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Accumulation over the Greenland ice sheet from historical and recent records

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Abstract. Water accumulation, defined as precipitation minus evaporation, was estimated over all of Greenland as part of a program to understand changes in ice sheet mass and elevation. Over 360 historical and recent point accumulation estimates on the Greenland ice sheet were evaluated, and 276 estimates that were judged to be high quality were used to develop the accumulation map. The data set includes 99 points developed as part of four investigations of the past 5-15 years; these are judged to have the greatest accuracy. Using kriging, the average accumulation over Greenland is estimated to be ~30 g cm^{-2} yr^{-1}. For the interior part of the ice sheet above 1800 m elevation, where most of the data were acquired, the average accumulation is also estimated to be ~30 g cm^{-2} yr^{-1}. There are still many areas on the ice sheet, including northwest, southeast, and southern Greenland, where accumulation is highly uncertain, exceeding the mean ice sheet uncertainty at a point of ~20-25%. In these regions, further sampling will be required to reduce uncertainty in both regional and ice-sheet-wide accumulation.

1. Introduction

Accurate ground-based point estimates of water accumulation on the Greenland ice sheet are essential for estimating accumulation, a critical ingredient for both ice-sheet-wide and point mass balance studies. Traditionally, long-term averages of accumulation, defined here as precipitation minus evaporation, have been used to infer and help predict changes in ice sheet mass balance and thus sea level [*Intergovernmental Panel on Climate Change,* 1996]. Ground-based point estimates are also critical as ground truth points for ice-penetrating radar that has the potential to track accumulation changes over wide areas and to estimate changes in elevation for radar and laser altimeters [*Krabill et al.*, 2000]. For these purposes, accurate, highly resolved records of accumulation are needed [*McConnell et al.*, 2000a, this issue; *Mosley-Thompson et al.*, this issue; *Davis et al.*, this issue].

Historical average accumulation values up to about 1980 were compiled by *Bender* [1984] and by *Ohmura and Reeh* [1991]; the latter also compiled coastal precipitation data. *Ohmura et al.* [1999] updated these compilations with selected published and unpublished data developed over the past two decades and did a more thorough analysis of coastal precipitation data. They addressed problems of merging records from the ice sheet, which represent precipitation minus evaporation, with coastal precipitation data to estimate both the precipitation and evaporation components of ice-sheet-wide accumulation.

As part of the Program for Arctic Regional Climate Assessment (PARCA), we have developed accurate point estimates of annual accumulation for over 40 locations on the ice sheet. All of these point estimates are based on shallow cores that were dated with near zero uncertainty in recent decades [*Anklin et al.*, 1998; *McConnell et al.*, 2000b; *Mosley-Thompson et al.*, this issue].

In the current analysis we have developed ice-sheet-wide accumulation estimates and considered the uncertainty in accumulation estimates relative to the long-term mean. We also present our assessment of historical and recent data, and include an updated compilation of historical data, for use in spatial accumulation estimates. Accumulation has been estimated for nearly 100 points on the ice sheet in the past 2 decades and for more than 250 additional points prior to that time. In the current analysis we use the recent points plus more than half of the 250 historical point estimates to develop ice-sheet-wide accumulation maps.

2. Data and Methods

We divided the analysis of point accumulation data into two parts: 1) a review of historical data from field studies carried out prior to about 1981 and 2) data from field studies carried

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out since then. The quality of the more recent data is generally excellent, with most points yielding accurate year-by-year accumulation estimates as well as multidecadal average accumulation. The quality of the earlier data is quite variable, with some points being of comparable quality to the more recent data, but with many of the points based on only 1-2 year accumulation measurements. Net snow accumulation at a point on the ice sheet is influenced by both regional precipitation and the redistribution of snow by wind at spatial scales from centimeters to tens of kilometers. The latter results in an uncertainty of 3-5 cm of water each year (standard deviation) for a 1-year accumulation measurement from an ice core [*McConnell et al.*, 2000b]. In addition, regional precipitation varies significantly from year to year, especially in southern Greenland [*McConnell et al.*, this issue]. Thus estimates of accumulation on the basis of 1-2 years of records are highly uncertain. Both the recent and historical data include replicate and duplicate points; we have either combined these to give a single accumulation estimate for each location or used only the more recent, longer record in our compilation. In the current analysis none of the estimates based on a single year's measurement were used.

2.1. Historical records up to 1981

Using the compilations of *Bender* [1984] (264 points) and *Ohmura and Reeh* [1991] (252 points) as a starting point, we have assessed the data on the basis of information from the original references (where available). Most of these data were in both compilations, and to facilitate cross-referencing with those sources, we have adopted the same notation as the original authors (Table 1). A key concern in including, versus eliminating, point accumulation data from our compilation was the number of years in the record, as well as the accuracy of the methods used. The length of record for more than half of the 252 points compiled by *Ohmura and Reeh* [1991] is 1 year, and only ~50 points include or exceed 10 years (Figure 1). Locations for the points are shown in Figure 2. Unless otherwise noted, only the average accumulation for the period of record was available; detailed, year-by-year data were only available in a few cases.

During the late 1950s and early 1960s several traverses were sponsored by the U.S. Army Transportation Board and by the U.S. Army Snow, Ice and Permafrost Research Establishment (SIPRE), which was merged into the U.S. Army Cold Regions Research and Engineering Laboratory in 1961. The three Lead Dog (L-D) points in Table 1 (shown as U.S. Army Corp of Engineers; (USACE) in Figure 2) are from a 1960 traverse along the northern region of the Greenland ice sheet, which was conducted as a feasibility study by the U.S. Army Transportation Board [*Lead Dog*, 1960]. Four 5-m pits were made using a bulldozer. Detailed stratigraphic studies were conducted on the pit walls, and the average reported record length was 11 years. *Langway* [1961] reported 16 point accumulation estimates from snow pits, using the same methods (LWY in Table 1). Dropping the three points with fewer than 5 years and averaging one point with one reported by L-D for the same location gives the 13 Langway points shown in Table 1. The average record length of these estimates is 7 years.

The largest data set (56 points) comes from work by *Benson* [1962], who traversed the central and northwest portions of the ice sheet. The purpose of those expeditions

Table 1. Historical Accumulation Data

Point	Latitude, Longitude	E[a]	A[b]	Period
B-00-10(B-10)	76.78, -66.36	1146	30.0	1952-1954
B-0-27	76.45, -66.83	765	50.0	1953-1955
B-0-31	76.45, -66.52	699	55.0	1953-1955
B-0-35 [b]	76.52, -66.38	874	67.0	1952-1955
B-0-60-1-0	76.73, -65.42	1310	65.0	1943-1954
B-1-10	76.80, -64.89	1419	40.0	1947-1954
B-1-20	76.89, -64.40	1486	33.0	1946-1954
B-1-30	76.96, -63.90	1519	25.0	1943-1954
B-1-40	77.05, -63.39	1571	23.0	1942-1954
B-1-50	77.14, -62.89	1630	23.0	1942-1954
B-1-60-2-0	77.24, -62.33	1704	21.0	1933-1954
B-1A-10	77.02, -62.37	1720	36.0	1951-1955
B-1A-20	76.92, -62.00	1660	45.0	1952-1955
B-2-10	77.24, -61.67	1788	25.0	1944-1954
B-2-100	77.00, -56.01	1992	40.0	1938-1954
B-2-125	77.04, -54.52	2152	32.0	1947-1955
B-2-150	77.05, -52.92	2273	27.0	1947-1955
B-2-175	77.06, -51.33	2392	24.0	1946-1955
B-2-20	77.22, -61.02	1864	30.0	1941-1954
B-2-200	77.06, -49.60	2475	22.0	1942-1955
B-2-225	77.07, -48.02	2536	18.5	1939-1955
B-2-250-4-0	76.97, -46.98	2616	16.5	1939-1955
B-2-30	77.18, -60.40	1887	38.0	1937-1954
B-2-40	77.18, -59.73	1885	40.0	1946-1954
B-2-50	77.15, -59.10	1877	40.7	1944-1954
B-2-60	77.13, -58.43	1905	39.0	1944-1954
B-2-70	77.10, -57.82	1919	40.0	1938-1954
B-2-80	77.06, -57.20	1944	39.5	1946-1954
B-2-90	77.03, -56.56	1904	41.0	1947-1954
B-4-100	75.64, -43.95	2778	18.8	1939-1955
B-4-125	75.30, -43.42	2821	20.5	1940-1955
B-4-150	74.93, -42.97	2851	21.0	1939-1955
B-4-175	74.59, -42.55	2873	22.0	1940-1955
B-4-200	74.22, -42.17	2918	23.0	1940-1955
B-4-225	73.87, -41.80	2941	23.0	1941-1955
B-4-25	76.64, -45.70	2491	17.5	1939-1955
B-4-250	73.52, -41.42	2972	23.0	1943-1955
B-4-275	73.17, -41.10	3003	25.0	1941-1955
B-4-300	72.82, -40.75	3046	27.0	1945-1955
B-4-375	71.77, -39.60	3131	29.5	1945-1955
B-4-400	71.43, -39.33	3126	30.5	1945-1955
B-4-425-5-0	71.08, -38.97	3123	30.5	1945-1955
B-4-50	76.32, -45.10	2720	17.5	1939-1955
B-4-75	75.99, -44.58	2749	18.5	1940-1955
B-5-115	70.45, -43.58	2646	47.0	1950-1955
B-5-160	70.18, -45.37	2342	53.0	1950-1955
B-5-170	70.11, -45.73	2283	55.0	1950-1955
B-5-180	70.04, -46.13	2206	55.0	1950-1955
B-5-190	69.98, -46.50	2146	55.0	1950-1955

