Little ice age clearly recorded in northern Greenland ice cores

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Abstract. Four ice cores drilled in the little investigated area of northern and northeastern Greenland were evaluated for their isotopic ($\delta^{18}O$) and chemical content. From these rather uniform records a stable isotope temperature time series covering the last 500 years has been deduced, which reveals distinct climate cooling during the 17th and the first half of the 19th century. Timing of the preindustrial temperature deviations agrees well with other northern hemisphere temperature reconstructions, however, their extent (~1 °C) significantly exceeds both continental records as well as previous southern and central Greenland ice core time series. A 20-30 % increase in the sea salt aerosol load during these periods supports accompanying circulation changes over the North Atlantic. Comparison with records of potential natural climate driving forces points to an important role of the long-term solar influence but to only episodically relevant cooling during years directly following major volcano eruptions.

Introduction

Detailed knowledge of natural temperature changes during the last centuries is most crucial to identify controlling climate forcing factors [Crowley et al., 1993, Lean et al, 1995] and, eventually, to assess the significance of an anthropogenic greenhouse warming. The scarcity of reliable long-term instrumental records calls for the use of sensitive temperature proxies to extend the time span covered. Isotopic ($\delta^{18}O$, δD) records from Greenland ice cores belong to the most reliable passive climate archives for the northern hemisphere providing high-resolution information on condensation temperature as well as on evaporation conditions in the water vapour source areas [Johnsen, 1989]. However, Little Ice Age (LIA) climate variations, found in many continental temperature proxies with considerable scatter in duration and extent [Briffa et al., 1990, Scuderi, 1993, Grove, 1988], appear only very subdued in central and southern Greenland ice cores [Dansgaard et al., 1985, Stuiver et al., 1995, Johnsen et al., 1997]. This lack of LIA evidence in these cores questions either the hemispherical representativeness of such events or the sensitivity of Greenland ice core archives in recording late Holocene climate changes. Here we present isotopic and chemical records retrieved from four ice cores drilled in northern Greenland which uniformly show evidence of distinct cooling periods during the last five centuries. Possible reasons for the higher climate variability in that region are addressed and the influence of potential natural climate driving forces on these variations are evaluated.

Samples and methods

The ice cores presented here were drilled during the summers of 1993-95 along the North-Greenland-Traverse (NGT) which, among others, covered the essentially unexplored area northeast of the main Greenland ice divide (see Fig. 1). Along the 1600 km long traverse in total 13 ice cores (covering the last 500-1000 years) were drilled and an extensive surface snow study (more than 40 shallow firn cores and pit studies) was performed. To date four of the deeper ice cores (B16, B18, B21, B29 in Fig.1) have been dated with an accuracy better than ± 3 years by identification of volcanic horizons in quasi-continuous SO_4^{2-} and DC-conductivity profiles in combination with annual layer counting in high resolution γ-ray attenuation density measurements and continuous flow analysis Ca^{2+}- and NH_4^+-stratigraphies. The cores were subsampled in approximately 1-3 year resolution and analysed for their isotopic ($\delta^{18}O$) and (except B29) their

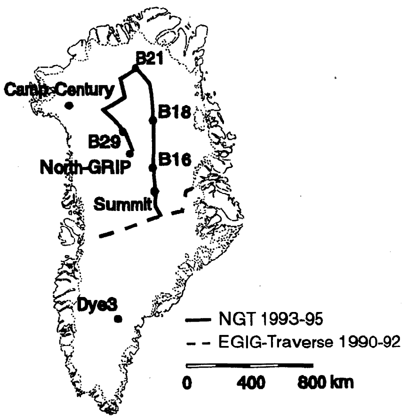

Figure 1. Geographical location of the NGT drill sites B16, B18, B21 and B29. Also indicated are the positions of major deep drilling projects as well as the routes of our traverse studies recently performed on the Greenland ice sheet.

