CLIMATE OSCILLATIONS AS RECORDED IN SVALBARD ICE CORE δ^{18}O RECORDS BETWEEN AD 1200 AND 1997

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ABSTRACT. We apply two different time series analytical tools to δ^{18}O records from two Svalbard ice cores. One ice core is from Lomonosovfonna at 1250 m a.s.l. and the other from Austfonna at 750 m a.s.l. These cores are estimated to cover at least the past 800 years and have been dated using a combination of known reference horizons and glacial modelling. Wavelet analysis reveals low frequency oscillations on the 60–120-year scale on the lower elevation site Austfonna while the higher altitude site on Lomonosovfonna does not reveal such variability throughout the record. The second method, **Significant Zero Crossing of Derivates (SiZer)** does not resolve the low-frequency periodicity seen in the wavelet analysis. The low-frequency variability resolved by the wavelet analysis is similar to what has been found in various climate records including instrumental temperatures and tree-rings, and has been proposed as the most important oscillation for the observed trends in Arctic air temperatures.

Key words: Ice cores, Svalbard, climate change, oxygen isotopes

Introduction

Evidence for ongoing changes in the Arctic climate has been accumulating during the last decade, particularly with regards to sea ice and permafrost (e.g. Johannessen *et al.* 1999; Osterkamp and Romanovsky 1999). However, since Arctic climate and climate proxy records are relatively short, it is difficult to assess just how significant these changes are in a longer time perspective. Different proxy records thus become an important source of information about environmental changes over the last few hundreds of years (*e.g.* Overpeck *et al.* 1997). Naturally, decadal-scale variability such as the **North Atlantic Oscillation** (**NAO**) (Hurrell 1995) and the **Arctic Oscillation** (**AO**) (Thompson and Wallace 1998) has been the focus in the most recent past. Using a combination of observational data and modelling results, Polyakov and Johnson (2000) suggest that the decadal AO acting in concert with a multi-decadal **low-frequency oscillation** (**LFO**), on a time scale of 60–80 years, drive large amplitude natural variability in both the ocean and atmosphere in the Arctic. In a more recent study based on a number of instrumental temperature records from the Arctic, Polyakov *et al.*

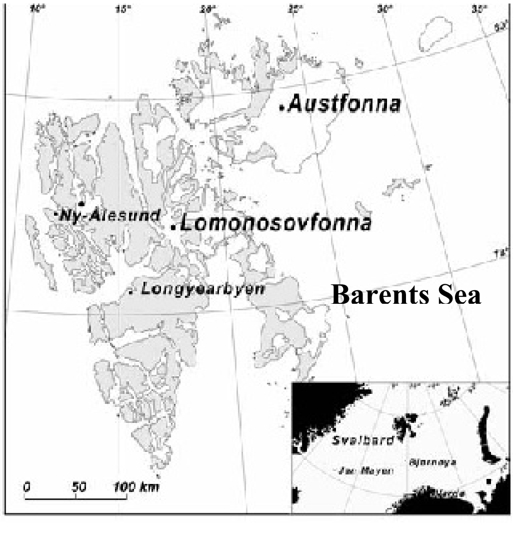

Fig. 1. Map of Svalbard showing the Lomonosovfonna and Austfonna ice core positions.