Table 1. (continued)

Point	Latitude, Longitude	E[a]	A[b]	Period
B-5-20	71.00, -39.67	3071	33.5	1946-1955
B-5-200	69.92, -46.93	2012	60.0	1950-1955
B-5-210	69.87, -47.30	1963	58.0	1950-1955
B-5-220	69.80, -47.67	1861	56.0	1953-1955
B-5-90	70.63, -42.62	2763	45.0	1948-1955
B68B-2120-68A	77.19, -55.90	2078	33.0	1950-1953
LWY-2	77.72, -59.57	2025	20.2	1951-1958
LWY-4	78.62, -53.00	2096	16.8	1949-1958
LWY-5	79.02, -49.13	2147	15.9	1950-1958
LWY-6	79.72, -51.42	1843	19.9	1950-1958
LWY-7	80.38, -54.05	1524	24.8	1952-1958
LWY-8	80.75, -55.33	1420	26.5	1953-1958
LWY-9	79.47, -44.32	2215	13.9	1947-1958
LWY10-LD0	80.00, -39.63	2071	12.3	1946-1958
LWY-11	80.65, -39.63	1960	17.4	1948-1958
LWY-12	81.30, -39.73	1803	19.6	1950-1958
LWY-I-270	79.90, -43.03	2145	13.5	1952-1957
LWY-I-90	77.98, -52.50	2296	15.9	1950-1957
LWY-I-I80	78.92, -48.20	2205	13.8	1949-1957
L-D-4	80.02, -38.42	2028	12.0	1953-1959
L-D-11	80.03, -35.57	1924	13.9	1943-1953
L-D-21	80.00, -31.25	1690	20.1	1951-1959
M-S-30	76.78, -61.88	1553	54.8	1956-1961
M-S-20	76.92, -61.67	1728	46.8	1954-1961
M-S-40	76.65, -62.15	1262	60.3	1958-1961
M-P42-7(S-10)	77.05, -61.38	1819	36.5	1954-1961
M-P42-11(N-8)	77.28, -61.17	1886	21.4	1954-1961
M-P42-13(N-16)	77.42, -61.30	1874	18.2	1954-1961
M-P42-15(N-25)	77.52, -61.47	1868	16.2	1954-1961
M-P42-17(N-35)	77.57, -62.17	1760	18.2	1954-1961
M-P42-19(N-44)	77.58, -62.75	1655	22.5	1954-1961
M-P42-21(N-55)	77.62, -63.45	1510	24.3	1955-1961
M-R-59-0	66.57, -47.20	1903	30.0	1954-1959
M-R-59-46	66.40, -45.52	2230	33.0	1955-1959
M-R-59-66[b]	66.32, -44.80	2316	33.0	1955-1959
M-R-59-86	66.22, -44.14	2410	37.0	1955-1959
M-R-59-250[c]	64.48, -42.96	2439	77.0	1957-1959
M-R-59-275	64.49, -43.83	2650	57.0	1957-1959
M-R-59-300	64.50, -44.68	2672	30.0	1955-1959
M-R-59-325	64.47, -45.62	2486	32.0	1954-1959
M-R-59-350	64.45, -46.58	2323	39.0	1956-1959
M-R-59-375	64.43, -47.51	2139	47.0	1956-1959
M-R-59-425	63.72, -47.32	2191	41.0	1956-1959
M-R-59-475	63.20, -46.30	2548	56.0	1957-1959
M-R-59-525[c]	62.50, -46.00	2376	66.0	1957-1959
M-R-59-550[c]	62.21, -45.65	2411	72.0	1957-1959
M-R-59-575[c]	62.02, -45.03	2385	80.0	1958-1959
M-R-59-600[c]	61.83, -44.40	2160	90.0	1958-1959
M-R-60-75	62.51, -45.23	2574	56.0	1958-1960

Table 1. (continued)

Point	Latitude, Longitude	E[a]	A[b]	Period
M-R-60-127[c]	63.22, -45.07	2709	43.0	1957-1960
M-R-60-1-75[c]	65.85, -44.62	2423	64.0	1958-1960
M-R-60-1-96	66.05, -45.15	2320	37.0	1958-1960
M-R-60-1-117	66.27, -45.70	2208	39.0	1957-1960
M-A-HIRAN-26[c]	68.25, -35.60	2925	23.0	1956-1963
M-A-HIRAN-28	70.62, -36.17	3138	23.0	1956-1963
G(C)-DYE3-P	65.20, -43.78	2465	49.1	1243-1971
G(C)-DYE-2	66.48, -46.33	2100	34.3	1736-1973
G(C)-MILCENT	70.30, -45.00	2410	49.5	1177-1973
G(C)-A-1985	70.64, -35.82	3092	28.2	1610-1973
G(C)-B-1985	70.65, -37.48	3138	30.0	1705-1973
G(C)-C-1985	70.68, -38.79	3072	31.2	1931-1973
G(C)-D-1985	70.64, -39.62	3018	33.5	1755-1973
G(C)-E-1985	71.76, -35.85	3087	20.7	1698-1973
G(C)-F-1985	71.49, -35.88	3092	21.8	1912-1973
G(C)-H-1985	70.87, -35.84	3102	25.4	1920-1973
G(C)-CRTE-T43	71.12, -37.32	3172	26.5	552-1973
G(C)-SUMMIT	72.29, -37.98	3210	24.0	1904-1974
G(C)-N-CENT	74.62, -39.60	2930	13.2	1406-1973
G(C)-N-SITE	75.77, -42.44	2850	15.1	1943-1973
G(P)-SD-KOIDE	63.55, -44.60	2821	56.5	1963-1973
G(P)-DS-1[c]	63.60, -44.25	1847	68.6	1966-1973
G(P)-BDS	64.50, -44.33	2760	50.5	1963-1973
G(P)-SDS-1	65.67, -44.77	2620	47.3	1962-1973
G(P)-SDS-2	65.53, -44.12	2618	56.8	1964-1973
G(P)-SDS-3[c]	65.83, -44.12	2640	60.8	1965-1973
G(P)-SAS[c]	65.68, -44.18	2497	57.1	1964-1973
G(P)-SNS-2[c]	65.92, -42.72	2365	104.0	1968-1973
G(P)-SN[c]	66.20, -43.67	2494	62.9	1965-1973
G(P)-A1	67.45, -41.98	2536	52.3	1963-1973
G(P)-A1-S1[c]	67.00, -41.63	2563	63.8	1965-1973
G(P)-A1-S2	67.82, -42.90	2606	37.3	1959-1973
DANS-3008[c]	64.85, -44.65	2652	36.7	1963-1972
DANS-16B	65.05, -44.33	2581	41.7	1963-1972
DANS-11.5	65.12, -44.18	2547	41.3	1963-1972
G(B)-D2-DS2	63.55, -44.93	2503	43.1	1961-1973
G(B)-D3-DS3	63.70, -44.53	2488	48.0	1961-1973
G(O)-P36	64.95, -45.07	2630	39.0	1960-1973
G(O)-SITE-DIV	65.05, -44.00	2620	39.2	1960-1973
G(O)-P20	65.08, -44.43	2610	38.0	1960-1973
G(O)-SNS-1	66.47, -44.83	2457	38.4	1960-1973
G-OHIO1001	65.39, -47.32	2022	45.3	1955-1980
G-OHIO1002	65.39, -47.76	2164	35.2	1965-1980
G-OHIO1005	65.39, -48.89	1860	54.6	1956-1980
G-OHIO2001	65.11, -45.31	2519	37.8	1959-1980
G-OHIO2002	65.07, -45.71	2586	36.6	1959-1980
G-OHIO2005	65.14, -46.89	2442	36.3	1955-1980
G-OHIO3005	65.12, -44.80	2591	46.3	1959-1980
G-OHIO3007	65.01, -44.35	2666	40.9	1958-1980

