The thermal structure of Hansbreen, a tidewater glacier in southern Spitsbergen, Svalbard

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Ice temperature measurements were taken from three shallow and five deep (to bedrock) boreholes on Hansbreen, Svalbard, in selected years between 1988 and 1994. In general, results show a subpolar, polythermal structure. The glacier accumulation zone is of warm ice within the entire vertical profile except in the uppermost layer of seasonal temperature fluctuations where there is an upper cold ice layer in the ablation zone which varies in thickness and may even be absent in the western lateral part. The upper layer of cold ice thins along the glacier centre-line from the equilibrium line altitude down to the glacier front. The depth of the pressure melting, indicating the base of the cold ice layer, was defined at the borehole measurement sites but was not manifested as an internal reflection horizon using multi-frequency radar methods. The isotherm lies about 20 m above a radar internal reflecting horizon near the equilibrium line altitude and about 40 m above it in the frontal part of the glacier. The internal reflection horizon almost certainly reflects the high water content within temperate ice and not the cold/temperate ice interface. At 10 m depth, the temperatures are 2–3°C higher than the calculated mean annual air temperatures, demonstrating the importance of meltwater refreezing on the release of latent heat.

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Introduction

Svalbard glaciers have been recognised as subpolar in temperature structure since the classification of Ahlmann (1935), where a layer of cold ice is underlain by temperate ice at temperatures at the pressure melting point. The thickness of the cold layer generally increases from the equilibrium line down to the glacier terminus. This traditional view of the longitudinal temperature distribution within a Spitsbergen glacier was outlined by Schytt (1964) and, with respect to the consequences for glacial hydrology, discussed by Baranowski (1977). However, both direct and indirect data from Svalbard glaciers suggest that his picture of the thermal structure of different glaciers in the archipelago is more complicated than previously suspected (e.g. Jania 1988). The term "polythermal glacier", introduced by Fowler & Larson (1978) and developed by Blatter (1990), is particularly relevant to the glaciers of Svalbard. A combination of data from temperature measurements and radio-echo soundings from glaciers in northwestern Spitsbergen shows that the relatively small and thin (<150 m) Brøggerbreen is cold and frozen to its bed along its entire length. The thicker Lovénbreen is temperate in the middle and higher parts but cold and frozen to its bed in the ablation area. Kongsvegen has a temperate accumulation zone and an 80–100 m-thick cold layer below the equilibrium line (Hagen 1992). A strong internal reflector of radar signals from the interface between cold and temperate ice (with significant free water content) has been stressed at a number of glaciers (Dowdeswell et al. 1984; Mačeret & Žuravlev 1985; Bamber 1987) and later supported by direct borehole measurements of temperature (c.f. Hagen 1992).

This paper describes studies of ice temperature variations in Hansbreen, a tidewater glacier in southern Spitsbergen, and discusses the results in the context of the thermal character of other Svalbard glaciers and ice caps (Fig. 1). Although the general model of the thermal structure of Svalbard glaciers put forward here is not new, the studies reported in this paper provide additional information regarding ice temperatures within a tidewater glacier and emphasise unusual features in their distribution.

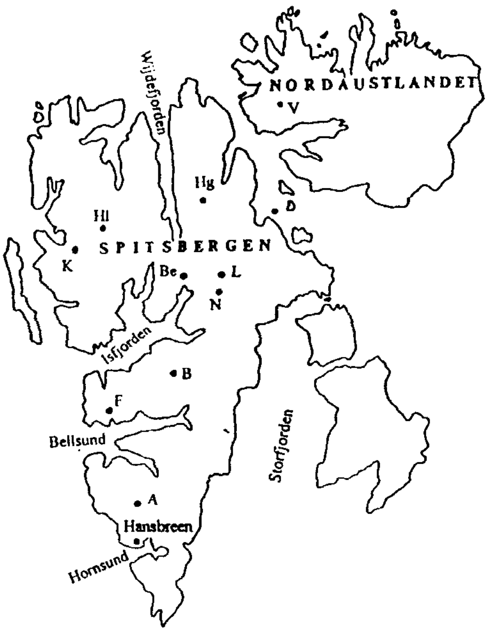

Fig. 1. Svalbard, location map of Hansbreen and the glaciers studied with respect to ice temperatures (Table 5): V = Vestfonna, Hg = Hoghetta, Hl = Holtedahlfonna, K = Kongsvegen, Be = Bertilbreen, L = Lomonosovfonna, N = Nordenskioldbreen, B = Brøgerbreen, F = Fridtjovbreen, A = Amundsenisen.

A general description of Hansbreen

Hansbreen is a grounded tidewater glacier which flows into the fjord of Hornsund, southern Spitsbergen (Figs. 1 and 2). The glacier covers an area of about 57 km^2 and its length is about 16 km. The mean slope angle of the glacier is 1.5°. The glacier tongue is about 2.5 km wide and terminates as a 1.5 km long ice-cliff. The lateral parts of the front are based on land.

The bedrock topography is known from a ground-based radio-echo soundings survey in 1989 (Glazovskij et al. 1991). More than 75% of the glacier bed lies below sea level. The bed area below sea level extends as far as 12 km up the glacier from the ice-cliff. The glacier thickness increases gradually from the lower part of the ablation zone (150–200 m) towards the middle part of the glacier, where it is about 300 m thick. The maximum ice thickness is about 400 m. Three over-deepened rock basins with a depth of more than 100 m below sea level are distinguishable in the longitudinal profile (Fig. 5). They are separated from each other by rock sills rising up to depths of −50 m. The ice thickness in the western tributary glaciers exceeds 200 m.