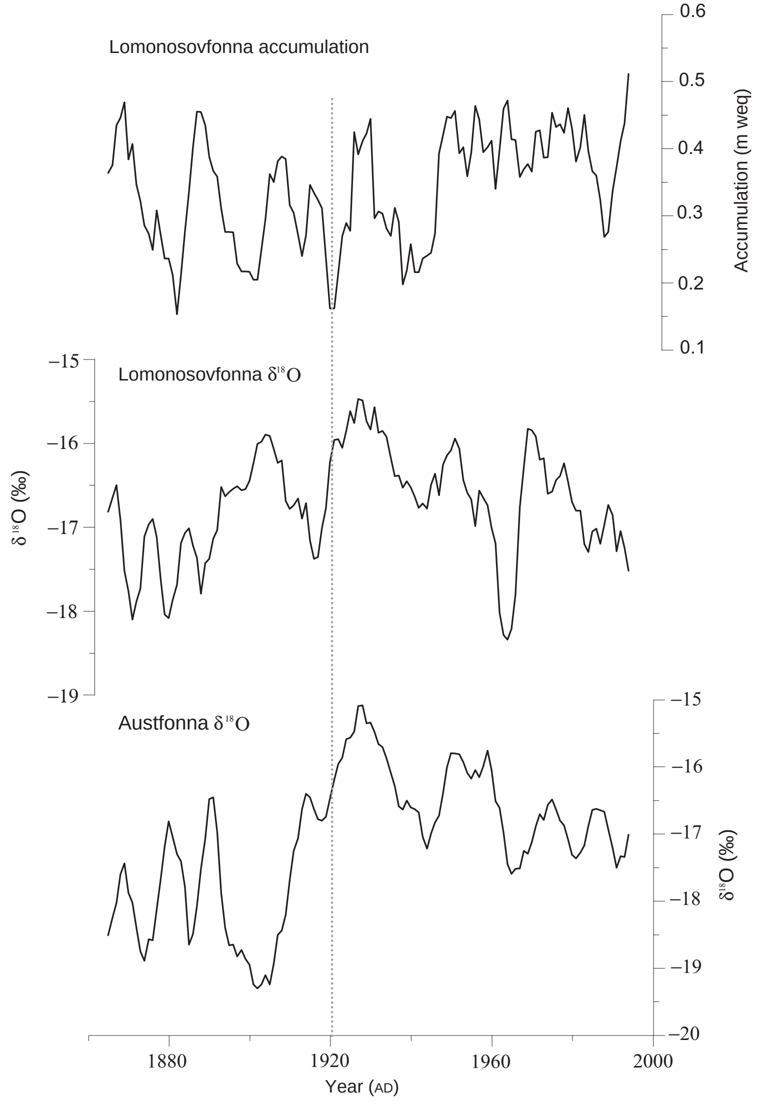

Fig. 2. The Lomonosovfonna accumulation record, the Lomonosovfonna and Austfonna $\delta^{18}O$ records, the Longyearbyen (grey) and Vardø (black) temperature records, the reconstructed winter NAO, and the sea ice area records from Nordic seas (Vinje 2001). All records are 5-year means for the period 1864–1997. The stippled line is marking the time around 1920 when temperature increased rapidly in Svalbard. The correlation coefficients are shown in Table 1

(2003a) suggest that multi-decadal LFO changes are the most important for observed trends in Arctic air temperature and sea level pressure.

For Arctic climatic studies the Svalbard archipelago is in an unusual geographical position, both from atmospheric and oceanographic perspectives. Svalbard has an extension of the North Atlantic Current to the west, the Barents Sea to the east and the Arctic Ocean to the north (Fig. 1), each with their respective specific oceanographic conditions (*e.g.* Loeng 1991). In addition, the climate is modulated atmospherically by alternating high pressure cold-air systems from the northeast and low pressure warm-air systems from the south-west (*e.g.* Hisdal 1998).

The temperature record from Svalbard starts in 1911, and is one of the longest instrumental records from the Arctic. A homogenized record was created by combining several records from different locations in the vicinity of Longyearbyen at Isfjorden (Fig. 1) (Nordli *et al.* 1996). After a temperature

