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The near-surface ice thermal structure of the Waldemarbreen, Svalbard

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Abstract: The near-surface ice thermal structure of the Waldemarbreen, a 2.5-square km glacier located at 78°N 12°E in Spitsbergen, Svalbard, is described here. Traditional glaciological mass balance measurements by stake readings and snow surveying have been conducted annually since 1996. The near-surface ice temperature was investigated with automatic borehole thermistors in the ablation and accumulation areas in 2007–2008. The mean annual surface ice temperatures (September–June) of the ablation area were determined to be -4.7°C at 1 m depth and -2.5°C at 9 m. For the accumulation area, they were -3.0°C at 2 m, and -2.3°C at 10 m depth between September and August. On the Waldemarbreen, at 10 m depth, the mean annual near-surface ice temperature was 4.0°C above the mean annual air temperature in the accumulation area. The Waldemarbreen may thus be classified as a polythermal type with cold ice which is below the pressure melting point and a temperate ice layer in the bottom sections of the glacier and with a temperate surface layer only during summer seasons. At a depth of 10 m, temperatures are of the order of -2°C to -3°C.

Key words: Arctic, Spitsbergen, ice temperature, thermal regime, glacier.

Introduction

Glaciers are dominant in Svalbard's relief, covering over 60% of the archipelago (Hisdal 1985). Systematic studies on mass balance include about ten Svalbard glaciers (Jania and Hagen 1996; WGMS 2007, 2008; Sobota 2005, 2007a–d). Although the analysis in this paper refers only to the Waldemarbreen, other Kaffiøyra Plain glaciers, including the Irenebreen which has been investigated since 2001 and the Elisebreen since 2005, have also been studied.

The main aim of this research was to take measurements in order to define annual vertical time variation of near-surface ice temperature at the characteristic points (the ablation and the accumulation areas) of the Waldemarbreen, as well as to define the role of air temperature and the influence of meltwater and snow cover on the near-surface thermal structure during both the ablation and winter seasons in 2007–2008. Moreover, by using automatic temperature thermistors, and the facility of conducting the research throughout a whole year, it was possible to study seasonal changes in the near-surface thermal structure of the glacier. Furthermore, vertical temperature variability of the surface ice could be analysed, *i.e.* measurements were taken at a depth where annual temperature oscillations becomes negligible, and comparing these with the mean annual air temperatures. These studies have enabled to establish what kind of glacier the Waldemarbreen is in thermal classification. The near-surface ice thermal structure of this glacier is an important supplement to the regional studies of the mass balance of the Kaffiøyra glaciers, as carried out since 1996 (Sobota 2005, 2007a, b, d, e).

Glaciological methods of mass balance estimation involve repeated point measurements at the glacier surface in order to determine the rates of ablation and accumulation. These methods involve estimation of local mass balance using ablation poles, supplemented by studies of the snow cover in pits (Østrem and Brugman 1991; Kaser *et al*. 2003; Bamber and Payne 2004; Hubbard and Glasser 2005). The results of the mass balance studies of the Waldemarbreen are quite similar to other Svalbard glaciers which terminate on land (Hagen *et al.* 2003; WGMS 2007, 2008; Sobota 1999, 2000, 2005, 2007a–e; Błaszczyk *et al.* 2009; Zemp *et al.* 2009).

Ice temperature significantly influences the glacier's dynamics, movements and mass changes. Moreover, the thermal regime of glaciers determines the routes of glacial water circulation. It also shapes the character of the water flow and the drainage pattern. Thus, investigations of the thermal structure of a glacier are an important part of the glaciological research carried out directly on ice. They are often expensive and complicated, especially when deep drilling and installation of measuring equipment is involved.

It is generally accepted that the thermal regime of a glaciers directly controls glacier mass balance, hydrology and dynamics (Fisher 1955; Baranowski 1977; Paterson 1981; Blatter and Haeberli 1984; Krass *et al.* 1991; Key and Haefliger 1992; Dowdeswell *et al.* 1995; Björnsson *et al.* 1996; Jania 1997; Hodgkins *et al.*1999; Nagornov *et al.* 2001, 2006; Rabus and Echelmeyer 2002; Hooke 2005; Willis *et al.* 2007; Reijmer and Hock 2008). Unfortunately, direct measurements of thermal regimes are only available for very few glaciers worldwide.

Cold glaciers are defined as firn ice bodies showing permanently sub-freezing temperatures over minimum period of one year. Glaciers are temperate if their firn and ice is at pressure melting point. Most of the existing glaciers are neither cold nor temperate throughout. Such ice bodies are called polythermal (*e.g.* Baranowski 1977; Paterson 1981; Hooke 2005).

Until recently, determinations of thermal structure of the Waldemarbreen have been based only on indirect studies, *i.e.* the results of the detailed measurements of the elements of the mass balance, as related to our knowledge of glacial zones, morphology, development of the associated river network, naledies and glacier outflow. The temperatures of the near-surface layers of a glacier are influenced by

