

Annual accumulation at two sites in northwest Greenland during recent centuries

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Abstract. During summer 1995, 150-m firn and ice cores were drilled to determine annual accumulation rates at two Greenland sites, 73.84°N, 49.49°W (NASA-U site) and 78.53°N, 56.83°W (Humboldt glacier site). Annual layers were identified in the cores using multiple parameters: $\delta^{18}\text{O}$ and concentrations of dust, H_2O_2 , NH_4^+ , Ca^{2+} , and NO_3^- . Using all parameters together to define annual layers resulted in a 350-year record for the NASA-U core with no dating uncertainty. For the lower-accumulation Humboldt core, the dating uncertainty is about 5 years over the 852-year period of record, with no uncertainty over the past 200 years. Annual accumulation over the periods of record at the two sites averaged about 0.34 and 0.14 m water equivalent, respectively. A set of 20-m firn cores drilled near the main 150-m cores showed that interannual variability of accumulation exceeded spatial variability at NASA-U. The Humboldt cores showed equal spatial and interannual variability. The accumulation rates at both sites showed a low-frequency variation of about 100 years, and both sites showed 200-year cumulative fluctuations of about 2 m from mean accumulation rates. Compared to central Greenland and to NASA-U, the Humboldt core showed higher annual accumulation rates around 1760–1810, possibly indicating a changed circulation pattern for the more northern part of Greenland in that period.

1. Introduction

Since the first glaciological studies on polar ice sheets, the distribution of annual accumulation rates has been of special interest. For Greenland, different accumulation maps have been prepared by *Diamond* [1958], *Bader* [1961], *Benson* [1962], *Mock* [1967], and most recently by *Ohmura and Reeh* [1991]. In 1991, NASA began an airborne program to establish the accuracy of laser altimetry over the Greenland ice sheet. From this evolved the Program for Arctic Regional Climate Assessment (PARCA), with the main goal of measuring and understanding the mass balance of the Greenland ice sheet. One objective of PARCA is to develop accurate estimates of the year-by-year accumulation rate

during the most recent centuries at various sites on Greenland from analyses of 20-m to 150-m deep firn and ice cores. In this paper we report the accumulation history and spatial variability for two sites in northwest Greenland and compare them to other published records.

2. Methods

In summer 1995, two 150-m ice cores and several shallow cores were drilled (Figure 1) east of Upernavik (NASA-U, 73.84°N, 49.49°W, 2370 m elevation) and on the Humboldt glacier (Humboldt, 78.53°N, 56.83°W, 1985 m elevation) using a 100-mm (4-in) electromechanical drill. Additional shallow cores (25 m) were taken to determine the spatial variability of the annual accumulation rate estimates. In addition, a 13-m shallow core was drilled using a 76-mm (3-in) hand auger at Crawford Point (69.85°N, 47.12°W, 2000 m elevation), which is located along the Expedition Glaciologique Internationale au Groenland (EGIG) line. The results from the Crawford Point shallow core are discussed only briefly

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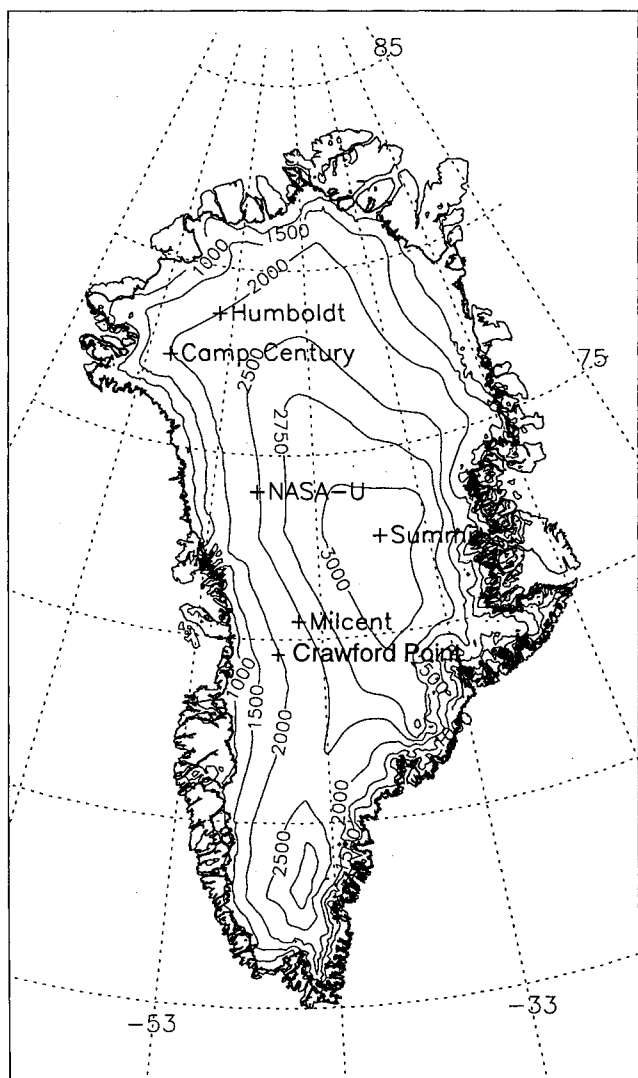


