Available online at www.sciencedirect.com
SCIENCE DIRECT®
Physics and Chemistry of the Earth 28 (2003) 1217–1228
PHYSICS and CHEMISTRY of the EARTH
www.elsevier.com/locate/pce

Ice cores from Svalbard—useful archives of past climate and pollution history

Elisabeth Isaksson [a,*], Mark Hermanson [b], Sheila Hicks [c], Makoto Igarashi [d], Kokichi Kamiyama [d], John Moore [e], Hideaki Motoyama [d], Derek Muir [f], Veijo Pohjola [g], Rein Vaikmäe [h], Roderik S.W. van de Wal [i], Okitsugu Watanabe [d]

[a] *Norwegian Polar Institute, N-9296 Tromsø, Norway*
[b] *University of Pennsylvania, Philadelphia, PA 19104, USA*
[c] *Institute of Geosciences, Fin-90014, University of Oulu, Oulu, Finland*
[d] *National Institute of Polar Research (NIPR), Tokyo 173-8515, Japan*
[e] *Arctic Center, University of Lapland, Fin-96101 Rovaniemi, Finland*
[f] *Environment Canada, Burlington, ON L7R4A6, Canada*
[g] *Department of Earth Sciences, Uppsala University, S-75236 Uppsala, Sweden*
[h] *Institute of Geology at Tallinn Technical University, Tallinn 10743, Estonia*
[i] *Institute for Marine and Atmospheric Research Utrecht, 3508TA Utrecht, The Netherlands*

Received 13 December 2002; received in revised form 3 June 2003; accepted 5 August 2003

Abstract

Ice cores from the relatively low-lying ice caps in Svalbard have not been widely exploited in climatic and environmental studies due to uncertainties about the effect of melt water percolation. However, results from two recent Svalbard ice cores, at Lomonosovfonna (1250 m asl) and Austfonna (750 m asl), have shown that with careful site selection, high-resolution sampling and multiple chemical analyses, it is possible to recover ice cores with partly preserved annual signals. These cores are estimated to cover at least the past 600 years and have been dated using a combination of known reference horizons and glacial modeling. The $\delta^{18}O$ data from both Lomonosovfonna and Austfonna ice cores suggest that the 20th century was the warmest during the past 600 years. A comparison of the ice core and sea ice records from this period suggests that sea ice extent and Austfonna $\delta^{18}O$ are linked over the past 400 years. This may reflect the position of the storm tracks and their direct influence on the relatively low altitude Austfonna. Lomonosovfonna may be less sensitive to such changes and primarily record atmospheric changes due to its higher elevation. The anthropogenic influence on Svalbard environment is illustrated by increased levels of non-sea-salt sulphate, nitrate, acidity, fly-ash and organic contaminants particularly during the second half of 1900s. Decreased concentrations of some components in recent decades most likely reflect emission and use restrictions. However, some current-use organic pesticide compounds show growing concentrations in near surface layers.

Keywords: Ice core chemistry; Climate variability; Organic contaminants; Pollen; Svalbard

1. Introduction

Ice cores from the polar ice sheets have contributed much information on climate variability both on inter-annual and ice age time scales (e.g. Fischer et al., 1998a; Petit et al., 1999). However, ice cores from the glaciers outside the main ice fields have not received as much attention, partly because of surface melting during the summer season which could alter the original ice core record (e.g. Koerner, 1997).

Svalbard is positioned in an area characterized by shifting boundaries both in the atmosphere and ocean, thus the climate in this area is highly variable throughout the year. The general large-scale atmospheric circulation is influenced by the low pressure area over Iceland and the high pressure area over Greenland and the Arctic Ocean. Mild air from lower latitudes is transported towards Svalbard with prevailing westerly and southwesterly winds. However, in the northern part of the archipelago easterly and northeasterly winds

* Corresponding author. Tel.: +47-77-75-05-15.
E-mail address: elli@npolar.no (E. Isaksson).

1474-7065/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pce.2003.08.053

dominate and climate in Svalbard is therefore characterized by variations in movement of these two extreme air masses. The presence of warm Atlantic Waters flowing northward as a continuation of the Gulf Stream contributes to high average temperature during the winter, a characteristic feature for Svalbard (Hisdal, 1998).

Svalbard is remote from major pollution sources, with the exception of coalmines at Barentsburg, Sveagruva, Pyramiden and Longyearbyen (the largest settlement in operation since 1911) (Fig. 1). However, evaluation of air mass trajectories and the seasonal movement of the atmospheric polar front shows that Svalbard is affected by long distance transport of contaminants from industrial areas, including eastern and western Europe and Canada (Gjessing, 1977; Staebler et al., 1999; Goto-Azuma and Koerner, 2001). Organic air contaminant measurements at Ny-Ålesund since 1994 show measurable concentrations of many legacy organochlorine contaminants and annual cyclical concentration patterns, related to either changes in long distance transport or condensation to or evaporation from snow surfaces as temperatures change (Oehme et al., 1996).

Sixty percent of the Svalbard archipelago is covered with glaciers and ice caps offering many opportunities to drill ice cores. During the past three decades groups from the former Soviet Union (e.g. Tarrusov, 1992) and Japan (e.g. Fujii et al., 1990; Goto-Azuma et al., 1995) have conducted ice core projects on various parts of the islands. Even though several ice cores have been drilled, very few have been studied in detail. The main problem with most of the previous Svalbard ice cores has been determining how much of the original record has been altered by melting (Koerner, 1997). In general the results from the previous cores suggest similar major climatic trends as recorded in other ice cores from the Arctic, but many questions remain concerning the timing of events and shorter time scale changes. In many cases the dating is insufficient due to a combination of melting, crude sampling and few analyzed chemical species. However, published data from one of the previous ice core locations, Lomonosovfonna, indicated better preserved stratigraphy than the other sites on Svalbard (Gordiyenko et al., 1981). Therefore this was selected as one of our drill sites (Fig. 1). Our second drill location was on Austfonna (Fig. 1), where some of the deepest ice on Svalbard has been found. The estimated ice depth is almost 600 m (Dowdeswell et al., 1986). The cores from Lomonosovfonna and Austfonna have been dated using a combination of known reference horizons and glacial modeling and are estimated to cover at least the past 600 years (Isaksson et al., 2001; Watanabe et al., 2001).

In this paper we discuss results from both Lomonosovfonna and Austfonna ice core sites regarding climate and anthropogenic pollution with the main aim of showing the potential application of Svalbard ice core records to a wide range of environmental studies.

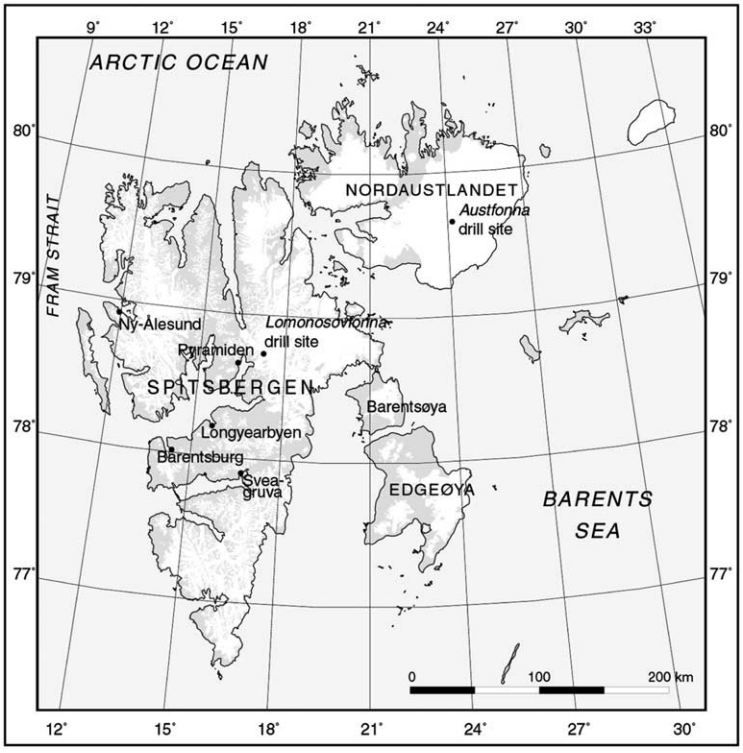

Fig. 1. Map of Svalbard with the ice core locations on Lomonosovfonna and Austfonna included.

