Atmospheric circulation and cyclone frequency variations linked to the primary modes of Greenland snow accumulation

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[1] Data from 34 Greenland firn cores, extending from 1982 to 1996, are used to identify spatial accumulation variability patterns and their associated atmospheric circulation and cyclone frequencies. The first principal component, representing west-central Greenland accumulation, is correlated to NAO variability, having increased southwesterly (northeasterly) flow over that area during high (low) accumulation winters. The flow is linked to a relative increase in cyclone activity on the west central region of the ice sheet during high accumulation periods. The second principal component represents accumulation over southeastern Greenland where strong westerly flow leads to high accumulation and an increase in lee cyclones on the east and southeast coast. The study provides evidence that increased cyclone activity occurs over, or immediately adjacent to, areas experiencing anomalously high accumulation and it is important to distinguish lee cyclones from "Icelandic" cyclones, as they produce opposite precipitation effects over the ice sheet. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1827 Hydrology: Glaciology (1863); 1863 Hydrology: Snow and ice (1827); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3349 Meteorology and Atmospheric Dynamics: Polar meteorology. **Citation:** Rogers, J. C., D. J. Bathke, E. Mosley-Thompson, and S.-H. Wang (2004), Atmospheric circulation and cyclone frequency variations linked to the primary modes of Greenland snow accumulation, *Geophys. Res. Lett.*, *31*, L23208, doi:10.1029/2004GL021048.

1. Introduction

[2] Understanding the mass balance of the Greenland ice cap is important in assessing the future potential of increases in sea level if the planet undergoes a major warming. This necessitates identification and evaluation of mechanisms controlling the ice sheet's mass balance. To this end NASA initiated the Program for Arctic Regional Climate Assessment (PARCA) to collect a diverse set of observations [*Thomas et al.*, 2001]. These included the collection of a spatially distributed array of firn and ice cores from various regions of the ice sheet to improve estimates of net mass accumulation and its temporal variability [see *Mosley-Thompson et al.*, 2001, Figure 1]. The annual layer thicknesses (annual mass accumulation) were determined using multiple seasonally varying proxy indicators (dust, nitrate and $\delta^{18}O$) measured in continuous samples cut from the firn cores. To estimate the annual mass accumulation, the firn depths were converted to water equivalent depths using empirically derived functions based upon discontinuous density profiles. Details of sampling, dating, and conversion to water equivalent are reported by *Mosley-Thompson et al.* [2001].

[3] The atmosphere is a key control of the mass balance of Greenland and several studies have focused on its role in temperature-related oxygen isotopic studies [e.g., *White et al.*, 1997; *Rogers et al.*, 1998]. Fewer studies however, have focused directly on the link between atmospheric circulation variability and Greenland accumulation. *Appenzeller et al.* [1998] used accumulation data from 5 separate sites, combined them into one long west-central Greenland ice accumulation time series, and found that the record was correlated to annual NAO values ($r = -0.22$; significant at 95%) between 1865–1982. They also reported an NAO link to west central Greenland net precipitation (precipitation minus evaporation) from 1979–1993 using European Centre for Medium-Range Weather Forecasting (ECMWF) reanalyses. *Bromwich et al.* [1999] found a strong association ($r = -0.75$) between the NAO index (NAOI) and total Greenland precipitation from 1985–1995 based on ECMWF operational analyses. The highest correlations are for winter (DJF) NAOI values and seasonal precipitation totals in both west-central and southern Greenland, where accumulation is higher if the Icelandic Low is weak and displaced toward the Labrador Sea. The purpose of this study is to improve our understanding of the spatial patterns of Greenland mass accumulation using the large array of PARCA cores. The accumulation records from the spatial array are evaluated using principal components analysis [*Bathke*, 2004] to identify their spatial variability and subsequently link it to atmospheric circulation and cyclone frequencies.

2. Data and Methodology

[4] The Greenland data are derived from an array of PARCA firn and ice cores that have annual net accumulations at 34 sites in central and southern Greenland (south of 73°N) for a common period from 1982–1996. Rotated principal component analysis (RPCA) is performed on the 34 annual accumulation records to obtain a representation of the dominant spatial modes of the accumulation fields [*Bathke*, 2004]. A varimax rotation procedure is applied to redistribute dataset variance so as to emphasize unique spatial patterns, rather than simply maximize dataset variance as is done in unrotated eigenvector solutions. Four eigenvectors were rotated in the procedure, based on the location of the first major shelf in the plot of eigenvalues

