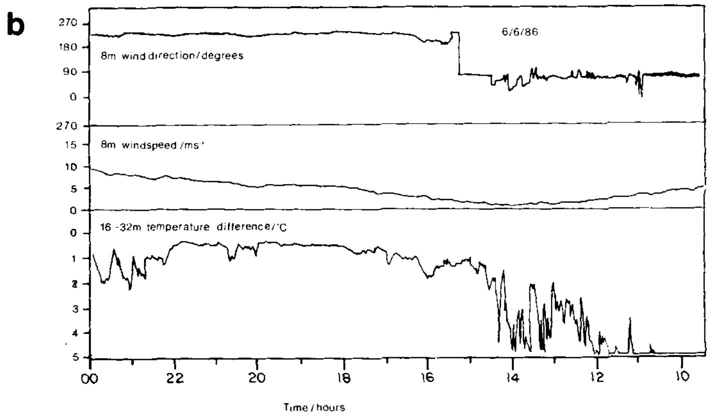


Fig. 3. 6 June 1986 data. **a.** The SODAR chart showing the ground-based shear layer increasing in depth from about 40 m at 1600 Z to about 200 m at 0200 Z. Note the waves in the easterly flow before 1900 Z. **b.** Graphs of 8 m wind direction and speed and 16–32 m temperature difference.

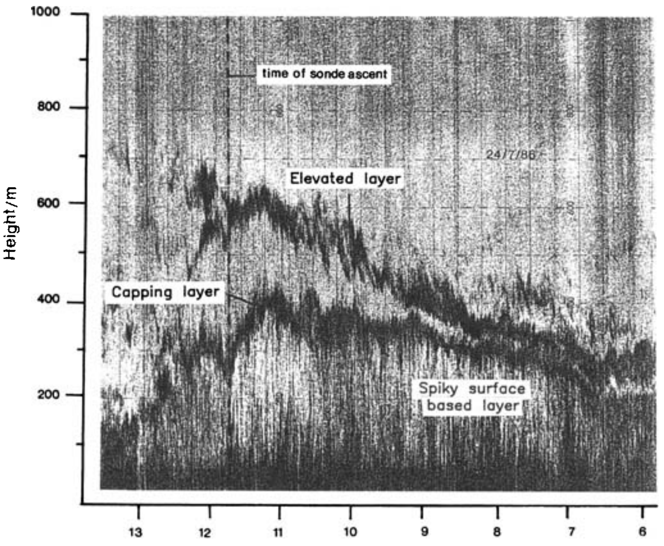
sloped inversion wind regime discussed above. Also note the wavy nature of the wind direction trace in the easterly flow before 1500 Z compared with the relatively smooth trace in the westerly which follows.

Brown & Hall (1978) warn that, 'when winds exceed 15–20 ms^{-1} even 200 m above a strong surface based inversion, the turbulence generated may be strong enough to erode the continuous ground-based layer leaving only bursts or spikes of turbulent patches. Such echoes strongly resemble convective plumes on the facsimile record'. Such a spiky ground-based layer often appears on the Halley SODAR charts, and it is described in detail below.

The spiky ground-based layer

The spiky ground-based layer is an echo type appearing frequently on the SODAR charts at all times of the year. The spiky echo is often capped by a strongly reflecting layer, and resembles the signature on facsimile charts of convective plumes growing beneath a nocturnal inversion. However, profiles of potential temperature through these layers show that they are weakly stably stratified, often with a strong inversion present at the surface, which rules out temperature inhomogeneities associated with thermal convection as the cause of the echo. The echo may persist for periods ranging from several hours to several days. During such periods the surface wind direction at Halley is westerly and the 16–32 m temperature difference on the mast becomes very small. An example of the spiky surface-based layer, which occurred on 24 July 1986, is shown in Fig. 4a. Fig. 4b shows the wind and temperature difference data for the 24 July 1986 event. The temperature difference gradually becomes smaller as the spiky echo persists. Such behaviour is typical of spiky echo periods, and supports the view that the echo signifies turbulence in the surface layers which gradually erodes the stable stratification. Fig. 4c shows the radiosonde profiles of potential temperature and wind speed and direction obtained from the flight through the layer shown in Fig. 4a. The temperature profile reveals a strong inversion in the lowest 50 m and the well-mixed layer extending from 50 m up to about 400 m corresponding to the depth of the spiky echo in Fig. 4a.