2. Description of ice cores and methods

2.1. The Lomonosovfonna ice core

In April of 1997 a 121 m deep ice core was retrieved from Lomonosovfonna, the highest ice field at Svalbard (1250 m asl) (Fig. 1; Table 1). Radar measurements at the core site suggested that the bedrock would have been reached within 5 m. The drilling was an international collaboration between scientists from several countries. Thermistors placed in the snow pack in the vicinity of the ice core site between April and August of 1999 indicates that, at least during this particular year, the summer melt is refrozen within the annual layer. The ice core has been sub-sampled with 5 cm resolution in order to detect any seasonal signals, which would make the dating more reliable than has been possible for previous ice cores from Svalbard. Our analysis has involved the most commonly analyzed ice core species, such as Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}, methanesulphonic acid (MSA), acidity (H^+), ^2H and $\delta^{18}O$. The ^{137}Cs content was determined by high-resolution gamma spectrometry and the 1963 radioactive layer was determined to be at 18.50–18.95 m core depth, providing an important reference horizon for dating and estimation of the mean accumulation rate (Pinglot et al., 1999). Both field- and analytical methods are described in Jauhiainen et al. (1999) and Isaksson et al. (2001).

The time scale of the core was based on a simple age depth model based on pure shear (Nye, 1963) and tied with the known dates of prominent reference horizons (the 1963 radioactive layer and the 1783 Laki volcanic acid layer). In addition, the chemical analysis suggest that annual or pseudo-annual signals are preserved and this has made it possible to obtain an annual time scale back to at least 1715 (Isaksson et al., 2001; Pohjola et al., 2002a). For the purpose of this paper the Nye time scale with the input parameters being the total ice depth at the drill site and the mean accumulation rate has been used.

We have studied the effects of the periodic melt on both the ions and isotopic signals through different quantitative approaches and found that during the warmest summers as much as 50% of the annual accumulation may melt and percolate into the firn, while during an average year it may be less than 25% (Pohjola et al., 2002b). Despite the melt effect annual or biannual cycles were detected in most of the investigated parameters and thus we concluded that this ice core record can provide a reliable high-resolution environmental record.

In addition to the previously mentioned analyses we have also performed analysis of naphthalene, a polycyclicaromatic hydrocarbon (PAH) compound. The analytical methods are described in Vehviläinen et al. (2002).

Finally, pollen and fly-ash (spherical carbonaceous particles: SCP) were analyzed from 12 contiguous slices from the uppermost 36 m of the core, where each sample is estimated to cover about 7 years. The ice was cut in the cold room and melted in closed glass beakers. A tablet containing a known quantity of an 'exotic marker' (*Lycopodium* spores, Stockmarr, 1971) was added to each sample after melting. The sample was then filtered, the filter paper acetolyzed, the residue treated with 10% KOH, washed and mounted in silicone oil. For a sub-sample of each slice all pollen grains were identified and counted, together with two size classes of charcoal ($<40\mu$ and $>40\mu$), SCPs and the added *Lycopodium* markers. The values are expressed as number per cm^2 of surface area, per 7-year slice. The pollen taxa are grouped into three categories on the basis of their possible source of origin: (i) locally growing herbs, (ii) plants commonly present in the vegetation of northern Fennoscandia and (iii) thermophilous species which are definitely of more southern origin (south of 60°N).

2.2. The Austfonna ice cores

During the spring of 1998 a Japanese drilling team with Norwegian participants drilled a 118 m deep core on the summit of Austfonna 750 m asl (Fig. 1; Table 1) (Watanabe et al., 2000). The aim was to reach to 300 m during one season but bad weather condition prevented this. Therefore, it was decided to continue the drilling the following year and in April–May of 1999 a 289 m core was successfully retrieved (Motoyama et al., 2001). Both these ice cores have been analyzed in 0.25 m parts (equivalent to between 1 and 10 years) for Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}, MSA, acidity (H+) and $\delta^{18}O$. The analytical methods are described in more detail in Watanabe et al. (2001). Also in these ice cores the dating was based on a combination of reference horizon from 1963 (Pinglot et al., 2002) and Laki (1783) in combination with glacial modeling using the accumulation rate as input (Watanabe et al., 2001).

Table 1
Information about the drill sites

Site	Latitude N	Longitude E	Altitude (m asl)	Drill year	Drill depth (m)	Annual accumulation (m weq)
Lomonosovfonna	78°51′53″	17°25′30″	1250	1997	121	0.36
Austfonna	79°48′03″	24°00′21″	750	1998	118	0.45
Austfonna	79°50′00″	24°01′00″	750	1999	289	0.45

There is more summer melting on Austfonna than on Lomonosovfonna due to the lower altitude and the melt index has been estimated to 67% by Koerner (1997). With a percolation depth of several meters (Tarrusov, 1992) it is not possible to obtain as high-resolution environmental information as from Lomonosovfonna. Using the Mg^{2+}/Na^{+} ratios in both recent snow and along the ice core it has been possible to quantify the melting through time (Iizuka et al., 2002). According to this melt indicator there is a clear difference between the amount of melt before and after 1920.

A variety of organic contaminants were investigated in the 1998 Austfonna core, and in this paper we show examples from major contaminant classes. These include organochlorine (OC) pesticides, which have been mostly banned in circumpolar countries (de March et al., 1998), and current use organophosphorus (OP) pesticides, some of which have been used as OC substitutes.

The upper 48 m of the 1998 core segments were divided into nine different samples, dating back to 1936. Each sample was melted in a stainless steel tank, then pumped through a column of XAD-2 at 200 mL min^{-1}. The XAD-2 columns were returned to the analytical laboratory and extracted in a clean room (positively pressured with carbon and HEPA filtered air). The XAD-2 was extracted in a chromatographic column eluted with methanol, followed by dichloromethane (DCM). The solvents were combined and water was removed in a separatory funnel. The water was again extracted with additional DCM, which was combined with the other solvents. The combined solvents were passed through a funnel of Na_2SO_4 to remove remaining water, then concentrated and exchanged to isooctane using a rotary evaporator. The samples were fractionated on a silica gel chromatographic column topped with Na_2SO_4, by eluting first with with hexane, and then 50:50 DCM:hexane. Non-polar compounds (some OC pesticides and PCBs) eluted in the hexane fraction, and more polar compounds, including other OC compounds and OPs in DCM:hexane. The eluents were transferred to isooctane, and analyzed by GC-MS (electron ionization mode) using selected ion monitoring of two characteristic ion fragments for each compound. Individual OPs and OCs were quantified by external standard calibration and results expressed as ng/L.

