A meteorological and glaciological experiment on a blue ice area in the Heimefront Range, Queen Maud Land, Antarctica

SVEA 1992/93 Field Report

Institute for Marine and Atmospheric Research
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1. Introduction

The Antarctic continent is an important area for at least two reasons. The mass balance of the Antarctic ice sheet determines to great extend sea level changes on various time scales (Warrick and Oerlemans, 1991). Furthermore, since Antarctic ice can be very old it is possible to track quaternary climate change.

It is generally accepted that the Antarctic ice sheet has a positive surface mass balance everywhere. However, a number of small regions exist where the surface mass balance is negative. Apart from the dry valley's, these areas mostly occur in the vicinity of nunataks and mountain ranges and are commonly called blue (bare) ice areas. In these more or less wind-shielded areas, ice is moving upward and evaporates at the surface. These blue ice areas can maintain to exist if snow-drift divergence and precipitation are low and evaporation rates high. Both elements seem to exist as a result of the local climate around nunataks. Possibly, blue ice areas are sensitive to climate change (Orheim and Lucchitta, 1990)

Because of the upward moving ice flow, blue ice areas are the only places where very old ice might reach the surface. This provides an excellent and relatively cheap way to obtain Antarctic ice for $^{14}C/^{12}C$ dating, for relative dating via $\delta^{18}O$-concentrations and for a number of other kinds of analysis.

As part of the Norwegian/Swedish/Finnish expedition to Queen Maud Land, Antarctica (NARP/SWEDARP 92/93), a detailed meteorological experiment was carried out on a blue ice area near the Swedish research station SVEA (74° 35' S, 11° 13' W). This blue ice area is located in a U-shaped valley called Scharffenbergbotnen (Figure 1). The measuring period covered 49 days (23 December - 10 February) in which on 7 sites several meteorological quantities were measured. Furthermore, balloon soundings and synoptical observations were performed. The measuring period seems to be long enough to get insight in the meteorological processes over the blue ice area. In addition, ice cores and surface samples have been taken.

2. Logistics

In the joint Norwegian/Swedish/Finnish expeditions to Antarctica, these 3 countries are in turn responsible for the logistic organisation. In the 1992/93 expedition, it was Norway's turn. They arranged two ships, Lance and Polarbjørn, for transportation of equipment and people to Antarctica. The expedition members flew to Cape Town on the December 6 and then went on board Polarbjørn for a 11 day boat trip to Rampen, the ice shelf edge at 72° S, 16° W. Transportation on the Antarctic continent was carried out by helicopter or snow scooter. A list of the relevant activities concerning the expedition is given below:

May 16-23	training course in Norway with all expedition members
July 12-14	testing drilling equipment in Austria
September/October	calibrating and testing of meteorological equipment at the KNMI and at Cabauw, the Netherlands
November 10	departure of Polarbjørn from Bergen, Norway with all equipment
December 6/7	departure of Bintanja, van den Broeke and Portanger from Schiphol, Amsterdam and arrival at Cape Town
December 10	departure of Polarbjørn from Cape Town with expedition members
December 15	Polarbjørn passes Bouvet Island
December 22	Polarbjørn arrives at Rampen
December 22/23	helicopter transportation of equipment to Svea and Wasa
December 23	erection of mast 1 on plateau Amundsenisen
December 25/26	reference experiment
December 28/29	transportation of equipment from Wasa to Svea
January 1	first balloon sounding
January 9	first day of ice core drilling
January 19	transportation of ice cores to Wasa by snow scooter
February 10	last day of meteorological experiment
February 11	packing of equipment
February 12	transportation of equipment and people to Wasa by snow scooter
February 23/24	transportation of equipment to Rampen by snow scooter
February 26	transportation of ice cores to Polarbjørn by snow scooter/helicopter and retrieval of mast 1 by helicopter; Polarbjørn departs from Rampen
March 3	Polarbjørn passes Bouvet Island
March 8	Polarbjørn arrives at Cape Town
March 9	Expedition members arrive at Schiphol, Amsterdam
April 3	Polarbjørn arrives in Bergen, Norway

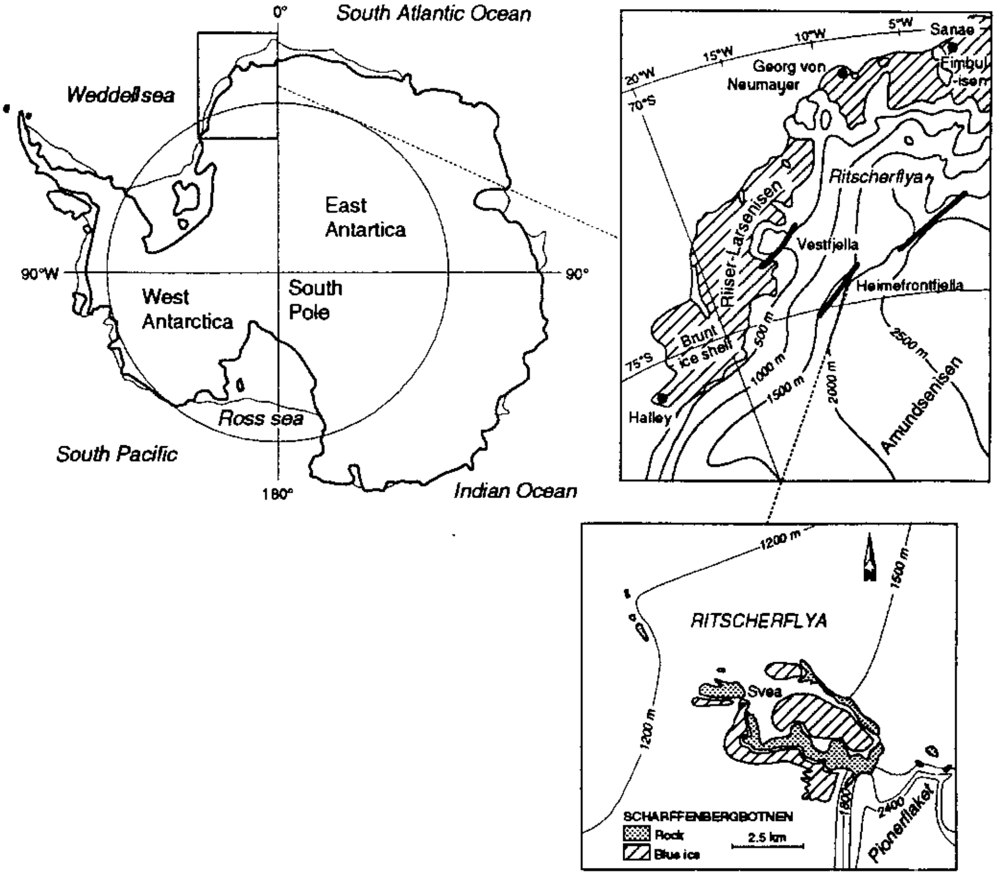


Figure 1. Map showing the location of the Heimefront Range and Scharffenbergbotnen valley in Antarctica

On the way up from Rampen to Svea it appeared that there was not enough helicopter fuel available to fly all equipment directly to Svea. Therefore, part of the equipment, including the drilling equipment, was transported to Wasa and picked up later with snow scooter. Also, most of the equipment was transported back from Svea to Rampen (350 km) by snow scooter. Mast 1 was the only mast which could not be reached during the experiment either by feet or snow scooter. Its transportation was therefore dependent on helicopter availability. Luckily, on December 23 and February 26 fair weather enabled us to use helicopter in placing and retrieving the mast, respectively. The other 6 masts were located in and around the Scharffenbergbotnen valley and could easily be reached by snow scooter.

The arrival of the Polarbjørn at Rampen.

3. Meteorological equipment and data acquisition

In essence, the equipment is the same as successfully used in earlier expeditions to Austria, Switzerland, Greenland (Bintanja et al. 1990, Boot et al., 1991) and Antarctica (Bintanja et al., 1991). It is used in ablation zones as well as in accumulation zones. In this experiment, we erected 7 masts, each containing several different sensors. The total construction consists of an aluminium frame with 4 legs on which the mast is attached. At several heights, horizontal bars are connected to the mast on which the sensors are mounted. The complete sensor configuration is given in the following table:

Mast 1	temperature at 2 and 6 m:	ventilated Aanderaa 2775
	wind speed at 2 and 6 m:	Aanderaa 2740
	wind direction at 6 m:	Aanderaa 2750
	short-wave radiation up and down at 1.5 m:	Kipp CM14
Mast 2	temperature at 0.5, 2 and 6 m:	ventilated Rotronic YA-100
	relative humidity at 0.5, 2 and 6 m:	ventilated Rotronic YA-100
	wind speed at 0.5, 2 and 6 m:	Aanderaa 2740
	wind direction at 6 m:	Aanderaa 2750
	short-wave radiation up and down at 1.5 m:	Kipp CM14
	total radiation up and down at 1.5 m:	Aanderaa 2811

