Mem. Natl Inst. Polar Res., Spec. Issue, **51**, 377–386, 1996

Scientific Paper

ICE CORE ANALYSES AND BOREHOLE TEMPERATURE MEASUREMENTS AT THE DRILLING SITE ON ÅSGÅRDFONNA, SVALBARD, IN 1993

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Abstract: Two ice cores (184.62 m and 49.21 m depth) were drilled in the middle area of Åsgårdfonna, northeastern part of Svalbard, by the Japanese Arctic Glaciological Expedition, 1993 (JAGE '93). None of them reached to the bedrock. Stratigraphic observation and bulk density measurement were carried out for each ice core at the drilling site. The depth of the firn-ice transition was about 6 m. Transparent layers and low density layers indicated the occurrence of several warm and cold climatic conditions in this region. In order to find the cause of the time gap observed in the ice core from Høghetta, on top of Åsgårdfonna, the stratigraphy of both ice cores was compared with each other. Temperature measurements in the boreholes showed a unique profile, that is, it had negative temperature gradient at depths from about 30 m to 130 m. Numerical calculation using a steady state model was applied to reconstruct the unique profile of ice temperature.

1. Introduction

Ice core drillings with *in-situ* analyses were carried out on Åsgårdfonna in the northern part of Svalbard by the Japanese Arctic Glaciological Expedition, 1993 (JAGE '93) with cooperative work by the Norwegian Polar Research Institute (Norsk Polarinstitutt).

Previous expeditions (JAGE '87 and '92) have suggested changes of the climate and environment during the last few hundred years in various parts of the Arctic region (*e.g.* FUJII *et al.*, 1990 ; TAKAHASHI *et al.*, 1993). For example, analyses of ice cores drilled at Høghetta, the top of Åsgårdfonna, indicated that glaciers in Svalbard shrank considerably during the hypsithermal (FUJII *et al.*, 1990). One of the objectives of JAGE '93 is to reveal the climatic and environmental changes around Åsgårdfonna from ice core analyses.

The field research was carried out from June to July, 1993. The ice field is located in the middle part of Åsgårdfonna, in northern Svalbard (N79°26′38″, E16°42′39″; 1140 m

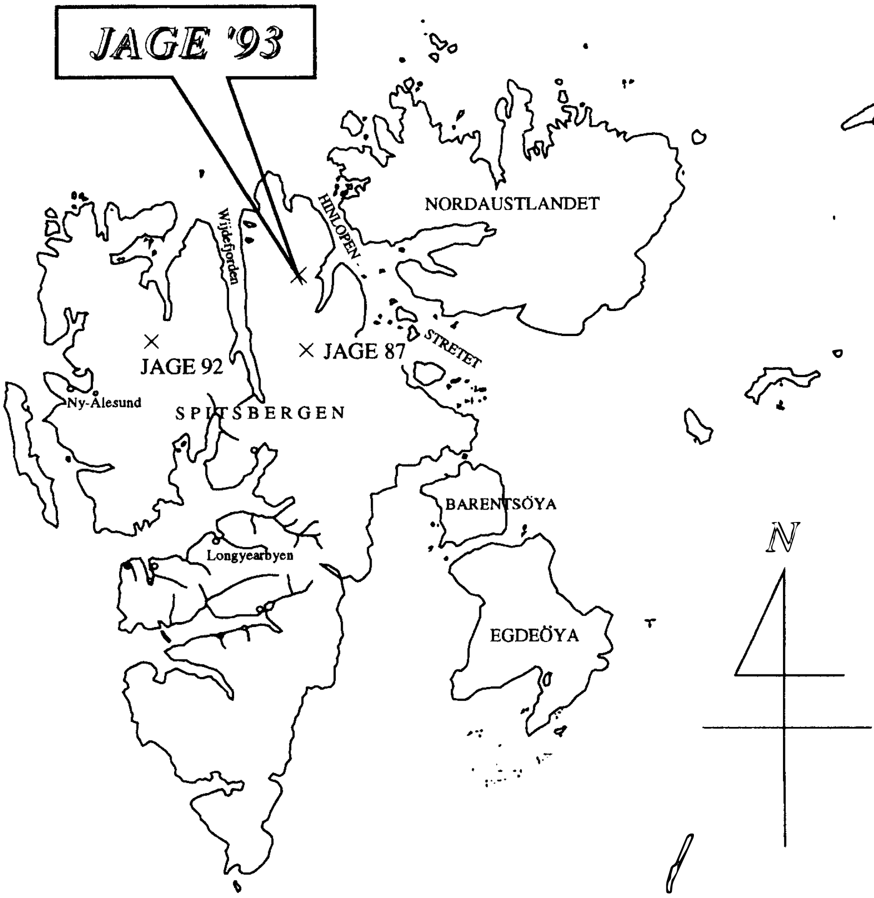

Fig. 1. Location of drilling sites of JAGE '87, '92 and '93 in the northern part of Svalbard.