Table 1. (continued)

Point	Latitude, Longitude	E[a]	A[b]	Period
WHIL-2003	64.93, -45.58	2566	38.8	1961-1981
WHIL-2004	64.97, -46.02	2485	39.5	1961-1981
WHIL-2006	65.28, -45.83	2457	38.6	1961-1981
WHIL-2007	65.23, -45.40	2530	36.9	1961-1981
WHIL-3008	64.85, -44.65	2701	39.9	1961-1981
PATER-A16	77.47, -29.45	1860	13.0	1952-1954
PATER-A31	77.67, -33.23	2100	10.0	1952-1954
PATER-A58	78.06, -40.72	2440	12.0	1952-1954
PATER-A73	78.02, -45.61	2530	11.0	1952-1954
PATER-B102	77.92, -46.43	2520	12.0	1952-1954
PATER-B107	77.67, -47.93	2530	12.0	1952-1954
PATER-B64	78.04, -42.75	2510	15.0	1952-1954
PATER-B81-77	77.24, -24.90	1100	19.5	1952-1954
PATER-B9	77.32, -27.93	1710	11.0	1952-1954
PATER-C	76.72, -47.33	2671	14.0	1952-1954
PATER-C1	76.88, -46.20	2695	17.0	1952-1954
PATER-C2	77.03, -45.13	2664	15.0	1952-1954
PATER-C3	77.20, -44.03	2652	17.0	1952-1954
PATER-C4	77.38, -43.02	2616	16.0	1952-1954
Quer-K3[c]	69.66, -49.25	1219	22.0	1950-1959
Quer-CAMP-VI[c]	69.74, -48.07	1677	40.0	1952-1959
Quer-MILCENT	70.31, -44.58	2449	48.7	1955-1960
Quer-DEP480	72.51, -29.97	2310	18.1	1945-1960
CARREFOUR	69.83, -47.43	1850	57.0	1948-1967
HAMIL-N-ICE	78.07, -38.48	2345	9.1	1878-1953
NISHIO-PRT-1	66.87, -46.27	2000	38.5	-
MULLER-V	77.07, -70.42	1100	46.3	1968-1974
MULLER-D	78.20, -71.75	1080	22.4	1968-1974

[a] Elevation meters above sea level.
[b] Annual Accumulation g cm^{-2} yr^{-1}.
[c] Eliminated from spatial interpolation based on semivarigram.

was to collect information on accumulation, facies delineation, mean annual temperatures, and snow characteristics pertinent to logistical operations on the ice sheet. The point measures of accumulation from these expeditions are based on 1-4 m deep snow pits and firn cores up to 10 m in length, collected at 30-80 km intervals. These measurements have an average record length of 10 years, and 49 points have records of more than 5 years. Annual layers were identified from visual stratigraphy, with snow pit density profiles measured by weighing SIPRE tubes. Detailed profiles were published, and the accuracy of the annual accumulation estimates for the years covered by the data are judged to be relatively good. Besides the points in Table 1, 21 other points were dropped because of short record lengths and availability of other, better data in the vicinity; 3 colocated points were averaged. An updated compilation is given by *Bender* [1984] and a reprint of a 1962 Benson report [*Benson*, 1996].

The U.S. Army Corps of Engineers reported accumulation for 32 additional points in the south and northwest parts of the ice sheet [*Mock*, 1965; *Mock and Alford*, 1964; *Mock and Ragle*, 1963; *Ragle and Davis*, 1962] (M in Table 1). These data were derived from pit studies, as noted above. The average record length for the 32 points is 4 years. Although 12 of the points have fewer than 4 years of records, they were retained because they are from areas with few data and were consistent with nearby points.

A number of shallow cores were collected and analyzed in connection with Greenland Ice Sheet Project (GISP) 1 activities in the 1970s. Average accumulation for 14 points, designated G(C), are reported by *Clausen et al.* [1988] and *Dansgaard et al.* [1985]. Three additional points were not included, as more recent records were available for the sites. While the average record length is over 350 years, values reported by *Clausen et al.* [1988] are for the period 1943-1973. Accumulation was determined from annual cycles of $\delta^{18}O$. Detailed records for most cores have not been published; however, the quality of these records is judged to be good. Efforts are underway to distribute the annual accumulation data (S. Johnsen and H. Clausen, personal communication, 2000). Sixteen points reported by H.B. Clausen et al. (personal communication, [1984] as cited by *Bender*) were from 11-m cores, with no details available. Because some were replicate cores from the same location, or from the same location as *Dansgaard et al.* [1985] points, the 16 were combined into 12 points in Table 1, indicated by GISP(P). They are assumed to represent accumulation up to 1973, and the average record length is 9 years. One point was colocated with the Koide point reported by *Ohmura and Reeh* [1991], so the two were averaged. The three points (DANS) reported by *Dansgaard et al.* [1985] in the Dye 3 vicinity represent 9-year averages and are based on $\delta^{18}O$ and visual stratigraphy profiles. Seven points in the Dye 2 and Dye 3 vicinity associated with GISP 1 were taken from *Ohmura and Reeh* [1991] and referred to *Dansgaard et al.* [1985]; the points were identified, but no accumulation values were given by *Bender* [1984]. Accumulation was based on $\delta^{18}O$ profiles from 10-m firn cores. As the cores were clustered around only two locations, they were averaged into the two GISP(B) points in Table 1. Four GISP 1 points southwest of Dye 3, labeled G(O) in Table 1, were only reported in the *Ohmura*

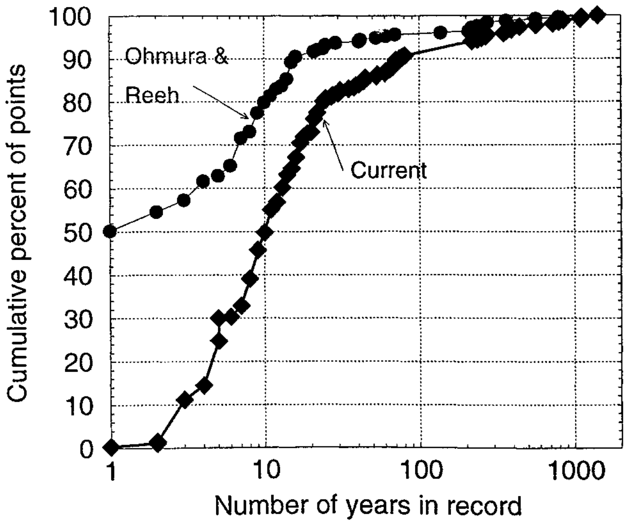

Figure 1. Distribution of record lengths for point accumulation estimates.

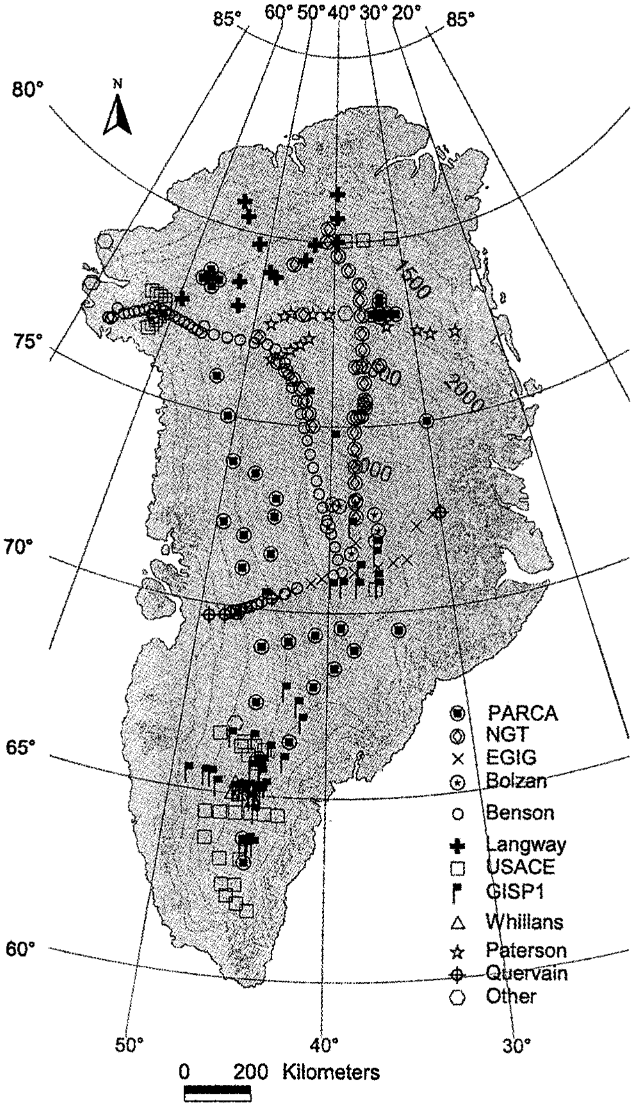

Figure 2. Locations of historical and recent point estimates of accumulation.

and Reeh [1991] tabulation and referred to a table of *Radok et al.* [1982] and are assumed to be based on analysis of 10-m cores as described above for G(P).