Mast 3	temperature at 0.5, 2 and 6 m:	ventilated Rotronic YA-100
	relative humidity at 0.5, 2 and 6 m:	ventilated Rotronic YA-100
	wind speed at 0.5, 2 and 6 m:	Aanderaa 2740
	wind direction at 6 m:	Aanderaa 2750
	short-wave radiation up and down at 1.5 m:	Kipp CM14
	total radiation up and down at 1.5 m:	Aanderaa 2811
	snow temperature at -5, -10, -20, -40 and -80 cm:	PT500-probes
Mast 4	temperature at 2 and 6 m:	ventilated Aanderaa 2775
	wind speed at 2 and 6 m:	Aanderaa 2740
	wind direction at 6 m:	Aanderaa 2750
Mast 5	temperature at 2 and 6 m:	ventilated Aanderaa 2775
	wind speed at 2 and 6 m:	Aanderaa 2740
	wind direction at 6 m:	Aanderaa 2750
	short-wave radiation up and down at 1.5 m:	Kipp CM14
Mast 6	temperature at 2 and 6 m:	ventilated Aanderaa 2775
	wind speed at 2 and 6 m:	Aanderaa 2740
	wind direction at 6 m:	Aanderaa 2750
Mast 7	temperature at 2 and 6 m:	ventilated Rotronic YA-100
	relative humidity at 2 and 6 m:	ventilated Rotronic YA-100
	wind speed at 6 m:	Aanderaa 2740
	wind direction at 6 m:	Aanderaa 2750
	short-wave radiation up and down at 1.5 m:	Kipp CM14

Some specifications of the sensors:

sensor	type	range	unit	precision
air temperature	Aanderaa 2775	-44 to +49	°C	0.1
air temperature	Rotronic YA-100	-30 to +28	°C	0.1
humidity	Rotronic YA-100	0 to 100	%	2
wind speed	Aanderaa 2740	0.2 to 60	m/s	0.2
wind direction	Aanderaa 2750	0 to 360	deg	4

sensor	type	spectral range	precision
pyrradiometer	Aanderaa 2770	300 to 60000 nm	3 W/m^2
pyranometer	Kipp CM14	305 to 2800 nm	2 W/m^2

Each mast is equipped with a datalogger, in which data can be stored locally up to 28 hours, if necessary. Furthermore, there is a power unit (for ventilation of sensors and transmitting power) consisting of a 24 Ah battery, a 12 Watt solar panel and a backup lithium battery. Normally, the sampling frequency is 2 minutes. Data is transmitted to the computer in Svea about every hour. This system of data transmission is called RIDAS (Radio Interfacing Data Acquisition System). The system of sequential transmission of data by all masts on one frequency is fully computer steered. On-line graphical display of the data allows quick adjustments and provides more insight in on-going physical processes. When a complete day of data is received, 10, 30, 60 minute averages as well as daily averages are computed. Since the instruments were calibrated before the expedition, a complete 'cleaned' dataset is available the day after the measurements and further calculations can be performed. The complete data set of the 50 day measuring period amounts to approximately 80 Mb.

Mast 2, located on the blue ice area near the ice fall.

Specification of the applied data acquisition equipment:

- data loggers: especially made RUU
- radio transceiver: Kenwood TM431A/TH45
- radio-telemetry: Packet Radio, Protocol AX25, 1200 Baud, 451 MHz
- computers: Macintosh Powerbook 170, Macintosh IICX, Macintosh Portable
- two 44 Mb removable drives

Some problems have been come across with respect to the dataloggers. During certain periods, several dataloggers failed to send data or sent crippled data to the base station, probably somehow caused by low temperatures and/or drifting snow. Especially mast 5 suffered from this problem, which resulted in loss of data. Mast 1, situated on the plateau Amundsenisen, experienced heavy snow drift and rime causing the solar panel to be snow-covered completely. When the battery power became too low, it stopped transmitting. However, considering the extreme circumstances the total system worked quite good since 90 % of all possible data was obtained.

During 3 weeks of testing at Cabauw, the Netherlands, some inaccuracies in the temperature-, humidity- and radiation sensors have been observed. Therefore, it was decided to perform a reference experiment before the actual experiment started. On the 25th and 26th of December, mast 2, 3, 4, 5 and 7 were placed on a gentle snow slope near Svea. All sensors were placed at the same height above the surface to obtain good inter comparison. The results were appeasing, since the temperature sensors differed at most 0.4 °C, relative humidity 3% (absolute) and short-wave radiation 2% (relative).

Additionally, we attempted to measure the surface temperature at mast 2 and 3 during selected periods with a SOAR thermo-eye and a surface temperature sensor. Data from these sensors were stored in a Grant Squirrel 1200 Datalogger (12 channels) which was downloaded every 3 to 6 days. Actinic flux measurements were carried out at mast 2, 3 and 7 during selected periods as well. The latter sensor is especially made and has been used before in the Netherlands and the Azores.

The location of each mast was determined with GPS. For this purpose, as well as for navigation in the field, we used two hand-held Magellan GPS NAV-1000 receivers.

A cabled balloon sounding system was used to study the vertical structure of the atmospheric boundary layer. One sounding took about 45 - 60 minutes. They were performed at 03, 09, 15 and 21 GMT. During a total of nine days soundings were intensified to once every three hour. The system can only be operated if surface winds do not exceed 10 m/s, a condition fortunately often fulfilled during the 1992/93 expedition. Specifications of the system are listed below:

- balloon 1: 12 m^3, helium, type Airborne K-65, weight 7.3 kg
- balloon 2: identical to balloon 1 but with heavier coating
- cable: 2500 m Twaron, weight 1 g/m
- winch 1: electric, 750 Watt, especially made RUU
- winch 2: identical to winch 1
- sonde: AIR tethersonde with sensors for
    - air temperature
    - humidity from a carbon hygristor
    - wind speed
    - wind direction
    - pressure
- ADAS (Atmospheric Data Acquisition System) receiver operating at 404 MHz

The ADAS receives samples every 10 second and sends the data to the base station. In total, 100 soundings were carried out of which 95 can be used for data analysis. Some mechanical problems were encountered with the winches, but after repair they worked without problems. In table 1 some information about the balloon data set is summarised.

Time	**No.of ascents**	**General information**
		Average maximum altitude:
00 GMT	9	
03 GMT	13	Balloon 1 1413 m
06 GMT	9	Balloon 2 808 m
09 GMT	16	
12 GMT	10	Number of ascents:
15 GMT	14	
18 GMT	11	Balloon 1 13
21 GMT	13	Balloon 2 82

Table 1. General information about the balloon soundings.

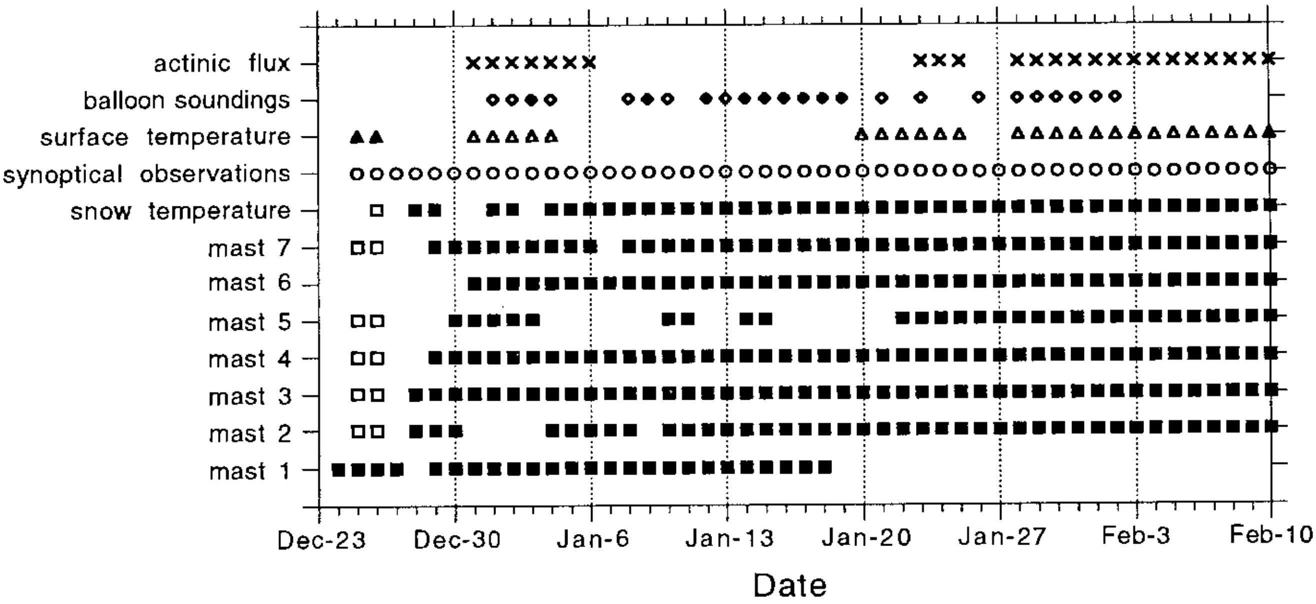


Figure 2. Performance of the different instruments during the meteorological experiment.

All balloons suffered from leaking to some extend due to cracks in the coating, probably caused by low temperatures. After only 13 ascents, strong winds and low temperatures in the period 4 to 7 January 1993 made the first balloon useless owing to leakage. The second balloon, made of heavier material, lasted the rest of the expedition with some minor repairs. The larger mass of this balloon, however, lowered the average altitude reached from over 1400 m with the first balloon to 800 meter with the heavier version (table 1). In total 8.5 bottles of helium were used (70 m^3).