The mass balance of Hansbreen has been measured since the winter season of 1988/1989. In recent years the mean equilibrium line altitude has varied between 320 m a.s.l. and 370 m a.s.l. Superimposed ice layers have been observed within and near the equilibrium line altitude zone each year. In 1989, the equilibrium line altitude lay at 325 m a.s.l. and the accumulation area ratio (AAR) was 0.46. In 1988/1989 the average winter balance was +0.97 m w.e., the summer balance −1.15 m w.e., and the average net surface balance was −0.18 m w.e. If the mass loss due to iceberg calving is taken into consideration, the corrected average net balance is about −0.53 m w.e.

The dynamics of the lower part of the glacier have been monitored systematically by means of terrestrial photogrammetry since 1982 (Jania & Kolondra 1982; Jania 1988). The glacier surface velocity in the profile located ca. 0.5 km from the ice cliff is about 60 m a^{-1} (averaged for the profile). In the upper part of the ablation zone, the velocity is about 30 m a^{-1} at the centre-line. Glacier velocity accelerates significantly towards the terminal ice cliff. The average velocity near the terminus profile exceeds 210 m a^{-1}. The mean annual calving speed is about 250 m a^{-1} and annual calving flux amounts to 22 × 10^6 m^3 of ice.

Ice temperature measurements

The first direct measurements of the ice temperature of Hansbreen were performed in 1979 by Grześ (1980) in a hole located in the lower western lateral part of the glacier about 100 m a.s.l. (site G in Fig. 2). Resistant thermometers were used, but the reliability of the technique was not discussed by the author. However, Wheatstone bridge measurements of electrical resistivity suggest that a high level of accuracy might have been achieved using this method. The results demonstrated the occurrence of temperate ice in the profile, except in the thin upper layer of seasonal temperature changes (Fig. 3A).

Two deep holes were drilled using a 50 mm-diameter thermo-electric "hot point" drill in the autumn of 1988. The holes were located near the glacier front, in the zone of superimposed ice near the equilibrium line (Jania & Pulina 1990),

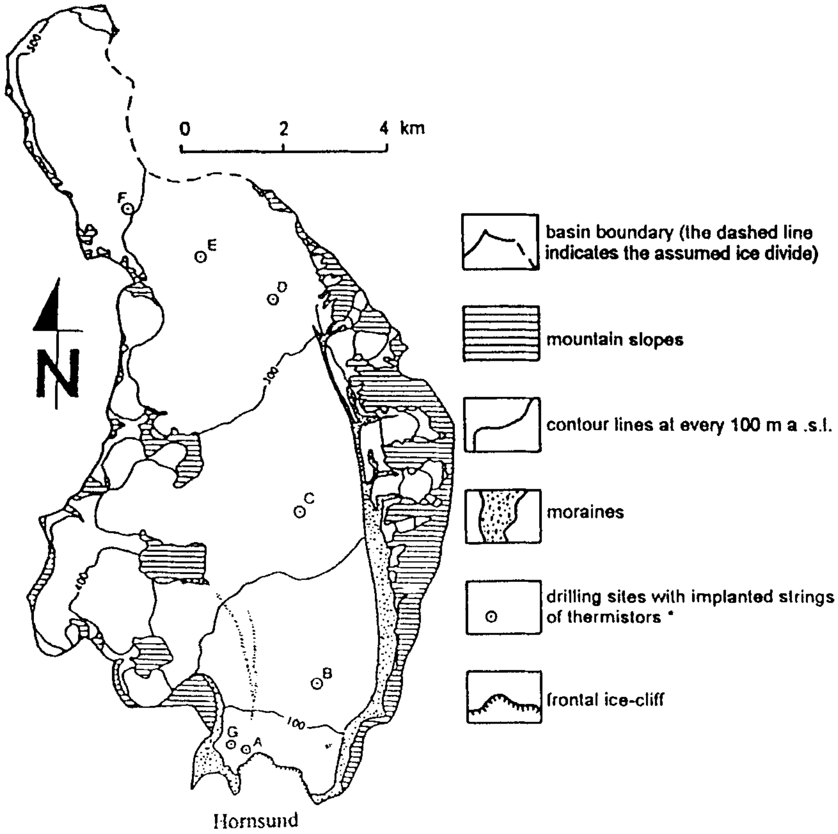

Fig. 2. Sketch map of Hansbreen basin with location of drilling sites. * = data from sites A–G B–F are shown in Tables 1–4 and described in the text.

at sites A and D respectively (Fig. 2). A mixture of polyethylene glycol with water was applied as an antifreeze during the drilling. Platinium thermistors Pt 100 with triple wire connections were used. The resistance was measured by an ohmmeter of 0.1% accuracy. This corresponds to a temperature error of ±0.26°K. However, when the calibration errors and differences between resistance of wires in the cables are included, the absolute error is probably about ±0.4°K.

The thermal structure near the front obtained from this method was similar to results obtained by Grześ (1980), with temperate ice being recorded (Fig. 3B). The string of thermistors reached a depth of 250 m in site D (Fig. 2), where the total glacier thickness is about 330 m. The results of measurements from 1988/1989 are summarised in Table 1. Due to severe weather conditions at the time of mounting a data-logger and possible interactions between anti-freeze liquid, ice and cables or the insulation of the thermistors, the accuracy of measurements is probably not wholly consistent. Cold ice was found down to a depth of 60–100 m (Fig. 3C). The thermistor at a depth of 250 m indicated ice at the pressure melting point temperature.