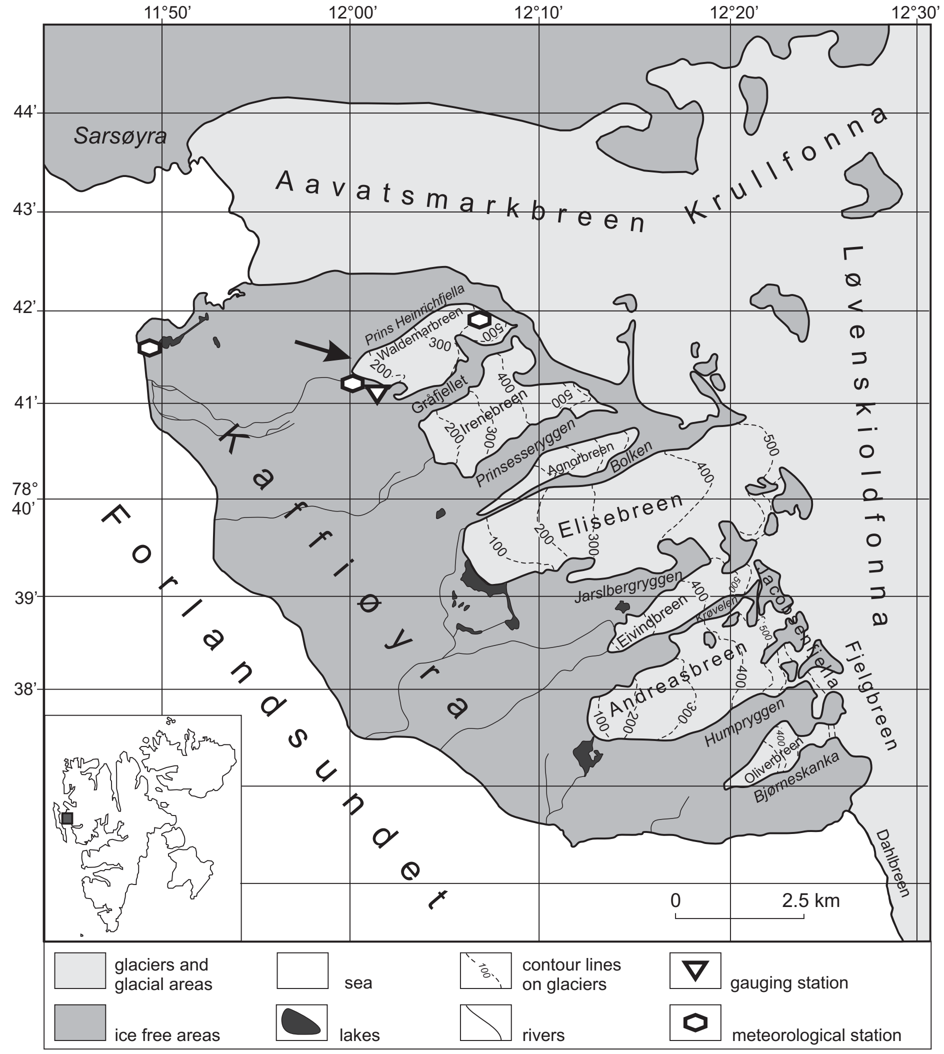

Fig. 1. Location map of the Waldemarbreen (arrow), Svalbard.

seasonal changes of the energy balance of its surface and associated changes in the thermal conductivity (Jania 1997). This is clearly visible during the summer season in the case of the ablation area of the Waldemarbreen (which lacks a snow cover) and the accumulation zone (which has one). Meltwater, which increases the temperature of both firn and the upper snow layers almost to the melting point, is an important influence in this context.

Melt water percolates into snow-firn layers. The intensity of melting during the summer months is proportional to the third power of the mean air temperature (Krenke and Khodakov 1966). Thus, learning the magnitude of summer melting is crucial for studying the changes in the mass balance and dynamics of glacier.

Studying the thermal structure of entire glaciers has proved to be very useful in enabling investigations to make comparisons between them (Jania 1997). Such research is especially significant in the case of internal accumulation, which may pose an important element of the input part of the glacier mass balance (Schneider and Jansson 2004; Reijmer and Hock 2008).

Study area

The Waldemarbreen is located in the northern part of the Oscar II Land, Kaffiøyra, north-western Spitsbergen (Fig. 1). Kaffiøyra is a coastal lowland situated on the Forlandsundet. In the north, it is bordered by the Aavatsmarkbreen, which terminates in Hornbaek Bay, and, in the south, by the Dahlbreen and the bay of the same name. In the east, Kaffiøyra is bordered by seven glaciers which descend from the Prins Heinrich and Jacobson mountains. From north to south, these are: Waldemarbreen, Irenebreen, Agnorbreen, Elisebreen, Eivindbreen, Andreasbreen and Oliverbreen (Fig. 1). The glaciers are a dominant element in the landscape of Kaffiøyra, covering *ca*. 255 km^2 (Lankauf 2002).

The Waldemarbreen is about 3.5 km long and has an area of 2.5 km^2. The ice originates in one cirque and flows from an elevation of more than 500 m to the present snout at about 150 m a.s.l.

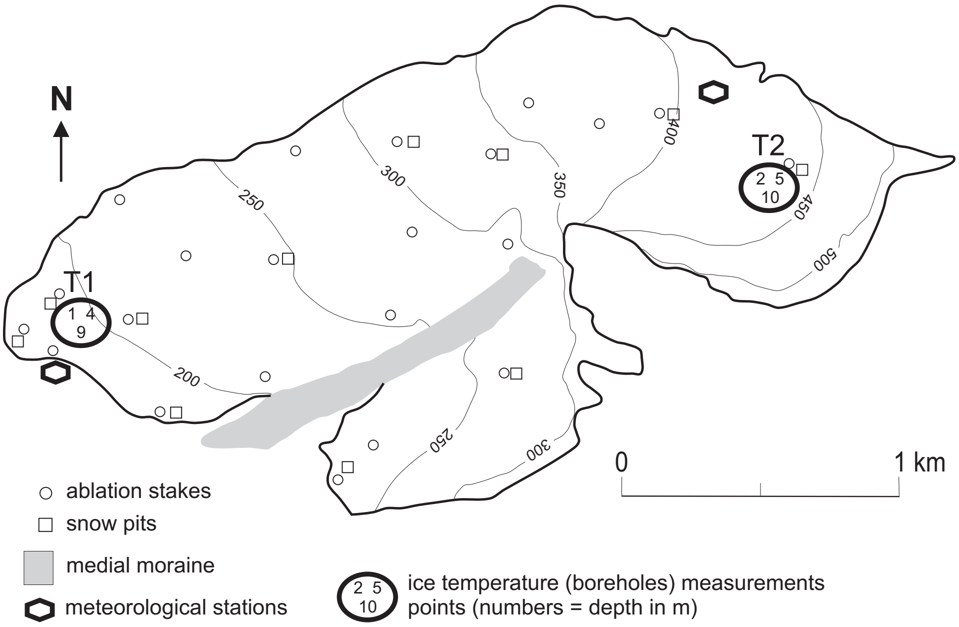

Fig. 2. The near-surface ice temperature measurements points (boreholes) location on the Waldemarbreen.

Methods

Direct measurements of the mass balance of the Waldemarbreen were taken between 1996 and 2008. The components of the glacier balance and selected meteorological parameters were measured both on the glacier and at Kaffiøyra. The glacier runoff was also measured (Fig. 1). The measurements of surface ablation were made every 5–10 days from July to September each year. The measurements were taken at 22 points on the glacier surface. All the ablation poles were inserted 10 m deep by means of a steam driven *Heucke Ice Drill* (Heucke 1999). Measurements of snow accumulation were taken in April or the early part of May each year (Grześ and Sobota 1999, 2000; Sobota and Grześ 2008). Snow density, structure, grain type and hardness values were measured in pits and at representative points (Fig. 2). The balance year adopted for this project lasted from October to September of the following year**.** This period of time included both the entire accumulation and ablation seasons. The direct measurement method, based on a number of ablation poles, remains the most precise and most frequently used glaciological method (Østrem and Brugman 1991; Kaser *et al.* 2003; Bamber and Payne 2004; Hubbard and Glasser 2005).

In order to study the near-surface ice thermal structure of the Waldemarbreen two measurement points were installed on the glacier in summer 2007 (Fig. 2). Temperature measurements were made in 2007–2008 in both the ablation and accumulation areas of the Waldemarbreen. At one point (T2), located in the ac-

Fig. 3. Ice temperature measurements point (T2) in the accumulation area of the Waldemarbreen during spring and summer.

cumulation area of the glacier, temperature thermistors were placed at 2, 5 and 10 m depth (Fig. 3). At a second point (T1), located in the ablation area, the thermistor depths were at 2, 5 and 10 m depth (owing to the surface melting of the glacier, after the end of the ablation season, the thermistor depths used for the analysis were 1, 4 and 9 m). The thermistors automatically register the ice temperature changes at the 10-minute intervals. Their accuracy is ±0.2°C, whereas their resolution is 0.03°C. The measurement range of the devices is from -40°C to +75°C. The location of the measurement sites should enable investigations of the thermal structure of the near-surface layers of the Waldemarbreen to take place throughout the entire balance year. Also, the air temperatures were registered simultaneously on automatic devices also located in both the ablation and accumulation areas of glacier.