Figure 2 shows the performance of all meteorological instruments applied in the experiment. A measuring day is considered complete if at least 90% of the data is received. The reference experiment is indicated by white squares and black triangles. White diamonds indicate 1 to 4 balloon soundings per day and black diamonds indicate 5 soundings or more. Black triangles indicate surface temperature measurements during the reference experiment. Until the 31st of January, surface temperatures were measured near mast 3, after that near mast 2.

4. Glaciological equipment and methods

The glaciological part of this expedition consisted of the drilling of ice cores and collecting surface samples of the blue ice of Scharffenbergbotnen. The ice core drilling logistics were fully prepared by Job van Roijen. The final analysis of the ice cores and the surface samples will be performed in the physics laboratory of Utrecht University. Some background information of the glaciological experiment is given in the following section.

4.1 Surface sampling

Along a section over two different blue ice areas (Figure 2) surface samples were taken for $\delta^{18}O$ analysis (Reeh et al., 1987). The distance interval between the different sampling locations was 100 meters and fixed by GPS. In one interval every 10 meter a sample was taken, while in one 10 meter interval every meter a sample was taken. In total 53 samples were collected. All samples were sealed in plastic and will be transported to Utrecht in frozen condition.

4.2 Radiocarbon dating of ice cores.

Absolute dating of ice is important for all people working with ice samples, to have a frame of reference for their results. Three methods for the absolute dating of ice samples are currently in use: counting of year layers (only possible in accumulation areas, high accuracy), modelling of ice flow and the radio-active decay of naturally abundant matter like, in our case, graphite. In the nuclear physics laboratory of Utrecht University the latter method is being improved. Accelerator Mass Spectrometry enables us to measure the $^{14}C/^{12}C$ ratio of graphite samples of as little as 30 micrograms, extracted from CO_2 in the air bubbles included in the ice cores. This implies that an ice sample of 5 kg suffices for a dating with a limit of 20,000 years B.P. (van de Wal et al., 1993). Results obtained with samples from a depth of 50 m from the

Caroline ice core (Adelie Land, East Antarctica) revealed an age of 16,000 years, the oldest radiocarbon dated ice sample. Besides dating of ice samples the method also provides means to estimate long term ablation (of the last 15 - 100 years) with reasonable accuracy (10 to 30%).

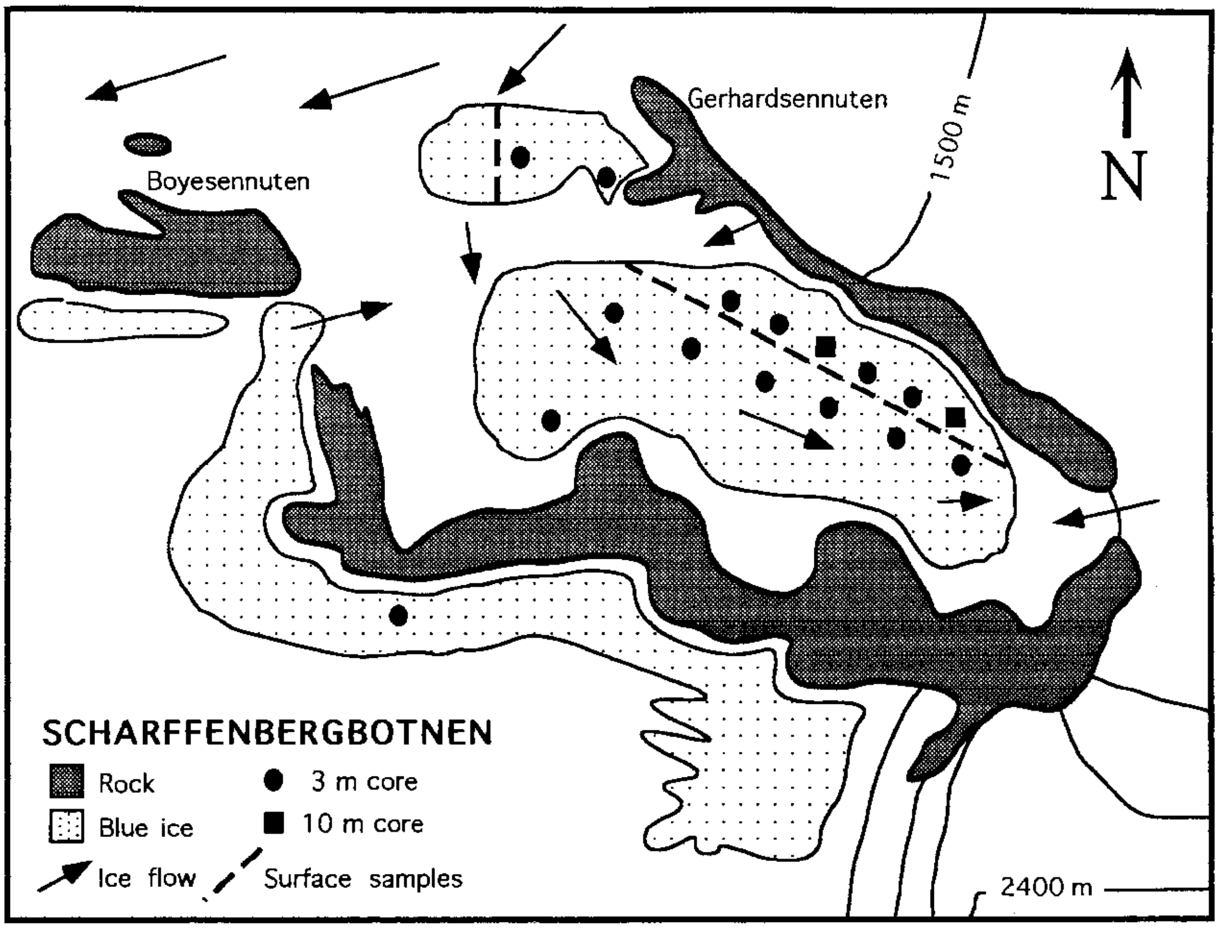


Figure 2. Main ice flow, drilling locations and surface sample section.

The two major sources of ^{14}C contamination of the air in ice cores are penetration of melt water and in situ production of ^{14}C caused by penetration of cosmic radiation in the uppermost 1.5 meter of the ice (Lal et al., 1990). At the north-western edge of Scharffenbergbotnen, the glacier ice is deflected from the main ice flow and enters the basin, see figure 2. There the ice surfaces owing to the negative mass balance in this area. The very old ice that is probably present at the surface of Scharffenbergbotnen and the absence of melt water provides an excellent opportunity to determine a correction for the ^{14}C contamination caused by cosmic radiation. This correction can be used for dating ice samples from cores drilled elsewhere.

Ice core drilling

During this expedition ice cores were successfully drilled along two sections in the blue ice of Scharffenbergbotnen. These sections probably both run approximately perpendicular to the isochrones (lines of equal age). In total 14 cores of three meters and two cores of 10 meters length were drilled, see figure 9. All locations were fixed with hand held GPS-receivers. We used an improved and expanded drill head of 4-inch in diameter that was powered by a hand-held Stihl motor. Tests with the equipment have previously been carried out on glaciers in Norway and Austria. The drill head and the other parts were manufactured by the University of Amsterdam, the Free University of Amsterdam and the University of Utrecht, and performed very well in the field. No drilling liquids of any kind were used, since this would contaminate the ice and make it worthless for radiocarbon dating. A three meter core took typically 45 minutes to drill, with a mean sample length of 30 cm that corresponds to approximately 2.5 kilos of ice. A 10-meter core took approximately three hours to drill. A spare motor and drill (3 inches in diameter, sold commercially) were not used. All cores (more than 200 in total, amounting up to 500 kg of ice) were sealed in plastic after being flushed with helium to avoid contact with modern air. Finally they were packed in shock-absorbing material and dug in the snow in insulated, aluminum cases. The temperature in the snow at 2 meter depth is approximately -18 °C and guarantees sufficient cooling of the ice cores.

During transport to Wasa and to the ship the temperature of the ice cores was not allowed to increase above -12 °C. To achieve this several freeze packs were included in each box during transport. The ice cores have been shipped back to Bergen (Norway) in freezing containers at -20 °C. From there they have been transported by truck to a freezing facility in Utrecht for age-determination.

5. Preliminary results of meteorological measurements

Because of the effective and fast data acquisition system we were able to examine the data and perform some calculations *during the expedition*. The results should therefore be considered as preliminary. However, some interesting phenomena are (briefly) discussed.

5.1 General meteorological situation

The general idea of the experiment was to gain understanding of the typical meteorological circumstances in and around a blue ice area, related to the large scale katabatic flow. Therefore, 5 meteorological masts were placed on a section along the Scharffenbergbotnen Valley (Figure 3).

mast	distance to Svea (km)	height (m.a.s.l.)	surface type
1	8.0	2550	snow
2	5.0	1170	ice
3	2.0	1260	snow
4	4.0	1200	snow
5	11.0	1150	snow
6	3.0	1350	ice
7	0.1	1280	ice

Table 2. General information about the mast locations.

Mast 6 was placed on a blue ice area south-west of the valley and mast 7 was placed close to Svea on a small blue ice area and served as a reference for the balloon measurements. The masts outside the valley (mast 4 and mast 5) are located to measure the (relative) undisturbed circulation. At mast 2 and 3, located on ice and snow, respectively, all components of the surface energy balance were (in)directly measured. Table 2 shows some mast characteristics.

