Local to regional-scale variability of annual net accumulation on the Greenland ice sheet from PARCA cores

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Abstract. A suite of spatially distributed cores collected under the Program for Arctic Regional Climate Assessment (PARCA) provides an unprecedented opportunity to assess local to regional variability of annual accumulation rates over the Greenland ice sheet. PARCA cores are unique in their broad spatial distribution and accurate dating of annual layers using multiple seasonally varying indicators. The core data provide (1) a more rigorous evaluation of spatial and temporal variations in accumulation rates, (2) critical input to ice sheet mass balance estimates, (3) ground truth measurements for satellite observations and climate model–based precipitation estimates, and (4) important constraints on paleoclimatic interpretations from ice cores. Multiple closely spaced cores demonstrate that signals of high-frequency (annual to possibly decadal scale) climate variability preserved in the ice sheet are partially masked by glaciological noise. Two 350-year accumulation histories, one from northwest Greenland and one from the summit area, reveal significant multidecadal variability. The regional trends show long periods (60–90 years) of strong positive correlation and an equally long period of strong negative correlation. Since 1940 the trends have been decoupled. This spatial variability reflects the strong modulation of Greenland precipitation (and the climate information it contains) by changes in North Atlantic atmospheric circulation patterns. Proxy records from the PARCA cores document that climate reconstructions from a single core must be interpreted cautiously, with application of appropriate filters to reduce local noise and careful extrapolations from local to regional scales. Richer, more robust ice core-derived data sets should result from combining multiple, more widely spaced cores to produce regional stacked records.

1. Introduction

The well-documented twentieth century warming of the Earth's surface temperatures [*Hansen et al.*, 1999; *Levitus et al.*, 2000; *National Research Council*, 2000] has focused attention on the possibility of future global climate and environmental changes. The retreat of many small ice caps and glaciers in middle to low latitudes is well documented [*Thompson et al.*, 1993; *National Research Council,* 1998], and global glacier runoff has contributed 25-50% of the estimated sea level rise in the past 100 years [Warrick *et al.*, 1996]. In light of possible future sea level rise a pressing need exists for precise knowledge of the mass balances of the Antarctic and Greenland ice sheets, but accurate balance assessments remain elusive. One goal of the Program for Arctic Regional Climate Assessment (PARCA) is to determine how accurately satellite-based observations represent in situ physical parameters. Ice cores provide point measurements of various physical and chemical properties including the annual mass accumulation, a key input to ice sheet mass balance calculations. Thus PARCA investigators initiated an intensive ice core drilling program to collect a suite of shallow and intermediate depth cores distributed over Greenland with the explicit goal of assessing the current spatial distribution of annual net accumulation (A_n).

In the last 50 years, A_n has been measured at many sites by overland traverses [*Benson,* 1962; *Bales et al.*, this issue] and at fewer sites where cores have been drilled [*Langway et al.*, 1985; *Alley and Bender*, 1998]. The older traverse data, although quite valuable for obtaining many estimates quickly, are limited in several ways. Density was frequently estimated using ram hardness rather than actual measurement, and the dating was based upon a single parameter, visible stratigraphy, exposed in pit walls [*Benson*, 1962]. *Ohmura and Reeh* [1991] (hereinafter referred to as OR) and *Ohmura et al.* [1999] incorporated most of the available accumulation data to produce a comprehensive Greenland

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Paper number 2001JD900067.
0148-0227/01/2001JD900067$09.00

accumulation map. A_n measurements from additional PARCA sites have been included with a subset of the OR data to produce an updated accumulation map [*Bales et al.*, this issue]. Although the mean "ice sheet-wide" accumulations are almost identical (30 g cm^{-2} yr^{-1} versus 29 g cm^{-2} yr^{-1} for OR) the accumulation distributions differ in four regions as described by Bales *et al.* [this issue].

Table 1 presents the basic information from 49 PARCA cores obtained between 1995 and 1998, and Figure 1 illustrates their locations along with the 1999 cores that are still under analysis. PARCA cores were drilled either at field camps in place for several weeks or by a commuter program using fixed-wing aircraft that wait on site during drilling. Cores collected by the latter mode rarely extended below 20 m, but often cores were drilled at two sites in 1 day. This paper describes the multiparameter approach to the dating of these cores, quantitatively assesses local spatial variability of A_n, examines details of regional A_n variability, and presents two 350-year regional A_n composites.

Table 1. Summary of PARCA Cores Drilled Between 1995 and 1998[a]

Core Name	Year Drilled	LAT., °N	LONG., °W	ELEV., masl	Depth, m	Oldest Year, A.D.	Accumulation Average ± σ Entire Record	Accumulation Average ± σ 1979-1994
NASA-U-1	1995	73.842	49.498	2369	151.24	1645	0.344±.089	0.315±.073
NASA-U-2	1995	73.842	49.498	2369	20.85	1965	0.330±.073	0.318±.074
NASA-U-3	1995	73.842	49.498	2369	20.46	1965	0.324±.087[b]	0.306±.095[b]
Humboldt-M	1995	78.527	56.830	1995	146.50	1153	0.141±.040	0.154±.041
Humboldt-N	1995	78.751	56.830	1905	21.00	1927	0.146±.041	0.132±.039
Humboldt-E	1995	78.598	55.699	2045	20.50	1929	0.147±.039	0.145±.030
Humboldt-S	1995	78.315	56.826	2058	20.70	1924	0.139±.041	0.131±.026
Humboldt-W	1995	78.452	57.958	1924	20.60	1924	0.139±.042	0.130±.042
GITS-Core 1	1996	77.143	61.095	1887	21.80	1965	0.344±.065	0.326±.070
GITS Core 2	1996	77.143	61.095	1887	120.50	1745	0.365±.101	0.327±.085
Tunu-1	1996	78.017	33.994	2113	69.00	UD	UD	UD
Tunu-2	1996	78.017	33.994	2113	19.00	UD	UD	UD
Tunu-N25	1996	78.330	33.888	~2050	14.94	~1925	~0.090[c]	0.085[d]
								0.072[e]
Tunu-E25	1996	78.000	32.927	~1990	11.87	NAS	NAS	0.111[d]
								0.085[e]
Tunu-W25	1996	78.030	35.064	~2460	14.97	~1918	~0.082[c]	0.077[d]
								0.064[e]
Tunu-N50	1996	78.464	33.841	~2050	15.01	~1933	~0.105[c]	0.108[d]
								0.104[e]
Tunu-E50	1996	77.978	31.863	~2090	15.01	~1919	~0.085[c]	0.084[d]
								0.081[e]
Tunu-W50	1996	78.039	36.136	~2060	15.05	~1936	~0.110[c]	0.118[d]
								0.084[e]
Tunu-S7.5	1996	77.959	34.013	~2470	14.97	1942[f]	~0.119	0.138
								0.132[d]
								0.092[e]
South Dome-1	1997	63.149	44.817	2850	24.57	1978	0.668±.125	0.665±.132
South Dome-2	1997	63.149	44.817	2850	15.30	1986	0.682±.141	NA
North Dye 3-1[g]	1997	66.000	44.501	2460	18.66	1976	0.452±.096	0.449±.102
North Dye 3-1[g]	1997	66.000	44.501	2460	17.29	1978	0.453±.104	0.458±.105
Tunu South-1	1997	69.5	34.5	2650	20.56	1975[f]	0.460±.116	0.452±.124
Tunu South-2	1997	69.5	34.5	2650	10.23	1987[f]	0.446±.109	NA
Tunu South-3	1997	69.5	34.5	2650	10.27	1987[f]	0.439±.113	NA
NASA East-1	1997	75.0	30.0	2631	20.19	1931	0.148±.048	0.148±.050
NASA East-2	1997	75.0	30.0	2631	10.81	1968	0.153±.048	0.153±.040
7147	1997	71.05	47.230	2134	19.86	1974	0.431±.088	0.414±.091
7247	1997	71.926	47.487	2277	20.02	1974[f]	0.430±.093	0.415±.102
7551	1997	75.0	51.0	~2200	21.12	1965	0.325±.090	0.300±.085
7653-1	1997	76.0	53.0	~2200	14.93	1978[f]	0.349±.088	0.337±.086
7653-2	1997	76.0	53.0	~2200	4.98	1993	0.398±.059	NA
6945-1	1998	69.0	45.0	~2150	18.56	1977[f]	0.424±.122	0.420±.122
6943	1998	69.2	43.0	~2500	17.65	1976[f]	0.388±.083	0.384±.081
6941	1998	69.4	41.0	~2765	11.71	1985	0.400±.095	NA
6939	1998	69.6	39.0	~2955	12.25	1982	0.338±.092	NA
6841	1998	68.0	41.0	~2640	12.03	1987	0.491±.146	NA
6745	1998	67.5	45.0	~2250	12.06	1984	0.379±.078	NA
6839	1998	68.5	39.5	~2790	11.89	1985	0.395±.145	NA
6938	1998	69.0	38.0	~2920	12.20	1983	0.361±.072	NA
6642-2	1998	66.5	42.5	~2380	20.53	1982	0.646±.157	NA
6345	1998	63.8	45.0	~2730	14.82	1977	0.332±.058	0.335±.059