A new system of more precise ice temperature measurements was then developed. Pt 100 thermistors with quadruple connections were used. This new survey was based on the quasi-compensation method for measuring the resistance of a platinium thermistor. The principle of measurement is the same as in the compensation method, but the compensator was replaced by a high-input resistance millivoltmeter (10 MΩ). The temperature measurements were calculated

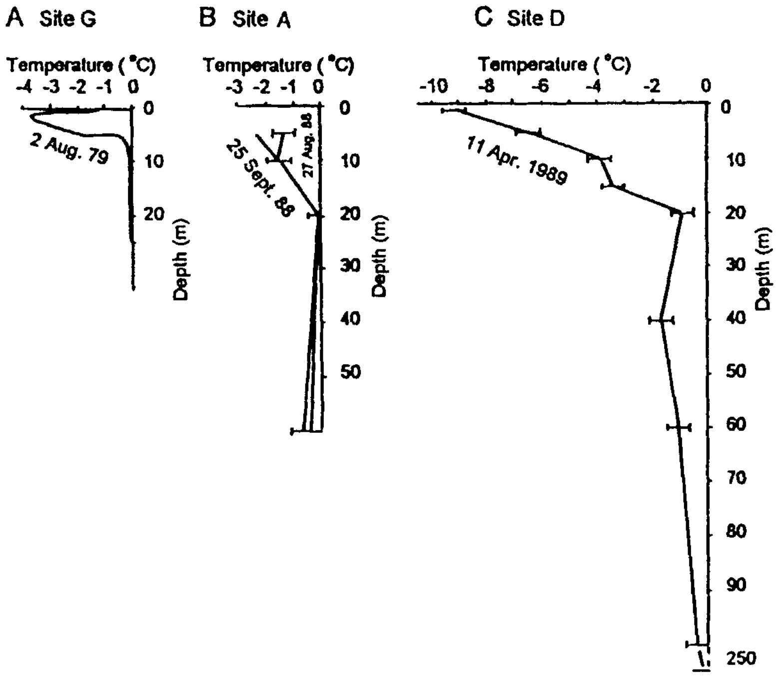

Fig. 3. Thermal profiles of Hansbreen based upon the preliminary temperature measurements: A, at site G in 1979 (Grześ 1980); B, at site A in 1988/1989; C, at site D in 1988/1989 (Jania & Pulina 1990). For location see Fig. 2.

Table 1. Results of temperature measurements at sites A and D in 1988 and 1989 (absolute error ±0.4°C).

(a) Site A (drilling on 15 August 1988). Temperatures in degrees centigrade.

Date	Depth 0.5 m	10 m	20 m	60 m
27 Aug. 1988	-1.3	-1.5	0.0	-0.4
25 Sept. 1988	-2.4	-1.5	0.0	-0.7

(b) Site D (drilling on 25 September 1988). Temperatures in degrees centigrade.

Date (hour)	0.1 m	1 m	5 m	10 m	Depth 15 m	20 m	60 m	100 m	250 m
17 Oct. 1988 (22.30)	-7.5	-4.7	-3.0	-4.7	-3.0	-0.5	—	-1.2	-0.4
2 April 1989 (21.50)	-10.3	-9.9	-6.6	-3.9	-3.9	-0.6	-0.8	-0.7	-0.2
7 April 1989 (19.00)	-9.8	-9.5	-6.7	-4.0	-3.9	-0.6	-0.9	-0.6	-0.2

— indicates lack of data

Table 2. Results of temperature measurements in shallow holes at sites B, C and E in the period of 1992–1994 (absolute error ±0.03°C).

(a) Site B (drilling on 30 September 1991). Temperature in degrees centigrade.

	Depth			
Date	5 m	10 m	15 m	20 m
5 Oct. 1991	-1.90	-2.24	-1.74	-1.23
16 Oct. 1991	-1.89	-2.24	-1.42	-1.25
8 Feb. 1992	-2.97	-2.00	-1.60	-1.15
1 March 1992	-3.21	-2.05	-1.63	-1.15
20 March 1992	-3.10	-2.16	-1.66	-1.15
31 March 1992	-3.42	-2.23	-1.68	-1.18
20 April 1992	-3.49	-2.34	-1.76	-1.20
5 Sept. 1993*	-0.27	-1.21	—	-0.37
7 Nov. 1993**	-8.56	-2.93	—	-0.63
4 June 1994**	-6.92	-4.59	—	-2.48

(b) Site C (drilling on 24 September 1991). Temperature in degrees centigrade.

	Depth			
Date	5 m	10 m	15 m	20 m
14 Oct. 1991	-2.35	-2.91	-2.5***	-1.90
9 Jan. 1992	-2.79	-2.63	-2.44	-1.98
8 Feb. 1992	-3.00	-2.63	-2.42	-1.98
1 March 1992	-3.25	-2.63	-2.42	-2.00
20 March 1992	-3.46	-2.65	-2.39	-2.00
31 March 1992	-3.56	-2.68	-2.39	-2.00
20 April 1992	-3.59	-2.70	-2.37	-2.00
27 April 1992	-3.74	-2.73	-2.37	-2.0
5 Sept. 1992	-3.24	-3.53	-2.62	-2.13
17 Sept. 1992	-2.73	-2.96	-2.47	-2.03
7 Nov. 1993	-2.59	-3.30	-2.75	-2.16
28 May 1994	-6.49	-4.08	-2.88	-2.26
1 Oct. 1994	-2.72	-3.95	-3.11	-2.33

(c) Site E (drilling on 1 October 1991). Temperature in degrees centigrade.

	Depth			
Date	5 m	10 m	15 m	20 m
Sept. 1993	-0.05***	—	-0.12***	0.0***

* after opening of new crevasses close to the measurement profile.
** during and after very cold winter with very thin snow cover.
*** wider error bar (±0.1°C).
—lack of data.

from the ratio of voltage drops in the thermistor and the standard resistor. The application of only one millivoltmeter eliminated any instrument error. The thermoelectricity voltage error was eliminated by changing the battery polarity. The resolution of the millivoltmeter and the accuracy of the standard resistor is 0.01%. The absolute temperature error of this method is not greater than ±0.03°K. Using this method, temperatures were measured in 1991 and 1992 in two 20 m-deep holes and, in 1993, in three holes, sites B, C and E respectively (Fig. 2). Data from these locations are presented in Table 2. Due to tension flow in the terminal part of the glacier, new wide crevasses were opened on both sides close to the thermistor profile at site B beween the end of

Table 3. Results of temperature measurements in deep holes at sites B, D and F in 1994 (absolute error ±0.02°C).