The wind speeds may be as low as 6 ms^{-1} throughout the profile (much lower than the 15–20 ms^{-1} required by Brown & Hall (1978) for the onset of the spiky echo) during spiky echo events at Halley, but there may be another mechanism by which vigorous turbulence may be generated near the surface. It is likely (Anderson, personal communication 1989) that there was a polynya in the Weddell Sea to the west of the Brunt Ice Shelf for much of the winter of 1986. Air from the west may, therefore, have had to pass over open water in its passage across the Weddell Sea. The relatively warm water surface would warm the air from the surface, partially destroying the inversion, and perhaps lowering the Richardson number sufficiently to enable turbulence to



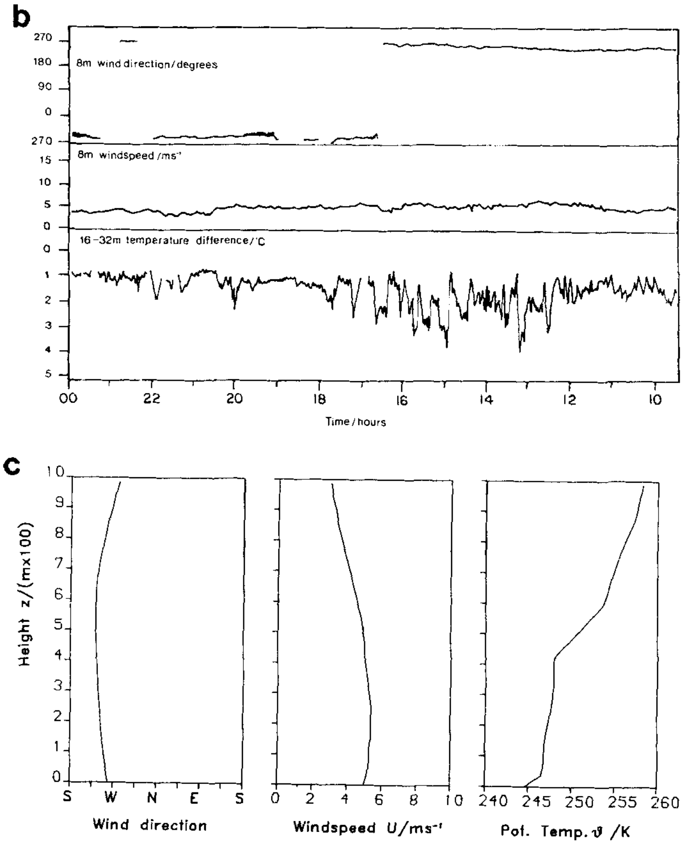


Fig. 4. Data for the 24 July 1986 occurrence of the spiky ground-based layer. **a.** The SODAR chart showing the spiky ground-based echo in the lowest 300 m. Note the strong capping layer and the rising wavy layer above it which splits at about 1130 Z. **b.** Graphs of 8 m wind direction and speed and 16–32 m temperature difference. **c.** Profiles obtained from the radiosonde ascent through the spiky ground-based echo at the time shown in a.

break out. Such a turbulent layer might persist as the air flowed back on to the ice surface, although the layers closest to the surface would be chilled rapidly by contact with the ice.

Gravity currents

Very sudden changes of surface wind direction to easterly, a sudden decrease in temperature, and the onset of wavy activity in the temperature difference and wind direction traces, mark what appears to be the passage of shallow gravity currents across the Halley site. Such events can sometimes be identified on the SODAR charts although on several occasions, because of high winds, there are no SODAR data available.