Results of the near-surface ice temperature investigations

Temporal variations of ice temperature. — Significant differences in the temperature values and variations of the near-surface ice layer, in both ablation and accumulation zones of the Waldemarbreen, were recorded during the 2008 summer season. The most uniform temperature values were recorded at 9 and 10 m depth and the largest differences at 1 and 2 m. In the beginning of summer season, the ice temperature at 1–2 m depth at the ablation zone was higher than that at the accumulation zone. This was the result of the snow cover in the accumulation area, which insulated the glacier ice against the changes in the air temperatures. It is to be emphasised, however, that, during the summer season, the temperature of the surface layer of ice in the accumulation area was close to the pressure melting point.

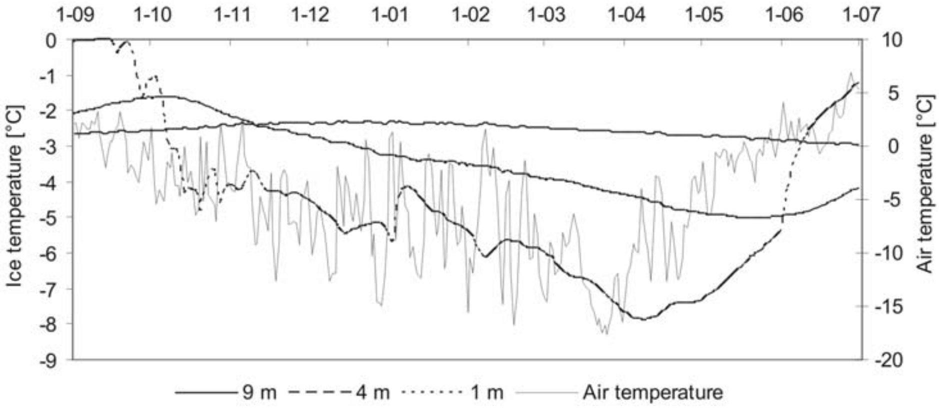

Fig. 4. Temporal variations of daily near-surface ice temperatures in the ablation area of the Waldemarbreen and daily air temperature in 2007–2008. Air temperature data based on the Department of Climatology, Institute of Geography, *Nicolaus Copernicus* University (IG NCU).

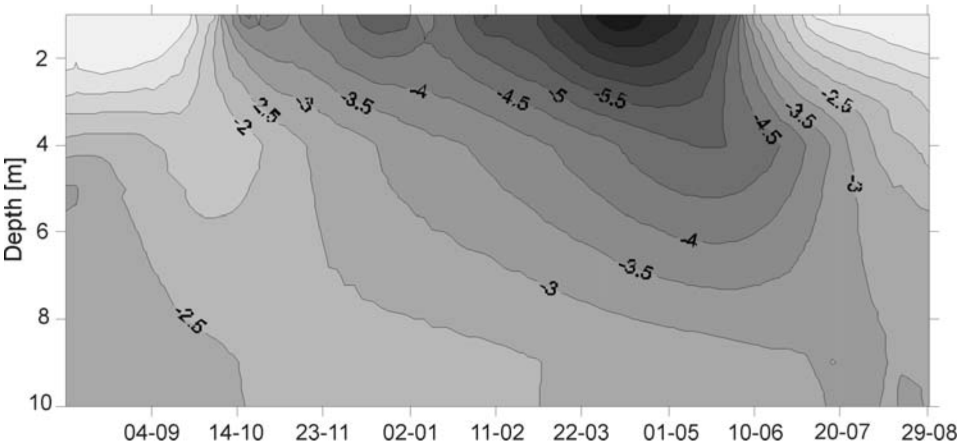

Fig. 5. The near-surface ice temperature in the ablation area of the Waldemarbreen in 2007–2008.

The near-surface ice temperatures of the Waldemarbreen changed significantly throughout the year. At the end of the summer (ablation) season, in the ablation area of the glacier, the mean daily temperature at 1 m depth reached ice melting point, and was higher than the temperature of the overlying layer. As the winter approached, however, ice temperatures at that depth fell to the lowest recorded value of -7.9°C (Fig. 4). At 4 and 9 m depths, the temperature plot showed smaller oscillations and lower values were recorded in the summer season. At 4 m depth, the propagation of the cold wave was much delayed compared to 1 m depth. At 9 m depth, however, the ice temperature was even throughout the entire research period (Fig. 5). The minimum temperature at 4 m depth was -5.0°C, whereas at 9 m depth it was -3.0°C.

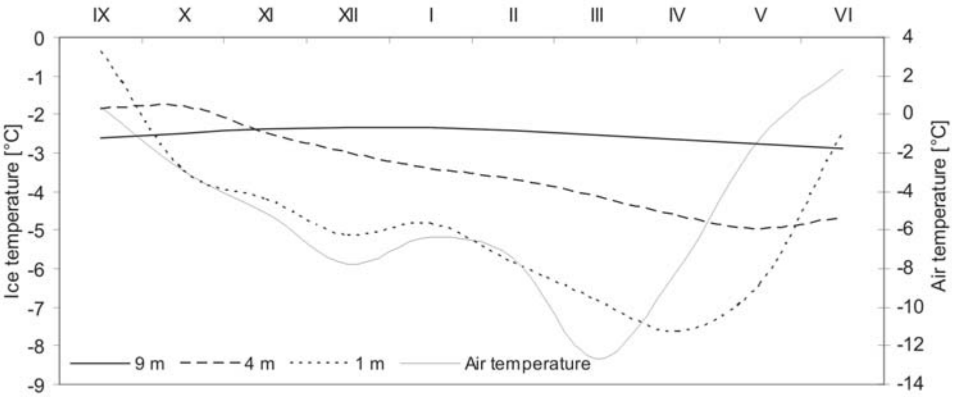

Fig. 6. Temporal variations of monthly near-surface temperature in the ablation area of the Waldemarbreen and monthly air temperature in 2007–2008 (air temperature data based on the Department of Climatology IG NCU).

Table 1

The near-surface ice temperatures (°C) in the ablation and accumulation zones of the Waldemarbreen in 2007–2008.