a.s.l.; see Fig. 1) about 35 km north of Høghetta. A shallow type electro-mechanical coring system (type ILTS-100, Geo. Tec. Co. Ltd.) was used for ice-core drilling. It was newly designed to drill through several hundred meters of ice core rapidly.

2. Field Research

Two drillings were performed about 1 m apart, reaching depths of 184.62 m (site 1) and 49.21 m (site 2), respectively. Neither drilling reached the bedrock.

After an ice core was obtained, the distributions of air bubbles with various shapes, visible impurities and dust layers were observed beside the boring site and recorded in true scale on a narrow roll of graph paper which was placed adjacent to the core. The temperature at the drilling site was about the freezing point. The weight of the ice core was measured with a Robervel balance at ± 3 g resolution. Diameters of the ice core were measured by a slide caliper at ± 0.03 cm resolution. The ice core length (the average about 41 cm) was measured more than three times and the average value was used to calculate the bulk density of the ice core. The average error of the measurement was estimated to be approximately 1.3%. Whole ice cores were transported to a cold room in Ny-Ålesund by a helicopter for further analyses.

Measurements of ice temperature in each borehole were conducted during one night after the ice coring operation was finished. The direct-contact thermistor sensor system was used for the present study. This system was introduced in JAGE'92 (KAMEDA *et al.*, 1993). The ice temperature at each site was measured every 1 m intervals from the surface to 10 m depth. Below 10 m, the interval of ice-temperature measurements is about 10 m at site 1 whereas about 5 m intervals at site 2. The accuracy of stabilized ice-temperature was estimated to be ± 0.08°C in the present study. Details of the measurement were the same as those carried out in JAGE'92 (KAMEDA *et al.*, 1993).

3. Results

3.1. Stratigraphic observations

At depths ranging from the surface to about 49 m, we used the data of site 2 for the stratigraphic analyses. We classified the distribution patterns of air bubbles into five types for simplicity. Type S is a snow layer. Type H has high concentrations of spherical and connected air bubbles. This type sometimes included thin transparent ice layers. It is considered to be a remnant of firn pores. This type of air-bubble distribution was also observed in ice cores of Snøfjellafonna, western part of Svalbard (KAMEDA *et al.*, 1993).

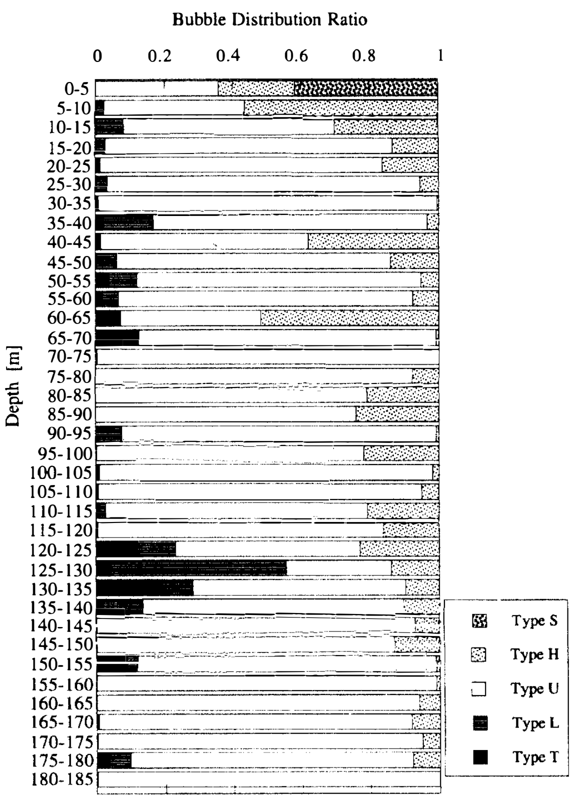

Fig. 2. Stratigraphic profiles of the air-bubble distribution ratio every 5 m. type S: snow, type H: high concentration of air bubbles, type U: "uniform distribution type", type L: low concentration of air bubbles, and type T: transparent ice.

