Tellus (1992), *44B*, 422–429

Complexity of the wind field as observed by a sodar system and by automatic weather stations on the Nansen Ice Sheet, Antarctica, during summer 1988–89: two case studies

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(Manuscript received 9 August 1991; in final form 26 February 1992)

ABSTRACT

In the Antarctic boundary layer, some phenomena appear to be particularly enhanced with respect to those at midlatitudes. Thermal stratifications are present almost all year and can substain drainage flows of different types. Several episodes of flows with different potential temperature and consequently with different buoyancy were observed on the Nansen Ice Sheet by a sodar. Two case studies are presented in which a comparison with the data of the automatic weather stations located on the Reeves and the Priestley glaciers as well on the Nansen Ice Sheet have been used. As a main result, we saw that during the summer time, the flow from the Reeves glacier may superimpose the one from the Priestley, in contrast with the current opinion based on the automatic weather station measurements averaged over the entire year. Also, an episode of barrier-katabatic flow interaction is shown in which the first is negatively buoyant in comparison with the second. Since the wind profile frequently showed a great variability with height, the importance of using remote sensing sensors in studies that realistically want to model the dynamics of the Antarctic boundary layer has been emphasized.

1. Introduction

The characteristics of the Planetary Boundary Layer (PBL) in the Antarctic environment may be very different when compared to those at midlatitudes: the presence of a thermal inversion in the Antarctic PBL is a common condition with a few exceptions during the summer period when, mainly in the deglaciated coastal areas, convection is sometimes observed (Mastrantonio et al., 1990). The thermal stratification, because of the damping of vertical momentum fluxes, makes the superimposition of flows with different temperature, wind velocity and direction possible. These stratifications may be revealed by the strong echo layers present in the facsimile record of an echosonde. The flows may be characterized by different originating processes (gravity-driven flows, breezes, barrier winds), or by channelling effects of the orography. In these situations the surface measurements may be conducive to misleading conclusions, e.g., on the rôle of transport processes leading to variations in the presence of chemicals, and to the lack of correlation between measurements obtained in the same area, essentially because of the complex three dimensional patterns of the flows. Indeed the transport of chemicals in both horizontal and vertical directions is strongly related to the temperature and wind speed and direction in the lower troposphere. Furthermore, an explanation of the chemical composition of snow has to take into account the transfer between air and snow occurring in the surface layer. Most of the measurements and studies of Antarctic air flows have been based on data obtained with manned or automatic instruments (Schwerdtfeger, 1984; Bromwich, 1989a) providing measurements at only one level, close to the ground, without giving any information on the vertical profile. In other cases, aircraft measurements have been performed to study particular katabatic winds episodes (Gosink, 1982;

Parish and Bromwich, 1989). Only occasionally remote sensing sensors have been used to monitor the atmosphere (Neff and Hall, 1976).

The katabatic wind regime in the Victoria land area has been extensively studied utilizing the data from AWSs (Automatic Weather Stations) (Bromwich et al., 1990a) as well as from aircraft (Parish and Bromwich, 1989). Bromwich (1989b) points out that in this area the main route for katabatic mass transport to sea level is via the Reeves Glacier, and draws attention to the complex trajectories that the stream from the Priestley Glacier takes before merging with the Reeves stream in Terra Nova Bay.

It is the purpose of the present paper to show the great variability that the wind can have both in intensity and direction in the vertical and how a sodar system may be suitable to describe such variability. In Section 2, after a brief description of the instrumentation, an example of superimposed gravity-driven currents will be presented, highlighting the advantages of utilizing both wind profiles and surface measurements for a correct reconstruction of the three dimensional pattern of the air flows. A case study of barrier winds superimposed by katabatic winds will be also shown.

