Reconstructing climate variability from Greenland ice sheet accumulation: An ERA40 study

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[1] Re-analysis data covering the period 1958–2001 are used to investigate the relationship between regional, inter-annual snow accumulation variability over the Greenland Ice Sheet (GrIS) and large scale circulation patterns, cyclone frequency, and strength. Four regions of the GrIS have been identified that are highly independent with respect to accumulation variability. Accumulation indices of three of these regions are associated with distinct large-scale circulation patterns: Central-western GrIS reveals an inverse relationship with a NAO-like pattern, the south-west a positive correlation with a high pressure bridge from central North Atlantic to Scandinavia, and the south-eastern GrIS a positive correlation with a high-pressure anomaly over the Greenland Sea. These large-scale patterns also impact European climate in different ways. Accumulation variability in north-eastern GrIS, however, is dominated by cyclones originating from the Greenland Sea. Thus, Greenland ice core accumulation records offer the potential to reconstruct various large-scale circulation patterns and regional storm activity.
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1. Introduction

[2] Snow accumulation rates (defined as snow fall – snow evaporation) deduced from Greenland ice core records have been recently used to study the mass balance of the Greenland Ice Sheet (GrIS) and climate variability over a range of different time scales [*Hanna et al.*, 2005; *Bales et al.*, 2001; *McConnell et al.*, 2000a; *Crüger and von Storch*, 2002; *Crüger et al.*, 2004]. In particular, the influence of the North Atlantic Oscillation (NAO) on the snow accumulation on the GrIS was used to reconstruct a NAO-index (NAOI) beyond the instrumental period [*Appenzeller et al.*, 1998a, 1998b]. The accumulation rates from the NASAU ice core (73.84°N, 49.49°W) in North-Western Greenland, for instance, revealed a significant correlation ($r = -0.57$) with the instrumental NAOI. However, the agreement among the various pre-instrumental NAOI reconstructions including NASAU is not significant [*Luterbacher et al.*, 2002a, 2002b].

[3] One explanation could be that the NAO itself is not stationary in time with a change in the position of its centers of action [*Christoph et al.*, 2000; *Raible et al.*, 2005] and/or with a change in the regime behaviour [*Raible et al.*, 2001; *Casty et al.*, 2005] leading to a different signal in proxy records. Additionally, there is essentially no correlation of ice-core accumulation with the NAOI in other parts of the GrIS or average GrIS accumulation rates [*Hanna et al.*, 2005]. This is consistent with the conclusions drawn from findings of *Appenzeller et al.* [1998a] showing that NAO predominately modulates the accumulation only in the northwest of the GrIS.

[4] While the NAO is clearly reflected in the ice core accumulation records from northwestern GrIS, it might not be the most prominent circulation pattern affecting accumulation rates in other parts of the GrIS. Thus, rather than identifying the NAO in GrIS accumulation rates, here we reverse the question and determine the synoptic atmospheric circulation patterns that modulate the inter-annual variability of annual accumulation rates in various regions of the GrIS and investigate the influence of cyclone characteristics on the annual accumulation rates over Greenland. This is done using re-analysis data fields.

2. Data and Analysis Techniques

[5] NCEP-NCAR re-analysis [*Kalnay et al.*, 1996; *Kistler et al.*, 2001] and the European Centre for Medium-Range Weather Forecasts re-analysis data set (ERA40) [*Simmons and Gibson*, 2000] are used with a $1^\circ \times 1^\circ$ horizontal resolution for ERA40 and $2.5^\circ \times 2.5^\circ$ for NCEP-NCAR. The overlapping period of the data sets from 1958–2001 is used in this study. The analysis is based on yearly data averaged from March to March to account for the annual resolution of ice core data, which are often dated using the spring peaks of calcium or sodium concentrations. However, the results do not change in any significant way if the data are averaged from January to January, and all the conclusions below remain the same.

[6] The study is based on classical correlation- and composite analyses. For the composite analysis the fields of all the years in which the corresponding index time series exceeded + or fell below − one standard deviation from the mean are averaged separately. The difference between these two averages is shown in this study giving information about the amplitude, whereas the correlation analysis exhibits the phase relation between indices and fields. Different accumulation rate and cyclone indices were created for the correlation- and composite analysis.