Figure 1. Location map, showing ice coring sites.

and presented in section 3. The main NASA-U core was drilled in a 1.5-m-deep pit, whereas the shallow NASA-U cores and the Humboldt cores were drilled from the surface. Besides the cores, the upper 2 m of the firn were studied in pits at both 150-m core sites to account for deficiencies in the near-surface core quality. Pit studies at NASA-U allowed the dating of the 150-m core to be extended to the surface. Density along the NASA-U and Humboldt cores was determined directly in the field by measuring and weighing each individual piece of core before bagging. For all cores we established uninterrupted records for six different physical or chemical parameters that exhibit seasonal variations: dust, $\delta^{18}\text{O}$, H_2O_2 , NH_4^+ , Ca^{2+} , and NO_3^- . Owing to compacting and loss of snow in the very top of the firn cores, we did not use the density measurements from the upper 1.5–2 m and calculated annual accumulation rates only below this depth. Depending on the drilling site, three to five of the independent parameters were used to estimate annual layer thickness on any given part of the cores. We also made visual stratigraphy observations in

the field using a light table, but unfortunately this did not provide as accurate an annual indicator as did the other parameters.

All dust analyses were performed at the Byrd Polar Research Center at Ohio State University, together with the $\delta^{18}\text{O}$ measurements on the NASA-U core. The remaining chemical species were analyzed by the Department of Hydrology and Water Resources at University of Arizona.

Insoluble dust samples were prepared and analyzed in a Class 100 clean room. The Coulter Model TA-II equipped with a 30- μm aperture tube counts particles ($0.63\ \mu\text{m} \leq \text{diameter} \leq 16.0\ \mu\text{m}$) in 16 size ranges. The concentrations are reported as the total number of particulates per milliliter of meltwater and are reproducible to within 5%. A Finnigan MAT-Delta E, with a precision of 0.1‰, was used for the NASA-U $\delta^{18}\text{O}$ analyses, which are standardized against Vienna SMOW (V-SMOW) and are reproducible to 0.1‰.

The chemical trace species, H_2O_2 , Ca^{2+} , NO_3^- , and NH_4^+ were analyzed with a self-built continuous flow analysis (CFA) system, similar to that described by *Sigg et al.* [1994], with two major differences. First, for the Ca^{2+} reagent we substituted a more sensitive fluorescence reagent based on a reaction with the tetracarboxyl ligand quin-2 [Clarke et al., 1988]. Second, we added a channel to the system to measure NO_3^- concentrations of the meltwater as well, using a colorimetric method [American Public Health Association (APHA), 1995]. Though we also analyzed for formaldehyde (HCHO) using the CFA system, HCHO cannot be used as an annual indicator since its seasonal signal is smoothed out in the top meter of the firn [Staffelbach, 1990]. We are interested in HCHO because it is an important parameter for modeling atmospheric oxidation capacity [Thompson, 1996], and the HCHO results will be presented in another paper. The reproducibility of the CFA system was very good, as shown in Figure 2.

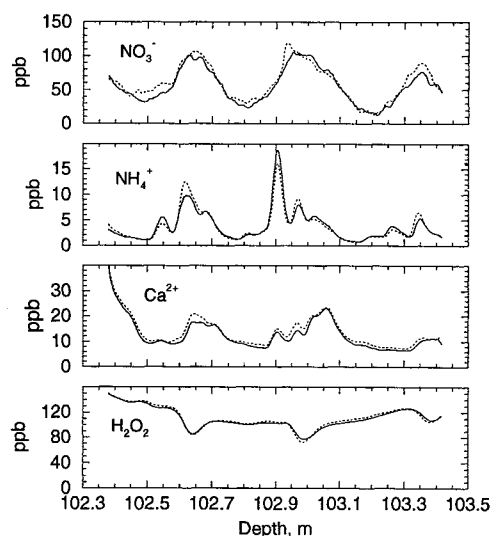


Figure 2. Replicate analyses (solid and dotted lines) on adjacent pieces cut from a 1-m section of NASA-U core to show the reproducibility of the melter analyses.