Month	The accumulation zone (T2)		
	10 m	5 m	2 m
IX	-2.5	-2.5	-1.2
X	-2.4	-2.3	-1.4
XI	-2.4	-2.2	-1.8
XII	-2.3	-2.3	-2.8
I	-2.2	-2.5	-3.4
II	-2.2	-2.8	-3.8
III	-2.2	-3.0	-4.2
IV	-2.3	-3.3	-4.9
V	-2.3	-3.6	-5.2
VI	-2.4	-3.7	-3.7
VII	-2.5	-3.4	-2.1
VIII	-2.5	-2.9	-1.4
Mean	-2.3	-2.9	-3.0
Month	The ablation zone (T1)		
	9 m	4 m	1 m
IX	-2.6	-1.9	-0.4
X	-2.5	-1.8	-3.5
XI	-2.4	-2.5	-4.2
XII	-2.3	-3.0	-5.1
I	-2.4	-3.4	-4.8
II	-2.4	-3.7	-5.8
III	-2.5	-4.1	-6.8
IV	-2.7	-4.7	-7.6
V	-2.8	-5.0	-6.4
VI	-2.9	-4.7	-2.4
Mean	-2.5	-3.5	-4.7

The lowest mean monthly temperature at 1 m depth in the ablation area of the glacier, -7.6°C, was recorded in April. The lowest value at 4 m depth was recorded in May, at 9 m depth, in June. The temperature values were -5.0°C and -2.9°C, respectively (Fig. 6, Table 1).

At the end of the summer (ablation) season, at 2 m depth in the accumulation zone the mean daily ice temperature was close to the melting point, and was higher than the temperature of the underlying layers. However, when winter approached, the ice temperature in this part of the glacier and at this same depth fell significantly. The minimum values were higher than in the case of the ablation area of the glacier. At 2 m depth, the minimum ice temperature was -5.1°C; at 5 m depth, it

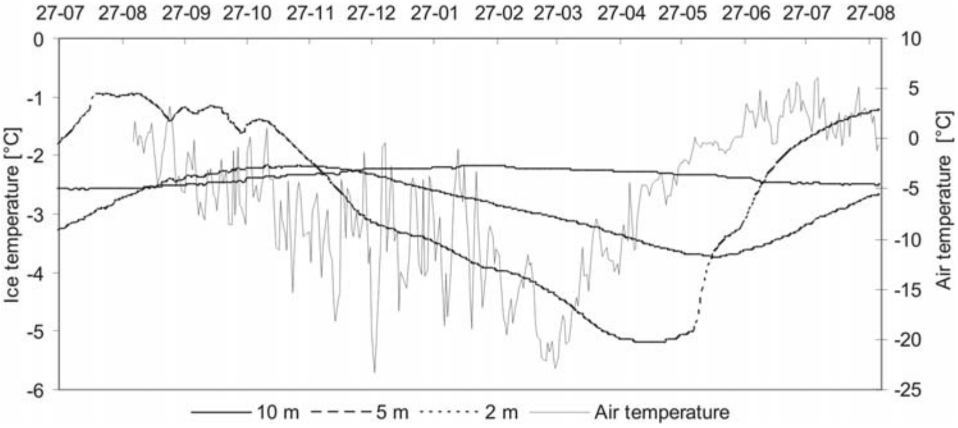

Fig. 7. Temporal variations of daily near-surface ice temperature in the accumulation area of the Waldemarbreen and daily air temperature in 2007–2008 (air temperature data based on the Department of Climatology IG NCU).

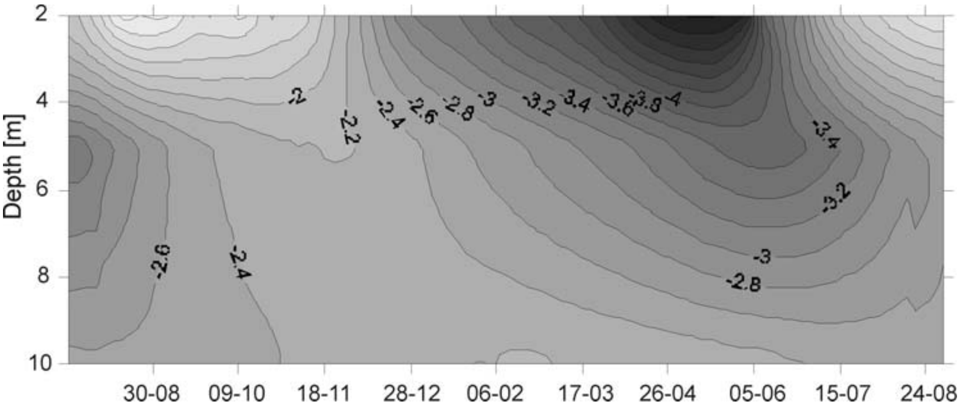

Fig. 8. The near-surface ice temperature in the accumulation area of the Waldemarbreen in 2007–2008.

was -3.8°C, and at 10 m depth, it was close to the value recorded in the ablation zone at 9 m depth, -2.6°C (Fig. 7).

As in the case of the ablation zone of the Waldemarbreen, compared to 2 m depth, the propagation of the cold wave at 5 m depth was much delayed (Fig. 8). At 10 m depth, the ice temperature was consistent throughout the entire period. It is significant that, when compared to the research point in the accumulation zone, the ice temperature at 1–2 m depth in the ablation area was higher than in the underlying layers for a much shorter period of time.

The lowest mean monthly ice temperature at 2 m depth in the accumulation area of the glacier was recorded in May, -5.2°C. At 5 m depth, the lowest value was recorded in June, while at 10 m depth in July, August and September. The ice temperatures amounted to -3.4°C and -2.5°C, respectively (Fig. 9, Table 1).

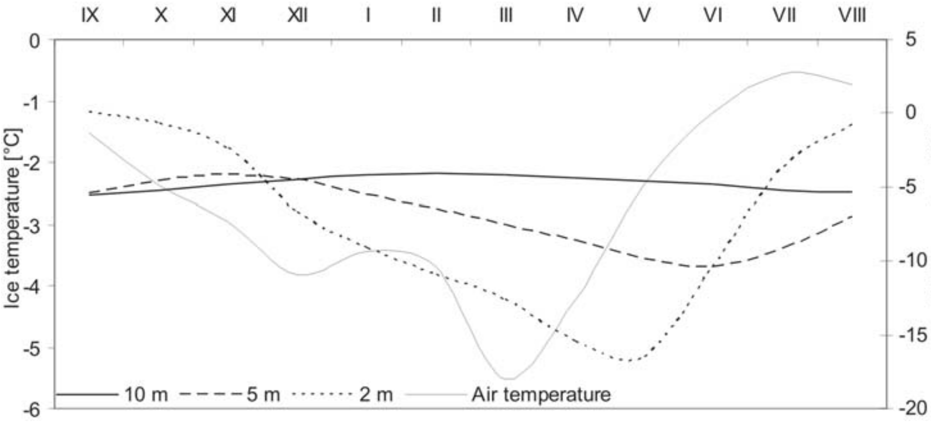

Fig. 9. Temporal variations of monthly near-surface ice temperature in the accumulation area of the Waldemarbreen and monthly air temperature in 2007–2008 (air temperature data based on the Department of Climatology IG NCU).