The sharpest, and most obvious, appearance of a shallow gravity current on the 1986 Halley SODAR records occurs on the record of 19 May. The SODAR chart for the period is shown in Fig. 5a.

It can be seen in the figure that a strong echo in the lowest 70 m of the chart appears suddenly at about 0740 Z and persists for several hours. It is important to note that the echo in the lowest 40 m of the chart before 0740 Z is the blacked-out surface layer discussed in the Introduction. The faint horizontal band at about 80 m is an echo from one of the buildings at the Halley site. Fig. 5b shows the wind and temperature difference data for the period. The time of the appearance of the nose on the SODAR chart is marked by abrupt changes of wind direction and of temperature difference. The waviness of the wind direction trace after the passage of a front is typical of gravity currents (Simpson 1987, p. 55). The radiosonde ascent at 1201 Z (Fig. 5c) shows a weak wind speed maximum at the surface and an easterly surface wind direction. For this event data recorded at 0.1 Hz on the mast were also available. Temperatures at heights of 2, 5, 15 and 32 m have been derived from these data, and these have been used to plot a contour map of temperature for the period (Fig. 5d). The sharp front, characteristic nose, and the shallow depth of the gravity flow can be seen clearly in Fig. 5d. Similar shallow gravity currents have been identified by Kottmeier (1986) on the Ekstrom Ice Shelf in Antarctica. The echo on the SODAR chart may represent a layer forced to rise over the nose of cold air, rather than the actual nose itself which is probably hidden in the blacked-out surface layer.

Waves and elevated layers

Wave activity is apparent on a large proportion of the SODAR charts. The waves have a variety of periods ranging from about 30 min to about 2 min. Often many periods are present simultaneously. Such a broad spectrum of wave activity leads to a variety of appearances on the facsimile charts.

Some short period wave activity has already been described in connection with turbulence in the spiky ground-based layer. Such short period wave activity also occurs frequently in layers aloft. Even on the relatively time-compressed facsimile charts some structure can occasionally be seen in such layers. Fig. 6a shows the brief appearance of a well-defined wave of period 2–3 min in a thick elevated layer. The wave only remains well-defined for about 20 min after which time the structure appears to break down into turbulence. It is important to remember that the strong reflections detected by the SODAR do not necessarily indicate the presence of turbulence, but only the presence of temperature inhomogeneities, and so the layer may persist on the SODAR chart for much longer than the lifespan of the turbulence that produced it. The darker edges of turbulent layers aloft indicate how the strongest temperature gradients (and hence the strongest acoustic backscatter) become concentrated at the edge of such turbulent regions. As the turbulence within the layer gradually smooths out the temperature inhomogeneities, the echo gradually becomes weaker. What was originally a single echo in the middle of the layer on the chart becomes a double one. Repetition of this process can lead to the appearance of multiple layers on the SODAR charts (Ottersten *et al.* 1973).

A slow radiosonde ascent was made through the layer at 500 m shown in Fig. 6a, and the vertical profiles obtained are shown in Fig. 6b. The wind profile shows the jet structure which is a common feature in easterlies at Halley, and which is a result of the slope pressure gradient force discussed above. The pattern on the SODAR chart shown in Fig. 6a is characteristic of such jets (Neff & Coulter 1986). The wind shear associated with the bottom of the jet produces the ground-based shear layer from the surface up to about 300 m at 0100 Z, and the wind shear associated with the top of the jet leads to the appearance of the thick elevated layer between 350 and 600 m. The wind maximum is marked by the thin echo-free region between the ground-based and the elevated layers.