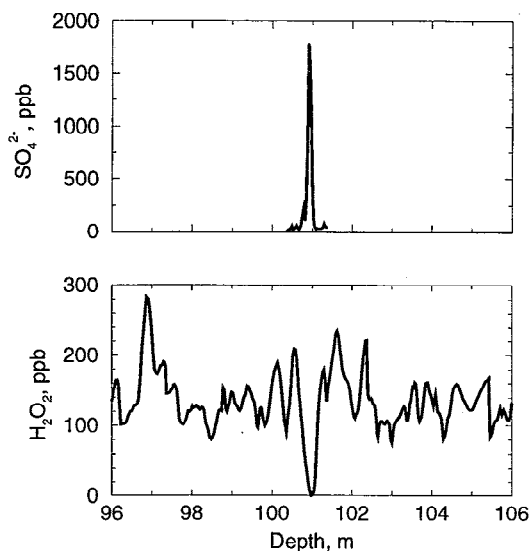


Figure 3. 10-m section of NASA-U core showing depression in H_2O_2 , marking the 1783-84 Laki event, which is confirmed by the SO_4^{2-} concentration peak.

Discrete samples were measured using a 40-mm resolution for dust and $\delta^{18}\text{O}$ along the NASA-U core and a 30-mm resolution for dust along the Humboldt core. For the species measured with the CFA system, the resolution is defined as the drop of a step function to the $1/e$ fraction [Sigg *et al.*, 1992], which was 19 mm for H_2O_2 , 15 mm for NH_4^+ , 25 mm for Ca^{2+} , 30 mm for NO_3^- , and 25 mm for HCHO . Resolution was limited by capillary rise of meltwater in the firn and by dispersion in the tubing in the CFA system. The detection limits were 0.2 ppb for H_2O_2 , 0.1 ppb for NH_4^+ , 0.2 ppb for Ca^{2+} , and 3 ppb for NO_3^- .

The cores from NASA-U, Humboldt, and Crawford Point were dated by counting annual layers, and in the former two the volcanic eruption of Laki provided a time stratigraphic marker for the 1783/84 horizon [Hammer, 1977; Fiacco *et al.*, 1994]. The Laki eruption was clearly identified in the NASA-U and Humboldt cores as a SO_4^{2-} peak that is coincident with a minimum in the H_2O_2 signal (Figure 3). Normally, the calcium spring peak was used to determine the final picks of the annual counter, and the other parameters were used to rule out double peak or missing peak features in the calcium record.

3. Results

Throughout much of the NASA-U cores, the seasonal signal was distinct for four-five parameters, as shown in Figures 4a and 4b. For Humboldt, the seasonal signal was distinct for at least two parameters (Figures 4c and 4d), calcium and dust. Seasonality can be determined only in those sections of the Humboldt core where, besides Ca^{2+} and dust, NO_3^- or NH_4^+ also showed clear annual cycles. Seasonal variations in the deposits of dust and calcium are preserved throughout the Humboldt core. Comparison among the different seasonally

varying constituents illustrates differences in the timing of their maximum deposition. Coupled with the fact that precipitation does not occur evenly throughout the year and that the annual timing of maximum flux may be modulated by synoptic scale processes, the annual layer thickness for any given year will depend upon the specific parameter used for layer identification. Finally, multiple or missing concentration peaks for any given parameter in some years can also contribute a significant uncertainty to the determination of trends in annual accumulation rates.

The quality of each parameter as a seasonal indicator depends on the average accumulation at the site as well as depth in the core. Where the accumulation rate is high enough to preserve the seasonal signal of $\delta^{18}\text{O}$ and H_2O_2 , these two parameters are generally the clearest seasonal indicators. For Humboldt, H_2O_2 was a good seasonal indicator only in the shallow firn; Ca^{2+}