2. Experiment location and instrumentation

The data was obtained during a campaign carried out in Victoria Land by the Italian Antarctic Research Program during the summer of 1988–89. A three-axis sodar with 1.2 m diameter antennas (Fig. 1) was operational from 26 December 1988 to 4 February 1989 on the Nansen Ice Sheet (74.79° S, 163.31° E), a large flat area at the confluence of the Reeves and Priestley glaciers. At that time, American (Keller et al., 1990) and Italian AWSs (Bromwich et al., 1990a) were also operational in the same area. In Fig. 2 the geography of the area as well as the locations of the American (09, 31, 05, 21) and the Italian (52, 50) AWSs are shown.

The design of the sodar system and the algo-

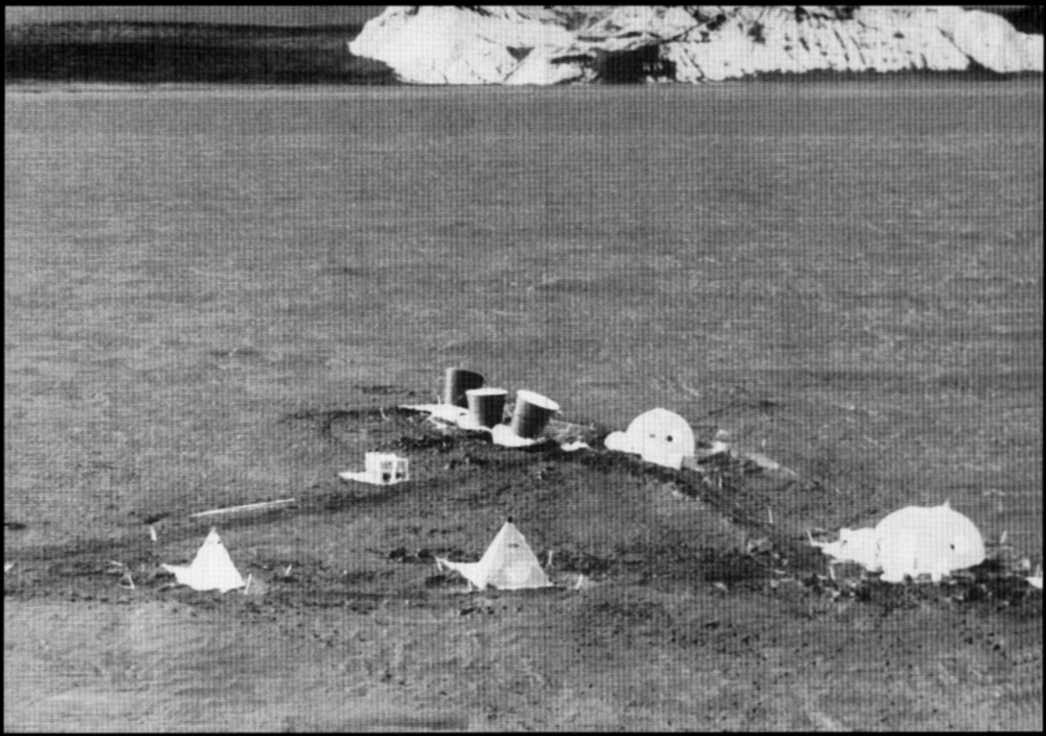

Fig. 1. The sodar on the Nansen Ice Sheet.

