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The North Atlantic Oscillation and its imprint on precipitation and ice accumulation in Greenland

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Abstract. Interannual to decadal fluctuations in net precipitation and ice accumulation are examined over Greenland. It is shown that in western Greenland these fluctuations are correlated with the North Atlantic Oscillation. The analysis is based on two complementary data sources: A highly resolved net precipitation and accumulation history over 15 years derived form the reanalysis data of the European Centre for Medium-Range Weather Forecasts and a composite ice accumulation record representative for the western part of Central Greenland. It is suggested that western Greenland snow accumulation is a good proxy for the NAO index with the potential for the reconstruction of a long time series.

Introduction

Ice cores drilled in Central Greenland provide a detailed climate history that covers a wide variety of different time scales. One question that arises is to what extent they register climate fluctuations away from Greenland. In the North Atlantic region a dominant source of interannual to decadal climate fluctuations is the North Atlantic Oscillation (NAO). Its behavior is manifested in various climate parameters and also influences the climate on adjacent land masses such as Europe and Greenland [e.g. *VanLoon and Rogers*, 1978; *Wallace and Gutzler*, 1981; *Hurrell*, 1995; *Hurrell and Van Loon*, 1997 and others]. Hence the establishment of a long-term NAO time series is an important contribution to a better understanding of decadal climate fluctuations and their role in past European climate events such as the little ice age [*Wanner et al.*, 1997].

Typically the NAO is measured by an index calculated from the difference between Azores and Iceland monthly mean surface pressure data. The oscillation is present throughout the year but strongest during winter. For the instrumental period (the last ~150 years) the annual and winter season indices are well known, however little is known about the historical behavior of the NAO that could be extracted from paleo-climatic records.

The isotopic composition of ice cores can be used to reconstruct a temperature record [e.g. *Johnsen et al.*, 1995 and others]. It was found that extreme modes of the NAO index are reflected in isotopic signals [*Barlow et al.*, 1993] and a band-passed frequency analysis showed a clear relation between the isotopic record and the NAO index [*White et al.*, 1996; 1997]. However an unambiguous identification of the NAO events for the last ~200 years has remained difficult. Climate extremes related to the NAO oscillation are also reflected in tree ring data [*D'Arrigo et al.*, 1994]. European and North American tree ring data could be used to reconstruct a winter NAO index for the last 200 years [*Cook et al.*, 1997]. These data suggested that the NAO was at least present back to the beginning of the 18th century. In this paper we will show that the NAO has an imprint in net precipitation and ice accumulation rates in western Greenland, which suggests that these two parameters are prime candidates for the reconstruction of a long NAO time series.

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Data

The analysis is based on two complementary climatologies. A highly resolved reanalyzed net precipitation and accumulation climatology over Greenland and a composite ice core accumulation record constructed from 5 different ice cores representative for the western part of Central Greenland.

Net Precipitation

The monthly mean climatology was calculated from predicted precipitation and evaporation rates using the European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA) [*Gibson et al.*, 1997]. The reanalysis data were produced by a state-of-the-art frozen-in assimilation forecast model and hence the climatology is not adversely affected by any model changes as known from standard operational analysis. The data have a high horizontal resolution of ~1.25 ° × 1.25 ° corresponding roughly to ~50 × 100 km and cover the period from 1979 to 1993 with 6-hourly intervals (for example the precipitation rate valid at 15 GMT was calculated as the difference between the 18 h and 12 h forecast). The net precipitation was defined as the difference between total precipitation and evaporation whereas the net snow accumulation was calculated as the difference between solid precipitation only and evaporation. Unlike sea level pressure or sea surface temperature the precipitation and evaporation rates are model derived fields and hence depend on various physical parameterizations [*Kalnay et al.*, 1996, see below].

The derived mean annual precipitation (area averaged over all of Greenland) is 0.36 m yr^{-1}, the mean net precipitation is 0.34 m yr^{-1}, whereas the mean net snow accumulation (as defined above) is less and amounts to 0.26 m yr^{-1} water equivalent. The highest annual mean net precipitation rates (Fig. 1a) occurred in the south-east of Greenland (up to ~1.4 m yr^{-1}), a band with a relative maximum of up to ~0.4 m yr^{-1} was found along western Greenland whereas the net precipitation decreases down to less than 0.1 m yr^{-1} in the north Central-region. Both the calculated mean values as well as the distribution, in particular the orographically induced enhanced precipitation band, compare favorably with observed data [*Ohmura and Reeh*, 1991].