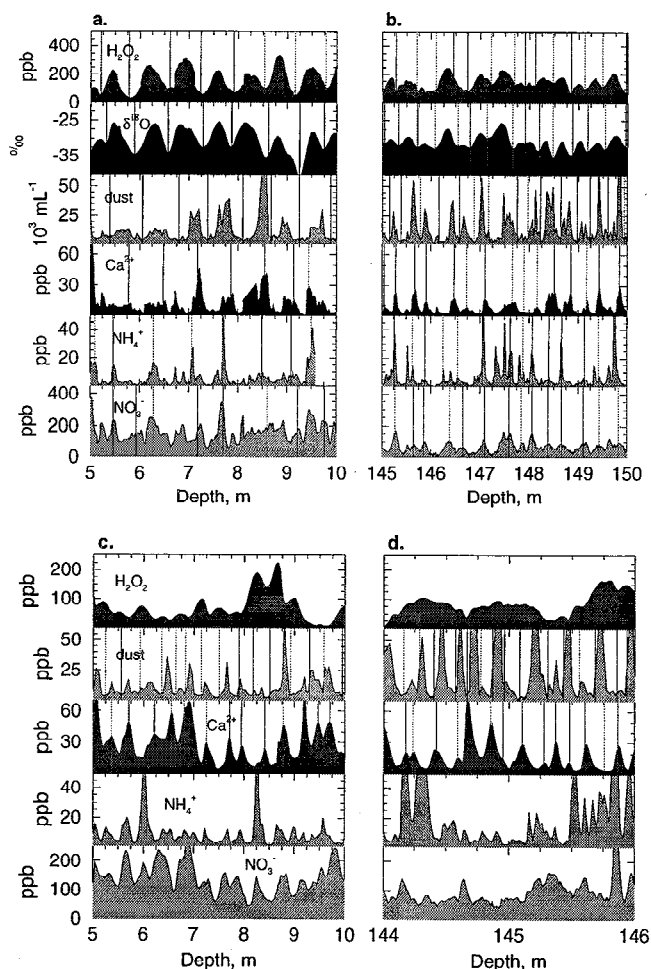


Figure 4. (a and b) Comparison of six markers from two different 5-m sections of NASA-U core 1. Vertical lines mark annual layers. (c and d) Comparison of two annual markers from two different sections of Humboldt main core. Note that dust and Ca^{2+} are not exactly in phase for the lower part of the Humboldt core, mainly due to difficulties in precisely registering samples cut at different times from this low-accumulation core and analyzed with slightly different resolutions.

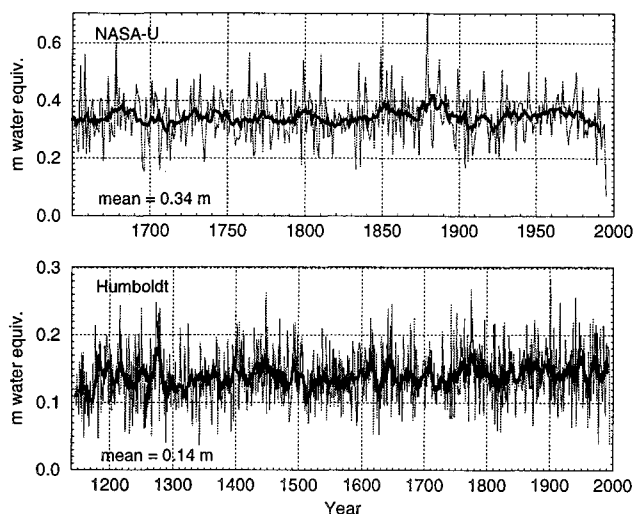


Figure 5. Annual accumulation for NASA-U and Humboldt based on calcium.

and dust were the best seasonal indicators throughout the core. In the top 60 m of the NASA-U core, H_2O_2 and $\delta^{18}\text{O}$ were the best seasonal indicators. Whereas $\delta^{18}\text{O}$ was still a very good annual indicator below 60 m in the NASA-U core, the H_2O_2 signal became less distinct due to diffusion and destruction of H_2O_2 owing to interactions with dust [Sigg and Neftel, 1991; Fuhrer *et al.*, 1993]. NO_3^- was a good seasonal indicator in portions of cores; in the most recent decades, the natural NO_3^- signal is masked by anthropogenic influences. NH_4^+ background concentrations change typically from 2 to 15 ppb, and NH_4^+ often exhibited double or even triple peaks within a year. This and the fact that the seasonal NH_4^+ signal was frequently masked by plumes from forest fires, raising the background concentration tenfold, made NH_4^+ less reliable as a dating tool. Using these multiple parameters, we were able to resolve all discrepancies between the different parameters along the full length of the deeper NASA-U core. The accuracy of the dating is illustrated by correctly dating the volcanic Laki 1783/84 event by layer counting. Also,

for the shallow cores from NASA-U and Humboldt, we could resolve all discrepancies among the different parameters, eliminating all dating errors. In the deeper Humboldt core, we estimate a dating uncertainty of about 5 years over the 852-year record, which is based on those short intervals along the core where the parameters failed to give an unambiguous indication of annual layers.

The annual layer thicknesses were corrected for thinning with depth due to vertical strain rates. Following Dansgaard and Johnsen [1969], we calculated vertical strain rates for NASA-U of about 2.0×10^{-4} per year and for Humboldt of about 1.0×10^{-4} per year. This calculation is based on the estimated thickness of the ice sheet at NASA-U and Humboldt of 2080 and 1900 m, respectively [Chuah *et al.*, 1996], which is equivalent to about 2055 and 1875 m ice, respectively. We have not made any flow correction to the annual layer thickness, since horizontal velocities of the ice sheet at NASA-U and Humboldt are 45.7 m per year (263°) and 17.4 m per year (317°), respectively (G. Hamilton, Ohio State University, personal communication, 1996), and the recent accumulation map for Greenland [Ohmura and Reeh, 1991] suggests that the source areas for accumulation during the past 350 years, east of NASA-U, lie along a flat or only slightly positive accumulation gradient and that the accumulation gradient at the Humboldt site is flat or slightly negative in the upflow direction.