Table 1. (Continued)

Core Name	Year Drilled	LAT., °N	LONG., °W	ELEV., masl	Depth, m	Oldest Year, A.D.	Accumulation Average ± σ Entire Record	Accumulation Average ± σ 1979-1994
6348[h]	1998	63.8	45.0	~1960	15.00	NASM	NASM	NASM
7249	1998	72.2	49.4	~2170	15.25	1986	0.556±.123	NA
7347	1998	73.6	47.2	~2600	12.24	1981	0.294±.082	NA
7345	1998	73.0	45.0	~2815	14.60	1975	0.284±.069	0.274±.078
7145	1998	71.5	45.0	~2615	12.01	1986	0.457±.106	NA
7245	1998	72.25	45.0	~2770	12.11	1984	0.378±.067	NA

[a]Layer thicknesses (meters of water equivalent) are calculated from successive winter dust minima unless indicated otherwise in the text, masl is meters above sea level. Data from the year of drilling are eliminated from all averages as that year is incomplete. The five Humboldt cores were corrected for thinning using a strain of 0.0001 year^{-1} and the two GITS cores were corrected for thinning using a strain of 0.00034 year^{-1} [*Dansgaard and Johnsen*, 1969]. The three NASA-U cores were corrected for thinning using a strain of 0.0002 year^{-1} [*Anklin et al.*, 1998]. The Not included are two short (< 5 m) duplicate cores, two Dye 2 cores (not complete), and the Crawford Point core that was not datable. Abbreviations are as follows: LAT. means latitude, LONG. means longitude, ELEV. means elevation, NAS means it is undetermined as the annual signal is not preserved because of glaciological noise, NASM means it is undetermined as the annual signal is not preserved because of melting, NA means it is not applicable as the record did not extend back to 1979, UD means yet to be determined because the dating is imprecise and other time-stratigraphic data (e.g., volcanic events) will be needed.

[b]The initial year in this core is 1993.

[c]This is the best estimate of accumulation with no estimate of dating precision.

[d]The average value for 1963-1996 is based on the 1963 beta radioactivity horizon. The drilling year, 1996, is not a complete year.

[e]The average value for 1952-1962 is based on the beta radioactivity horizons, 1952 and 1963.

[f]Dating error is estimated to be ±1 year.

[g]Site formerly called Saddle.

[h]Core 6348 drilled in 1998 was not datable due to excessive melt.

2. Constructing Annual Accumulation Histories From Firn and Ice Cores

A_n histories were constructed for each core using a combination of seasonally varying parameters and specific time-stratigraphic markers. At the Ohio State University discrete samples were cut from the cores and analyzed for $\delta^{18}O$ and insoluble dust concentrations, while selected core sections were measured for beta radioactivity and SO_4^{2-} concentrations. At the University of Arizona the concentrations of H_2O_2, NO_3^-, NH_4^+, and Ca^{2+} were measured using a continuous flow system [*Führer et al.*, 1993; *Anklin et al.*, 1998].

Determining annual layer thicknesses is a multistep process. First, the timescale is determined by accurately dating the core. For this all available seasonally varying parameters are used simultaneously and in conjunction with other known time-stratigraphic horizons (beta radioactivity or volcanic horizons). Figure 2 illustrates a 7-m section of the GITS core for which seasonal variations of dust, $\delta^{18}O$, SO_4^{2-}, and NO_3^- allow accurate dating, as confirmed by increased concentrations of excess sulfate from the eruptions of Tambora in 1815 and an unidentified volcano in 1809 [*Dai et al.*, 1991].

Once all annual layers are identified, the length of the firn core is converted into a water equivalent (WE) length using density variations with depth. Mass and volume measurements were made on each piece of core as it was recovered at the drill site (averaging 10–20 measurements per 10-m section of core). These measurements were repeated again in the laboratory before sampling. Density functions were determined for each core site by modeling the depth-density data with a polynomial function of three to five terms that in most cases explained >95% of the variance. The final layer thicknesses were determined as the difference between the depths (in WE) of successive low or high values of a particular constituent. There is no glaciological standard for calculating layer thicknesses although most previous Greenland A_n records were based on either $\delta^{18}O$ or dust concentrations.

Measurement of multiple seasonally varying constituents for the PARCA cores allowed exploration of the sensitivity of reconstructed layer thicknesses to the specific parameter used. *J. F. Bolzan* (personal communication, 2000) compared $\delta^{18}O$ histories from nine shallow cores in the Summit region with contemporaneous microwave brightness records and concluded that the summer $\delta^{18}O$ maximum occurs consistently within a 6-week window centered on July. Thus *Bolzan and Strobel* [1994] and *van der Veen and Bolzan* [1999] used the summer $\delta^{18}O$ maximum to construct their annual layer thicknesses. Using a model of atmosphere-to-snow chemical transfer, *McConnell et al.* [1998] reported that the winter minimum in H_2O_2 occurs in January, while the timing of summer maximum varies from year to year. *Neftel* [1996] reported that in Greenland the H_2O_2 maxima and minima lag those of $\delta^{18}O$ by about 2 months. Diffusion of $\delta^{18}O$ within the firn and the subsequent smoothing of the annual signal has long been recognized [*Johnsen*, 1977], and like $\delta^{18}O$, H_2O_2 is also modified postdepositionally. *Wolff* [1996] noted that at the Greenland Summit a seasonal difference in H_2O_2 of 10 ppb at the surface diminishes to <2 ppb at 70 m depth and suggested that H_2O_2 provides the best example of a species that is smoothed by diffusion throughout the firn sequence. *Neftel* [1996] reported that the initial seasonal H_2O_2 signal experiences a more pronounced smoothing than the $\delta^{18}O$ signal, and it has a mean displacement length of 120–130 mm over the entire firn column (i.e., depth from the surface to solid ice). Although the degree of diffusion varies for different species, when the annual accumulation falls below the diffusion length of a particular chemical species, the annual signal will eventually be obliterated [*Johnsen*, 1977]. For example, the low accumulation in the Humboldt region (~140 mm WE) precluded using either $\delta^{18}O$ or H_2O_2 for dating the 150-m core. Here dust and calcium were used, as insoluble dust concentrations are not significantly modified postdepositionally in the dry snow

