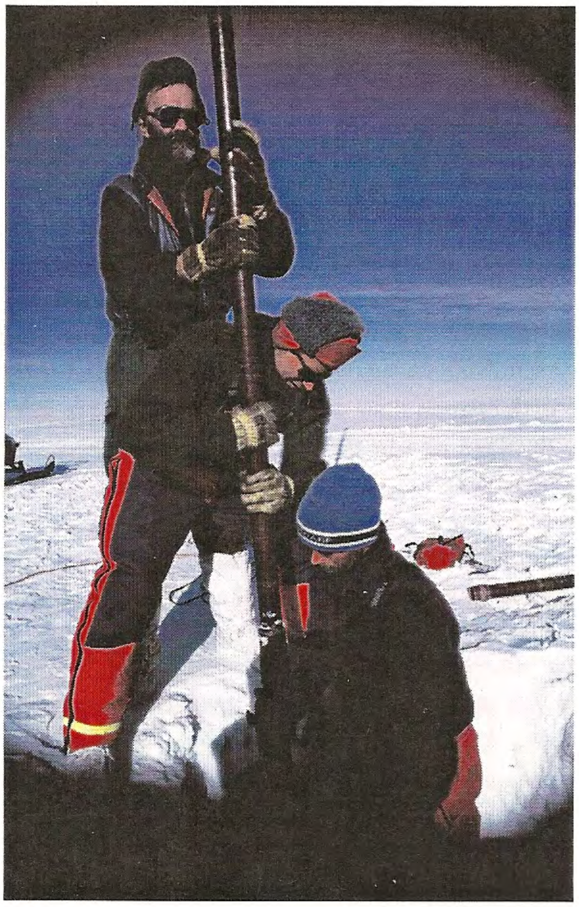
EPICA Dronning Maud Land pre site survey 1996/97



Field Report

June 1997

EPICA Dronning Maud Land pre site survey 1996/97

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1. Introduction

Within the European Project for Ice Coring in Antarctica (EPICA) it is planned to obtain two deep ice cores from the Antarctic ice sheet within the next decade. The first one will be drilled at Dome Concordia (Dome C), starting in the 1997/98 season, and should provide scientists with one of the longest undisturbed climate archives, extending more than 500 ka. The second core site should be characterised by higher accumulation rates with a dominant contribution of precipitation from the South Atlantic Ocean (the 'Atlantic signal'), to make the link with climate data obtained from the Greenland ice sheet and obtain more detailed information of the last glacial cycle. Although it is clear that this core will be drilled somewhere in Dronning Maud Land (DML), which is one of the least explored regions of Antarctica, its exact position is yet to be determined. To this end, a reconnaissance phase has been planned to produce data on accumulation rate, ice depth and dynamics, bedrock and surface topography, snow/ice chemistry and meteorology. This phase will consist of several pre site surveys, the first one of which started in the field season 1995/96 with an extensive German airborne radio-echo sounding campaign, yielding valuable information on ice thickness, surface and bedrock topography over a large area. The Norwegian/Swedish/Dutch ground traverse during the last field season 1996/97, is another part of the pre site survey work done within the EPICA programme. This report describes in somewhat more detail the activities during that traverse, as well as some preliminary scientific results.

2. The traverse

The *EPICA DML pre site survey 1996/97* was part of the Norwegian Antarctic Research Expedition (NARE) and involved 10 persons: 2 scientists from The Netherlands, 2 scientists from Sweden and 6 persons from Norway, of which 3 logistic personnel and 3 scientists. Figure 1 shows the traverse area, including the routes from the unloading place on the ice shelf to Troll station (72°01'S, 2°32'E, 1298 m a.s.l.) and from Troll station onto the plateau via the glacier Slithallet. Before the start of the traverse, small groups operated on snow mobiles in the area north of Troll as well as along the route between Troll and the main depot on the plateau, doing the planned scientific work at sites A, B and C. Before these groups started out, a helicopter reconnaissance was flown over all these routes as well as over the planned traverse route as far as 7°E, covering approximately one-third of the route towards the projected endpoint of the traverse (75°S, 15°E). In the same period, snow- and ice depth radar were operated from tracked vehicles on supply trips between Troll and the unloading place on the ice shelf.

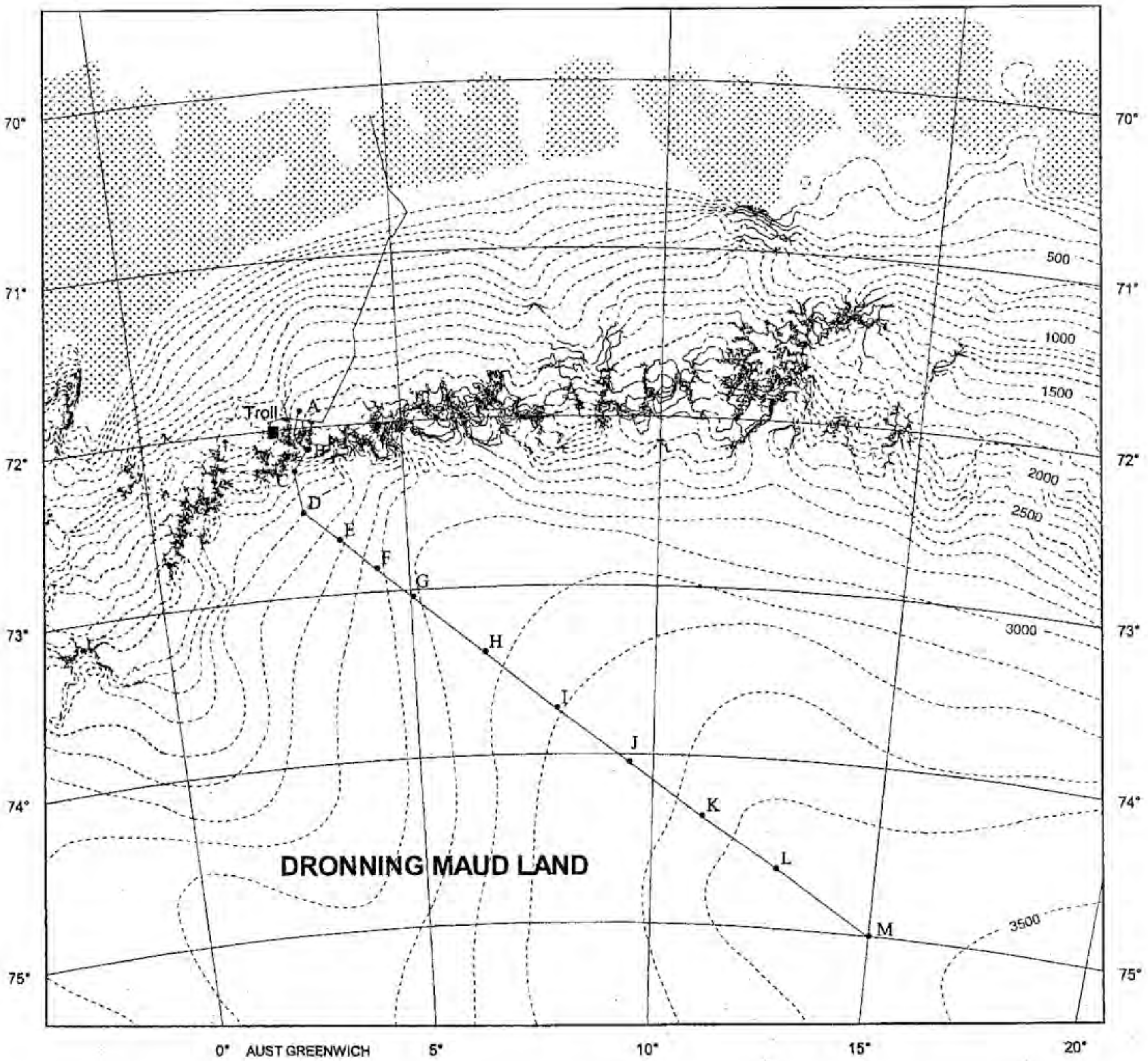


Fig. 1. Topographic map of the working area, showing the routes between the unloading location at the ice shelf and Troll, and subsequent routes onto the plateau. Letters correspond to locations in Tables 1 and 2.

The actual traverse started out from Troll (1298 m a.s.l.) on January 16 1997, towards the main fuel depot that had been established by helicopter some 25 km south of Troll (site C) at an altitude of approximately 2400 m a.s.l. Before departure from Norway, Landsat TM images of the area south of Troll had been carefully studied in order to identify crevasses, which laid the basis for the final route between Troll and site D. After site D, the traverse route followed a south-easterly course along the ice ridge leading towards Dome Fuji. Table 1 presents the progress of the traverse during the subsequent three weeks, and defines the position of camps and some of the locations where scientific work was done (sites C to M). A complete listing of these sites can be found in Section 3.

Table 1. Traverse itinerary.

Date (1997)	*Travel dist. (km)*	*Camp location*	*Elevation (m a.s.l.)*	*Site*	*Other information*
16-17 Jan.	68	72°15'S, 02°53'E	2400	C	Traverse main depot, loading
18 Jan.	88	72°52'S, 04°21'E	2840	F	Crevasses 3-4 km on both sides of the route between C and D
19 Jan.	52	73°10'S, 05°34'E	-	-	
20 Jan.	38	73°23'S, 06°28'E	3074	H	
21 Jan.	60	73°43'S, 07°56'E	3174	I	
22 Jan.	40	73°56'S, 08°58'E	-	-	Delayed start due to white-out
23 Jan.	80	74°21'S, 11°06'E	3341	K	
24 Jan.	60	74°39'S, 12°47'E	3406	L	
25-28 Jan.	76	75°00'S, 15°00'E	3453	M	Traverse turning point
29 Jan.	76	74°39'S, 12°47'E	3406	L	
30 Jan.	60	74°21'S, 11°06'E	3341	K	
31 Jan.	60	74°03'S, 09°30'E	3268	J	
1 Feb.	60	73°43'S, 07°56'E	3174	I	
2 Feb.	80	73°15'S, 05°53'E	-	-	
3 Feb.	70	72°52'S, 04°21'E	2840	F	
4-5 Feb.	88	72°15'S, 02°53'E	2400	C	Traverse main depot, visit D2
6 Feb.	68	72°01'S, 2°32'E	1298	-	Troll station

The traverse team travelled with two Hägglunds 206 tracked vehicles, used to pull equipment and supply sledges, and four Polaris Wide Track snow mobiles. On the sledges pulled by the tracked vehicles stood one large hut (10 m^2) that was used for cooking, eating and relaxing, and a small hut (6 m^2) that housed temperature-sensitive equipment and was equipped with two beds. Eight expedition members slept in a large Weatherhaven tent and in a Scott-Amundsen tent. More details on logistics can be found in section 10.

