Regional sensitivity of Greenland precipitation to NAO variability

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[1] The North Atlantic Oscillation (NAO) is a primary mode of interannual climate variability for the North Atlantic Ocean Basin and influences the climate over much of Europe and parts of North America. Knowledge of past variability of this oscillatory system is essential for efforts to understand, model, and predict future climate variability, particularly under a warming Earth scenario. As Greenland precipitation is modulated by the NAO, ice core-derived accumulation histories are incorporated into multi-proxy reconstructions. New ice core records from Greenland demonstrate that the NAO's influence on accumulation is temporally and spatially variable. The results presented indicate that (1) NAO modulation of accumulation is strongest and most persistent along the west-central side of Greenland, (2) records from central Greenland should be avoided and (3) the spatial character of the precipitation response to NAO variability has been influenced by the 20th century warming in the high Arctic.

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1. Introduction

[2] The North Atlantic Oscillation (NAO) refers to variations in the distribution of atmospheric mass between the Arctic and the subtropical Atlantic. It may be characterized by an index calculated as the difference in mean monthly surface pressure anomalies between Iceland and the Azores. Meteorological observations allow reconstruction of various NAO indices back to 1874 A.D. [*Rogers*, 1984], to 1864 A.D. [*Hurrell*, 1995], and to 1821 A.D. [*Jones et al.*, 1997]. Longer reconstructions have used annually resolved proxy records from tree rings [*Cook*, 2003, and references therein] and ice cores [*Appenzeller et al.*, 1998a, 1998b; *Vinther et al.*, 2003] with mixed success. *Luterbacher et al.* [2002] combined instrumental and documentary proxy records to reconstruct a seasonal NAO record to 1500 A.D. while multi-proxy approaches have yielded reconstructions back to 1750 A.D. [*Cullen et al.*, 2001] and to 1400 A.D. [*Cook*, 2003]. With one exception [*Appenzeller et al.*, 1998b], the Greenland records used in these reconstructions were from older cores (e.g., Dye 3) or cores from the central region of the ice sheet [GISP2 and GRIP].

[3] Six annually resolved ice core histories acquired as part of the PARCA (Program for Arctic Regional Climate Assessment) Project [*Thomas and PARCA Investigators*, 2001] now allow further investigation of the impact of NAO on the temporal variability and spatial distribution of Greenland accumulation and hence, on their potential to contribute to NAO paleo-reconstruction efforts. Here we expand on the study by *Appenzeller et al.* [1998a] who correlated the spatial pattern of precipitation over the North Atlantic and Greenland as predicted by the ECMWF ERA-15 re-analysis (http://www.ecmwf.int/research/era/Project/index.html) with the NAO Index [*Hurrell*, 1995] from 1979 to 1993. They found that the strongest linear relationship (negative) between snow accumulation and the NAO lies west of central Greenland. Using five records from west-central Greenland (Figure 1, small dots) they derived a composite proxy accumulation record (1865–1982) that they correlated ($R = -0.22$; $p < .0001$) with the Hurrell Annual NAO Index. The explained variance ($R^2 = .048$) is low as the five cores lie outside the region of maximum NAO influence along the western side of Greenland (Figure 1, boxed area) as identified by their spatial correlation map. *Appenzeller et al.* [1998b] used an ice core-derived accumulation history from the NASA-U core (Figure 1), collected as part of PARCA in 1995, to construct a proxy history that was much better correlated to NAO ($R = -0.57$, $R^2 = 0.325$) over the observational period (1865–1994).

[4] Generally, when NAO is positive, stronger westerlies reduce the southwesterly flow that brings moisture to Greenland resulting in an overall average reduction of accumulation. Conversely, when NAO is negative, the large-scale atmospheric flow is more frequently from the southwest bringing more moisture to the ice sheet, particularly the southern region [*Rogers and van Loon*, 1979; *Hurrell*, 1995; *Bromwich et al.*, 1999]. Thus, accumulation records from southern Greenland were anticipated to be the most promising for NAO reconstruction.