The corrected annual accumulation rates based on the Ca^{2+} record are plotted in Figure 5 for NASA-U (mean accumulation rate 0.34 m water equivalence per year) and Humboldt (mean accumulation rate 0.14 m water equivalence per year), together with a 10-year running mean. For these two sites, there are no previous accumulation data available. However, our annual averages are considerably lower than the values suggested by the recent accumulation map developed by Ohmura and Reeh [1991], 0.34 versus 0.50 and 0.14 versus 0.20 m water equivalence, respectively. The NASA-U and Humboldt cores contained records extending back 350 and 852 years (1645–1994 and 1143–1994), respectively

Table 1. Summary of Records From NASA-U and Humboldt Glacier Cores

Core	Length, m	Years	Mean Accumulation, m water eq.	σ Accumulation, water eq.
<i>NASA-U</i>				
Core 1	150	1994–1645	0.343	0.085
Core 2	20	1994–1965	0.336	0.064
Core 3	20	1993–1965	0.326	0.083
<i>Humboldt</i>				
Main core	150	1994–1143	0.138	0.041
Core east	20	1994–1929	0.145	0.040
Core west	20	1994–1924	0.138	0.046
Core north	20	1994–1927	0.144	0.038
Core south	20	1994–1924	0.138	0.046

Mean accumulation is in meters water equivalent; σ accumulation is in water equivalent.

(Table 1). There was no statistically significant trend in the NASA-U annual accumulation rates over the period of record, whereas the Humboldt data show an increasing trend of about $1.3 \pm 0.4\%$ per century over the period of record. For NASA-U, about 30 years and 10 years averaging is needed to get a mean accumulation within 2.5% and 10%, respectively, of the 350-year mean. At Humboldt, the required averaging periods are twice as much. These results highlight the advantage of shallow 20-m cores over even shallower (4-6 m) snow pits for estimating average accumulation rates with small uncertainties.

Though we used all of the measured parameters except HCHO to define annual layers, each independently gives a different estimate of the accumulation in a given year, as discussed above. We illustrate this difference by comparing layer thickness based upon seasonal variations of Ca^{2+} and H_2O_2 (Figure 6). Individual years varied by as much as 50% between parameters, illustrated by the histograms of differences in Figure 6b (left side) that extend to about ± 0.5 times the mean accumulation. Taking 5-year averages greatly reduced the considerable scatter in annual values, and the scatter is absent in the 25-year averages.

Two 20-m firn cores drilled near the main 150-m NASA-U core showed that interannual variability of annual layer thickness exceeded spatial variability (Figure 7). One 20-m core was within 50 m of the main core, and the other was 2 km away. However, at the Humboldt site, 20-m cores drilled 25 km west, east, north, and south of the 150-m core showed similar spatial and temporal variability. Temporal variability, expressed by the coefficient of variation (Figure 7), was slightly higher at Humboldt as compared to NASA-U. The spatial variability in the set of Humboldt cores is greater than in the set of NASA-U cores. It is possible that this greater spatial variability is due to the greater distance

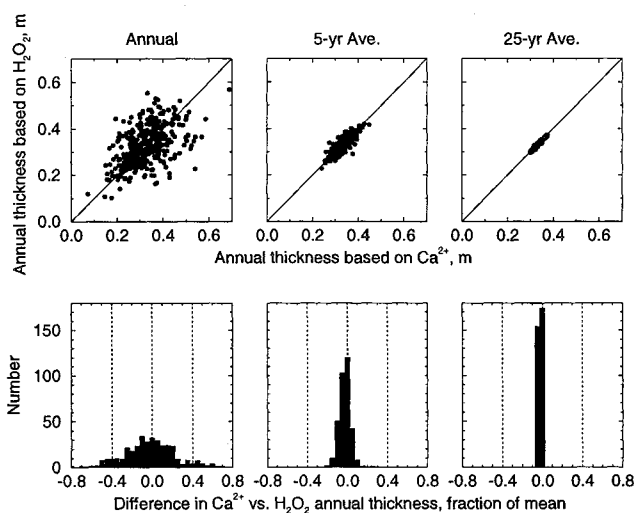


Figure 6. Comparison of annual layer thickness from NASA-U core 1 using Ca^{2+} versus H_2O_2 . (a) Comparison for annual 5-year and 25-year averages; (b) histograms of differences between thickness based on Ca^{2+} versus H_2O_2 for the same data.