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major and trace ion content. Details concerning sampling protocols, analytical procedures and time series analysis of the records are described elsewhere (Fischer et al., Sulfate and nitrate firn concentrations on the Greenland ice sheet: 1. Large scale geographical deposition changes, submitted to *J. Geophys. Res.*, 1998, Fischer et al., Sulfate and nitrate firn concentrations on the Greenland ice sheet: 2. Temporal anthropogenic deposition changes, submitted to *J. Geophys. Res.*, 1998).

Results and discussion

From the core chronologies a 50% drop in snow accumulation rate, down to 10-15 cm water equivalent (WE) per year, northeast of the Greenland Summit was derived (see Table 1). These accumulation rates are ~ 30% lower than previously published values [Ohmura and Reeh, 1991] for northeastern Greenland and together with mean annual temperatures below -30 °C throughout the investigated area, define a climatological regime quite distinct from the rest of the ice sheet. Profiles for three year averages in $\delta^{18}O$ of the NGT cores, the GRIP-Summit [Johnsen et al., 1997] and the Dye3 [Dansgaard et al., 1985] ice cores together with their long-term trends are plotted in Fig. 2. Going from south to north in Fig. 2 an approximately four fold increase in the long-term $\delta^{18}O$ variability is found. The trend variations are well correlated within the northern Greenland ice cores B18, B29 and B21 (r = 0.42, 0.62, 0.83) and clearly exceed the point-to-point variability in the isotopic snow stratigraphy. Thus, the NGT $\delta^{18}O$ records point to a consistently higher sensitivity of northern Greenland ice archives in recording isotope variations as compared to southern and central Greenland drill areas. Such an unexplained amplification in the long-term $\delta^{18}O$-variation was already suggested by the Camp Century ice core, northwest Greenland, both during the current millenium as well as the last glacial/interglacial transition [Johnsen et al., 1970, Dansgaard et al., 1985]. The similar isotopic variability at this relatively high accumulation site (~35 cm WE/a) makes an artifact caused by the extremely low accumulation rate in our NGT cores (e.g. caused by loss of certain seasonal snow strata) very unlikely. Also, firn temperature measurements performed in the region of the NGT and at Camp Century reveal no significant evidence for a latitudinal change in the spatial $\delta^{18}O$/temperature relationship, that could cause erroneously high isotope anomalies. The higher variability in northern Greenland isotope temperatures can, therefore, be considered as a real climatological effect specific for this region. Southern and partly also central Greenland precipitation is dominated by cyclones over the Labrador Sea during the winter-half-year [Chen et al., 1997].

Table 1. Geographical location of the drill sites together with respective core average and standard deviation for $\delta^{18}O$ in ‰ and snow accumulation rate in cm WE/a.

Site	Latitude	Longitude	Altitude	$\delta^{18}O$	Accum.
B16	73°56'N	37°38'W	3040 m	-37.1±0.6	14.2±2.2
B18	76°37'N	36°24'W	2508 m	-36.7±1.1	10.6±1.9
B21	80°00'N	41°08'W	2185 m	-34.6±1.1	10.8±2.0
B29	76°00'N	43°30'W	2874 m	-35.7±1.0	15.2±1.8