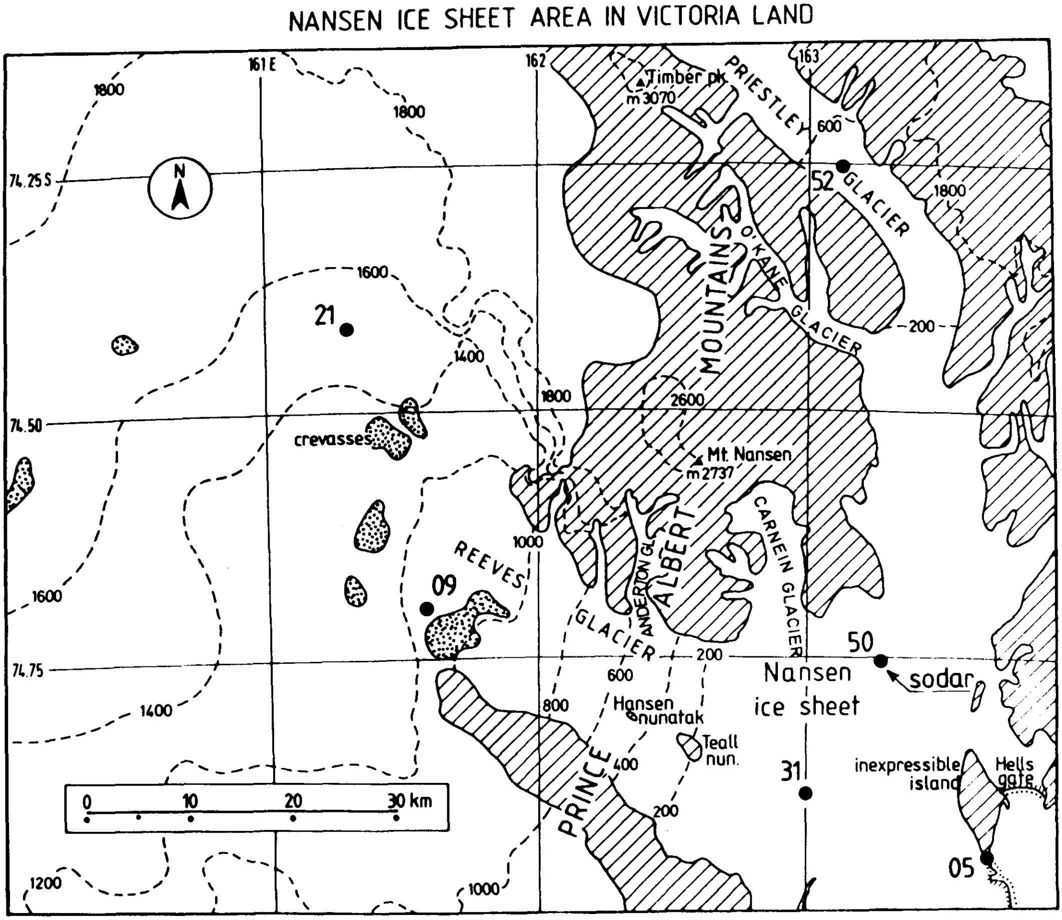

Fig. 2. Map of Victoria Land area showing the location of the sodar (74.78° S, 163.31° E) and AWSs 31 (74.88° S, 163.00° E), 05 (74.92° S, 163.60° E), 50 (74.78° S, 163.31° E), 09 (74.70° S, 161.57° E) and 52 (74.26° S, 163.13° E), 21 (74.30° S, 161.30° E).

rithms to analyze the echoes have been described in detail by Elisei et al. (1986) and Mastrantonio and Fiocco (1982). The sodar is capable of simultaneously radiating bursts of different tones for each antenna every 6 s and of receiving and simultaneously analyzing the echoes generated by each tone. In addition to the on-line analysis (giving 15-minute mean values of wind speed and direction) the three echoes and a reference signal were stored on a four-channel analog tape recorder to allow for successive analysis.

The surface data from the AWSs has been used for a comparison with the sodar results and for the reconstruction of the flow patterns.

3. Superimposed flows and wind shear

The area under investigation is Terra Nova Bay, and in particular, the confluence zone of the Priestley and the Reeves glaciers on the Nansen Ice Sheet. The presence of these glaciers strongly characterize the wind regime observed in this area. The Priestley extends from North-West to South-East for more than 100 km with a basin 5–8 km wide, going South for more than 40 km before reaching the Nansen Ice Sheet; the Reeves is about 30 km long, wider than the Priestley (about 15 km) and terminates on the Nansen Ice Sheet too. The catchment basins located on the plateau work as confluence zone for the air masses flowing toward the coast (Bromwich et al., 1990b).