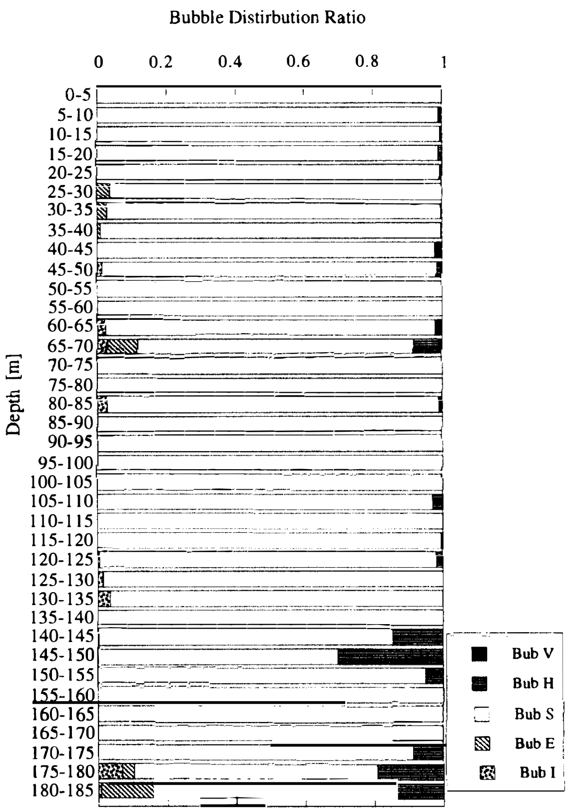

Fig. 3. Stratigraphic profiles of the air-bubble shape ratio every 5 m. Bub V: vertically elongated type, Bub H: horizontally elongated type, Bub S: spherical type, Bub E: elongated and inclined type, and Bub I: irregular type.

Type U is the uniform distribution type (pattern A of Fig. 2 in KAMEDA *et al.*, 1989). Type L is a layer having a low concentration of air bubbles, and type T is a transparent ice (containing no air bubbles).

Figure 2 shows the average ratio of each type of distribution in every 5 m. This figure shows that the shallowest ice cores consisted of snow, firn and ice. At depths shallower than about 30 m, the firn gradually transforms into ice of type U distribution with depth. The type U distribution is dominant in all depths. However, we observed type H frequently. The transparent layers (type L and T) were also observed over all depths, but relatively high ratio regions were observed at depths around 60–70 m and around 110–140 m.

The shapes of air bubbles were also classified into five types: vertically elongated (Bub V), horizontally elongated (Bub H), spherical (Bub S), elongated and inclined (Bub E), and irregular shape (Bub I). Inclinations of boreholes were not measured but were considered to be small. Figure 3 shows the average ratio of each type in every 5 m interval. This figure indicates that the dominant shape of air bubbles is spherical. Bub V were observed a little at shallow depths. On the other hand, Bub H were widely observed at depths around 145–150 m and in the deepest part. Inclined bubbles were observed at depths around 60–70 m and in the deepest part. Irregular bubbles were also found together inclined bubbles, and also observed at depths around 110–140 m.

Small visible impurities were observed at several depths. It is not certain whether they are sand particles or organic matter yet. Most of them are about 1 mm in diameter.

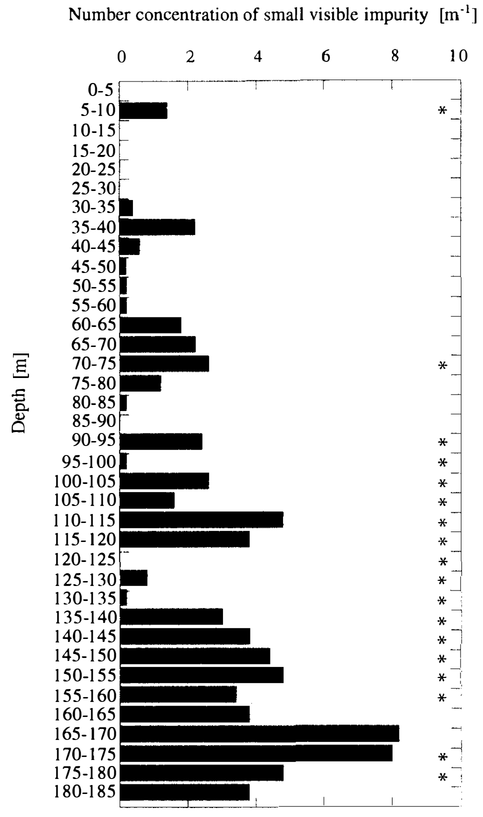

*Fig. 4. Average number-concentration of visible impurities in every 5 m. * denotes the depth where dust layers were observed.*