Longer period waves (>3 min) have a clearly wavelike structure on the facsimile charts. Such waves may have a variety of causes. King *et al.* (1987) discuss an event when a wave with an 11-min period was observed at the surface at Halley, and they propose that it was created by a dynamical instability aloft. A similar event seems to have occurred on 22 July 1986 when a wave develops at about 700 m (Fig. 7a). The radiosonde wind profiles, shown in Fig. 7b. show a strong shear of both wind speed and direction, suggestive of a frontal surface, at the level of the wave on the SODAR chart. The Richardson number is reduced below 0.25 in this region. The wave has a period of about 5 min, a period which is also apparent in the multiple layers below, suggesting that these layers may be influenced by the formation of the wave aloft. The amplitude of the wave grows to a maximum of about 100 m at 1100 Z. The amplitude of the wave and the

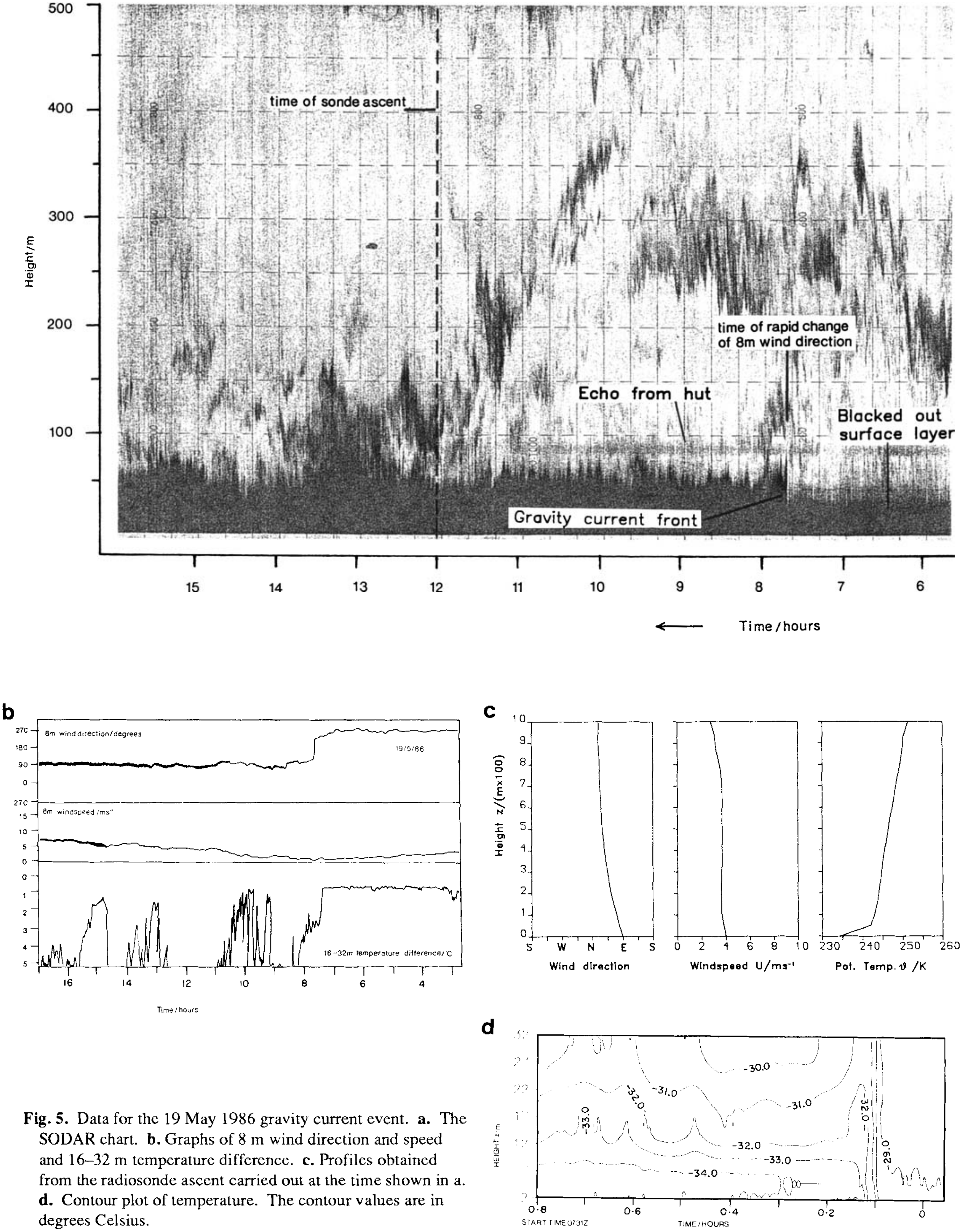
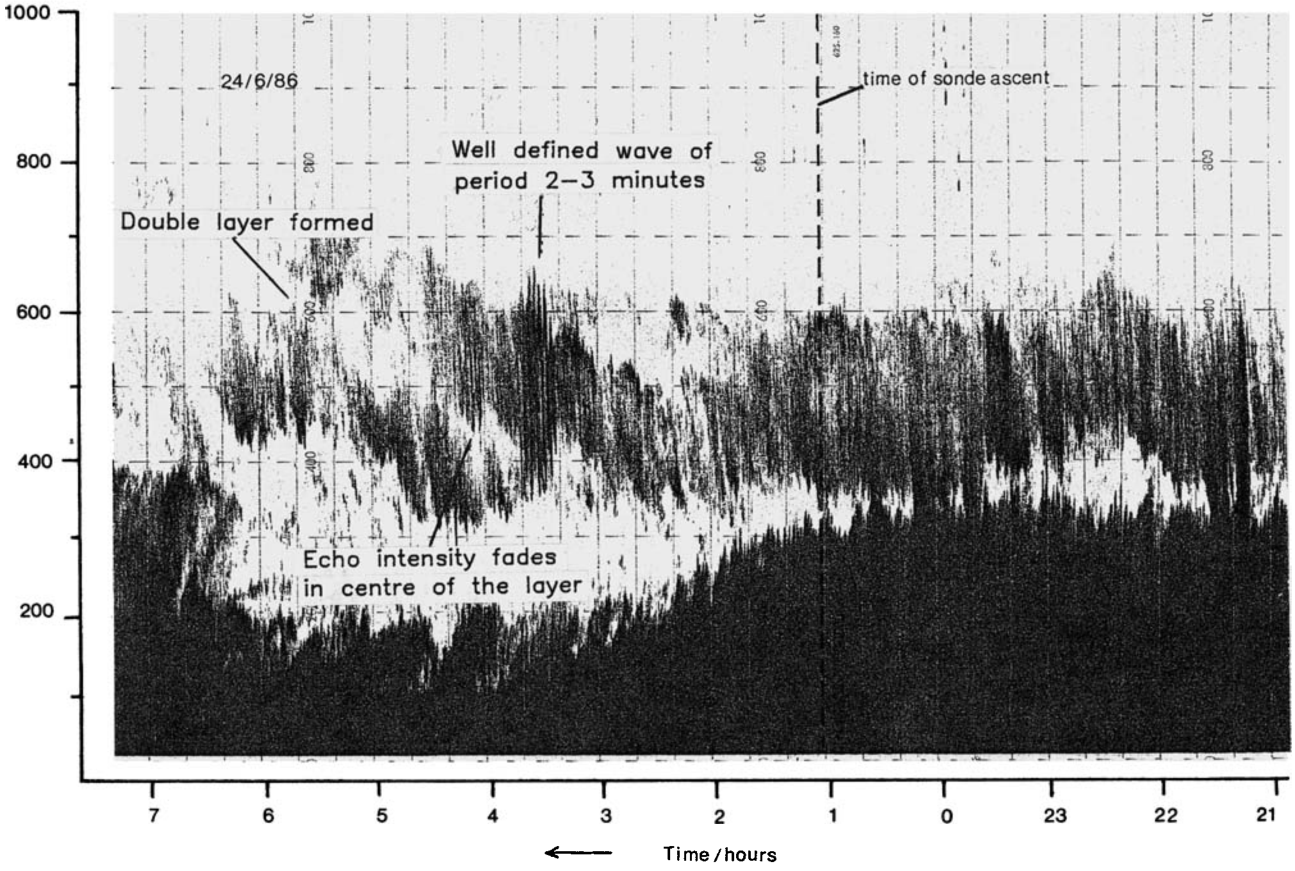


Fig. 5. Data for the 19 May 1986 gravity current event. **a.** The SODAR chart. **b.** Graphs of 8 m wind direction and speed and 16–32 m temperature difference. **c.** Profiles obtained from the radiosonde ascent carried out at the time shown in a. **d.** Contour plot of temperature. The contour values are in degrees Celsius.