Accumulation for nine additional GISP 1 points west of Dye 3 came from an unpublished report of cores and pits collected in 1980 by *Whillans* [1987]. Cores were 10-21 m in length, with density measured in the field and laboratory. Cores were dated based on annual variations in $\delta^{18}O$ and confirmed by identification of beta radioactivity horizons. The average accumulations are judged to be very good, with some uncertainty in density values. Potentially, the year-by-year accumulation could be developed for many of these sites using the $\delta^{18}O$ records. Two replicate cores were averaged, giving the eight G-OHIO points in Table 1. Five cores that were collected as part of related field efforts [*Whillans,* 1987] are labeled WHIL in Table 1. Methods are the same as for the G-OHIO cores. The average record length for the 13 cores is ~21 years. Some additional sites that were identified by *Whillans* [1987] were not included in our tabulation because they are at or near the 13 locations in Table 1.

Bender [1984] listed 22 points from northern Greenland from work by Paterson and colleagues in the early 1950's however, seven of these points were dropped because of their proximity to points with longer records, and two other colocated points were merged, giving the 14 points listed in Table 1 (PATER in Table 1). We retained these 14 points in Table 1 despite their short records because they are from areas with few data and were consistent with nearby points. Accumulation was apparently based on stratigraphic analysis of two annual cycles in snow pits.

Ohmura and Reeh [1991] tabulated 10 points from work by Quervain and colleagues in the 1960's; however, as several were close together, we eliminated six and averaged two others with nearby records, resulting in four points (Table 1). Average record length is ~7 years, on the basis of stratigraphic analysis in the pits.

A few points came from very local investigations that reported only a few data. The single Carrefour point [*Ohmura and Reeh,* 1991], near the Expédition Glaciologique Internationale au Groenland (EGIG) line, is from a 20-m core, with the average accumulation taken from *Ohmura and Reeh* [1991]. The Hamilton site, west of the PARCA Tunu cores in north central Greenland, is a 75-year record based on visual stratigraphy in a deep pit. Because it was our experience at the Tunu sites that visual stratigraphy did not match that well, the Hamilton number has considerable uncertainty. The Nishio point was reported by *Ohmura and Reeh* [1991], with no details available. *Müller et al.* [1977] reported accumulation for three points in northwestern Greenland on the basis of shallow cores and pits. As two points were very close, we averaged them giving the two locations in Table 1.

The Henrickson, Koch-Wegener, and Merc-Quervain data in the *Ohmura and Reeh* [1991] tabulation were not used in our analysis. The Henrickson point, west of Dye 2, was apparently only a single year estimate and is in a region with more reliable data. The Koch-Wegener traverse, conducted in 1912-1913, involved point measurements at 36 locations using single-year stratigraphic sequences. Annual accumulation was determined from the amount of water between two seasonal layers, with corrections made for the varying density of winter and summer layers. Altogether, we dropped or merged data from 99 of the 252 points listed by *Ohmura and Reeh* [1991]. Therefore the total number of what we consider good quality accumulation estimates developed prior to 1981 is 177.

2.2. Data Developed After 1981

PARCA data are based on multiparameter analysis of ice cores, most of which were ~20 m in length; four sites had deeper cores [*Anklin et al.,* 1998; *McConnell et al.,* this issue, 2000b; *Mosley-Thompson et al.,* this issue](P in Table 2). The median record length is 21 years. Besides PARCA, there are three other recent reports of accumulation on the ice sheet: 1) the North GRIP traverse [*Fischer et al.,* 1998; *Friedmann et al.,* 1995; *Fischer,* 1997], 2) the EGIG line [*Anklin et al.,* 1994; *Fischer et al.,* 1995], and 3) the Summit region [*Bolzan and Strobel,* 1994] (Table 2).

PARCA cores were collected between 1993 and 1999, with year-by-year accumulation values developed from multiple parameters measured along the cores ($\delta^{18}O$, dust, H_2O_2, Ca^{2+}, NH_4^+, NO_3^-, and electrical conductivity). Absolute dating of some cores was confirmed using beta radioactivity from

Table 2. Recent Accumulation Data

Point	Latitude, Longitude	E[a]	A[b]	Period
P-NASA-U	73.83,-49.48	2368	34.0	1645-1694
P-HUMB	78.52,-56.82	1995	14.0	1143-1192
P-HUMB-N	78.73,-57.20	1995	14.4	1927-1994
P-HUMB-E	78.52,-55.77	1995	14.5	1928-1994
P-HUMB-S	78.30,-56.47	1995	13.8	1924-1994
P-HUMB-W	78.45,-57.88	1995	13.8	1925-1994
P-GITS	77.18,-61.08	1910	33.9	1745-1796
P-TUNU	78.02,-33.98	2110	11.4	1550-1595
P-TUNU-N25	78.32,-33.88	2030[c]	9.8	1925-1996
P-TUNU-E25	78.00,-32.92	1989[c]	10.2	1952-1996
P-TUNU-W25	78.02,-35.05	2148[c]	7.3	1918-1996
P-TUNU-N50	78.45,-33.83	1998[c]	10.4	1932-1996
P-TUNU-E50	77.97,-31.85	1925[c]	8.3	1952-1996
P-TUNU-W50	78.04,-36.14	2060[c]	11.0	1936-1996
P-TUNU-S7.5	77.95,-34.00	2092[c]	12.2	1942-1996
P-S-DOME	63.15,-44.82	2850	67.0	1978-1996
P-SADDLE	66.00,-44.50	2460	45.0	1975-1997
P-Tunu-South	69.50,-34.50	2650	45.0	1974-1996
P-NASA-E	75.00,-30.00	2631	15.0	1952-1997
P-7147	71.05,-47.23	2134	43.0	1974-1996
P-7247	71.92,-47.48	2277	43.0	1974-1996
P-7551	75.00,-50.90	2200	32.5	1965-1996
P-7653	76.00,-53.00	2200	35.0	1978-1996
P-6945	69.00,-45.00	2147[c]	45.5	1977-1997
P-6943	69.20,-43.00	2498[c]	40.2	1977-1997
P-6941	69.40,-41.00	2764[c]	38.4	1985-1997
P-6939	69.60,-39.00	2954[c]	33.4	1982-1997
P-6841	68.00,-41.00	2638[c]	47.5	1987-1997
P-6745	67.50,-45.00	2204[c]	37.0	1984-1997
P-6839	68.50,-39.50	2787[c]	38.5	1985-1997
P-6938	69.00,-38.00	2947[c]	35.9	1983-1997
P-6642	66.50,-42.50	2381[c]	58.9	1980-1997
P-6345	63.80,-45.00	2733[c]	32.4	1977-1971
P-7249[d]	72.20,-49.40	2600	55.6	1986-1998
P-7347	73.60,-47.20	2600[c]	28.9	1980-1997
P-7345	73.00,-45.00	2814[c]	28.9	1975-1997
P-7145	71.50,-45.00	2632[c]	42.9	1986-1998
P-7245	72.50,-45.00	2781[c]	28.0	1984-1997
P-CRAWFORD	69.85,-47.12	2000	48.0	1983-1989
P-UAK1	65.50,-44.50	2560[c]	47.8[c]	-
P-UAK4	65.47,-46.09	2355[c]	34.7[c]	-
P-UAK5	65.44,-46.55	2260[c]	34.9[c]	-
NGT-GRIP	72.57,-37.62	3230	21.0	-
NGT03-B16	73.93,-37.62	3080	14.0	1600-1993
NGT06-B17	75.25,-37.62	2900	9.4	1600-1993
NGT14-B18	76.62,-36.40	2600	9.8	897-1993
NGT19-B19	78.00,-36.38	2340	9.0	871-1993
NGT23-B20	78.83,-36.50	2147	9.7	1912-1993
NGT27-B21	80.00,-41.13	2185	10.8	1960-1993
NGT30-B22	79.33,-45.90	2603[c]	14.4	-
NGT33-B23	78.00,-44.00	2543	11.0	-
NGT37-B26	77.25,-49.22	2598	17.7	-
NGT39-B27-28	76.65,-46.48	2733	17.0	-
NGT42-B29	76.00,-43.48	2874	15.2	-
NGT45-B30	75.00,-42.00	2947	16.0	-
NGT01	73.03,-37.65	3179[c]	17.2	1991-1994
NGT02	73.50,-37.65	3096[c]	15.5	1991-1994
NGT04	74.40,-37.63	2925[c]	13.3	1990-1994
NGT05	74.85,-37.63	2845[c]	12.6	1990-1994
NGT07	75.25,-37.22	2763[c]	14.1	1991-1994
NGT08	75.28,-36.90	2750[c]	11.6	1990-1994
NGT09	75.50,-36.40	2716[c]	11.7	1990-1994
NGT10	75.57,-36.53	2695[c]	11.7	1990-1994
NGT11	75.65,-36.32	2665[c]	12.9	1990-1994
NGT12	75.72,-36.40	2669[c]	13.6	1991-1994
NGT13	76.17,-36.40	2589[c]	13.1	1990-1994
NGT15	76.62,-37.37	2555[c]	11.5	1991-1994
NGT16	76.62,-34.47	2395[c]	14.8	1992-1994
NGT17	77.07,-36.40	2414[c]	12.4	1990-1994
NGT18	77.52,-36.40	2325[c]	11.0	1990-1994
NGT22	78.42,-36.43	2177[c]	11.5	1987-1994
NGT25	79.23,-37.95	2165[c]	9.8	1987-1994
NGT26	79.62,-39.50	2175[c]	11.3	1988-1994
NGT28	80.35,-41.13	2073[c]	13.1	1989-1994
NGT40	76.45,-45.45	2755[c]	16.4	-
NGT41	76.23,-44.48	2798[c]	16.2	-
NGT43	75.67,-42.97	2869[c]	15.6	-
NGT44	75.33,-42.47	2898[c]	15.4	-
EGIG-T05	69.83,-47.27	1905	46.7	1982-1989
EGIG-T09	70.00,-46.37	2107	41.9	1981-1989
EGIG-T17	70.37,-44.13	2530	44.6	1981-1989
EGIG-T21	70.53,-43.05	2692	43.7	1981-1989
EGIG-T27	70.77,-41.53	2868	40.2	1982-1989
EGIG-T31	70.90,-40.63	2960	34.9	1980-1989
EGIG-T41	71.07,-37.92	3150	24.9	1978-1989
EGIG-NST08	71.87,-37.77	3190	22.9	1987-1992
EGIG-T47	71.20,-35.93	3100	22.1	1983-1991
EGIG-T50	71.30,-34.58	2985	22.7	1989-1991
EGIG-T53	71.35,-33.43	2870	23.2	1982-1991
EGIG-T61	72.22,-32.32	2800	18.7	1983-1991
EGIG-T66	72.47,-30.75	2675	16.8	1985-1991
BO-S-13	72.88,-39.15	3163	21.1	1951-1986
BO-S-15	72.97,-37.70	3182	16.3	1945-1986