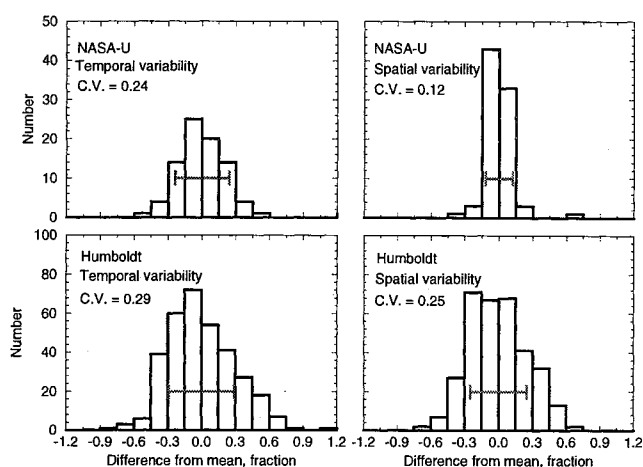


Figure 7. Histogram of spatial and temporal differences for 3 NASA-U cores (28 year) and 5 Humboldt cores (66 year). Spatial variability values calculated as difference between annual value for individual core and three-core (NASA-U) or five-core (Humboldt) mean for each year. Temporal variability values calculated as difference between annual value for individual core and 28-year (NASA-U) or 66-year (Humboldt) mean for that core. C.V. indicates coefficient of variation.

among the five cores at Humboldt than among the three cores at NASA-U, since the surface roughness is a regional rather than a local parameter. Examination of high-resolution topographic profiles for Humboldt, developed from a GPS (Global Positioning System) survey of the site shows a typical wavelength of the surface undulation to be 3-5 km; therefore the five cores originate from different surface slopes. The NASA-U cores were much more closely spaced.

For the Crawford Point core, no density data were available, and, after shipping the core back to the laboratory, its cylindrical surface condition was too inhomogeneous to determine accurate densities. Therefore we adapted and extrapolated the density profile determined for the T5 site during the EGIG traverse in 1990 [Anklin *et al.*, 1994], which is 6 km from Crawford Point (69.82°N , 47.25°W). It is unlikely that density changes much over this short distance. Adapting this density profile, we calculated a mean accumulation rate of 0.48 m water equivalence per year for this site, based on a 13-year average. This is in good agreement with the previously reported accumulation rate at T5 of 0.47 m water equivalence over the 7-year period 1983-1989 [Anklin *et al.*, 1994]. However, Benson [1962] reported somewhat higher accumulation rates for two sites close to Crawford Point: 0.60 m water equivalence (69.91°N , 46.95°W , 2012 m elevation) and 0.63 m water equivalence (69.82°N , 47.30°W , 1963 m elevation), based on 5 years of record at each site.

4. Discussion

The advantage of multiparameter layer counting is that the seasonality of the parameters often have differ-

ent natural sources and thus peak at different times during the year. Multiparameter methods have also been discussed by Meese *et al.* [1997]. If during a given year accumulation is small or absent during one or more seasons, the annual signals for a species can be missing or indistinct. Certain years can thus have an ambiguous annual indication in one parameter yet be unambiguous in others. Dust and Ca^{2+} have their major source from airborne soil and peak in Greenland in spring [Whitlow *et al.*, 1992]. The condensation temperature of precipitation is indicated by $\delta^{18}\text{O}$ [Dansgaard *et al.*, 1973] and has its maximum in June-July. H_2O_2 is produced in the atmosphere in the presence of UV-B radiation and water vapor. Measurements from Sigg [1990] indicate that for Summit (Greenland) the H_2O_2 concentration peaks during late summer, July-August. NH_4^+ has two main sources: biological activity producing NH_3 emissions and biomass burning [Legrand *et al.*, 1992; Dibb *et al.*, 1996; Whitlow *et al.*, 1994]. Since emissions from biomass burning are typically 10 times the background concentrations, they can mask the seasonal signal induced by the biological activity. The NH_4^+ concentration peaks in late spring [Fuhrer *et al.*, 1996]. NO_3^- has two major sources, the land and the marine biosphere, and shows a clear seasonal signal in most of the Greenland ice cores. The advantage of knowing the exact timing of peaks and troughs of different parameters is to estimate subannual accumulation changes as shown by Fuhrer *et al.* [1996].

Changes in long-term accumulation patterns over the Greenland ice sheet have been studied by comparing accumulation records from central Greenland (Summit at Greenland Ice Sheet Project 2 (GISP2) [Meese *et al.*, 1994]), south central Greenland (Milcent [Clausen *et al.*, 1988]), western Greenland (NASA-U), and northwestern Greenland (Camp Century [Clausen *et al.*, 1988] and Humboldt) (Figure 8). The different records show similarities during some decades and centuries but not during others, which possibly indicates changes in circulation pattern over the Greenland ice sheet over decades/centuries. Similarities are found in the records from NASA-U and Summit between 1650-1820 and after 1860 (Figure 8). During the later period, an apparent and unexplained 10-year lag was observed. However, between 1820 and 1860, NASA-U shows a similar increase in accumulation as the northwestern sites, which is not seen in the Summit record. Weak similarities also exist between the northwestern site (Humboldt) and Summit from 1840-1920 and more strongly from 1450-1650 (data not shown). Besides a steep decrease in the accumulation record from Milcent between 1740 and 1760, which is not seen in the Summit record, these two sites have been in phase since 1650.