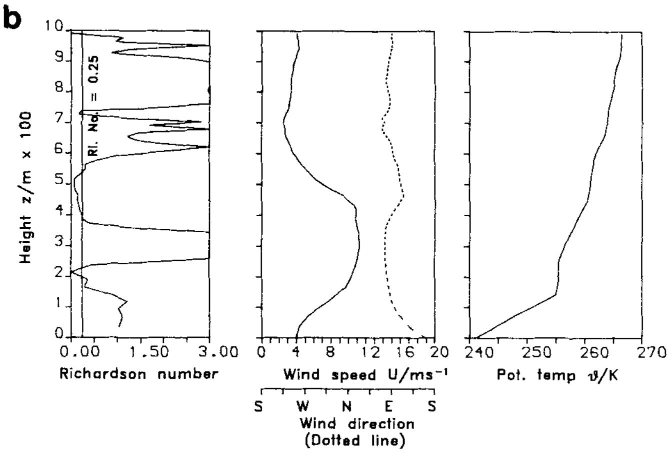


Fig. 6. 24 June 1986 data. **a.** The SODAR chart showing shear layers at the surface and aloft typical of a jet structure in the wind profile. **b.** Profiles obtained from the radiosonde ascent made at the time shown in a. Note how the jet maximum corresponds to the height of the thin echo-free layer in a.

strength of the echo decrease over the next 1.5 h until the wave at 700 m can no longer be seen. The 5-min period wave activity between the ground and 400 m persists for several hours, however.

Rees & Mobbs (1988) have studied wave events at Halley using data obtained from the instrumentation installed on the mast during STABLE. They discussed in detail the wave event of 25 May 1986, during which many wavy layers, all in phase, are visible on the SODAR chart. The waves persist for several hours without appearing to break. Rees & Mobbs (1988) suggest that a possible mechanism for the formation of the waves is topographic forcing by the irregular terrain at the Hinge Zone or by ridges in the Brunt Ice Shelf.

Turbulent layers reaching the surface

Occasionally elevated turbulent layers appear to work their way down to the surface. This produces a characteristic pattern on the SODAR charts, an example of which is shown in Fig. 8. In the figure the thick turbulent layer between 200 and 400 m at 2100 Z slowly descends over the next 2 h. Then, in the period from 2230 Z to 0300 Z, a series of pulses