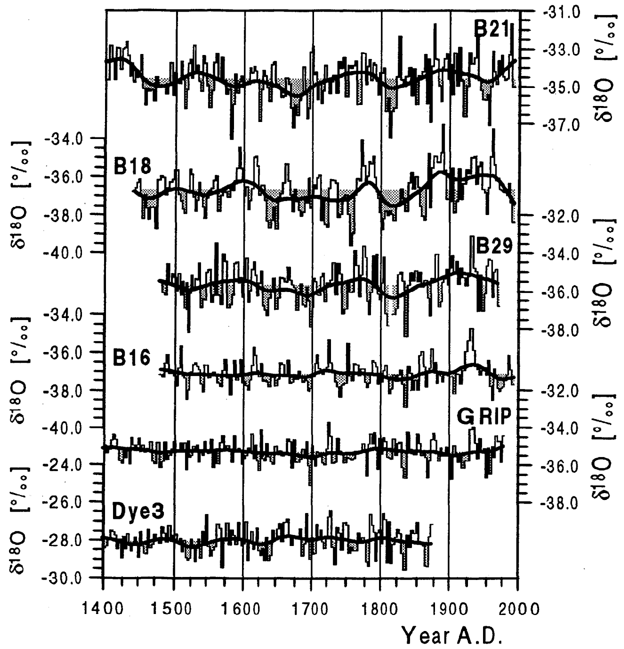

Figure 2. Record of three year $\delta^{18}O$ averages (thin line) in southern (Dye3), central (GRIP-Summit, B16) and northern (B29, B18, B21) Greenland ice cores from 1400 A.D. to present. Natural cubic spline approximations (thick lines, p=0.0001) indicate the long-term trend and were shown to be virtually equivalent to Gaussian low pass filtering and singular spectrum reconstructions.

Such storms transport relatively warm air masses onto the ice sheet (often 10-20 °C warmer than the monthly average), where the high isotopic signature specific to these precipitation events may mask a long-term temperature trend. In contrast, cyclonic influence is progressively reduced further north, especially in the precipitation shadowing northeast of the main ice divide. Instead, northern Greenland receives more precipitation in summer [Chen et al., 1997]. Accordingly, lower isotopic values during the LIA might either be due to on average lower summer temperatures or to increased winter precipitation in northern Greenland caused by intensified storminess over the North Atlantic and/or storm track changes.

In order to reduce depositional noise in the isotopic records and to extract a spatially representative northern Greenland temperature record, we stacked the isotopic deviations in data and long term trends of the three northern regime ice cores B18, B21 and B29. In this stacked profile (see Fig. 3a) several distinct long term isotope anomalies can clearly be identified: an extended cooling period throughout most of the 17th and the first half of the 18th century and a distinct cold spell in the first half of the 19th century, coincident with the last maximum of glacier advance in the Alpes [Grove, 1988]. Deviations of the isotopic trend from the record average during these cold periods amount up to -0.7 ‰ which, applying the spatial $\delta^{18}O$/temperature-gradient of 0.67 ‰/°C for the Greenland ice sheet [Johnsen et al., 1989], translates to a temperature change on the order of 1 °C on the century time scale. Applicability of spatial $\delta^{18}O$/temperature-gradients on temporal changes have been recently questioned. Borehole temperature calibrations by Cuffey et al. [1994] and Johnsen et al. [1995] have shown that for the time span investigated

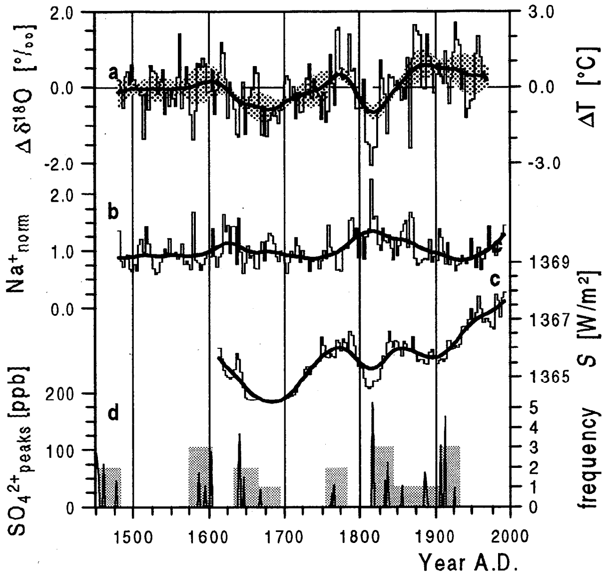

Figure 3. a) stacked isotope record of core B18, B21 and B29 for the time span 1480-1969: Thin line represents the average of the triannual data sets, thick line and grey shading the mean and standard deviation of the spline approximations after subtracting the core averages, b) stacked record of Na^+ concentrations in core B16, B18 and B21. To allow for different absolute sea salt level in each core, which are largely caused by the different altitude of the drill sites, Na^+-concentrations were normalized to the individual core average, c) three year intervals of reconstructed solar irradiance for the time span 1612 to 1993 [Lean et al., 1995], d) SO_4^{2-} concentration above background (thin line) and frequency in a 30 year interval (grey bars) of stratospherically derived volcano horizons in the annual record of core B21.

