

# The record of rapid changes in the Arctic and their impact on glaciers in Svalbard

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## Abstract

We present data on the Lomonosovfonna (Svalbard) ice core records of accumulation rate, nitrate, MSA, and naphthalene showing the impact of both natural change (including the end of the Little Ice Age) and anthropogenic impacts (mainly in the Twentieth Century). The ice core is shown to contain a reliable record of ionic and isotopic composition despite some seasonal melting. Resolution is typically biannual, and results from the upper 3/4 of the core span the past 300 years. Nitrate, naphthalene, and accumulation rate all rise most significantly in the 1950s, and at least the first two are due to anthropogenic forcing. Additionally we present data from radar surveys on the state of many glaciers in Svalbard. We show that several are in severe decline when compared with their historical records of extent and will probably disappear over the next 100 years. Radar data can be used to map the extent of superimposed ice – an important factor in the mass balance of Arctic glaciers, and one that is difficult to measure by traditional methods. The radar and ice core data are also combined to give a broad regional view of accumulation rate variation both spatially and over different time intervals.

**Keywords:** Svalbard, Lomonosovfonna, glacier, ice core, paleoclimate, nitrate, MSA, accumulation, mass balance, radar, naphthalene

## Introduction

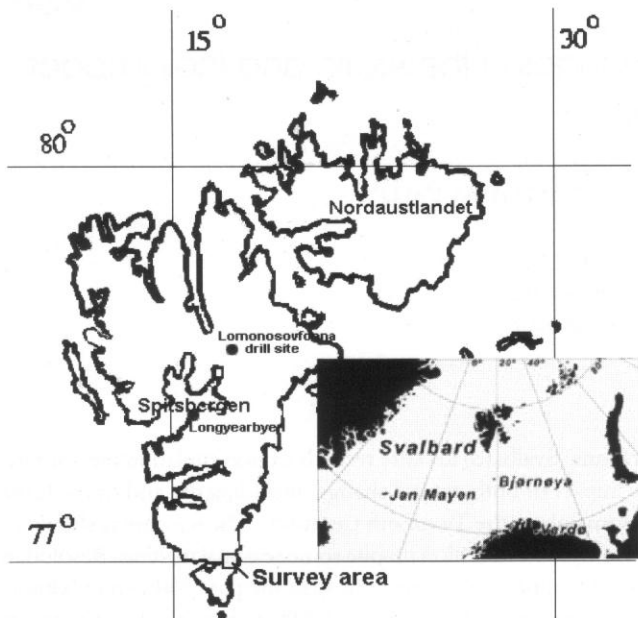
This paper summarizes the main results from a series of expeditions to Svalbard beginning in 1997. Two main fields are described: analyses of the Lomonosovfonna ice core (e.g. Isaksson *et al.*, 2001; Pohjola *et al.*, 2002a) which has provided the best record of past climatic and anthropogenic impacts from the Svalbard archipelago, and radar surveys of the state of glaciers in Spitzbergen. The details of the results may be found below, and are not purely the authors' own work. The ice core drilling program has been a cooperative effort, between Finnish, Swedish, Norwegian, Dutch, Estonian, French and British groups. The radar sounding work was also only possible due to the combined efforts of Polish and Norwegian groups in addition to our own.

## Methods

For the ice core analysis we used liquid ion chromatography methods which are detailed in Jauhiainen *et al.*, (1999) and Kekonen *et al.* (2002). For the ground penetrating radar surveys we used methods explained in detail in Moore *et al.*, 1999 and Pälli *et al.* (2002).

## Results: Lomonosovfonna Ice Core

Ice cores are well known for being one of the best archives of information of the past, with respect to climatic and environmental changes. One problem is that most high resolution data available from the northern hemisphere are from the cold dry firn zone in interior Greenland; this biases the data in terms of atmospheric circulation characteristics that are typical for this region.



**Figure 1.** Location map of Svalbard. The radar survey area is marked with a black outlined rectangle and the Lomonosovfonna drill site with a big black dot. The inset shows the regional setting.

In order to get a more comprehensive view of the climatic and environmental change on more global, or hemispherical scale we need data from other locations outside the large ice sheets.