[7] Four accumulation rate indices were defined for the central-western (*CW*; 70–75°N, 40–50°W), the north-eastern (*NE*; 76–82°N, 30–40°W), the south-western (*SW*; 63–66°N, 47–48°W), and the south-eastern (*SE*; 63–65°N, 44°W, 64–66°N, 43°W, and 65–66°N, 42°W) part of Greenland by de-trending and standardizing the

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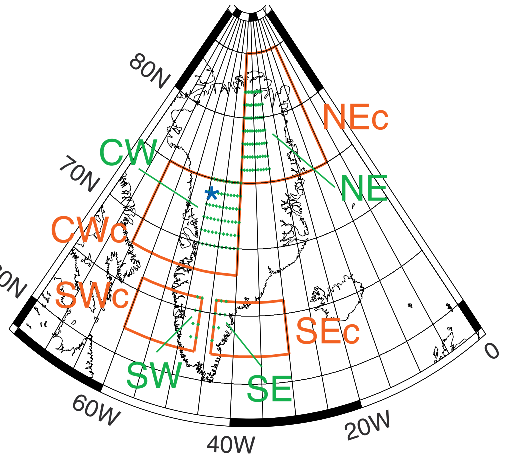

Figure 1. Overview of the different regions used for the calculation of the accumulation (green) and cyclone indices (red). Blue asterisk is the location of the NASAU ice core.

spatial averages (Figure 1). Accumulation rates in the four regions are representative for larger areas of the GrIS (Figure 2). Note that due to the definition of the accumulation rate (i.e. snow fall – snow evaporation) there are also positive and negative correlations outside dry snow areas. The four areas of significant correlation cover most of the GrIS, suggesting that a much finer division is not necessary. The choice of the regions was also motivated by the fact that Greenland ice core data from these areas are available.

[8] Additionally, four cyclone activity indices are derived from the number of cyclones times their mean strength (measured by the mean geopotential height difference over 1000 km [*Raible and Blender*, 2004]) traveling along the central-western coast (*CWc*; 68–75°N, 65–40°W), the north-eastern coast (*NEc*; 75–85°N, 40–10°W), the south-western coast (*SWc*; 62–66°N, 60–47°W), and the south-eastern coast (*SEc*; 62–66°N, 44–30°W) of Greenland (Figure 1). These indices are used to investigate the importance of cyclones for the accumulation over Greenland and to identify their origin, because mean cyclone tracks can be interpreted as back trajectories. To create the cyclone indices, a standard cyclone tracking scheme [*Blender et al.*, 1997] is applied to the re-analysis data of the 1000 hPa geopotential height in 6-hourly resolution.

3. Results and Discussion

[9] The ERA40 accumulation rate climatology exhibits a maximum in southeastern Greenland with a decline to the north-west (not shown). It resembles the observed pattern and variability over the GrIS [*Hanna et al.*, 2005; *Bales et al.*, 2001; *McConnell et al.*, 2000a]. Comparing NCEP-NCAR with ERA precipitation, NCEP-NCAR data strongly overestimate precipitation in central and south-eastern Greenland and show reduced precipitation in the southwest (not shown). This is likely linked to the different orography as well as differences in the precipitation parametrization schemes used in the two reanalyses.

[10] Moreover, the mean cyclone density in the period 1958–2001 of the ERA40 re-analysis data sets shows a maximum between Greenland and Iceland resembling the observations (not shown). Comparing again both re-analysis data sets we find a strong difference in cyclone density in the Hudson Bay resembling the findings of *Hodges et al.* [2003] which can be traced back to differences in the orography. Because of these strong deviations we limit the subsequent discussion to ERA40 results.

[11] The correlations between the accumulation indices of the four regions are mainly low *CW–NE*: $r = 0.13$, *CW–SW*: $r = 0.45$ *CW–SE*: $r = 0.15$ *NE–SW*: $r = 0.28$, *NE–SE*: $r = 0.16$, *SW–SE*:$r = -0.07$, only *CW–SW* being significant at the 95% level. Correlating the four indices with the accumulation rate over Greenland reveals four distinct areas (Figure 2). The high degree of independence of the accumulation rates among the various regions of the GrIS is consistent with ice core data [*Crüger et al.*, 2004].