NAO index

The annual NAO index covering the instrumental period from 1862 to present is based on a scaled pressure difference between Azores and Iceland [*Hurrell*, 1995] and has been normalized for this study. A similar index has been defined based on reanalyzed surface pressure data.

Ice accumulation rates

The ice accumulation rates used in this study were collected from different laboratories that used different calculation methods. Typically, an ice accumulation record is calculated from signals that show strong seasonal variations [*Steffensen*, 1985], together with a measured or modeled ice density profile. Data from five ice cores, located in the western part of Central Greenland (marked in Fig. 1b), were available. We have constructed two accumulation records based on chemical and isotopic measurements. One is from a core drilled during the North Greenland Traverse (B29) and another one is from the core drilled during the Summit drill project EUROCORE [*Sigg and Neftel, 1991*]. In addition a record from the Summit drill project GISP2 [*Cuffey and Clow*, 1997 and others] and two records (core B and D) from the 1984 - 85 post GISP campaigns in Central Greenland [*Clausen et al.*, 1988] were used.

A composite ice accumulation profile was created based on a simple mean of the five records in order to reduce the uncertainty associated with single core measurements. The resulting profile is shown in Fig. 3 (solid line, scaled with -1.). It is representative for the western part of Central Greenland, includes 118 years covering the period 1865 to 1982 and it corresponds approximately to the instrumental records of the annual NAO index. Strong variations on both interannual and interdecadal time scales are seen.

The role of the North Atlantic Oscillation

Both measured ice accumulation rates in Greenland [e.g. *Anklin et al.*, 1994; 1998; *Meese et al.*, 1994], and precipitation over the North Atlantic region [e.g. *Walker and Bliss*, 1939; *Hurrell*, 1995], showed clear fluctuations on interannual to decadal time scales. It was found that the net precipitation over the Labrador Sea and western Greenland is reduced during high NAO index phases. We analyzed this pattern in more detail using our high resolution reanalyzed climatology and linear cross correlation maps between the monthly mean net precipitation fields and a monthly mean NAO index. The correlation is negative over the Labrador Sea and also over western and Central Greenland whereas over eastern Greenland, the Irminger Basin and Iceland the correlation is positive (Fig. 1b).

In western Greenland one standard deviation in the NAO index is linked to a variation in net precipitation of ~0.1 m yr^{-1}. This translates into an expected difference of up to ~0.3 to 0.4 m yr^{-1} between extremely high and low NAO index states. An area-averaged snow accumulation rate representative for western Greenland (averaged approximately over the blue region in Fig. 1b) is shown in Fig. 2 (solid line, scaled with -1.). To emphasize the inter-annual signal the data were smoothed with a 12-month running-mean filter and after that normalized. As expected the variations in the negative net snow accumulation rates correspond roughly to variations in NAO index (Fig. 2). The cross correlation coefficient between the two monthly data series (linear trend removed) is -0.47, the one for the 12 month running average data series is -0.49, whereas for the annual mean data the cross correlation coefficient increases to -0.58. All correlation coefficients are statistically significant above the 99% interval using a one-sided Student's t-test. Slightly higher correlation coefficients occur when the analysis is restricted to the 4 winter months only (December to March). It increases from -0.47 (for all monthly data) to -0.51 (winter monthly data only). Assuming that the precipitation and evaporation over Greenland and its interannual signal are correctly represented by the ERA forecast model the correlation analysis suggests that about 1/3