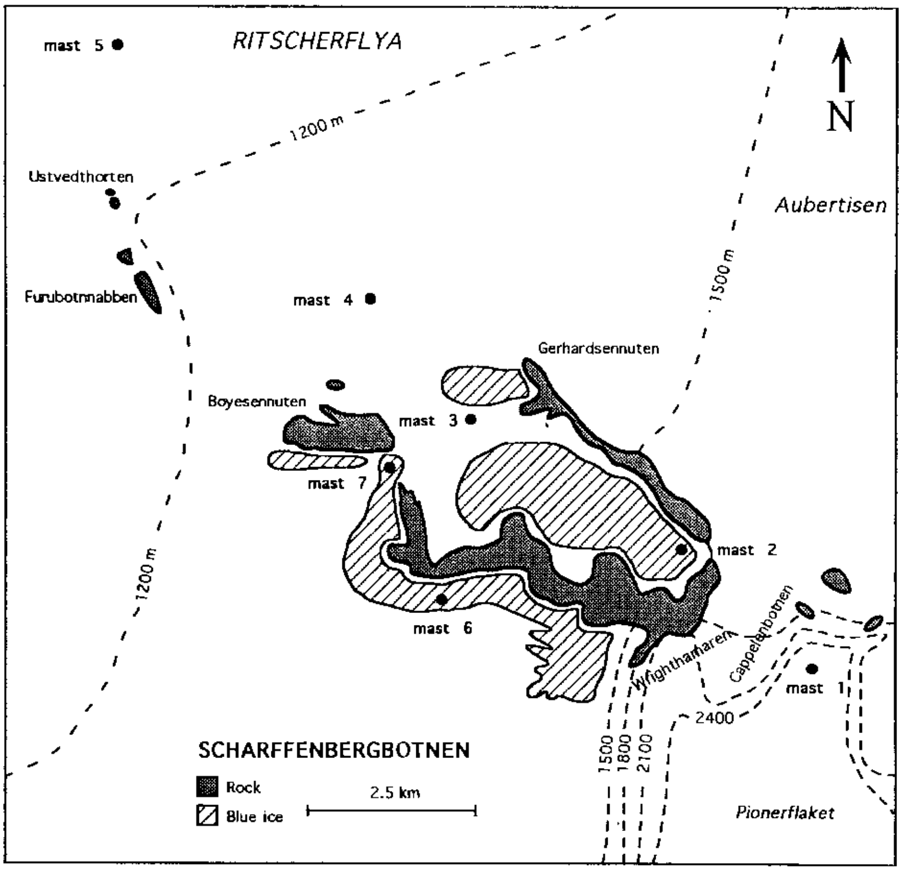
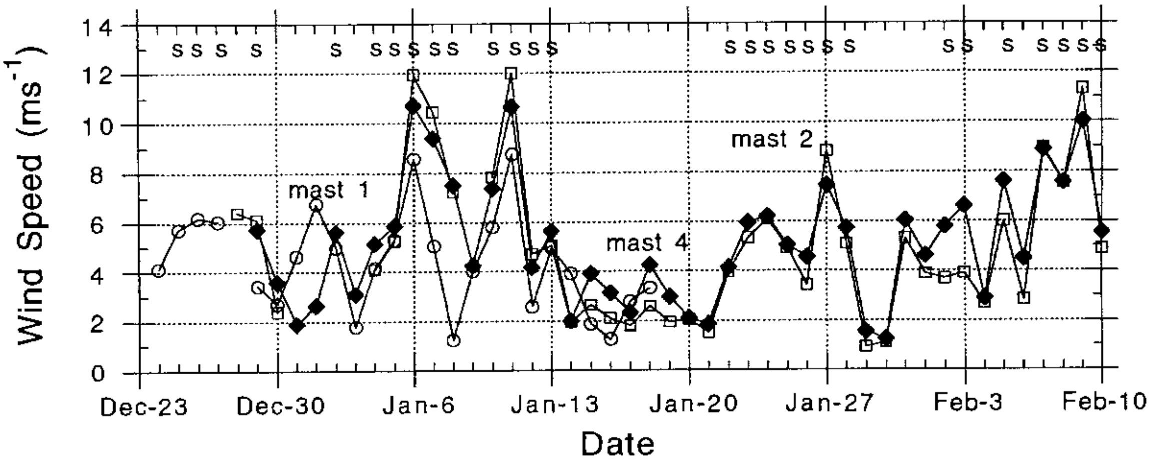
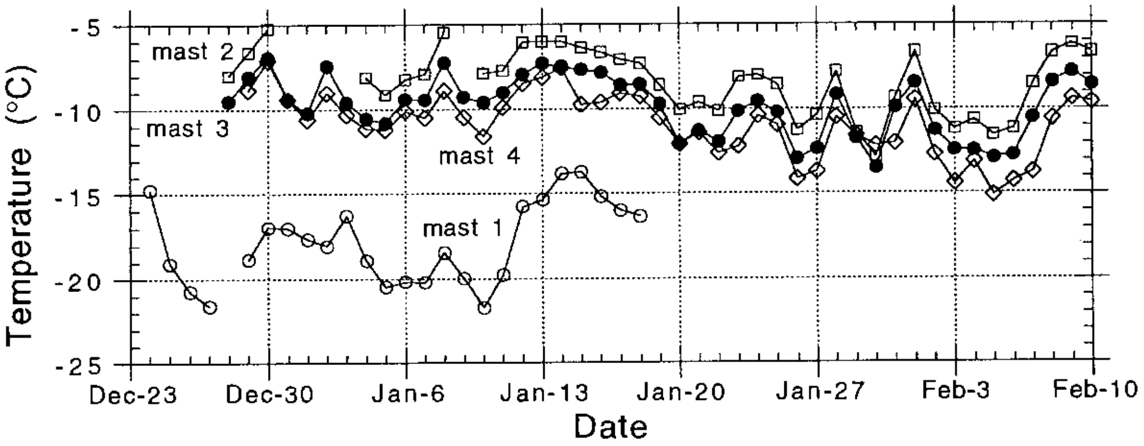


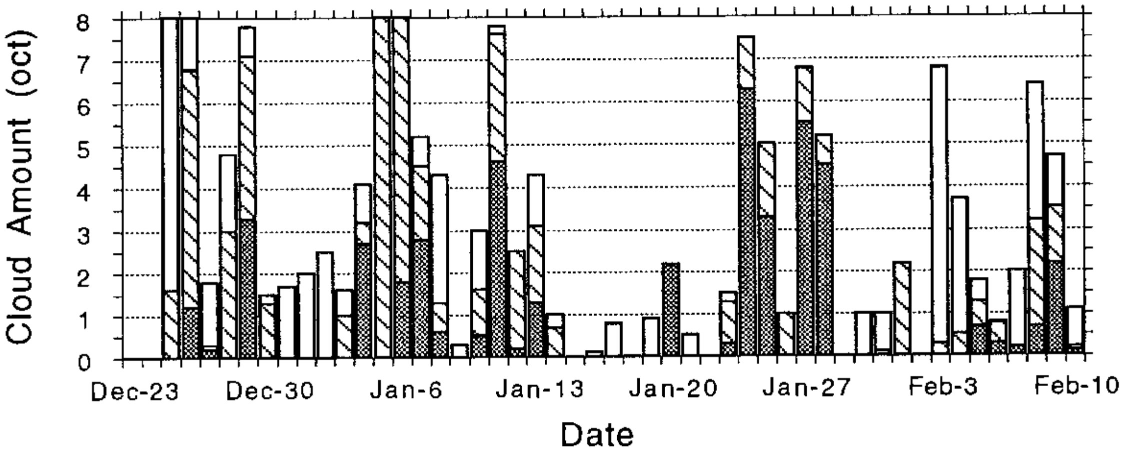
Figure 3. Location of the different measuring sites.

In Figure 4 the daily mean cloudiness, air temperature, snow temperatures at 3 depths, relative humidity and wind speed for the various masts are shown. The measuring period was characterised by periods of fair weather during which a local circulation in and around the valley could develop. Then, the wind speed was mostly low and the cloud cover consisted mainly of altocumulus and cirrus. Some periods of bad weather came by, caused by depression activity, advecting humid air inland. These periods were characterised by high wind speed and large amounts of low clouds like (nimbo)stratus and stratocumulus. On 3 days some snowfall was observed. A more thorough discussion about circulation types will be given in section 5.3.

Comparing temperatures of mast 2, 3 and 4 we can see that the temperature decreases going southward out of the valley. This was also observed by Jonsson (1992) and can be characterised as typical for this valley. We will treat this subject more thoroughly in section 5.2. The snow temperature measurements show a cooling of the snow layer over the entire measuring period although some periods of warming have occurred.