During the campaign, cases in which flows originated in the Priestley as well as in the Reeves glaciers were recorded separately at the sodar location. In addition, several episodes were observed in which the flows coming from the two glaciers, because of the different potential temperatures, superimposed each other: in nearly all these cases the stream from the Reeves appeared to be warmer than the one from the Priestley. This behaviour matches the corresponding potential temperatures measured at stations 52 and 09, indicating that the Reeves glacier airstream, being a couple of degrees warmer than the Priestley, is positively buoyant compared to the Priestley. This result appears to be different from that of Bromwich (1989b), and of Bromwich et al. (1990a): these authors, comparing the mean potential temperatures of the two flows on an annual basis (from February 1988 to January 1989), indicated that the air flow descending from the Priestley is, on the average, positively buoyant compared to that descending from the Reeves. The discrepancy between our results and theirs may imply that different mechanisms (such as those that control the surface radiation budget on the two glaciers or the originating processes on the catchment basin)

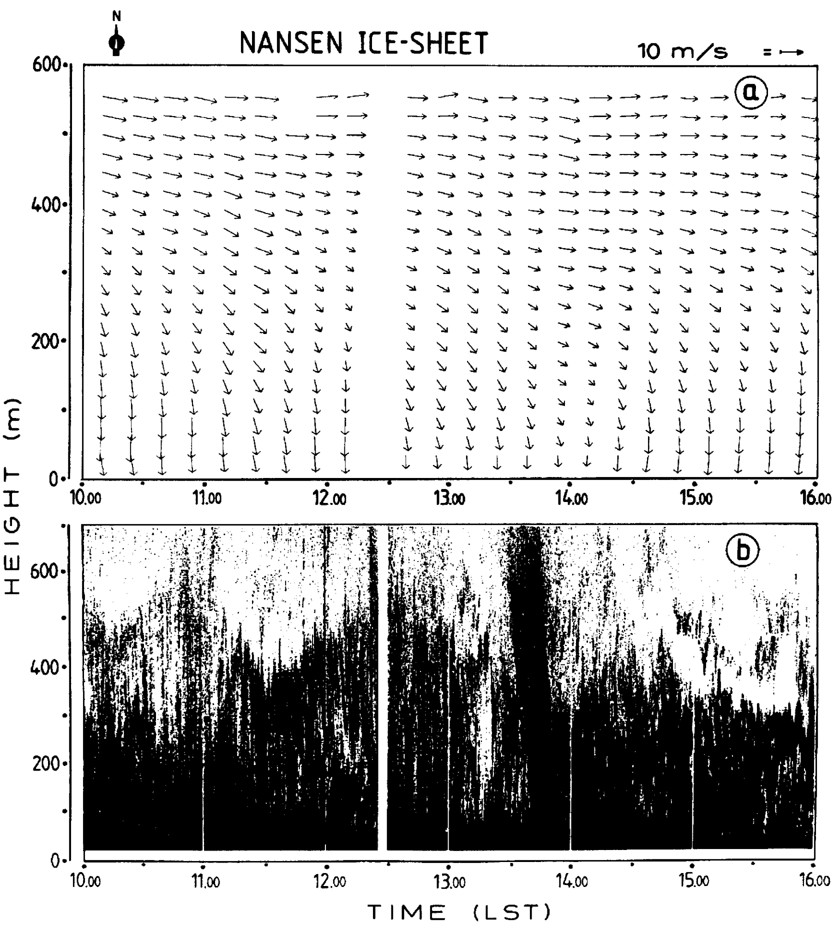

Fig. 3. (a) Wind profiles given by sodar for 9 January 1989 from to 10:00 to 16:00 LST (an incomplete arrow in the graph indicates that the vertical velocity has not been used in deriving the horizontal wind velocity). (b) Facsimile representation.

regulate the behaviour of the flows in the course of the year. Recently, from an analysis of the difference of the potential temperature between station 09 and station 52 for the whole of 1989 came out that this difference, from the beginning of February, is always negative, reaching a minimum of $-3° \div -4°$ in July, and then keeps increasing up to the beginning of November, sometimes assuming positive values in the months of November, December and January (Pellegrini's personal communication, 1991). A more detailed analysis of these phenomena would be justified in the future.