On normal travel days, the traverse team split up in three groups: after break-up of camp, usually between 10 and 11 am, two snow mobiles with three persons left directly for the next location, thereby marking a safe route for the Hägglunds (marking the route with flags every fifth km). Two persons on the remaining snow mobiles zigzagged between points situated 5 km on each site of the main route to perform kinematic GPS measurements. For safety reasons, the two scooter parties met at each crossing point, i.e. every 10 km. After arrival at the camp site, the two scooter parties would establish camp and perform drillings and pit studies before the slower tracked vehicles arrived. Five persons travelled with the Hägglunds, carrying out radar and meteorological measurements.

The turning point of the traverse, located at 75°S, 15°E at an elevation of approximately 3450 m a.s.l., was reached on January 25th. After a stay of three days at the turning point, the traverse team started back northwards along the same track, and reached the site of the main depot on February 4th. During the traverse, weather conditions had generally been favourable, with good visibility and low wind speeds. On the way in, bad visibility had held up the traverse team for only half a day. On the way out, strong winds (12-15 m s^{-1}) caused bad visibility and drifting snow on February 3rd. In spite of the high altitude and the advanced season (temperatures at the high plateau ranged between -30 and -45°C) all equipment functioned properly and no serious delays were encountered. Total travel distance from Troll and back was 1122 km, and the average distance covered on travel days was 66 km. Figure 2 schematically shows the traverse route and locations of the various glaciological, meteorological and GPS-related activities.

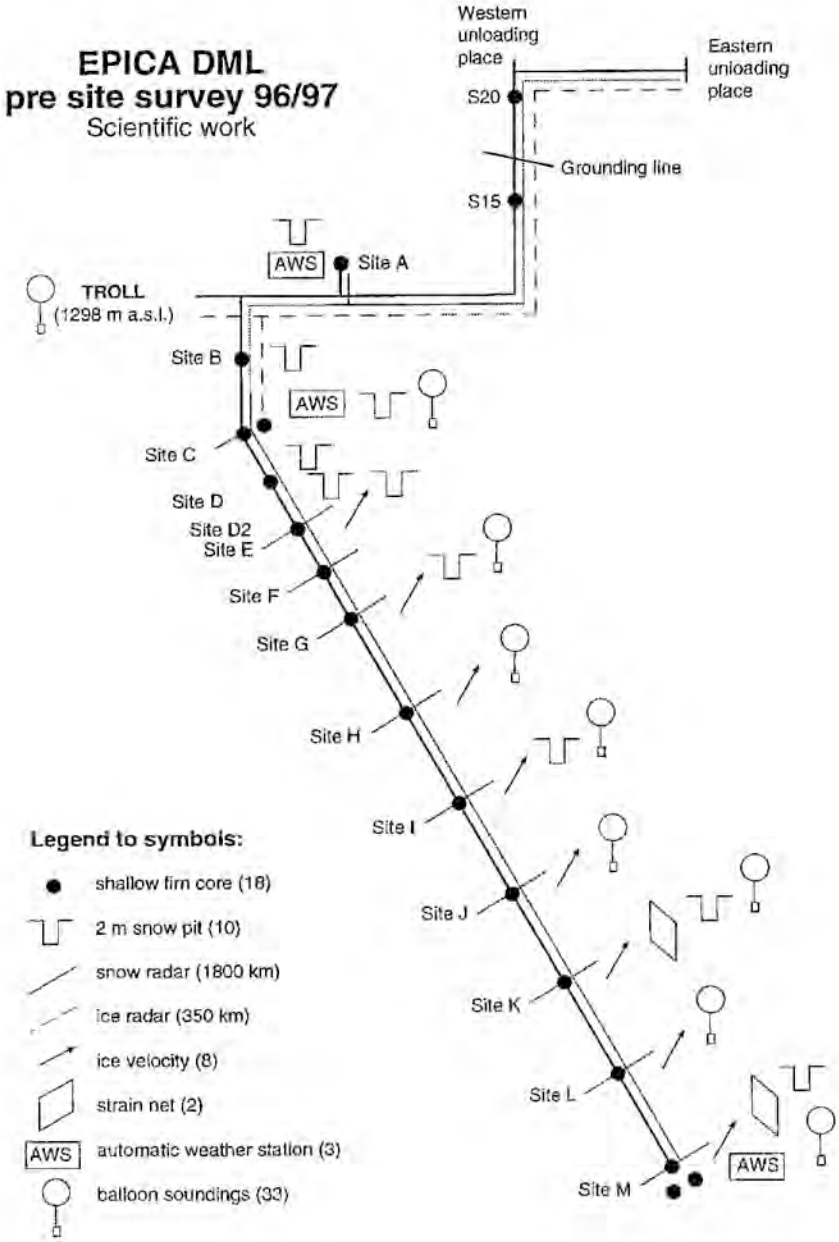


Fig. 2. *Schematic outline of travel routes and scientific work. Numbers in brackets in legend indicate totals.*

3. Shallow firn cores

Aims

Shallow firn cores are widely used in mass balance and climate research (e.g. Peel and Mulvaney, 1992; Isaksson *et al.*, 1996). Most of the shallow (10-20 m) firn cores that were drilled during the traverse will be analysed to obtain local accumulation rates, which are both of general interest and serve to calibrate the snow radar signal (see section 5: Snow radar). It is anticipated that a 20 meter firn core represents 100-200 years of accumulation on the plateau but considerably less (about 20-30 years) in the coastal area. In both cases, however, the records reach back to volcanic and bomb horizons, enabling the dating of certain levels and hence the assessment of integrated accumulation figures. Volcanic eruptions and bomb horizons can be found by means of electroconductivity measurements (ECM, Hammer, 1980) and analysis of β-activity along the core segments. In addition, oxygen isotope ratios ($\delta^{18}O$) along the core gives information on the yearly accumulation rates, and serves as a check on the other dating methods, although the yearly cycle in low-accumulation areas is often not very distinct.

Three 20 m cores as well as surface snow samples from every drilling site were taken for chemical analysis (^{10}Be, Uppsala University, site C; Halogenated hydrocarbons, Linköping University, site M; Ionic composition, Stockholm University, site MM). Researchers at Linköping University will investigate the presence and origin of triflouro-, monochloro-, dichloro- and trichloroacetate in precipitation. The results for the snow samples could definitively confirm or disprove the existence of a substantial natural source of haloacetates in precipitation. Firn samples will be analysed to compare concentrations in the precipitation of today and of pre-industrial origin. If possible, they will also be used in an on-going study on the chemical character and origin of absorbable organic halogens (*AOX*) in precipitation. From the ionic composition (Stockholm University) we obtain information on seasonal variability of climate and environment 100-200 years back in time. Temporal variations show us which compounds were forming the aerosol (i.e. how the ions were combined), whether the aerosol was acidic or alkaline and in which state the compounds were deposited (as gases or in aerosol form).

Methods and equipment

The firn cores were drilled with a PICO drill system, consisting of a 3 inch core barrel, 1 and 2 m long extensions and a upper part that connects the system of extensions to an electrical drill. At temperatures below -35°C it was found that the polyester of the drilling extensions became brittle, so that using it for extended periods at these temperatures would result in damage. We started out with a 220V/650 W Hilti drilling machine, which generally generates enough rotation power (50 Nm) to drill down to 20 m depth in dry firn.

***Table 2.** Information on shallow firn cores, snow pits and 10 m temperatures. N.a. means 'not available'. If borehole depth is less than 10 m, temperature was measured at the lowest possible level.*

Site	*Location*	*Elevation (m a.s.l.)*	*Shallow firn core (m)*	*2 m snow pit*	*T_{10m} (°C)*
S_{20}	70°14'26"S, 04°48'41"E (1)	48 (1)	20.1	no	-18.3
S_{15}	71°11'32"S, 04°35'51"E (1)	800 (1)	15.1	no	-21.3
A	71°54'00"S, 03°05'00"E (1)	1420 (1)	13.3	yes	n.a.
B	72°08'01"S, 03°10'31"E (1)	2044 (1)	11.8	yes	-29.4
C	72°15'04"S, 02°53'28"E	2400	12.3; 17.2	yes	-31.7
D	72°30'00"S, 03°00'00"E (1)	2610 (1)	11.9	yes	-36.5
D2	72°35'51"S, 03°21'17"E (1)	2750 (1)	no	yes	no
E	72°40'42"S, 03°39'46"E	2751	10.1	yes	-37.6 (2)
F	72°51'41"S, 04°21'06"E (1)	2840 (1)	10.0	no	-40.4
G	73°02'26"S, 05°02'39"E	2929	10.2	yes	-41.0 (2)
H	73°23'11"S, 06°27'38"E	3074	9.8	no	-44.9
I	73°43'27"S, 07°56'26"E	3174	10.3	yes	-47.0
J	74°02'41"S, 09°29'30"E	3268	10.2	no	-48.8 (2)
K	74°21'16"S, 11°06'13"E	3341	9.9	yes	-50.5
L	74°38'50"S, 12°47'27"E	3406	9.0	no	-52.0
M	74°59'59"S, 15°00'06"E	3453	19.9; 20.0	no	-54.2
MM	App. 1 km SE of M	-	20.1	yes	-54.2

(1) no DGPS measurements available

(2) no overnight measurement

In the field, we used a Honda 1 kW generator to power the drilling system, the output current alternating at 60 Hz. However, when powered by a much stronger Hatz (2.5 kW) generator, the Hilti was heated up too much, resulting in internal short-circuiting. After that we switched to a 36V/350W Hilti drilling machine, connected to a converter (220 to 24 V). When powered with 36 V, it was found that the internal safety slip of this machine prevented effective operation. The lower rotation power of this machine (app. 25 Nm) forced us to hand-drill at depths greater than 10 m. A 10 m firn core took three persons typically 3-4 hours to drill and pack, whereas the drilling and packing of a 20 m firn core consumed an entire working day with up to 6 people in the drilling team. Usually the snow in the upper layer was poorly sintered, and therefore density was measured in a pit and snow samples taken with 5 cm interval (except at site A). Individual core pieces were measured and weighed, then packed in plastic and sealed. It was found that, due to the low temperatures, operating the balance with an external power supply was preferable to batteries. The sealing device, a Sealboy 235 SA, worked well even under very cold conditions.

