Variability of accumulation in northwest Greenland over the past 250 years

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Abstract. During summer 1996, a 120-m firn and ice core was drilled to determine annual accumulation rates at a northwest Greenland site (GITS, 77.1392°N, 61.0422°W, 1910 m elevation). Annual layers were identified in the core using multiple parameters: $\delta^{18}O$ and concentrations of dust, hydrogen peroxide, ammonium, calcium and nitrate. Using all parameters together to define annual layers resulted in a 251-year record with a dating uncertainty of one year within that period. Annual accumulation over the period of record averaged about 0.37 m water equivalent. Comparing this record with four other multi-century long records from the west central and northwest portion of the ice sheet shows many periods when decadal-scale fluctuations in accumulation at the different sites are in phase. Overall variations in accumulation in this portion of the ice sheet were ± 8-9% per decade, versus ± 25% for individual cores. Annual accumulation at GITS showed a significant correlation with a 12-month North Atlantic Oscillation index (Pearson's R = -0.32 with a significance level of > 99%), though the correlation was slightly lower than for two cores roughly 350 and 700 km south.

Introduction

Accumulation estimates for the Greenland ice sheet have been based on point measurements made at over 250 locations, over a period of more than 70 years [*Ohmura and Reeh*, 1991]. The variability of ice sheet accumulation over time is of particular interest for studying changes in the mass balance of the ice sheet. However, the natural variability over space and time is superimposed upon the long-term trends, making them difficult to decipher. Here we report the accumulation history from a new core in northwest Greenland. We then use these data, together with other published records, to examine the decadal-scale variability of accumulation for the west-central and northwest portions of the ice sheet.

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Methods

In summer 1996, 120-m and 21-m ice cores were drilled at the Greenland Ice Sheet Training Facility (GITS, 77.1392°N, 61.0422°W, 1900 m elevation) using a 100-mm (4-in) electromechanical drill (Figure 1). The cores were about 30 m apart. For both cores we established uninterrupted records for six different physical or chemical parameters that exhibit seasonal variations: dust, $\delta^{18}O$, hydrogen peroxide, ammonium, calcium and nitrate. Analytical methods were described previously [*Anklin et al.*, 1998]. Core density was determined directly in the field by measuring and weighing each individual piece of core before bagging. The cores were dated by counting annual layers, and in the deeper core the volcanic eruption of Laki provided a time stratigraphic marker for the 1783/84 horizon [*Hammer*, 1977; *Fiacco et al.*, 1994].

Results

Using the multiple-parameter approach we were able to resolve dating discrepancies between the different parameters along the full length of the core. The accuracy of the dating is illustrated by correctly dating the Laki 1783/84 volcanic event by layer counting. Within the depth interval from the surface down to the Laki horizon we estimate an uncertainty of one year, based on those short intervals along the core where the parameters failed to give an unambiguous indication of annual layers. We estimate the date at the bottom of the 120-m core to be 1745, giving 251 complete years in the record. The uncertainty between the Laki horizon and the bottom is one year, owing to the loss of one 0.9 meter length of core during drilling. The bottom of the shallow core (21 m) was dated at 1965, giving a 31-year record. Annual layer thicknesses were adjusted to account for thinning at depth due to the vertical strain. Following *Dansgaard and Johnsen* [1969], we calculated a vertical strain rate, assumed to be constant from the surface to 400 meters above the bed. Using the current average layer thickness (0.387 m ice equivalent) and the 1966 ice sheet thickness [*Dansgaard and Johnsen, 1969*] at Camp Century 2 km away, a vertical strain rate of 3.4×10^{-4} per year was calculated. In reality the core