2. Data and Methods

[5] The locations of the six PARCA cores (D1, D2, D3, Raven, GITS, and NASA-U) are shown in Figure 1 along with the Summit site where two older, previously published, Site T cores were drilled 4 km apart in 1989 [*Mosley-Thompson et al.*, 1993]. These ice core records are used here to further investigate the spatial and temporal character of the relationship between snow accumulation over Greenland and NAO variability. The net annual accumulation, henceforth $\bar{A}_n$, is the thickness of the annual

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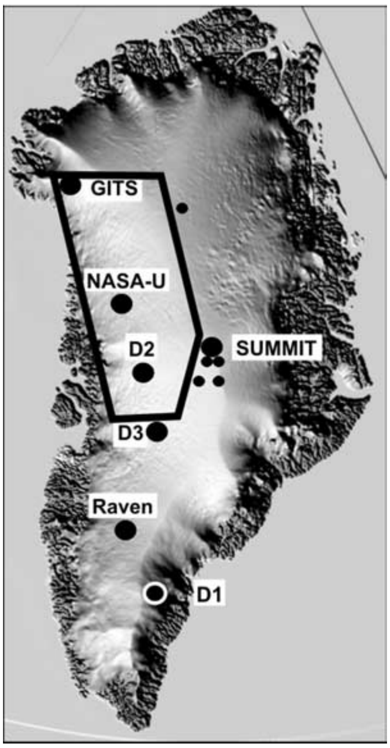

Figure 1. Locations are shown for the ice core records and regions discussed in the text.

layer of accumulated snow expressed in water equivalent (w.e.). A major advantage of these $\bar{A}_n$ records is that they were extracted, analyzed and dated by the same investigators using a consistent set of procedures. Moreover, unlike many earlier records, $\bar{A}_n$ histories for the six PARCA cores were determined using three seasonally varying parameters: the insoluble dust concentrations and oxygen isotopic ratios ($\delta^{18}O$), both measured at The Ohio State University (OSU), and hydrogen peroxide (H_2O_2) measured at the University of Arizona. The time scales were further confirmed with Beta radioactivity horizons from thermonuclear bomb tests and by identification of known volcanic eruptions [*Mosley-Thompson et al.*, 2001, 2003]. The $\bar{A}_n$ value extracted for a given year varies slightly with the seasonal indicator used because "annual" markers, the seasonal indicators, are not exactly contemporaneous [*Mosley-Thompson et al.*, 2001]. For example, the correlation between $\bar{A}_n$ based on annual dust minima versus annual $\delta^{18}O$ minima (from 1865 to 1994) for NASA-U is 0.82 (R^2 = 0.67, $p < .0001$) and for core D2, R is 0.84 (R^2 = 0.71, $p < .0001$). Regardless of the seasonal indicator used to define the $\bar{A}_n$ values, they reflect a combination of the climatological (input) signal associated with atmospheric processes (precipitation) and a noise signal imposed post-depositionally by surface (e.g., wind) and glaciological (e.g., diffusion in firn) processes. To reduce noise, annual time series derived from ice cores are routinely filtered (smoothed) prior to comparison with other time series. After smoothing with a 5-year triangular filter (discussed later) the correlations improve dramatically to 0.93 (R^2 = 0.87, $p < .0001$) and 0.92 (R^2 = 0.85, $p < .0001$), for NASA-U and D2, respectively.

[6] The $\bar{A}_n$ histories were calculated as follows. Two annual layer thicknesses records were derived for each core, one based on successive winter $\delta^{18}O$ minima and one based on successive winter dust minima. The resulting records (for one core) were averaged to produce that core's $\bar{A}_n$ history (Figure 2). Reliance on the winter minima results in an annual record approximating the calendar year (winter to winter). The $\bar{A}_n$ record for Summit (not shown, previously published) is the average of two $\bar{A}_n$ histories based only on winter dust minima in the two Site T cores.