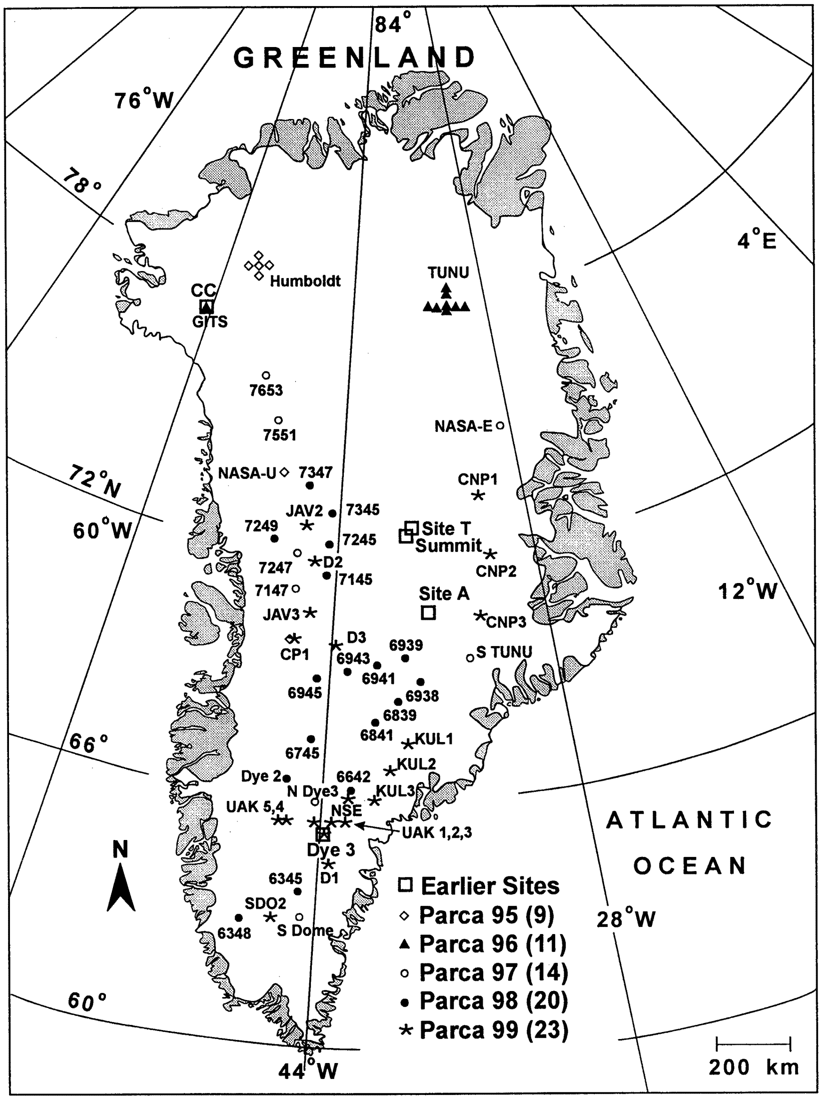


Figure 1. Locations of PARCA cores are shown along with selected earlier cores.

facies. However, the timing of the winter dust minimum is more variable, although it generally occurs between November and February. Certainly, the number of seasonally varying constituents measured on most of the PARCA cores will provide an excellent opportunity to better constrain the seasonality of other constituents such as dust, Ca^{2+}, and NO_3^-.

To investigate the sensitivity of reconstructed A_n records to the annual indicator used, the dust, $\delta^{18}O$, and H_2O_2 winter minima and the summer $\delta^{18}O$ maxima were used to reconstruct A_n in four cores collected along the 69°N parallel between 39° and 45°W (Figure 1). Table 2 illustrates the mean and standard deviation (σ) using each indicator for (1) the entire length of record, (2) their period of overlap (1986–1998), and (3) their period of overlap with the upper 5 years (1994–1998) removed. Here the firn is most friable, the core quality is generally the poorest, and the seasonal signals, especially of $\delta^{18}O$ and H_2O_2, tend to be more noisy because of the lack of postdepositional smoothing that quickly eliminates subannual features associated with discrete precipitation events. Although one parameter does not consistently yield the smallest σ, H_2O_2 gives the smallest σ at two sites and ties with $\delta^{18}O$ at a third site. Nevertheless, all seasonal indicators are subject to some disturbance by local surface processes. In fact, glaciologically there is no single "correct" parameter for determining A_n as some are better constrained in their timing and others are better preserved after deposition. The A_n records presented in this paper are arbitrarily based on winter dust concentration minima that are less prone to postdepositional modification. The reader is reminded that dating (determining the number of years) is different from determining discrete A_n estimates.

As noted above the five cores drilled on Humboldt Glacier (northwest Greenland) were dated using only dust and Ca^{2+}. Annual signals in the other chemical species were not preserved because of the low A_n of ~140 mm WE that required cutting samples ~20 mm long to analyze 6–8 samples per accumulation year. Thus 4902 dust samples were analyzed for the 146.45-m core containing 842 years (A.D. 1153–1994). As all dates in this paper are years A.D., henceforth the designation is eliminated. Figure 3 illustrates well-preserved seasonal variations in dust and Ca^{2+} in the lowest part of the Humboldt core. Although annual layers are more clearly defined by the dust concentrations measured on discrete samples, at times both profiles are required to resolve very thin layers. Dating by layer counting may be confounded by aperiodic disruption of the annual depositional cycles by erosion and redeposition of surface snow. Excess sulfate is used to identify well-known, older volcanic horizons (Figure 4). The well-known eruptions of Laki and Tambora were also identified but are not shown, as the focus here

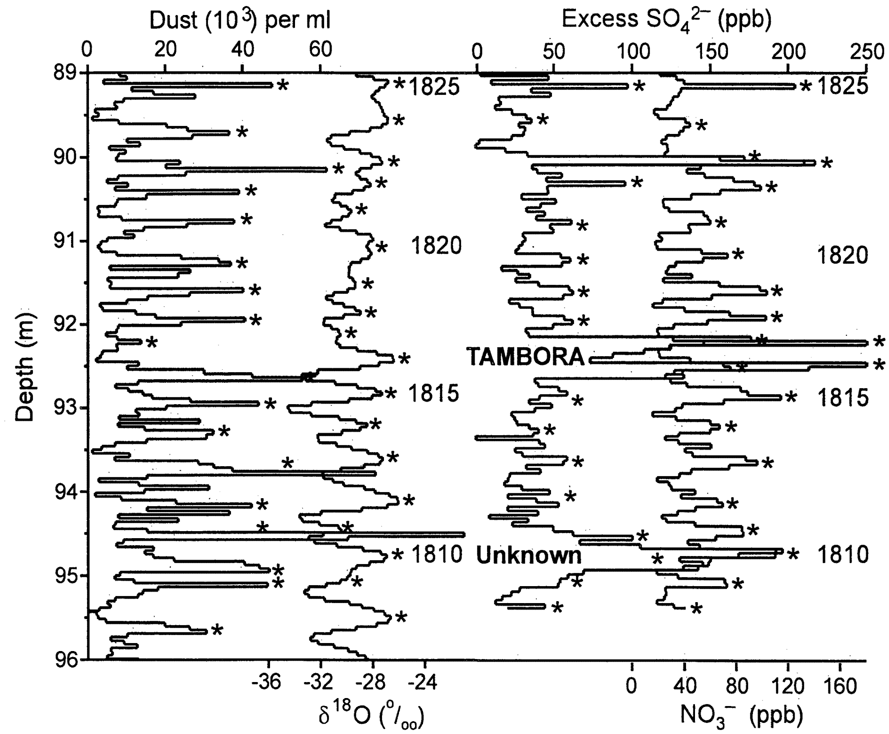


Figure 2. This 7-m section of the GITS (1996) core illustrates seasonal variations in dust, $\delta^{18}O$, and NO_3^- along with the excess sulfate (EXS) from the 1815 eruption of Tambora and an unidentified but well-known eruption in 1809. The asterisks indicate the spring dust peak and the summer peaks in the other species ($\delta^{18}O$, EXS, and NO_3^-).

is on the deeper part of the core where accurate dating is more difficult. The 1601 eruption of Huaynaputina in Peru [*Thompson et al.*, 1986] was perfectly dated by layer counting, but the two eruptions of Mount St. Helen's (1483 and 1479) were dated as 9 and 8 years too old, respectively. The prominent 1179 eruption of Katla [*Clausen et al.*, 1997] was also dated as 8 years too old. Identification of these events gives a dating precision of ~1% at the bottom of the core. Such precision is possible by high-resolution analysis (6–8 samples per year) of multiple seasonally varying parameters. Dating of the Humboldt core was revised using these volcanic horizons to establish a bottom age of 1153.