Figure 4 shows the average number of particles included in every 5 m. Dust layers were also observed at depths shown by "*" in Fig. 4. This figure indicates that the visible impurities are mainly included in ice cores deeper than about 90 m.

3.2. Density profile measurements

Bulk density profiles of ice cores shallower than 60 m at both sites are shown in Fig. 5. The measurement errors are also shown by the error bars. The profiles of both sites coincide well with each other. Figure 5 shows that the bulk density sharply increases from the surface to about 6 m depth where the density is more than 850 kg m^{-3}. Below about 6 m depth, the increasing rate of the bulk density of ice cores becomes small, and the density reaches about 920 kg m^{-3} at depth of about 30 m.

Some ice cores were observed to have small densities (*e.g.*, at about 6, 23 and 41 m depth). These ice cores include air bubbles of type H distribution. The density values suggest that this layer contains remnants of firn pores. These ice cores were found at the same depth in each borehole.

3.3. Borehole temperature measurements

Temperature profiles of each borehole are shown in Fig. 6. This figure indicates that

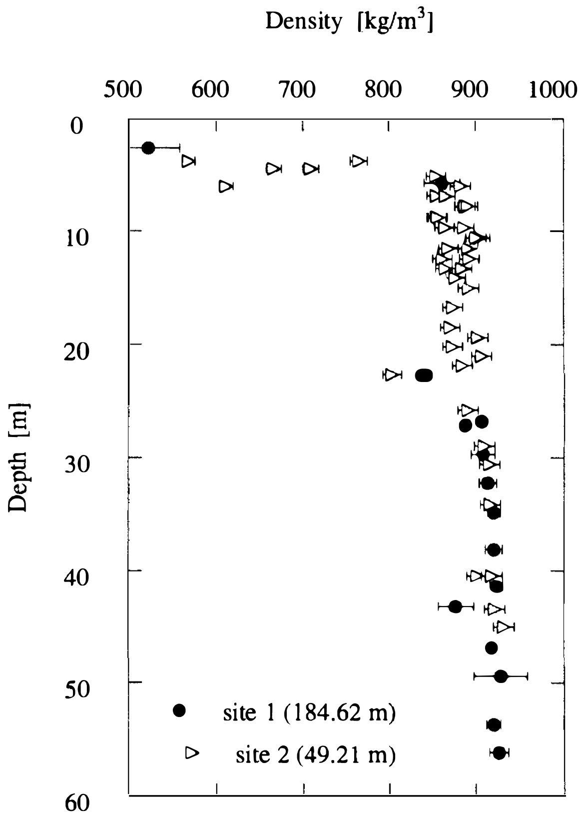

Fig. 5. Density profiles of shallower ice cores drilled at two drilling sites with error bars. (●: site 1 and ▷: site 2)