Wind Speed (ms^{-1})
14
12
10
8
6
4
2
0
s s s s
s s s s s s s s s s
s s s s s s s
s s s s s s s
mast 1
mast 2
mast 4
Dec-23
Dec-30
Jan-6
Jan-13
Jan-20
Jan-27
Feb-3
Feb-10
Date


Temperature (°C)
-5
-10
-15
-20
-25
mast 2
mast 3
mast 4
mast 1
Dec-23
Dec-30
Jan-6
Jan-13
Jan-20
Jan-27
Feb-3
Feb-10
Date


Cloud Amount (oct)
8
7
6
5
4
3
2
1
0
Dec-23
Dec-30
Jan-6
Jan-13
Jan-20
Jan-27
Feb-3
Feb-10
Date

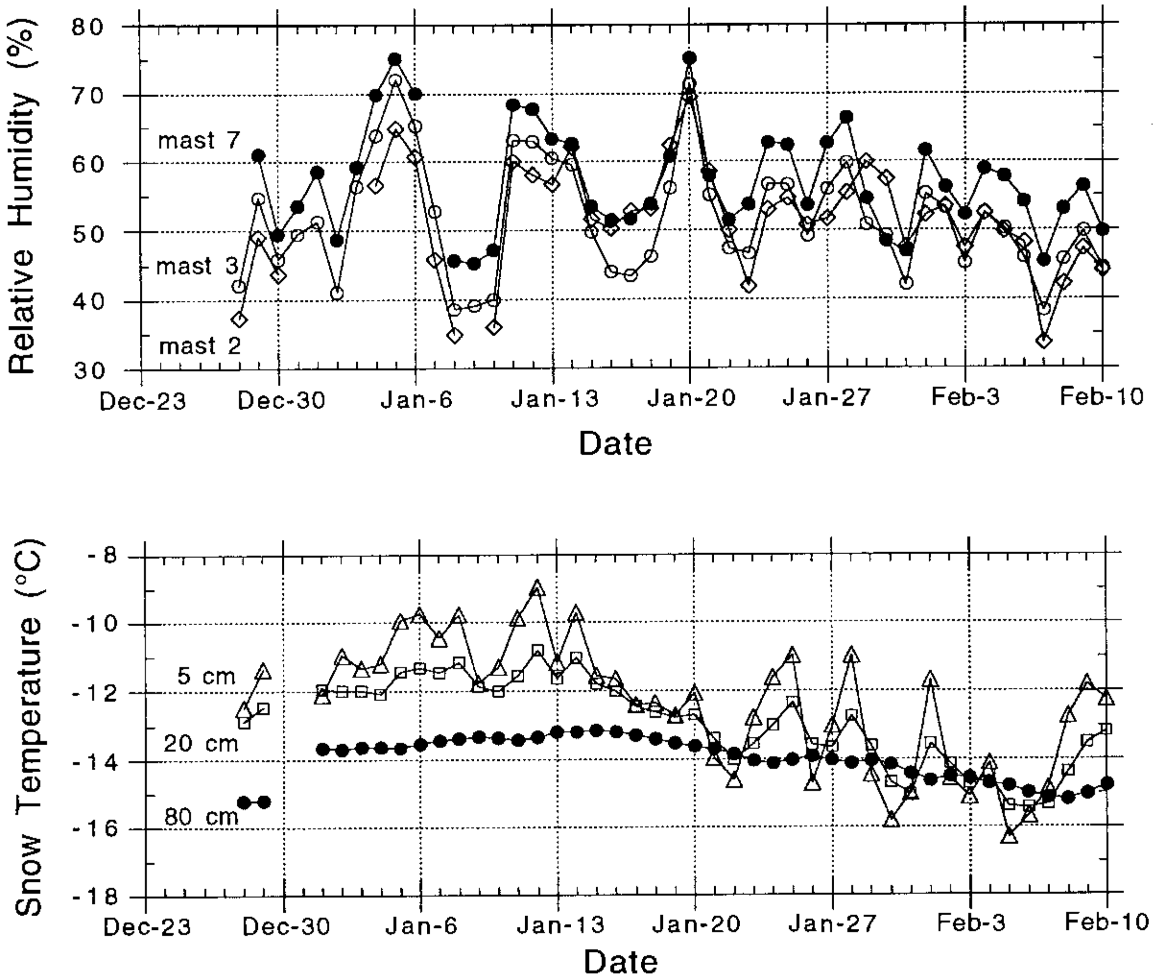


Figure 4. Daily mean values of temperature (2m), wind speed (6m) and relative humidity (2m) at selected masts, cloudiness as observed at Svea and snow temperatures at 3 depths near mast 3. 's' indicates snowdrift observed at Svea. High clouds are indicated by white areas, middle clouds by hatched areas and low clouds by dark-grey areas. A new snow pit was dug on 1 January, causing a gap in the snow temperature measurements.

The average cloudiness is 3.1 octas (low clouds 0.9, middle clouds 1.2 and high clouds 1.0). The averaged values for the measuring period of temperature, relative humidity, wind speed and albedo for the various masts are given in table 3. Also, minimum and maximum hourly mean values are given. We can see the temperature decreasing 3.1 °C going from mast 2 to 5. The values of the wind speed are difficult to interpret since different circulation types occur. However, comparing the wind speed at mast 1 and 5 where the wind was coming from easterly directions most of the time, we see a decreasing wind speed with height. This is typical for Antarctic katabatic flow, having a low level wind speed maximum. Especially at mast 2 and 7 the wind was very gusty due to orographic effects. One distinct difference between a snow surface and a blue ice surface is its albedo as can be seen in table 3. This will enhance the difference in surface energy balance between snow and ice, see section 5.2.

Comparing these values to measurements of earlier years (Jonsson, 1992), we can note that the temperatures are 5 °C lower than in January 1988, relative humidity was 5 % lower, and the wind speed is somewhat higher. As a result, the summer ablation rate was lower this year. Melting of ice in the valley was observed only once.

mast	temperature (2m) (°C)			relative humidity (2m) (%)			wind speed (6m) (m/s)		albedo
	min.	mean	max.	min.	mean	max.	mean	max.	mean
1	-23.7	-17.9	-8.4				4.4	10.7	0.84
2	-17.1	-8.3	-1.9	24.3	51.5	81.4	4.9	15.9	0.56
3	-17.8	-9.8	-3.3	26.9	51.6	88.0	4.2	11.5	0.81
4	-20.1	-10.8	-2.0				5.2	13.7	
5	-21.6	-11.4	-2.0				5.8	14.3	0.80
6	-19.9	-10.1	-3.0				3.9	15.1	
7	-18.0	-9.8	-3.7	34.6	57.2	84.3	4.9	14.9	0.52

Table 3. Measuring period averaged values of temperature, relative humidity, wind speed and albedo at the various masts (based on hourly averages). Averages are calculated from all available data (see Figure 1).

5.2 Local climate and surface energy balance

The valley of Scharffenbergbotnen has a unique climate. Because it is shielded from the large scale katabatic flow, a local circulation can develop. This circulation, together with the surface properties of the ice and the presence of relatively warm rocks causes a surface energy balance that is typical for an Antarctic blue ice area. The evaporation rate is very high causing a local upward ice movement.

The surface energy balance is composed of the following quantities: net short-wave radiation (SWnet), net long wave radiation (LWnet), sensible turbulent heat flux (SH), latent turbulent heat flux (LH) and the heat flux into the snow (B). In Figure 5, these terms are given for the 31^{st} of January on mast 3 on snow, together with the total surface energy balance. This day was selected since the surface temperature measurements seemed to be reliable. It was characterised by almost clear sky (only some cirrus), a gentle westerly wind at night and a strong easterly wind in the afternoon.

The turbulent heat fluxes are calculated from temperature, wind speed and humidity measurements at various heights using the Monin-Obukhov similarity theory with stability corrections according to Duynkerke and Van den Broeke (in press). The outgoing long wave radiation is calculated from surface temperature measurements and the heat flux in the snow from snow temperatures at two depths (the diffusivity is calculated using a measured density of 400 kgm^{-3}). The rest of the quantities are measured directly.

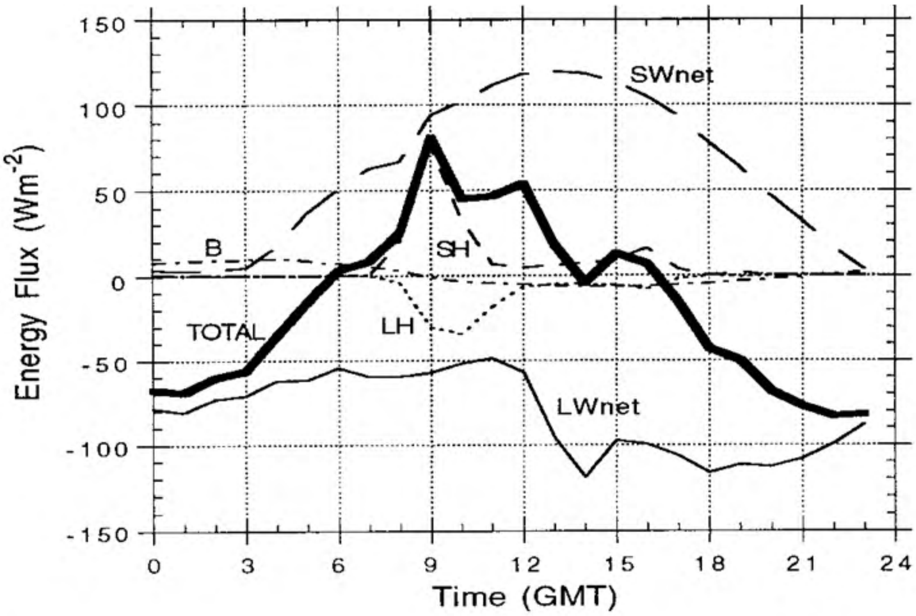


Figure 5. Surface energy balance components at mast 3 on 31 January. Positive values indicate fluxes towards the surface.