Fieldwork and preliminary results

Table 2 shows details of the shallow firn core program. As a preliminary result, we show the mean density of the first 10 m of the snow pack as a function of 10 m temperature in Fig. 3. If we disregard the two drillings north of Troll (S_{15} and S_{20}), where annual mean temperatures exceed -25°C and regular melting occurs during summer, the average density of the first 10 m appears to be a linear function of annual mean temperature, with an approximate slope of 4 kg m^{-3} $°C^{-1}$. Figure 4 shows uncorrected ECM measurements performed on the core drilled at site E. A preliminary dating suggests that eruption of Agung at Bali (1963) can be traced back as a level of elevated acidity at about 6.5 m depth. In combination with the density data of the overlying layer, this would suggest a yearly accumulation of 94 mm w.e. per year at this location, which is not unreasonable.

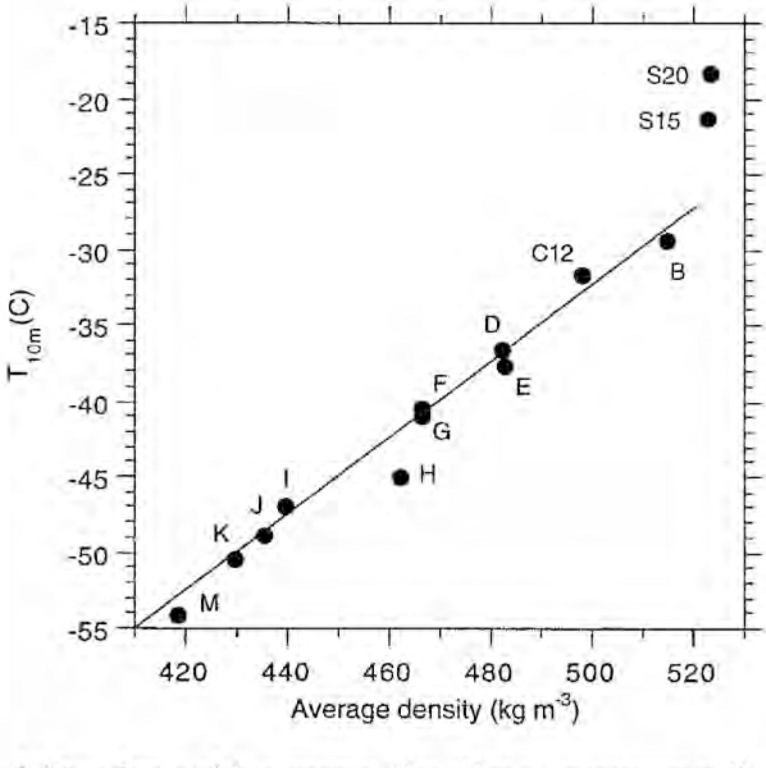


Fig. 3. Mean density of the uppermost 10 m of firn vs. temperature at 10 m depth.

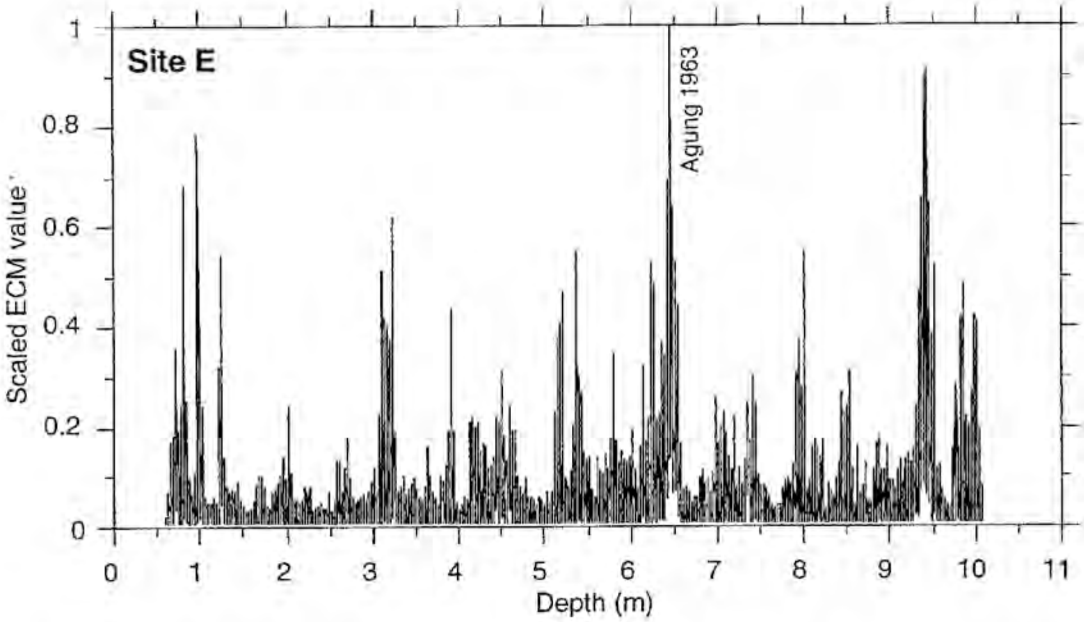


Fig. 4. Raw ECM data of core E. The probable location of a layer with elevated acidity values owing to the eruption of Agung (Bali, 1963) is indicated.

4. Snow sampling in pits

Aims

The snow samples collected during the traverse will be used for ion concentration analysis and oxygen isotope studies. The ions and isotopes that will be analysed are Natrium (Na^+), Potassium (K^+), Nitrate (NH_4^+), Magnesium (Mg^{2+}), Calcium (Ca^{2+}), Chloride (Cl^-), Nitrate (NO_3^-), Sulphate (SO_4^{2-}), Methanesulfonate ($CH_3SO_3^-$) and oxygen isotopes ($\delta^{18}O$). The spatial variability of the deposition of major components of atmospheric aerosol (seen as ions in the snow) reveal where the influencing sources are located. The calculated scale heights for different ions indicate where in the atmosphere they were transported (regional marine compounds in lower layers, long-range transport compounds at higher levels of the atmosphere). The deposition patterns along transport paths (showing a decrease with distance) are connected to deposition processes in the present climate.

Methods and equipment

To make sure the samples were taken without contamination from local sources, sampling was performed in three stages: first the main pit was dug using normal shovels and clothing. Then the upwind wall for sampling was prepared after which the sampling itself took place. These last two stages were performed in clean suits and with clean equipment. All tools used for sampling are made of polyethylene, and were thoroughly washed with double-deionized water (resistivity > 18 MΩ) from a Milli-Q system. Samples were collected in pre-cleaned (double-deionized water) 60 ml polypropylene Nalgene bottles.

Fieldwork and preliminary results

During the traverse a total number of 10 snow pits was dug, all 2 m deep (Table 2), and sampled at 2 cm intervals. Each pit was situated 100 - 150 m upwind of any local contamination source such as Hägglunds, snow mobiles and generators. The upwind wall was used for sampling and all spoils were dumped in the downwind direction in order to avoid direct contamination. All samples were transported in isolated boxes to Stockholm. After the sampling, density was measured with a resolution of 5 cm.

The first three pits at sites A, B and C, were sampled according to the technique used during the Swedish ITASE traverse 1993/94, which means collecting the samples from top to bottom. In order to get better data quality, a new sampling routine was used on the remaining sites. Here, instead of sampling from top to bottom, the sampling started from a depth of 180 cm and samples were collected every 2 cm up to the surface. By doing so, it was avoided that snow from higher levels fell down on the remaining sampling surface, thereby contaminating it.

5. Snow radar

Aims

Snow accumulation is a mass balance parameter that is characterised by large variations over the ice sheet surface. When an initially even snow cover is exposed to wind, the snow may be redistributed in a pattern with a very high spatial variability. Surface topography has a strong impact on the wind systems, and thus also on the snow accumulation pattern. The highest spatial variability in snow accumulation can therefore be expected in areas with an undulating surface topography. The snow cover may be redistributed also in areas with a flat surface, resulting in sastrugi fields. When locating a suitable drill site for the EPICA deep core it is important to find a place characterised by a low spatial variability in snow accumulation. Otherwise the climatic information obtained from the core may not be representative for the area and difficult to interpret. High resolution snow radar soundings give an opportunity to obtain information on the present snow cover distribution along continuous profiles. This two-dimensional information is an important complement to the traditional point studies of snow accumulation, such as stake measurements, pit studies and firn- and ice core analyses.

The information obtained from snow radar soundings is also important in a more general context, namely the mass balance of the Antarctic ice sheet. The ice sheet mass balance is a matter of great concern in discussions and predictions of ice sheet response to climatic change. The present-day mass balance is not well established. The main reason for this is that large parts of the Antarctic continent are still unknown, with a lack of field data on mass balance parameters. The data available on snow accumulation consists primarily of point measurements concentrated to the easily accessible regions near the coast. In calculations of the ice sheet mass balance the snow accumulation has to be estimated for very large parts of the ice sheet. This introduces significant uncertainties. Continuous snow radar registrations along profiles give information on the spatial variability in snow accumulation to make reliable estimates of accumulation rates over large areas.