[12] The correlation and composite maps of the four regional accumulation indices with the 500 hPa geopotential height reveal distinctly different patterns (Figures 3a–3d). Accumulation anomalies in CW are connected with a NAO-like pattern, e.g., positive accumulation anomalies are linked with an extended high-pressure blocking situation south of Greenland owing to a negative NAO-like pattern (Figure 3a) and vice versa. This blocking-like situation leads to a weakening of the westerlies and an enhanced anomalous circulation to central-western Greenland. For Europe typical negative NAO precipitation and temperature patterns will result [*Hurrell*, 1995]. The correlation with the *NE* (Figure 3b) and the *SW* (Figure 3c) indices reveals a high pressure bridge from central North Atlantic to Scandinavia for positive accumulation indices. The *NE* correlation map is rather weak whereas the correlations with the *SW* index are highly significant. In the case of positive accumulation anomaly in the *SW* the westerlies are significantly strengthened over the southern tip of Greenland. This circulation pattern suggests dry conditions over central Europe. For a positive *SE* accumulation index another blocking-like pattern with a center over Northern Scandinavia to Spitsbergen is found (Figure 3d). This pattern suggests a flow regime transporting moist air masses to south-eastern Greenland and cold and dry air from the Arctic/Siberia to central Europe.

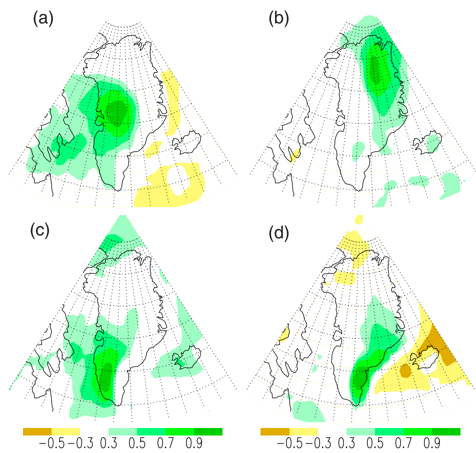

Figure 2. Correlation of accumulation rates (snow fall - snow evaporation) with the accumulation indices for (a) central-western *CW*, (b) north-eastern (*NE*), (c) south-western (*SW*) and (d) south-eastern (*SE*) Greenland revealing distinct areas with largely independent accumulation variability. Shading indicates significant correlation coefficients at a level of 95%.