(a) Site B2 - 128 m a.s.l. (drilling on 13 May 1994). Temperature in degrees centigrade.

	Date		
Depth	22 May 1994	4 June 1994	29 Sept. 1994
10 m	-2.89	-2.93	-2.17
25 m	-0.10	-0.17	-0.41
40 m	-0.05	-0.06	-0.07
55 m	-0.07	-0.08	-0.07
70 m	-0.07	-0.09	-0.09
176 m	-0.16	-0.15	-0.15
206 m	-0.33	-0.35	-0.26

(b) Site D2 - 324 m a.s.l. (drilling on 21 April 1994). Temperature in degrees centigrade.

	Date			
Depth	3 May 1994	17 May 1994	4 June 1994	5 Oct. 1994
10 m	-3.93	-4.07	-3.31	-3.15
25 m	-2.43	-2.44	-2.53	-2.55
40 m	-1.55	-1.55	-1.58	-1.58
55 m	-0.89	-0.91	-0.91	-0.90
70 m	-0.09	-0.32	-0.44	-0.46
85 m	-0.06	-0.08	-0.09	-0.21
100 m	-0.06	-0.07	-0.08	-0.09
115 m	-0.08	-0.09	-0.09	-0.09
130 m	-0.08	-0.09	-0.09	-0.10
145 m	-0.09	-0.10	-0.10	-0.11
160 m	-0.09	-0.11	-0.12	-0.12
175 m	-0.12	-0.14	-0.14	-0.15
190 m	-0.12	-0.14	-0.15	-0.15
205 m	-0.13	-0.15	-0.15	-0.15
220 m	-0.14	-0.15	-0.16	-0.16
235 m	-0.15	-0.16	-0.17	-0.18
250 m	-0.16	-0.18	-0.19	-0.20
260 m	-0.17	-0.18	-0.19	-0.21
270 m	-0.18	-0.19	-0.19	-0.22
280 m	-0.19	-0.19	-0.21	-0.22
290 m	-0.19	-0.20	-0.21	-0.22
300 m	-0.21	-0.22	-0.22	-0.24
310 m	-0.22	-0.22	-0.23	-0.24
320 m	-0.22	-0.23	-0.23	-0.25
330 m	-0.21	-0.23	-0.24	-0.25

(c) Site F—405 m a.s.l. (drilling on 4 May 1994). Temperature in degrees centigrade.

	Date		
Depth	17 May 1994	22 May 1994	5 Oct. 1994
5 m	-0.44	-0.55	-0.01
10 m	-0.03	-0.03	-0.01
25 m	-0.02	-0.02	-0.02
40 m	-0.03	-0.03	-0.04
50 m	-0.03	-0.04	-0.04
55 m	-0.06	-0.09	-0.04
70 m	-0.07	-0.06	-0.05
80 m	-0.05	-0.05	-0.06
110 m	-0.09	-0.09	-0.09

Table 3 (continued).

(c) Site F—405 m a.s.l. (drilling on 4 May 1994). Temperature in degrees centigrade (continued).

	Date		
Depth	17 May 1994	22 May 1994	5 Oct. 1994
140 m	-0.09	-0.10	-0.10
170 m	-0.13	-0.13	-0.12
200 m	-0.15	-0.14	-0.17
230 m	-0.15	-0.15	-0.19
260 m	-0.17	-0.17	-0.21
290 m	-0.19	-0.18	-0.22

April 1992 and September 1993. This is what probably caused the failure of the thermistor at a depth of 15 m. The crevasses also caused significant disturbance of temperatures, warming after the summer of 1993 and cooling during and after the cold and dry winter of 1993/1994. A similar cooling during the same winter was noted at site C (Table 2).

Three new deep holes were drilled using hot water equipment for the implanting of thermistors in the spring of 1994. Two were located close to the previous temperature profiles (ca. 100 m to the N) at sites B and D (Fig. 2) (hence, B2 and D2). Ceramic NTC UUB31J1 thermistors with double wire connections were applied. This thermistor is about 4% $^\circ K^{-1}$ sensitive, i.e. ten times more than the Pt 100 thermistor. Because of the greater sensitivity of this thermistor and its resistance (which is considerably higher than that of the cable), only a four-and-a-half-digit ohmmeter was used. Additionally, in each string of thermistors, one precision-reference resistor was included. This permitted a correction for the changes in cable resistance and thus eliminated the ohmmeter error. This method ensures an accuracy of temperature better than ±0.02°C and a of resolution is ±0.01°C. Data are presented in Table 3 and Fig. 4. The latest measurements of Hansbreen temperatures come from a Polish–Swiss project on the energy balance and the origin of the polythermal structure of the glaciers.

Discussion

Hydrothermal conditions

Although measurements were made in different years with different accuracies, the results are not contradictory. Between 1991 and 1994, measurements were made with accuracy greater than five hundredth of a degree. The distinction between temperate and cold ice in the profiles may thus be defined to a high degree of accuracy. The problem of the nature of the boundary between cold and temperate ice is very important for the elucidation of many features of the glaciers of Svalbard. Part of the problem is defining what is meant by temperate glacier ice (Paterson 1981). Due to the presence of impurities within ice (e.g. salts, gases, dust), the real (observed) pressure melting point temperature is lower than the pure liquid equlibrium temperature. Harrison (1975) studied the problem on Blue Glacier in Washington, USA, and recorded temperatures as precisely as ±0.005°C. He found that, except close to the surface, temperature varies linearly with depth, and the ice is about 0.02°C colder near the surface and 0.04°C colder at 192 m depth when compared with the simplest model (pure liquid phase equilibrium). A general agreement exists between Harrison's results and the gradients measured in the temperate layers of Hansbreen ice (Fig. 4). The exceptions are the temperatures recorded near the glacier bed in the frontal part of the tongue at sites A and B2 (Figs. 3B and 4A). Both boreholes reached the bed near or below sea level. The lower temperatures found there might be related to the presence of sub-sea permafrost which probably extends underneath the frontal part of the glacier. However, the fine-grained, probably marine, sediments found at the bottom of the holes provide a more convincing explanation for the slightly lower temperatures. The invasion of these sediments, with significant saline content, into the lowermost part of both boreholes in the neighbourhood of the thermistors might have caused contamination.