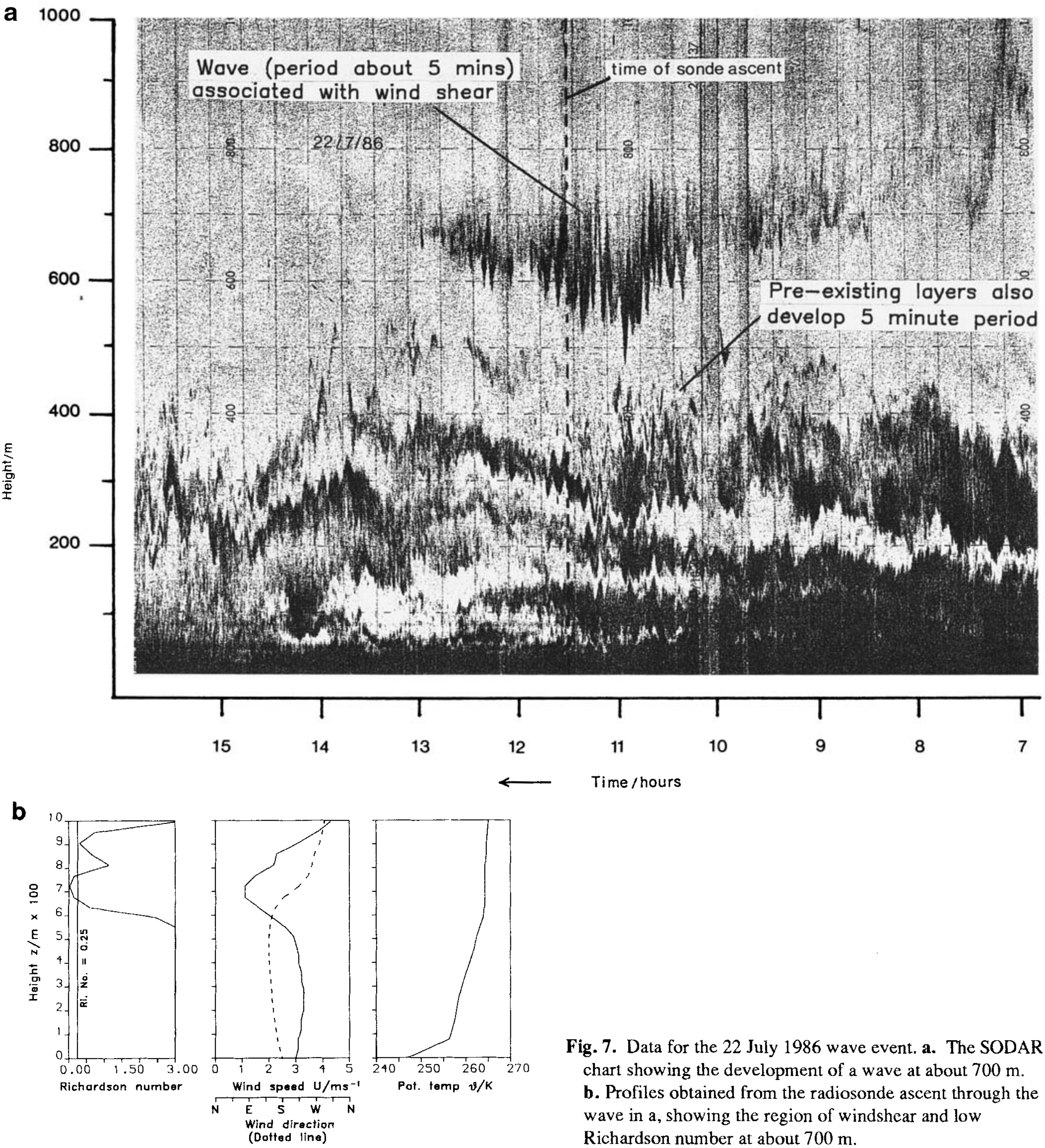


Fig. 7. Data for the 22 July 1986 wave event. **a.** The SODAR chart showing the development of a wave at about 700 m. **b.** Profiles obtained from the radiosonde ascent through the wave in a, showing the region of windshear and low Richardson number at about 700 m.

of turbulence descend from about 200 m to the top of the blacked-out surface layer. Such a pattern may be due to a process often observed in the nocturnal boundary layer, in which the stable surface layer is continually eroded from above, producing bursts of turbulent activity at the surface (Businger 1972). On some occasions the presence of descending turbulent layers is apparent in the wind and temperature records from the instrumentation on the mast, but often very little effect is observed at the surface and it may be, in such cases, that the very strongly stably stratified surface layer remains impenetrable to the descending turbulence.