In the Tunu region (Figure 1), A_n is even lower and more variable than at Humboldt. The only precise dates (Figure 5) are the beta radioactivity horizons (1952 and 1963) from atmospheric thermonuclear testing [*Koide and Goldberg*, 1985; *Picciotto and Wilgain*, 1963] identified in 7 shallow cores (~15 meter long). Six cores were drilled, one each 25 and 50 km north, west, and east from the main core, and a seventh core was drilled 7.5 km south of the main

Table 2. Mean and Standard Deviation of A_n for Four Neighboring Cores With Layer Thicknesses Determined Using Dust Minima, $\delta^{18}O$ Minima, $\delta^{18}O$ Maxima, and H_2O_2 Minima[a]

Core[b]	Time Interval	Dust Minimum	$\delta^{18}O$ Minimum	$\delta^{18}O$ Maximum	H_2O_2 Minimum
6945	1977–1997[c]	0.424±0.122	0.423±0.093	0.428±0.112	0.445±0.101
	1986–1997	0.442±0.127	0.443±0.089	0.440±0.102	0.444±0.089
	1986–1993	0.469±0.108	**0.456±0.075**[d]	0.466±0.106	**0.456±0.075**[d]
6943	1977–1997[c]	0.388±0.083	0.385±0.096	0.393±0.134	0.402±0.085
	1986–1997	0.399±0.087	0.399±0.099	0.410±0.128	0.397±0.081
	1986–1993	**0.415±0.068**[d]	0.418±0.069	0.420±0.118	0.409±0.069
6941	1985–1997[c]	0.400±0.095	0.385±0.087	0.388±0.077	0.384±0.069
	1986–1997	0.393±0.095	0.388±0.090	0.386±0.081	0.391±0.068
	1986–1993	0.377±0.081	0.382±0.065	0.396±0.071	**0.392±0.061**[d]
6939	1982–1997[c]	0.338±0.092	0.334±0.080	0.339±0.080	0.334±0.053
	1986–1997	0.332±0.082	0.336±0.065	0.336±0.080	0.337±0.047
	1986–1993	0.334±0.088	0.337±0.050	0.339±0.059	**0.342±0.033**[d]

[a]Units are in meters of water equivalent.
[b]See Figure 1 for core locations.
[c]Data are shown for the entire length of each core record and for both their entire common period (1986–1997) and a common period (1986–1993) that excludes years since 1993 to eliminate variability due to poorer quality core.
[d]Value is the smallest σ for the cores' common period (1986–1993).

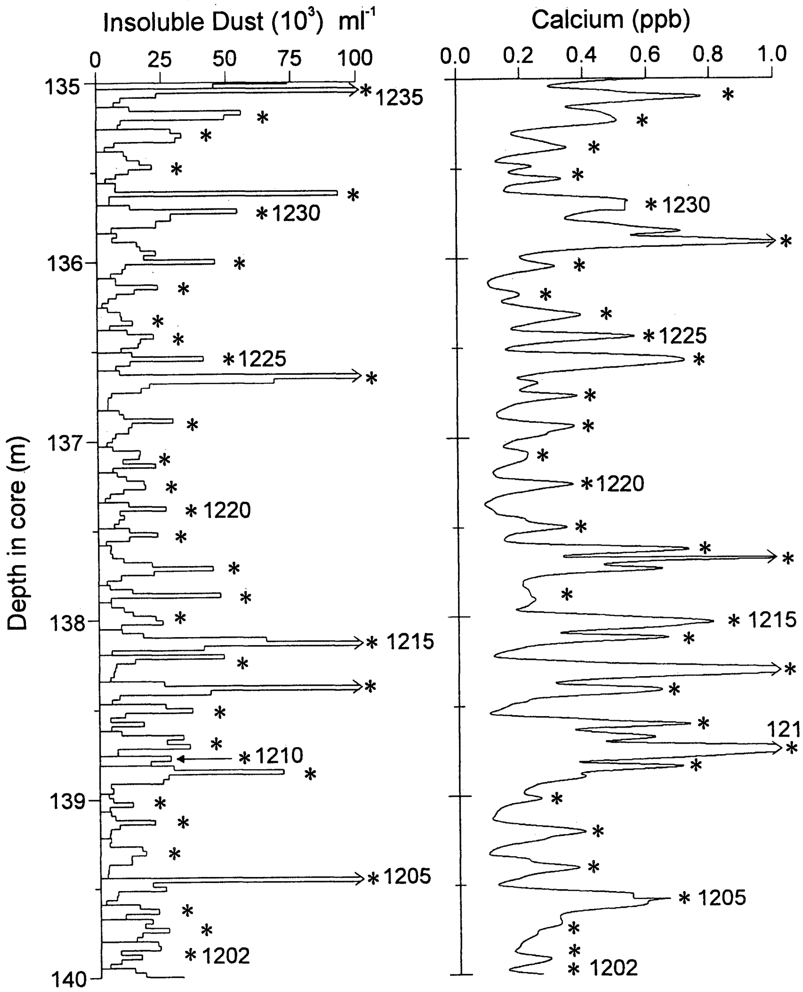


Figure 3. Seasonal variations of insoluble dust and Ca^{2+} are shown for a 5-m section near the bottom of the Humboldt (1995) core. The asterisks indicate the spring peaks in dust and calcium.

core site. A_n varies significantly among these sites with the lowest value (74 mm WE at site E-25) and the highest value (122 mm WE at site S-7.5) differing by 65% (Figure 5 and Table 1). The dating precision of the main Tunu core (69.03 m long) is undetermined awaiting calibration by major volcanic horizons. In summary, the 49 PARCA cores (Table 1) were dated using a broad range of techniques, with the primary goal of absolute dating with annual resolution.

3. Spatial Variation of Accumulation

When a history of A_n, dust, or $\delta^{18}O$ is reconstructed from a single core, it is important to know how well it represents the natural variability of the climate system. Drilling and analysis of deep cores covering thousands of years are expensive and time consuming so often only one core is retrieved at a site. In general, cores drilled in the 1960s and 1970s were not analyzed at high temporal resolution as climate changes were assumed to occur rather slowly. In the last 2 decades, numerous proxy records, including ice cores, have revealed that regional and global climate experience large, high-frequency events [*Alley et al.*, 1993; *Taylor et al.*, 1993], so histories are now reconstructed with the finest time resolution possible. However, any reconstructed annual layer contains both a climate signal imposed by atmospheric processes and noise imposed by glaciological processes. This noise may arise from the movement of surface snow by wind erosion and redeposition, the influence of both small-scale surface features (local sastrugi) and larger-scale, slow-moving dunes on the accumulation pattern, isotopic diffusion of chemical species in the firn, and possible modification during densification and ice flow. The only way to quantitatively separate the climate signal from glaciological noise is to collect multiple cores within an area and compare the results.

The PARCA core collection includes some sets of multiple cores (Table 1). Most of the duplicate cores were collected in close proximity (i.e., within a few tens of meters), but at Humboldt, Tunu, and NASA-U, cores were collected more systematically and farther apart (2–50 km). Time averaging of A_n reduces the spatial variability (local noise), and as the averaging interval is lengthened, the resulting estimate of A_n should become more regionally representative. Practical questions arise. How many years (i.e., filter width) should be averaged to capture most of the climate signal and reduce the superimposed noise? Does the required filter width depend on the regional average A_n?