[7] These seven $\bar{A}_n$ histories were correlated with *Hurrell*'s [1995] annual (Jan to Dec) NAO Index to explore the relationship between Greenland $\bar{A}_n$ and NAO variability and how this relationship varies spatially (Table 1). To facilitate comparison of our results with those of *Appenzeller et al.* [1998b], our $\bar{A}_n$ series and the NAO series were treated similarly (detrended, standardized and smoothed using a 5-point triangular filter with weights 1, 2, 3, 2, 1). Our study differs from theirs in two respects: (1) we have included six additional accumulation records and (2) the serial correlation within each time series is evaluated and the significance tests (p values) for the correlations are adjusted accordingly. This method uses Theorem 11.2.2. of *Brockwell and Davis* [1991, p. 410]. In brief, inspection of the form of the filter (its influence on the accumulation time series) and the autocorrelation function for each series suggests that after lags of five years, the autocorrelation function is not significantly different from zero. This allows

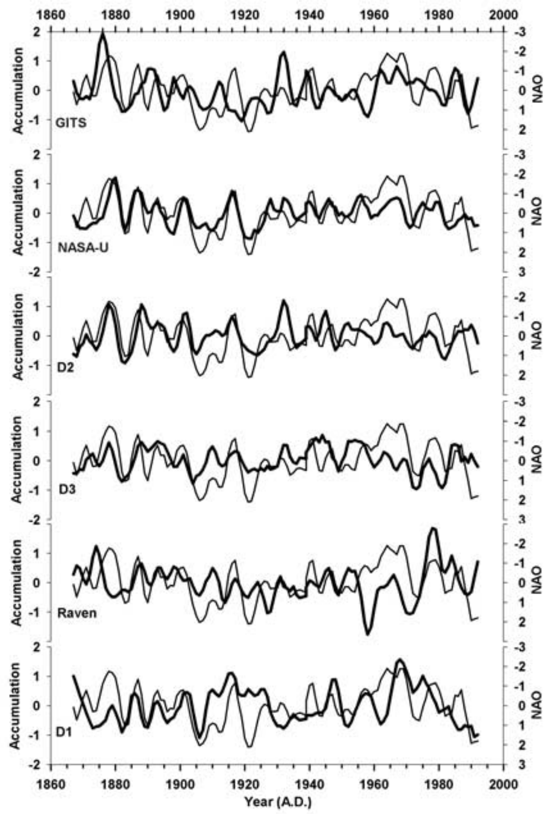

Figure 2. Accumulation histories (darker lines) for six PARCA cores are shown along with the annual NAO Index [*Hurrell et al.*, 1995]. See color version of this figure in the HTML.

Table 1. Correlations Between A_n and NAO for Each Core, Stack 1 (NASA-U, D2), and Stack 2 (NASA-U, D2, GITS), Shown for the Entire Observational Period (1865–1994) and the pre- and post-1925 Intervals[a]

	1865–1994			1865–1925			1926–1994		
	R	R^2	p value	R	R^2	p value	R	R^2	p value
GITS	−0.316	0.100	**0.0344**	−0.358	0.128	0.1042	−0.198	0.039	0.2765
NASA-U	−0.632	0.399	**0.0000**	−0.729	0.532	**0.0007**	−0.482	0.233	**0.0116**
D2	−0.365	0.133	**0.0104**	−0.526	0.277	**0.0126**	−0.144	0.021	0.4331
D3	−0.275	0.075	0.0733	−0.394	0.156	0.0638	−0.154	0.024	0.4645
Summit	0.078	0.006	0.6064	−0.215	0.046	0.3080	0.313	0.098	0.1393
D1	−0.265	0.070	0.0973	−0.087	0.008	0.6895	−0.467	0.218	**0.0438**
Raven	−0.085	0.007	0.5810	−0.229	0.052	0.2685	0.001	0.000	0.9959
Stack 1	−0.551	0.304	**0.0002**	−0.689	0.475	**0.0012**	−0.340	0.116	0.0728
Stack 2	−0.562	0.315	**0.0002**	−0.705	0.497	**0.0015**	−0.345	0.119	0.0540

[a]Significance levels exceeding 95% are in bold.

the reported p values to be calculated using the above theorem, truncating the infinite sum for the variance of the correlation coefficient at lags ±5.