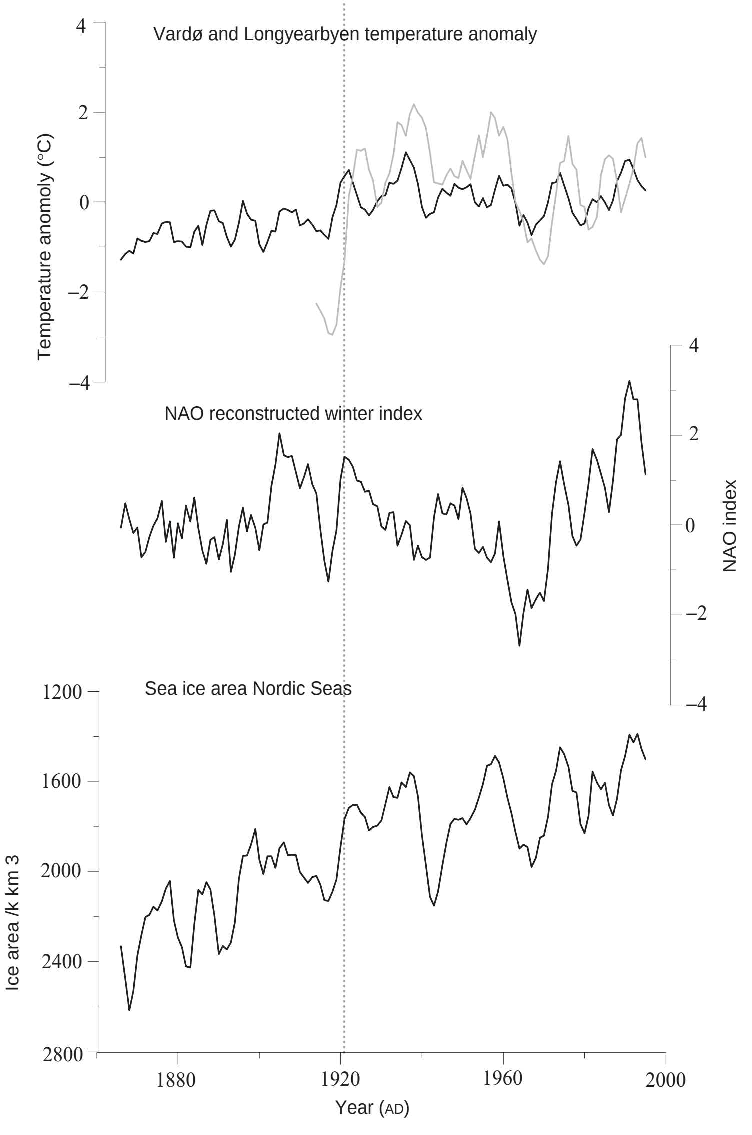

Fig. 2. Continued

minimum in 1917 there is an abrupt temperature increase starting a warm period, which lasted up to the late 1930s (Fig. 2). After a cooler period that culminated in the late 1960s there has been a significant increase in temperature, but Svalbard is still somewhat colder than it was in the 1930s. There is no significant trend for the entire instrumental record, but there are significant trends on decadal scales (Hanssen-Bauer and Førland 1998). In addition, precipitation has increased during the instrumental period by about 25% (Førland *et al.* 1997). Some of the precipitation increase is associated with warmer air temperatures and thus more effective rain-gauge catch; the remainder has been attributed to changes in the atmospheric circulation (Hanssen-Bauer and Førland 1998). Precipitation rates vary regionally around the archipelago, but the general picture is that most precipitation is brought by easterly winds, therefore leading to a marked east–west gradient (Hisdal 1998).

Ice core records from Svalbard

Since the 1970s a number of ice cores have been drilled on the many glaciers and ice caps in Svalbard; however, most of these ice core records either cover short time periods or have time gaps created by negative balances at the drill sites during past warm periods. Russian groups drilled seven cores in central Spitsbergen between 1975 and 1987. The deepest core was 566 m and drilled to the bedrock on Austfonna in 1987 (Tarussov 1992). An extensive review of the Soviet ice cores is given by Kotlyakov *et al.* (2004). Between 1987 and 1999 Japanese scientists drilled several medium long cores in northwestern Spitsbergen, Vestfonna and Austfonna (*e.g.* Watanabe *et al.* 2001).

Unfortunately proper dating of the early deep Svalbard ice cores has been hampered by a combination of melting producing ice layers, coarse sampling, and limited analysis of chemical species (e.g. Koerner 1997). As a result Svalbard ice cores records have not been fully utilized for climatic reconstruction. However, two of the most recently drilled Svalbard ice cores from Lomonosovfonna (Isaksson *et al.* 2001) and Austfonna (Watanabe *et al.* 2001) have demonstrated that with proper site selection, high-resolution sampling, and multiple chemical analyses (*e.g.* Isaksson *et al.* 2001; Pohjola *et al.* 2002a,b), it is possible to recover ice cores in which even annual signals are preserved. These two recent Svalbard ice cores have been dated to cover at least the past 800 years (Kekonen *et al.* 2002; Watanabe *et al.* 2001).

In our previous work comparing the Lomonosovfonna and Austfonna δ^{18}O records to instrumental records, we found that the overall pattern in the δ^{18}O records is similar to the Longyearbyen air temperature record (Isaksson *et al.* 2005), as well as to the Vardø temperature record from northern Norway between 1840 and 1997 (Kohler *et al.* in prep.). The use of annual data results in low correlation coefficients, which is not surprising considering that even a 1-year core-dating error confounds simple regression, and that there exists a complex transfer function relating surface air temperatures and δ^{18}O deposition in snow (e.g. Dansgaard 1964). Regressions using 5-year block averaging, which reduces the effect of dating errors, yields statistically significant relations, and leads us to conclude that δ^{18}O is a valid temperature proxy for Svalbard, despite the complications induced by melting. The melt index in these two ice core (see next section) suggests that melt does not penetrate more than about 5 years. The ample evidence that the 1900s were the warmest century of the past 600 years, suggests that the older parts of the ice core records should be less disturbed by melting and that the climate records from this time period have even better preserved information than the recent time period. In this paper we will assess both the oxygen isotope data and the accumulation records from the Lomonosovfonna and the 1999 Austfonna ice cores with the focus on possible links to large-scale climate variability for the period AD 1200–1997.

Data and analysis

Lomonosovfonna

This 121 m deep ice core was drilled at the summit of the ice field at 1250 m a.s.l in the spring of 1997. The total ice depth at the drill site was estimated to be just a few metres more than the ice core length. The core was sampled for δ^{18}O with 5 cm resolution (Isaksson *et al.* 2001). The core is dated (Kekonen *et al.* 2002) using the well-known Nye (1963) relation, constrained by depths of the radioactivity peaks found in the core, which appear in 1964/65 and 1954 (Pinglot *et al.* 1999), and the 1783 Laki volcanic eruption. The melt index (Koerner 1997) in this core was on average 41% (Pohjola *et al.* 2002a). The annual accumulation rate at the core site is about 36 cm **water equivalent** (**w.e.**). The oxygen isotope stratigraphy has also been used to count summer peaks back to 1715, thus providing an annual time scale for this time period (Pohjola *et al.* 2002b), and providing a means to estimate the dating error, roughly ±5 years down to the Laki reference horizon. In this paper we use the modelled time scale since the emphasis is on the long time scale. The oxygen isotope record from this ice core has previously been discussed by Isaksson *et al.* (2001, 2003, 2005).