Two sets of PARCA cores, the five drilled at Humboldt and three drilled at NASA-U, provide useful insight. At Humboldt, four ancillary cores were drilled 25 km north, east, south, and west of the central core site to depths (ages) of 20.77 m (1928), 20.27 m (1929), 20.44 m (1924), and 20.63 m (1924), respectively. The five cores contain a 66-year overlap from 1928 to 1994 (the most recent complete year of accumulation), and their A_n are shown in Figure 6. Comparison of their means using analysis of variance for each set

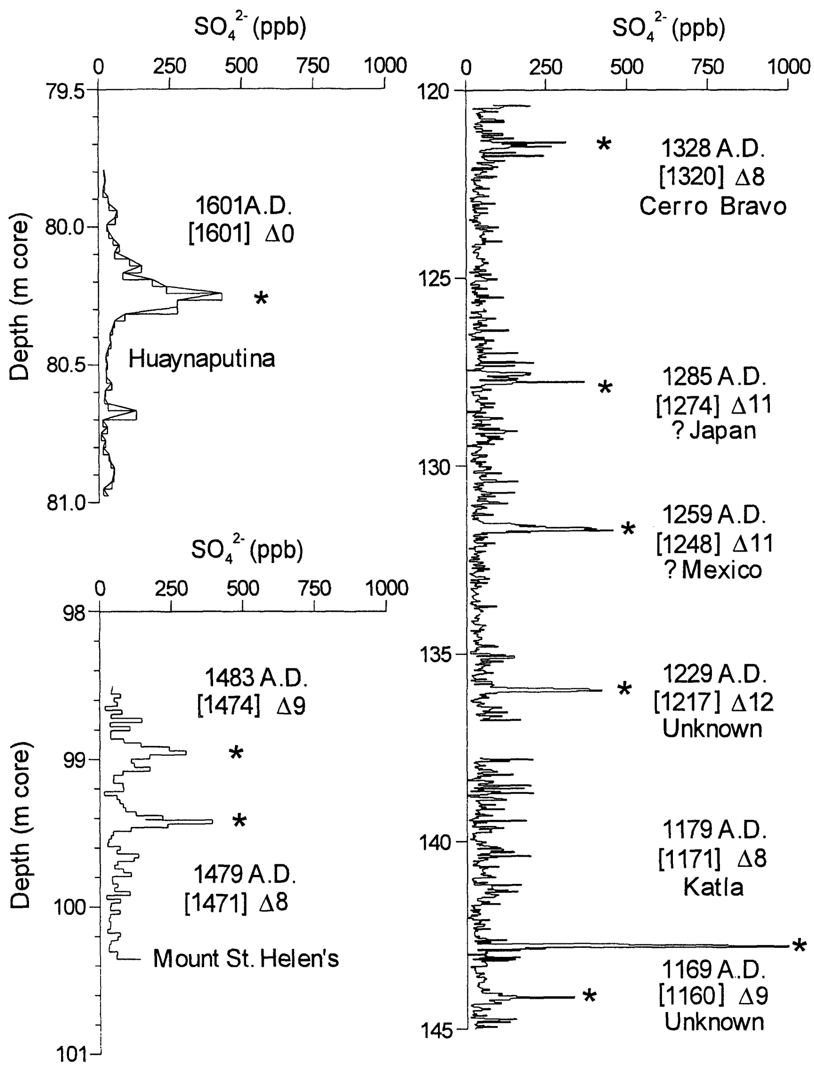


Figure 4. Volcanic events previously identified in other Greenland cores [*Clausen et al.*, 1997] illustrate the dating precision (denoted by Δ) possible in Humboldt cores (1995) with high resolution, multi-parameter dating (in brackets).

of two cores reveals that they are not statistically different at the 95% confidence level. Although their means are not statistically different, this does not prove that they may be considered the same.

The five Humboldt A_n records were averaged for successively longer time intervals (Figure 7). Table 3 illustrates the ratio of the range of their means to the stacked mean (right column). Clearly, the 5- and 10-year average A_n are quite different, and the 10-year averages still contain a large (~20%) contribution from local spatial variability. A 20-year average contains ~10% contribution from spatial variability, and increasing the averaging interval does not further reduce the ratio. Thus a 20-year running mean (RM) is used for Humboldt A_n (back to 1153) to reduce spatial variability to ~10% of the five-core stacked mean. Variations in the 20-year RM of A_n are assumed to be spatially representative of the region within a 25-km radius and to primarily reflect climate variability. In reality, A_n in the region southwest of the main core site is slightly lower than sites to the northeast (Figure 7 and Table 3). A similar comparison (Table 4) for the three cores at NASA-U (A_n ~350 mm WE) indicates that an averaging interval of 10 years is sufficient to reduce spatial variability below 5%. Thus, to reduce glaciological noise, a 20-year RM is used where A_n is less than 250 mm WE and a 10-year RM is used where A_n exceeds 250 mm WE. This is consistent with results from *McConnell et al.* [2000a], who analyzed local spatial variability with six sets of multiple cores. Their Table 2 illustrates that for the four sites with A_n > 330 mm WE the ratio of signal to noise (S/N) ranged from 8.2 to 3.3 (average 6.37), while at the two sites with A_n < 150 mm WE the S/N ratios were < 1.0. Thus, in regions with lower A_n a longer time average must be used to reduce spatial variability and enhance the longer-term, larger-scale trends.

Figure 8 illustrates the 20-year RM of A_n for the entire Humboldt record (1153–1994) along with A_n calculated between known volcanic events (bold line). A_n in this region has increased modestly (~9 mm WE or ~6%) over the last eight centuries. Of more interest are periods (Figure 8) of sustained below-average A_n (1310–1400 and 1700–1740), above-average A_n (1400–1500 and 1840–1900), and large (up to 30%), rapid shifts of A_n within a decade. The latter likely reflect rapid reorganization of the large-scale atmosphere-ocean circulation regime in the North Atlantic, but additional contemporaneous cores with equivalent dating precision would be required to confirm this. Although the Humboldt 842-year A_n history reveals numerous rapid, short-term changes, overall A_n has increased only modestly in this part of northwest Greenland.

A few more A_n histories covering the last 4 centuries are available. Figure 9 illustrates A_n for PARCA cores extending back at least several centuries and includes three earlier cores from the

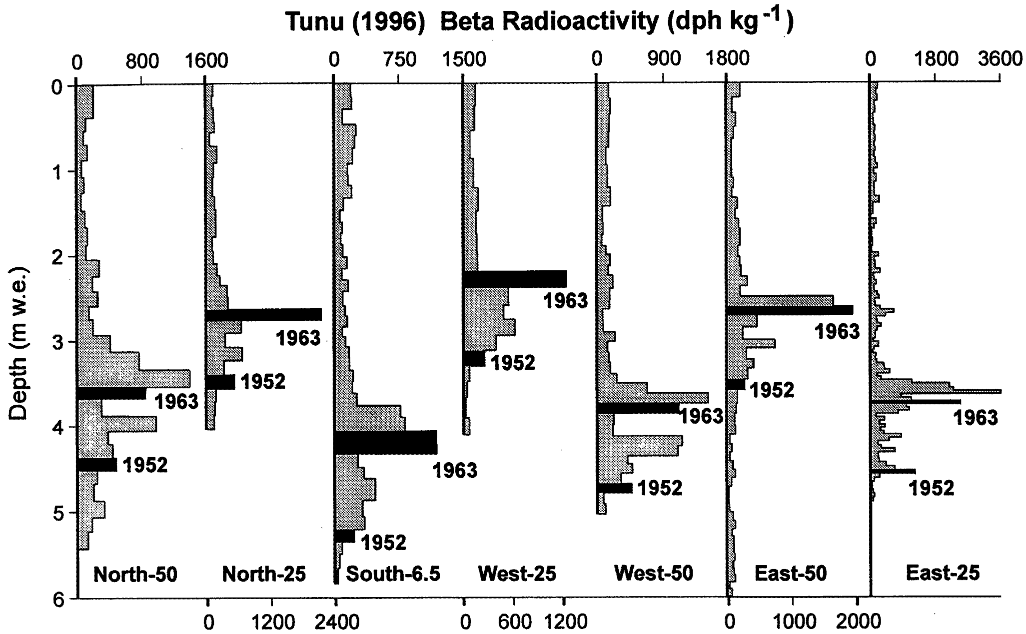


Figure 5. The 1952 and 1963 beta radioactivity horizons from atmospheric thermonuclear tests recorded in seven cores from the Tunu region (Figure 1) demonstrate the large spatial variability in accumulation. Depths are in water equivalents (WE).