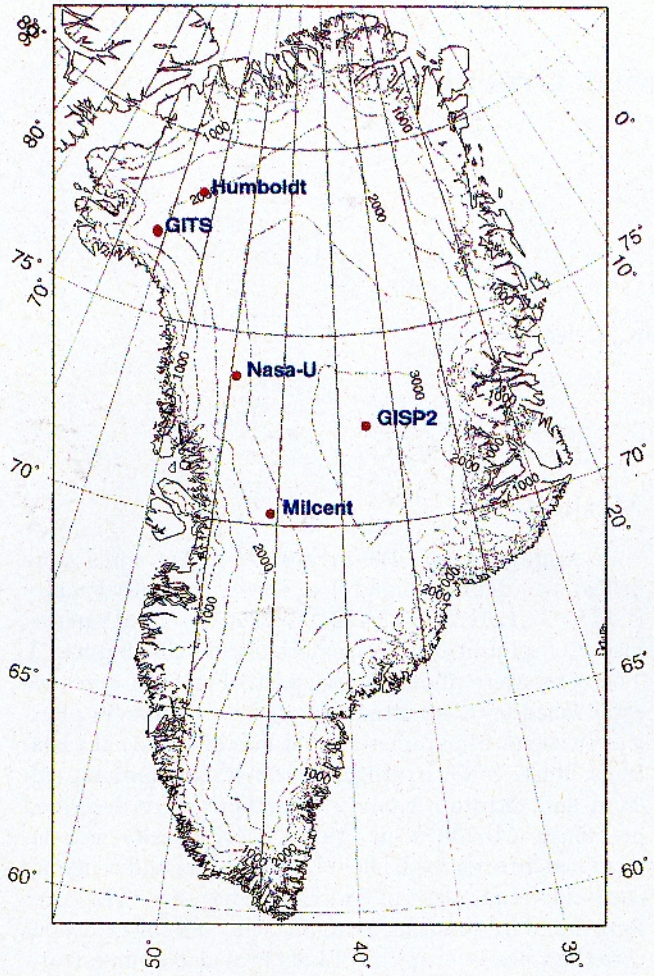

Figure 1. Location map, showing ice coring sites. Camp Century is the same location as GITS.

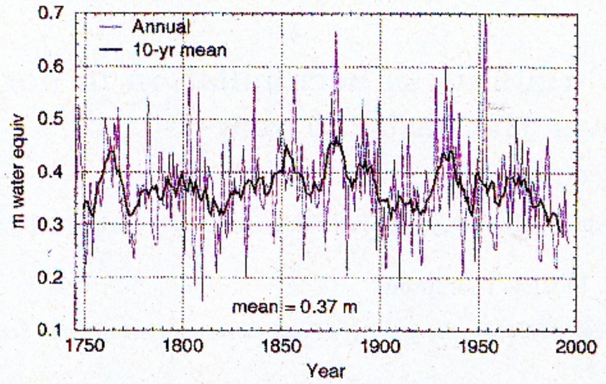

Figure 2. Annual accumulation for GITS based on calcium. Other annual markers were used to resolve discrepancies in the calcium record, and distinguish annual peaks from sub-annual peaks.

is short compared to the 1387-m thick ice sheet so that the reconstructed layer thicknesses are not highly dependent on the specific strain rate applied. A quick sensitivity calculation reveals an average accumulation rate of 0.370 m (water equivalent, w.e.) for the 251 years using 3.4×10^{-4} per year and 0.360 m w.e using 1×10^{-4} per year. No adjustments for thinning due to flow were included as the horizontal velocities of the ice sheet at GITS are only 4.1 m per year (202°) [*Hamilton and Whillans*, 1999].

The adjusted annual accumulation rates calculated using the annual calcium peaks are plotted in Figure 2 for the deeper core, together with a 10-year running mean. Three previous cores drilled in the vicinity of this site gave average accumulation rates (in meters w.e.) nearly the same as the current core: i) 0.35 over 100 years, 1966 core at 77.167°N, 61.133°W [*Crozaz and Langway*, 1966], ii) 0.35 over 216 years, 1977 core at 77.17972°N, 61.10974°W, and iii) 0.35 over 138 years, 1977 core at 77.22122°N, 61.80012°W [*Clausen et al.*, 1988]. No thinning corrections were made to these records. There was no statistically significant trend in the annual accumulation rates over the period of record. The 21-m core had an average accumulation of 0.351 m water equivalent; over the same 31-year period the 120-m core average was 0.370.

Temporal variability, expressed by the coefficient of variation for the full length of the core, was 0.26 for the 251-year record; values for the 31-year record were 0.19 and 0.23 for the two cores, similar to that observed for two other sites in northwest Greenland, Nasa-U and Humboldt [*Anklin et al.*, 1998]. For their overlapping 31 years, the correlation coefficient between the annual values for the two cores is 0.64, but application of a five-point triangular filter with weights 1,2,3,2,1 removes