3. Climate reconstructions

The $\delta^{18}O$ records from our two ice core sites correspond relatively well with each other from about 1920 to present (Fig. 2). It appears that the more northerly position of Austfonna does not affect the $\delta^{18}O$ content in the snow, despite the fact that there is a temperature gradient of 2.5 °C/° latitude during the winter months (Hisdal, 1998). This may be due to compensation of the about 500 m altitude difference between the two sites. If we assume that the altitudinal effects is 0.1 per mille/100 m, as has been estimated by Pohjola et al. (2002b) comparing precipitation data from Ny-Ålesund with Lomonosovfonna ice core data, Lomonosovfonna should have about 0.5 per mille lower $\delta^{18}O$ values than Austfonna.

The ice core $\delta^{18}O$ records show the same main features as the instrumental record from Longyearbyen starting in 1911 (Nordli et al., 1996) (Fig. 2) with the general picture showing warming from 1920 to mid-1950s, and from the mid-1970s to present, interrupted by two periods with colder temperatures, in the 1940s and from mid-1950s to the mid-1970s. These low-frequency oscillations at a time scale of 60–80 years fit in the pattern suggested by Polyakov and Johnson (2000) as dominating for Arctic air temperature. The abrupt warming around 1920, which is very strong in the instrumental record, is more pronounced in the Austfonna $\delta^{18}O$ record than in the Lomonosovfonna core. Hanssen-Bauer and Førland (1998) found that this abrupt shift in climate around 1920 could not be explained by circulation changes only, and suggested that the varying extent of sea ice could be the missing link. With this information on hand we expect the ice core records to be less affected by percolating melt water prior to about 1920 and believe that the oxygen isotope record is a reliable climatic indicator also before 1920 when no instrumental records are available for comparisons. Additional evidence for the quality of data for the most recent century are results suggesting that since 1920, the MSA in the Lomonosovfonna ice core corresponds with sea ice and sea surface temperature (SST) on a multi-year basis (O'Dwyer et al., 2000).

Before about 1900 the Austfonna record shows more negative $\delta^{18}O$ values than at Lomonosovfonna (Fig. 3), thus suggesting that colder conditions prevailed there. We believe that the reason for this can be found in the comparison of the ice core and sea ice from this period suggesting that sea ice extent and Austfonna $\delta^{18}O$ are related over the past 400 years (Fig. 4). This may reflect the position of the storm tracks and their direct influence on the relatively low altitude Austfonna. Lomonosovfonna may be less sensitive to such changes and primarily record atmospheric changes due to its higher elevation. Based on the 400 year time series of sea ice extent reconstructed from ship logs, Vinje (1999, 2001) suggested that the sea ice extent in the Barents Sea is lagging the temperatures in England by about 7 years, thus, the Austfonna oxygen isotope record is a valuable climate proxy.

The $\delta^{18}O$ data from both Lomonosovfonna and Austfonna ice cores suggest that the 20th century was the warmest during at least the past 600 years (Fig. 3). The $\delta^{18}O$ records suggest colder conditions between

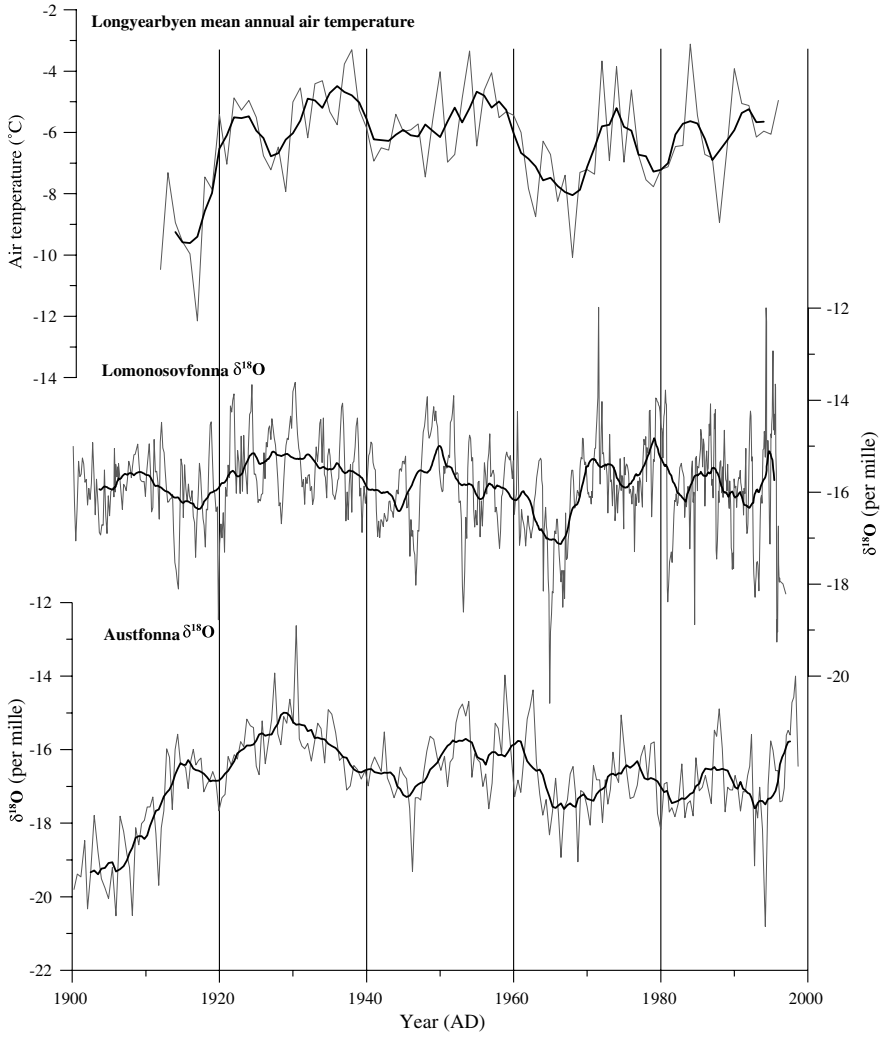

Fig. 2. The $\delta^{18}O$ records from Lomonosovfonna and Austfonna from the 20th century with the mean annual temperature records from Longyearbyen (Nordli et al., 1996). The grey line is the unsmoothed data and the black line the running mean for an equivalent of 5 years.

about 1500 and 1900, with a particularly cold phase between 1750 and 1860. Warmer conditions, also with less sea ice (Vinje, 1999), seem to have prevailed during the decades centered around 1750. The general warming trend is further supported by the borehole temperature record from Lomonosovfonna, which suggests a temperature increase of more than 2 degrees from about the end of the 1800s (Van de Wal et al., 2002). There are few climate proxy data from Svalbard covering the same time period as in the ice cores. One sediment core from the pro-glacial lake Linnévatnet suggests that the Holocene glacial maximum occurred during the Little Ice Age (Grove, 1988) with the starting of a major advance in the 14th and 15th centuries and culminating in the 19th century (Svendsen and Mangerud, 1997).

The longest temperature records from mainland Norway date from 1858, so different types of proxy data must be used for earlier periods. A reconstructed summer temperature record from the Trondheim area based on farmers' diaries suggests that the last part of the 1830s, the 1840s and the 1860s were particularly cold (Nordli, 2001). As on Svalbard, the 1930s were the warmest decade in the Trondheim record. A dendrochronlogical reconstruction of summer temperatures between AD 1358 and 1992 from northern Norway suggest that the coldest periods were the 1450s, 1540s, the whole 17th century and the period 1880–1910 (Kirchhefer, 2001), which is largely in agreement with our Svalbard ice core data.