An example of coexisting flows is given in Fig. 3a for 9 January 1989 from 10:00 to 16:00 LST; we report only the central part of the whole episode that lasted for 18 h. This figure depicts the behaviour of the horizontal wind field (the arrows indicate the wind intensity and direction) with height as a function of time. As shown in the graph from the ground level up to approximately 200 m, a katabatic wind coming from the North, e.g., from a direction aligned with the axis of the Priestley is present, while in the upper layers, after a transitional region of about 200 m characterized by lower velocities (about 5 m/s), the wind seems to follow the axis of the Reeves glacier. Fig. 3b shows the facsimile recording for the same period: strong echoes are present at the interface between the ground and the low atmosphere (around 50 m), and at the interface between the two katabatic flows (400 m) as a consequence of the wind shear. This behaviour is very similar to that depicted by Neff (1988) for a katabatic flow with a maximum velocity at low level. The strong signal around 13:45–14:00 LST is due to snow or graupel precipitation. Table 1 gives the horizontal wind speed, the direction and the potential temperature for 9 January at 10:00, 13:00 and 16:00 LST for stations 31, 05, 50, 52, 21 and 09 (Fig. 2). The sodar measurements given in this table refer to the first echo layer received by the sodar (around 40 m) and to the 3-m level for AWSs. The wind directions measured by stations 31 and 50 are quite close (within 20°) to the sodar ones and suggest that a flow coming from North is present in the lower layers crossing the Nansen Ice sheet. Station 50, though located approximately in the same position of sodar, gives, as expected, a lower wind speed because of the friction occurring in the surface layer. Unfortunately, the winds at stations 09 and 21 are too low to help in trying to draw

Table 1. *Wind intensity, direction and potential temperature at 3 m above ground level at 10:00, 13:00, 16:00 LST for stations 31, 05, 50, 52, 21 and 09. The sodar data refer to the first level (about 40 m above ground level). Where data is not available a * is given in the table*

Time (LST)	Station	Wind (m/s)	Direction (degree)	Potential temperature (K)
10:00	sodar	10	353	*
	09	2	161	277
	31	3	15	276
	50	7	10	272
	05	6	308	273
	52	7	330	276
	21	3	19	*
13:00	sodar	6	355	*
	09	4	212	277
	31	3	346	276
	50	5	10	273
	05	8	308	275
	52	2	170	275
	21	2	326	*
16:00	sodar	9	4	*
	09	4	193	278
	31	3	21	271
	50	5	360	273
	05	8	308	275
	52	1	180	274
	21	1	244	*

any conclusion on the wind regime on the Reeves Névé. Actually, station 21 measures a low wind speed almost in the downslope direction, while station 09 does not seem to have a similar behaviour. Parish and Bromwich (1989) obtained similar airplane measurements in the same area; inspite of this, numerical modelling shows streamlines converging into the Reeves Glacier. Furthermore, the wind direction in the upper layers of the sodar profile indicates the presence of a flow descending the Reeves glacier. Because of this, even if at station 09 we do not observe a downslope flow, the current has to enhance and become gravity driven along the glacier, as we do not have evidence of other mechanisms that could produce this descending flow. Since station 09 did not work properly after 14 October 1988, the wind intensity values of 09 were multiplied, as suggested by Bromwich et al. (1990a), by a factor equal to 2.12. Station 05 t all times gives a very constant wind direction of around 300°; this value is the predominant winter wind direction observed by this station (Bromwich, 1989a) when the katabatic airstream from Reeves is negatively buoyant in comparison to the Priestley one (Bromwich et al., 1990) and the Reeves constitutes the primary route of the katabatic flow out into Terra Nova Bay (Bromwich, 1990b). The analysis of the wind direction in this location would lead us to the conclusion that the airstream from Reeves, climbing over the one from Priestley, reaches the station location. The temperature measurements, anyway, do not clearly support this hypothesis. In conclusion, it is only thanks to sodar profile that it was possible to detect, over the Priestley airstream, the katabatic flow descending from the Reeves. The contemporaneous presence of these flows may be explained if we analyse the potential temperature of AWSs number 09 and 52 on the Reeves and the Priestley glaciers respectively. During the period under investigation, station 09, which may be considered representative of the Reeves glacier temperature, indicated that the potential temperature of the Reeves was on average 2° or 3° higher than the Priestley (station 52). In Fig. 4, the mean profile for the same day as Fig. 3 is given, but for the entire period of 18 h (from 00:00 to 18:00 LST), because this is the interval during which the flow pattern appears practically the same. The lower part of the profile is obtained by selecting the directions of arrival in a 30° wide range around 360°, while the upper part of the profile refers to the direction of arrival in the 40° wide range around 265°. The mean profile either in the lower (below 300 m) and upper part displays the characteristic shape of a gravity driven flow.