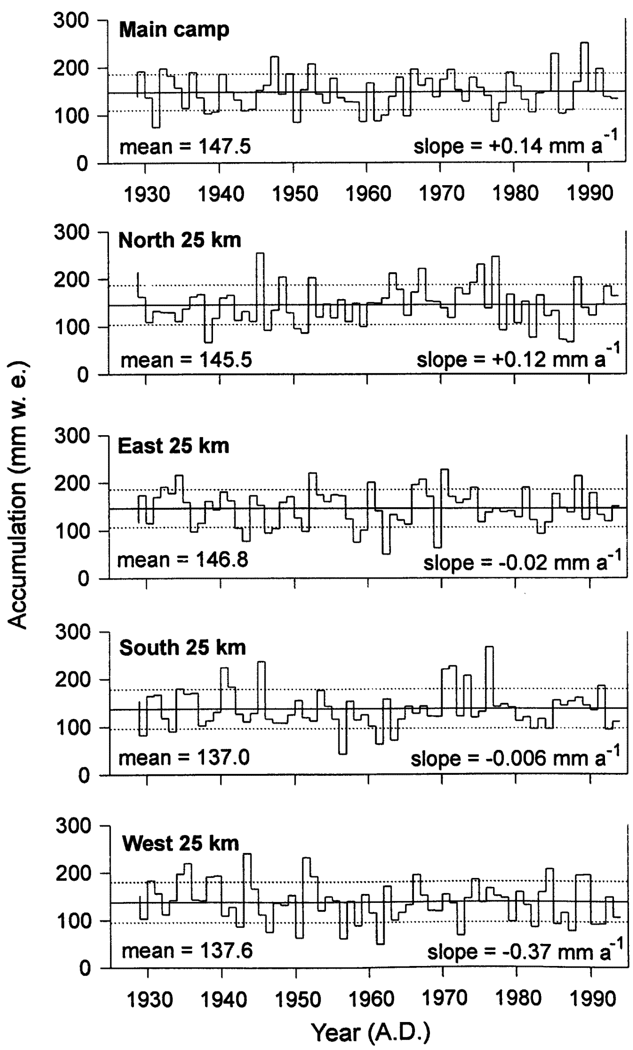


Figure 6. Annual accumulation for 66 years from five Humboldt (1995) cores, along with their means and slopes, reveals no obvious twentieth century trend in A_n in this region. The dashed lines indicate $\pm$ 1 σ.

central Greenland region, namely the Greenland Ice Sheet Project (GISP2) core, and the Site T and Site A cores [*Mosley-Thompson et al.*, 1993]. The GISP2 core [*Cuffey and Clow*, 1997] and Site T core were drilled within 1 km of each other but were dated by different investigators using different seasonally varying parameters. The layer thicknesses in both cores were corrected for thinning using different approaches as discussed in their respective references. For the period shown (1650–1988) the average A_n are 222 (GISP2) and 218 (Site T) mm WE. Although the unsmoothed A_n records are weakly correlated (R= 0.126, R^2= 0.016, and significance = 98%), if the records are smoothed using a 20-year RM, similar A_n trends become apparent (Figure 9) and the records are more strongly correlated (R=0.494, R^2=0.255, and significance = 99.9%). Although encouraging, this suggests that 75% of their variance may not have a common origin. A simple sensitivity study reveals that a 20-year averaging interval is a good choice for the central Greenland summit area. For comparison, using a 10-year RM the two A_n records have an R^2 of 0.138, while a 15-year RM gives an R^2 of 0.213 and a 25-year RM gives an R^2 of 0.265. Thus increasing the filter width beyond 20 years does not increase R^2 substantially. These results serve as a strong caution to users of ice core-derived A_n data. Specifically, it is essential to return to the source of the data and consider carefully the role of glaciological noise. Also, older cores are likely to be based on fewer seasonally varying parameters (increasing the dating error), and different approaches may have been used to determine the layer thicknesses and to adjust them for thinning with depth.

Figure 9 demonstrates that it is important to consider spatial variability when using A_n from a single long core for climate reconstructions and ground truth estimates. Model output and remotely sensed data have a much larger spatial footprint than a

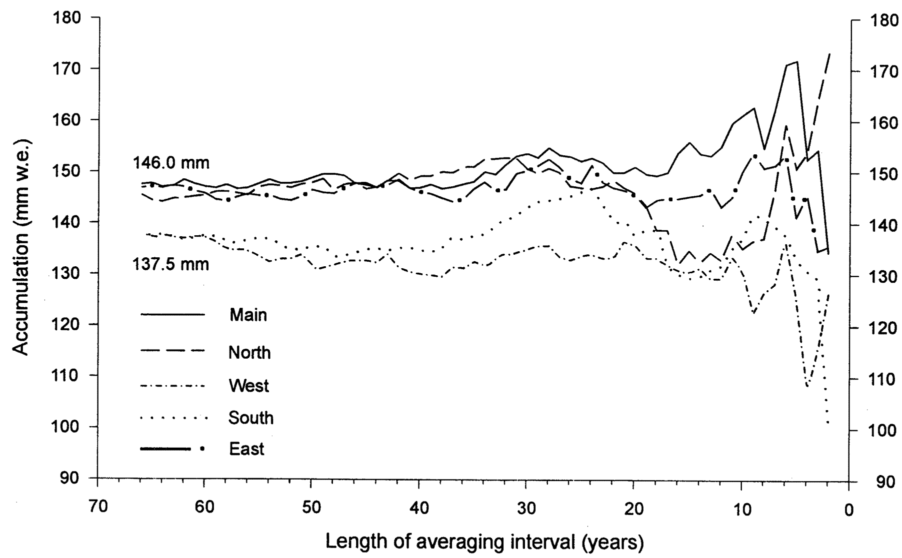


Figure 7. Average A_n for the 5 Humboldt cores are shown as the length of the averaging interval is increased from 2 years (rightmost) to 66 years (leftmost). The south and west cores converge to a lower 66-year average (~137.5 mm WE) than the three cores to the north and east (~146 mm WE).

core that samples a 100-mm-diameter area. Therefore core results will be most useful when multiple, widely spaced cores are combined to eliminate (or significantly reduce) glaciological noise.

4. A Multicentury (Ice Core) Perspective of Greenland Accumulation

Figure 9 confirms that A_n histories for cores from the same region still contain differences in spite of averaging over 10 and 20 years. Even if it were possible to remove all the glaciological noise, the records would not be identical, as the climate-driven forcing of precipitation (snowfall) is also spatially variable. To facilitate the use of ice core-derived A_n histories for larger spatial-scale climate studies, individual core records should be composited to provide a regional A_n history.