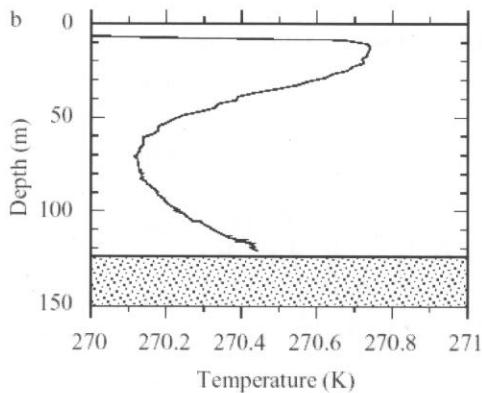
Svalbard is positioned in a climatically interesting area and is vulnerable to temperature changes in the North Atlantic Current. Several ice cores have been drilled on Svalbard ice fields through the years. In general, the results from the earlier ice cores studies suggest major climatic trends similar to those recorded in other ice cores from the Arctic. However, many questions remain concerning the timing of events and shorter time-scale changes and determining how much of the original record has been altered by melting (Koerner, 1997). Published data from a previous ice core on Lomonosovfonna drilled in 1976 (Fig. 1), indicated better preserved stratigraphy than the other sites on Svalbard (Gordiyenko *et al.*, 1981). Therefore we selected Lomonosovfonna as our coring site with the aim to perform higher resolution sampling than accomplished in previous studies of ice from this site.

We retrieved a 121 m ice core at the summit (1250 m asl) and a number of shallow ice cores along Nordenskjöldbreen (Fig. 1) in early May

1997. In this paper we present accumulation data from the shallow ice cores and data from ice structural logging, analyses of water isotopes, nitrate, MSA (methanesulphonic acid) and NAP (naphthalene) of the uppermost 80 m of the deep core, covering the time period between about 1700 and 1997. We discuss the potential for extracting high-resolution environmental and climatic data from this site by comparing the ice core data to other climate and environmental records from the area.

#### **The borehole temperature records**

As part of this project temperature measurements were performed in the 120 m deep bore hole. At this site the ice thickness based on radar measurements is 126.5 m and the mean annual accumulation rate is 380 kg m<sup>-3</sup>. The measurements over the interval from 15 m depth to 120 m depth show a nearly isothermal profile with a mean value of -2.8 °C and a standard deviation of 0.2 °C (Fig. 2). The measurements reveal a minimum in the temperature at a depth of approximately 70 m and a temperature gradient of 0.011±0.004 °C per metre near the bottom. The temperature minimum and rela-



**Figure 2.** The Lomonosovfonna borehole temperature record, reprinted from Van de Wal *et al.* (2002) with permission of the International Glaciological Society.

tively low temperature gradient cannot be explained in terms of a steady state climate. Numerical calculations with a simple 1D diffusion-advection model (van de Wal *et al.*, 2002) show that the temperature increased at a maximum rate of 0.02–0.025 K/yr over the last hundred years, the total temperature increase amounting to 2.0–3.0 K. Forcing the model with the observed record at Svalbard airport revealed that in the 19<sup>th</sup> century the surface temperature was at most 2.5 K lower and that the instrumental observations started during a period with temperatures comparable to the end of the 19<sup>th</sup> century. The data are of particular interest for historical simulations since often no other temperature data are available in polar areas.

### Melting and preservation of signals

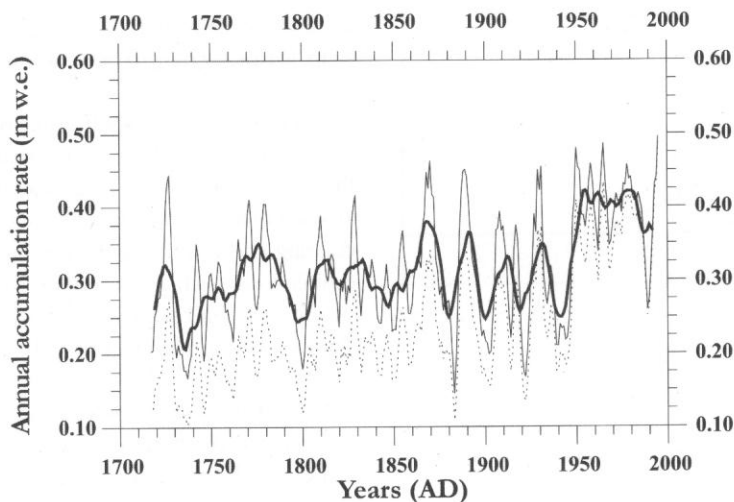
A major problem with extracting climatic and environmental records from ice cores taken from ice fields situated below the dry firn zone (Benson, 1961) is the post-depositional altering of the atmospherically deposited strata by the movement of water through the ice column. Studying the available climatological data from the region, Pohjola *et al.*, (2002a) find that the summit of the ice field is affected by melt most summers. Moreover, the available data suggest that the melt each summer varies between small to moderate amounts to ~50 % melt of the annual averaged accumulation during the warmest summer on record, and ~25 % melt in a median summer. Thus, most meltwater can be

retained within the annual strata. Formation of ice lenses each winter, or during a summer cold snap, forms barriers to percolation between layers.