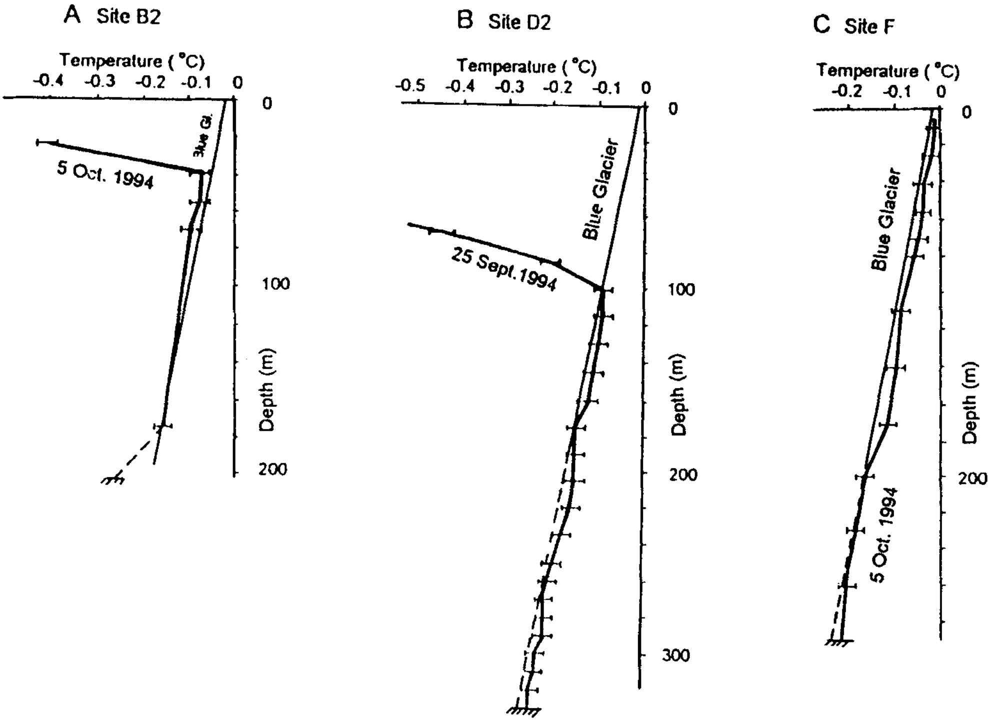

Fig. 4. Thermal profiles of Hansbreen from measurements in 1994: A, in the frontal part near site B (at B2); B, near the equilibrium line altitude, 100 m north from the site D (at D2); C, at the site F in accumulation zone (see Fig. 2 for location). Error bars are indicated. The linear gradient of temperatutes within the temperate ice of Blue Glacier, Washington, U.S.A. (from Harrison 1975) is added for comparison. Broken lines indicate the extrapolation or interpolation of data. The temperature scale is expanded and differs from that of Fig. 3.

Additional salt and mineral particles are probably responsible for the unexpected cooling of the near-floor part of the profiles. Clearly, the problem of position of the permafrost limit requires further study.

Some differences were found between the linear gradient obtained by Harrison and downhole measurements at site F (Fig. 4C), for example the presence of warmer firn and ice to a depth of about 200 m. This could have been an effect of the percolation of meltwater during the ablation period, on the one hand, and a significant demineralisation of the firn layers on the other. The winter snow cover in the accumulation zones of glaciers in Wedel Jarlsberg Land contains a relatively high amount of salts from sea spray in the air (summary content for the whole snow cover thickness is 24 g m^{-2} as an average in Amundsenisen, at 720 m a.s.l. in southern Spitsbergen). Recent studies of this phenomenon (1989/1990–1993/1994) show that the majority of salts are flushed out from the snow cover and upper firn by percolating meltwater during summer (the average salt content in the one-year-old firn is 1.1 g m^{-2}, or less than 5% of the original content). The net accumulation is about 50% of the winter accumulation (Głowacki and Pulina, pers. commun.). This implies that much of the meltwater migrates down to the firn, particularly where slopes are low in glacial accumulation zones. Near site F on Hansbreen, the summer melting is about 0.7 m (w.e.), which constitutes about half of the total accumulation. No data are available on the salt content in the deeper firn layers and the glacier ice of Hansbreen. However, the thermal profile from site F suggests a low salt content down to the 200 m level. Analysis of the relations between snow/firn/ice chemistry and firn/ice temperatures needs data from parallel observations in the same site. In studies of the thermal structure of the Svalbard glaciers, such processes and phenomena should not be ignored.

The relatively clear delineation of the cold-temperate ice transition surface is the most important result of the comparison of Harrison's studies with the Hansbreen data. The depth of this boundary is self-evident in Fig. 4. For the first time in studies of Svalbard glaciers, the interface between cold and temperate ice has been determined directly to an accuracy of ±3 m in depth. In the equilibrium line altitude zone (site D), the thickness of the cold ice is about 95 m and, in the lower ablation zone (site B), about 45 m (Fig. 4). The results confirm the previous temperature measurements down to 20 m depth, where negative temperatures were noted (Table 2). By contrast, in the lateral part of the terminus (site G), the less precise measurements of Grześ (1980) suggest the occurrence of only temperate ice (Fig. 3A). Our first drilling in 1988 (site A in the crevasse zone near terminus) discovered temperate ice at the 20 m level. However, bearing in mind the low measurement accuracy (·0.4°K), the temperature could have been slightly colder than the pressure melting point, as was the case at site B2 at the 25 m level (Fig. 4A). Existing data seem to show that the western lateral stream of the glacier may be entirely temperate. If the ice is really cold at this location, its temperature is below the pressure melting point by only about 0.4°C. In the middle of the ablation zone (site C), cold ice exists at the 20 m level, which suggests a continuous cold ice layer between the equilibrium line altitude and the glacier terminus.