For northwest Greenland the Humboldt, GITS, and NASA-U cores were used to produce an A_n history. For each site all available data were used to produced a stacked A_n record. Thus, at Humboldt the 1929–1994 average is based on five cores, but before 1929 it is based on a single core. At GITS and NASA-U the average for the period back to 1965 is based on two and three cores, respectively,

Table 3. Mean and Standard Deviation of A_n for Averaging Intervals of Increasing Length for Five Cores from the Humboldt Region in Greenland[a]

Averaging Interval, years	Main Core	North Core	East Core	South Core	West Core	Five Cores Stacked	Range / Stacked Mean
5	171.8 ± 44.4	150.8 ± 20.9	141.2 ± 21.6	133.2 ± 31.4	125.6 ± 40.1	144.5 ± 14.0	0.319
10	161.2 ± 46.0	135.1 ± 40.7	150.2 ± 29.7	137.2 ± 28.3	130.9 ± 47.4	142.9 ± 22.6	0.216
20	151.0 ± 40.0	145.9 ± 48.5	145.5 ± 29.5	137.7 ± 37.7	135.8 ± 39.7	143.3 ± 21.7	0.106
30	153.6 ± 37.0	150.6 ± 43.4	150.2 ± 36.6	143.2 ± 40.1	134.9 ± 37.1	146.5 ± 22.4	0.128
40	146.9 ± 37.0	149.1 ± 40.5	146.1 ± 39.4	134.5 ± 42.2	130.3 ± 38.4	141.5 ± 22.8	0.133
50	148.8 ± 37.6	147.8 ± 43.7	146.4 ± 39.3	135.2 ± 41.5	131.8 ± 40.7	142.0 ± 23.3	0.120
60	147.0 ± 36.6	145.4 ± 42.1	145.7 ± 39.5	137.8 ± 41.4	137.2 ± 43.7	142.6 ± 22.6	0.068

[a]Units are in millimeters of water equivalent. See Figure 1 for location of the Humboldt region.

Table 4. Mean and Standard Deviation of A_n for Averaging Intervals of Increasing Length for Three Cores From the NASA-U Site in Greenland[a]

Averaging Interval, years	Core 1	Core 2	Core 3	Three Cores Stacked	Range / Stacked Mean
5	301.2 ± 72.9	297.4 ± 93.0	275.5 ± 127.9	291.4 ± 78.2	0.101
10	316.5 ± 60.7	315.4 ± 80.9	307.4 ± 110.1	313.1 ± 67.7	0.029
20	327.3 ± 75.8	333.1 ± 70.8	320.6 ± 93.8	327.0 ± 59.9	0.038
29[b]	335.5 ± 81.2	332.7 ± 72.6	324.1 ± 86.9	330.8 ± 58.2	0.034

[a]Units are in millimeters of water equivalent. See Figure 1 for the location of NASA-U.
[b]The maximum period of overlap is 29 years.

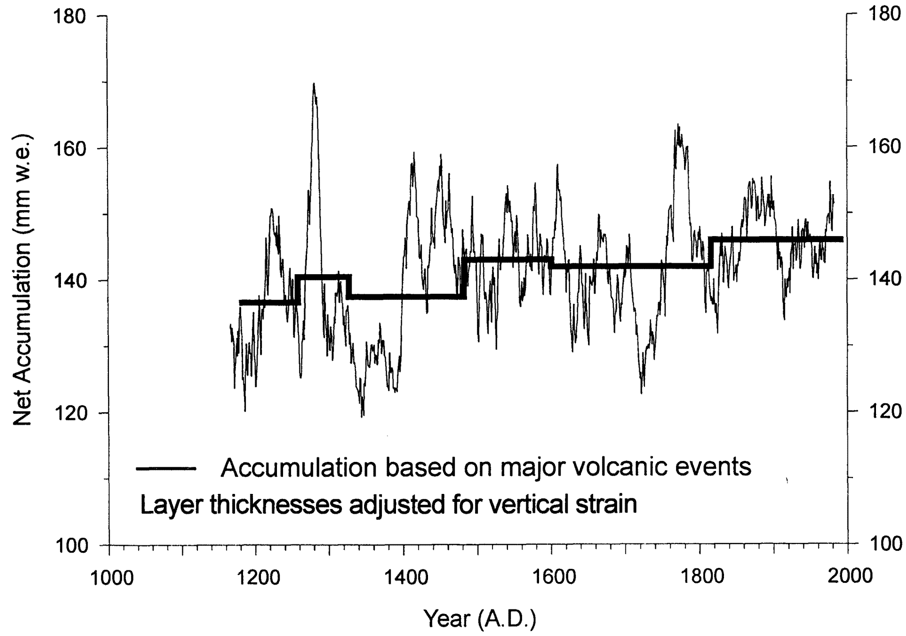
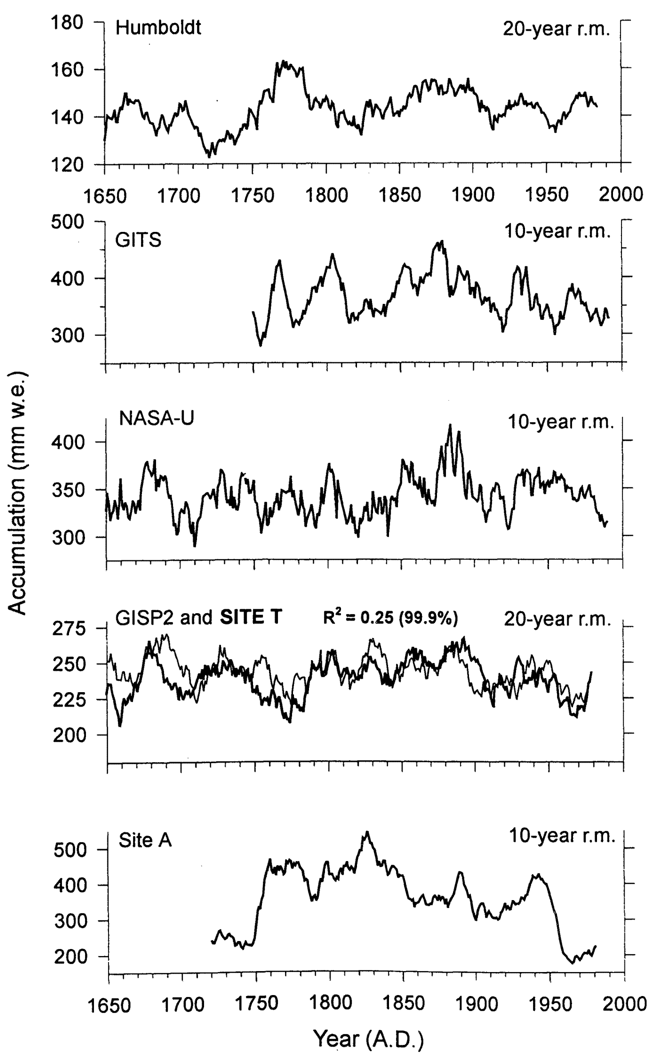


Figure 8. The 842-year A_n record from Humboldt smoothed with a 20-year running mean (RM) is shown (fine line) along with the average A_n between known volcanic events (bold line). Extended periods of above- and below-average A_n, as well as rapid changes, are evident, but over the 842-year record, A_n increased only ~6%.



but it is based on a single core before 1965. Each A_n record was converted to standardized deviations ((observation - mean)/standard deviation) or Z scores. The annual Z scores for the Humboldt, GITS, and NASA-U cores were averaged to produce the composite A_n for northwest Greenland (Figure 10). The same approach was used for the GISP2, Site T, and Site A cores to produce a composite A_n for central Greenland (Figure 10). The mean and σ for calculating the individual Z scores were based on the 251 years (1745 to 1985) that all six sites (or stacked records where applicable) have in common. The regional stacked accumulation records (Figure 10) clearly reveal that long (multidecadal) periods of similar and dissimilar trends are better highlighted by comparing their 20-year running means (bold lines). Over the entire 340-year record the annual data (fine lines) are not related (R=0.033, R^2=0.001, and not significant), but the 20-year running means of A_n are weakly related (R=0.262, R^2=0.068, and significance = 99.9%). The subsequent discussion refers only to 20-year running means of A_n.

Visual inspection of Figure 10 reveals that over most of the 340-year record the A_n histories are strongly correlated, but the sign of their relationship changes over time. Only since 1940 have the A_n trends in northwest and central Greenland been decoupled (R^2=0.016 and not significant). The regional A_n composites are strongly and positively related during two time intervals (1680–1770 and 1880–1940). Conversely, from 1770 to 1880 the A_n composites are strongly and negatively related. The selection of the above time periods for comparison is arbitrary, selected by visual inspection of the records. This discussion highlights the likelihood of multidecadal changes in the North Atlantic's large-scale ocean-atmospheric regime that delivers precipitation to the Greenland ice

Figure 9. Longer A_n records from three cores in northwest Greenland (Humboldt, GITS, and NASA-U) and three cores in central Greenland (GISP2, Site T, and Site A) are shown as 10- or 20-year running means as noted (depending upon regional A_n). Large regional variability is evident.