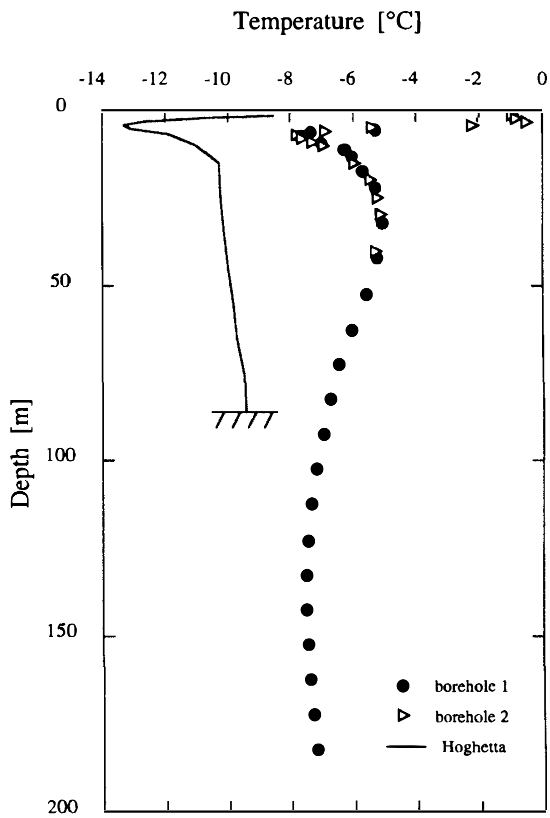

Fig. 6. Ice temperature profiles of two boreholes of JAGE '93 (●: site 1 reaches to 184.62 m and ▷: site 2, 49.21 m) and that of JAGE '87 (KAWAMURA et al., 1991) (solid line: it reached the bed rock).

two temperature profiles coincide well with each other. Figure 6 also shows the temperature profile of Høghetta (solid line; KAWAMURA *et al.*, 1991).

Ice temperatures above 4.5 m depth are higher than −1°C. Then the ice temperature rapidly decreases from 4.5 m to 7.5 m depth, where the temperature reaches a minimum (−7.8°C). From 7.5 m to about 30 m depth, ice temperature increases with depth and takes a local maximum value (−5.0°C) at about 30 m depth. Below 30 m depth, ice temperature gradually decreases with depth down to about 130 m where the temperature takes another minimum value (−7.5°C). This negative temperature gradient was not observed at Høghetta. Below about 130 m depth ice temperature increases again down to the bottom of the borehole, −7.1°C at 182.0 m. Here the temperature gradient, W, is about 0.014°C m^{-1}. This value is very similar to that of Høghetta, $W = 0.0139$°C m^{-1} (KAWAMURA *et al.*, 1991).

4. Discussion

4.1. Sedimentary conditions at the drilling site

The bulk density of ice cores increased sharply with depth from the surface to the depth of about 6 m. In this depth interval, the snow and firn gradually transformed to ice with depth. Therefore we decided that the depth of the firn-ice transition was about 6 m for the present drilling site. The ice temperature above the transition depth is higher than below. This relatively high temperature may result from sunshine and atmospheric air penetrating into this layer.

The bulk density increased gradually from the depth of about 6 m (about 850 kg m^{-3}) to about 30 m (about 920 kg m^{-3}). In this depth interval, type H decreased and type U increased with depth. These results indicate that ice is slowly compacted with depth.

Below 30 m depth, the bulk densities of ice cores were almost 920 kg m^{-3}. However, we observed ice cores which included large amount of type H air bubbles (*e.g.* at about 23, 41 and 62 m). Since this layer is a remnant of firn, the ice formation process of this layer is considered to be different from the present process observed above 6 m. We speculate that the residual firn below the firn-ice transition indicates that the temperature of this layer was relatively low at the moment of transition.

On the other hand, types T and L are remarkable at depths of 60–70 m. In this layer, we observed air-bubble types of Bub E and I. This result indicates that this transparent layer may result from a large amount of melt water. Therefore we considered that the temperature of this layer was relatively high at the moment of transition. We also observed the transparent layer at depths of 110–140 m. This may be evidence of another warm period.

Below 130 m at the present drilling site, the temperature gradient, W, becomes positive, and gradually increases with depth. At the bottom of the borehole (site 1), $W =$ 0.014°C m^{-1} which is very similar to the value at Høghetta ($W = 0.0139$°C m^{-1}). Since the borehole bottom of Høghetta touched the bedrock, W is defined by the geothermal flux. Then the present drilling site should have the same geothermal flux as the bedrock. The radio echo-sounding surveys (MACHERET *et al.*, 1985) indicated the ice thickness around the present drilling site to be about 200 m. Therefore the bedrock at the present drilling site may be just below the borehole bottom. This conclusion is also supported by stratigraphic analysis. Since the temperature at the depth of 182.0 m is –7.1°C, the temperature at the bedrock is estimated to be about –6.8°C, which indicates that ice is frozen on the bedrock. If so, the large shear stress caused by the glacier flow will elongate the spherical bubbles horizontally or with some inclination. The large amount of horizontally elongated and inclined bubbles at the bottom of the borehole suggests that the bedrock is just below that point.

There is another layer of horizontally-elongated bubbles at depths of 145–150 m. It is difficult to imagine that the elongated bubbles in this layer resulted from the shear stress of ice deformation. This layer may be formed by the effect of high temperature which is assumed to exist at the layer just above (110–140 m). Further information is required to understand the details of this ice core.