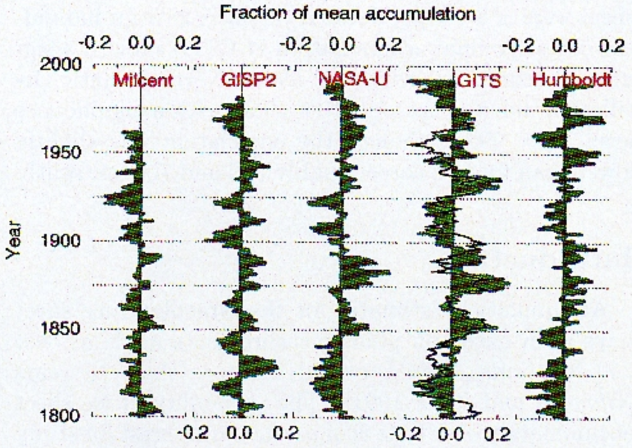

Figure 3. The accumulation records for the three cores in northwest Greenland are compared to two older cores from central Greenland, and to the Camp Century core. Camp Century and Milcent were based on *Claussen et al.* [1988], with data from the NOAA Paleoclimate Program's International Ice Core Data Cooperative (www.ngdc.noaa.gov/paleo/icecore/greenland/gisp/gisp.html). GISP2 was based on *Meese et al.* [1994], with data from The Greenland Ice Cores CD-ROM, 1997 (Available from the National Snow and Ice Data Center, University of Colorado at Boulder, and the World Data Center-A for Paleoclimatology, National Geophysical Data Center, Boulder, Colorado). Graphs are 10-year running means, normalized to their period of record since 1800 A.D. Heavy line on GITS graph is accumulation record for the Camp Century core.

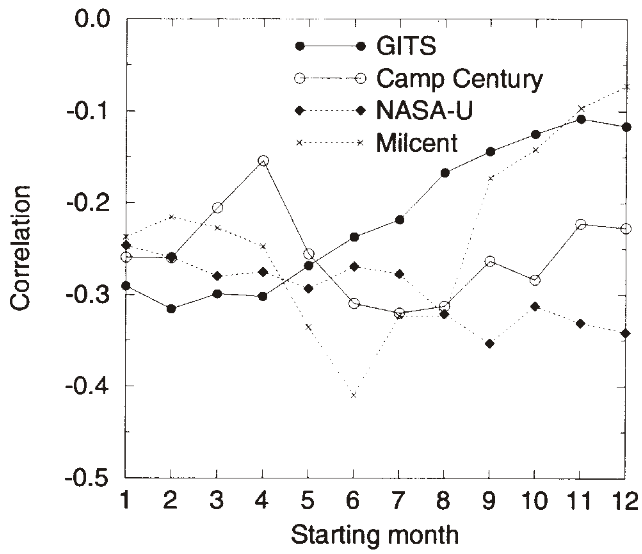

Figure 4. Correlation of annual accumulation for four cores with 12-month NAO, starting in different months (e.g. January NAO is Jan.-Dec., February NAO is Feb.-Jan).

some local small-scale spatial variability and increases their correlation to 0.86.

Discussion

There is a good match between the 10-year running mean accumulation from the GITS core and that from a 1977 core that was only about 2 km away (Figure 3), with a correlation coefficient of 0.46 for the triangular filtered data and 0.50 for the ten-year running means. However, it should be noted that annual layers in the 1977 core were based on a single annually varying parameter ($\delta^{18}O$), resulting in greater uncertainty in the dating of that core, and possibly reducing the correlation with the GITS core. As indicated, decadal averages for the GITS core fluctuated by as much as ± 25% of the mean, slightly more than for other cores from the west central and northwestern part of the ice sheet. Records from the five locations shown on Figure 1 exhibit similar patterns during some decades but not during others, possibly suggesting multi-decadal changes in the dominant circulation patterns over Greenland. In particular, the 10-year means for the GITS core showed the best correlation with NASA-U (r = 0.48), with the Milcent core next (r = 0.37). The weakest relationships were with Humboldt (r = 0.23), which is surprising as this is the closest core site to GITS, and with GISP2 (r = 0.25), which is not so surprising as this site is near the summit in the central part of the ice sheet. All correlations were significant at confidence level of >99%.

Some of the temporal variability in the GITS core can be attributed to the North Atlantic Oscillation (NAO). Correlation between the smoothed (five-point triangular filter applied) Nasa-U accumulation record and the NAO was reported previously [*Appenzeller et al.*, 1998] and a similar analysis of the GITS record shows lower correlation (r = -0.39) than at Nasa-U (r = -0.66); the

Table 1. Summary of correlations between ice cores and NAO indices (a)

Site	Time span	12-month period	Pearson's R	Spearman rank order
GITS	1865-1995	Feb-Jan	-0.316	-0.298
Camp Century	1865-1974	Jul-Jun	-0.320	-0.298
Nasa-U	1865-1994	Sep-Aug	-0.353	-0.342
Milcent	1865-1966	Jun-May	-0.410	-0.494

(a) Algorithms from Numerical Recipes

significance of both is greater than 0.99. We computed correlation coefficients between the unsmoothed annual accumulation records and an annual average NAO spanning various 12-month periods. NAO was calculated following Hurrell [*1995*], using sea-level pressures from the Azores and Iceland. Using a significance threshold of 0.5×10^{-3} at which the null hypothesis (NAO and accumulation are not correlated) may be rejected, all cores but GISP2 showed significant correlation to NAO using both parametric (Pearson's R) and non-parametric (Spearman Rank Order) correlations (Figure 4 and Table 1). For example, "annual" accumulation measured at GITS was found to correlate most significantly with an annual average monthly NAO from February of the year of the core measurement, to January of the following year. Because springtime dust peaks were used as annual markers, the annual accumulation reflects roughly the snowfall from April to the following March. The strongest correlation with the February to January NAO index suggests that NAO shifts may precede shifts in snow accumulation at GITS.

