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# Two ice-core $\delta^{18}$O records from Svalbard illustrating climate and sea-ice variability over the last 400 years

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**Abstract:** Ice cores from the relatively low-lying ice caps in Svalbard have not been widely exploited in climatic studies owing to uncertainties about the effect of meltwater percolation. However, results from two new Svalbard ice cores, at Lomonosovfonna and Austfonna, have shown that with careful site selection, high-resolution sampling and multiple chemical analyses it is possible to recover ice cores from which part of the annual signals are preserved, despite the considerable meltwater percolation. The new Svalbard ice cores are positioned in different parts of Svalbard and cover the past 800 years. In this paper we focus on the last 400 years. The $\delta^{18}$O signals from the cores are qualitatively similar over most of the twentieth century, suggesting that they record the same atmospheric signal. Prior to AD 1920, the Austfonna ice core exhibits more negative $\delta^{18}$O values than Lomonosovfonna, although there are intermittent decadal-scale periods throughout the record with similar values. We suggest that the differences reflect the effect of the inversion layer during the winter. The pattern in the $\delta^{18}$O records is similar to the Longyearbyen air-temperature record, but on an annual level the correlation is low. The Austfonna record correlates well with the temperature record from the more distant and southwesterly located Jan Mayen. A comparison of the ice-core and sea-ice records from this period suggests that sea-ice extent and Austfonna $\delta^{18}$O are related 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 free atmospheric changes instead of variations in sea-ice extent, the latter is probably a result of its higher elevation.

**Key words:** Ice-cores, climatic change, $\delta^{18}$O records, meteorology, sea ice, oxygen isotopes, stable isotopes, Svalbard, late Holocene.

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**Figure 1** Location map of Svalbard and the drill locations on Lomonsovfonna and Austfonna

## Introduction

Svalbard is situated in a climatically sensitive area at the turning point of the North Atlantic Current, where warm air masses from the southwest meet the cold Arctic air from the northeast, i.e., both the atmospheric and oceanic polar fronts (Figure 1). The warm Atlantic Water current splits south of Svalbard, with one branch continuing north through the Fram Strait and into the Arctic Ocean, and the other branch flowing into the Barents Sea (Loeng, 1991).

The large-scale circulation around Svalbard is characterized by variations between two extreme weather types. The first is depressions arriving from the southwest, which advect mild air as they move in a northeasterly direction. This situation can give relatively high average temperatures at any time during the winter, a characteristic feature for Svalbard. The second weather type is characterized by a low-pressure area over Iceland and a high-pressure area over north Greenland and the Arctic Ocean, resulting in cold easterly and northeasterly winds over Svalbard (Hisdal, 1998).

The geographical position of Svalbard makes heat transport to this area very sensitive to changes in both ocean currents and air masses. Relatively little is known about the climatic conditions here before the instrumental period began in 1911. By combining several records from the vicinity of Longyearbyen at Isfjorden (Figure 1), a continuous record has been created (Nordli *et al.*, 1996). The most characteristic feature is the abrupt warming that occured after a temperature minimum in 1917 and lasted to the late 1930s (Figure 2) – the early twentieth-century warming (see Bengtsson *et al.*, 2004, for discussion and references). After a cooler period that culminated in the late 1960s there has been a significant increase in temperature, but Svalbard is still colder than it was in the 1930s. No significant trend can be found for the entire instrumental period, although there are significant trends on a decadal scale (Hanssen-Bauer and Førland, 1998). The general pattern of the spatial variation of temperature in Svalbard is that the northern and eastern parts are cooler because of the influence of cold polar air and drift ice with a temperature gradient of about 2.5°C per degree latitude from south to north during the winter months but much less during the summer months (Hisdal, 1998).

During the instrumental period, precipitation in Svalbard has increased by about 25%, probably as a result of changes in atmospheric circulation (Førland *et al.*, 1997; Hanssen-Bauer and Førland, 1998). The average precipitation varies around the archipelago and, despite the Atlantic depressions, most precipitation is brought by easterly winds causing an east–west gradient (Hisdal, 1998).

Information regarding climate variations on Svalbard before the instrumental period is largely restricted to different climate proxy-archives with limited time resolution. For example, Holocene climatic variability in Svalbard has been studied using shoreline displacements (raised beaches), lichenometric studies (algae growth curves), moraine forms (glacier front variations) and sediment cores taken from lakes, and from the fjords and surrounding sea shelf areas around the Svalbard archipelago (e.g., Salvigsen *et al.*, 1992; Hjort *et al.*, 1995). Information on the more recent past, including the period commonly referred to as the 'Little Ice Age' (LIA) at about AD 1450–1850 (Grove, 2001) has therefore largely been lacking. Svalbard glaciers seem to have been at their maximum extent around the beginning of the 1900s (Hagen *et al.*, 1993), just prior to the general warming of the Arctic. A valuable climatic archive is the sea-ice reconstructions around Svalbard based on records from whaling and sealing ships compiled by Vinje (1999, 2001). This work has shown that the period before 1920 was characterized by heavy sea ice interrupted by periods with more modest sea-ice conditions.