View on the blue ice area in the Scharffenbergbotnen valley.

It is obvious that the net short-wave radiation is the largest positive term in spite of the large albedo of 0.81. The surface looses most of its energy through long wave radiation. The turbulent heat fluxes are zero at night due to a very stable stratification. When the easterly wind speed increases at 8h the sensible heat flux starts to heat the surface and cool the air. The latent heat flux is negative at daytime indicating that evaporation occurs. The heat flux into the snow is positive at night, indicating warming of the surface and cooling of the sub-surface snow layers. At daytime, this situation has reversed. The total surface energy flux is positive for only 10 hours. This is the time when the surface temperature increases. Compared to the radiation components, the turbulent fluxes and heat flux into the snow are small when calculating daily averaged fluxes, see table 4.

Net short-wave radiation	60
Net long wave radiation	–82
Net radiation	–22
Sensible heat flux	8
Latent heat flux	–5
Snow heat flux	1
Net surface flux	–18

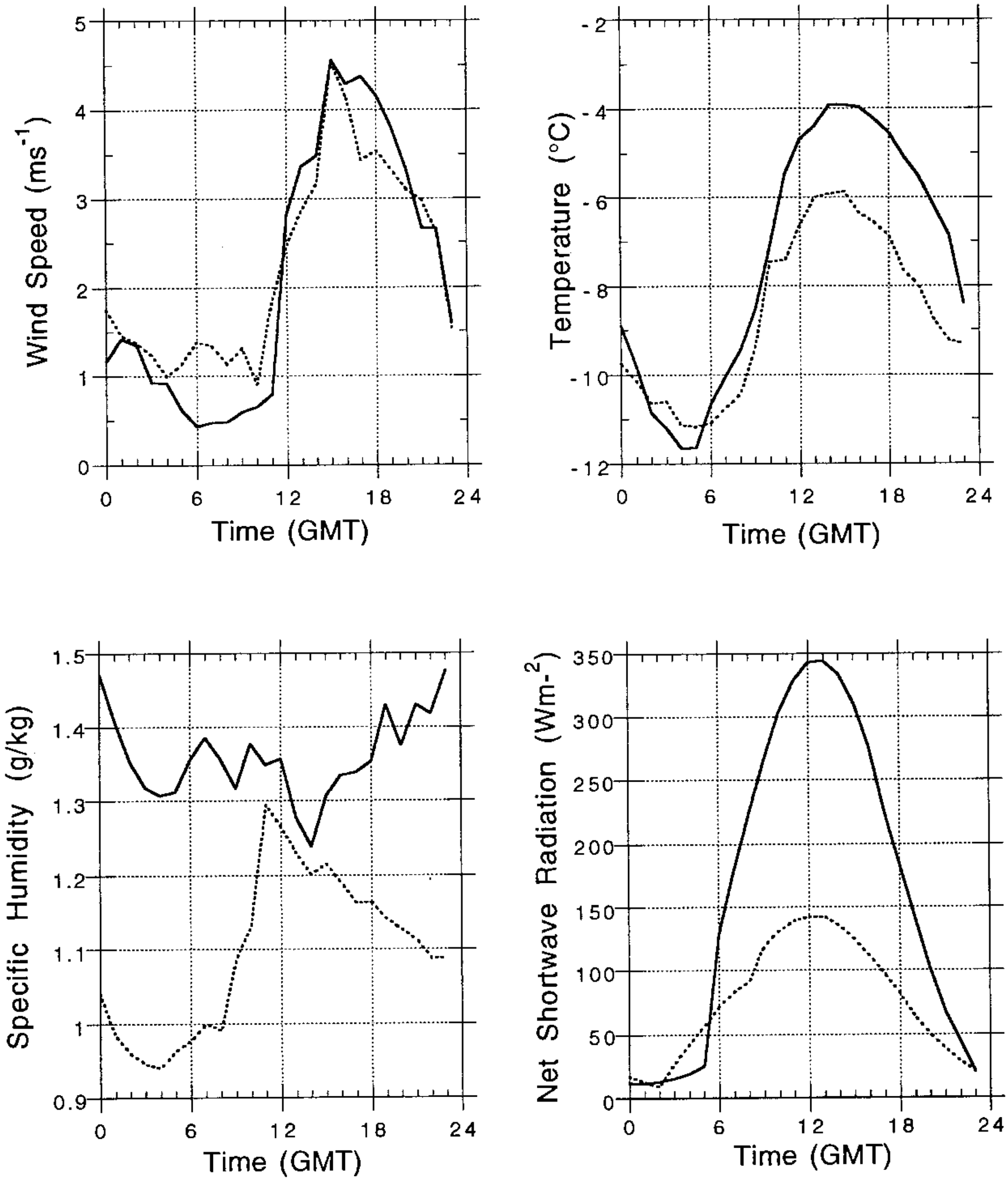
Table 4. Daily mean surface fluxes for 31 January.

The average net surface flux is negative indicating that the surface is cooled on this particular day. Furthermore, the uppermost snow layers are cooled as the average heat flux into the snow is positive.

Even though these values are calculated for only one day, they compare well with the measurements of Wendler et al. (1988) although their measuring site was located on a relatively undisturbed snow slope in Adelie Land, East Antarctica, while mast 3 was located inside the valley. One must bear in mind that measuring uncertainties together with all the assumptions used in the calculations can cause considerable errors in the various fluxes. We will not go deeper in this, but the total error could be of the same order of magnitude as the average net surface flux.

The differences between the surface energy fluxes observed at mast 2 and 3 are interesting and probably typical for the difference between a snow and blue ice surface. Unfortunately, the surface temperature could be measured at only one location at the time and the upward total radiation measurements do not seem to be very reliable. Therefore, we will only treat the differences in short-wave radiation and turbulent fluxes. In the future, the complete surface energy balance will be studied using a surface energy balance model.

In Figure 6 some meteorological variables as well as surface heat fluxes averaged for the period of 16 to 19 January are shown. This period is characterised by low cloud amount and a low wind speed which has a pronounced daily cycle typical for the local climate of the valley. The surface wind direction is west for most of the time, however sometimes at daytime a stronger, easterly wind appears, see section 5.3.



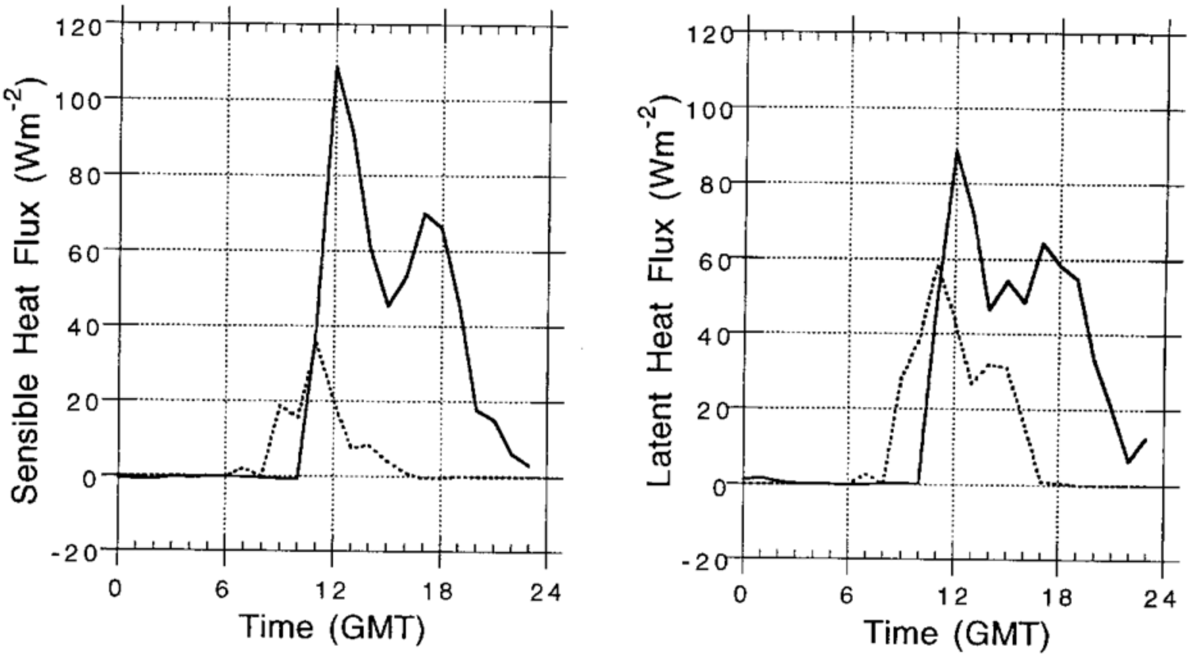


Figure 6. Wind speed (6m), temperature (2m), specific humidity (2m), net short-wave radiation, sensible heat flux and latent heat flux on mast 2 (solid line) and mast 3 (dotted line) averaged for 16 to 19 January 1993. Positive sensible and latent heat fluxes indicate cooling of the surface.

Because of the lower surface albedo, the net short-wave radiation is much larger for ice. This leads to heating of the surface and, consequently, a more unstable stratification on the ice at daytime. Therefore, the turbulent heat fluxes are larger over ice cooling the surface and warming the air, causing a more pronounced daily temperature cycle over ice (the roughness length for momentum, calculated during neutral or near-neutral conditions, seems to be approximately the same for mast 2 and 3).