4. Pollution records

4.1. Long-term changes as revealed by the ion records

Naturally, the marine aerosols are dominating the Svalbard ice cores records. In the Lomonosovfonna ice core sodium and chloride are accounting for 63% and

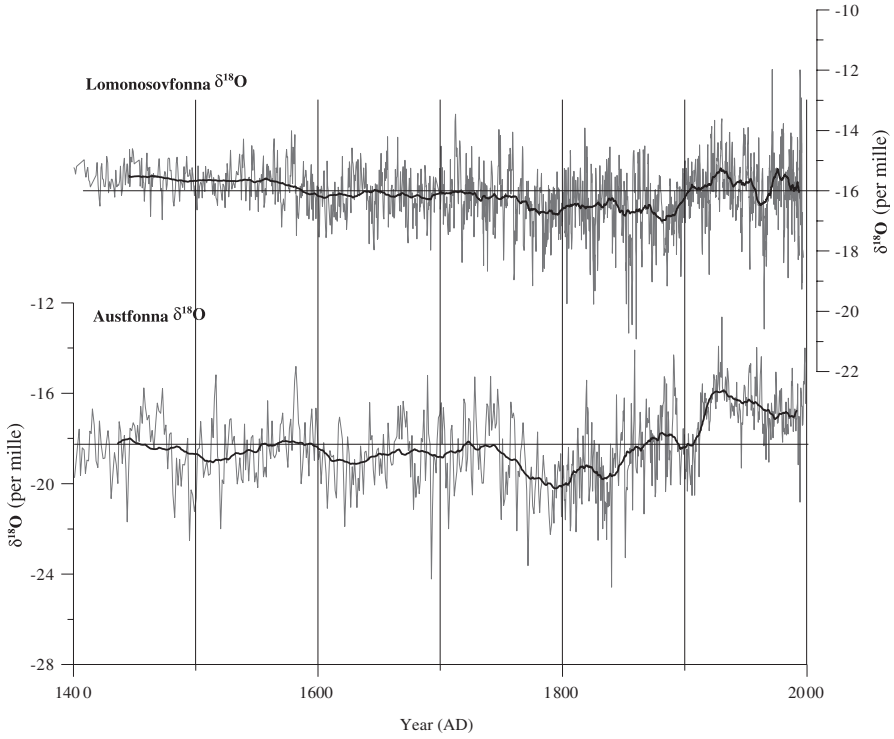

Fig. 3. The $\delta^{18}O$ records from Lomonosovfonna and Austfonna (adapted from Watanabe et al., 2001) from 1400 AD to present. The grey line is the unsmoothed data and the black line the running mean for an equivalent of 25 years. A line representing the mean for all samples for each core is also included.

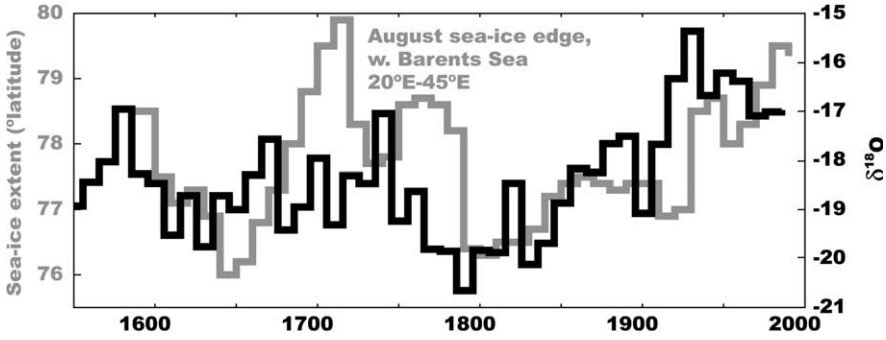

Fig. 4. The decadal scale Austfonna $\delta^{18}O$ record (black) corresponds well to the August sea ice record (grey) from western Barents Sea, compiled with data from whaling ships (Vinje, 1999). This is suggesting that $\delta^{18}O$ in the precipitation is directly influenced by distance to moisture source in the Austfonna ice core.

sulphate for 14% of the whole ice core soluble ion concentrations (Kekonen et al., unpublished data). The impact of the industrial revolution on Svalbard environment is illustrated by increased levels of sulphate, nitrate and acidity during the 20th century (Isaksson et al., 2001; Simoes and Zagorodnov, 2001; Kekonen et al., 2002). The nitrate records from both ice core sites show a pronounced increase in the 1950s (Fig. 5). Although global NO_x emissions started to increase in the 1860s (Erisman and Draaijers, 1995; Klimenko et al., 2000) the amounts reaching Svalbard were not large enough to be detected in either of these ice cores until the 1920s at Lomonosovfonna. Maximum concentrations in the Austfonna ice core were reached in the mid-1970s and then started to drop rapidly in the mid-1980s, a possible effect of stricter emission controls on NO_x. Non-sea-salt sulphate concentrations begin to increase by 1850 and continue into the 1980s, with some decrease in the most recent years (Moore et al., unpublished data). The decreasing trend is also reflected in the aerosol measurements in Ny-Ålesund were the sulphate data show an almost 60% decrease from 1980 to 1997 (Tørseth et al., 1999). It is interesting to note that the trends in Svalbard ice core data are in general agreement with

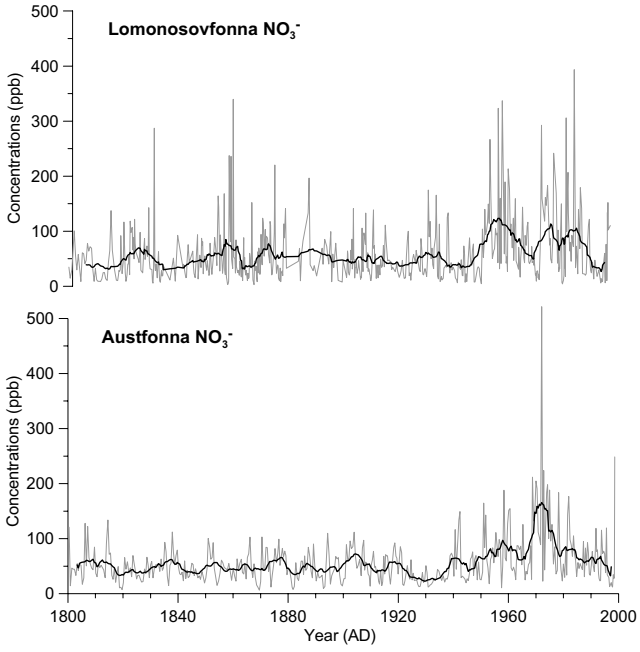

Fig. 5. The nitrate records from Lomonosovfonna (adapted from Kekonen et al., 2002) and Austfonna (adapted from Watanabe et al., 2001) for the periods 1800 to the present. These records are illustrating the beginning of the relatively sharp anthropogenic influence around 1950. The black line the running mean for an equivalent of 25 years.

Greenland ice core records, which suggest that there is a major increase in nitrate after 1950 while sulphate started to rise earlier, around 1890 (Fischer et al., 1998b).

There is a possibility that local sulphate sources may also be part of the record. Mining activities in nearby Pyramiden (Fig. 1) (35 km from the Lomonovfonna drill site), in operation from 1947 to 1990, coincide with an increase in the sulphate record. Furthermore, the closing of the mining activities in Pyramiden in 1990 may have contributed to the decreasing sulphate concentrations on Lomonosovfonna during the last decade. Using the emission estimates from various sources, Goto-Azuma and Koerner (2001) have shown that the sulphate record from one Svalbard ice core at Snøfjellafonna in the vicinity of Ny-Ålesund (Fig. 1) closely resembles the total sulphate emission record from Eurasia between about 1940 and 1990, excluding a substantial contribution from local Svalbard sources.