About 60% of the islands in Svalbard are ice-covered and, naturally, ice-core studies have the potential of being a valuable palaeoclimatic indicator for this area. Since the 1970s several ice-cores have been drilled in Svalbard by groups from both the former Soviet Union (e.g., Tarussov, 1992) and Japan (e.g., Watanabe *et al.*, 2001), but very few of these have been studied in detail. In many cases the dating is insufficient owing to a combination of melting, coarse sampling and limited analysis of chemical species (Koerner, 1997). As a result, the available ice-core records have not been fully utilized for climatic reconstruction.

In this paper we investigate the $\delta^{18}$O records, with a focus on the last 400 years, from two recently drilled Svalbard ice-cores on Lomonosovfonna and Austfonna (Figure 1, Table 1). The $\delta^{18}$O records are investigated from a proxy-temperature perspective, focusing on the differences between the records. Both ice caps have been drilled previously. A 200-m core was drilled on Lomonosovfonna at 1020 m a.s.l. in 1976, which yielded a partially preserved seasonal stratigraphy in oxygen isotopes (Gordiyenko *et al.*, 1981), and which was dated to the twelfth century based on calculations of the accumulation rate during the last decades. In 1987 Austfonna was drilled to bedrock (566 m) by a group from the former USSR (Tarussov, 1992).

In our previous work with the new Lomonosovfonna ice core we have been able to show that it correlates with other local climatic parameters such as air temperature, sea ice and sea-surface temperature (SST), on a multiyear basis (O'Dwyer *et al.*, 2000; Isaksson *et al.*, 2001) since 1920. In addition, Pohjola *et al.* (2002a) have shown that the isotopic composition seems to have undergone relatively little reorganization resulting from percolation of meltwater during the period 1920–1997. It is therefore reasonable to expect that the ice-core record is even less affected by percolating meltwater prior to 1920 and that the $\delta^{18}$O record is a reliable climatic indicator given the colder temperatures of the nineteenth century.

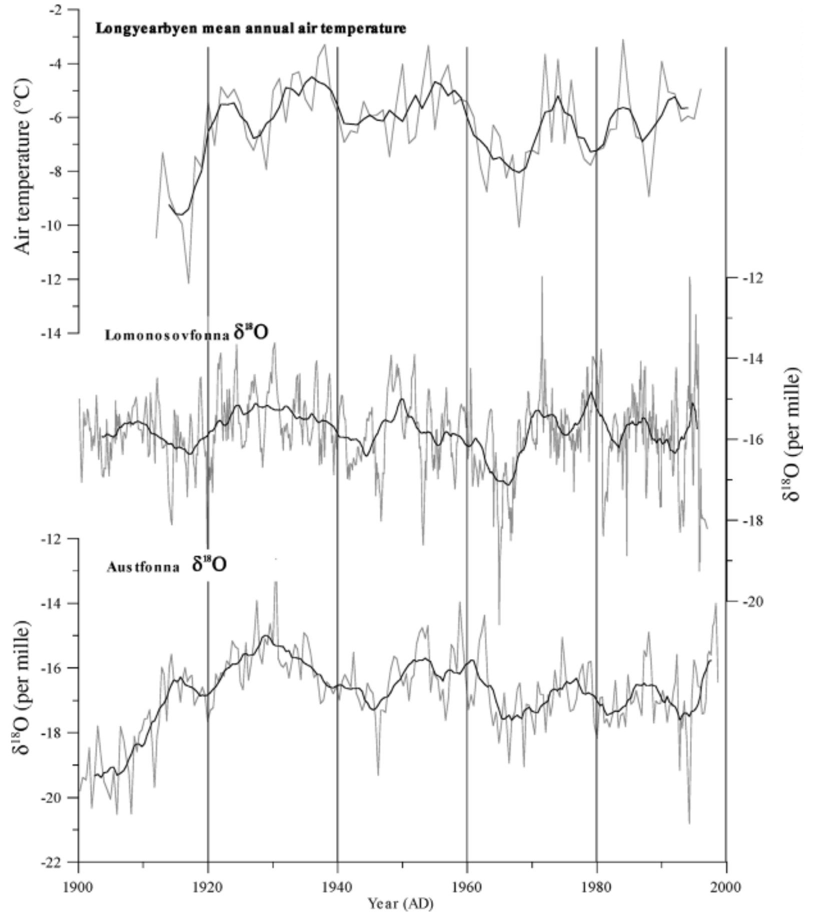

**Figure 2** The $\delta^{18}$O records from Lomonosovfonna and Austfonna from the twentieth century are compared with the mean annual temperature records from Longyearbyen (Nordli *et al.*, 1996). The grey line is the unsmoothed data and the black line the running mean for an equivalent of 5 years (from Isaksson *et al.*, 2003)