Three diagnostics for the quality of the preservation of atmospherically deposited signals in the ice core record were investigated to study the amount of alteration affecting the record by percolating and refreezing meltwater: 1) the most mobile ions, such as the anions associated with strong acids ( $\text{NO}_3^-$  and  $\text{SO}_4^{2-}$ ) showed up to 50 % elution from firn layers, and ~50 % higher concentrations in ice. The least sensitive parameter was the water isotopes, which had no detectable difference in distribution between the ice facies. 2) The number of peaks/cycles showed by most ionic species and water isotopes were close to that expected if an annual cycle was present. Indications are that the record suffers some dilution and diffusion, but still preserves atmospherically deposited signals in their originally deposited strata. 3) The similarity between the ice core record and coastal station records suggest that it is possible to recover a climatologically meaningful water isotope record from the summit of Lomonosovfonna. The ice core thus holds a climatic and environmental record preserved with an annual or bi-annual resolution.

### The record of past accumulation rates

Pohjola *et al.* (2002b) use the upper 81 m of the record of stable isotopes of water from the long ice core to construct an ice core chronology and the annual accumulation rates over the ice field. The isotope cycles are counted in the ice core record using a model that neglects short wavelength and low amplitude cycles. We find approximately the same number of  $\delta^{18}\text{O}$  cycles as years between the two known reference horizons in the core (the 1963 radioactivity horizon, and the 1783 acidic layer from the Laki volcanic eruption), and assume these cycles represent annual cycles. Testing the validity of this assumption using cycles in  $\delta\text{D}$  shows that both records give similar numbers of cycles. Using the  $\delta^{18}\text{O}$  chronology, and de-compressing the accumulation records using the Nye flow model (Nye, 1963), the annual accumulation for the ice core site back to 1715 AD



**Figure 3.** The calculated annual accumulation rates between 1715–1996 AD. The lower curve, (dashed line), shows the compressed annual thickness from the ice core. The upper curve (thin line) is the de-compressed annual thickness, giving the accumulation rates. Both curves are plotted using a weighted 5-year running mean. The thicker line is the 11-year running mean of the de-compressed accumulation rates. Reprinted from Pobjola *et al.* (2002b), with permission of the International Glaciological Society.

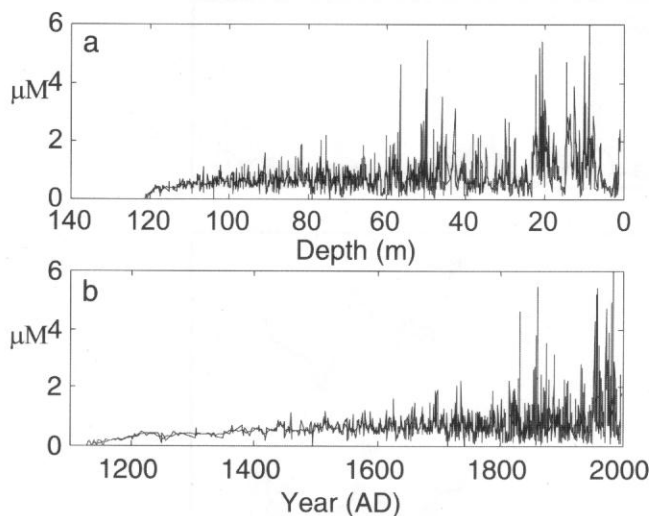
can be calculated (Fig. 3). We find that the average accumulation rate from 1715 to 1950 was on average 0.30 m w.e. Accumulation rates increased ca. 25 % during the later part of the 20<sup>th</sup> century to an average of 0.41 m w.e. for the period 1950–1997.

### The nitrate record

Nitrate in ice cores has been the subject of intense research activity for many years. It has many complex sources and is subject to several post-depositional processes (Wolff, 1995). Nitrate sources include continental, atmospheric and stratospheric contributions (Clausen and Langway, 1989). The two precursors to nitrate in ice cores are nitrogen oxide ( $\text{NO}_x = \text{NO} + \text{NO}_2$ ), and nitrous oxide ( $\text{N}_2\text{O}$ ). Nitric acid, the end product of  $\text{NO}_x$ , is rained out either as the free acid or, having reacted with ammonia, as ammonium nitrate ( $\text{NH}_4\text{NO}_3$ ). The main anthropogenic nitrogen oxide emission sources are automobile engines and the combustion of fossil fuels. Anthropogenic sources of nitrous oxide are combustion processes and use of nitrogen fertilizers. Svalbard is relatively close to large industrialized regions in northern Eurasia.