In the accumulation zone (site F) only temperate firn and ice were found. At site E, at the 20 m level, the pressure melting point temperature was measured one year after the installation of thermistors.

The depth of the cold-temperate transition surface was compared with the results of low frequency radio-echo soundings studies in spring 1989 along a long profile. The low frequency recorded indicates thinning of the upper cold ice layer from the equilibrium line altitude to the glacier terminus (Fig. 5). The average thickness

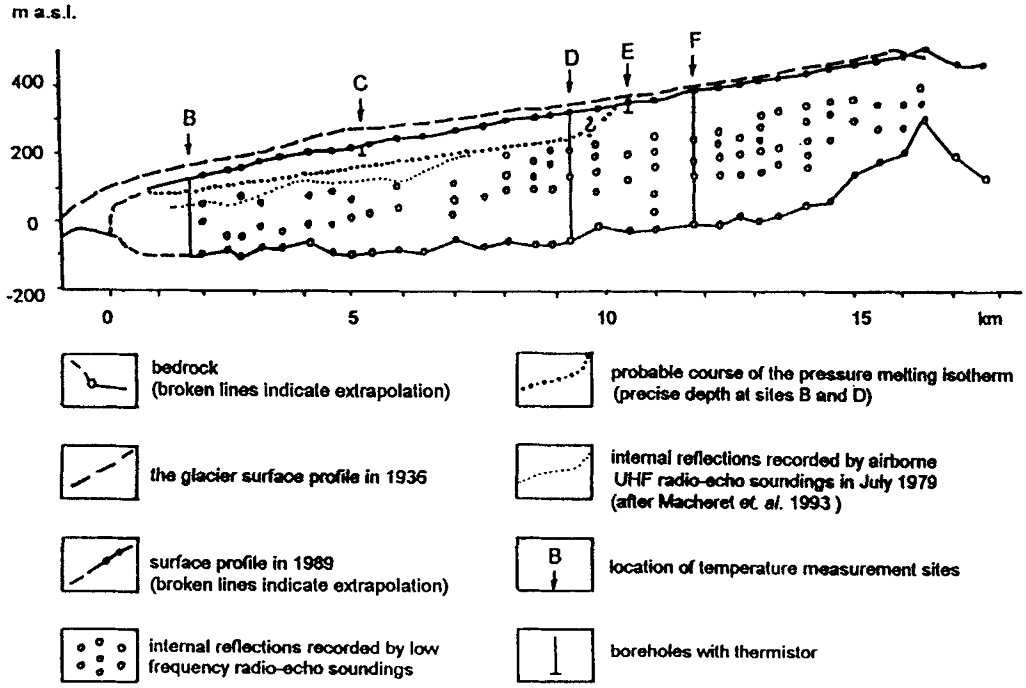

Fig. 5. Longitudinal section of Hansbreen along the centre-line based upon geodetic surveys and ground low frequency radio-echo soundings in 1989 (Glazovskij et al. 1991; Jania & Pulina 1990). Points of survey and soundings are indicated.

of the cold ice is less than 1/3 that of the total glacier thickness. One might expect a complex distribution pattern in the thickness of the cold layer, such as described for Storglaciaren, Sweden (Holmlund & Erikson 1989). Above the equilibrium line altitude, the cold layer seems to decline sharply over a distance of less than 1.5 km between sites D and E (Fig. 5). One possible explanation for this phenomenon might be associated with the precise location of site D. The drilling profile did not lie exactly on the centre-line, but was located slightly to the east, to avoid the crevassed area on the centre-line. Thus, site D may represent in part the thermal character of ice originating from the more easterly lower part of the accumulation zone where there is a prevalance of superimposed ice. Abrupt changes in cold-layer thickness over a short distance were also observed by radio-echo soundings on other glaciers in Svalbard (Hagen 1992; Bjørnsson et. al. 1996).

Our studies have revealed the main features of the thermal structure of Hansbreen (Fig. 5). Temperate ice dominates in the accumulation area of the glacier. Near the equilibrium line, a layer of cold ice overlies thick temperate ice. The cold ice layer continues but becomes thinner near the glacier terminus. Below the layer of seasonal changes (20–25 m), temperatures are negative but significantly different: ca. –2.5°C (25 m) near the equilibrium line altitude, ca. –2.0°C (20 m) in the middle of the ablation area, to about –1.2°C (20 m) and –0.4°C (25 m) in the lower reaches. The temperature of cold ice therefore increases significantly down the glacier. This increase is also obvious at the 10 m level (Table 4). Hence, the cold layer becomes negative in temperature down the glacier both at the 10 m and 20 m (25 m) levels.

The temperature gradient across the pressure melting isotherm (cold-temperate transition surface) is very low and varies between only 0.008°C m^{-1} and 0.024°C m^{-1}. It is nearly one order of magnitude weaker than assumed earlier by some authors (e.g. 0.1°C m^{-1}, Bamber 1987).