here, the actual $\delta^{18}O$/temperature-gradient most likely was slightly lower (i.e. 0.5-0.6 ‰/°C), implying even colder conditions during the LIA. The timing of the NGT isotope temperature variations agrees surprisingly well with long-term deviations found in the reconstructed northern hemisphere summer temperature record compiled by Bradley and Jones [1993]. The extent of the NGT cooling, however, is more than 4 times larger than what is observed in their record. The last 150 years in our record are characterized by ~0.7 °C warmer temperatures compared to the record mean. The northern hemisphere temperature trend since 1850 [Jones et al., 1986], however, is not reflected by our stacked ice core record. The most striking difference is an unparalleled warming over the Greenland ice sheet at the end of the 19th century which is missing in the hemispherical record (in the year 1889 a massive melt layer was consistently found in our and other Greenland ice cores [Clausen et al., 1988]). An unequivocal temperature trend during the last three decades (as clearly seen in the compilation of Jones et al. [1986]) cannot be discerned in our record due to the high scatter between the three cores at the boundaries of the data set.

Referring to periods of colder temperatures a decrease of precipitation is expected due to the decrease in atmospheric water vapour load over the ice sheet. In contrast to glacial/interglacial temperature changes, where this is observed [Alley et al., 1993], such variations in accumulation rates cannot be seen during the LIA cooling. A 20 % decrease in snow accumulation during the last 50 years in core B16 is the only significant long-term deviation found in our data. The latter agrees with findings from other central Greenland ice cores [Clausen et al, 1988, Meese et al., 1994] and questions a recent greenhouse warming induced increase in snow accumulation. Investigations by Kapsner et al. [1995] on the GISP2 accumulation record revealed only slight (1% per °C) temperature-coupled accumulation changes during the Holocene which cannot be resolved in our low accumulation records. Instead, they concluded that snow accumulation over the ice sheet is primarily governed by circulation changes as is also the case for variations in aerosol load during the last 11000 years [O'Brien et al., 1995]. A stacked profile for three year averages in sea salt concentration along the NGT is plotted in Fig. 3b. Comparison of the sea salt and $\delta^{18}O$ profiles reveals a close inverse relationship from point to point as well as for the long-term trend with 20-30 % higher sea salt concentrations during the LIA cold periods. The correlation coefficient for the triannual data set is -0.37, significantly different from zero on the 1‰ level. In view of the seasonal maximum of sea salt firn concentrations in northern Greenland in winter, this anticorrelation supports higher storminess over the North Atlantic during the LIA, leading to enhanced export of sea salt aerosol and increased advection of relatively cold air masses to the northern Greenland ice sheet in the winter-half-year.