Precipitation sampling at Ny-Ålesund, Svalbard, since 1980 shows a direct response to long range transport of air masses from Eurasia (Arctic haze), (Tørseth *et al.*, 1999).

Kekonen *et al.* (2002) present the nitrate record (Fig. 4). Only rather small nitrate changes may be assigned to natural climate changes in the past. The data show a continuous increase from about the 12<sup>th</sup> century to the middle of the 16<sup>th</sup> century with higher, fairly stable values throughout the period from the middle of the 16<sup>th</sup> century to the middle of the 19<sup>th</sup> century. The increase in nitrate concentrations from the 12<sup>th</sup> century to the middle of the 16<sup>th</sup> century may be an artefact due to loss of impurities in aqueous solution migrating towards the warmer base of the ice cap, where they are lost. The most clear-cut changes of the nitrate concentrations in the Lomonosovfonna ice core are due to anthropogenic effects. The growth of nitrate concentrations at the middle of the 20<sup>th</sup> century is an atmospheric signal resulting from growing  $\text{NO}_x$  emission. Other ice core records from the Arctic show similar trends (Goto-Azuma and Koerner, 2001; Mayewski *et al.*, 1986). We observe rather variable correlation between nitrate and ammonium. It seems clear that for some periods am-



**Figure 4.** a) The nitrate concentrations ( $\mu\text{M}$ ) of the Lomonosovfonna ice core as a function of depth b) and age. Reprinted from Kekonen *et al.* (2002), with permission of the International Glaciological Society.

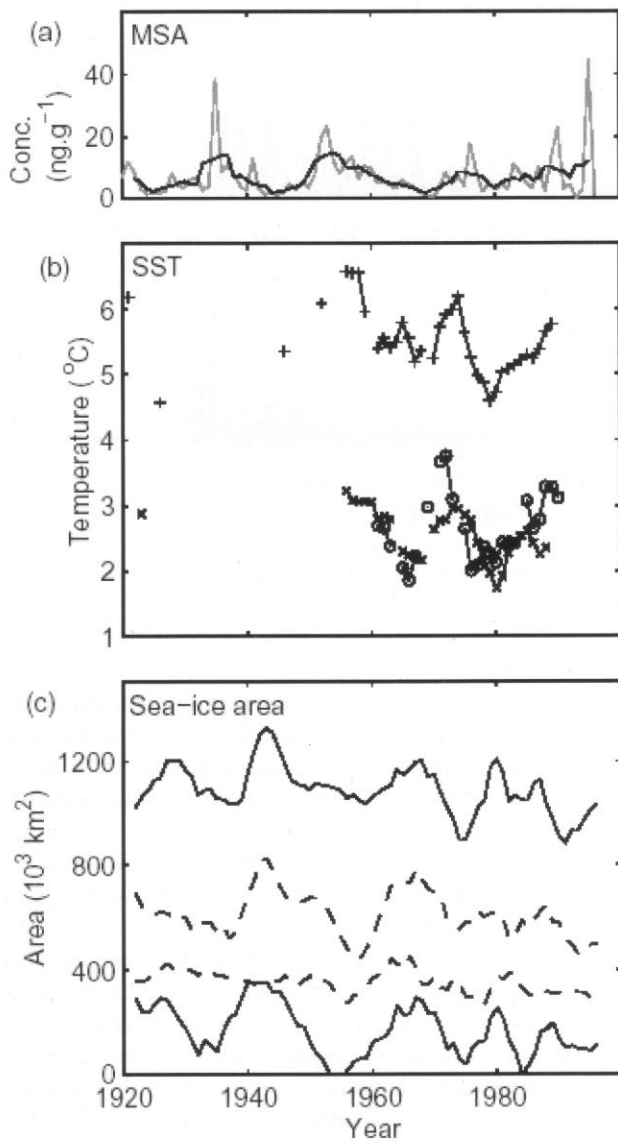
monium nitrate is common, possibly related to variations in atmospheric acidity. Calcium is sometimes associated with nitrate possibly through influence of dust particles on nitrate volatilisation.