Austfonna

During the spring of 1999 a 289 m deep core was drilled on the summit of Austfonna 750 m a.s.l, where the total ice depth is about 600 m (Motoyama *et al.* 2001) (Fig. 1). This core has been analysed in 25 cm sections (equivalent to to one and ten years for the uppermost and lowermost core parts respectively) and has been dated to about AD 1200 (Watanabe *et al.* 2001) using the Nye relation. The average melt index for Austfonna has been estimated to be 67% (Watanabe *et al.* 2001). The annual accumulation

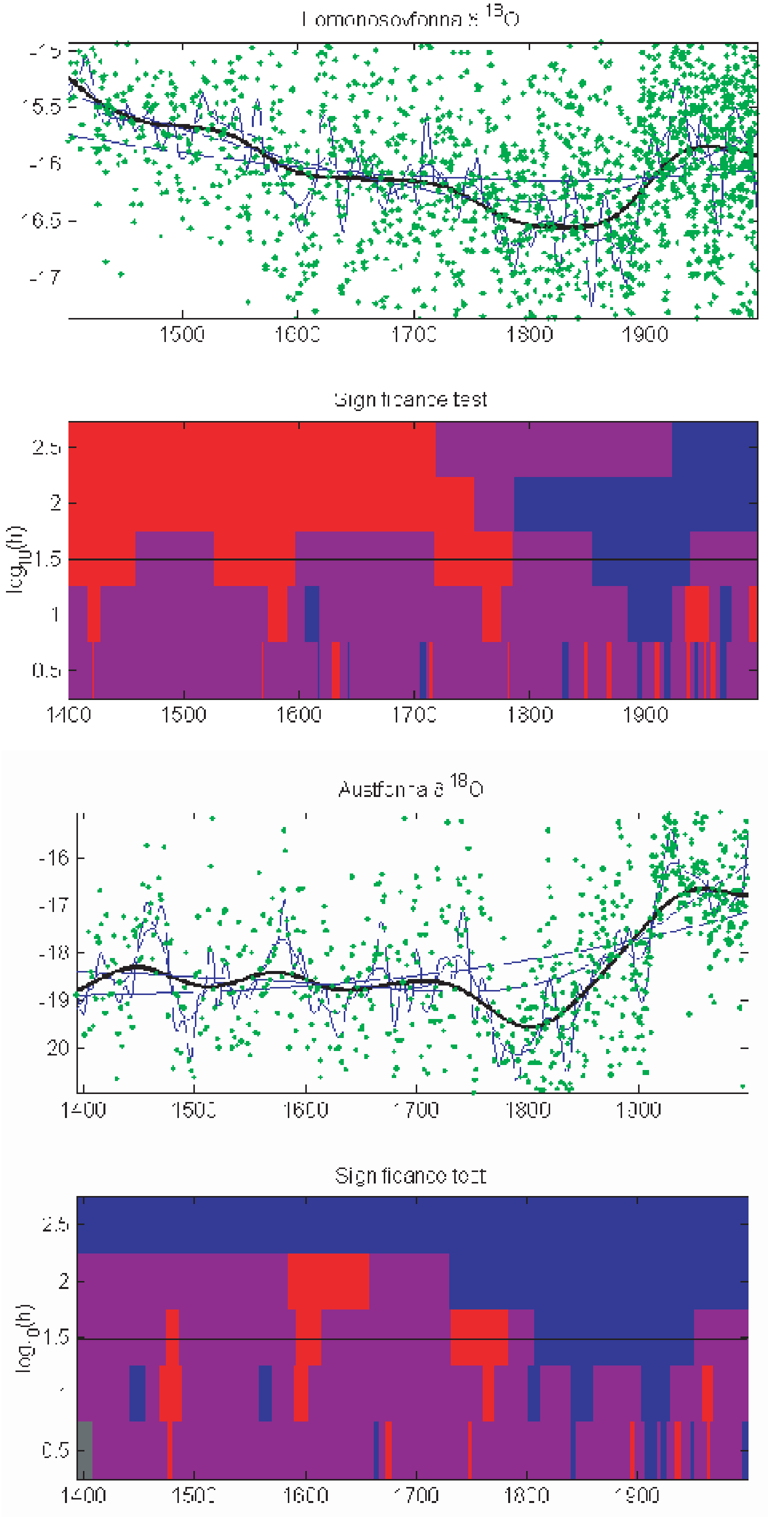

Fig. 3. SiZer analysis of Lomonosovfonna and Austfonna $\delta^{18}O$ records for AD 1400–2000 (modified from Isaksson *et al.* 2005). Upper panels: dots, $\delta^{18}O$ samples; lines, family of smooths obtained for various versions of the bandwidth (h). Lower panels SiZer significance test at 95% confidence level. Colour coding: purple, no significant trend; blue, significant increase; red, significant decrease

rate at the drill site has been estimated to about 40 cm w.e. The oxygen isotope record from this ice core has been discussed previously together with the Lomonosovfonna ice core (Isaksson *et al.* 2003, 2005).