4.2. Fly-ash (spherical carbonaceaous particles, SCPs)

SCPs (fly-ash) are produced by burning fossil fuels at high temperatures (e.g. Wik and Renberg, 1996). They tend to be larger in size and more abundant near the source and become fewer and smaller with distance from the source. They are recognized in pollen samples as opaque, black spherical objects. They are distinguished from charcoal on the basis of shape: the charcoal always has straight or jagged edges. Charcoal, particularly the small size class (<40μ) was the most abundant particle in the ice samples. Larger pieces of charcoal and the SCPs occurred in frequencies of the same order as the pollen grains. The values of both are illustrated in Fig. 6a.

The highest values of charcoal are recorded in the period 1949–1980, i.e. after the re-opening of the coal-mines until the time of general reduction in emissions. Much of this charcoal may very well be local in origin. This is in keeping with the observation from snow pits that charcoal is being deposited all the year round.

The SCP values first increase in the late 1920s, early 1930s and have similar higher values during the period 1949–1972, falling dramatically from 1973 onwards. SPCs have also been recorded in a network of pollen monitoring stations in northern Fennoscandia. Fig. 6b illustrates how the values from the nine northernmost of these sites compare with the Lomonosovfonna values. The Fennoscandian data are, unfortunately, only available for the period 1982–1996 (Hicks, 2001) and so a comparison is only possible with the two youngest ice core slices. At both Lomonosovfonna and one site in northern Norway (near Kautokeino) there is slightly more fly-ash in the period 1989–1996 than in 1982–1988. For all the other sites, the earlier period has higher fly-ash values. Even so, the ice core values are far less than the Fennoscandian ones. Fly-ash is consistently more abundant in Eastern Finnish Lapland (sites closer to the Kola peninsula) than in western Finnish Lapland. The temporal distribution pattern of SCP in Lomonosovfonna (Fig. 6a) is very similar to that in varved lake sediments in Sweden (Wik and Renberg, 1996). The trend is not unlike that of the sulphur emissions and could indicate a common origin. At the atmospheric sampling station at Zeppelinfjellet in Ny-Ålesund black carbon, sulphur-dioxide and sulphate concentrations are highly correlated (Eleftheriadis et al., 2001).

4.3. Organic contaminants

4.3.1. PAH

The only PAH that we could detect in the ice from Lomonosovfonna given the small sample size was naphthalene (Vehviläinen et al., 2002). This record spans the past century. The naphthalene concentrations show an increase from about 1940s to the 1980s and prior to the 1930s it was below our detection limit (Fig. 7). The naphthalene concentrations are much lower than what has been reported from Agassiz Ice Cap in the Canadian Arctic (Peters et al., 1995) but about 50 times higher than from interior Greenland ice core sites (Kawamura et al., 1994). Because the general picture is also consistent with the increase in the late 1940s of the population and mining activities in Svalbard (Arlof, 1996) local sources could be contributing to this trend. However, considering the levels of naphthalene in Lomonosovfonna compared with values in Arctic Canada,

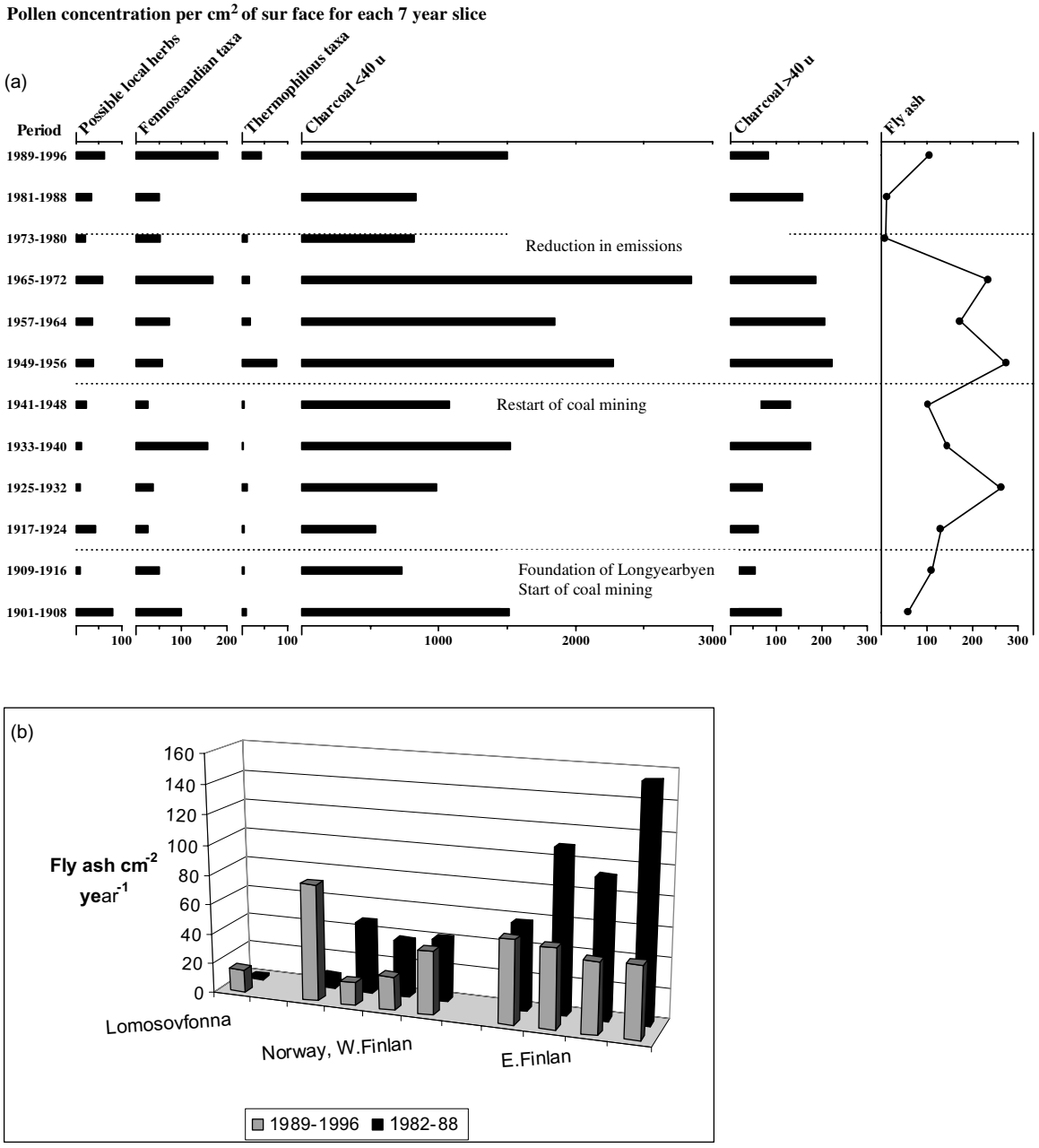

Fig. 6. (a) Pollen, charcoal and fly-ash content of contiguous ice slices from the Lomonosovfonna ice core. (b) Average annual fly-ash deposition values for two 7-year periods for the Lomonosovfonna ice core and for two regions in northernmost Fennoscandia. The amount of fly-ash in the ice core is only a fraction of that being deposited on the mainland. The fact that the earlier 7-year period has higher values on the mainland while it is the later 7-year period, which has the highest values at Lomonosovfonna may indicate that the two deposition areas have slightly different sources.

we do not believe that the local sources associated with coal mining and local fossil fuel burning are substantial. Correlation of naphthalene with physical and chemical parameters in the core strongly suggests wintertime deposition of naphthalene with Arctic haze. This is also suggested by air measurements in Ny-Ålesund, which are continuously measured (Tørseth et al., 1999). Naphthalene and biphenyl contribute to 70% of the measured PAH compounds in Ny-Ålesund. For a more thorough discussion concerning the naphthalene results we refer to the paper by Vehviläinen et al. (2002).