### The MSA record

Methanesulfonic acid (MSA) in the snow deposited on a glacier forms a stratigraphic record of atmospheric concentrations. The only source of MSA appears to be the atmospheric oxidation of dimethyl sulfide (DMS), which is emitted by marine biota (Saltzman *et al.*, 1986). The MSA record has therefore been used as an indicator of the strength of the marine biogenic source of DMS. MSA concentrations in the ice will be affected by 1) conditions at the source location influencing primary productivity, phytoplankton species, and air-sea exchange of DMS, 2) atmospheric conditions influencing the oxidation pathways of DMS or altering the source location, 3) conditions at the glacier. Thus variations in air and sea temperatures, precipitation patterns, sea-ice conditions, winds and ocean currents can affect MSA concentrations, and all these parameters are intimately linked through the complex interactions of the climate system. O'Dwyer *et al.* (2000) examine the MSA record for the period

from 1920 to 1996 in the ice core. During this period observations of sea-ice extent and ocean temperature are available for the region around Svalbard, and these can be compared with MSA concentrations (Fig. 5).

The variation of MSA in the ice core is very different from that in the Greenland ice cores (Whung *et al.*, 1994; Legrand *et al.*, 1997), demonstrating that trends over the Arctic region are not uniform. In contrast to the Greenland ice cores we find a negative correlation with sea-ice extent and a positive correlation with sea surface temperature (SST), *i.e.*, high MSA concentrations are associated with years when the surrounding ocean is warm and has reduced sea-ice extent (Fig. 5). SST and sea-ice extent are strongly linked, so it is not clear from this correlation analysis which has the most important influence on MSA. In the Arctic Ocean, however, sea-ice and sea-ice meltwater are seen to strongly affect DMS production (Leck and Persson, 1996). Possible links between reduced sea-ice extent and high MSA are the larger area of open water available for biological production, and the longer period of time for which ice-free water is present in years with reduced sea-ice extent.



**Figure 5.** (a) Annual mean (grey) and five-year running mean (black) of MSA concentration. (b) Five-year running means of SST in the Barents Sea in summer (+) and winter (x), and west of Svalbard in autumn (o). (c) Five-year running means of sea ice extent in April and August to the east (full lines) and west (broken lines) of Svalbard. O'Dwyer *et al.* (2002), copyright 2000 American Geophysical Union. Reproduced by permission of American Geophysical Union.

### The naphthalene record

Measurements of polycyclic aromatic hydrocarbons, (PAHs) in the ice core showed only naphthalene (NAP) to be detectable (Vehviläinen *et al.*, 2002). Fig. 6 shows that prior to the 1930's NAP was below the determination limit, but increased to the 1980's. In general, concentrations (5–53 ng kg<sup>-1</sup>) are six times lower than Agassiz Ice Cap, Canada (personal communication from A.J. Peters, 15.3.2000), but about 50 times higher

than in Greenland (Jaffrezzo *et al.*, 1994). Correlation of NAP with physical and chemical parameters in the core strongly suggests wintertime deposition of NAP with Arctic haze. Post-depositional effects of periodic melting appear slight, probably due to the hydrophobic nature of NAP. The contribution of small coal mining activities on Svalbard to the record appears to be small compared with anthropogenic emissions from long-range sources.



### Results: The glacier record of climate change from radar surveys.

Ground-penetrating radar has been used successfully on many different glaciers and for snow studies in Svalbard. It has been a very good tool to study snow accumulation, glacier hydrology, glacier hydrothermal structure and glacier bedrock depths. We have collected a unique data set from many different glaciers that are representative the glaciers in Svalbard.

#### *Spatial and temporal variability of snow accumulation around Lomonosovfonna*

Arctic glacier mass balances contain a record of current climatic change and, by extrapolation, should yield a warning of future changes (Jania and Hagen, 1996). For the overall balance of the arctic ice masses accurate information on snow accumulation is required. The traditional methods used such as repeated stake measurements, snow probing, or stratigraphic studies in snow pits and firn core studies provide insufficient information about the spatial variability in snow accumulation.

Pälli *et al.* (2002) studied the spatial variability of snow accumulation on the upper parts of Nordenskjöldbreen on Lomonosovfonna in Svalbard (Fig. 1) using ground-penetrating radar (GPR) data and data from three ice cores along the radar profile. Ice cores provide excellent archives of past climate and environmental change but data are limited to the drill site. Radar is routinely used to map spatial distribution of glacier

properties for which there is an associated change in dielectric impedance, such as the interface between glacier ice and bed (ice thickness), the interface between cold and warm ice in polythermal glaciers, or internal layering in snow or ice.

In addition to being able to quickly image long profiles, radar, with its relatively wide beamwidth and large spatial footprint, images ice properties averaged over greater horizontal areas than does the equivalent data obtained from ice cores. Thus, a marker horizon which may be absent in an individual core due to local accumulation variations, can nevertheless be detected in a radar image taken over the core site. Using radar, data from cores separated from each other by distances of up to 10s of kilometers can be correlated and the spatial behavior of snow layers, and thereby accumulation between layers, mapped between the cores.