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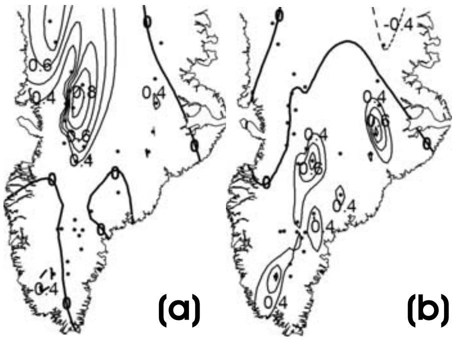

Figure 1. The rotated principal component (RPC) loadings of ice accumulation for (a) RPC 1 and (b) RPC 2. Loadings greater than absolute ±0.4 are contoured with solid lines (dashed if negative).

associated with each eigenvector. Only the first two patterns are described here, accounting for 23.8% and 15.4% of the unrotated dataset variance, respectively. RPCs consist of spatially distributed numerical loading values. The highest values among them determine which core sites comprise each component. The RPCs also consist of scores that are time series of the component that indicate whether a relatively positive (high) or negative (low) value of accumulation occurs in a given year among the core sites comprising the component.

[5] Atmospheric circulation data consist of NCEP/NCAR reanalysis monthly 700 hPa height and sea level pressure (SLP) fields. The NAOI is updated from *Rogers* [1984] and based on pressure differences between Ponta Delgada, Azores, and Akureyri, Iceland. Analysis of surface cyclone frequencies is performed using *Serreze*'s [1995] cyclone tracking algorithm on NCEP/NCAR 6 hourly 2.5° × 2.5° grid data. The algorithm identifies sea level pressure cyclones and tracks them from genesis to cyclolysis across the hemisphere by seeking grid points around which the pressure becomes gradually larger in all directions, and subsequently places the cyclones on a 50 km × 50 km grid using a bilinear interpolation routine. The method identifies virtually all cyclones and data filtering eliminates cyclones with lifetimes less than 12 hours, presumed to be false cyclones.

3. Results

[6] RPCA was performed on annual Greenland accumulation data. The first mode of variability is characterized by high loadings on 10 cores in west central Greenland (Figure 1a) with a minor area of negative loadings on 2 cores in the extreme south. The second mode has high loadings on 11 cores in southern and southeastern Greenland (Figure 1b). These 2 modes are the focus of this study; the third and fourth patterns have loadings on isolated core sites and lack the spatial coherence apparent in the first two modes [*Bathke*, 2004]. Time series scores of the principal components (Figure 2) are uncorrelated due to constraints of the varimax rotation procedure. Although uncorrelated, both RPC time series share features such as high positive scores in 1996, a year of unusually high accumulation [*McConnell et al.*, 2001, Plates 1 and 3].

[7] RPC1 accumulation scores are correlated r = −0.55 (95% confidence) to the normalized NAOI averaged over the months DJFM (Figure 2). This correlation supports the *Appenzeller et al.* [1998] link between the NAO and their composite west-central Greenland core. The DJFM period is used throughout this study as statistical relationships between atmospheric circulation and ice accumulation were found to be most significant in this season compared to all other combinations of months.

[8] The 6 highest (positive), and 6 lowest (negative), annual accumulation RPC scores were determined and the associated mean DJFM 700 hPa and SLP fields were obtained. RPC1 DJFM 700 hPa heights are characterized by a ridge over eastern Greenland in both high (Figure 3a; 1985, 88, 90, 91, 94, 96) and low (Figure 3b; 1982, 83, 84, 89, 92, 93) accumulation years although heights are substantially lower in the latter. The net 700 hPa height (Figure 3c) and SLP (Figure 3d) differences between high and low accumulation years are largest and most significant over the Barents Sea, with positive values extending southwestward and encompassing Iceland. The southern NAO pole of opposite sign occurs near the Bay of Biscay in both data sets, and is illustrated in Figure 3d. The sign of the differences in Figures 3c and 3d correspond to that of SLP/height anomalies during high accumulation winters (negative NAO mode) with anomalous southwesterly geostrophic flow over west-central Greenland. Anomalous northeasterly flow would occur across west-central Greenland when the 700 hPa heights and SLPs are unusually low over eastern Greenland (NAO positive mode), giving rise to lower accumulation winters. The DJFM 700 hPa Baffin Bay low is deeper and closer to Greenland during low accumulation years (Figure 3b compared to Figure 3a). The implied storm activity associated with this feature thus seems to have little effect on accumulation.