A correlation between the ice temperature and the air temperature was attempted. At all the investigated depths, the largest ice temperature ranges were recorded when the air temperature was above 0°C, *i.e.* during the melting season. When the mean daily air temperature decreased, the ice temperature at 1–2 m and 4–5 m depths also decreased. However, at 9–10 m depth the ice temperature was practically unchanged throughout the entire study period.

Vertical range of ice temperatures. — Throughout most of the year the vertical range of mean monthly ice temperature at the ablation area of the Waldemarbreen showed an increase with depth. Only during the summer months did temperature fall with depth. This is presumably related to the process of ice-warming at the near-surface of the glacier. It is also noted that the mean amplitude of daily ice temperatures at a depth of 9 m from September to June did not exceed 1°C. At 4 m depth, it was 3.6°C, wheras, at 1 m depth, it was the largest and amounted to 8.1°C. Similar values were also recorded in the case of the mean monthly temperatures: at 9 m it was 0.6°C, at 4 m depth it was 3.2°C, wheras at 1 m depth it was the largest and amounted to 7.3°C (Fig. 10).

The fall in the mean monthly temperature value with increasing depth, as recorded in the accumulation area of the glacier, lasted longer than that in the ablation area. During the summer season, an ice temperature fall with depth down to 5 m was recorded, whereas at greater depths, a temperature increase was recorded (Fig. 11). The largest ice temperature variability with depth was recorded in summer, during the melting of snow and ice.

The largest difference in ice temperatures in the accumulation area at 2 m and 10 m depths, -2.9°C, was recorded in May, whereas the lowest, 0.4°C, was recorded in July (Fig. 12). During the winter months, an increase in ice temperature with increasing depth was recorded, which was mainly the result of the cooling of

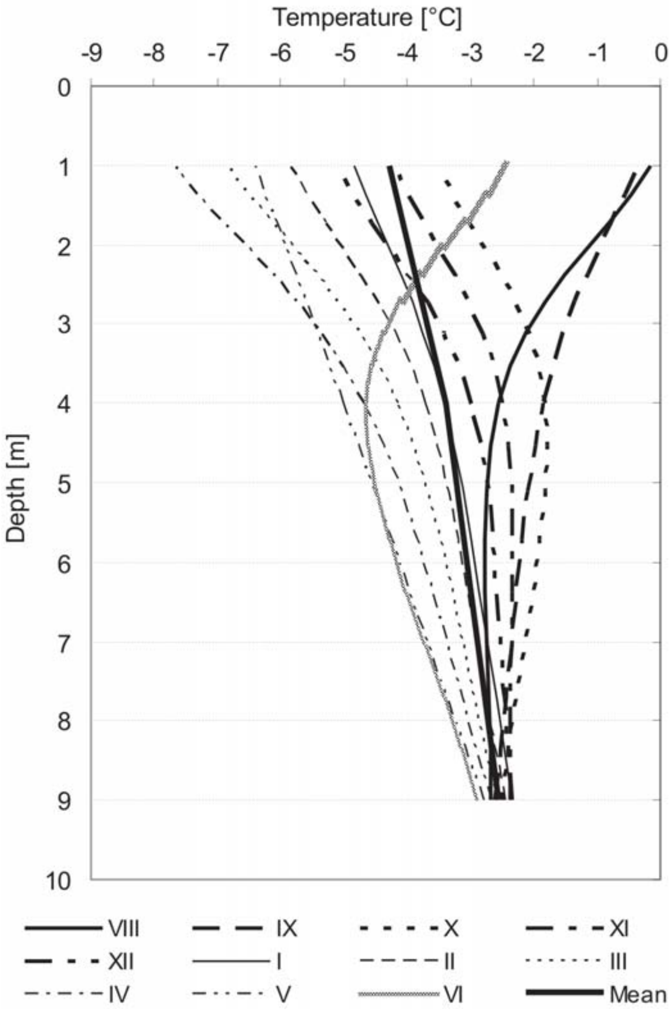

Fig. 10. Temperature profiles in the ablation area (T1) of the Waldemarbreen in 2007–2008.

the glacier surface. During the summer season the ice temperature increased with increasing depth, which mainly resulted from the warming of the near-surface layers by solar radiation, and percolating meltwater.

In this part of the glacier, at 10 m depth, the mean annual amplitude of daily ice temperatures was 0.4°C. At 5 m depth, it was less than half of the value recorded for the ablation area, *i.e.* 1.6°C, whereas at 2 m depth, it was the largest -4.2°C. Similar values were also recorded in the case of the mean monthly ice temperatures: at a depth of 10 m, it was 0.3°C; at 5 m depth, it was 1.5°C, and, at 2 m depth 4.0°C, it was the largest (Fig. 12).

The snow temperature measurements at the T2 point, revealed that temperature falls when depth increases (Fig. 13). The difference in temperature on the

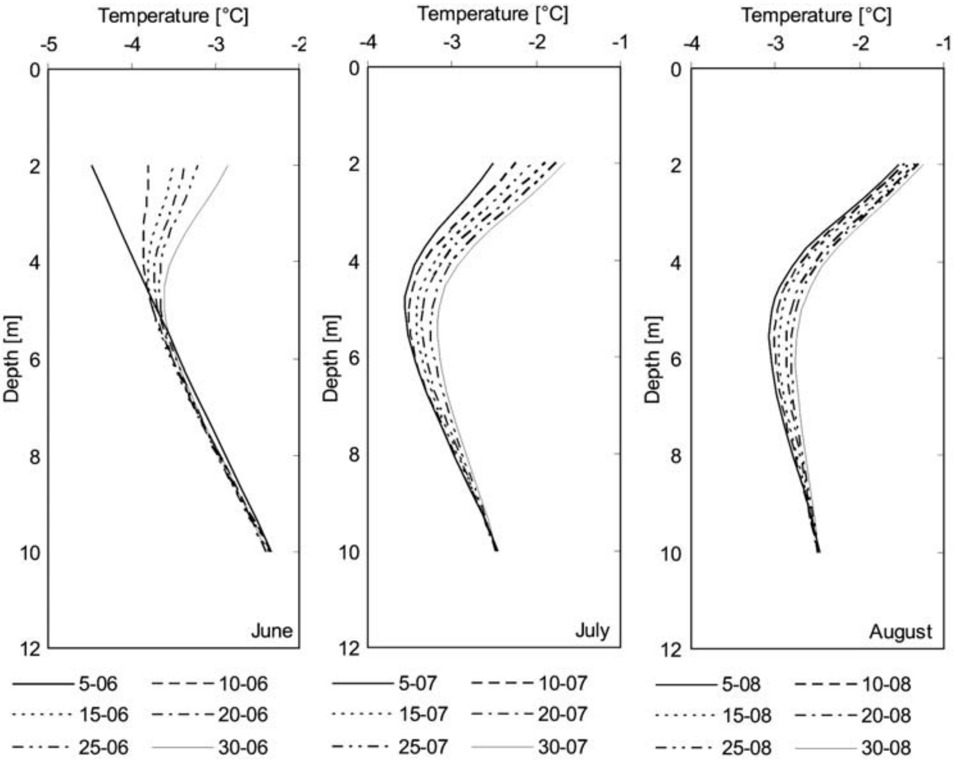

Fig. 11. Temperature profiles in the accumulation area (T2) of the Waldemarbreen in summer 2008.

snow surface and above ice was over 5°C. This strongly indicates that the snow layer insulates against the influences of the air temperature changes on ice temperature.