3. Results and Discussion

[8] Six of the seven $\bar{A}_n$ histories used here are shown in Figure 2 along with Hurrell's annual NAO Index (thinner line). The statistical summaries of the correlations between the annual NAO Index and each $\bar{A}_n$ record are in Table 1. The $\bar{A}_n$ records from Summit and Raven are poorly correlated with NAO and the Summit record is positively correlated which is unexpected. For the entire period (1865–1994) only GITS, NASA-U and D2 ice cores have R values (−0.316, −632, −0.365, respectively) significant at the 95% level and only the R value for NASA-U is significant at the 99% level ($p < .0001$). These three cores are located in west-central to northwestern Greenland, the region (Figure 1, box) where the NAO and modeled (ERA-15) precipitation correlation (negative) field was found to be strongest [*Appenzeller et al.*, 1998a]. These results covering the entire NAO observational period (1865–1994, Table 1) support the contention by *Appenzeller et al.* [1998a] that the relationship between NAO variability and Greenland accumulation is most strongly recorded in west-central Greenland. Their conclusion was drawn using a different approach, described earlier, and a much shorter observational period (1979–1992).

[9] Next we produced two stacked $\bar{A}_n$ histories: Stack 1 (NASA-U, D2 cores) and Stack 2 (GITS, NASA-U, D2 cores) to assess whether a combined $\bar{A}_n$ record providing larger spatial coverage would better capture NAO variability. Neither of the stacked records yields an R value exceeding that from NASA-U (Table 1). These results point clearly to the NASA-U region ($R^2 = 0.399$) as a possible "sweet spot" for NAO reconstruction. The reasons for the apparent sensitivity of precipitation to NAO variability in this region are not immediately evident; however, this is under investigation.

[10] Figures 2 and 3 reveal that the three west-central $\bar{A}_n$ records (Stack 2, bold, Figure 3) are more similar to the NAO record (lighter line) before the mid 1920s than after (vertical dashed line) when higher northern latitudes experienced a rapid, large-scale warming (Figure 3) documented in both meteorological observations [*Rogers*, 1985; *Jones and Moberg*, 2003] and proxy records [*Overpeck et al.*, 1997].

[11] To explore the temporal variability within the $\bar{A}_n$ records, separate R values were calculated for the pre- and post-1925 periods. The p values were calculated accounting for serial correlation; thus, the shorter time series necessarily require higher R values to achieve an equally acceptable level of significance ($p < .05$). Prior to the 1920s warming (1865–1925) only two $\bar{A}_n$ histories, NASA-U and D2 that are located squarely in west-central Greenland, show a statistically significant ($p < 0.05$) relationship with the annual NAO. For NASA-U the explained variance exceeds 50% ($R^2 = 0.532$) and for D2 it exceeds 25% ($R^2 = 0.277$). The two core (NASA-U, D2) and three core (NASA-U, D2, GITS) stacked records explain 47% and 49% of the variance, respectively.