It is obvious that the difference in air temperature between the ice and snow increases as the sensible heat flux increases over ice at around 11h. Apparently, the air above the snow becomes unstable somewhat earlier (9h), when the turbulent fluxes increase. The net long wave radiation will probably be larger (negative) over ice due to its warmer surface, although the incoming long wave radiation can be larger near mast 2 also due to downward radiating 'warm' rocks.

The ice heat flux will probably show a more pronounced daily cycle than the snow heat flux. At mast 3, the specific humidity clearly has a daily cycle connected to the evaporation which starts at 9h. This relationship is absent above ice by some unknown reason. The horizontal advection process is not treated here but can be very important.

	ice	snow
Wind speed 6m (ms^{-1})	2.1	2.2
Temperature 2m (°C)	–7.4	–8.6
Specific humidity 2m (g/kg)	1.4	1.1
Net short-wave radiation (Wm^{-2})	163.2	76.6
Sensible heat flux (Wm^{-2})	–25.7	–5.1
Latent heat flux (Wm^{-2})	–25.1	–12.5

Table 5. Mean meteorological and surface flux quantities for the period 16 to 19 January.

On the blue ice near mast 2 the ablation rate is higher than at mast 3 on snow, in agreement with stake measurements in the Scharffenbergbotnen valley from earlier years (Jonsson, 1992). According to stake measurements this year, the daily mean evaporation rate on the ice is 0.94 mm w.e./day for the period of 27 December to the 10 February (Figure 7) which is lower than other years. This ablation rate compares with the measurements of Fujii and Kusunoki (1982) near Mizuho Station in December and January. The daily cycle of evaporation is also apparent in their measurements. An ablation of 0.94 mm w.e./day is equivalent to a daily mean latent heat flux of 30.8 Wm^{-2} (the density of the blue ice has a value of 850 kgm^{-3}). If we compare this with the calculated latent heat flux for the selected period (table 5), the agreement is quite good. From Figure 7 we can see that during the selected period the ablation is somewhat less than average so the agreement will be even better.

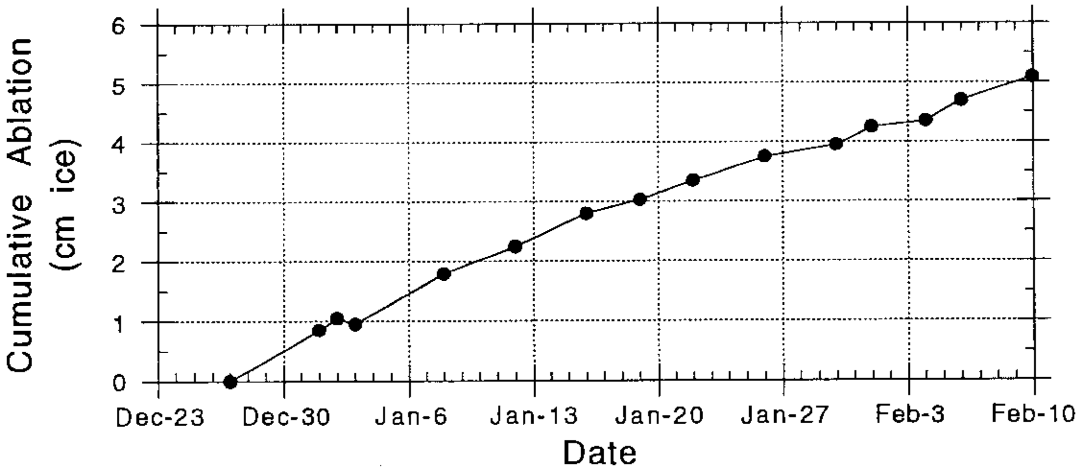


Figure 7. Cumulative ice ablation at mast 2 on the blue ice measured at a nearby stake.

To conclude this section, it is clear that the complete surface energy balance can be calculated if surface temperature measurements are accurate. Otherwise, a surface energy balance model must be used. The difference in surface energy fluxes between snow and ice surface is large. The calculated latent heat flux on ice agrees well with the measured ablation although in other periods this agreement appears to be less favourable.

Our main goal concerning future research is to determine the surface energy fluxes at various masts, probably also using a surface energy balance model. Then, we will try to distinguish between various weather (circulation) types. Also, the variation of the surface energy fluxes along the section mast 1, 2, 3, 4 and 5 can be studied. It is expected that interesting differences along this section can occur.

5.3 Local circulation in the Scharffenbergbotnen basin

The flow near the surface is important for the mass balance of blue ice areas, directly by divergence of drifting snow (Takahashi et al., 1988), indirectly by generation of turbulent fluxes enhancing evaporation and heat transfer (Fujii and Kusunoki, 1982). Some preliminary and qualitative results concerning the local circulation in and around Scharffenbergbotnen as observed during the 1992-93 experiment are presented in this section.

As a preliminary result, we can discern three types of surface circulation in the Scharffenbergbotnen basin. The occurrence of either type of circulation depends mainly on the strength of the large scale katabatic wind. The Antarctic katabatic winds are famous for their strength, persistence and directional constancy. Only the katabatic winds observed on the Greenland ice sheet are of comparable scale and persistence (Van den Broeke et al, in press). In the area of the Scharffenbergbotnen basin the prevailing direction of the large scale katabatic flow is between 30 and 100 degrees (Jonsson, 1992). Its strength depends strongly on the synoptic forcing of depressions and high pressure areas that are moving along the coast (King, 1989). Analysis of the synoptic weather systems should clarify the different mechanisms that are involved in forcing the surface winds near Svea.

The first type of flow that was observed is a shallow nocturnal katabatic wind that only develops if the large scale katabatic wind is weak, and, aided by the sheltered character of the basin, more often inside than outside the basin. The thickness of this layer typically is 10-20 meters with wind speeds at 2 meter reaching 1 to 4 m/s. The maximum wind speed is reached at 2 to 4 meter altitude. The direction of the flow is along the local fall line of the surface slope. This situation persists during the nigbt, provided that no mixing with upper layer air is forced by increasing high level wind speeds and the cooling near the ground is maintained (no clouds). Very large temperature inversions of up to 2 K/m are the main forcing mechanism for this flow type, which has been well studied in mountainous areas.

Flow type two is observed in the morning and early afternoon under fair weather conditions. The low albedo of the blue ice and the relatively sheltered character of Scharffenbergbotnen induces a warmer climate at daytime than its immediate surroundings. A local low pressure area is formed, enhancing a low level circulation into the basin. The thickness of this layer equals one to several hundreds of meters, its strength seldom exceeds 5 m/s. If the large scale katabatic flow is weak, this circulation can persist throughout the day. This type of flow could be dominant during the summer period when the continental scale katabatic flow is substantially weaker than during the winter season.

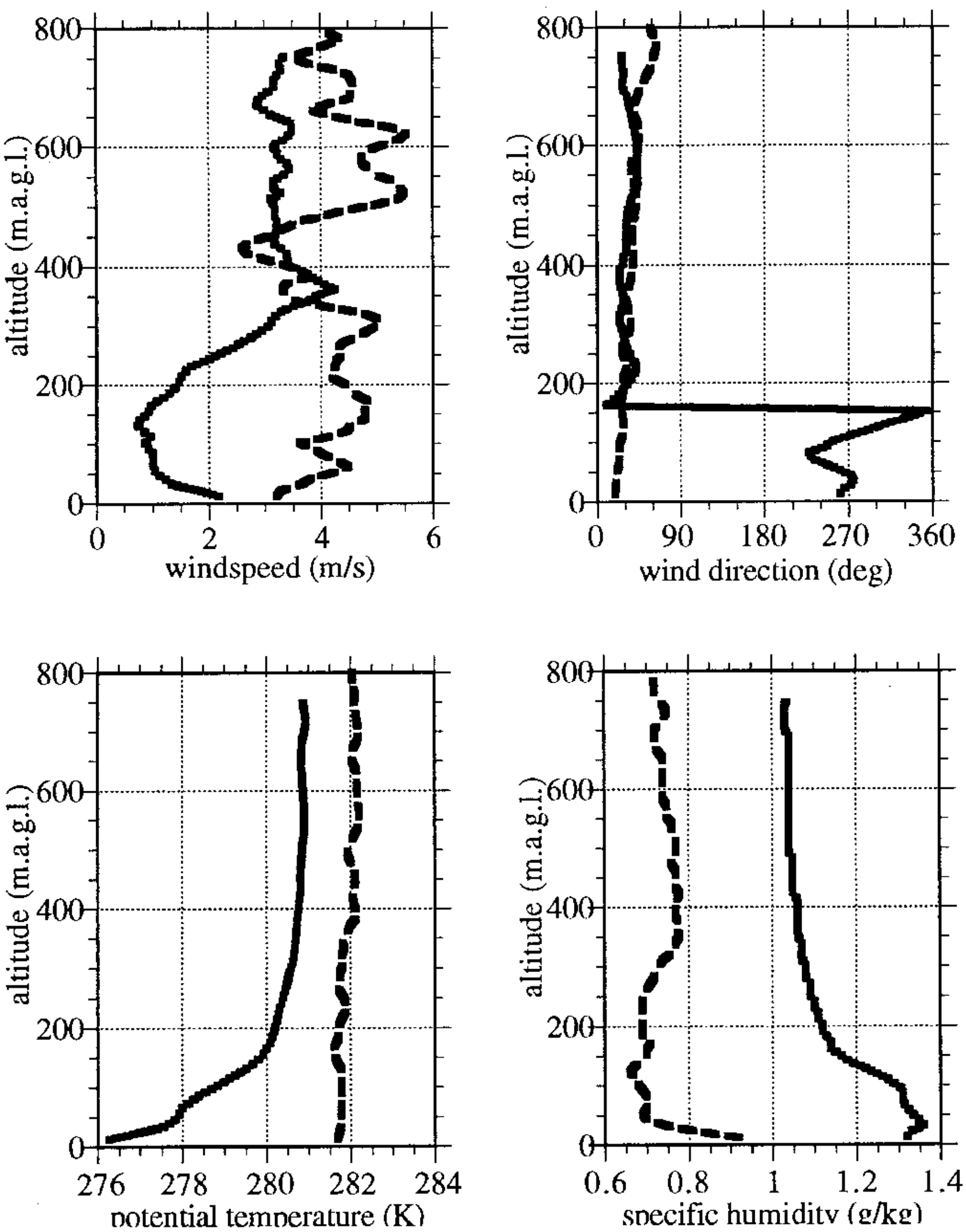


Figure 8. Profiles measured 16 January 1993 at 3h GMT (solid line) and 15h GMT (dashed line).