Changes in circulation pattern over Greenland might be explained with changes in open water areas in the source region. The precipitation along the northwestern part of Greenland is governed by the Baffin Bay low, which travels along the western coast of Greenland advecting moisture from the Labrador Sea north. This cyclone is strengthened by the warm surface water in

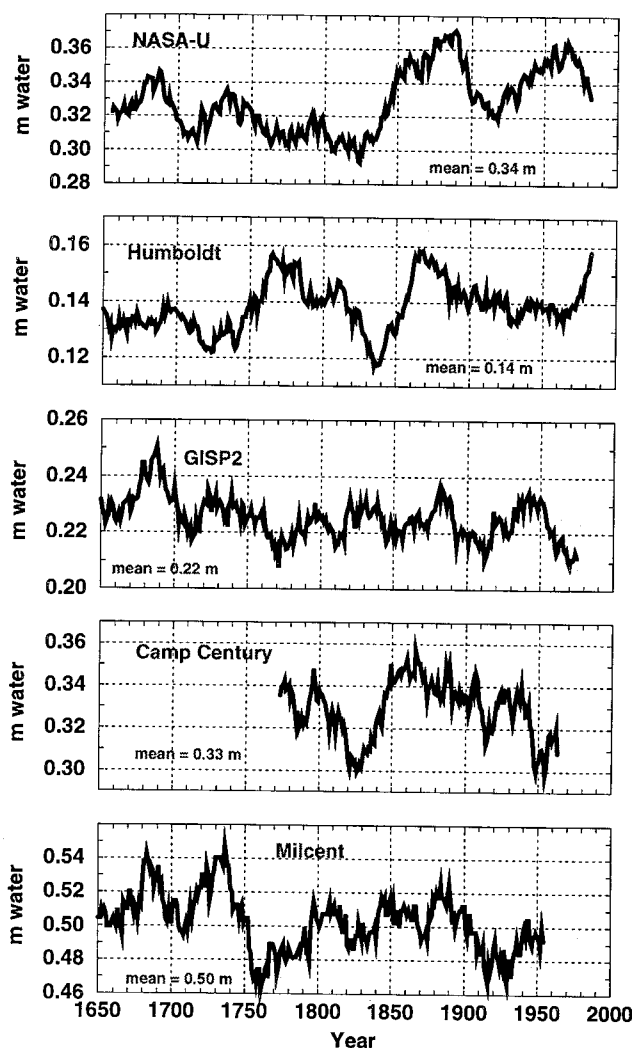


Figure 8. Comparison of 25-year running averages of annual thickness for NASA-U and Humboldt cores, with other published data. GISP2 based on Meese *et al.* [1994]; Camp Century and Milcent based on Clausen *et al.* [1988]. Averages based on periods shown on graphs.

northern Baffin Bay known as the North Water polynya, a sea ice anomaly that acts as a local water vapor source during winter and spring [Steffen, 1985]. Much of the winter and spring precipitation in northwestern Greenland originates from the open ocean surface in the North Water polynya. The open water area has large interannual variability [Steffen, 1991], and thus we believe that the accumulation record shown in the northwestern ice cores [Clausen *et al.*, 1988] reflects this relationship.

While changes in long-term accumulation trends could be explained by open water areas, it is also interesting that the accumulation rate at NASA-U and Humboldt seems to be related to solar activity changes. Using power spectrum analysis, we identified prominent frequencies with 7-, 11- and 83-year cycles in Greenland accumulation records. These frequencies are similar to the 7-, 11-, and 87-year solar cycles [Attolini *et al.*, 1988]. Accumulation variations with an 11-year cycle