## Materials and methods

### The Lomonosovfonna ice core

In April 1997, a 121-m-deep ice core was retrieved from Lomonosovfonna, the highest ice field at Spitsbergen (1250 m a.s.l.) (Figure 1, Table 1). Radar measurements at the core site suggest that the ice core nearly reached the bottom. Dating with a glaciological flow model (Nye, 1963), using the 1963 $^{137}$Cs peak (Pinglot *et al.*, 1999) and the Laki 1783 eruption as reference horizons, suggests that the core contains at least 800 years of climate and environmental information (Kekonen *et al.*, 2002).

The ice core was subsampled in 5-cm pieces to detect seasonal signals for the best possible dating. Such high-resolution analysis has not previously been performed on Svalbard ice cores. Our analysis involves the most common species, such as $Na^+$, $K^+$, $Mg^{2+}$, $Ca^{2+}$, $Cl^-$, $NO_3^-$, $SO_4^{2-}$, $NH_4^+$, $CH_3SO_3^-$, acidity ($H^+$), $\delta^{18}$O, and δD. More details on the analytical methods can be found in Jauhiainen *et al.* (1999) and Isaksson *et al.* (2001). The chemical analysis suggests that annual or pseudo-annual signals are preserved, permitting the development of an annual timescale back to 1920 using ions (Isaksson *et al.*, 2001) and to the early eighteenth century using $\delta^{18}$O (Pohjola *et al.*, 2002b). The melt index (Koerner, 1997) in this core was on average 41% (Pohjola *et al.*, 2002a).

### The Austfonna ice core

During the spring of 1999 a 289-m-deep core was drilled on the summit of Austfonna, 750 m a.s.l. (Motoyama *et al.*, 2001) (Figure 1, Table 1). At the present time, the 1999 Austfonna ice core has been analysed in 25-cm sections (equivalent to between 1 and 10 years for the uppermost and lowermost core parts, respectively) for the same chemical components as the Lomonosovfonna core, and has been dated to about AD 1200 using the Nye model. The average melt index for Austfonna has been estimated at 67% (Watanabe *et al.*, 2001).

### Statistical analysis

To evaluate the significant trends and cycles in the $\delta^{18}$O data we use the statistical tool Significant Zero Crossings of Derivatives (SiZer) (Chaudhuri and Marron, 1999; Godtliebsen *et al.*, 2003) on the unsmoothed data. SiZer is a graphical tool used to decide quantatively if the slope of the dervative is statistically significant at a given smoothness, therebye

**Table 1** Ice core site information

| | Latitude N | Longitude E | Altitude (m a.s.l.) | Accumulation since 1963 (m w eq/a) | Drill year | Drill depth (m) |
|---|---|---|---|---|---|---|
| Lomonosovfonna | 78° 51′ | 17° 25′ | 1250 | 0.36 | 1997 | 121 |
| Austfonna | 79° 50′ | 24° 01′ | 750 | 0.45 | 1999 | 289 |