4.2. Comparison of ice core analyses with those at Høghetta

Results at Høghetta showed climatic variations for several hundred years (FUJII *et al.*, 1990). During 220 and 110 BP (years before present), the climate was apparently cold and stormy. After that period, the climate became calm with some cold/warm fluctuations. However, before 220 BP, there is a time gap from 220 BP to about 4000 BP at depth about 50 m. This time gap is considered to be due to negative mass balance of the glacier during the hypsithermal. In order to discuss the cause of the time gap, we compare the stratigraphy, density profile and temperature profile obtained in the present study with those of Høghetta because the present drilling site is located on the same glacier.

Although the time scale of ice cores in the present study has not been determined, we estimated it from the net mass balance. The net mass balance b was estimated to be about 1.2×10^{-8} m s^{-1} (as the thickness of ice) from measurements of snow pit and tritium concentration, and from the stratigraphy of shallow cores (IGARASHI, personal communication).

The stratigraphic analyses at the present drilling site indicate evidence of climate variation. The warm periods were observed in ice cores of 60–70 m and 110–140 m depths, which are estimated to be about 200 BP and about 400 BP, respectively. On the other hand, the relatively cold periods were observed in ice cores of about 23 m, 41 m and 62 m, which are estimated to be about 72 BP, 131 BP and 194 BP, respectively.

Comparing these ice cores, it is considered that the mass balance after 220 BP has been positive even if the climate has been warm, and that before 220 BP, the mass balance had been negative due to the very warm climate. However, the unconformity between about 4000 BP and 220 BP requires a large amount of ice disappearance. The stratigraphy of the present ice core shows that there were two warm climate periods during the last 400 BP, but the period was too short to account for the large amount of ice disappearance only by the negative mass balance. Since surges occurred in some glaciers in east-northern Svalbard (FUJII, personal communication), we considered that a large glacier surge is one possible cause of ice disappearance.

The ice temperature decreased with depth to the minimum value (–7.8°C) at 7.5 m, and then increased to the local maximum (–5.0°C) at 30 m. This profile is qualitatively similar to that at Høghetta (KAWAMURA *et al.*, 1991). This indicates that the propagation of cold waves in winter is similar between the present drilling site and Høghetta. However, the absolute temperature difference between them is about 5°C over this depth region. This difference is too large to result from the difference of altitude. We will discuss the temperature deviation of the present borehole from the steady state condition.

4.3. Comparison of ice temperature profiles with steady state model

PATERSON (1994) suggested the simplest solution of a steady state flow. This solution included some assumptions: the horizontal velocity is negligible and the vertical velocity v is taken as $v = -by/h$, where the y-axis is vertical and positive upward from the bottom of the glacier, and h is ice thickness. This model represents the temperature profile at Høghetta very well with the variables $W = 0.0139°\text{C m}^{-1}$, $h = 85.5$ m, $b = 5.7 \times 10^{-9}$ m s^{-1} and the surface temperature $T_s = -10.4°\text{C}$. We applied this model to the present drilling site conditions to discuss the temperature deviation from the steady state. For the calculation, we use $W = 0.014°\text{C m}^{-1}$, $h = 200$ m and $b = 1.2 \times 10^{-8}$ m s^{-1} and T_s as a fitting parameter.

We can choose T_s to fit the steady state profile to the shallow temperature profile at this drilling site or the deep temperature profile. If $T_s = -5.4°\text{C}$, the deep ice temperature is about 4°C colder than that in the steady state. Usually a colder deep ice temperature can be interpreted as being due to cold ice flow from upstream. However, the altitude difference between the drilling site and Høghetta, only about 60 m, is too small to make such a large ice temperature difference.

Then we assume that $T_s = -9.6°\text{C}$ in order to fit the profiles in deep parts of the borehole. This value of T_s is reasonable because the difference of T_s between the two sites is 0.8°C, which can be accounted for by the difference of altitude. Each point in Figs. 7a and 7b shows the depth variation of the temperature deviation from the steady state profile, ΔT. This figure shows that ΔT is about 4.1°C from about 5 m to 30 m, and that it decreases with depth down to about 170 m. The variation of ΔT above 15 m may result from the surface temperature variation and the cold wave of the winter of 1992–1993.