The principal aim of this study is to map the spatial variations of snow accumulation. A continuous snow radar profile has been recorded extending from the ice shelf to the polar plateau at 3500 m a.s.l. At coring locations, the radar registrations will be used to determine the spatial representativity of the cores with respect to snow accumulation. The relations between spatial variability in accumulation and physical parameters such as surface slope and topography, altitude, distance from mountain ranges and open sea will be analysed. The investigated region will also be divided into areas with characteristic spatial variability in snow accumulation.

Methods and equipment

The snow radar registrations reveal subsurface stratigraphy of the snow pack along the profile (Fig. 5a). The snow layers are assumed to represent time horizons, i.e. one layer has been formed during a specific occasion or limited period of time. In the processing of the data the principle is to follow a specific reference layer throughout the registrations along the travel route in order to register the variations in snow layer depth. In order to obtain the annual average accumulation rate along the route, the snow layer will be dated through correlation to firn core analyses. The radar profiles were positioned by GPS measurements using a logging interval of 15 s, corresponding to a horizontal distance of 35-40 m. The GPS data will be corrected differentially against a reference station that was operational at Troll station. The distance between adjacent sounding points was set to 5 m, giving a very high spatial resolution of the data.

The depth of the reference layer is calculated by using density data from firn cores that were retrieved along the travel route. Snow depth is transformed into water equivalents using density data from the firn cores. When calculating the depth of the reference layer, it is necessary to make a geometric correction for the non-vertical ray path related to antenna separation. However, refraction effects in the snow pack may be neglected. The above described method has been reported by Richardson *et al.* (in press). The radar has previously been used for studies of spatial variability in snow accumulation along a 1040 km long profile located approximately 10° further west in Dronning Maud Land (Richardson, 1995). The snow radar used is a synthetic pulse stepped frequency carrier wave radar, described in Hamran and Aarholt (1993) and Hamran *et al.* (1995). The system is based on a HP Network Analyser (8753B), transmitting a sequence of 201 frequencies evenly distributed over an adjustable bandwidth (maximum range 0.3-3.0 GHz). The radar is controlled by a 486 computer. Two different frequency ranges were applied using two types of antennae (Table 3). A dual-frequency GPS, P-code (Ashtec Z XII) was used for positioning the radar registrations. The radar was installed in one of the Hägglunds with the antennae mounted on a steel frame on the outside of the vehicle.

Fieldwork and preliminary results

Radar soundings were performed continuously along the trail from the shelf edge at the eastern unloading place (70° 08'S, 05°16'E) to Troll station, and from Troll to the EPICA traverse turning point on the polar plateau (75°S, 15°E, Fig. 2). All sections were sounded using both antennae type A and B (Fig. 5a, b). On the polar plateau, transverse profiles with length ranging between 1 and 10 km were recorded at a number of sites (Table 4), in order to determine the geographical representativity of accumulation data derived from firn cores.

Although the radar data are not yet processed, some preliminary results can be given. On the polar plateau, good results were obtained from the shallow radar sounding down to 12 m depth. There appears to be a snow layer which is possible to trace along the entire traverse route. The lower frequency antennae gave less good results. Layering within the upper 50 m snow pack was recorded in some areas, but seems to be absent in general. Detailed post processing may help to reveal layering in these data. In the coastal area good results were obtained using both antenna types, revealing clear layering in the snow pack at shallow depths (down to 12 m) as well as at larger depths (down to 50 m). The shallow snow radar soundings will be calibrated and dated, by using data from firn cores that were drilled at sites S_{20}, S_{15} and A.

In the beginning of the season (4-7 January 1997) it was found that the registrations recorded around noon were of a poor quality, impaired with strong surface reflections and indistinct snow layering.

***Table 3.** Data on snow radar antennae and radar characteristics.*

Antenna type	*Notation*	*Frequency range (MHz)*	*Penetration depth (m)*
A	AEL APN-106AA	800-2300	12
B	Allgon 7125.04.05.00	750-1050	50

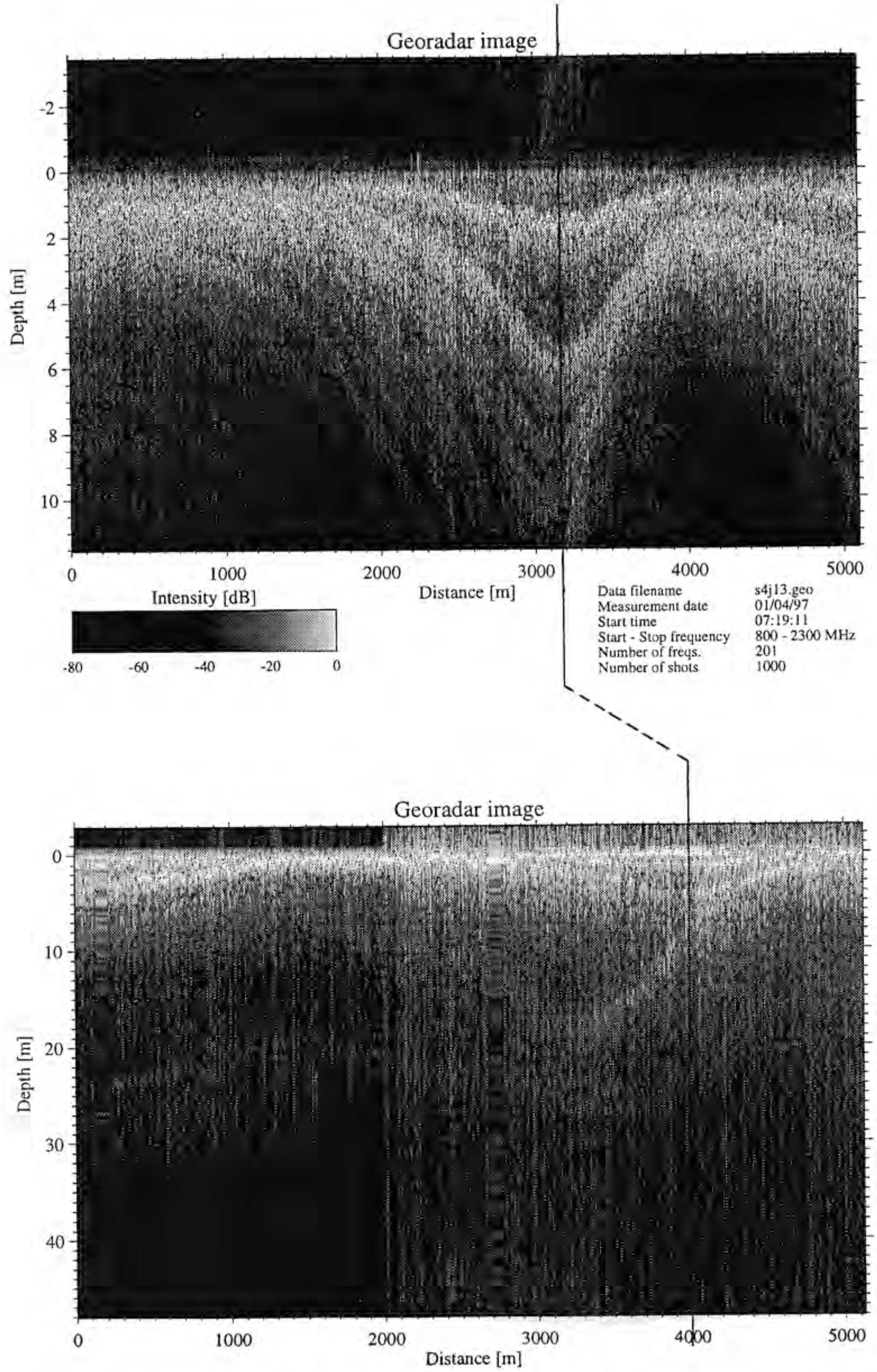


Fig. 5. Radar registrations retrieved along the same profile (70°45' S, 05°19' E - 70°47' S, 05°17' E), using different frequency ranges. Fig. 5a (upper panel) shows the stratigraphy within the upper 12 m of the snow pack (antenna A). Fig. 5b (lower panel) reveals the layering within the upper 50 m (antenna B). The location of the registrations is not perfectly matching, and we have inserted vertical lines to indicate shots taken at the same position. Note that the snow layer geometry is dislocated at greater depth, indicating a shift in the accumulation pattern over longer time periods.

Table 4. *Length of transverse radar profiles recorded at various drill sites.*

Site	*Total length of perpendicular profile*	*Comments*
C	1 km	
D	-	unsafe area
E	2.5 km towards SW	unsafe area to NE
F to L	5 km	
M	10 km	

This problem was probably generated by the relatively high air temperatures and associated melting at the snow surface. At the high frequencies used (800 - 2300 MHz) the radar is very sensitive to liquid water, which causes a strong reflection and makes it difficult to penetrate through the surface. The snow radar soundings were repeated along the same trail at lower temperatures in the end of the season (14-16 February), this time with good results. We also found that the high frequency antennae (A) caused disturbances of the navigation c/a-code GPS receiver (Garmin 120) and to some extent also of the logging p-code GPS receiver. Efforts to separate the radar and GPS antennae as far as possible and using metal shields did not reduce the disturbances to an acceptable level. The Trimble Navigator GPS receiver was not disturbed by the high frequency radar signal.

Calibration tests of the snow radar were made at site A, where steel reflectors were pushed into the snow pack at two different depths, 205 cm and 155 cm. The reflectors were marked by four bamboo stakes along a 2-3 m line. The reflectors and bamboo stakes were left at site A, and the reflector depths may be resurveyed by manual probing. The tests were performed in warm weather around noon (possible surface melting) on 6th January 1997 and in cooler weather (no surface melting) on 9th February 1997.