To map accumulation layers outward from the ice core sites using GPR the following steps are taken. First, reflecting horizons are dated using the 1963 (bomb test) and 1986 (Chernobyl) horizons dated in the ice cores. Depths of known ages can then be converted to radar times. In dry firn this is straightforward, and is accomplished via a two-component mixing relation (e.g. Robin, 1975). Next, the dated radar times are associated with the appropriate reflecting horizon, as closely as possible. The reflecting horizons must then be tracked through the GPR profiles. The final step is to convert the two-way radar travel times back into depth units, to calculate accumulation rates.

Fig. 7 shows 40–60 % spatial variability in snow accumulation over short distances along the profile. Comparing the annual average accumulation rates for the two periods 1986–99 and 1963–99 indicate an increased accumulation during the past decade over the entire length of the profile. This illustrates the importance of combining GPR and core data as there is essentially little change in accumulation rates for the two periods at Core 10 (the deep core, c.f. Fig. 3), at the summit of Lomonosovfonna. While the increase is within the conservatively estimated error limits, it is consistent with recent changes in precipitation in Svalbard detected in meteorological records at Hornsund, Longyearbyen, and Ny-Ålesund.

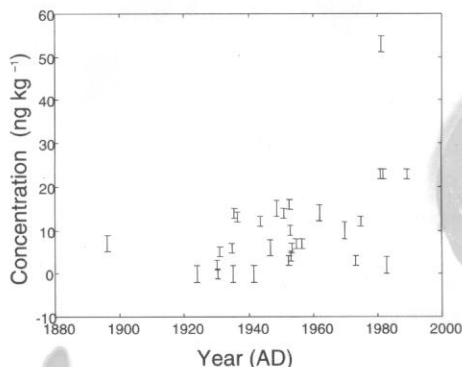


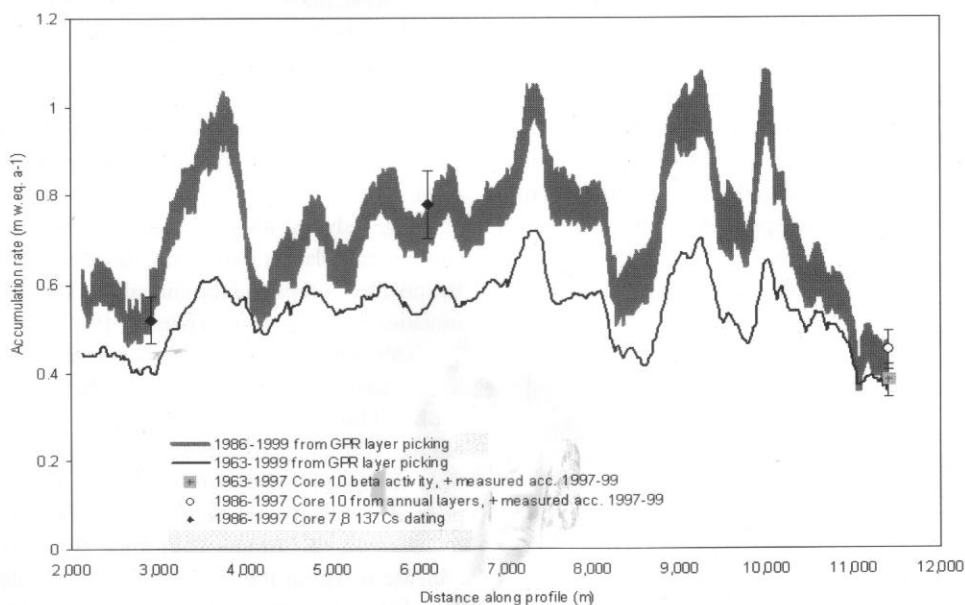
Figure 6. Naphthalene (NAP) concentration along the Lomonosovfonna ice core.

### ***Firn-ice transition zone features of polythermal glaciers in Svalbard***

On polythermal glaciers, where superimposed ice represents a significant component of glacier mass balance, the firn line (i.e. snow line) position and the equilibrium line are not the same. The firn line, unlike the equilibrium line, is the physically recognisable boundary between firn and ice on the glacier surface at the end of the melt season (Paterson, 1994). On polythermal glaciers the firn line marks the transition zone to down-glacier cold ice at the surface. The transition from water-permeable firn to impermeable cold ice evolves as the snowpack in the upper firn part of the glacier becomes wet with meltwater in the summer (e.g. Benson, 1961). The water that percolates down and partly refreezes in the deeper layers raises the temperature of the firn to the melting point. However, down-glacier of the firn line the ice becomes impermeable, preventing penetration of meltwater except via crevasses or moulins. The ice is then cooled below the melting point during the winter. This transition is