Discussion

Traditional mass balance measurements by stake readings and snow surveying have been conducted annually since 1996 on the Waldemarbreen in northwest Spitsbergen, Svalbard. The mass balance, accumulation, melt, runoff and thermal structure of the Waldemarbreen were studied. The mass balance of the Waldemarbreen was estimated by both direct field glaciological measurements (1996–2009) and climatological and geodetic methods (Sobota 2007e).

The daily course of ice temperature at 1 m depth showed a relation with changes of daily air temperature values. And there is a delayed reaction of ice temperatures to the oscillations of air temperatures. In the case of 1 m depth, the delay lasts several days. This interdependence is even weaker in the case of the accumulation zone of the glacier, where the snow cover has an important influence in

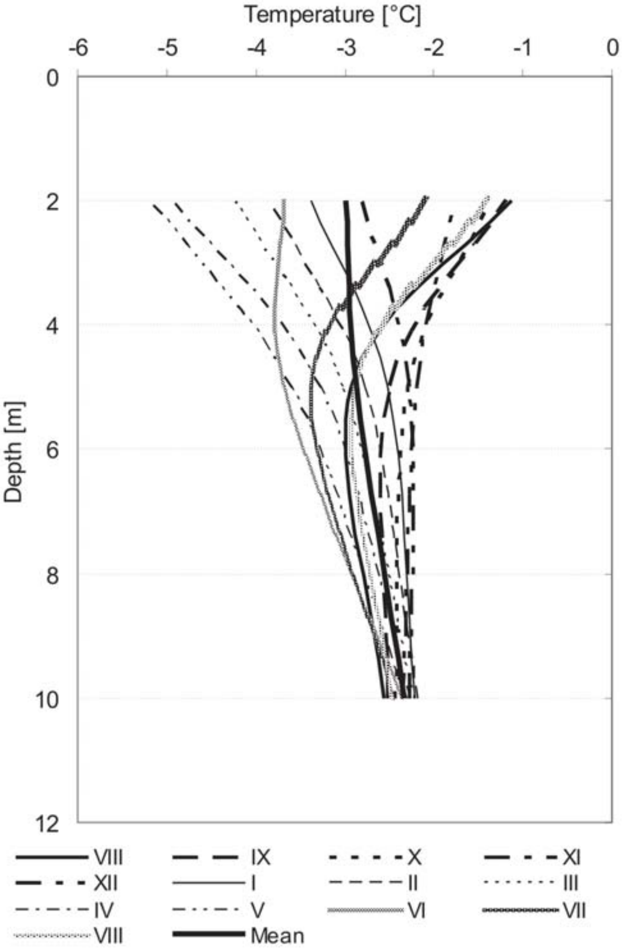

Fig. 12. Temperature profiles in the accumulation area (T2) of the Waldemarbreen in 2007–2008.

shaping the coefficient of heat dissipation which results in slowing the propagation of the cold wave. At the measurement point in the ablation area of the Waldemarbreen at 1 m depth, temperature changes were also recorded during the period with the snow accumulation, the thickness of which was up to 1 m. Eventually, each change in the daily air temperatures was reflected in the oscillations of the ice temperatures although the delay is variable. For instance, at the beginning of January 2008, the mean daily temperature rose above 0°C; this was followed by a rise in the ice temperature at 1 m depth by over 1°C at the end of the first third of the same month. A similar situation was observed at the beginning of February. Then, in March, the lowest air temperatures were recorded, which also resulted in a significant decrease of the ice temperatures. These short-term oscillations in the ice temperatures do not exclude a general tendency to a decrease in ice temperatures at 1 m depth at the end of the summer season.

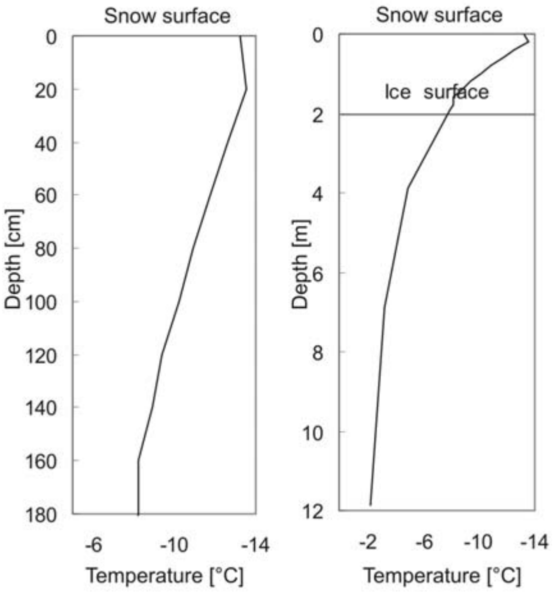

Fig. 13. Snow and ice temperature profiles at the near-surface ice temperature measurements point (T2) on the Waldemarbreen – 16th of April, 2008.

In both the accumulation and ablation zones, falls of ice temperatures are observed down to 5 m. In the case of the measurement point (T2) such a range of temperatures was recorded throughout the entire study period, whereas in the case of the ablation area (T1), the temperature dropped also below 5 m depth at the end of the ablation season (Figs 10, 12).

Owing to snow insulation temperatures in the ablation zones of some glaciers may be somewhat warmer than the mean annual temperature. In addition, percolating meltwater reaches the snow/ice interface soon after melting starts in the springs, thus warming the ice faster than would be the case with conduction alone. The temperature at a depth of about 10 m in a glacier has been shown to be very close to the mean annual air temperature. However, it is important to note that, in some situations, this approximation does not hold very good (Menzies 2002; Hooke 2005) and in the case of the accumulation area of the Waldemarbreen, the mean temperatures at 10 m depth showed the lowest temperature range and were higher than the annual mean air temperature by 4.0°C. The mean annual air temperature (September–August) in the accumulation area was -6.3°C, whereas for the ice at 10 m depth it was -2.3°C. The difference between the ice temperatures at the depth, where the seasonal variation of temperature becomes negligible, and mean annual air temperature is characteristic for an area which has air temperatures above 0°C, mainly during the summer season.