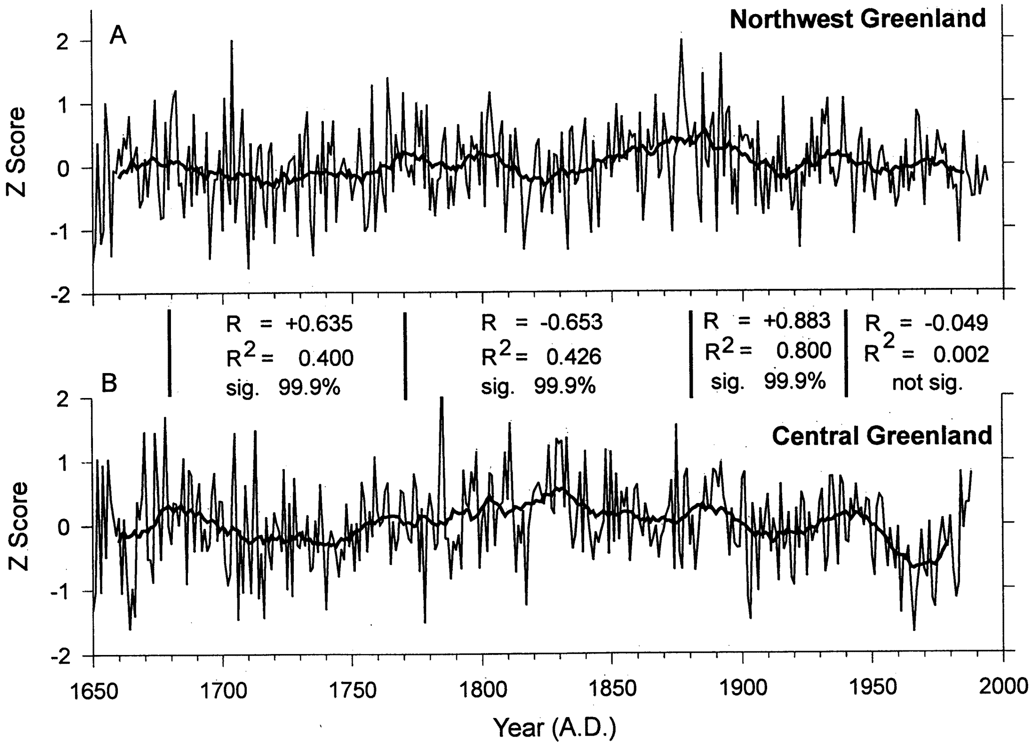


Figure 10. Comparison of the stacked and smoothed (20-year RM) A_n composites for (a) northwest and (b) central Greenland reveal extended periods of strong positive (1680–1770 and 1880–1940) and negative (1770–1880) correlation. Since 1940, A_n trends in the two regions have been decoupled. The time period used to determine the mean and σ for calculating the Z scores was the common period (1745–1985) among all the records. Shown are both the annual Z scores (fine line) and their 20-year RM (bold line). The time periods for which correlations are calculated were selected by visual inspection to illustrate that multidecadal accumulation trends in different regions may be dominated by the same large-scale precipitation pattern at some times and not at others.

sheet and the differential impact this might have on regional precipitation patterns. Such multidecadal oscillations are now recognized as dominant features in the North Atlantic where the most recent periodicity to be identified, ~70 years [*Kerr*, 2000; *Delworth and Mann*, 2000], has been dubbed the Atlantic Multidecadal Oscillation. Long regional ice core-derived accumulation histories, like those presented here, cannot necessarily be extrapolated to an ice sheet-wide A_n record. The latter will require integration of A_n histories from the different accumulation regimes over the ice sheet.

5. Discussion and Conclusions

The accumulation and climate histories emerging from the PARCA core collection promise the best dated and most spatially extensive data set for Greenland to date. These data provide (1) an initial baseline against which future assessments will reveal accumulation trends, (2) input to mass balance estimates [*Abdalati et al.*, 1998; *Thomas et al.*, 1998, this issue], (3) ground truth data for both satellite-based observations [*Davis et al.*, 1998] and model simulations of precipitation distribution [*Bromwich et al.*, 1998], and (4) histories of accumulation and climate for widely distributed sites around Greenland.

The A_n histories demonstrate that the influence of glaciological noise on the climate signal is modulated by the accumulation rate. A simple sensitivity study presented here suggests that in regions of higher annual accumulation (>250 mm WE) as much as 95% of the local noise may be removed using a 10-year average. Where A_n is < 250 mm WE, a longer averaging interval, ~20 years, may be required to reduce local noise by 90%. Certainly, selection of a precise averaging interval is subjective, and the length of the required time average may be reduced by spatial averaging. Therefore drilling more cores in an area and averaging them to create a regional stacked A_n record provides a richer and more robust data set for both glaciological and climatological investigations. These regional stacked A_n records can be combined to reveal interesting larger-scale climate trends. The regional A_n composites for northwest and central Greenland demonstrate that A_n trends are strongly in and out of phase for decades at a time, suggesting multidecadal changes in the atmospheric circulation regime. Under one configuration both northwest and central Greenland experience above-normal accumulation (relative to their respective means), but between 1770 and 1880 the dominant circulation appears to have changed bringing less accumulation to the northwest and more accumulation to the central region. These observations suggest that efforts to reconstruct North Atlantic Oscillation (NAO) variability from single ice cores [*Appenzeller et al.*, 1998], as well as from other proxy records [*Cook*, 1998], should be pursued cautiously [*Schmutz et al.*, 2000]. As more regional composites from different proxy records emerge, efforts to extend the NAO record beyond 1840 may prove more successful.

For the immediate PARCA goal of assessing the Greenland ice sheet mass balance, the ice core-derived A_n records place important limitations on satellite-based measurements of surface elevation [*McConnell et al.*, 2000a] and model-derived precipitation estimates [*McConnell et al.*, 2000b, this issue]. Particularly urgent is the need to develop longer A_n composites for the southern third of the ice sheet on both sides of the north-south divide. Recent altimeter surveys [*Davis et al.*, 1998; *Krabill et al.*, 1999; *Zwally et al.*, 1998] reveal significant spatial variability but little overall change. For example, in the south *Davis et al.* [1998] find thickening west of the ice divide and thinning on the east side. Their observational period is only 10 years, so that short-term changes in snow accumulation are likely to influence the altimeter observations. Studies of accumulation-driven elevation change from 1978 to 1988 suggest that much of the observed elevation change is likely the result of temporal and spatial variability in snow accumulation [*McConnell et al.*, 2000a]. As A_n over the southern ice sheet varies strongly from year to year, it is imperative that ice core and altimetry measurements are contemporaneous [*McConnell et al.*, this issue]. Certainly, longer regional A_n composites from a suite of carefully sited cores, coupled with longer-term altimeter observations, would contribute substantially to future mass balance evaluations. It is imperative that all newly acquired cores be analyzed for multiple seasonally varying constituents with accurate dating as the highest priority.

Acknowledgments. This work was supported by NASA grants NAG5-5032 and 6817 to the Ohio State University, NASA grants NAG5-5031 and 6779 to the University of Arizona, and NASA grant NAGW-4248 and NSF/OPP grant 9423530 to the University of Colorado. Drilling and logistical support was provided by the University of Nebraska Polar Ice Coring Office. Field and laboratory assistance was provided by J. Box, J. Burkhart, M. Davis, K. Henderson, A. Nolin, and B. Snider. This is contribution 1187 of the Byrd Polar Research Center.

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(Received July 19, 2000; revised January 17, 2001; accepted January 23, 2001.)