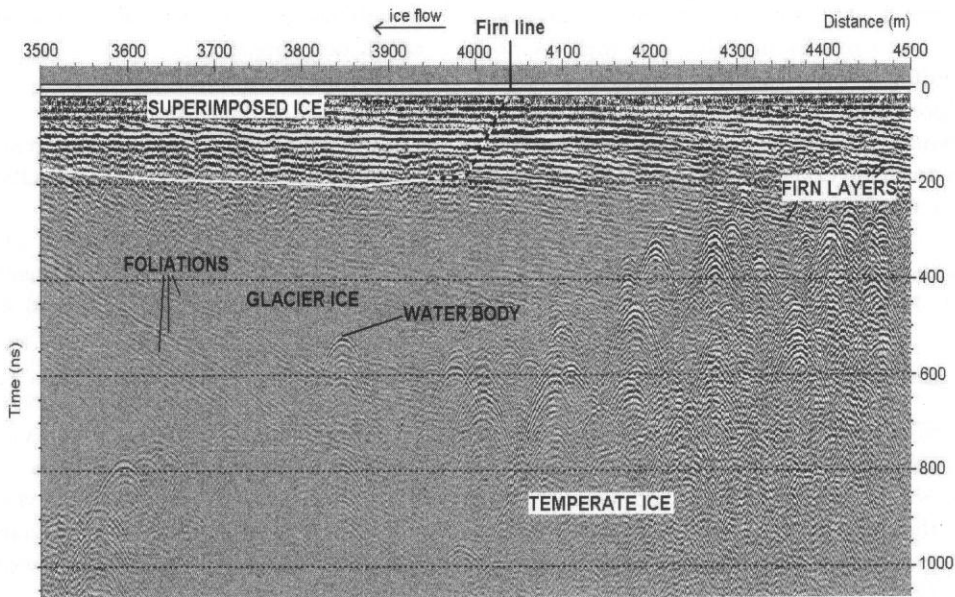
therefore, complex, starting in the low percolation (soaked) zone and finishing in the superimposed ice zone (Paterson, 1994, p.10). Radar is an excellent tool for studying the firn/ice transition of a glacier because of the large difference in dielectric permittivity between water, firn and ice.

Pälli *et al.* (in press a) used GPR data from four different polythermal glaciers in Svalbard to study their firn-ice transition zones and discuss differences in hydrological structures. The firn line and the whole firn-ice transition zone can be clearly detected with GPR (Fig. 8). Similar structures in the firn-ice transition area were observed, though with different emphasis on each glacier. The limited resolution and the sporadic nature of the reflections means that the overall extent of superimposed ice is difficult to measure accurately. The nature of the reflections in the superimposed ice zone, which seem mainly to come from the interface of the superimposed ice and the underlying glacier ice, are uncertain, but most easily explainable by increased water content of a few percent at sporadic locations within the superimposed ice.



**Figure 7. a)** Annual accumulation rates (calculated from accumulation in 1986–1999, and 1963–1999) versus distance. Reprinted from Pälli *et al.* (2002), by permission of the International Glaciological Society.





**Figure 8.** 50-MHz radar profile from Werenskioldbreen. Dipping foliations are seen clearly in the cold ice, and a strong hyperbolic diffraction indicating a likely water body. The region of superimposed ice, estimated by the presence of weaker sub-parallel layering and sporadic hyperbolic diffractions down-glacier of the firn line, is delimited by the white line, and where it is hard to determine, by the dashed line. Reprinted from Pälli *et al.* (in press a), with permission of the International Glaciological Society.

### Glacier changes in southern Spitsbergen 1901–2000

The future of glaciers in the Arctic will be primarily one of shrinkage, although it is possible that in a few cases they will grow as a result of increased precipitation (IPCC, 2001). In the Arctic, extensive land areas show a 20<sup>th</sup> century warming trend in air temperature of as much as 5° (IPCC, 2001). As result of the warming since the end of “Little Ice Age”, and the associated shift towards consistently negative glacier mass balance in Svalbard (Jania and Hagen, 1996), some glaciers which formerly surged are now apparently unable to build up the reservoir-area mass and geometry for a new surge. Those glaciers that suffer great reduction in the accumulation area will suffer ever-increasing melting and over some time that depends on altitude, thickness, speed and size they will eventually become ice-free areas.