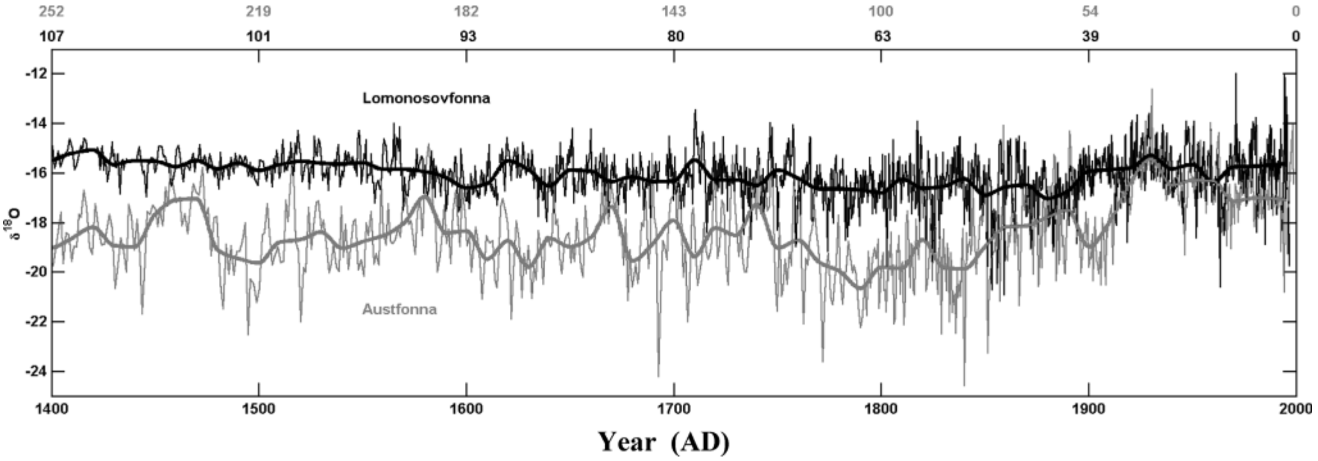

**Figure 3** The last 600 years of the $\delta^{18}O$ records from Lomonosovfonna (black) and Austfonna (grey) on the applied timescales derived from the Nye model. The thin lines are equivalent to the annual average and the thick lines are a decadal smoothing

allowing one to pick out variations that may be attributable to an underlying structure in the data set, as opposed to noise or sampling variability (Godtliebsen *et al.*, 2003). In SiZer, significant features are found at different scales, e.g., at different levels of data smoothing. Colour-coding is used to visualize statistical significance of the data trends at various smoothing timescales. This is controlled by the size of the smoothing window (bandwidth *h*) and location (*x*) for the signal. For each scale and location of signal, SiZer tests whether the smoothing has a derivative significantly different from zero.

## Results and discussion

### Temporal variability in the $\delta^{18}O$ records

The $\delta^{18}O$ records from both Lomonosovfonna and Austfonna ice cores suggest that the twentieth century was the warmest century, at least during the past 600 years (Figure 3). This overall warming is also seen in the ice-core borehole temperature profile from Lomonosovfonna (van de Wal *et al.*, 2002). The overall picture suggested from the SiZer analysis of the $\delta^{18}O$ records shows that there is a significant cooling trend on Svalbard from about AD 1500 to the end of the 1800s, followed by a warming thereafter (Figure 4a and b). The most negative $\delta^{18}O$ values, i.e., the coldest local temperatures, appear to have been between about 1760 and 1900. This cold period is somewhat more prounounced and longer in the Austfonna record, where it lasts from between about 1750 and 1840. In particular, the years around the eruption of Laki in 1783 seem to have been cold, something that is also suggested from reconstructed sea-ice record from Svalbard (Vinje, 1999). Both $\delta^{18}O$ records indicate a warmer period in the eighteenth century, which also is in line with Vinje's (1999) historical sea-ice compilation. For example, ship records show that during this time period, Whalers Bay north of Svalbard was open (Figure 5).

The strong warming at the beginning of the 1900s is the dominant feature in both ice-core records (Figure 4), which is not surprising judging from the strong impact it had on instrumental records from the Arctic (Bengtsson *et al.*, 2004). As has been pointed out in our previous work (Isaksson *et al.*, 2001) a comparison with the instrumental air-temperature record from Longyearbyen suggest that the $\delta^{18}O$ records are related to temperature on a multiyear basis (Figure 2). We assume that Austfonna is largely affected by the same weather patterns as central coastal Spitsbergen, as has been observed during a four-month stay on Austfonna during the USSR drilling there in 1985 (Arkhipov *et al.*, 1987). It thus 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 per degree of latitude during the winter months (Hisdal, 1998). It is likely that the altitudinal effect, which has been estimated to 0.1‰/100 m (Pohjola *et al.*, 2002a) is compensating for the approximately 500 m altitude difference between the two sites.

In addition to the warming trend already discussed the $\delta^{18}O$ data from the two ice cores are similar in trends and amplitude over most of the twentieth century (Figure 2). Prior to 1920, however, the Austfonna $\delta^{18}O$ record exhibits more negative $\delta^{18}O$ values than does Lomonosovfonna (Figures 3 and 4). The very pronounced increase in the Svalbard instrumental air-temperature record around 1920 (Figure 2) is clearly significant on the SiZer analysis in both ice-cores (Figure 4 a and b), but the amplitude of the increase is more prounounced in the Austfonna record.

The cause of the early twentieth-century warming is still under debate. Model work has indicated that atmospheric circulation changes alone cannot explain the whole change (Hanssen-Bauer and Førland, 1998). Sea-ice variability has been suggested as another possible cause (Benestad *et al.*, 2002). Based on newly digitized daily meterological records it was suggested recently that an increase in cloud cover can explain two-thirds of the warming in the Longyearbyen instrumental record (Nordli and Kohler, 2003).