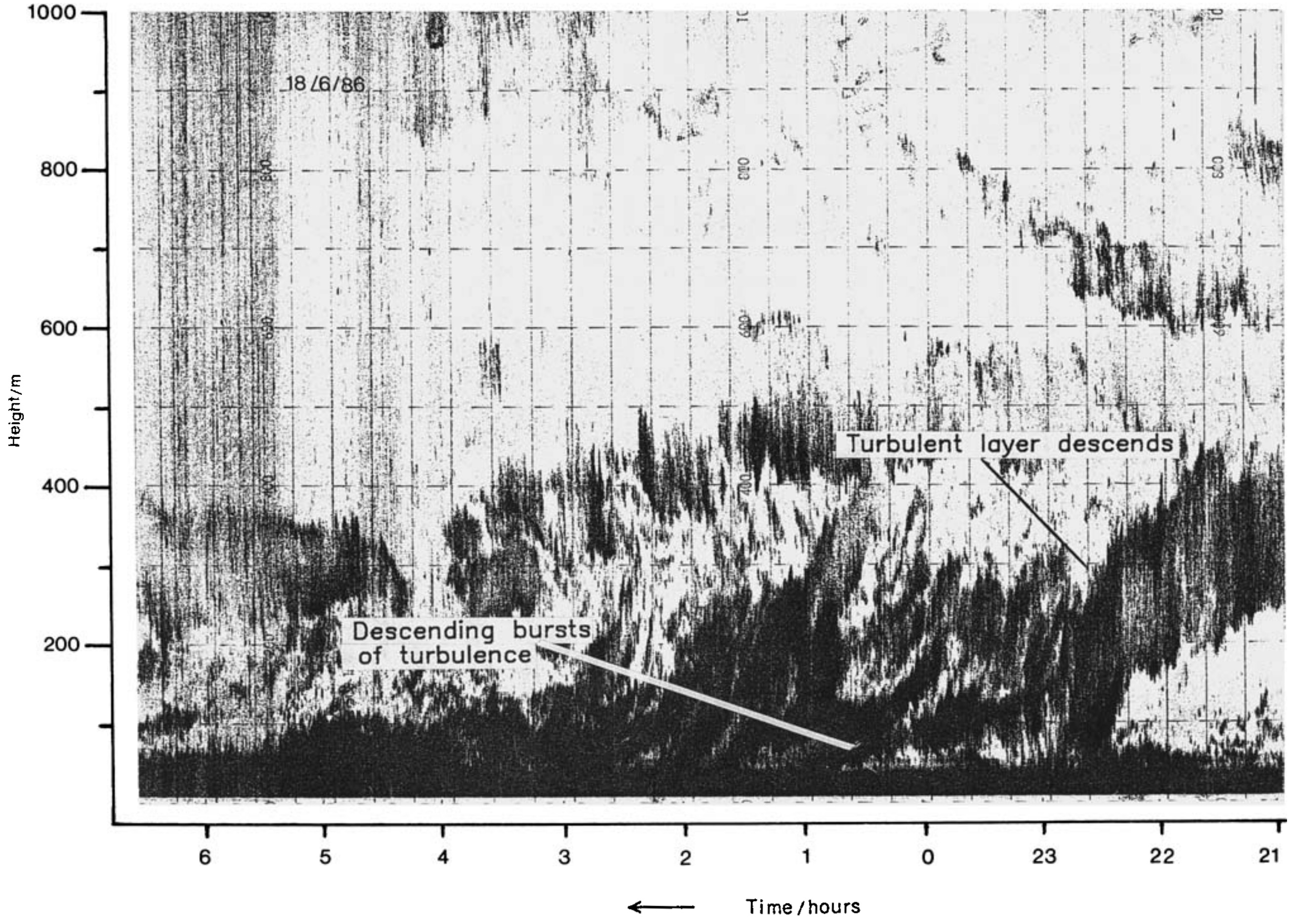


Fig. 8. 18 June 1986 SODAR chart showing turbulence periodically working down to the surface.

Conclusion

From the study of the SODAR charts and the data from the mast instrumentation we have seen that the westerlies at Halley are associated with low stability near the surface, giving rise to the characteristic spiky echo pattern. The westerly flows sometimes end abruptly as a shallow gravity current moves in from the east. A cold, shallow gravity current might re-establish a strong surface-based inversion and, via the slope inversion wind effect, encourage a strong easterly flow to persist at the surface, showing up as multiple wavy layers on the SODAR charts.

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