Significant Zero Crossings of Derivatives (SiZer)

To evaluate the significance of trends and cycles in the $\delta^{18}O$ records, we use the statistical tool Significant Zero Crossings of Derivatives (SiZer) (Chaudhuri and Marron 1999; Godtliebsen *et al.* 2003). SiZer is a graphical tool which first smooths data at various time scales, and then quantitatively determines which parts of the smoothed features are statistically significant at a given threshold. In SiZer plots, colour-coding is used to visualize the statistical significance of the data trends at the various smoothing time scales. Significance is then a function of the threshold (in this case, $P = 0.05$), the size of the smoothing window (bandwidth h) and location (time) for the signal. For each scale and location of the signal, SiZer tests whether the smooth has a derivative significantly different from zero. SiZer essentially allows us to get away from the tedious fact that a regression-derived trend can change dramatically depending on which years are used, and to visually identify rapidly those parts of the record that do or do not have significant trends.

Wavelet

Decomposing a time-series into wavelets allows highlighting of the variability features at different time scales (Torrence and Compo 1998), and is essentially a tool to visualize the frequency content of a signal as it varies through time. The main purpose of our analysis is to investigate the variability in $\delta^{18}O$ records with a multi-decadal to centennial periodicity. We use a 'Mexican Hat' wavelet, a derivative of the Gaussian wavelet (Equation 1):

$$\psi(x) = \frac{2}{\pi^{\frac{1}{4}}\sqrt{3}} e^{-\frac{x^2}{2}} (1 - x^2) \qquad (1)$$

The wavelet power spectrum of a discrete sequence X_n (signal) is defined as:

$$W_n^2(s) \;=\; \sum_{n'=0}^{N-1} X_{n'} \psi^* \left[\frac{(n - n')\delta t}{s} \right] \qquad (2)$$

where δt is a time-increment in X_n, s is a scale which is related to a Fourier frequency and ψ^* is the complex conjugate of a shifted and rescaled version of the time-localized mother wavelet. The significance of the maximums in the decomposition was tested at 90% and 95% confidence levels against a red noise background (see Torrence and Compo (1998) for further details), assuming lag–1 autocorrelations $\alpha = 0.7$ and $\alpha = 0.5$ for Austfonna and Lomonosovfonna time-series, respectively.

Results and discussion

SiZer analysis of the $\delta^{18}O$ records shows a significant cooling trend on Svalbard from about AD 1500 to the end of the 1800s, followed by a rapid warming at the beginning of the 1900s (Fig. 3). The cooling trend is more evident in the Lomonsovfonna record while the Austfonna record seems to show more multi-decadal cyclic behaviour. In both records the most negative $\delta^{18}O$ values, *i.e.* the coldest local temperatures, appear between about 1760 and 1900. The $\delta^{18}O$ values at the location of the 1783 Laki eruption are some of the most negative during the last 600 years (Isaksson *et al.* 2005).

Previous work on the temporal variability of the Austfonna and Lomonosovfonna $\delta^{18}O$ records (Isaksson *et al.* 2003, 2005) showed that the $\delta^{18}O$ signals from the Lomonosovfonna and Austfonna ice cores are qualitatively similar over most of the 20th century, suggesting that they record the same atmospheric signal (Fig. 2). The behaviour diverges prior to 1920, with the Austfonna ice core showing much more negative $\delta^{18}O$ values than Lomonosovfonna on decadal to multi-decadal time scales. We propose that this is the result of a stronger winter inversion layer prior to the 1920s, which would have impacted the lower-altitude Austfonna site more than at Lomonosovfonna. This explanation is supported by recent analysis of newly digitized temperature data taken at different elevations in the inner Isfjorden area, which show that before 1917 the higher elevation sites did not record such low temperatures during the winter months as did the coastal station Isfjord radio (Nordli and Kohler 2003). Daily meteorological observations at Isfjord radio point towards an associated change in cloud cover during this period (Nordli and Kohler 2003).