4.3.2. Pesticides

A widely-used OP pesticide, methyl parathion, has a short record of increasing concentrations at Austfonna beginning in the 1970s (Fig. 8). Since OP pesticides would be expected to decompose in the environment within weeks, the appearance of this compound in 20

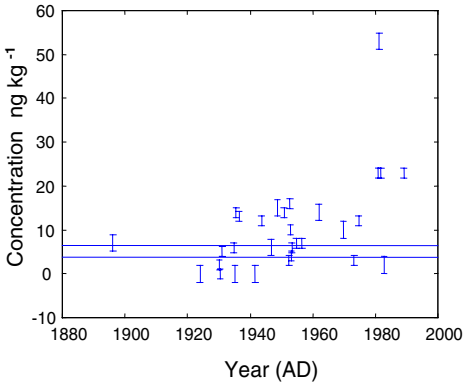

Fig. 7. The naphthalene record from the Lomonosovfonna ice core. The error bars show the detection limits and the horizontal lines the determination limits for two sets of samples (adapted from Vehviläinen et al., 2002).

year old ice suggests that the decomposition processes have been slowed or stopped once the compounds are trapped in the glacier. Since pesticides are not used on Svalbard—which is free from insects—the accumulation of methyl parathion shows that atmospheric transport from its source to Svalbard is faster than typical decomposition processes. Methyl parathion has an estimated atmospheric half-life of 0.2 days based on reaction with hydroxyl radical (SRC, 2002) and thus only a minor fraction of the chemical emitted in use areas in the mid-latitudes would be expected to reach Svalbard. The short record of this compound requires further research to determine more details about its input and longevity.

Dieldrin, a pesticide used widely in Europe and North America since the 1950s until being banned in the 1980s, shows declining inputs at Austfonna since the late 1970s (Fig. 8). While the declining trend would be predicted from use patterns, the increase in use of this pesticide before the 1970s in not clearly evident in the ice except for a large peak in the 1950s.

The opposing trends of methyl parathion and dieldrin concentrations at Austfonna since about 1980 are characteristic of expected inputs resulting from pesticide use in the mid-latitudes. The appearance of both pesticides shows that long-range transport is delivering contaminants to Austfonna. The inputs observed here represent net accumulation. These pesticides would be expected to undergo post-depositional revolatilization as has been observed for the more volatile organochlorines (Franz et al., 1997) as well as degradation, in the case of methyl parathion. However, little is known about overall rate of these processes.

5. Pollen grains as atmospheric tracers

Pollen grains in ice cores can be used to help identify sources and transport paths of atmospheric materials reaching the ice caps (Bourgeois, 1986). Our first experimental work on the Svalbard ice indicates that the quantity of pollen in the ice is insufficient for a statistically valid reconstruction of vegetation, but the taxa present can potentially indicate their region of origin. These possibilities have not yet been fully explored in the

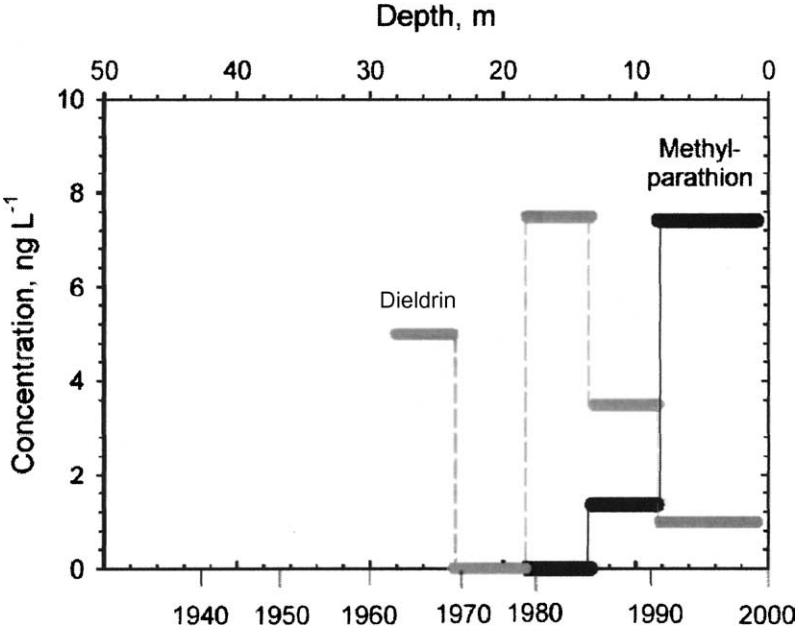

Fig. 8. Profiles of methyl parathion and dieldrin in the Austfonna ice core drilled in 1998. The relative high concentrations of methyl parathion in near surface layers suggest a current use and growing inputs of these compounds while dieldrin shows declining input since the late 1970s.

European Arctic. While pollen provides information about the sources and paths of airmasses, it also offers a second link to pollution studies: pollen grains are relatively large airborne particles (the largest $>40\mu$) and therefore act as transporters of particle-associated contaminants (metals, sulphur, PAH) (Cerceau-Larrival et al., 1991).

The pollen taxa recovered from the ice (Fig. 6a) show that their origin is probably entirely from Europe. No taxa of exclusive North American origin were recorded although some of the recorded taxa occur on both continents. Taxa of northern Fennoscandian origin were the most abundant, exceeding those of local herbs as expected. Amongst the Fennoscandian taxa, trees (predominantly birch and pine) are well represented. Trees produce pollen in much greater quantities than herbs, and pollen of both birch and pine are easily transported over great distances. Given the vast areas of forest in Fennoscandia and the meagre herbaceous vegetation on Svalbard it is not surprising that this more distant source is better represented than the local source. The pollen of thermophilous taxa must have the most distant origin. This pollen group is more abundant during the period 1949–1996 than from 1901 to 1948. In general there are slightly more pollen in more recent times than earlier, although the actual quantities are so small that the difference cannot be demonstrated statistically.

Nevertheless, the actual quantity of pollen recovered from the ice seems to be higher than that recorded in the East Canadian ice caps. The numbers illustrated in Fig. 6a are calculated relative to cm^{-2} of ice surface for the 7-year period that each sample covers. This means a total pollen deposition of between 1 and 50 grains $cm^{-2}\,year^{-1}$. Comparable values are hard to find, as values are most commonly expressed as pollen concentration $litre^{-1}$ of water. However, Short and Holdsworth (1985) give values of 1–8 grains $cm^{-2}\,year^{-1}$ for samples from the Penny Ice Cap on Baffin Island. The actual quantity of pollen is most probably related to the distance between the vegetation sources and the ice core locations coupled with the direction and strength of the prevailing winds.

6. Summary and conclusions

In this paper we have provided several examples of both climate and pollution records from ice cores from two different sites in Svalbard. Despite the fact that the atmospheric records in these ice cores probably have been altered to some degree by melt these records still provide information about major trends in atmospheric variability of both climate parameters and pollution history. Thus, we believe that with careful site selection, high-resolution sampling and multiple chemical analyses, Svalbard ice cores are extremely useful for a wide range of environmental studies.

Continuous instrumental time series are lacking at Svalbard before 1912 and therefore high-resolution ice core data are particularly valuable for documenting early environmental history. By using ice cores, the historic regional climate variability can be established and the apparent spatial climate and circulation differences in the Svalbard archipelago can be better understood. For example, aerosol measurements from Ny-Ålesund show that during warm periods the air masses originates from the west while during cold periods the opposite is true, with air masses coming in over the Barents Sea (Staebler et al., 1999). Ny-Ålesund air sampling results further suggest that the marine air masses from the west have higher concentrations of sea salts while the colder and drier Barents Sea air is enriched in sulphate (Hara et al., 1997). Finding these results in ice cores facilitates the possibility to trace dominating air masses so that their frequency can be reconstructed (i.e. Kreutz et al., 1997).