Averaging the six cores from the five locations gives an indication of how accumulation on that portion of the ice sheet has fluctuated. The 1980's were the lowest decade, about 9% below average, with the 1850's and 1870's the highest, about 8% above average (Figure 5). This decadal-scale fluctuation points out one source of uncertainty in using shallow cores or snow pits from different time periods for accumulation studies [e.g. *Ohmura and Reeh*, 1991]. Potentially, longer records such as those shown on Figure 3 could be used to scale shorter records from the same part of the ice sheet to a common time period. For example, the ac-

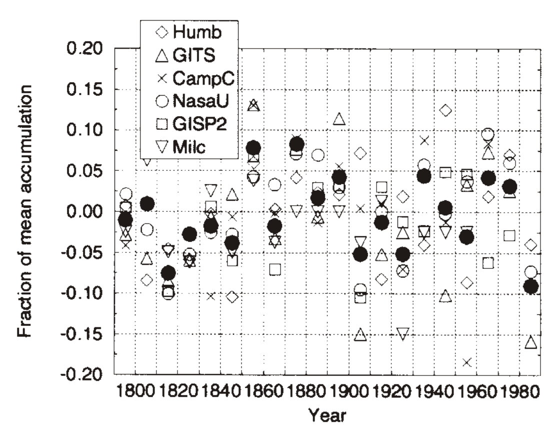

Figure 5. Comparison of decadal average accumulation for cores from west-central and northwest Greenland. Data from Figure 3.

cumulation in the 1970's relative to the 200-year mean was 1.03; so dividing records from the region that only cover the 1970's by 1.03 would give a better estimate of the 200-year mean accumulation.

Conclusions

Using multiple dating parameters to define annual layers resulted in a 251-year record for the 120-m GITS core, with a dating uncertainty of one year within that period. Multi-century long records from five sites show many periods when fluctuations in decadal accumulation at the different sites are in phase. Accumulation during the decade of the 1980s was the lowest in the last 200 years while that during the 1960's and 1970's was well above average.

Approximately one third of the observed variability in annual accumulation at GITS and other west-central and northwest Greenland ice core sites can be linked to the NAO. However, the correlation with NAO is relatively weak for cores further inland such as Humboldt and GISP2. The NAO signal is stronger in cores further south, and a new more-accurately dated core in the vicinity of Milcent should provide a very good proxy NAO record.

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References

Anklin, M., R. C. Bales, E. Mosley-Thompson, and K. Steffen, Annual accumulation at two sites in northwest Greenland during recent centuries, *Journal of Geophysical Research, 103(D22)*, 28,775–28,783, 1998.

Appenzeller, C., T. F. Stocker, and M. Anklin, North Atlantic Oscillation dynamics recorded in Greenland ice cores, *Science, 282*, 446–449, October 1998.

Clausen, H. B., N. S. Gundestrup, S. J. Johnsen, R. Bindschadler, and J. Zwally, Glaciological Invetigations in the Crete Area, Central Greenland: A Search for a New Deep-Drlling Site, *Annals of Glaciology, 10*, 1988.

Crozaz, C., and C. C. Langway, Jr., Dating Greenland firn-ice cores with Pb210, *Earth and Planetary Science Letters*, 194, 1966.

Dansgaard, W., and S. J. Johnsen, A flow model and a time scale for the ice core from Camp Century, Greenland, *Journal of Glaciology, 8(53)*, 215–223, 1969.

Fiacco, Jr., R. J., T. Thordarson, M. S. Germani, S. Self, J. M. Palais, S. Whitlow, and P. M. Grootes, Atmospheric aerosol loading and transport due to the 1783-84 Laki eruption in Iceland, interpreted from ash particles and acidity in the GISP2 ice core, *Quaternary Research, 42*, 231–240, 1994.

Hamilton, G. S., and I. M. Whillans, *Personal communication*, 1999.

Hammer, C. U., Past volcanism revealed by Greenland ice sheet impurities, *Nature, 270*, 482–486, 1977.

Hurrell, J. W., Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, *Science, 269*, 676–679, 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*, 1,680–1,682, 1994.

Ohmura, A., and N. Reeh, New precipitation and accumulation maps for Greenland, *Journal of Glaciology, 37(125)*, 140–148, 1991.

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