In the ablation area, the mean ice temperature at 9 m depth, where the smallest ranges of temperature oscillations have been observed, were higher than the mean annual air temperature by 2.4°C. The mean annual air temperature (from Septem-

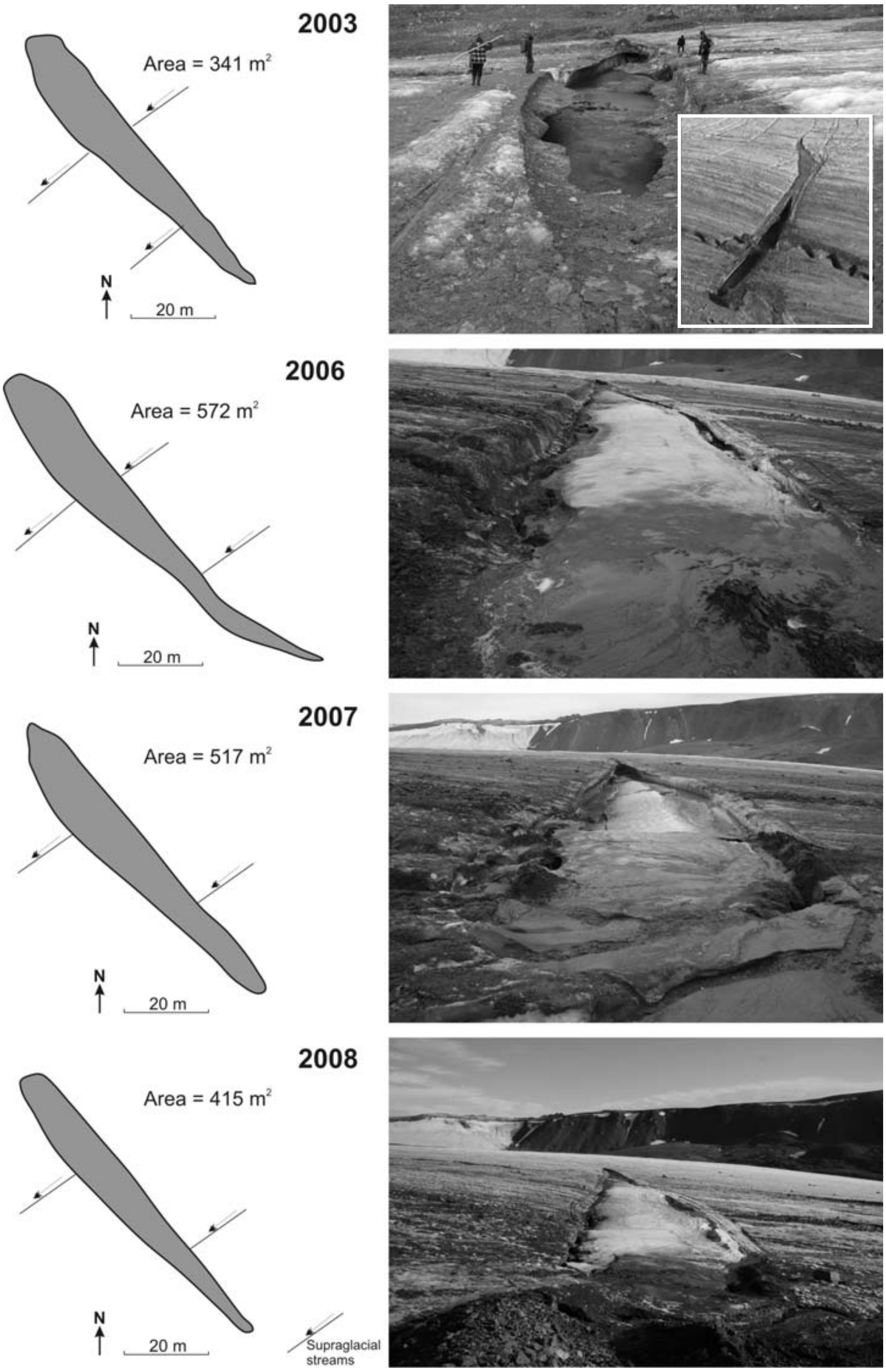

Fig. 14. A fissure on the Waldemarbreen in 2003–2008.

ber to June) for the ablation zone was -4.9°C, whereas for the ice at 9 m depth, it was -2.5°C (September to June).

During the winter season, the near-surface ice temperature of the Waldemarbreen was higher than the air temperature in both the accumulation and ablation zones. As a result, heat is lost from the glacier, which in turn, brings, a further fall in the ice temperature (Paterson 1981; Jania 1997; Hooke 2005). This phenomenon was identified in the following summer season, when the ice temperature again showed lower values than the air temperature. In the study period, minimum ice temperatures were recorded with a significant delay to the air minimum temperatures both at the snout and in the accumulation zone of the glacier.

Between September 2007 and June 2008, the mean annual ice temperature at 1 m depth was -4.7°C in the ablation area (T1), and -3.2°C in the accumulation area (T2) at 2 m depth. At 9 and 10 m depth, it was -2.5°C and -2.3°C, respectively (Table 1). It may be concluded, therefore, that the ablation zone is colder than the accumulation area which, influenced by percolation of meltwater, creates a layer of temperate ice at the pressure melting point. An abundance of meltwater means that winter cooling there has disappeared by the end of the summer season, and the upper parts of the firn layer reach temperatures close to the melting point (Jania 1997).

In some years, zones of wet snow and slush were observed at the accumulation area of the Waldemarbreen (Sobota 1999). This indicates that the glacier is fed by meltwater, which then determines the thermal conditions of the near-surface layers of the glacier. A snow cover was observed at the measurement point there during the entire study period. The melting process lowered the winter cooling down at the end of the summer season. As a result, the temperatures of the upper layers of the snow, firn and ice reached a level close to the melting point. At the measurement point (T2) located in the accumulation zone of the Waldemarbreen, the highest mean monthly ice temperatures at 2 m depth was -1.2°C as recorded in September. It is presumed that at a depth of 1 m or less, temperatures are close to the melting point. Thus, only in the summer season, the accumulation area of the glacier at a temperature is close to the melting point. During the other months, and especially in winter, ice temperatures fall to lower than -2°C.

On the basis of these measurements, which refer only to the near-surface layers of the glacier, it is difficult to define precisely the glacier's thermal type. However, it is clear that during the summer season, meltwater percolation and refreezing are significant, especially in the accumulation area. In the ablation area of the glacier, seasonal warming of the cold layer results from the downward heat conduction. Ablation is important in the thermal structure of the glacier. According to Jania (1997), it represents a significant factor in the thickness reduction of the near-surface layer of cold ice.

The thermal structure research on the near-surface layer of the Waldemarbreen indicates that, in the summer season, the glacier's temperature is close to the melting point, and decreases downwards. Throughout the rest of the year, the near-sur-

Fig. 15. Naledies at the forefield of the Waldemarbreen in Spring 2008.

face layer of the ice is cold, and the temperature increases downwards. In the accumulation zone of the glacier, the ice temperature is higher than in the ablation one. This may result from the higher activity of meltwater percolation in the accumulation area and the insulated role of snow.