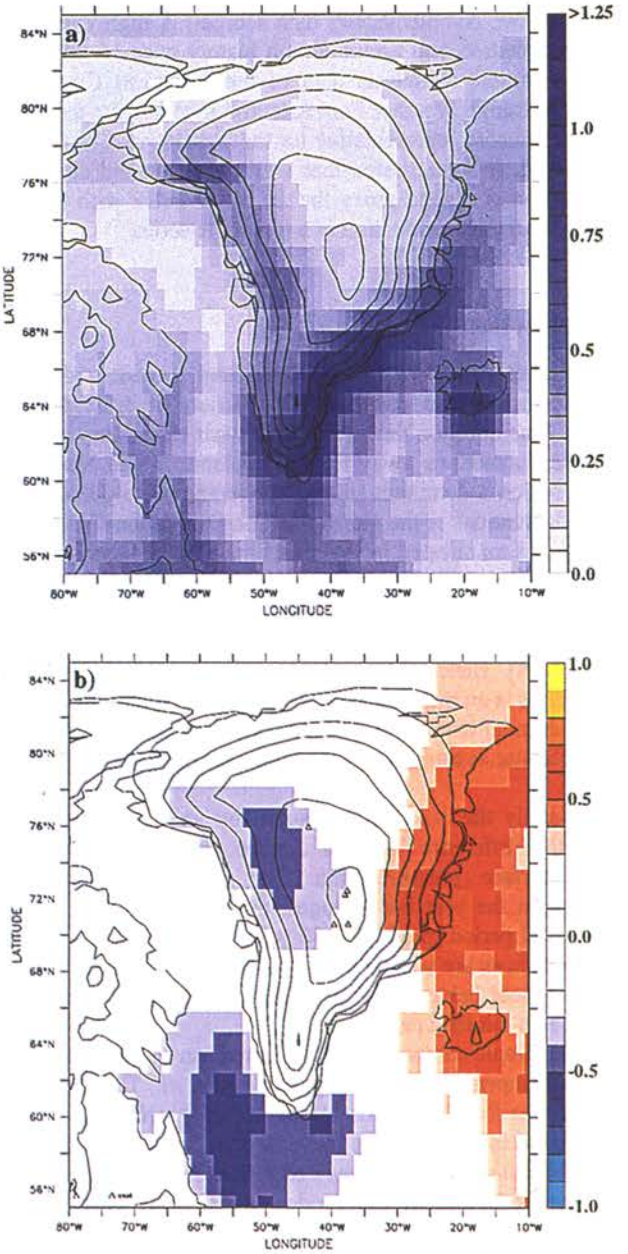

Figure 1. Mean net precipitation over Greenland (panel a, in m yr^{-1}) and cross correlation map between monthly mean net precipitation and monthly mean NAO index both derived from ERA reanalysis for the period 1979 to 1993. In (b) only areas with correlation coefficients above 0.3 are shown (significant above 99% level) and triangles mark the locations of ice core drill sites used in this study.

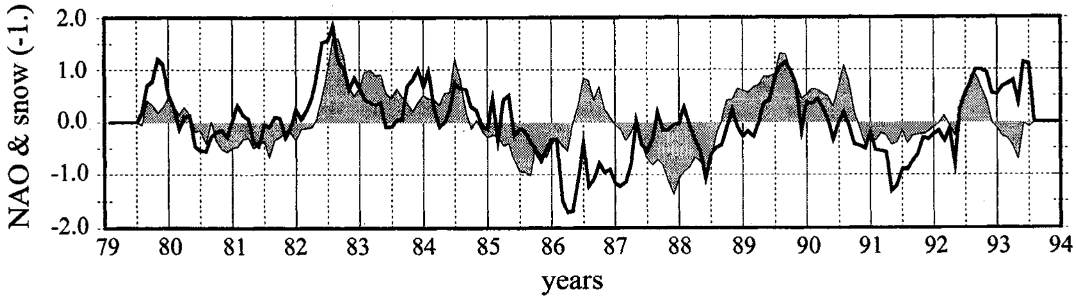

Figure 2. Snow accumulation rates over western Greenland (bold line, scaled with -1.) and NAO index (filled) both based on monthly reanalysis data for the period 1979 to 1993. To emphasize the inter-annual signal the data were smoothed with a 12-month running-mean filter and then normalized. The area average was taken over the blue region in Fig. 1b. The correlation coefficient of the raw data is -0.49.

(i.e. 0.47^2 to 0.59^2) of their variance can be explained by a simple linear relationship with the NAO index.