Table 2. (continued)

Point	Latitude, Longitude	E[a]	A[b]	Period
BO-S-31	72.33,-40.20	3105	26.2	1958-1986
BO-S-37	72.63,-35.93	3172	18.1	1947-1986
BO-S-51	72.92,-39.83	3105	27.4	1959-1986
BO-S-57	71.92,-35.95	3102	21.4	1964-1986
BO-S-571	72.20,-35.67	3140	18.5	1948-1986
BO-S-73	71.60,-38.13	3171	24.8	1956-1986

[a] Elevation, meters above sea level.

[b] Annual accumulation, g cm^{-2} y^{-1}.

[c] Elevation estimated from digital elevation map.

[d] Eliminated from spatial interpolation based on semivariogram.

[e] Preliminary value for 1999 PARCA core.

atmospheric nuclear testing and using volcanic horizons (mainly, Laki in 1783 or Tambora in 1815). Preliminary values are reported for three of the 1999 cores (UAK1, UAK4, and UAK5), with others still being analyzed. Details of the PARCA cores have been published by *Anklin et al.* [1998], *McConnell et al.*, [this issue, 2000b], *Bales et al.* [2001], and *Mosley-Thompson et al.* [this issue]. There may be minor differences between accumulation values in these references and those in Table 1 because of preliminary dating of the records, reporting averages for different time periods, and in a few cases, unresolvable dating uncertainties of ±1 year.

The north Greenland traverse (NGT), 1993-1995, involved 13 shallow cores (100-175 m depth) at ~150-km spacing, with an additional 23 snow pits (1.5-3 m depth) and firn cores (10-15 m depth) every 50 km in between. One snow pit was eliminated because of its close proximity to a core, and we added the North GRIP core to the compilation, giving the 36 values in Table 1. Cores B16-B19 were 89-149 m in depth, with dating based on volcanic horizons [*Friedmann et al.*, 1995]. Table 1 gives the full time span covered by the cores; however, accumulation values listed for these four cores are for the past two centuries, on the basis of 1783 Laki horizon. Values for B21 and B29 were taken from *Fischer et al.* [1998]; no time period was given for the two values. Results for some of the other NGT sites were taken from the dissertations of *Fischer* [1997] and *Jung-Rothenhäusler* [1998], with other (unpublished) data taken from the recent compilation of *Ohmura et al.* [1999]. The accumulation data in the cores are based on multiple annual parameters (e.g., $\delta^{18}O$ and Ca^{2+}), with volcanic reference horizons for absolute dating, and are very good; however, they should be regarded as preliminary until details are published by the researchers involved. The record length for the pits was taken from information in the dissertation of *Fischer* [1997]; the records are assumed to be up to 1994.

The EGIG traverse, by the Institut für Vermessungkunde, Technische Universität Braunschweig, Germany, in 1990-1992, repeated the east-west line located at ~70°N traversed ~30 years earlier [*Fischer et al.*, 1995]. It involved multiparameter analysis ($\delta^{18}O$, hydrogen peroxide, and major ions) of 18 shallow cores to depths of 3-11 m. Density was measured in the field on both cores and 1.5-m-deep pits. Five points were not included owing to replication. The average length of record for the 13 points in Table 2 is 7 years.

The *Bolzan and Strobel* [1994] data are from eight shallow cores in the vicinity of Summit and were dated based on annual variations in $\delta^{18}O$ and confirmed by identification of beta radioactivity horizons. The average record length is 36 years. These cores were collected as part of the GISP 2 program to assess spatial variability of accumulation in central Greenland.

In summary, since 1981 these four major investigations (GISP 2, NGT, EGIG, and PARCA) have contributed a total of 99 high-quality point estimates. These data, coupled with the better quality accumulation data prior to 1981, are used here to generate an improved accumulation map for the Greenland ice sheet using the 276 points in Tables 1 and 2.

2.3. Kriging

Interpolation to develop an ice-sheet-wide estimate of accumulation was accomplished using kriging. Because there were few data below ~1800 m in elevation (Figure 3), in addition to the data in Tables 1 and 2 we used 17 coastal points [*Bales et al.*, 2001; *Ohmura et al.*, 1999] to constrain estimates at lower elevations. A quadratic surface (second-order drift) was fit to the data points using a least squares fit, and residuals between the surface and data were determined. Residuals at grid points were then kriged, and the accumulation was calculated as the sum of the kriged and quadratic surfaces. Semivariograms were calculated at lag increments of 10 km for 30 lags. A spherical model with a nugget of 20 (g cm^{-2} yr^{-1})^2, a sill of 55 (g cm^{-2} yr^{-1})^2, and a range of 200 km was estimated from the semivariogram. A decision to delete 19 sites with short records and high uncertainty (see Table 1) plus one PARCA point (Table 2) was made after examining the contribution of individual data points to the semivariogram, resulting in our use of 256 points on the ice sheet plus the 17 coastal points for the interpolation. Because of the highly nonuniform distribution of the data points a search radius of 200 km using 4 to 16 points for kriging was used in areas with more densely distributed data, and a search radius of 400 km using 2 to 4

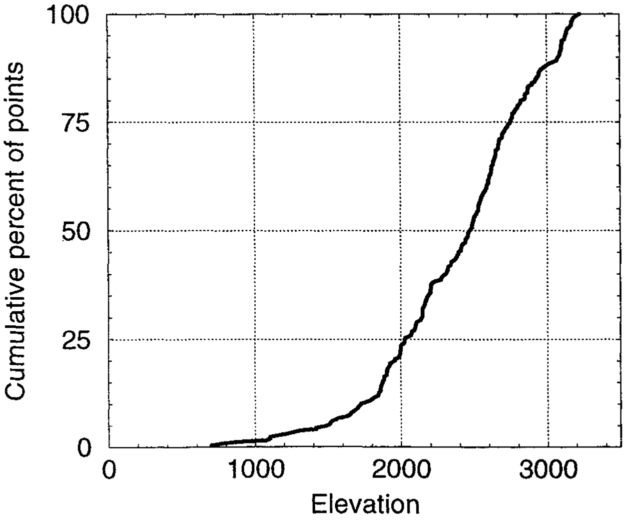

Figure 3. Elevational distribution of accumulation estimates from Tables 1-2.