The ground based snow radar soundings will be compared to ERS-2 data in order to test the possibilities to determine spatial variability in snow accumulation from satellite images. The ERS-2 takes registrations at 5.3 GHz, and the images have a spatial ground resolution of approximately 25×25 m. Four corner reflectors were placed out at EPICA site C at (72°15'07"S, 02°53'39"E; 72°15'35"S, 02°52'34"E; 72°15'39"S, 02°52'39"E; 72°15'07"S, 02°53'24"E), with inclination 27° and horizontal direction 199° S. The ERS-2- passage was on the 2nd of February. The radar soundings were performed in a grid-net on the 5th of February, and by that time the surface was covered with recently fallen snow. Photographs and notes on the snow surface characteristics were taken at corner reflector positions.

6. Ice depth radar

Aims

An ice depth radar was brought to map ice thickness variations and internal layering along the traverse. The radar was kindly lent to us by the British Antarctic Survey (BAS) in Cambridge. Data on ice thickness is necessary when calculating the mass balance, ice flow patterns and bedrock topography. In addition, the ice depth measurements may tell us whether there are cold- or temperate conditions at the ice sheet base.

Methods and equipment

The radar is based on three units: a BAS 60 MHz valve transmitter, a 60 MHz log receiver and a Tektronix 520 oscilloscope. Antennas used were of Yagi type. The system has been developed by H. Corr at BAS.

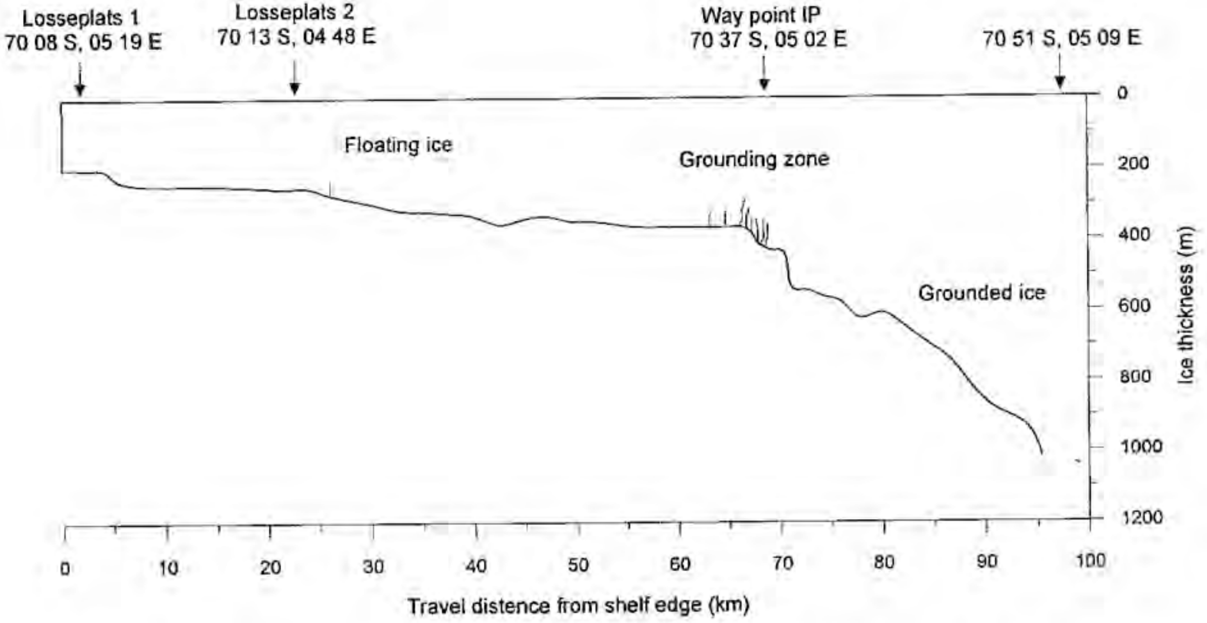


Fig. 6. Ice thickness profile of the ice shelf and grounding zone. Basal crevasses are indicated.

Fieldwork and preliminary results

Ice depth soundings were taken continuously along the trail from the shelf edge at the eastern unloading location to Troll station. Depth soundings were also performed along the initial part of the EPICA traverse on the polar plateau (Fig. 2). Unfortunately, the radar did not work properly and the maximum penetration depth recorded was about 1000 m. The functioning of various system components was tested in the field, but no failing part was found. However, bottom reflections were obtained along the trail from the shelf edge and approximately 100 km inland towards Troll (Fig. 6). We interpreted the location of the grounding line from the occurrence of basal crevasses. The crevasse density increased from a travel distance of 64 km until the 70 km point, and further inland no basal crevasses occurred. Along some sections north of Troll, internal layers were recorded at shallow depth (less than 220 m). Bottom reflections were registered nearby the mountain range Mühlig-Hoffmannfjella, where the maximum ice depth was less, about 600 m. The ice thickness beneath the glacier Slithallet is shown in Fig. 7. No bed reflections or internal layering was registered on the polar plateau except nearby the mountain range. We tried to modify the radar system in order to improve the possibilities to pick up internal layers on the expense of bed reflections, but without success. Fortunately, the German airborne radio-echo sounding programme collected data on ice depth by flying over the tracks of the traverse.

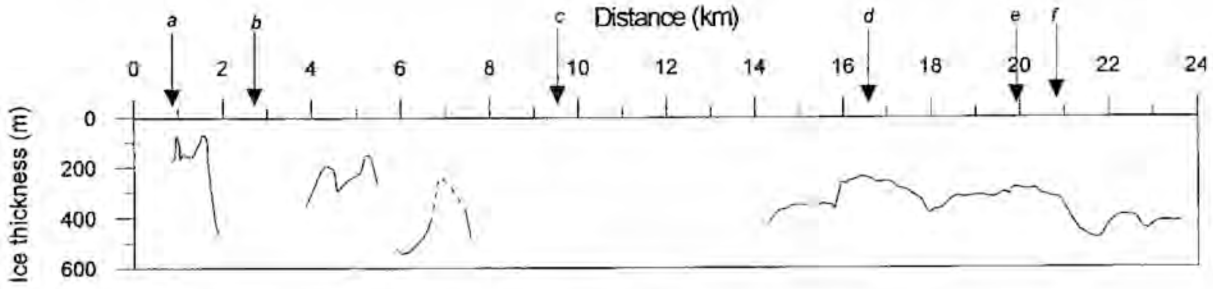


Fig. 7. Ice thickness profile from N to S along Slithallet, Muhlig-Hoffmanfjella. Positions: a) 71°56' S, 02°54' E; b) 71°57' S, 02°55' E; c) 72°01' S, 02°57' E; d) 72°05' S, 02°58' E; e) 72°06' S, 03°00' E; f)72°07' S, 03°04' E.

7. Meteorology

Aims

The meteorological activities during the traverse were focused on the erection of 3 Automatic Weather Stations (AWS) and the launching of a series of meteorological balloons. These data will hopefully learn us more on moisture transport mechanisms from the coastal areas towards the East Antarctic plateau. West DML is one of the least explored areas in the world, and the AWS data therefore also serve a general climatological interest. It is well known that synoptic disturbances that migrate eastwards along the coast of Antarctica do not penetrate far inland, and that the moisture content of the atmosphere decreases quickly further inland: by situating the AWS at different distances from the coast, moisture and heat transport processes can be studied in more detail. The moisture transport towards Antarctica takes place mainly in the free atmosphere (Fortuin and Oerlemans, 1992), whereas the layers closest to the surface experience flow towards the coast. Especially at the high Antarctic plateau, an important part of the accumulation takes place through deposition of ice crystals in the lowest layers of the atmosphere. With the employment of meteorological balloons the structure of this part and upper parts of the atmosphere can be mapped, and the main processes identified.

Methods and equipment

The AWS are designed by the technical staff of IMAU, and are of the same type as those employed previously in Greenland, Iceland and Antarctica (Berkner Island). The stations are dug in the snow in such a way that only the mast, sensor arms and 4 guying cables are above the snow, the sensors initially being 3 m above the surface. Temperature, humidity, wind speed and direction, radiation and snow height are measured with Aanderaa sensors. Two stations (those situated at sites A and M) are equipped with a thermistorstring with temperature sensors of the type Pt 100. At these stations, firn temperatures are measured at 0.25, 0.5, 1, 2, 4, 8 and 16 m depth. Sampling interval is 2 minutes, and with every passing of a polar orbiting satellite, the measurements of a 6 h period are transmitted to the Netherlands via the ARGOS satellite communication system. The stations operate on a set of Lithium batteries that can power the station for about 3 years.

For the balloon sounding system, a standard Vaisala MW 12 rawinsonde set was used to follow the 200 g He-filled balloons that carry up the sonde (Vaisala RS80-18G). This system is also used at many national meteorological services. The rawinsonde set collects upper air pressure, temperature, humidity, wind speed and direction with great precision, and automatically processes them into ASCII files. The MW12 system consists of a basic unit and software configuration, but with different options for wind finding. The system includes a Rawinsonde set, an UHF receiver and telemetry antenna, a PTU data processor, a data recorder with 2 DD diskette drives and a printer. Used probably for the first time in Antarctica, and certainly in Dronning Maud Land, is the newly developed GPS-based wind-finding. The special sonde contains a codeless, 8-channel digital GPS receiver with down transmission of the GPS data with 1200-baud FSK modulation and a wind vector update of 2 Hz. The wind computation is performed by the ground station.