In order to explain the temperature deviation profile, we apply the steady state models with variable T_s values. If the climate changes, not only T_s but also b, h and k should change. However, there is no information about these parameter changes at present, we apply the model with only one parameter.

The applied steady state model, which considers the vertical temperature distribution, is as follows:

$$\frac{\partial T}{\partial t} = k\nabla^2 T + v\frac{\partial T}{\partial y}, \qquad (1)$$

$$v = b\,\frac{h-y}{h},$$

where T is ice temperature, $k = 1.15 \times 10^{-6}$ m^2 s^{-1} is the thermal diffusivity of ice and y-axis is vertical, positive downward from the glacier surface. Since the results at Høghetta indicated that the climate became warm in the last several decades, we considered that the surface temperature difference, ΔT_s, increased 5°C during the last 100 years. The numerical calculations were performed with the time step of a year.

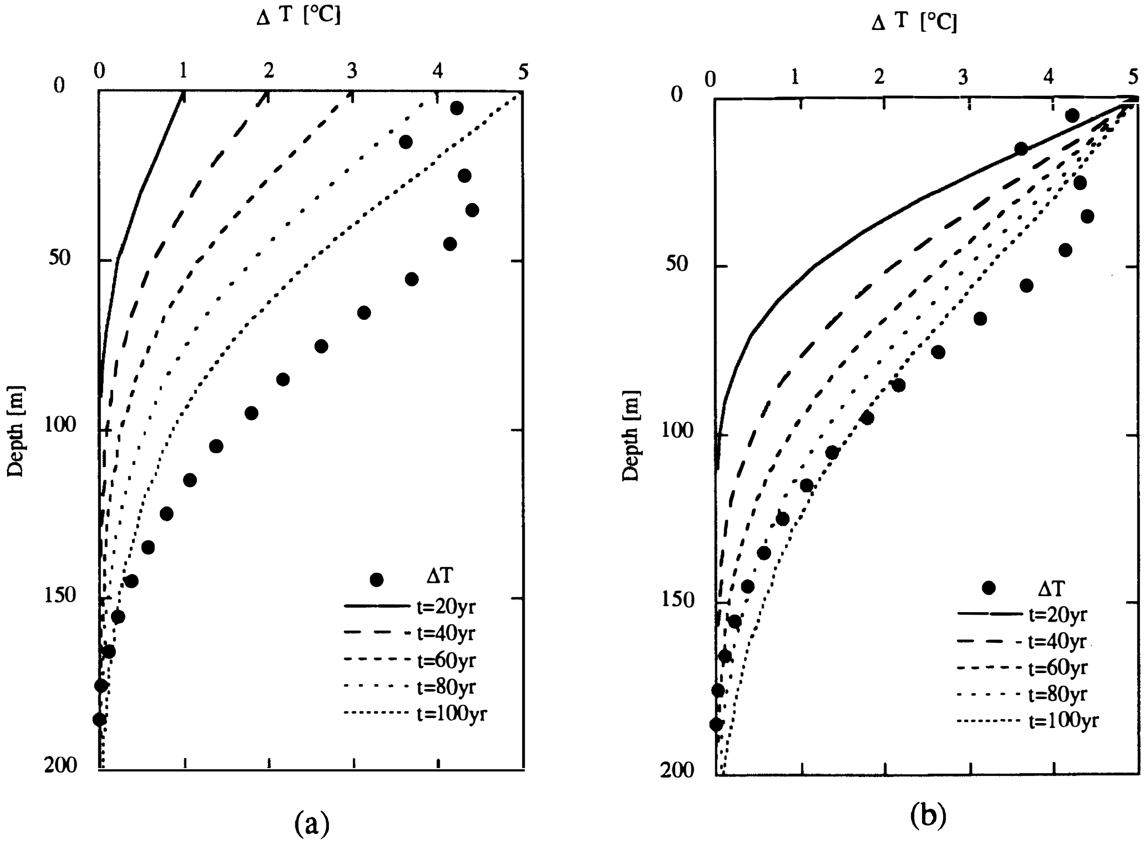

Fig. 7. Temperature difference, ΔT (denoted by ●), between the measured temperature profile and the one calculated by the steady state model vs. depth. The ice thickness and the net mass balance at the present drilling site are assumed to be 200 m and 1.2×10^{-8} m s^{-1}, respectively.

(a) Comparison of ΔT with a simulation in which T_s rose stepwise from $T_s = -9.6$°C at 100 BP by 1°C every 20 years to $T_s = -4.6$°C.