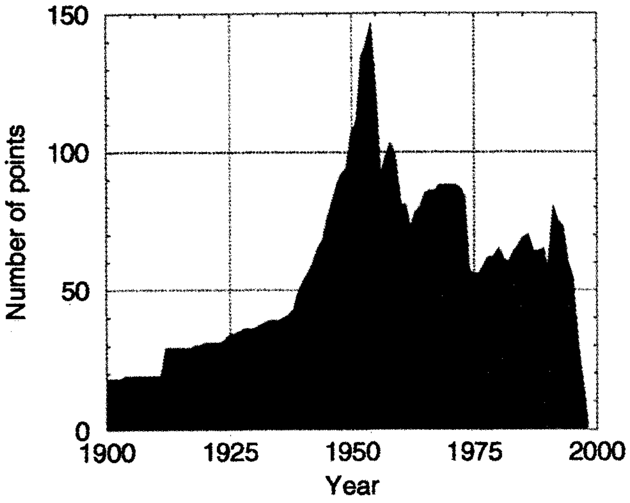

Figure 4. Time periods covered by data used in kriging analysis.

points for kriging was used wherever the 200-km search radius criteria could not krig a value because of too few data points. This produced kriged values in all areas of primary interest without undue smoothing in areas with densely distributed data.

3. Results

The mean length of record for the 256 points used was 10 years (Figure 1), with most of the data falling into the period 1940-present (Figure 4). The mean accumulation was 29 g cm^{-2} yr^{-1} for all 256 points, and 32 g cm^{-2} yr^{-1} for the 17 coastal points. Recent cores (Table 1) tend to be from higher accumulation regions (mean 32 g cm^{-2} yr^{-1}) than historical cores (mean 24 g cm^{-2} yr^{-1}); the mean value for PARCA cores is 30 g cm^{-2} yr^{-1}.

The kriged map (Plate 1) shows high accumulation areas (over 40 g cm^{-2} yr^{-1}) in the south, southeast, and west, with the northeast part of the ice sheet having low accumulation (under 20 g cm^{-2} yr^{-1}). The mean accumulation value for the ice sheet was 30 g cm^{-2} yr^{-1}. Contours of accumulation along the southeast and west central areas follow the general topography, but this pattern is less pronounced in the southwest and northeast. This map, which mixes data from multiple time periods, is nearly identical to that for a recent 2-decade period (1971-1990) [*Bales et al.*, 2001].

We evaluated cokriging as a means of capturing the elevation dependence of accumulation, but it failed to improve the result, in part because of large accumulation differences across the ice sheet. We also evaluated higher-order drift surfaces, which captured more of the variance in the drift but failed to improve the variogram. Using a higher order drift gave only a slight improvement at the lower elevations in that the accumulation pattern more closely followed topography; there was no effect in the parts of the ice sheet represented by data. The mean absolute residual for the points used in the kriging was 4.5 g cm^{-2} yr^{-1}, with only 20% greater than 10 g cm^{-2} yr^{-1} and 10% greater than 15 g cm^{-2} yr^{-1}.

Because the kriging, which was done on a 5-km grid, gave some discontinuities in accumulation in the near-coastal areas where data are sparse, we applied a 9 × 9 rectangular mean filter to the image. This procedure effectively eliminated the discontinuities without changing the main features or regional values of the accumulation. The discontinuities were manifested as closely spaced contours, resulting in 5-10 g cm^{-2} yr^{-1} differences in accumulation over a distance of several kilometers. We evaluated going to a larger grid (up to 25 km) and changing the search radius; however, the finer grid spacing in kriging followed by two-dimensional smoothing yielded the map with the fewest discontinuities.

4. Discussion

Over much of the central and northern parts of the ice sheet the kriged result gives an accumulation pattern that retains features of the map published previously by *Ohmura and Reeh* [1991] (Plate 2). Our mean ice sheet accumulation value is ~30 versus 31 g cm^{-2} yr^{-1} as reported by *Ohmura and Reeh* [1991] and *Ohmura et al.* [1999]. However, the actual difference for the ice sheet is only ~0.3 g cm^{-2} yr^{-1}, based on 30.5 g cm^{-2} yr^{-1} for PARCA from Plate 1 versus 30.8 g cm^{-2} yr^{-1} for the digitized *Ohmura and Reeh* [1991] map in Plate 2. Note that in Plates 1 and 2 we show accumulation estimates for the island as a whole. In most of Greenland the ice sheet boundary is near or a few kilometers coastward from the 1000-m contour shown in Plates 1 and 2. For all of Greenland the respective accumulation values are also close together, 30.1 versus 29.6 g cm^{-2} yr^{-1}.

There are four distinct areas of difference between our current map and that published by *Ohmura and Reeh* [1991] (Plate 3). First, the new PARCA data show much lower accumulation in the west-central region around 2500 m elevation between 68°N and 75°N and between 1500 - 2000 m elevation up to 77°N. This difference is based on the 1995-1998 PARCA cores in this region where few ice core data were previously available. Second, the new map shows greater accumulation along much of the western margin of the ice sheet below ~1800-2000 m elevation; this is below the elevation of most accumulation observations, and estimated accumulation is sensitive to the interpolation method. Third, we show a higher-accumulation region in the east central part of the ice sheet, which again results from the addition of PARCA shallow cores. Fourth, broad differences in the southern part of the ice sheet are based in part on new PARCA data, but the details of the accumulation estimates are sensitive to interpolation method.

Above 1800 m elevation our kriged value was 29.7 versus 30.8 g cm^{-2} yr^{-1} for *Ohmura and Reeh* [1991], a difference of ~4%. The large differences between our map and that of *Ohmura and Reeh* [1991] at lower elevations are due in part to differences in interpolation methods (i.e., kriging versus hand contouring). Below 1000-m elevation our kriged value was 29.8 versus 26.5 g cm^{-2} yr^{-1} for *Ohmura and Reeh* [1991], a difference of ~10%. However, the differences above the 2000 m contour are real and result from the additional accumulation information derived from the new (drilled since 1995) PARCA cores.

Despite the differences between the two accumulation maps the patterns in Plate 1 are still consistent with the description of atmospheric circulation put forth by *Ohmura and Reeh* [1991]. In winter, water vapor flow from the Icelandic low to the southeast and the Baffin Bay low to the southwest causes high precipitation in southern and western Greenland as air masses ascend over the ice sheet.

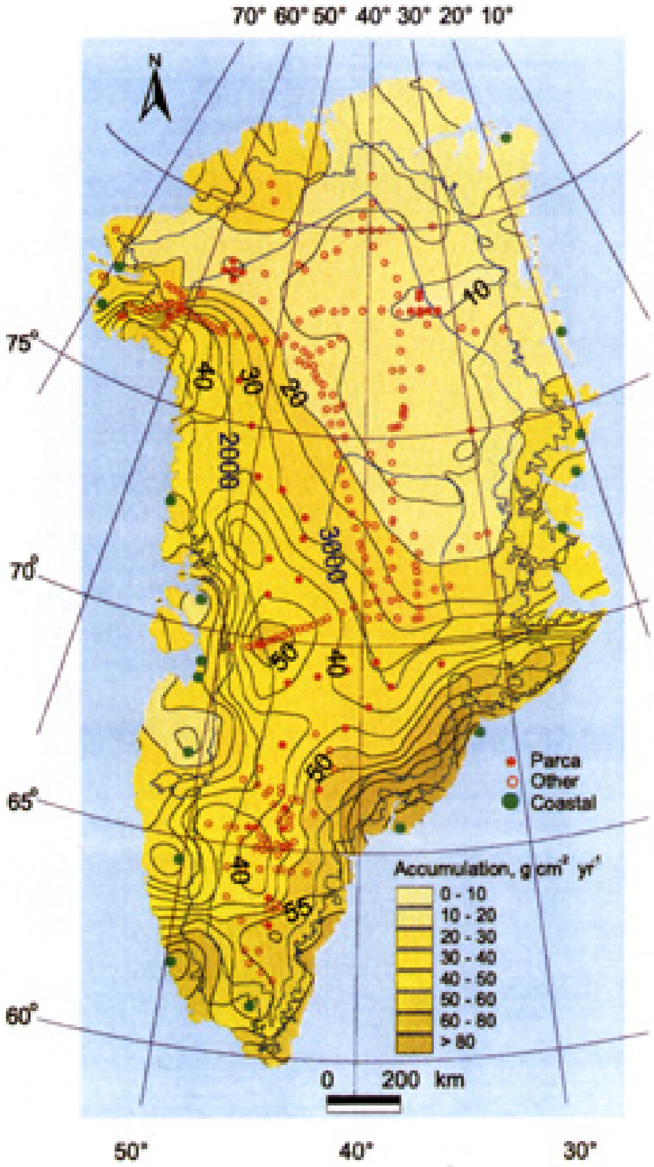

Plate 1. Accumulation map based on kriging. Shades of yellow show results for the entire island, with the accumulation contours shown just for the Greenland ice sheet. Contour and shading are accumulation in millimeters water equivalent. Also shown for reference are the 1000-, 2000-, and 3000-m elevation contours. (Digital SAR mosaic and elevation map of the Greenland ice sheet available from nsidc@kyros.colorado.edu.).