To investigate further the variability in the $\delta^{18}O$ records we apply wavelet analysis to the time-series. Figure 4a and b show the wavelet power spectra normalized on the respective standard deviations for each time-series. The normalization gives

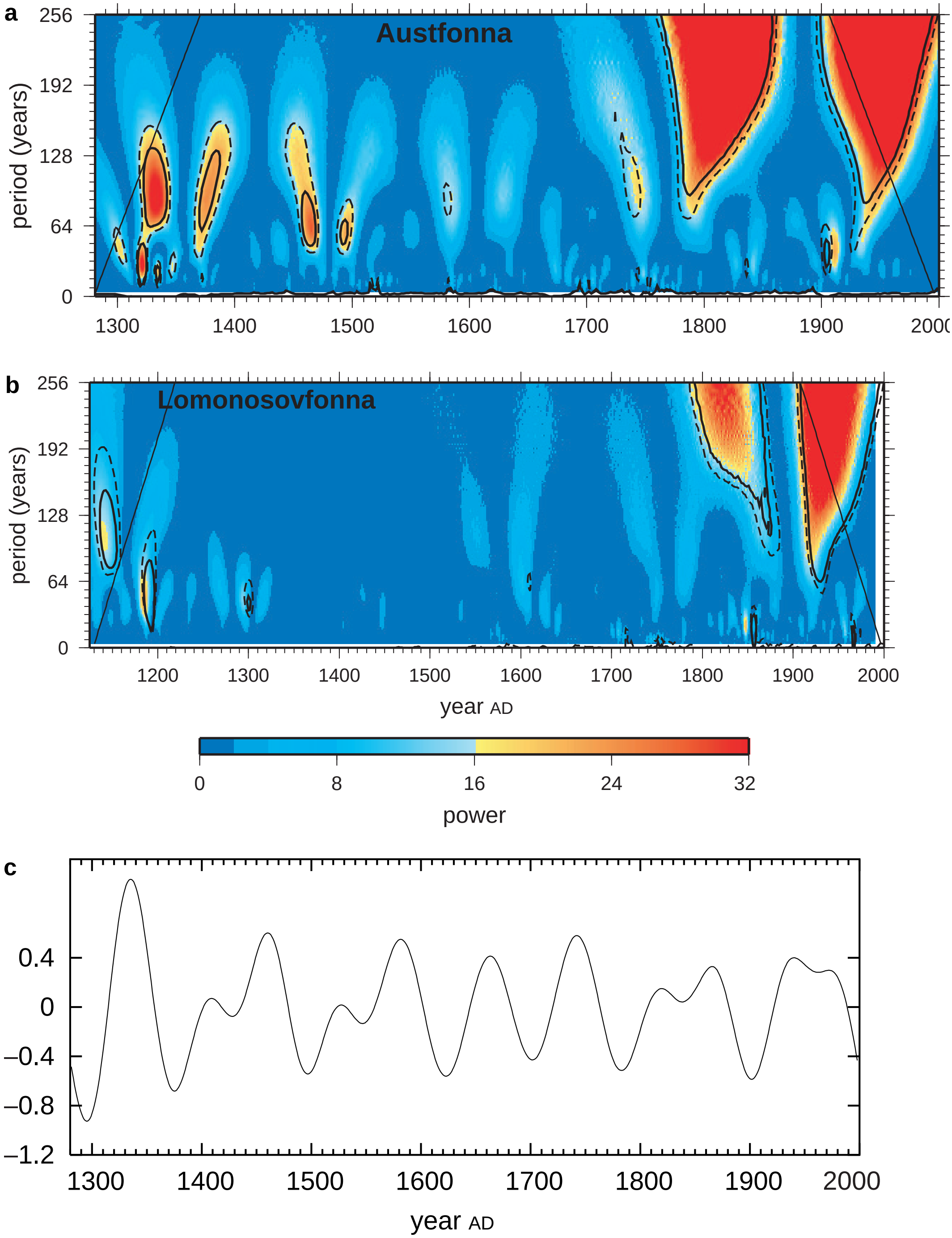

Fig. 4. The normalized wavelet power spectra for the δ^{18}O time-series from (a) Austfonna and (b) Lomonosovfonna. Thick and dashed contours enclose the regions where the wavelet power is above the red noise background with the 95% and 90% confidence levels, respectively. The cross-hatched areas indicate the 'cone of influence' where the edge effects due to zero padding become important (Torrence and Compo 1998). (c) Details at level 5 (scale 64 years) for the 6-level discrete wavelet transformation of the Austfonna time-series performed using the Db 8 wavelet (Daubechies 1990)