A fissure filled with meltwater, which was found in the northern part of the glacier, is evidence of temperate ice overlying cold ice in the summer season (Fig. 14). In 2003, its depth was calculated to be about 20 m. Melt water flowed into this fissure, which then drained into the middle section of this glacier.

Naledies (icings) represent an indication of the thermal regime of a glacier. They occur in the forefields of all glaciers in Kaffiøyra. No clear relation between sizes of naledies and associated glaciers was been established (Olszewski 1982; Grześ and Lankauf 1997; Grześ and Sobota 2000; Bukowska-Jania 2007). The naledies of the Waldemarbreen are formed in 4 zones *i.e.* supraglacial, inner, water gap and proglacial. The areal extent of naledies depends on water migration in the associated snow cover. Their thickness increases by capillary absorption of a snow cover and snow interception by damp surfaces (Grześ and Sobota 2000). Naledies in the forefield of the Waldemarbreen were also observed in 2008 (Fig. 15). Their areas were observed to be significantly smaller than in previous years.

It may be assumed that the Waldemarbreen is polythermal, with both cold ice (that is below the pressure melting point) and a temperate surface layer, though during summer. This temperate surface layer is influenced by seasonal temperature changes. In winter, all of the ice is below the melting point and temperate layers are present in near-floor sections of the glacier. This supposition is supported by the presence of naledies in the forefield of the Waldemarbreen. In respect of Baranowski's (1977) classification, it is a sub-polar glacier which warms to the melting point at its surface in summer, and thus produces meltwater. A similar thermal regime has been identified for other Svalbard glaciers (*e.g.* Krenke and Khodakov 1966; Baranowski 1977; Bamber 1989; Dowdeswell *et al.* 1995; Björnsson *et al.* 1996; Jania *et al.* 1996; Hodgkins *et al.* 1999; Nagornov *et al.* 2001, 2006; Degard *et al.* 2007; Willis *et al.* 2007). The Waldemarbreen is undoubtedly polythermal, with 10 m depth temperatures of -2 to -3 °C.

However, those classifications are highly simplistic, and, clearly, the thermal conditions of individual glaciers may vary significantly, both spatially and temporally (Sugden and John 1976; Jania 1997; Menzies 2002; Hooke 2005; Benn and Evans 2006).

Observations show that the glacier might be at a transitional stage between a polythermal and a cold type. Such a situation may be explained by a masked climatic warming in recent years; thus would have cause larger areas to be impermeable to water, which, in turn, favoured the existence of the cold ice layer (Jania 1997; Willis *et al.* 2007). In support of thus notion, it is emphasized that the area of the naledies at the forefield of the Waldemarbreen have decreased significantly in recent years. This suggests that the glacier may be gradually transforming into a cold type.

Conclusions

The near-surface ice temperature of the Waldemarbreen (Fig. 1) was investigated with automatic borehole thermistors in the ablation and the accumulation areas in 2007–2008 (Fig. 2). The investigation results indicate the importance of the air temperature, as well as that of meltwater and snow cover, for the establishment of the near-surface thermal ice structure of the glacier. These studies enable us to define the temporal and vertical variability of temperatures in the near-surface layers of the glacier. The main conclusions of this paper are:

During the 2008 summer season, significant differences were recorded in the temperature values and variations of the near-surface ice layer in both the ablation and the accumulation zones of the Waldemarbreen (Fig. 4–9).

The near-surface ice temperatures of the Waldemarbreen changed significantly during the study year. In the ablation area of the glacier, lower ice temperatures were recorded from October, whereas in the accumulation area from December. This mainly resulted from the fact that the area was covered by snow, which, in the accumulation area, is more intensive and appears earlier than at the snout.

The snow cover has insulated the near-surface ice temperatures of the glacier against the changes in the air temperatures. It is calculated that the spatial diversity of the near-surface thermal conditions of a glacier related to the size of snow accumulation in the different parts of the glacier in a given winter season.

The snow cover is also important in the determination of ice thermal conditions. It both delays and slows the cooling process.

It is also noted that, in the ablation area, the mean amplitude (September–June) of monthly ice temperatures at a depth of 9 m was 0.6°C. In the accumulation area at 10 m depth, the mean annual amplitude of daily temperatures was 0.3°C (Fig. 12). Similar values of the mean annual amplitudes have been determined by Paterson (1971, 1972, 1981), Harrison *et al.* (1975), Hooke (2005), Jania (1997), Zagorodnov *et al.* (1989), Zagorodnov and Arkhipov (1990), who agrees that the near-surface temperature of glaciers range at 10 m depth does not exceed 1°C.

In the case of the accumulation area of the Waldemarbreen, the mean annual ice temperature at 10 m depth was higher than the annual mean air temperature by 4.0°C. In the ablation area, the mean ice temperature at 9 m depth from September to June, was higher than the mean air temperature by 2.4 °C.

During the winter season the near-surface ice temperature of the Waldemarbreen was higher than the air temperature at both the accumulation and ablation zones. In the study period, minimum ice temperatures were recorded with a significant delay to the air minimum temperatures both at the snout and in the accumulation zone of the glacier.

The ablation zone of the Waldemarbreen is colder than the accumulation area which, influenced by percolation of meltwater, creates a layer of temperate ice at the pressure melting point.

On the basis of the measurements, which refer only to the near-surface layers of the glacier, it is difficult to define precisely the glacier's thermal type. However, it is clear that, during the summer season, meltwater percolation and refreezing are important processes, especially in the accumulation area.

Naledies may indicate the thermal regime of a glacier. Their areas in the forefield of the Waldemarbreen were observed to be significantly smaller then in previous years.

The Waldemarbreen is polythermal, with temperatures at 10 m depth of -2°C to -3°C, and both cold ice, that is below the pressure melting point, and a temperate surface layer, though during summer. In winter, all of the ice is below the melting point and temperate layers are present in near-floor sections of the glacier. It is emphasized that the designation as a thermal type of the Waldemarbreen is based solely on the temperature measurements of the near-surface glacier layer, but an indirect estimation, which is based on a measurement of the elements of the mass balance, morphology, naledies, development of the water system and its drainage network, is generally supportive of this conclusion.

It is possible that, eventually, the Waldemarbreen may evolue into a cold glacier type, as have the Austre Brøggerbreen, Midre Lovénbreen and other Svalbard glaciers (*e.g.* Ødegård *et al.* 1997; Rippin *et al.* 2005a, b; Willis *et al.* 2007), as an effect of climate warming in recent years.

The research is being continued, and, may later also be possible to learn the seasonal changes and the course of temperatures in the near-surface ice layers of the Waldemarbreen. The thermal regime of glaciers is an important first order control on glacier mass balance, ablation, accumulation, runoff, hydrology and dynamics.

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