In western Greenland it can be expected that the NAO oscillation is also found in ice accumulation records in particular in higher altitudes where ice melting rarely occurs. Anklin et al. [1994] reported consistent interannual variations in various short (~10 years) ice accumulation records measured in western Greenland. A comparison with our annual NAO index suggests, that the dominant signal can be linked to variations in the NAO pattern (not shown), but the short time series make an analysis difficult.

The composite ice accumulation record as calculated above is more suitable for a correlation analysis (Fig. 3) but it is representative for the Central and not for the western part of Greenland and hence a weaker correlation is expected. The correlation coefficient with the instrumental NAO index for the period 1865 to 1882 is -0.22 and increases to -0.25 and -0.29 when short interannual signals are removed using a simple 3 or 5-point running average filter. The amount of variability explained by this linear relation is small, accounting 5 to 10% (0.3^2) of the total variance. It should be noted that a part of the low correlation coefficients may also be attributed to uncertainties in the calculation of accumulation rates and to possible spatial variability in ice accumulation (e.g. redistribution by wind). But the correlation coefficient is of the order of the one expected from the ERA reanalysis (~0.3 for the western part of Central Greenland) and the correlation is still statistically significant above the 99% level using a one-sided Student's t-test. Thus our hypothesis that the NAO index has an imprint on ice accumulation rates is supported.

Concluding remarks

The correlation analysis based on ERA reanalysis data presented in Fig. 1b suggest that the correlation between NAO index and ice accumulation is strong in western Greenland but weaker in Central Greenland. Longer records from western Greenland have not yet been measured, but it can be anticipated that the correlation will substantially improve when an accumulation record calculated from the new west Greenland ice core NASAU (see *Anklin et al.*, 1998) is available. Such a record is a prime candidate for the reconstruction of an approximate NAO index that spans a length of time longer than the observational record.

The observed reduced/enhanced net precipitation over western Greenland during high/low NAO index states is in agreement with long-term station records of observed winter precipitation in Jakobshavn and Godthåb located on the west coast of Greenland [*Hurrell*, 1995]. It is also consistent with simple expectations inferred form variations in the atmosphere's mean circulation. During high index states the strength of the Iceland low is enhanced whereas the near surface temperature over Greenland is reduced [*VanLoon and Rogers*, 1978]. This suggests that overall more northerly and hence dryer air flows towards the western slope of Greenland. This is consistent with the observed decrease in the mean net precipitation, but a more detailed analysis remains to be done.

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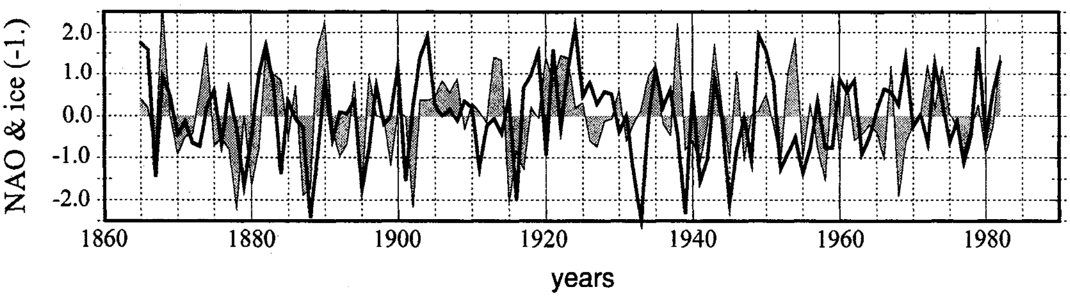

Figure 3. Composite annual mean ice accumulation rate (bold line, scaled with -1.) representative for the western part of Central Greenland and instrumental annual-mean NAO index (filled) for the period 1865 to 1982. Both curves are normalized and the correlation coefficient of the raw data is -0.22.

of Copenhagen, Denmark), the Greenland Summit Ice Cores CD-ROM, 1997 (available form the National Snow and Ice Data Center, University of Colorado, Boulder, USA) and the Climate Analysis Section at NCAR, Boulder, USA. We thank Dr. B. Stauffer for stimulating discussions.

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