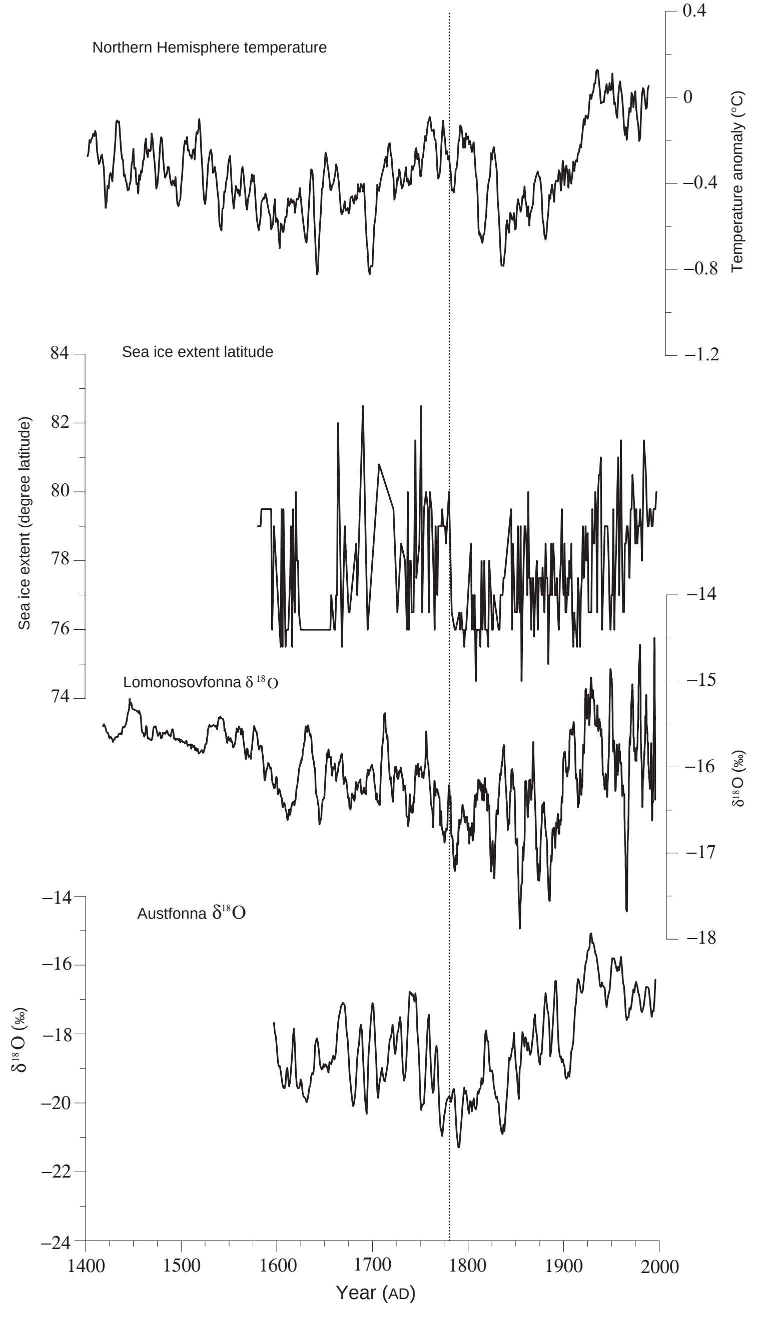

Fig. 5. The Northern Hemisphere air temperature anomaly record (Jones *et al*. 1998), the Barents Sea ice extent (Vinje 1999), and the $\delta^{18}O$ records from Lomonosovfonna and Austfonna. The data of the Laki eruption (1783) is marked with a stippled line for a time reference

a measure of the wavelet power relative to white noise background, thus simplifying the comparison of different spectra. Note that we use the same colour palette for both time-series. The Austfonna spectrum (Fig. 4a) demonstrates well-pronounced multi-decadal variability on time scales from *c*. 60 to *c*. 130 years, with little significant energy residing in finer scales. The statistically significant (at the 95% confidence level) maxima are observed around 1330, 1460, 1940 and respective minima

Table 1. Correlation coefficient matrix for Lomonosovfonna and Austfonna δ^{18}O, and Lomonosovfonna accumulation and different climate records. All data are 5-year means

Year 1866–1995	Sea ice	Sea ice W	Sea ice E	AO winter index	NAO winter index	Vardø annual mean *T*
Lomonosovfonna δ^{18}O	–0.40	–0.41	–0.32	–0.12	0.30	0.38
Lomonosovfonna acc.	–0.21	–0.28	–0.08	–0.06	–0.15	0.07
Austfonna δ^{18}O	–0.43	–0.51	–0.25	–0.14	–0.08	0.52

around 1380, 1490 and 1790. During the period from *c.* 1500 to *c.* 1780 this multi-decadal variability is somewhat attenuated, yielding maxima around 1580 and 1750, statistically significant at the 90% level. The variability on the scale longer than 64 years is also shown on Fig. 4b. The Lomonosovfonna record does not show this well-pronounced multi-decadal variability throughout the record (Fig. 4b). However, one can identify similar significant features having the same timing as in the Austfonna core. These features are maxima at around 1300, 1600 and 1950, and a minima in the first half of the 19th century.