There are intermittent decadal-scale periods throughout the record with similar $\delta^{18}O$ values in the two cores. In general, the two $\delta^{18}O$ records show higher correspondence in the 1900s than in the 1800s. There are several possible explanations involving differences in seasonality, effect of wind scouring of the winter snow of the precipitation (e.g., Fisher *et al.*, 1983) to why there are periods with more pronounced differences between the two $\delta^{18}O$ ice cores. A very likely explanation would be the variability of the strength of the inversion layer. A comparison of instrumental data from Isfjord Radio situated at sea level with expedition data from different elevations during the cold phase 1912–1918 revealed that the higher-elevation sites do not record such low temperatures as the Isfjord Radio station (Nordli and Kohler, 2003) and that cold temperatures prior to 1920 are due largely to an increased occurrence of inversion layers. The altitude of the ice-core site on Lomonosovfonna suggests that it is positioned above the temperature inversion (Bruemmer, 2004) and that the site

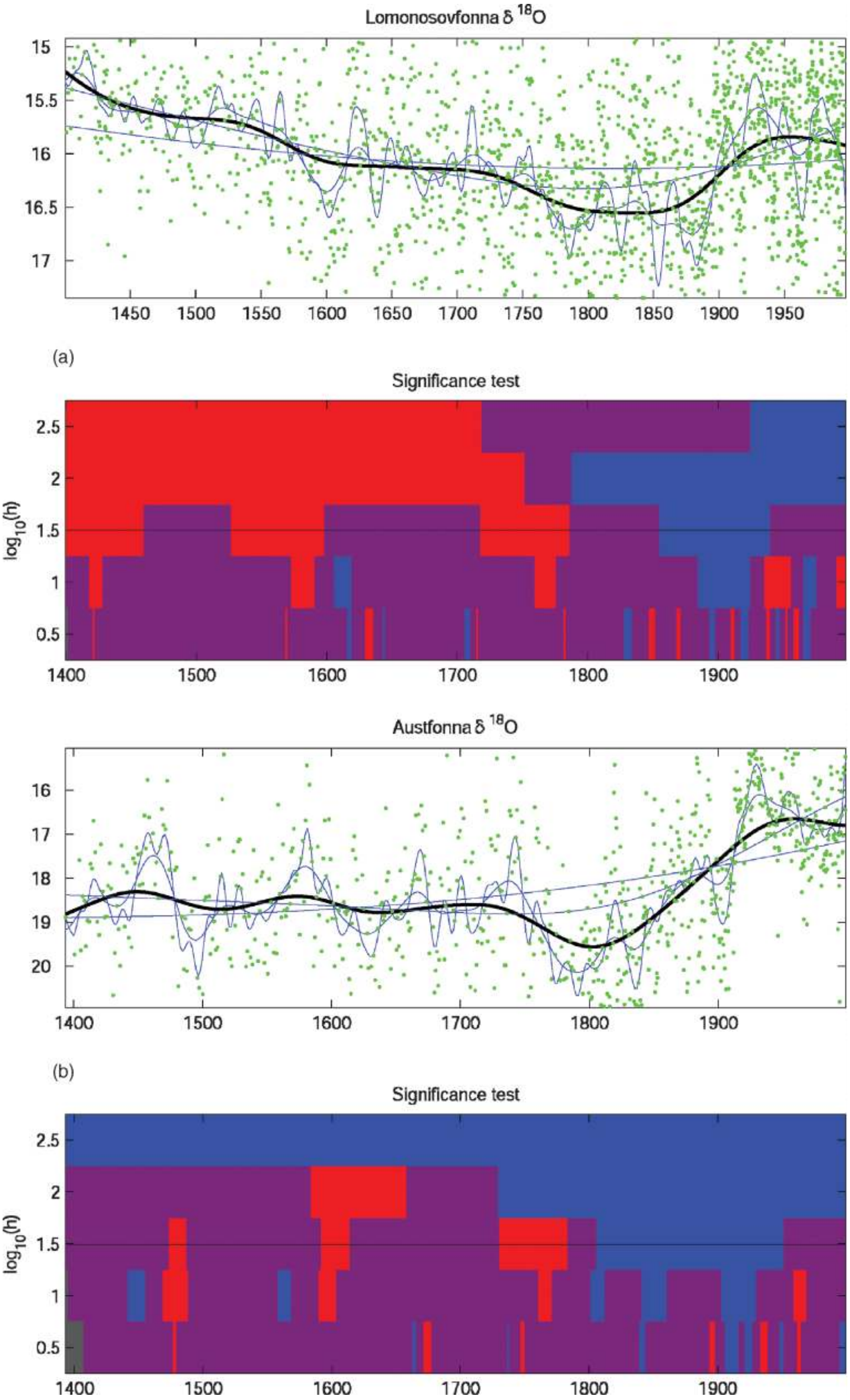

**Figure 4** SiZer analysis of the Lomonovfonna (a) and Austfonna (b) $\delta^{18}$O records from AD 1400. Upper panel: dots, $\delta^{18}$O samples; lines, family of smoothings obtained for various versions of the bandwidth (*h*). Lower panel: SiZer significance test at 95% confidence level. Colour coding is purple, no significant trend; blue, significant increase; red, significant decrease. The Lomonosovfonna record (a) indicates a long-term cooling between AD 1400 and 1780 and then a warming from about AD 1800 to present while the Austfonna record (b) suggests a long-term warming over the whole period. See text for a more complete discussion around this analysis