(b) Comparison of ΔT with a simulation in which T_s rose from −9.6°C to −4.6°C over 100 years.

The lines in Fig. 7a show the result of a simulation in which ΔT_s was made rise stepwise by 1°C in every 20 years. This indicates that the calculated temperature profile gradually reaches the observed value, but it requires higher ΔT_s to reconstruct the whole ΔT profile. On the other hand, the lines of Fig. 7b show the result of a simulation in which ΔT_s increased up to 5°C over 100 years. This figure suggests that the deeper part of the ΔT_s profile is well reconstructed for about 80 years, but the profile around 30 m depth is not well fitted if we choose $\Delta T_s = 5$°C. These results indicate that the positive value of ΔT can be explained by the increase of T_s over the last 100 years. However, a value of ΔT_s higher than 5°C for several decades is necessary to explain the large ΔT values around 30 m depth.

The variation of another parameter, such as b, h and k, may change the temperature profile. We will be able to obtain a better fitting curve considering these variations. These parameters are, however, not effective for the intensity of ΔT. Therefore we consider that a surface temperature change larger than 5°C has occurred at the present drilling site. The heat source of this temperature difference has not been revealed, but one possibility is the existence of melt water.

Further quantitative discussion is necessary to explain the unique temperature profile, and to reveal the history of the environmental changes around Åsgårdfonna.

Acknowledgments

We would like to express our sincere gratitude to Drs. J. O. HAGEN, Y. OHTA and other members of Norsk Polarinstitutt for their cooperation and support in the field work. We also acknowledge the staff of Kings Bay Kull Company A/S for their kind help in Ny-Ålesund.

We are very much indebted to Drs. H. ITO and S. USHIO of the National Institute of Polar Research for their kind support at the Japanese station in Ny-Ålesund. Thanks are also due to Dr. T. KAMEDA for providing the direct contact thermistor sensor system used in 1992. The members of JAGE '92 gave useful advice to our field observations. We wish to thank Drs. H. MOTOYAMA, H. NARITA, K. KAWASHIMA, H. YABUKI and K. OSADA for their helpful discussions, and Ms. S. SHIMIZU, Ms. M. MORI and Ms. A. ONO for their assistance in preparing figures.

This research was supported by a Grant of the International Scientific Research Program of the Ministry of Education, Science, Sports and Culture, Japan (No. 05051069).

References

FUJII, Y., KAMIYAMA, K., KAWAMURA, T., KAMEDA, T., IZUMI, K., SATOW, K., ENOMOTO, H., NAKAMURA, T., HAGEN, J. O., GJESSING, Y. and WATANABE, O. (1990): 6000-year climate records in an ice core from the Høghetta ice dome in northern Spitsbergen. Ann. Glaciol., **14**, 85–89.

KAMEDA, T., KAWAMURA, T., FUJII, Y. and ENOMOTO, H. (1989): Shapes and distribution of air bubbles in an ice core from Åsgårdfonna, Spitsbergen. Bull. Glacier Res., **7**, 221–226.

KAMEDA, T., TAKAHASHI, S., GOTO-AZUMA, K., KOHSHIMA, S., WATANABE, O. and HAGEN, J.O. (1993): First report of ice core analyses and borehole temperatures on the highest icefield on western Spitsbergen in 1992. Bull. Glacier Res., **11**, 51–61.

KAWAMURA, T., KAMEDA, T. and IZUMI, K. (1991): Preliminary results of structural analyses of an 85.6 m deep ice core retrieved from Høghetta ice dome in northern Spitsbergen, Svalbard. Bull. Glacier Res., **9**, 77–83.

MACHERET, Yu.Ya., ZHURAVLEV, A.B. and BOBROVA, L.I. (1985): Thickness, subglacial relief and volume of Svalbard glaciers based on radio echo-sounding data. Polar Geogr. Geol., **9**, 224–243.

PATERSON, W. S. B. (1994) : The Physics of Glaciers, 3rd ed. Oxford, Elsevier, 480 p.

TAKAHASHI, S., KOBAYASHI, S. and WATANABE, O. (1993): Field activities of the Japanese Arctic Glaciological Expedition to western Spitsbergen in 1991 and 1992 (JAGE 1991–1992). Bull. Glacier Res., **11**, 23–31.

(Received December 18, 1995; Revised manuscript accepted May 15, 1996)