[9] Large significant 700 hPa differences between the extreme high (1983, 84, 87, 88, 93, 96) and low (1982, 85, 86, 89, 94, 95) accumulation years of RPC2 occur over the central North Atlantic near 55°N (Figure 3e). The pressure differences decrease to the north, reverse sign over northern Greenland, and reach a minimum in Baffin Bay. The change in the pressure differences is largest over southern Greenland, Denmark Strait, and Iceland, representing stronger (weaker) than usual west-southwesterly geostrophic winds

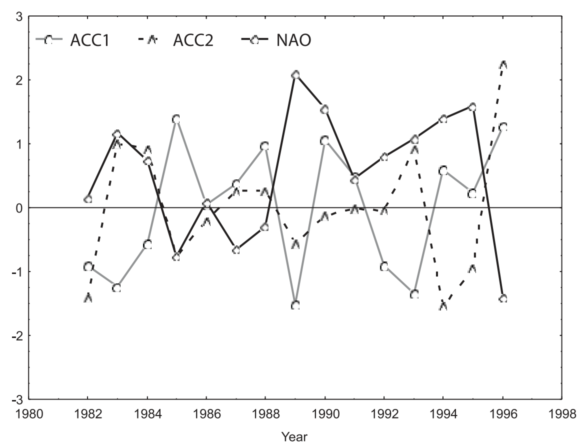

Figure 2. Time series, 1982–1996, of RPC1 and RPC2 scores and the NAOI in standardized units between +3 and −3.

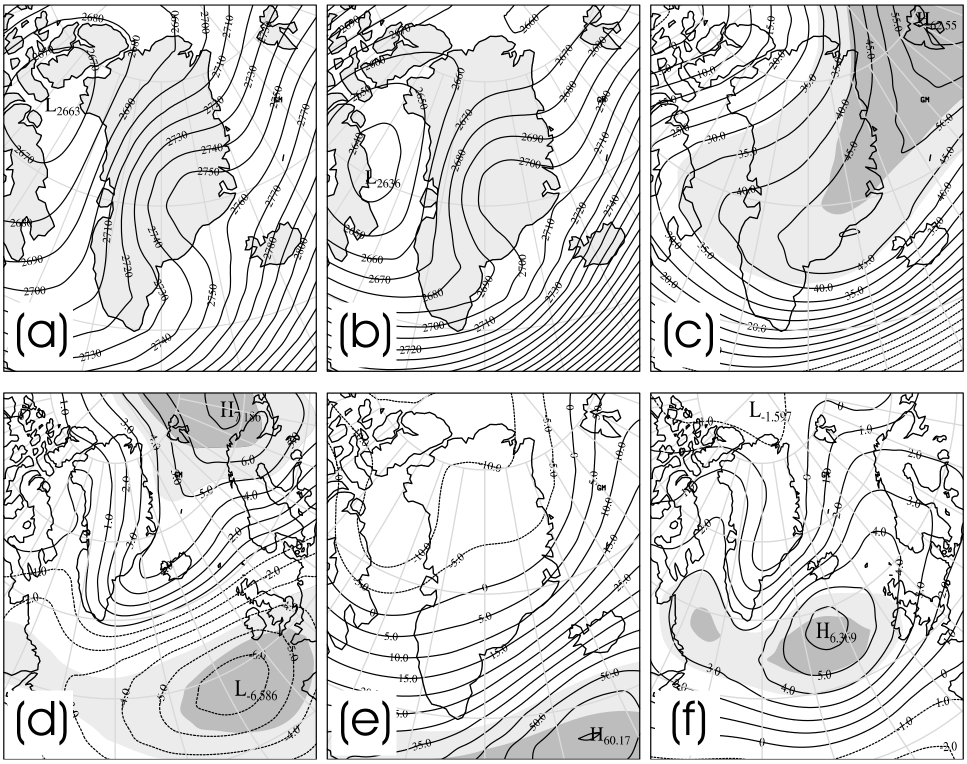

Figure 3. DJFM mean 700 hPa geopotential height fields during (a) high and (b) low accumulation years for RPC1. The net mean RPC1 (c) 700 hPa and (d) SLP differences between high and low accumulation years. (e) The net mean RPC2 700 hPa differences between high and low accumulation years and (f) the same but for sea level pressure differences. Areas with light and darker shading have differences statistically different from zero with 95% and 99% confidence, respectively, as obtained using a two-tail t-test.

over the region during high (low) accumulation winters. Negative mean SLP differences (Figure 3f) over eastern Greenland represent a weak trough (ridge) in high (low) accumulation winters. The zero line separating the negative and positive SLP differences (Figure 3f) passes through Denmark Strait and over Iceland signifying that the mean Icelandic Low, located just southwest of Iceland, has virtually the same spatial position and central mean pressure in both sets of winters. RPC2 scores are correlated r = −0.38 with the NAOI, significantly different than zero with only 80% confidence.