therefore does not record the coldest winter temperatures. We can assume that during periods with sea-ice cover in the winter the inversion layer will be more pronounced than when the water is open and the heat exchange weakens the temperature inversion. A sea-ice link is supported by decadal-scale similarities between the $\delta^{18}$O record from Austfonna and the August sea-ice record from Barents Sea over the period 1600 to present (Figure 6).

To explore further the possible link between sea ice and the Austfonna $\delta^{18}$O record we compare the smoothed 5-year

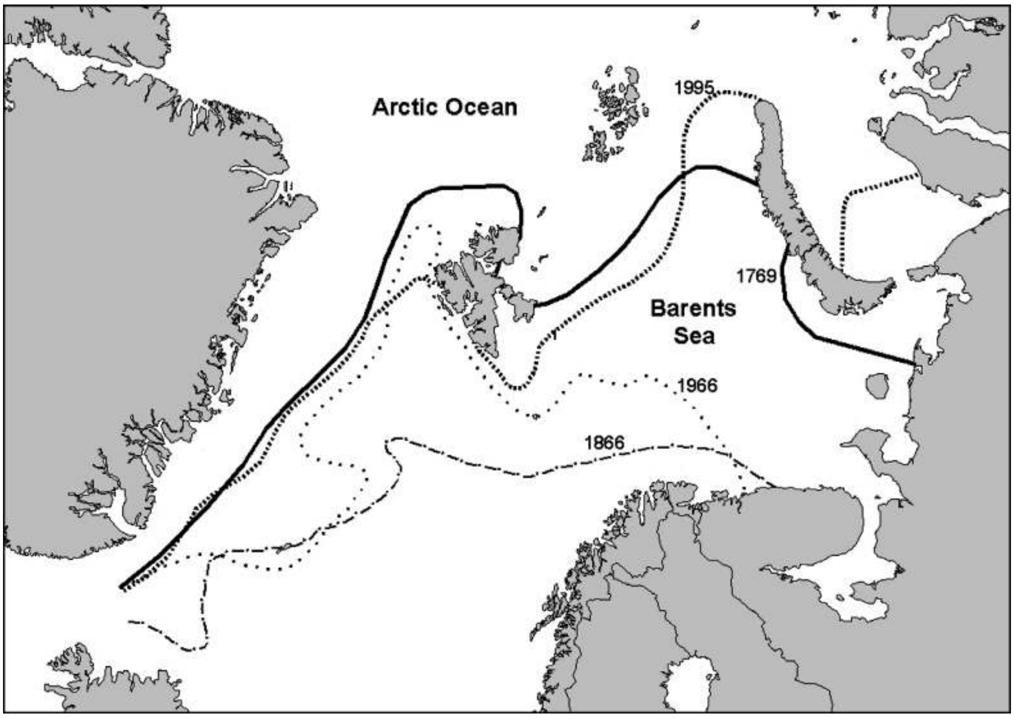

**Figure 5** Sea-ice edge location from some of the extreme years around Svalbard illustrating the large variability. Years with extreme April ice-edge locations were 1866 (maximum) and 1995 (minimum). The sea-ice edge for August 1769 is shows as an example of a year when Whalers Bay north of Svalbard was open. The 1966 ice edge illustrates an extreme April southerly position during the twentieth century (the map is modified from Vinje, 1999)

running mean $\delta^{18}O$ records from the two ice-cores with available instrumental temperature records from nearby locations Longyearbyen, Bjørnøya, Jan Mayen and Vardø (Figure 1). We find the best correspondence between Austfonna $\delta^{18}O$ and Jan Mayen mean annual temperature ($R^2 = 0.55$; Table 2) (Figure 7). Jan Mayen is positioned in the area between Iceland and Svalbard and has a typical maritime climate with a relatively small difference in temperature between winter and summer (Førland *et al.*, 1997). The island is situated in an area that experiences a high frequency of low-pressures and the sea-ice edge is often positioned in this area (Gabrielsen *et al.*, 1997). Judging from the position of the meteorological station in Isfjorden it is possible that the Longyearbyen temperature record reflects a more local climate, which is strongly linked to the sea-ice conditions in Isfjorden and therefore gives a relatively poor correlation with the ice-core records. In a recent study using temperature records from the Arctic and gridded sea-ice data, a strong link was found between the local climate in Svalbard and the ice-edge location (Benestad *et al.*, 2002). This connection was particularly strong after 1950, during which time the quality of the sea-ice data is good. The explanation for the lack of correspondence between these temperature records and the Lomonosovfonna $\delta^{18}O$ record might possibly lie in the higher elevation of this ice-core site, or that the snow was derived from a more distant source, which may have been less affected by the more severe sea-ice conditions that prevailed prior to the 1900s (Vinje, 1999) (Figures 5, 6). The best correlation for the Lomonosovfonna record is with Vardø (Table 2). The homogenized Vardø (Figure 1) monthly temperature record extends back to 1840 (Polyakov *et al.*, 2003) and in a multiproxy extension study of the winter temperature record from Svalbard it was found that the changes infered from the Lomonosovfonna $\delta^{18}O$ winter record are in line with the instrumental winter temperature record from Vardø (Kohler *et al.*, unpublished).