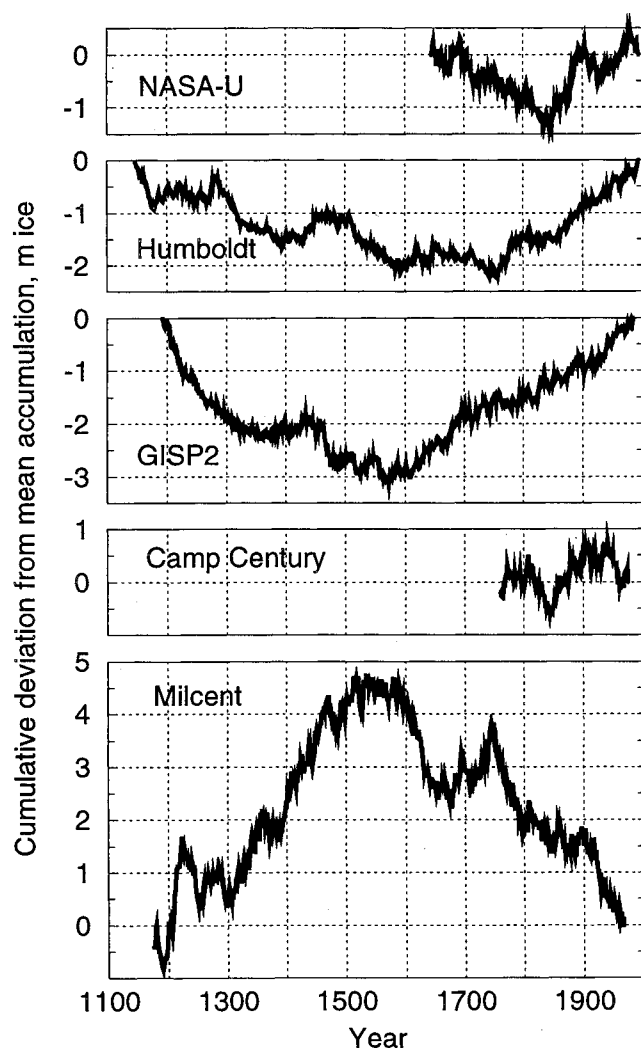


Figure 9. Accumulation trends at five sites given as cumulative difference from their respective means. See Figure 8 for sources of data. Curve calculated by subtracting mean from each annual value, then summing differences over time from the beginning of the record. Note that beginning and ending values are zero, i.e., no net difference over the period of record. Values expressed as ice equivalent using 917 kg m^{-3} as ice density.

have also been seen by *Steig et al.* [1998] and *Ram et al.* [1997].

One way to illustrate changes in the Greenland ice sheet mass balance is to calculate cumulative accumulation relative to mean accumulation for each site. This cumulative accumulation of ice is shown in Figure 9 for NASA-U, Humboldt, Summit, Camp Century, and Milcent. Assuming that the runoff rate of the Greenland ice sheet (discharge of ice to the sea and melting in the ablation zone) remained unchanged during the last millennium, then the positive values of the cumulative accumulation indicate that the ice sheet was higher than at present, and negative values mean that it was lower than at present. The runoff rate mainly depends on the ambient temperature, and the temperature, viscosity, and internal pressure of the ice sheet itself. There is no

indication of increasing ambient temperature at these sites during the last millennium. Further, ice is a very good insulator, and it is unlikely that the inside temperature of the ice sheet has changed during this period of interest. Since ice from the last glaciation has a higher viscosity than ice from the Holocene, the replacement of glacial ice with Holocene ice would lead to an increase of the altitude of the Greenland ice sheet due to the shifted mass balance. Further, increasing accumulation will also raise the altitude of the ice sheet and thus increase the internal pressure, which increases the runoff rate at the coast. Thus the cumulative accumulation rate may overestimate the rise of the ice sheet, owing to the viscosity and pressure dependence of the mass balance. Differences between minima and maxima on each graph of Figure 9 indicate the largest change in mass associated with the accumulation patterns. Over the period 1693-1845, the ice sheet at NASA-U had a net loss of 1.7 m ice equivalent, followed by a net gain of 1.9 m for 1845-1980. For the Humboldt glacier site there was a net loss of 2.2 m ice equivalent for 1143-1742, followed by a net gain of 2.2 m for 1742-1994. The respective net rates of change for the periods of increasing accumulation for the two sites are 1.4 and 0.9 meters per century, which corresponds to 3.8% and 5.8% of mean accumulation per century. These changes are comparable to those for Summit, Camp Century, and Milcent, which show maximum changes of 0.8, 1.4, and 1.6 meters per century, respectively (3.4, 3.9, and 2.9% of mean accumulation per century). For comparison, taking the ratio of areas for the Greenland ice sheet versus world oceans, 1 m of change in thickness for the Greenland ice sheet corresponds to about 4.3 mm of sea level change.

5. Conclusions

The accurate, high-resolution dating of the two cores reported here was only possible by using multiple parameters, since a particular species might show a weak signal in any given year. Using all parameters together to define annual layers, we were able to develop a 350-year record for the 150-m NASA-U core with no dating uncertainty. For the lower-accumulation Humboldt core, the dating uncertainty is about 5 years over the period of record and zero for the past 200 years. The real gain in accuracy from having multiple indicators derives from using them together, rather than from using each independently to define annual layers. Once annual layers have been identified using the multiparameter approach, any of the parameters can then be used to give an estimate of annual accumulation. Because of the offset in timing of peaks and troughs for different parameters, it should be possible to estimate subannual accumulation from these sorts of records.

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