The cores show organic contaminant profiles that reflect known production and use patterns in temperate climates. The presence of organophosphorus pesticides, many of which are still used and which are intended to dissociate once released into the environment, shows that the atmosphere is able to deliver these compounds to Svalbard before they decompose. Once these compounds are frozen in ice, which is reached at relatively shallow depths on Svalbard, the decomposition is likely impeded, and the compound may remain there for a very long time period.

Based on our present results we believe that the temporal and spatial variations of both climate and pollution within Svalbard can be better understood by careful examination of ice core records. Some of our current and future work involves detailed snow pit studies of major ions and $\delta^{18}O$ in order to understand the processes related to summer melt changing the deposition signal in the snow pack.

Acknowledgements

We want to thank all those individuals who made these ice core project possible. Logistical support came from NPI in Longyearbyen. We are grateful to Raija-Liisa Huttunen for making the pollen and fly-ash analyses and Audun Igesund for providing the map. Financial support came from Norwegian Polar Institute, NIPR, The Norwegian Research Council, The Finnish Academy, NARP, The Netherlands foundation for the Advancements of Pure Research (NWO), The Swedish Research Council and Stiftelsen Ymer-80. The paper benefited from very helpful comments by Roy Koerner, Bernard Lefauconnier and one anonymous referee.

References

Arlof, T., 1996. Svalbards historie 1596–1996. Aschehoug and Co, Oslo. p. 494.

Bourgeois, J.C., 1986. A pollen record from Agassiz Ice Cap, northern Ellesmere Island, Canada. Boreas 15 (4), 345–354.

Cerceau-Larrival, M.-T., Nilsson, S., Caneau-Pigot, A., Berggren, B., Verhille, A.-M., Carbonnier-Jarreau, M.-C., 1991. The influence of the environment (natural and experimental) on the composition of the exine of allergenic pollen with respect to the deposition of pollutant mineral particles. Grana 30, 532–546.

de March, B.G.E., DeWit, C.A., Muir, D.C.G., Braune, B.M., Gregor, D.J., Norstrom, R.J., Olsson, M., Skaare, J.U., Stange, K., 1998. Persistent organic pollutants. In: AMAP Assessment Report. Arctic Pollution Issues. Arctic Monitoring and Assessment Program, Oslo, Norway, pp. 183–372 (Chapter 6).

Dowdeswell, J.A., Drewry, D.J., Cooper, A.P.R., Gorman, M.R., Liestøl, O., Orheim, O., 1986. Digital mapping of the Nordaustlandet ice caps from airborne geophysical investigations. Ann. Glaciol. 8, 51–58.

Eleftheriadis, K., Nyeki, S., Colbeck, I., 2001. Black carbon and ionic species in the Arctic aerosol. Mem. Natl. Inst. Polar Res. Spec. Issue 54, 91–99.

Erisman, J.W., Draaijers, G.P.J., 1995. Atmospheric Deposition in Relation to Acidification and Eutrophication. Elsevier, Amsterdam. pp. 23–48.

Fischer, H. et al., 1998a. Little ice age clearly recorded in northern Greenland ice cores. Geophys. Res. Lett. 25 (10), 1749–1752.

Fischer, H., Wagenbach, D., Kipfstuhl, J., 1998b. Sulfate and nitrate firn concentrations on the Greenland ice sheet. 2. Temporal anthropogenic deposition changes. J. Geophys. Res. 103 (D17), 21935–21942.

Franz, T.P., Gregor, D.J., Eisenreich, D.J., 1997. Snow deposition of atmospheric semi-volatile organic chemicals. In: Baker, J.E. (Ed.), Atmospheric deposition of contaminants to the Great Lakes and Coastal Waters. SETAC Press, Pensacola, FL, pp. 73–107.

Fujii, Y. et al., 1990. 6000-year climate records in an ice cores from the Høghetta ice dome in northern Spitsbergen. Ann. Glaciol. 14, 85–89.

Gjessing, Y.T., 1977. Episodic variations of snow contamination of an Arctic snowfield. Atmos. Environ. 11, 643–647.

Gordiyenko, F.G., Kotljakov, V.M., Punning, Ya.-M.K., Vaikmäe, R., 1981. Study of a 200 m core from the Lomonosov ice plateau on Spitsbergen and the palaeoclimatic implications. Polar Geogr. Geol. 5 (4), 242–251.

Goto-Azuma, K., Koerner, R.M., 2001. Ice core studies of anthropogenic sulfate and nitrate trends in the Arctic. J. Geophys. Res. 106 (D5), 4959–4969.

Goto-Azuma, K. et al., 1995. An ice-core chemistry record from Snøfjellafonna, northwestern Spitsbergen. Ann. Glaciol. 21, 213–218.

Grove, J.M., 1988. The Little Ice Age. Methuen, London.

Hanssen-Bauer, I., Førland, E.J., 1998. Long-term trends in precipitation and temperature in the Norwegian Arctic: can they be explained by changes in atmospheric circulation patterns? Clim. Res. 10, 143–153.

Hara, K., Osada, K., Hayashi, M., Matsunaga, K., Iwasaka, Y., 1997. Variation of concentrations of sulfate, methanesulfonate and sulfur dioxide at Ny Ålesund in 1995/96 winter. Proc. NIPR Symp. Polar Meteorol. Glaciol. 11, 127–137.

Hicks, S., 2001. The use of annual arboreal pollen deposition values for delimiting tree-lines in the landscape and exploring models of pollen dispersal. Rev. Palaeobotan. Palynol. 117, 1–29.

Hisdal, V., 1998. Svalbard nature and history. Norsk Polarinstitutt, Oslo.

Iizuka, Y., Igarashi, M., Kamiyama, K., Motoyama, H., Watanabe, O., 2002. Ratios of Mg^{2+}/Na^{+} in snow pack and an ice core at Austfonna ice cap, Svalbard, as an indicator of seasonal melting. J. Glaciol. 48 (162), 452–460.

Isaksson, E., Pohjola, V., Jauhiainen, T., Moore, J., Pinglot, J.-F., Vaikmäe, R., van de Wal, R.S.W., Hagen, J.-O., Ivask, J., Karlöf, L., Martma, T., Meijer, H.A.J., Mulvaney, R., Thomassen, M.P.A., Van den Broeke, M., 2001. A new ice core record from Lomonosovfonna, Svalbard: viewing the data between 1920–1997 in relation to present climate and environmental conditions. J. Glaciol. 47 (157), 335–345.

Jauhiainen, T., Moore, J., Perämäki, P., Derome, J., Derome, K., 1999. Simple procedure for ion chromatographic determination of anions and cations at trace levels in ice core samples. Anal. Chim. Acta 389, 21–29.

Kawamura, K., Suzuki, I., Fujii, Y., Watanabe, O., 1994. Ice core record of polycyclic aromatic hydrocarbons over the past 400 years. Naturwissenschaften 81 (11), 502–505.

Kekonen, T., Moore, J., Mulvaney, R., Isaksson, E., Pohjola, V., van de Wal, R.S.W., 2002. A 800 year record of nitrate from the Lomonosovfonna ice core, Svalbard. Ann. Glaciol. 35, 261–265.

Kirchhefer, A., 2001. Reconstruction of summer temperatures from tree-rings of Scots pine (*Pinus sylvestris* L.) in coastal northern Norway. The Holocene 11 (1), 41–52.