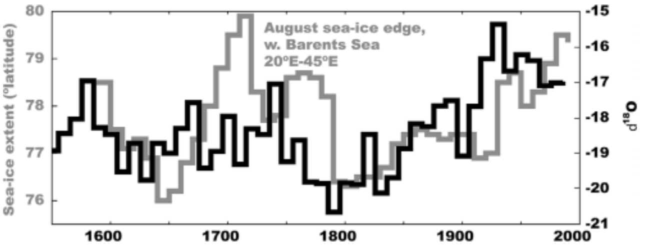

**Figure 6** The decadal-scale Austfonna $\delta^{18}O$ record (black) corresponds well to the August sea-ice record (grey) from western Barents Sea, compiled with data from whaling ships (Vinje, 2001). This suggests that $\delta^{18}O$ in the precipitation is directly influenced by distance from moisture source in the Austfonna ice-core (from Isaksson *et al.*, 2003)

## Svalbard ice-core records in relation to Arctic climate variability

Prior to the recovery of our ice cores, information on Svalbard climate variability for the last 400 years has been limited to the stable isotope record from the 1976 Lomonosovfonna ice core, where there appeared to be two pronounced cold periods, 1200–1500 and 1700–1900 (Gordiyenko *et al.*, 1981). Based on sediment cores from the proglacial lake Linnevatnet, Svendsen and Mangerud (1997) concluded that the Holocene glacial maximum occurred during the LIA with the begining of a major advance in the fourteenth and fifteenth centuries, culminating in the nineteenth century.

Several ice-cores from the Russian Arctic have been drilled but the cores drilled during the Soviet time period are poorly dated (Koerner, 1997) and data from more recent cores are currently not published to their full extent (e.g., Fritzsche *et al.*, 2002). Marine sediment core data from outside Franz Josef Land suggest that glaciers advanced during the past 1000 years and retreated after 1900, which on that scale is in agreement with the glacial history in Svalbard (e.g., Lubinski *et al.*, 1999).

**Table 2** Correlation coefficients between the $\delta^{18}O$ records from Lomonosovfonna and Austfonna and the instrumental temperature records from Longyearbyen, Jan Mayen, Bjørnøya and Vardø

| 5-yr mean $\delta^{18}O$ | 5-yr mean $T$ | $r^2$ | $F$ | $p$ |
|---|---|---|---|---|
| Austfonna | Longyearbyen | 0.13 | 2.02 | 0.18 |
| | Jan-Mayen | 0.57 | 15.76 | 0.00 |
| | Bjørnøya | 0.17 | 2.38 | 0.15 |
| | Vardø | 0.46 | 23.71 | 0.00 |
| Lomonosovfonna | Longyearbyen | 0.15 | 2.40 | 0.14 |
| | Jan-Mayen | 0.06 | 0.83 | 0.38 |
| | Bjørnøya | 0.04 | 0.50 | 0.49 |
| | Vardø | 0.31 | 12.50 | 0.00 |

There has been much discussion around the lack of a pronounced LIA signal in the stable isotope records from central Greenland ice cores (e.g., Barlow, 2001 and references therein), while in northern Greenland the stable isotope records for the past 500 years suggest a distinct climate cooling (Fischer *et al.*, 1998). In northern Greenland on Hans Tausen Iskappe the period between AD 1700 and 1900 appears to have been the coldest during the last 2000 years (Hammer *et al.*, 2001).

In general, the available climate-proxy data from the Arctic do not provide a coherent picture of annual climate variability through the last several hundred years (e.g., Overpeck *et al.*, 1997). The general pattern suggesting cold periods during the mid-seventeenth century and mid-nineteenth century, warm periods during the mid-sixteenth century and late eighteenth century, and then the abrupt warming to the twentieth century is in agreement with what the Svalbard ice-core records suggest.