The third type of circulation occurs when the large scale katabatic flow penetrates to the surface inside the basin. This type probably develops in combination with depression activity near the coast, 'helping' the katabatic flow to grow stronger so it removes the local circulation's of type 1 and 2. This can be accompanied by severe front passage phenomena like sudden high wind speeds, rise in temperature, drop in relative humidity and change in wind direction. The type three circulation is also observed during calm conditions if the net radiation near the surface becomes strongly positive and the mixing with upper layer air is enhanced, e.g. in the late afternoon on days with fair weather.

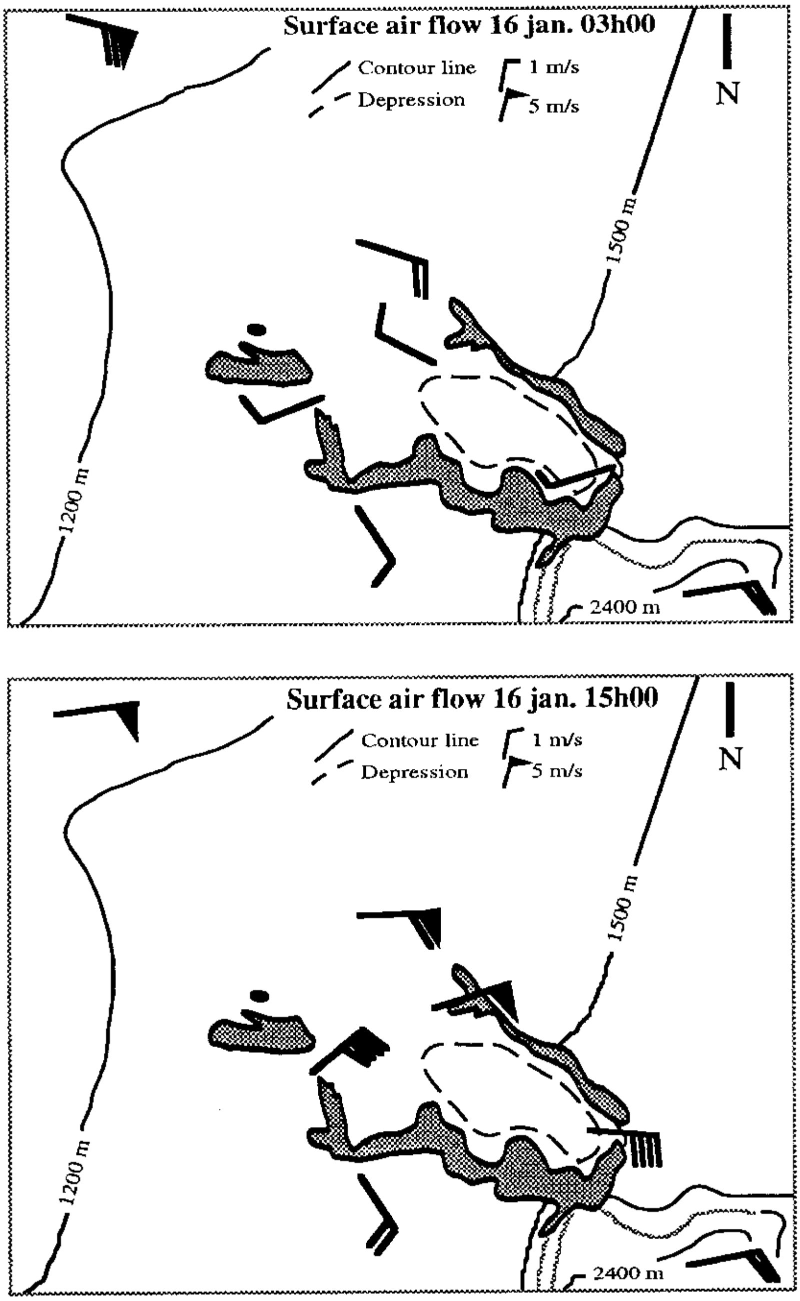


Figure 9. Observed surface winds on 16 January 1993 at 3h GMT (flow type 1) and 15h GMT (flow type 3).

All three types of surface flow occur in a strong daily cycle during days of fine weather: shallow katabatic flow into the basin at night, increasing flow into the basin in the morning and early afternoon and finally north-easterly flow in the late afternoon, sometimes strong enough for the snow to start drifting. Although no weather charts have yet been analysed, it is believed that the following mechanism is responsible for the occurrence of the different types of surface flow in Scharffenbergbotnen: if near the coast high pressure prevails, flow types one (night) and two (day) are most common and the latter one persists throughout the day. Low pressure activity near the coast will enhance flow type three, day and night, often associated with high wind speeds (up to 25 m/s), blowing snow and clouds, with or without precipitation. During the experiment no blowing snow has been observed during flow type one or two.

Some results of one day, 16 January 1993, are presented in Figures 8 and 9. The upper panel in Figure 9 shows the situation at the different masts at 03h GMT while the lower panel represents the afternoon situation at 15h GMT. Inside the basin (mast 2, 3 and 7) and in the lee side of mountains (mast 6) the surface flow at night is directed along the local fall line of the terrain slope. The balloon sounding of that time (Figure 8, solid line) reveals that the nocturnal katabatic layer near the surface is only some 20 m thick and forced by a large temperature gradient near the surface, induced by long wave radiative cooling (flow type 1). Above 150 m the large scale katabatic wind is present but weak, blowing with 3 to 4 m/s from the north-east. Outside the basin at mast 5 no influence of the mountains can be noticed. At this place the large scale katabatic flow determines the surface flow most of the time.

After a transition period in the morning the large scale katabatic flow penetrates to the ground inside the valley (flow type 3, lower panel of Figure 9) due to enhanced mixing when the surface radiation balance becomes positive at daytime. The whole column is well mixed and drier but with pronounced evaporation at the ground (Figure 8, dashed line). The flow is not strong enough to penetrate towards the surface at mast 6. It is interesting to note that the daytime katabatic wind at mast 5 is actually weaker than during the night, in agreement with other observations on undisturbed Antarctic slopes (Kodama et al., 1988). This indicates that mast 5 can be used as an undisturbed background situation, as originally planned. The above described daily cycle was observed during many days in January and February 1993, and it is probably the dominant wind regime during periods of fair weather in the Scharffenbergbotnen basin.

Future research will concentrate on analysis of large scale circulation in association with the observed local phenomena in Scharffenbergbotnen. Furthermore the relation with the mass balance in the basin will be more closely studied.

6. Concluding remarks

We may state that the overall results of this expedition seem to be good. Even though the equipment was never used when temperatures were below -5 °C for such a long time in earlier expeditions the equipment performed very well. Approximately 90 % of all possible data is retrieved. 100 balloon soundings were carried out, including 9 days with soundings every 3 hour. The ice core drilling appeared to be more easy than expected. Because of the very cold and hard ice, melting and refreezing near the drill head was not a problem, in contrast with earlier experiences on relatively warm glaciers in the Alps and Norway. In fact, transportation of the ice cores and keeping them cold was found to be the main part of the work. Some of the most important meteorological conclusions so far are listed below:

- The weather was rather variable with periods of calm, sunny weather during which some local circulation in and around the valley could develop and periods of bad weather caused by depression activity disturbing any local circulation.
- The local circulation in and around the Scharffenbergbotnen valley is difficult to interpret due to its topographical situation. However, some different circulation types can be recognised.
- The mean temperature during the measuring period was approximately -10 °C, significantly colder than other years. Temperatures inside the valley were 3 °C higher than outside the valley, mainly caused by the difference in surface energy balance.
- The difference in surface energy balance between a blue ice and snow surface is caused mainly by the difference in albedo.
- Turbulent fluxes are higher upward over ice i.e. larger evaporation rates and enhanced warming of the atmospheric surface layer. The mean evaporation rate was 0.94 mm w.e./day, also lower than other years.

7. Participants

R. Bintanja (field leader, Ph.D. Student)
M.R. van den Broeke (Ph.D. Student)
M.P. Portanger (technician)

General project leader:	J. Oerlemans
Logistic manager:	L.A. Conrads

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