Klimenko, V.V., Klimenko, A.V., Tereshin, A.G., 2000. Reducing emissions of trace greenhouse gases as an alternative to reducing emissions of carbon dioxide: part II. Therm. Eng. 47 (6), 476–483.

Koerner, R., 1997. Some comments on climatic reconstructions from ice cores drilled in areas of high melt. J. Glaciol. 43 (143), 90–97.

Kreutz, K.J., Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S.I., Pitalwala, I.I., 1997. Bipolar changes in atmospheric circulation during the little ice age. Science 277, 1294–1296.

Motoyama, H., Watanabe, O., Goto-Azuma, K., Igarashi, M., Miyahara, H., Nagasaki, T., Karlöf, L., Isaksson, E., 2001. Activities of the Japanese Arctic Glaciological Expedition in 1999 (JAGE 1999). Mem. Natl. Inst. Polar Res. Spec. Issue 54, 253–260.

Nordli, P.Ø., 2001. Reconstruction of nineteenth century summer temperatures in Norway by proxy data from farmers' diaries. Clim. Change 48, 201–218.

Nordli, P.Ø., Hanssen-Bauer, I., Førland, E.J., 1996. Homogeneity analyses of temperature and precipitation series from Svalbard and Jan Mayen. DNMI-Rapport, Norwegian Meteorological Institute 16/96 Klima.

Nye, J.F., 1963. Correction factor for accumulation measured by the ice thickness of the annual layers in an ice sheet. J. Glaciol. 4, 141–150.

O'Dwyer, J., Isaksson, E., Vinje, T., Jauhiainen, T., Moore, J., Pohjola, V., Vaikmäe, R., van de Wal, R., 2000. Methanesulfonic acid from a Svalbard ice core as an indicator of ocean climate. Geophys. Res. Lett. 27 (8), 1159–1162.

Oehme, M., Haugen, J.-E., Schlabach, M., 1996. Seasonal changes and relations between levels of organochlorines in Arctic ambient air: First results of an all-year-round monitoring at Ny-Ålesund, Svalbard, Norway. Environ. Sci. Technol. 30, 2294–2304.

Peters, A.J., Gregor, D.J., Teixeira, C.F., Jones, N.P., Spencer, C., 1995. The recent depositional trend of polycyclic aromatic hydrocarbons and elemental carbon to the Agassiz Ice Cap, Ellesmere Island, Canada. Sci. Total Environ. 160–161, 167–179.

Petit, J.R. et al., 1999. Climate and atmospheric history og the past 420,000 years from the Vostok ice core. Nature 399, 429–436.

Pinglot, J.F., Pourchet, M., Lefauconnier, B., Hagen, J.O., Isaksson, E., Vaikmäe, R., Kamiyama, K., 1999. Investigations of temporal change of the accumulation in Svalbard glaciers deducted from nuclear tests and Chernobyl reference layers. Polar Res. 18 (2), 315–321.

Pinglot, F., Vaikmae, R., Kamiyama, K., Igarashi, M., Fritzsche, D., Wilhelms, F., Koerner, R., Henderson, M., Isaksson, E., Winther,

J.-G., van de Wal, R.S.W., Fournier, M., Bouisset, P., Meijer, H., 2002. Ice cores from Arctic subpolar glaciers: chronology and post depositional processes deduced from radioactivity measurements. J. Glaciol. 49 (164).

Pohjola, V., Martma, T., Meijer, H.A.J., Moore, J., Isaksson, E., Vaikmäe, R., van de Wal, R.S.W., 2002a. Reconstruction of annual accumulation rates back 200 years based on the water isotope record from the ice field Lomonosovfonna, Svalbard. Ann. Glaciol. 35, 57–62.

Pohjola, V., Moore, J., Isaksson, E., Jauhiainen, T., van de Wal, R.S.W., Martma, T., Meijer, H.A.J., Vaikmäe, R., 2002b. Preservation of climatic signals in an ice field affected by periodical melt: a qualitative and quantitative study of the upper 36 m of an ice core from the summit of Lomonosovfonna, Svalbard. J. Geophys. Res. 107 (D4), 10.1029/2000JD000149.

Polyakov, I., Johnson, M.A., 2000. Arctic decadal and interdecadal variability. Geophys. Res. Lett. 27, 4097–4100.

Short, S.K., Holdsworth, G., 1985. Pollen, oxygen isotope content and seasonality in an ice core from the Penny Ice Cap, Baffin Island. Arctic 38, 214–218.

Simoes, J.C., Zagorodnov, V.S., 2001. The record of anthropogenic pollution in snow and ice in Svalbard, Norway. Atm. Environ. 35, 403–413.

Staebler, R., Toom-Sauntry, D., Barrie, L., Langendörfer, U., Lehrer, E., Li, S.-M., Dryfhout-Clark, H., 1999. Physical and chemical characteristics of aerosols at Spitzbergen in the spring of 1996. J. Geophys. Res. 104, 5515–5529.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollen Spores 13, 615–621.

Svendsen, J.I., Mangerud, J., 1997. Holocene glacial and climatic variations on Spitsbergen, Svalbard. The Holocene 7, 45–57.

Syracuse Research Corporation (SRC), 2002. PhysProp On line Demo. Available from <http://esc.syrres.com/interkow/physdemo.htm>.

Tarrusov, A., 1992. The Arctic from Svalbard to Severnaya Zemlya: climatic reconstructions from ice cores. In: Bradley, R.S., Jones, P.D. (Eds.), Climate since A.D. 1500. Routledge, London and New York, pp. 505–516.

Tørseth, K., Berg, T., Hanssen, J.E., Manø, S., 1999. Overvåking av langtransportert forurenset luft og nedbør. Atmosfærisk tilførsel, 1998. Statlig program for forurensningsovervåking, Norwegian Institute for Air Research (Rapport 768/99), p. 145.

Van de Wal, R.S.W., Mulvaney, R., Isaksson, E., Moore, J., Pohjola, V., Thomassen, M.P.A., 2002. Historical temperature reconstructions from temperature measurements in a medium-length bore hole on the Lomonosovfonna plateau, Svalbard. Ann. Glaciol. 35, 371–378.

Vehviläinen, J., Isaksson, E., Moore, J., 2002. The record of polyaromatic hydrocarbons (PAH) in an ice core from Svalbard. Ann. Glaciol. 35, 257–260.

Vinje, T., 1999. Barents Sea ice edge variation over the past 400 years. Extended abstract. Workshop on Sea-Ice Charts of the Arctic, Seattle, WA, World Meteorological Organization, WMO/TD No. 949, pp. 4–6.

Vinje, T., 2001. Anomalies and trends of sea ice extent and atmospheric circulation in the Nordic Seas during the period 1864–1998. J. Clim. 14 (2), 255–267.

Watanabe, O., Kamiyama, K., Kameda, T., Takahashi, S., Isaksson, E., 2000. Activities of the Japanese Arctic Glaciological Expedition in 1998 (JAGE 1998). Bull. Glaciol. Res. 17, 31–35.

Watanabe, O., Motoyama, H., Igarashi, M., Kamiyama, K., Matoba, S., Goto-Azuma, K., Narita, H., Kameda, H., 2001. Studies on climatic and environmental changes during the last few hundred years using ice cores from various sites in Nordaustlandet, Svalbard. Mem. Natl. Inst. Polar Res. Spec. Issue 54, 227–242.

Wik, M., Renberg, I., 1996. Environmental records of carbonaceous fly-ash particles from fossil-fuel combustion. J. Paleolimn. 15, 193–206.