In summary, it is evident there there are many large-scale similarities between the climate records but the lack of well-dated high-resolution palaeorecords is still a determining factor for understanding climate variability in the Arctic.

## Conclusions

Using two ice-core records from different parts of Svalbard we have been able to investigate some of the determining factors for the $\delta^{18}O$ content in Svalbard snow and ice. This suggests that the $\delta^{18}O$ record from the low-altitude Austfonna ice core is influenced by sea ice and may therefore be a good proxy for sea-ice variability back in time. The fact that the higher elevation Lomonsovfonna ice core indicates less severe temperatures during cold periods suggests that the sea ice in the Barents Sea has been extensive and that the moisture transport to the Austfonna ice cap was affected, while Lomonosovfonna samples moisture from a much wider area. High-resolution atmospheric modelling might be used to test this hypothesis. This study shows that Svalbard ice cores can provide important information on both local and regional climate variability in the Arctic, despite their relatively low altitude and periodic melt.

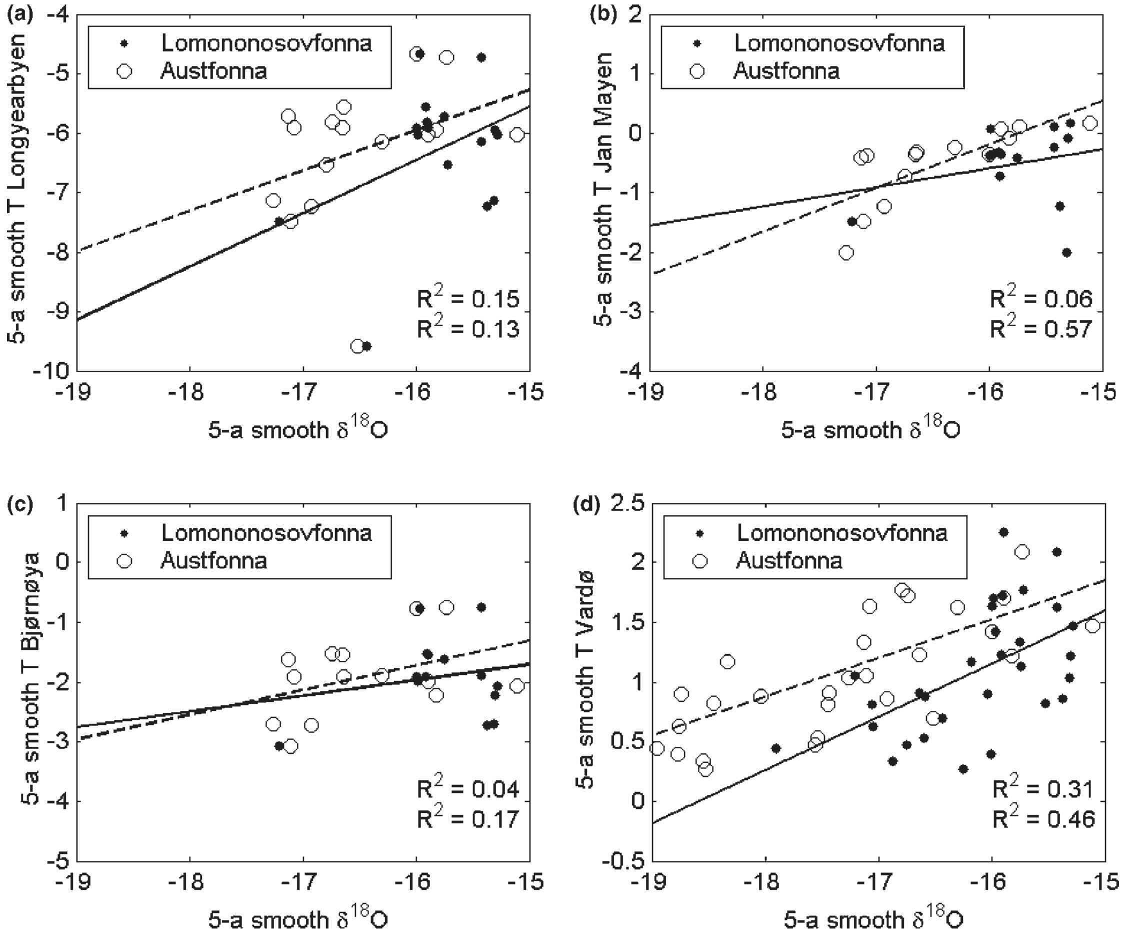

**Figure 7** Linear relationships between the $\delta^{18}O$ records and the mean annual temperature from (a) Longyearbyen, (b) Jan Mayen, (c) Bjørnøya and (d) Vardø. All records have been smoothed with a 5-year running mean filter and the best relation is between Austfonna and Jan Mayen. The correlation coefficients are listed in Table 2

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