Since the climate variations in the northern Greenland temperature record clearly exceed the noise level we attempt to determine the influence of natural climate forcing factors on these temperature changes. By identification of volcano horizons in the annually resolved sulfate profile of core B21, we were able to develop a history of 20 volcanic eruptions for the time span 1400-1950 which lead to significant sulfuric acid input onto the northern Greenland ice sheet via the stratosphere. Six further horizons derived from Icelandic eruptions were excluded from the analysis since their output is assumed to be transported onto the ice sheet via the troposphere. As depicted in Fig. 3, prominent eruptions show a direct effect on northern Greenland temperature which is confined to the three-year-interval following the main event. For example, in the case of the Tambora eruption, 1815, this is reflected in a short term ~1 ‰ decrease in the $\delta^{18}O$-profile corresponding to a ~1.5 °C temperature drop. The latter, however, is superimposed on a longer temperature decline which already started at the turn of the century and, therefore, cannot be caused by this eruption. In order to influence the stratospheric aerosol load and, thus, climate on a longer time scale, the frequency of volcanic eruptions has to rise above average. We adapted an approach by Crowley et al. [1993] and evaluated the frequency of eruptions occurring in a 30 year interval (see Fig. 3d). This parameter shows an ambiguous relationship with the observed long-term temperature variations. In contrast to the findings by Hammer et al. [1980] but supporting the reevaluation by Crowley et al. [1993], we conclude that the volcanic climate forcing is mainly limited to episodic events during which significant cooling may be encountered. In order to assess a possible influence of solar forcing on northern Greenland climate during the last centuries, we contrast our stacked $\delta^{18}O$ profile to reconstructed changes in total solar irradiance [Lean et al., 1995] for the time span 1600 to present (Fig. 3c). Previous to the onset of the industrial revolution, this reveals a suprisingly good long term covariance. The correlation coefficient over the entire time span covered by both parameters is 0.41 at zero lag for the triannual data set (significantly different from zero at the 1 ‰ level) and 0.74 for the smoothed long-term trends, implying that approximately 55 % of the trend variance can be explained by the long-term solar variation. Motivated by this good correspondence, we also investigated short term variations in the frequency domain, performing both maximum entropy and Blackman-Tukey frequency analysis on the $\delta^{18}O$ records of the annually resolved cores B21 and B29. In both cores a double peak at 11-12 years (as also observed in the GRIP and GISP2 cores [Johnsen et al., 1997, Stuiver et al., 1995]) could be found which is significantly different from red noise on the 95 % level and may be related to the 11 year solar cycle. However, the most prominent peak in the power spectrum of core B21 and B29 (significant at the 99 % level) is at ~17 years. The origin of this frequency so far remains unexplained but, surprisingly, it is also most prominent in an annually resolved $\Delta^{14}C$-treering record from northwestern America [Stuiver and Braziunas, 1993].

Conclusions

New northern Greenland isotope records reveal distinct LIA cool periods during the last five centuries in contrast to previous ice core studies from the southern and central Greenland ice sheet and are shown to be more sensitive in recording late Holocene climate changes. Thus, the new results suggest a higher variability in Greenland isotope temperatures during the late Holocene than hitherto assumed. In view of the Danish/European North-GRIP deep drilling, which is recently carried out on the Greenland ice sheet at 75°N, this new ice core will provide a more detailed history of Holocene climate in the Arctic. Although the causes for LIA climate variations are still not unambiguously known, our data point to a substantial solar influence which has to be reevaluated when longer time series from the northern Greenland ice sheet are available. Volcanic aerosols in the stratosphere, however, are unlikely to have a Holocene climate effect on the century and millenium time scale.

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References

Alley, R. B., D. A. Meese,, C. A. Shuman, A.J. Gow, K. C. Taylor, P. M. Grootes, J. W. C. White, M. Ram, E. D. Waddington, P. A. Mayewski and G. A. Zielinski, Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event, *Nature*, 362, 527-529, 1993.

Bradley, R. S. and P. D. Jones "Little Ice Age" summer temperature variations: their nature and relevance to recent global warming trends, *The Holocene, 3*, 367-376, 1993.

Briffa, K. R., T. S. Bartholin, D. Eckstein, P. D. Jones, W. Karlen, F. H. Schweingruber and P. Zetterberg, A 1400-year tree ring record of summer temperatures in Fennoscandia, *Nature, 346*, 434-439, 1990.

Chen, Q.-S., D. H. Bromwich and L. Bai, Precipitation over Greenland retrieved by a dynamic method and its relation to cyclonic activity, *J. Climate, 10*, 839-870, 1997.

Clausen, H. B. , N. S. Gundestrup and S. J. Johnsen, Glaciological investigations in the Crete area: A search for a new deep drilling site, *Ann. Glaciology, 10*, 10-15, 1988.

Crowley, T. J., T.A. Criste and N. R. Smith, Reassessment of Crête (Greenland) ice core acidity/volcanism link to climate change, *Geophys. Res. Let., 20*, 209-212, 1993.