Thermal structure and radar horizons

The interface between cold and temperate ice occurs above the uppermost internal reflecting horizons (IRH) recorded during ground-based low frequency radio-echo sounding in April 1989 (Glazovskij et al. 1991) and airborne ultra high frequency (UHF) radio-echo soundings in July 1979 (Mačeret & Žuravlev 1985). The difference is clearly visible at the sites of direct temperature measurements, about 40 m at site B and about 20 m at site D. Both values are significantly higher than any error of both radio-echo soundings. In the accumulation area, IRHs were registered by low frequency radar at the end of the winter. The uppermost IRH is not identical with the cold-temperature transition surface. This result confirms Bamber's (1987) conclusion about the origin of the IRHs in glaciers and does not contradict the results of Mačeret et al. (1993) which described a three-layer model. Changes in the depth of the IRH were noted during the airborne UHF radio-echo soundings of the neighbouring Werenskioldbreen between July 1979 and September 1984 (Mačeret et al. 1993). Seasonal fluctuations of the piezometric head within the glaciers of Svalbard are well known. Water level changes have been observed during speleological explorations of moulins in Hansbreen. In the area of site C, water level increases of about 20 m and of more than 30 m two kilometres upglacier were noted during the winter September/October

Table 4. Ice temperatures of the Hansbreen at the 10 m depth.

Site	Altitude (m a.s.l.)	Temperatures at 10 m depth	Date
Site F	405	0.0°C	22 May–5 Oct. 1994
Site D (ELA)	324	–3.5°C	17 May–5 Oct. 1994
Site C	225	–2.7°C	9 Jan.–17 Sept. 1992
Site B	127	–2.2°C	1 March–20 Apr. 1992 29 Sept. 1994
Site A	ca. 60	–1.5°C	25 Sept. 1988

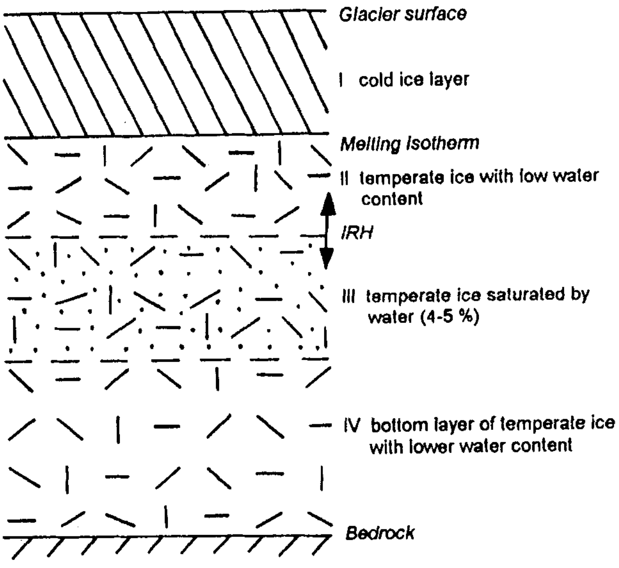

Fig. 6. A concept of the four-layer model of hydro-thermal structure of Hansbreen.

1991–May 1992 (J. Schroeder pers. commun.). Unfortunately, the data are barely sufficient for a precise interpretation. However, the increasing distance between the melting isotherm level and the UHF IRH down the glacier profile suggest a similarity with the hydraulic grade line (Bamber 1987) as affected by an active outflow from a R-channel at the glacier bed. Winter storage of water within the glacier continues until a more efficient basal drainage system develops sometime in the first half of the ablation season. The drainage system is fed by large quantities of meltwater in the first weeks of summer. Before the opening of the drainage channel system, water pressure rises and the piezometric head may reach the cold-temperate transition surface. Cold ice may be regarded as an impermeable layer (moulins are exceptions). Thus, the pressure of stored water may exceed overburden pressure. Geyser-like water spouts on the surface of Werenskioldbreen have been noted in the ablation zone and even in the accumulation area (Baranowski 1973; Głowicki 1982). The importance of the cold ice layer in the elucidation of the hydrology of glaciers is thus evident and confirms that there are significant fluctuations in the water levels in subpolar glaciers.

The interpretation of the radio-echo sounding data (Mačeret & Žuravlev 1985; Bamber 1987; Mačeret et al. 1993), together with the results of our temperature measurements, enable us to propose a model for the hydrothermal structure of the glacier which consists of four layers in the ablation zone (Fig. 6). The uppermost layer of ice (I) is cold and "dry". Below the cold-temperate transition surface, there is temperate ice with a seasonally-fluctuating bulk water content (II), (usually the ice is nearly "dry"). The first IRH forms the lower boundary of this layer. Temperate ice (III) with an anomalously high water content (4–5%) has been detected below the IRH by Mačeret et al. (1993). The layer is more than 60 m thick (up to 220 m). Temperate ice with a smaller content of water (IV) is placed by the authors between the bedrock and layer III. Intriguingly, layer III is oversaturated with water. Possibly this is due the presence of water inclusions in the form of micro-channels within the ice (Raymond & Harrison 1975). Indeed, such channels and fissures (diameter 4–8 mm) were found in a few levels of the ice-core from the Amundsenisen (Zagorodnov & Zotikov 1981). They contained highly mineralised water (Pulina 1986). Sea-spray salts deposited in the snow cover may be identified as a source of such higher mineralisation of water inclusions significantly deeper within the ice than the lower limit of firn. The seasonal fluctuations in depth of the IRH (i.e. the water saturated layer) at Werenskioldbreen suggest that layer II may have a similar structure.

Alternatively, the fluctuations occur only within layer III, whereas layer II is temperate and nearly impermeable because of the lack of microchannels. The problem needs additional study. However, we agree with Mačeret et al. (1993) that a multi-layer hydrothermal structure seems to be typical for many of the larger Svalbard glaciers.