Table 5. *Specifications of the Vaisala RS80-18G sonde.*

Measured variable	*Range*	*Reproducibility*[1]
Pressure	1060 to 3 hPa	0.5 hPa
Temperature	+60 to -90 °C	0.2 °C up to 50 hPa
Humidity	0 to 100 %	< 3 %
Wind vector	0 to 180 m s^{-1}	0.5 - 0.2 m s^{-1}

[1] *Data based on WMO International Radiosonde Comparison Phase I, II and III (WMO TD-195 and 451)*

***Table 6.** Installation details of Automatic Weather Stations (AWS).*

	Site A	*Site C*	*Site M*
Station no.	AWS-1	AWS-3	AWS-2
Connection date	31 Dec. 1996	3 Jan. 1997	28 Jan. 1997
Connection time (GMT)	11:50 GMT	13:00 GMT	14:50 GMT
cm of snow covering data logger	32	28	28
Position relative to drill site	6.4 m at 240°	-	6 m at 110°
Max. depth thermistor string	13 m	-	16 m
Data transmission to Utrecht ?	yes	no	yes

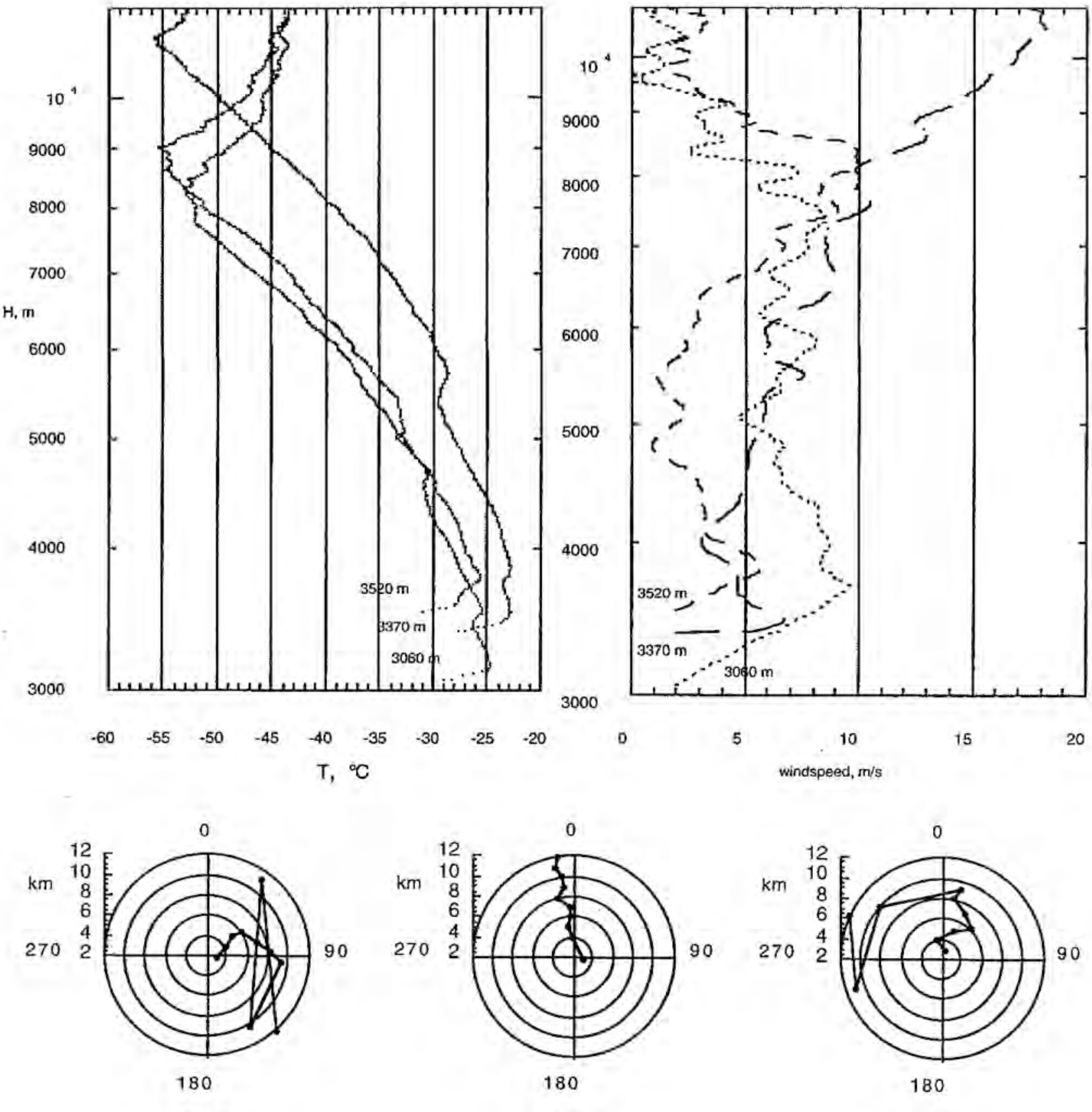
The measuring accuracy is twice as good as previous systems based on OMEGA or LORAN-C ground navigation. This GPS system is invaluable for Antarctic operations, as the older ground navigation systems are not reliable south of 73°S. Measurement specifications of the sonde are given in Table 5.

Field work and preliminary results

Before the start of the traverse, the three AWS were tested at Troll to see if any damage had occurred during transport. During intercomparison tests in Cabauw (The Netherlands) all internal systems had functioned well. During testing at Troll, however, the transmission of AWS-3 malfunctioned (probably due to problems in the ARGOS transmitter), and it was decided to place that station at site C. The internal datalogger is capable of storing data locally for at least 2 years. Because this site is relatively easily accessible from Troll station, we hope that the station can be repaired and the raw data collected within the next two years. Balloon sounding tests were carried out at Troll station. For comparison purposes, two soundings were performed at approximately the same time as at Neumayer station. A handhold tethered balloon system was also tested, using a kevlar cable. This system worked to an altitude of about 250 meters above ground level. After return to Troll three more balloons were launched.

***Table 7.** Overview of balloon soundings during the traverse*

Date	*Time (GMT)*	*Location*	*Weather type*
20 Jan.	22:15	site H	clearing up after whiteout, drifting
21 Jan.	23:00	site I	6/8 *As* clouds, good visibility
22 Jan.	22:00	73°56'S 08°58'E	1/8 *As* after whiteout
23 Jan.	07:00, 22:30	73°56'S 08°58'E, site K	sunny, 2/8 *Ci*
24 Jan.	10:00, 22:45	site K, site L	sunny, in evening 6/8 *Ac*
26 Jan.	15:30, 22:30	site M	sunny, some *Ac/As* clouds
27 Jan.	03:30, 09:30, 15:30, 21:30	site M	sun shining through 6/8 *As/Ci*
28 Jan.	03:30, 09:30, 16:00, 21:30	site M	7/8 *As*, some drift snow
29 Jan.	03:30	site M	6/8 *As*, sunny
30 Jan.	00:00, 18:30	site L, site K	mostly sunny, few high clouds 2/8 *As*
31 Jan.	07:00, 21:00	site K, site J	sunny, more cloud in evening 7/8 *As*
1 Feb.	07:15, 13:30, 19:00	site J, 73°50'S, 08°30'E, site I	sun shining through 7/8 *As*
2 Feb.	07:00, 20:45	site I, 73°14'S 05°53' E	sunny, 2/8 *Ac*
3 Feb.	14:00	73°02'S 05°06'E	drift snow, clouded 7/8 *St/As*
4 Feb.	21:45	site C	drift snow 6/8 *As*, clearing up
5 Feb.	07:00, 13:00, 17:45, 00:15	site C	sunny with high cloud 6/8 *As/Ci*



Site H
20 Jan. 97
3060 m

Site K
23 Jan. 97
3370 m

Site M
26 Jan. 97
3520 m

Fig. 8. Temperature and wind speed profiles and polar graphs of wind direction (showing changes with height) obtained around 22:30 GMT on the plateau. Measurements at site K are distinctly different from those at sites H and M: winds are from the north throughout the troposphere (approximately the first ten kilometres of the atmosphere) and temperatures significantly higher, resulting in a elevated position of the tropopause. Also note the temperature inversion close to the surface, a typical night-time phenomenon during the Antarctic summer but a permanent feature during the winter (Van den Broeke and Bintanja, 1995).

During the traverse, three to four times during each day clouds, snowdrift, pressure, temperature, relative humidity, wind and position were recorded in a logbook. The weather on the high plateau was generally fairly good. Most of the time Cirrus (*Ci*), Altocumulus (*Ac*) and Altostratus (*As*) clouds were observed between 0/8 and 4/8 only. Half a day was counted as whiteout. Most of the time there was little wind, typically between 1 and 3 m s^{-1}, blowing from a north-easterly direction. A wind speed of 8 m s^{-1} was recorded at the turning point, in combination with a temperature around -40°C. During the traverse, temperatures ranged between -13 and -45°C. Two AWS were successfully placed along the traverse at sites C and M, whereas the third AWS was erected at site A (Table 6). No AWS data can be shown before the raw data have been processed..

It was planned to take regular balloon soundings during clear weather. Moreover, during at least one full day period four soundings were to be taken in order to cover the different solar radiation balances at the surface. Table 7 shows that both objectives were fully met by successfully launching 33 balloons between 20 January and 5 February 1997. Most soundings were performed during good weather, but at the end of the traverse some balloons were released during clouded conditions with snowdrift. In Fig. 8 we present some preliminary results of the balloon soundings. Temperature, wind speed and a polar diagram giving the main changes of wind with height, are shown for three different sites and corresponding launching elevation of the surface. Further study of this kind of profiles, weather maps and data of the AWS hopefully will give clues on the Atlantic influence ('Atlantic signal') in this part of Dronning Maud Land.

8. Surface topography, ice velocity and ice deformation

Aims

Continuous kinematic GPS measurements were performed along the driven track and in a corridor 5 kilometres to each side of the track to determine surface elevation. This will enable us to compile a terrain model of the surface topography in a narrow band along the track. Because ice velocity is expected to be low, reliable measurements of this quantity are obtained through precise positioning of stakes, and remeasurement after some years. To this end, a set of stakes (3 on each location, one on the track and two 5 km on each side) was set out every 60 km (at drilling sites) and measured as static GPS. Ice in motion will undergo some degree of deformation, and a precisely positioned strain network can show strain at the sub centimetre level when remeasured. Because remeasurement of the EPICA strain nets are planned within several years, accuracy at the cm level can be obtained.

Methods and equipment

Measurements were performed with Ashtech Z-XII dual frequency GPS receivers. The Z-tracking of the Ashtech receivers gives very good phase measurements on both the frequencies used, with very few cycle slips, and are as such well suited for continuous kinematic GPS measurements. A total of four GPS receivers was brought on the traverse, together with the necessary equipment for downloading and processing data. One receiver was continuously operating at Troll station to provide a set of reference positions. GPS data collected for surface profiling and static stake measurements will be processed relative to the Troll receiver. This will give long distances between the reference station and the measuring units in the field, especially at the end of the traverse, which is unfavourable for the accuracy. However, it was the nearest and only possible reference station in operation.