Cuffey, K. M., Alley, R. B., Grootes, P. M., Bolzan, J. M. and Anandakrishnan, S., Calibration of the $\delta^{18}O$ isotopic paleothermometer for central Greenland, using borehole temperatures, *J. Glaciology, 40*, 341-349, 1994.

Dansgaard, W., H. B. Clausen, N. Gundestrup, S. J. Johnsen and C. Rygner, Dating and climatic interpretation of two deep Greenland ice cores, in *Greenland ice core: Geophysics, Geochemistry and the Environment,* edited by C. C..Langway, H. Oeschger and W. Dansgaard, American Geophysical Union, Washington, 1985.

Grove, J. M., *The Little Ice Age*, Routledge, London, 1988.

Hammer, C. U., H. B. Clausen and W. Dansgarrd, Greenland ice sheet evidence of post-glacial volcanism and its climatic impact, *Nature, 288*, 230-235, 1980.

Johnsen, S. J., W. Dansgaard, H. B. Clausen and C. C. Langway, Climatic oscillations 1200-2000 AD, *Nature, 227*,, 482-483, 1970.

Johnsen, S. J., W. Dansgaard and J. W. C. White, The origin of Arctic precipitation under present and glacial conditions, *Tellus, 41B*, 452-468, 1989.

Johnsen, S. J., D. Dahl-Jensen, W. Dansgaard and N. Gundestrup, Greenland paleotemperatures derived from GRIP bore hole temperature and ice core isotope profiles, *Tellus, 47B*, 624-629, 1995.

Johnsen, S. J., H. B.Clausen, W. Dansgäard, N. S. Gundestrup, C. U. Hammer, U. Andersen, K. K. Andersen, C. S. Hvidberg, D. Dahl-Jensen, J. P. Steffensen, H. Shoji, A. E. Sveinbjörnsdottir, J. White, J. Jouzel and D. Fisher, The $\delta^{18}O$ record along the Greenland Ice Core Project deep ice core and the problem of possible Eemian climatic instability, *J. Geophys. Res., 102*, 26397-26410, 1997.

Jones, P. D., T. M. L Wigley and P. B. Wright, Global temperature variations between 1861 and 1984, *Nature, 322*, 430-434, 1986.

Kapsner, W. R. , R. B. Alley, C. A. Shuman, A. Anandakrishnan and P. M. Grootes, Dominant influence of atmospheric circulation on snow accumulation in Greenland over the last 18000 years, *Nature, 373*, 52-54, 1995.

Lean, J., J. Beer R. and Bradley, Reconstruction of solar irradiance since 1610: Implications for climate change, *Geophys. Res. Let., 22*, 3195-3198, 1995.

Meese, D. A., A. J. Gow, P. Grootes, P. A. Mayewski, M. Ram, M. Stuiver, K. C. Taylor, E. D. Waddington and G. A. Zielinski, The accumulation record from the GISP2 core as an indicator of climate change throughout the Holocene, *Science, 266*, 1680-1682, 1994.

O'Brien, S. R., P. A. Mayewski, L. D. Meeker, D. A. Meese, M. S. Twickler and S. I. Whitlow, Complexity of Holocene climate as reconstructed from a Greenland ice core, *Science, 270*, 1962-1964, 1995.

Ohmura, A. and N. Reeh, New precipitation and accumulation maps for Greenland, *J. Glaciology, 37*, 140-148, 1991.

Scuderi, L. A., A 2000-year tree ring record of annual temperatures in the Sierra Nevada Mountains, *Science, 259*, 1433-1436, 1993.

Stuiver, M. and T. F. Braziunas, Sun, ocean, climate and atmospheric $^{14}CO_2$: an evaluation of causal and spectral relationships, *The Holocene, 3*, 289-305 1993.

Stuiver, M., P. M. Grootes T. F. and Braziunas, The GISP2 $\delta^{18}O$-record of the past 16500 years and the role of the sun, ocean and volcanoes, *Quat. Res., 4*, 341-354, 1995.

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