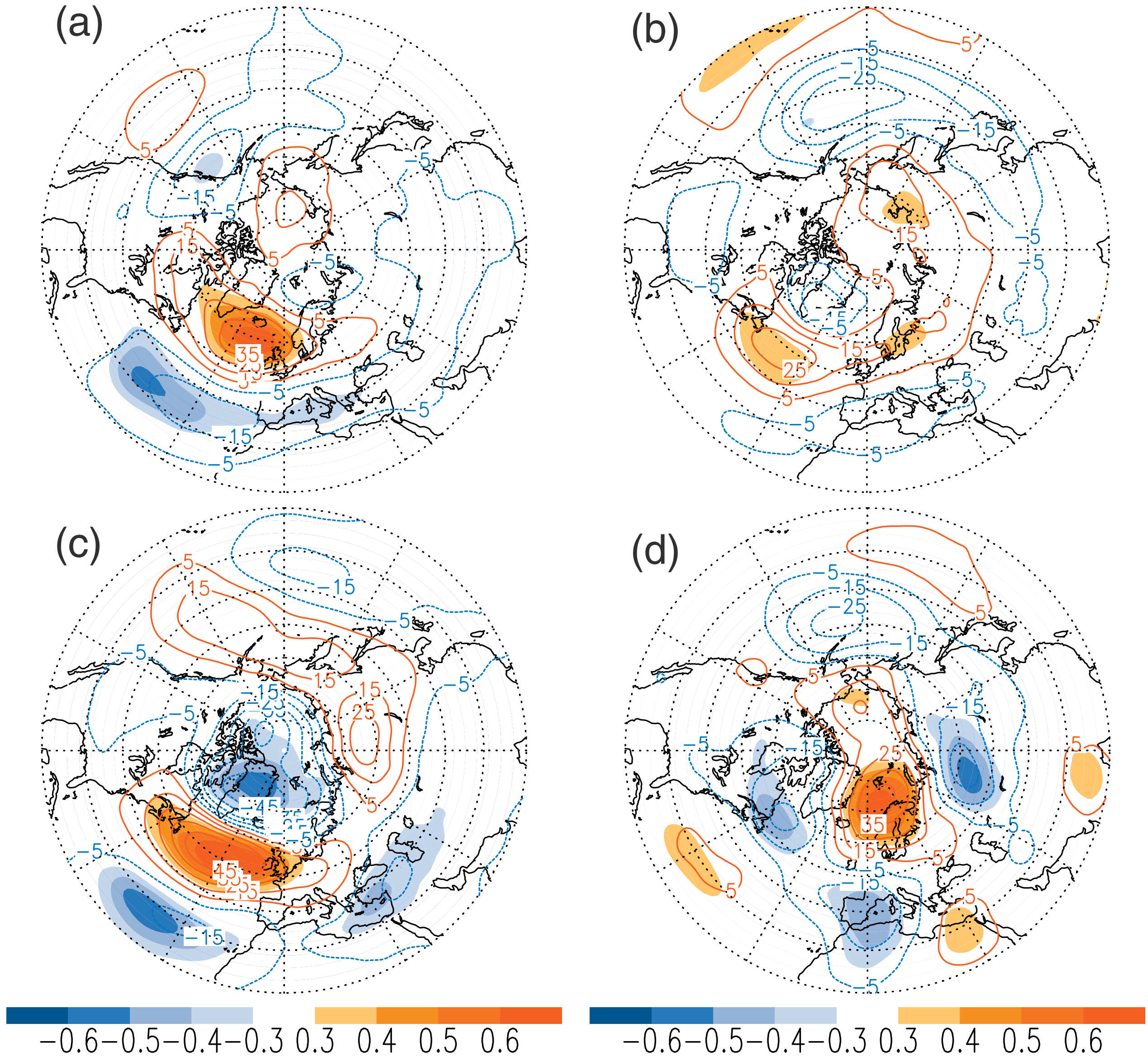

Figure 3. Relation between the 500 hPa geopotential height and (a) central-western, (b) north-eastern, (c) south-western, and (d) south-eastern accumulation index showing distinctly different circulation patterns. The shading indicates the correlation pattern significant at a level of 95%. The contours illustrate the composite analysis using ± one standard deviation of the corresponding accumulation index in geopotential height meters.

[13] The correlation maps of the *CWc*, *SWc*, and *SEc* cyclone indices with the accumulation rate exhibit low correlations over the GrIS (not shown). This indicates a negligible influence of cyclones on the accumulation in the corresponding inland areas. The accumulation rates in north-eastern Greenland, however, are significantly correlated with the *NEc* index (Figure 4). Thus, the cyclone frequency and strength are contributing substantially to the interannual variability of the accumulation rate in this region. The corresponding cyclone tracks (not shown) indicate that these cyclones mainly originate from the Greenland Sea.

4. Conclusions

[14] Interannual variability of snow accumulation in different regions of the GrIS was investigated in terms of large-scale atmospheric circulation patterns and cyclone activity using ERA40 data.

[15] Comparing the results of the geopotential height correlation maps (using the ERA40-derived accumulation indices) with the accumulation correlation maps (using the ERA40-derived cyclone indices) we show evidence that the accumulation variability in the *CW*, *SW* and *SE* areas of GrIS are influenced by distinct large-scale circulation patterns rather than cyclones. Each of these patterns also has a different impact on the climate over Europe. In contrast, the accumulation rate variations in the *NE* of the GrIS are dominated by the frequency and strength of cyclones originating from the Greenland Sea, rather than a large-scale circulation pattern.

[16] Thus, our results indicate that ice core derived accumulation records from the GrIS could not only be used in an attempt to reconstruct NAOI in the past (supporting previous

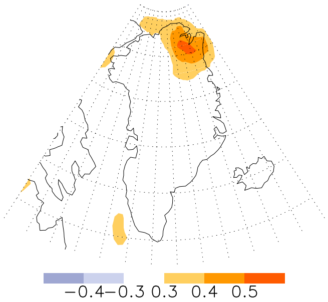

Figure 4. Correlation between the annual accumulation rate and the index of cyclones traveling along the north-eastern coast (NEc) of Greenland indicating a significant influence of cyclone frequency and strength on the inter-annual accumulation variability in this area. Shading indicates significant correlation coefficients at a level of 95%.

studies [*Appenzeller et al.*, 1998a]), but also two other indices related to distinctly different circulation patterns, as well as an index of cyclone activity over the Greenland Sea.

[17] Given that individual ice core accumulation records are subject to significant glaciological noise [*McConnell et al.*, 2000b] especially at low accumulation sites, regional averages should be used for reconstructions of indices. However, as our results indicate, only records from an area of similar meteorological influence (indicated by strong correlations of neighboring grid cells) should be included in such an average. It is interesting to note that the four identified areas correspond to different hydrological basins separated by ice divides [*Ohmura and Reeh*, 1991]. Therefore, only accumulation records from inland areas away from ice divides and domes should be used to reconstruct our indices. Additional independent indices might be obtained from other basins (e.g., NW Greenland) and possibly ice caps (e.g., Renland ice cap in eastern Greenland).

[18] The study has shown that ERA40 re-analysis data can be very useful for interpreting accumulation records, and could also be used in future studies based on ice core chemical records.

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