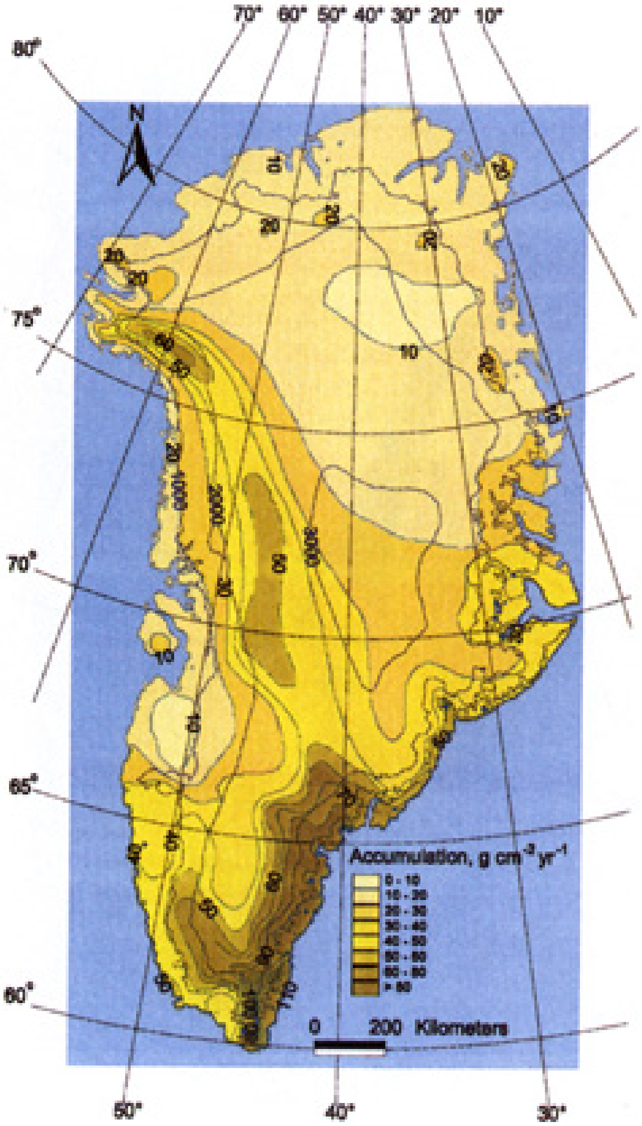

Plate 2. Accumulation map based on *Ohmura and Reeh* [*1991*]. The digital map was prepared by first digitizing the contour map from their paper, then gridding it.

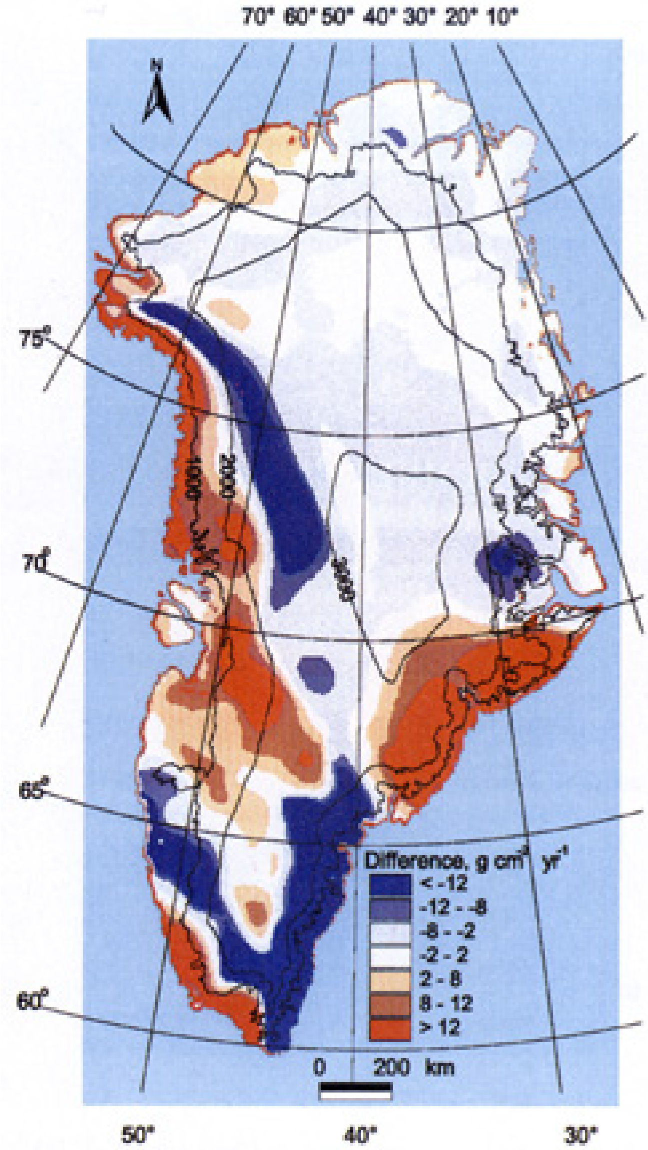

Plate 3. Difference between PARCA accumulation map and that published by *Ohmura and Reeh* [*1991*]. Red indicates that the PARCA map is higher, and blue that the *Ohmura and Reeh* [*1991*] map is higher, with darker shades indicating a greater difference.

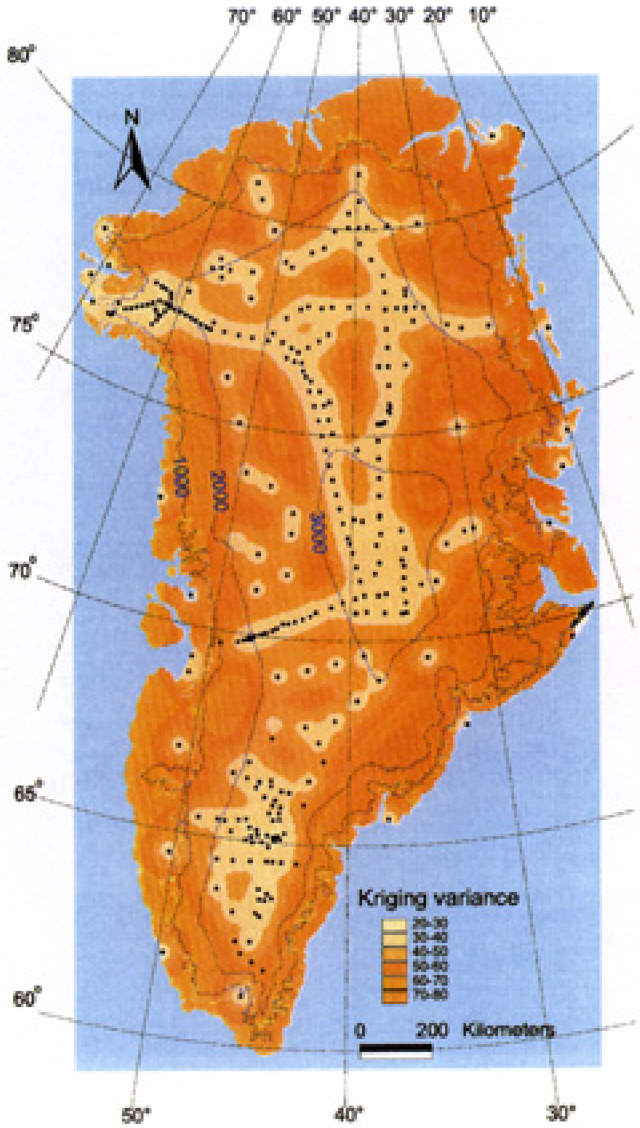

Plate 4. Kriging variance, shown with the points used to develop the kriged surface.