Large glacier systems are very rarely studied on Svalbard, however such vast low inclination ice masses are typical of the archipelago. Some of

them are low altitude, thin glaciers such as the Hornbreen - Hambergbreen glacier system (Fig. 1). Geomorphologic and remote sensing evidence show them to be of surge type. There are no mass balance records from Hornbreen and Hambergbreen area but the area was mapped by Russian-Swedish expedition “Mission Russe” in 1899–1901. Pälli *et al.* (in press b) mapped the bedrock and surface of Hornbreen and Hambergbreen and adjacent glaciers and compare changes in surface elevations, glacier extents and volumes with maps from Mission Russe to get an idea of what has happened in this area in past 100 years.

We find there has been a very significant change in area and volume of Hornbreen, Hambergbreen and adjacent glaciers during the past 100 years. The Hornbreen front has retreated by 13.5 km and Hambergbreen by 16 km. The volume of these glaciers together has decreased by 37–50 % (Fig. 9). Low altitude, flat glaciers such as Hornbreen and Hambergbreen are very sensitive to climate change and their only

maintaining mechanism in future would be from surges. However, the net accumulation in the area seems to be mostly negative and there is no significant mass input to Hornbreen from adjacent glaciers. Therefore in the present climate it would require a very long time (if ever) for the glacier to surge. The most likely future scenario is that the low-lying glaciated valley filled by Hornbreen and Hambergbreen may become a partially inundated ice-free isthmus within 100–150 years.

**Conclusions**

Detailed studies of the Lomonosovfonna ice record indicate:

- Nitrate shows a rise beginning at the start of the 20<sup>th</sup> Century, that accelerated in the 1950s.
- NAP concentration is intermediate between Greenland and Canadian Arctic.
- MSA seems to be directly related to sea ice in the Barents Sea
- Ions and isotopes in the ice core preserve an almost annual resolution, certainly the best record available from Svalbard
- The temperature profile in the borehole reveals temperatures today are 2 °C higher than the 19<sup>th</sup> Century

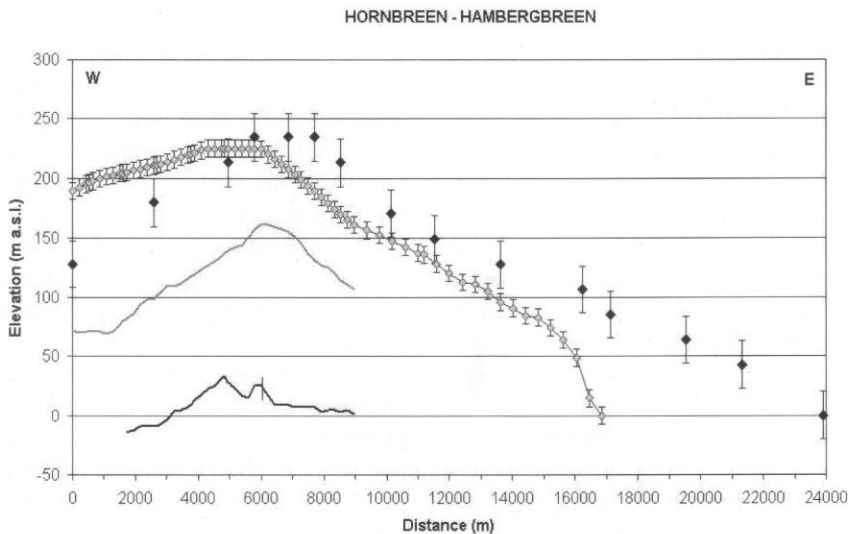
- Accumulation rates have varied by about 20% over the last 300 years, with much higher accumulation since 1950.

The main results of the glacier surveys are:

- Many of the glaciers show great retreat and decay since accurate surveys were made in 1900 and 1936.
- The large glaciers of Hornbreen and Hambergbreen that currently form a continuous glacier between Sörkappland and the main land will likely disappear in the next 100 years due to rising temperatures
- The valley between them will become a partially inundated isthmus, but still have a continuous land bridge above sea level.
- The polythermal glaciers in Svalbard are characterized by extensive superimposed ice zones that can be mapped using remote sensing methods such as radar.

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The efforts of Polish, Norwegian, Swedish, Dutch, Estonian, French and British scientists and support staff working on Svalbard over the duration of the project are gratefully appreciated, and made the work of group vastly more re-



**Figure 9.** Changes in surface elevation between 1900 (black squares), 1936 (grey squares) and 2000 (grey solid line) Hornbreen to Hambergbreen in the survey area marked in Fig. 1, the lower solid line is the bedrock. Reprinted from Pälli et al. (in press b), with permission of the International Glaciological Society.

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