In Fig. 5a, another case of superimposed flows is given for the period lasting from 20:00 LST of 15 January to 02:00 LST of 16 January. This episode starts after a period of moderate wind speed (values below 5 m/s) with angles of arrival mainly from the West and from the North (not shown in the figure). Sometime before 20:00 LST, a southerly airstream characterized by wind speeds of about 8 m/s, appears parallel to the Transantarctic mountains. Above it, another flow from the South-West is present with similar wind intensity. The height of the zone separating the two flows increases from 100–200 m at 20:00 LST to 300–400 m at 01:00 of the successive day. After 01:00 LST, this zone disappears and the wind

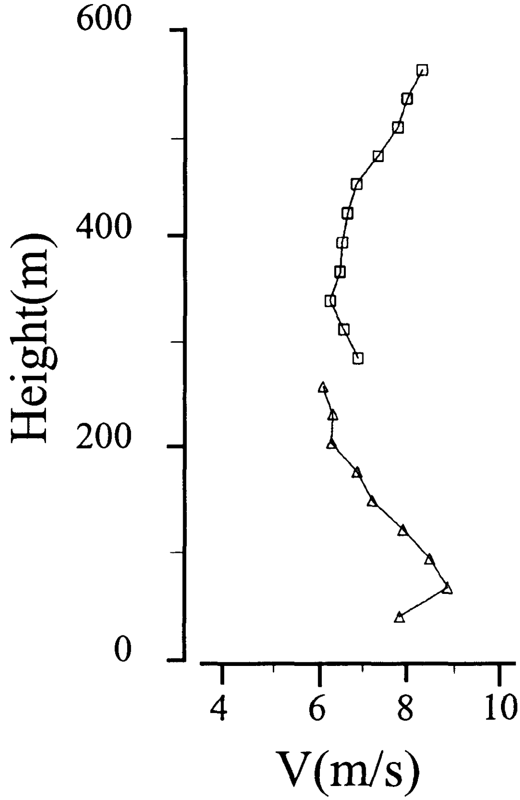

Fig. 4. Wind profile for the same day of Fig. 3, averaged from 00:00 to 18:00 LST.

(Fig. 5a) starts to back at all heights towards North North–East, suggesting a vertical mixing of the two flows. The facsimile record (Fig. 5b) confirms these results: the height of the zone between the two flows, indicated by the dark band in the lower part of the graph, increases with time. The upper band indicates the presence of a different circulation pattern in the upper region. This hypothesis seems to be confirmed by the analysis of the potential temperature at the 09 and 05 locations: if we attribute the potential temperature of 09 to the westerly flow and the 05 one to the southerly stream, considering also the time lag between the two locations, it comes out that the gradient of the two flows potential temperatures decreases with time (from about 4° to 0°), thus confirming the mixing. Incidentally, this is another example of how the sodar, through the facsimile recording and the wind profile, may help in explaining possible changes that occur in the