Surface profiling was performed with one receiver permanently recording on one of the Hägglund vehicles along the main track, while one receiver was operated on a sledge towed by a snow mobile. The snow mobile crossed the main track under a 45 degree angle and operated within a 5 km wide corridor centred around the main track. Positions were logged every 15 seconds, yielding a resolution higher than 100 m along the main track, and 100-150 m along the crossing track. For ice velocity measurements, data were recorded for some hours at each stake, with longer periods used (3-6 hours) at the southernmost points, where the distance to the reference station were largest. The two strain networks (sites K and M) consisted of nine stakes in a 2 by 2 km square. Locations were fixed with two stakes occupied with static reference receivers, while one receiver was moved around to the remaining 7 stakes, thus giving two vectors for each stake. All the stakes were visited twice in the measuring session of about 3 hours.

Fieldwork and preliminary results

On the inward trip, the Hägglund with GPS receivers was also equipped with the snow radar. Preliminary checks of the data showed that parts of the measurements were very noisy, with some data gaps as well. On the return trip the other Hägglund was also equipped with a receiver, which improved the situation. The data that have been processed so far indicate that a position error (one sigma) better than 0.25 metres can be achieved for most of the time. The estimated accuracy is probably too optimistic for the absolute altitude, but is expected to be representative for the epoch-to-epoch accuracy, or the relative accuracy of heights along the profile.

The stake positions for ice velocity have so far been calculated using the Ashtech PRISM software package for static GPS processing. The PRISM software is probably not ideal to get the best accuracy for the very long baselines, and a final processing is planned with other software. The preliminary results for each group of stakes has been corrected using a least squares adjustment relative to Troll station, giving results at the 0.1-0.3 m level for the southernmost points. Future processing will probably give results around 0.1 m or better for all velocity stakes. The strain nets have been processed using the PNAV kinematic GPS software from Ashtech, and the resulting vectors between stakes have been adjusted. The results are close to what could be expected, i.e. with adjusted relative accuracy of 3-5 ppm horizontally and somewhat better vertically. The better results for vertical positions can be explained from the small movements of the top each stake between occupations, which mainly influences the horizontal position.

9. Other work

10 m temperature

In each borehole 10 m temperature was measured with an ordinary thermistor cable. The seasonal cycle of temperature at this depth is reduced to 5% of the surface value. Therefore the 10 m temperature is a reasonably reliable measure for the yearly averaged surface temperature (Loewe, 1970). However, one should be careful when performing these measurements, because a significant period, preferably 10-20 hours (Seppälä, 1992) is needed for air in the borehole to settle down, the frictional heat of the drilling to dissipate away and the cable and sensor to reach thermal equilibrium with their environment. During the traverse, it was usually possible to leave the sensor in the borehole overnight, after which the reading was stable. Results of these temperature measurements are summarised in Table 2.

Figure 9 shows 10 m potential temperature, (corrected for height differences) together with the surface elevation as a function of the distance from the coast (assumed to be at 70°S). The maximum in potential temperature that occurs at the steepest part of the topography illustrates the influence of strong winds. These winds prohibit the formation of strong surface inversions and hence cause the surface temperatures to be higher. Strong winds, high temperatures and low relative humidity are probably responsible for the existence of blue ice areas in Dronning Maud Land, and the present data will for instance enable us to make a physical interpretation of temperature gradients observed between the AWS that were erected along the traverse route (see Section 7: Meteorology).

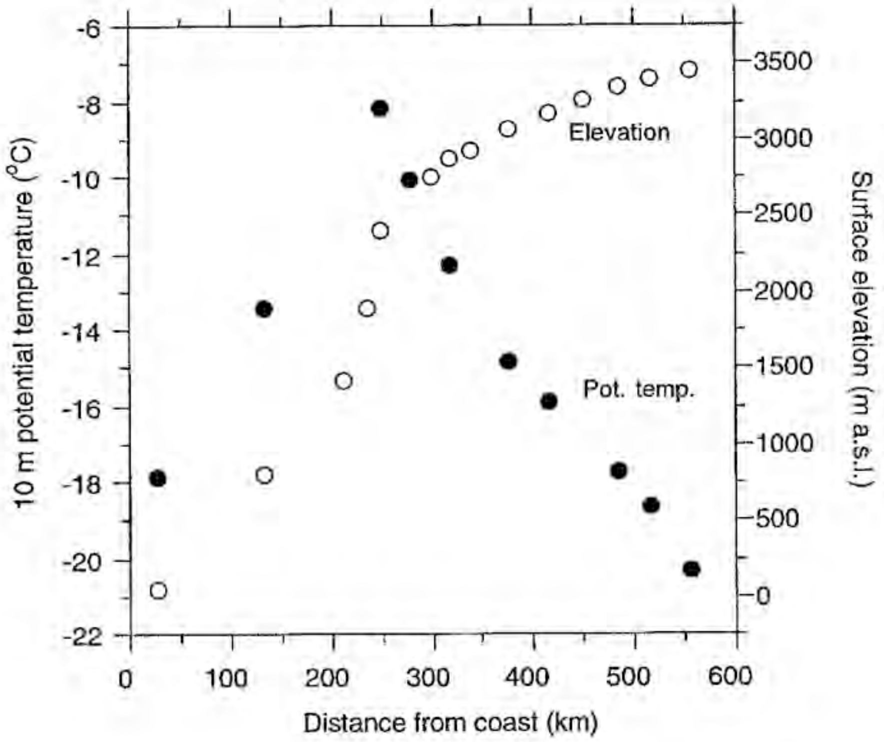


Fig. 9. *Potential temperature vs. elevation. Potential temperature is the temperature which a parcel of air would have if it were transported to sea level without heat exchange with the surroundings.*

Spectral albedo

Snow and ice reflect solar radiation very efficiently such that little of the incoming solar radiation is absorbed at the surface in polar regions. Even so, small changes in surface reflectance can affect the earth-atmosphere energy balance (Warren and Wiscombe, 1985). Thus, it is important to monitor and calculate the variability of the albedo of snow and ice. Accurate calculations of the energy exchange between snow and ice surfaces and the surrounding air mass can then be carried out.

The reflectance of snow and glacier ice shows a clear dependence on wavelength. Typically, the fraction of radiation reflected from fresh snow remains high in the visible region while a distinct drop occurs in the near infra-red region of the electromagnetic spectrum. Satellites like Landsat TM (Thematic Mapper), NOAA AVHRR (Advanced Very High Resolution Radiometer), and SPOT (Système Probatoire pour l'Observation de la Terre) carry sensors that record surface reflectance within the visible and infra-red wavelength regions. Consequently, satellite remote sensing enables studies to be made of surface characteristics such as topography, temperature, grain size variations, melting areas, and snow and glacier ice facies (Orheim and Lucchitta, 1988; Winther, 1993).

A FieldSpec radiometer was used to measure spectral albedo of snow surfaces both as ground truth measurements and for more basic studies of the variability of surface albedo at the polar plateau. Measurements were taken at sites A, B, C, M and around the Troll Station. Several measurements were taken at each location. The spectral measurements were supported by weather observations and the sampling of snow at different depths for later analysis of physical parameters like crystal size, shape and perimeter. The spectral reflectance data have not yet been processed.

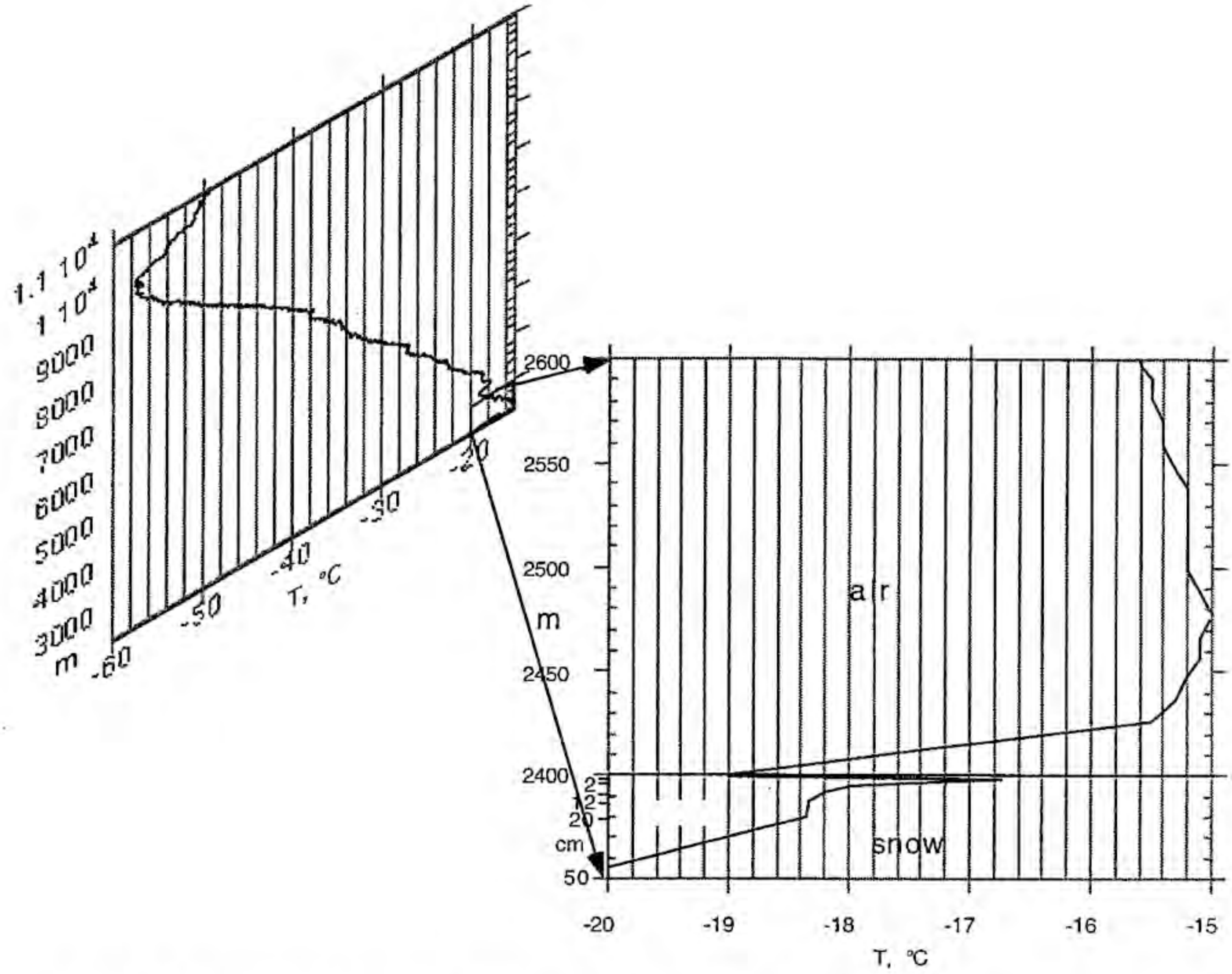


Fig. 10. Air and snow temperature measurements on 5 February 1997 at site C, 08:00 GMT.