[10] The net difference in DJFM cyclone frequencies occurring between high and low RPC1 accumulation years (Figure 4a) is positive over west-central Greenland, representing relatively higher cyclone frequencies in that area during high accumulation years. The ridge extending southwestward to Iceland in Figure 3d is linked here to fewer cyclones around Iceland in high accumulation (negative NAO) winters. High cyclone frequencies in low accumulation years (negative differences), occurring from southern Greenland to Iceland and then extending northeastward, represent storms that would help advect drier northerly flow westward across the ice cap. To the west, over Baffin Bay, the negative differences represent higher frequencies in low accumulation years (i.e., the Baffin low).

[11] The area along eastern Greenland has positive cyclone frequency differences for RPC2 (Figure 4b), signifying greater numbers during high accumulation winters in southeastern Greenland, and is linked to the weak trough in Figure 3f. Comparisons between Figures 4a and 4b show that RPC2 cyclones are much more frequent on the eastern coast, as well as over the adjacent East Greenland Current; areas where RPC1 NAO-related cyclone activity generally does not occur. In particular, a maximum occurs very close to the southeast coast, rather than over the area closer to Iceland, as was observed for RPC 1 cyclones in Figure 4a. The DJFM mean Icelandic low has nearly the same central pressure (996 and 994 hPa in high and low RPC2 accumulation, respectively) and in both cases is

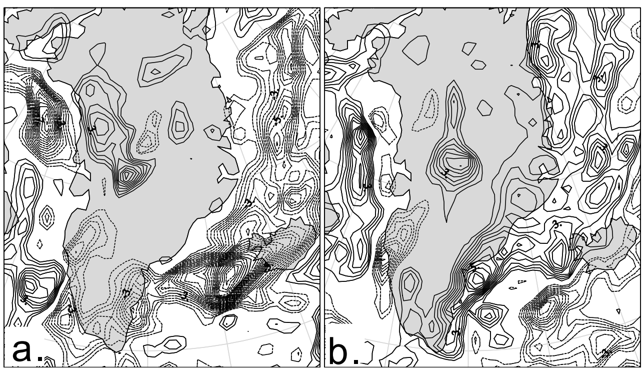

Figure 4. (a) DJFM cyclone frequency differences (intervals of 0.5 starting at absolute 1.0) obtained for high minus low RPC1 accumulation years and (b) the same but for RPC2.

centered near 63°N, 30°W. Thus higher cyclone frequencies, preferring the southeast and east coast, occur in high accumulation years when a slightly weaker mean Icelandic low occurs.

4. Discussion

[12] The results of Figures 3 and 4 can be summarized as follows. (1) High accumulation years in both west central and south-southeast Greenland occur in conjunction with enhanced winter 700 hPa westerly flow over those areas. Over west-central Greenland this occurs due to flow around an enhanced ridge over southeastern Greenland and Denmark Strait (Figure 3a) associated with weakening (higher pressure) of the surface Icelandic low, the negative NAO phase. (2) Stronger westerly flow over southern and southeastern Greenland is linked to the increased frequency of lee cyclones all along the ice cap's east coast, especially in the southeast, and has only a weak NAO association. (3) The occurrence of high accumulation years in the two focal areas of this study is linked to higher frequencies and relatively close proximity of winter cyclones. It has been suggested that increased precipitation in southern Greenland occurs with variations in the position and intensity of the Icelandic low, particularly displacement of a weak low toward the Labrador Sea (NAO negative mode) bringing moisture to the ice cap from the east or southeast [*Bromwich et al.*, 1999]. We agree that the moisture would occur due to uplift from the east but the source appears to be more immediately along the southeast and east coast in the form of lee cyclones and a weak trough in the seasonal mean pressures (Figure 3f). The occurrence of mean low-pressure areas in the North Atlantic [*Serreze et al.*, 1997] implies that individual cyclones cluster in that region. In the case of a weak mean low in the Labrador Sea, the cyclones comprising it would not only tend to be weak (or infrequent), but located a considerable distance from the ice sheet.

[13] One outstanding issue in Greenland climate research is a clearer understanding of the processes by which precipitation arrives on Greenland. Our results provide strong evidence in support of suggestions [*Chen et al.*, 1997; *Bromwich et al.*, 1998] that lee cyclogenesis is important in precipitation production over southern and eastern Greenland. *Chen et al.* [1997] suggest that it is necessary to distinguish between lee cyclones, which we view as being very close to the southeast and east coast of Greenland, as opposed to "Icelandic" cyclones with centers farther east and which are less important in bringing precipitation directly onto the ice cap – in fact which may actually encourage northeasterly flow (on their northern side) over the ice cap that effectively reduces precipitation production. Furthermore, as initially suggested by *Chen et al.* [1997], a positive feedback is established through time over southern Greenland in which the elevated ice cap creates storms that add to its physical size by enhancing precipitation deposition, assuring, in the absence of other long-term processes that might favor ablation, the continued development of future lee storms.

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