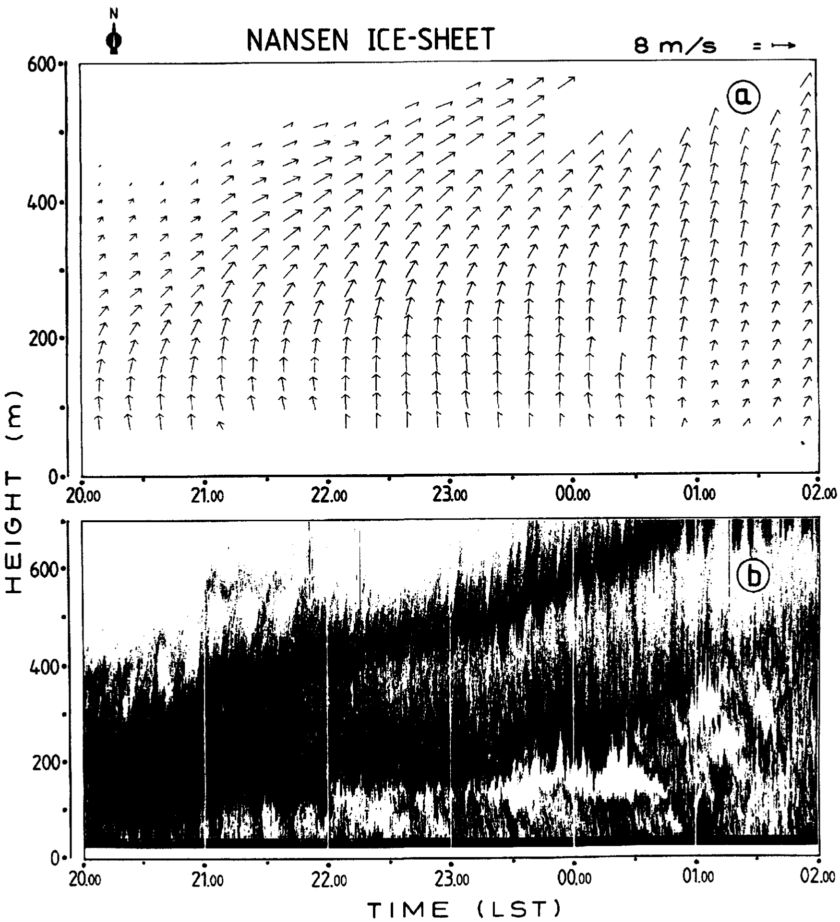

Fig. 5. (a) Wind profiles from 20:00 of 15 January 1989 to 02:00 LST of 16 January (an incomplete arrow in the graph indicates that the vertical velocity has not been used in deriving the horizontal wind velocity). (b) Facsimile representation.

surface measurements as a result of the vertical mixing of layers of different origin, previously separated by a positive temperature gradient.

In conclusion, the operation of a sodar in presence of gravity-driven flows on the Nansen Ice Sheet indicated the usefulness of the information contained in the wind vertical profile and helped to describe in a more general and realistic way the wind field regime in the Terra Nova Bay area. It evidenced the variability that the wind speed may assume with height, and showed that a superimposition of flows may occur at the confluence zone of the Reeves and the Priestley glaciers. From the analysis of our data, we found that during the summer the flow from the Reeves glacier, differently from what happens during the winter, may superimpose the one from Priestley. The analysis of the potential temperatures given by AWSs confirms that in these cases the flow from Reeves is warmer than the one from the Priestley, supporting in this way the sodar results.

Further work is needed to better understand the mechanisms regulating the flow behaviour in the course of the year and in particular the physical reasons underlying the change of the circulation in this area in the different seasons.

4. Acknowledgments

This work was supported by the Programma Nazionale Italiano Ricerche in Antartide. We gratefully acknowledge Mr. A. Pavoni who helped and participated in the field operations and Dr. A. Pellegrini who provided the Italian AWSs data. Further we would like to thank the reviewers for their useful comments that greatly helped in improving the clarity of the text.

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