Snow pit temperatures
For heat balance studies it is interesting to know the snow temperatures very precisely. At several places snow temperatures were measured at depths of 10 and 20 cm, and in a snow pit at site C temperatures at various depths up to 2 meter were measured every 4 hours during 24 h. Figure 10 shows a first result. Air and snow pit temperature measurements are combined to show the steep temperature gradients in both air and snow close to the air-snow interface.

Coffee cans
Coffee cans are markers that have been fixed at a certain depth in the firn pack (Hulbe and Whillans, 1994). A steel wire that is connected to the marker protrudes above the snow, and the absolute height of a point on this wire is measured with GPS with mm accuracy. By remeasuring several years later, the vertical displacement of the wire (and thus the marker) represents the sum of accumulation, densification of the firn pack between the surface and the marker and the vertical velocity of the ice. If the accumulation and densification are known (e.g. by shallow firn cores) and the vertical velocity component of the ice is estimated from the surface slope, the remaining vertical displacement will then reveal if the ice sheet is growing or shrinking. To reveal non-linearity of log-density with depth, at least

three coffee cans should be installed within several meters distance. 5 coffee cans was installed, 3 at site C (at depths of 17.5, 12.2 and 6.6 m) and one each at sites H (9.8 m) and K (9.9 m).

Accumulation stakes

A total of as much as 63 aluminium stakes (5 m long, diameter 32 mm, thickness 3.2 mm) was put out along the route, both from the shelf to Troll and on the plateau. Most of these stakes serve primarily as GPS reference points for ice velocity and ice deformation. Two stakes were placed close to each drilling location to determine the local accumulation independently from the firn cores.

10. Logistics

Vehicles

Two Hägglund tracked vehicles were used during the traverse. The same vehicles were also used on NARE 92/93 and have been stored at the Troll and Tor stations in DML since then. The two vehicles were equipped with a flatbed on the rear chassis for carrying loads. In addition one vehicle had a hydraulic crane and a snow plough, and the other a snow melting system (borrowed from Swedish Polar Research Secretariat), in which water was produced by circulating cooling water of the engine through the melter. Both Hägglunds were powered by a Mercedes Benz 6-cylinder turbo-charged diesel engine with a high altitude converter. HF and VHF radio and GPS were installed in the cabins. Fuel used for the engines was Jet-A1 mixed with 0.5% pro-long. Normally, the fuel consumption was 25-30 litres per 10 km, the speed with loads on the way south being 5-8 km h^{-1}. With light loads and downhill the speed increased to 12-15 km h^{-1}. When outdoor temperatures were below -25°C, the engines ran continuously on idle. Two short stops were necessary because of technical problems, namely a broken fan belt and a broken drive axle. Except for these minor problems the vehicles ran very well and needed only ordinary maintenance. Two four-runner sledges with sizes 6.1x2.4 metres were pulled by the Hägglunds. The maximum load we had on each sledge was about 8000 kg, while the weight of the sledge itself is 1350 kg.

We used four new snow mobiles type Polaris Widetrack LX, with water-cooled 500 cc engines, low/high forward and reverse gears and handwarmers. Two of the snow mobiles were equipped with GPS. Fuel consumption was 2-3 litres per 10 km. The snow mobiles, each with one sledge, were mainly used by the drilling and GPS teams and for reconnaissance and marking of the route. Each snow mobile group was always equipped with VHF radios, emergency beacon, tent, sleeping bags, food as well as equipment necessary for reconnaissance and, if necessary, rescue in crevassed areas.

Power supply

The traverse team needed 220 volts for scientific use. The main generator was a Hatz diesel 1D41Z/24 V with electric start, producing 4.5 kW. As a spare generator we had a smaller Hatz diesel E673 R36 of 3 kW. Both generators used Jet-A1 for fuel. The drilling group also made use of a portable generator, a Honda EX 1 kW.

Communication

Each day at 20 GMT the traverse team contacted Troll Station. On the traverse we had three systems for ordinary communication and one emergency system:

- A portable Inmarsat system from ABB with voice and e-mail system, powered by 12-36 V or 220 V. This system worked well during the entire traverse.

- Each Hägglund was equipped with a Icom IC-735 HF radio (100 W) and an automatic antenna tuner. A dipole antenna was used for communication with Troll Station. About 50% of the time we were standby for Troll. We had successful contacts with Troll around 80% of the time (at 20 GMT).
- VHF was used for internal communication (between snow mobile parties and the Hägglunds and between the two Hägglunds). In the Hägglunds and dwelling hut we used Icom VT 200 radios (25 W) with 2 m long antennas, while the snow mobile parties used hand-held Icom F30 LT radios (5 W).
- The traverse team carried three satellite-based emergency beacons, one on the tracked vehicle group and one on each of the snow mobile teams.

Accommodation

As cooking/dining/working facilities we brought two wooden huts. The largest hut measured 4 x 2.5 m and weighed app. 1000 kg. This hut was mainly used for cooking and eating. For cooking we used propane gas (about 30 kg propane for 3 weeks). For heating we had a Jet-A1 stove with a maximum capacity of 3 kW (fuel consumption 7-10 litres per day). An electric 1 kW stove was brought as spare. A VHF base station was mounted in this hut. The other hut measured 2.5 x 2.3 metres with a weight of 750 kg. This one was used for working and storage of temperature-sensitive scientific equipment. The Inmarsat system was placed in this hut, which was also equipped with two beds.

For sleeping we had one large Weatherhaven Endurance tent, comfortable for 6 persons. It was light (app. 40 kg) and easy to put up. On the plateau, night temperatures were well below -40°C, but with good sleeping equipment including light-weight bed, therm-a-rest mattress and woollen blanket the low temperatures generally created no problems.

11. Acknowledgements

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12. References

Fortuin, J. P. F. and J. Oerlemans, 1992: An atmospheric model for simulating the mass balance and temperature on the Antarctic ice sheet, *Zeitschrift für Gletscherkunde und Glazialgeologie* **26** (1), 31-56

Hammer, C. U., 1980: Acidity of polar ice cores in relation to absolute dating, past volcanism and radioechoes, *J. Glaciol.* **25**, 359-372.

Hamran, S-E. and E. Aarholt, 1993: Glacier study using wavenumber domain synthetic aperture radar: *Radio Sci.* **28** (4), 559-570.

Hamran, S-E., D.T. Gjessing, J. Hjelmstad and E. Aarholt, 1995: Ground penetration synthetic aperture radar: dynamic range and modes of operation. *J. Appl. Geophys.* **33**, 7-14.

Hulbe, C. L. and I. M. Whillans, 1994: A method for determining ice-thickness change at remote locations using GPS, *Ann. Glaciol.* **20**, 263-

Isaksson, E., W. Karlén, N. Gundestrup, P. Mayewski, S. Whitlow and M. Twickler, 1996: A century of accumulation and temperature changes in Dronning Maud Land, Antarctica, *J. Geophys. Res.* **101**, 7085-7094.

Loewe, F., 1970: Screen temperatures and 10 m temperatures, *J. Glaciol.* **9**, 263-268.

Orheim, O. and Lucchitta, B.K., 1988: Numerical analysis of Landsat thematic mapper images of Antarctica: Surface temperatures and physical properties. *Annals of Glaciology* **11**, 109-120.

Peel, D. A. and R. Mulvaney, 1992: Time-trends in the pattern of ocean-atmosphere exchange in an ice core from the Weddell Sea sector of Antarctica, *Tellus* **44B**, 430-442.

Seppälä, M., 1992: Stabilisation of snow temperature in Dronning Maud Land, Antarctica, January 1989, *Geografiske Annaler* **74A**, 227-230.

Richardson, C., 1995: Radar studies of snow accumulation and ice thickness, *in* Melander, O. and E. Grönlund *(eds.), Swedish Antarctic Research Programme 1993/94, a cruise report*, 20-26. Swedish Polar Research Secretariat, P.O. Box 5005, S-104 05 Stockholm, Sweden.

Richardson, C., E. Aarholt, S-E. Hamran, P. Holmlund and E. Isaksson: Spatial distribution of snow in western Dronning Maud Land, East Antarctica, mapped by a ground based snow radar. *J. Geophys. Res., (accepted Feb. 1997).*

Van den Broeke, M. R. and R. Bintanja, 1995: Summer time atmospheric circulation in the vicinity of a blue ice area in east Queen Maud Land, Antarctica, *Boundary-Layer Meteorol.* **72**, 411-438.

Warren, S.G. and Wiscombe, W.J., 1985: Dirty snow after nuclear war, *Nature* **313**, 467-470.

Winther, J-G., 1993: Landsat TM derived and in situ summer reflectance of glaciers in Svalbard. *Polar Research* **12(1)**, 37-55.