[12] In the post-1925 period, NASA-U is the only $\bar{A}_n$ history from west-central Greenland that remains significantly correlated ($R^2 = 0.23$, $p < 0.05$) with NAO and the D1 record from southeastern Greenland becomes significantly correlated (95% level) with NAO ($R^2 = 0.218$). These results indicate that precipitation variability in west-central Greenland was more sensitive to NAO variability prior to the strong Arctic warming than afterward. This may account in part for the conclusion by *Appenzeller et al.* [1998b], based on their wavelet analysis of the NASA-U $\bar{A}_n$ history,

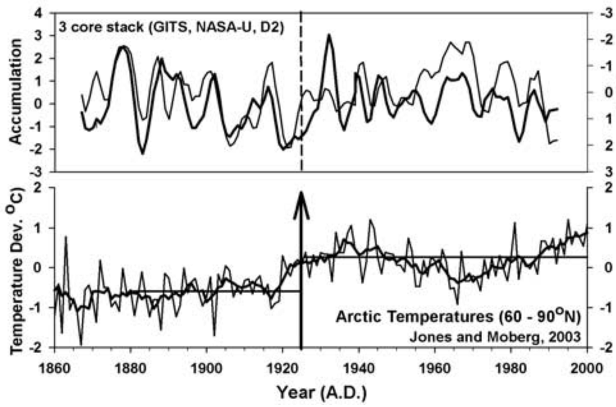

Figure 3. The stacked accumulation record (darker line) and NAO Index [*Hurrell et al.*, 1995] in the upper panel are compared with Arctic (60–90°N) temperature trends (annual and 5 year un-weighted running mean) from *Jones and Moberg* [2003] in the lower panel. See color version of this figure in the HTML.

that NAO forcing is intermittent. As central Greenland records continue to be used in multi-proxy reconstructions, it should be noted that the correlation between NAO and $\bar{A}_n$ at Summit is very low and even changes sign after the 1920s warming, thus confirming that central Greenland $\bar{A}_n$ records should not be used in NAO reconstructions.

4. Conclusions

[13] These results lead to the tentative conclusion that when it is warmer in higher latitudes, particularly over the Atlantic sector of the Arctic, the NAO influence on Greenland precipitation weakens along the west-central side of the ice sheet and strengthens in the southeastern region. This may partially explain why the NAO relationship with model-derived accumulation for the entire ice sheet [*Bromwich et al.*, 1999], for a recent, short time interval (1985–1995), was strongest over southern Greenland in winter. If our conclusions are valid, then the persistence of the positive phase of the NAO since the 1970s, coupled with the recent strong regional warming, may be partially responsible for the current reduction in surface elevation (ice sheet thinning) in southeastern Greenland [*Abdalati et al.*, 2001]. $\bar{A}_n$ at site D1 (Figure 2) in southeastern Greenland has been declining since the 1970s.

[14] Our study, based on an analysis of the most extensive collection of ice core-derived annual accumulation histories available, provides the strongest demonstration to date that the influence of the NAO on net accumulation over the Greenland ice sheet is spatially and temporally variable. These records confirm that the strongest and most persistent NAO modulation of accumulation occurs in the west-central part of the ice sheet. Moreover, this relationship appears to be sensitive to large-scale warming in high northern latitudes, such as occurred in the 1920s. After the warming (post-1925), the relationship between NASA-U $\bar{A}_n$ and the NAO weakened and the explained variance declined from 53% to 23%. These results (Table 1) caution that Greenland ice core records should not be used indiscriminately (or simply because they are of high resolution and readily available) in multi-proxy NAO reconstructions. We recommend that multi-proxy NAO reconstructions use only the NASA-U accumulation history. In addition, the D1 record suggests that accumulation in southeastern Greenland may be partially modulated (explained variance = 22%) by the NAO under warmer conditions in the high northern latitudes, as have persisted since 1925 (Figure 3). Although the PARCA core collection provides the best available combination of high temporal quality and broad spatial coverage, future efforts to reconstruct longer NAO histories using ice core $\bar{A}_n$ records should have as the highest priority the collection of new cores in west-central Greenland, in close proximity to the NASA-U site, and as a second priority the collection of new cores in southeastern Greenland, where rapid melting and ice sheet thinning are underway [*Abdalati et al.*, 2001].

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