Shallow ice temperatures

The data presented in the tables (Tables 1, 2 and 3) show, as expected, seasonal temperature changes within the active layer. The ice temperature at the standard 10 m depth (T_{10}) is widely used for comparison of the thermal status of glaciers (Paterson 1981; Blatter 1987), including the glaciers in Svalbard (Mačeret & Žuravlev 1985; Bamber 1978). Seasonal temperature fluctuations are easily demonstrable at this depth except in the accumulation zone. The winter "cold wave" can also be recognised at a deeper levels (15 m, even 20 m) but with a significant time delay (ca. 0.5 yr) and amplitudes of the order of 0.2°C. Nevertheless, averaged 10 m temperatures seem to be quite representative of particular parts of the glaciers.

Data from other Svalbard glaciers have been compiled for comparison with Hansbreen. The most detailed set of data relates to temperatures at the 10 m level (Table 5; cf Fig.1 for location). These temperatures have been compared with the mean annual air temperatures at the neighbouring meteorological stations. Table 5 also displays calculated air temperatures at the altitudes of points of the ice temperature measurements (an adiabatic lapse rate of 0.6°C per 100 m was used). Air temperatures might be lower by 1–2°C due to the influence of the local climate of glaciers (Koryakin et al. 1985). In all cases, T_{10} is significantly higher than the assumed air temperatures. This confirms the importance of heat transfer by the percolation of water (release of latent heat of fusion) within glacier accumulation zones. The phenomenon indirectly influences entire glaciers due to the advection of temperate ice to ablation zones. Penetration of short wave radiation to some depth in blue ice in the ablation zone also influences the shallow ice temperatures. Earlier studies determined the relations between the annual mean air temperatures, mass balance facies and the T_{10} in polar and subpolar conditions (Hooke et al. 1983; Blatter 1987). In such conditions, differences between the mean annual ice and air temperatures were observed, with the ice tending to be warmer than air. With respect to Svalbard glaciers, an important statistical relationship between T_{10} and the mean annual temperatures in the equilibrium line altitude zone (correlation coefficient $r = +0.87$), and an even stronger relationship in ablation areas ($r = +0.97$), has been established. The statistical probability of other results are 1% and 0.1% respectively. This suggests that the 10 m-level ice temperatures are in or near equilibrium with the contemporary climatic conditions.

The T_{10} temperatures of Hansbreen are highest among the data referring to the ablation area. The location of the glacier in the southwest part of the archipelago, where the influence of oceanic air masses (e.g. higher accumulation) is stronger, seems to be a reason for this. The accumulation areas of Svalbard glaciers are usually temperate or near temperate. The Hansbreen accumulation zone temperatures are typical for areas strongly affected by meltwater percolation and associated refreezing effects.

Conclusions

The polythermal structure of Hansbreen is similar to many larger Svalbard glaciers; it is of subpolar type. The upper, cold layer of ice is thinner and warmer by comparison with the other glaciers. The cold ice layer seems to be in a state of evolution (reduction of thickness and increase of temperature) as a reaction to climatic change.

The areal pattern of the cold ice layer (its presence and thickness) appears to be more complex than that proposed by more traditional models (e.g. Schytt 1964). Cold ice did not exist in the western lateral part of the glacier due to the proximity of "warm" tributary accumulation zone and the high ablation near to the terminus. Fluctuations in the depth of the IRH suggest the possibility of water level changes within the temperate ice which underlies the cold ice layer. A four-layer hydrothermal model of glacier thermal structure with depth seems to be adequate for the interpretation of the results of temperature measurements, radio-echo sounding data on IRHs and direct hydrological observations. The model is provisional and requires further simultaneous studies both of ice temperatures and of the radar reflection horizons.

Table 5. Temperatures of ice at the 10 m (T_{10}) Svalbard glaciers (degree centigrades).

Glacier	Atlitude (ma.s.l.)	Date	T_{10} (ice)	Meterol. station	Air T*	Period	Air T** (glacier)
(1) Vestfonna	312	15.07.58	-8.5	Murchinson-fjorden	-8.6	1957-58	-10.4
		5.08.58	-8.0				
	550	11&22.04.1958	-1.43				-11.9
		20.05.58	-0.86				-12.2
	622	26.06.58					
		27.07-3.08.58	-1.43				
(2) Hoghetta	1200	4.06.87	-11.0	Pyramiden	-7.1	1979-81	-8.5
(3) Holtedahl fonna	Firn/ice	—	-1.6	Ny-Ålesund	-6.0	1979-83	-8.5
(4) Kongsvegen	370	—	-4.75	Ny-Ålesund	-6.0	1979-83	-8.1
	630	—	ca. 0				-9.5
(5) Bertilbreen	475	May 1980	-4.75	Pyramiden	-5.4	1930-56	-9.2
	325		-4.25		-7.1	1979-81	-8.3
(6) Lomonosovfonna	1050	27.06.65	-2.67	Pyramiden	-5.4	1930-56	-11.0
		16.08.65	-2.33				
(7) Nordenskioldbreen	670	4.06.65	-5.0	Pyramiden	-5.4	1930-56	-9.3
	590	16.6.65	-4.33				-8.7
(8) Brøgerbreen	600	May 1980	-7.5	Longyearbyen	-6.2	1965-74	-10.0
				Lufthavn	-6.8	1979-83	-10.4
(9) Fridtjovbreen	400	July 1981	-3.0	Isfiord Radio	-5.2	1965-74	-7.5
					-4.9	1951-70	-7.2
(10) Amundsenisen	700	7&12.06.1980	-0.56	Hornsund	-4.9	1979-93	-9.1
(11) Hansbreen	320	2-12.04.1989	-3.9	Hornsund	-4.9	1979-93	-6.7
		5.10.94	-3.15				
	224	14.10.91	-2.91				-6.1
	128	16.10.91	-2.22				-5.5

Notes: Alt., altitude; T_{10}, temperature of ice at the 10 m depth; T*, mean annual air temperature at the nearest meteorological station; T**, calculated mean annual air temperature above place of ice temperature measurements (adiabatic cooling assumed as 0.6°C/100m).

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