A comparison of the wavelet analysis results with the SiZer output (Fig. 3) demonstrates a good agreement between the methods on a longer time scale (greater than 100 years). SiZer, however, does not resolve the 60–80-year periodicity seen in the wavelet analysis (Fig. 4). SiZer shows significant features for both Lomonosovfonna and Austfonna on decadal time scales, which are not seen in the wavelet decomposition. Given the fact that SiZer was designed for analysis of independent data and there are high values in the lagged autocorrelations for both time-series (Chaudhuri and Marron 1999), we suggest that these features are likely spurious. We note also a decreasing number of peaks on a finer time scale, as one goes further back in time. This is due to the uniform sampling size for the isotope analysis, which means each sample covers a progressively larger number of years as one progresses down-core. In the upper part of the core a typical time-increment in the isotope record is about 0.3 year, while there is only one value of δ^{18}O per two or three years on average in the bottom part of the core. However, this does not influence the results presented since our main goal is to determine multi-decadal periodicity.

After the Laki eruption in 1783, the low-frequency oscillations are superimposed onto a well-pronounced trend of increasing δ^{18}O (Fig. 3). These oscillations yield maxima in the 1820s, 1870s and 1940s (Fig. 4b). On longer time scales the oxygen isotope records qualitatively resemble the multi-decadal variability in sea ice extent in the Greenland and Barents seas over the last 250 years (Fig. 5). There are retreats of sea ice in the 1750s, 1800s, 1860s, 1920s–1940s and advances in the 1820s–1850s, 1890s and 1950s–1970s. The correlation coefficient between the isotope records and the April Barents Sea ice extent is between about –0.4 and –0.5 for the period 1864–1997, the period for which the sea ice data are of the best quality (Table 1). This is a relatively low value, but still significant, both statistically and when particularly considering the nature of these proxy records.

Low-frequency oscillations, similar to what we find in the Austfonna record, can be seen in the ice extent variability in the marginal Siberian seas (Polyakov *et al*. 2003b), and in the tree-ring-based reconstruction of the sea surface temperature variability in the central Atlantic (Grey *et al.* 2004). As mentioned, a dominating LFO at time scales of 60–80 years in Arctic temperatures has been suggested by Polyakov and Johnson (2000) and Polyakov *et al.* (2003a). North of 62° N two warm phases of the oscillation are known (1920 to mid-1950s, and from mid-1970s to present), and two cold phases (prior to 1920 and from mid-1950s to mid-1970s. It has been suggested that this mode of low-frequency oscillation is related to the thermohaline circulation in the North Atlantic (Delworth and Mann 2000), and the term 'Atlantic Multi-decadal Oscillation' (AMO) has been proposed (Kerr 2000). Grey *et al.* (2004) extended existing instrumental records of AMO, which start from 1856, as far back as AD 1567 using a compilation of tree-ring records. This composite record shows strong variability in the 60–100-year time band throughout the whole period from AD 1567, which is much in line with the variability in the δ^{18}O records from Austfonna. The longest pronounced negative anomaly in the tree-ring compiled record is from 1789 to

1848, which is also a long period with very negative values in both of the Svalbard δ^{18}O records following the Laki eruption. In addition to Laki, several other volcanoes such as Tambora in 1816/17 and Krakatau in 1883 had major eruptions during this time period that affected the global temperature negatively (for a review of the volcanic impact on temperature see Briffa *et al.* 2004).

The wavelet analysis does not show significant variability on decadal time scales. Nor do we find any significant correlation between the δ^{18}O records and either the NAO or the AO (Table 1). Vinje (2001) found a negative correlation between the maximum sea ice extent (April) and the winter index of NAO, and at least after 1960 Svalbard air temperature anomalies are related to the main atmospheric circulation which is directly associated with the NAO (Hanssen-Bauer and Førland 1998). A positive state of the AO index results in storms tracking further north, reaching into the Barents Sea. In addition it is also known that the inflow of warm Atlantic water to the Barents Sea is related to the AO (Dickson *et al.* 2000). In a study of the methanesulphonic acid (MSA) record between 1920 and 1997 from the Lomonosovfonna ice core it was suggested that the variability in this record could be linked to the import of warm Atlantic water to the Barents Sea (O'Dwyer *et al.* 2000), and thus to the AO.

An annual accumulation record from Lomonosovfonna has been compiled by Pohjola *et al.* (2002b), using seasonal cycles found in the δ^{18}O records down to 60 m (Fig. 2). Singular spectrum analysis (SSA) of these data suggests that accumulation has highly significant 2.1 and 21-year periodicities between 1715 and 1996 (Pohjola *et al.* 2000b). Our simple correlation analysis does not reveal any correspondence between accumulation with either temperature, sea ice, NAO or AO between 1866 and 1995 (Table 1).

Conclusions

Wavelet analysis has revealed low-frequency oscillations in the oxygen isotope records from two Svalbard ice cores. These cycles are about 60–120 years long and are significant throughout almost the whole time periods covered by the Austfonna ice core 1200–1999 and through part of the Lomonosovfonna ice core. The same cycle length is evident in other types of climate data and thus we conclude that despite the low altitude and summer melting, Svalbard ice cores can provide information on past climate variability. New techniques have made it possible to improve ice core analyses and dating possibilities and therefore it is of interest to obtain more cores from some of the previously drilled sites in the Arctic.

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