Precipitation diminishes as air masses descend in the north. In summer the west coast receives air masses with high water content following a similar pattern as in winter and contributing to the high precipitation in west central and northwest Greenland. Summer flow in the southeast is influenced by a high-pressure ridge with a northeast-southwest orientation, diminishing the amount of upslope flow in favor of flow parallel to the elevation contours.

Spatially, the kriging variance (Plate 4) indicates that areas with lower uncertainty are centered around field measurement points, which is not the case for those with higher uncertainty at lower elevations or other areas with few data. Near data points the square root of the kriging variance (standard deviation) is ~5-6 g cm^{-2} yr^{-1}, which represents an upper limit for the uncertainty in accumulation in those areas. Note that with a nugget of 20 the minimum possible kriging variance would be 20 or a standard deviation of ~4.5 g cm^{-2} yr^{-1}. The maximum would be ~7 g cm^{-2} yr^{-1}. The data-poor areas include: 1) the northeastern quadrant of the ice sheet, which is less accessible for ice coring because of its greater distance from the logistics base, 2) the far north, which is also distant, 3) the west central area, and 4) the east central area. In these four areas the standard deviation is ~8 g cm^{-2} yr^{-1}. Most of the data, and thus the smallest variance, can be found in the central part of the ice sheet and the inland area in the south, where the standard deviation is 5-7 g cm^{-2} yr^{-1}. The greatest opportunities to reduce overall uncertainty in total ice sheet accumulation with further sampling would be in those areas with both large variance and large accumulation: the west central (67°-69°N and 73°-76°N) and east central regions (67°-71°N).

As the point data used in this analysis are from different time periods, each has some uncertainty relative to the long-term mean. To assess this, we sampled accumulation for periods of different length from 200-year records for two previously published cores: a high-accumulation site (NASA-U, 34 g cm^{-2} yr^{-1}) and a low-accumulation site (Humboldt, 14 g cm^{-2} yr^{-1}). We then evaluated how well these shorter records approximated the 200-year mean (Figure 5). Sampling single years from the record gives one standard deviation of ±25-30% of the mean; sampling 10-year records from the 200-year time series, the standard deviation drops off to ±7%, and for 20 years it is ~±6%. Note that the standard deviation drops off slowly after ~10-20 years. The corresponding ranges of the minimum and maximum are ±80% of the mean for a single year and ±18% for a 10-year mean.

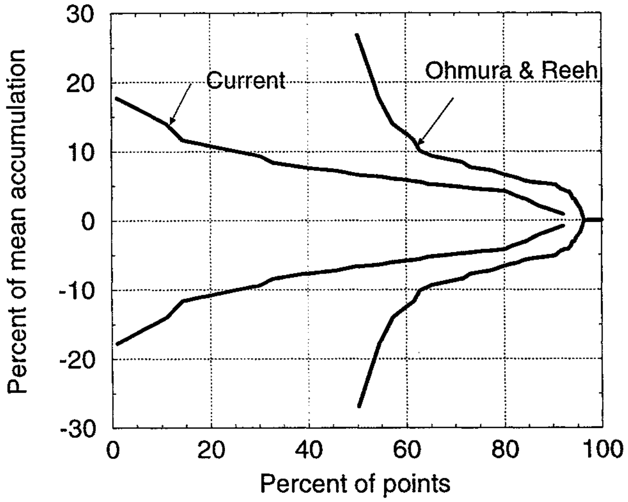

Figure 6. Uncertainty of how well the data points used in the spatial interpolations on Figures 5-6 the 200-year mean accumulation for those locations represent.

Combining Figures 1 and 5 illustrates the uncertainty associated with the points used for the spatial interpolation (Figure 6). The mean uncertainty relative to the 200-year mean for the pre-1981 data set compiled by *Ohmura and Reeh* [1991] is ~±28% (standard deviation) versus ~±7% for the data set used in the current analysis. Adding the recent points also significantly improves the interpolated values, as shown in the comparison of accumulation from PARCA cores versus interpolated values for those same points from the map in

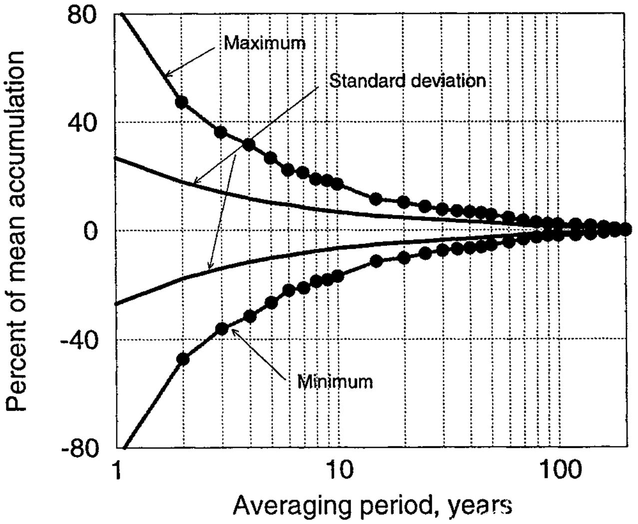

Figure 5. Range and standard deviation of accumulation records of different length samples from the most recent 200 years of record in the NASA-U and Humboldt cores.

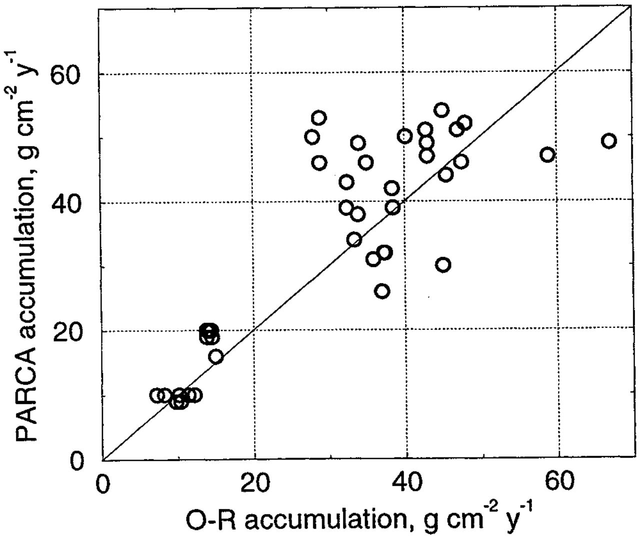

Figure 7. Point-by-point comparison of PARCA core locations versus accumulation on Figure 6. Also shown is a 1:1 line, to facilitate visual comparisons.

Plate 2 (Figure 7). Of the 39 points plotted, only 10 are within ±10%, with half within ±20% and 6 exceeding ±40% difference.

Finally, it should be noted that while our interpolation develops estimates of accumulation, defined as precipitation minus evaporation, over all of Greenland, factors other than evaporation can affect the change in mass at a point. In the dry snow zone, at higher elevations and latitudes on the ice sheet, the mass loss processes of wind redistribution and sublimation are implicitly included in our estimate. Below the dry snow zone but above the percolation zone, melting occurs, but meltwater does not flow downgradient; ablation is still limited to evaporation, sublimation, and wind redistribution. The ice cores used to develop the spatial map were from the portion of the ice sheet above the percolation zone. Within the percolation zone, and down to the edge of the ice sheet, no direct measurements of precipitation, ablation, or accumulation were available. In that region, accumulation, as defined in this research, is a defined but not a measured quantity. Similarly, precipitation minus evaporation is defined in the coastal region, with precipitation measured directly and evaporation estimated.

5. Conclusions

Of the more than 360 point accumulation estimates that have been developed over the Greenland ice sheet, there are only ~140 independent points with a record length of 10 years or more. About 130 of the point estimates are from a single year's measurement, and as estimates of the long-term mean accumulation, they have an uncertainty (standard deviation) of ~±25-30%. This single-year uncertainty is larger than the mean uncertainty indicated by the kriging variance over the ice sheet and the uncertainty in regional accumulation.

The point accumulation measurements developed during the past 2 decades, coupled with the 38 new estimates derived since 1995 from PARCA cores, represent a significant improvement in quality of data, as measured by record length, and a significant improvement in estimates of accumulation over the Greenland ice sheet. The part of the ice sheet from which most of the point accumulation estimates come, the inland area above ~1800 m elevation, has an average accumulation of ~30 g cm^{-2} yr^{-1} and an average uncertainty (standard deviation) at a point of no more than 7 g cm^{-2} yr^{-1}, or 24%. The ice-sheet-wide accumulation value, also 30 g cm^{-2} yr^{-1}, is slightly lower than reported previously. Because there are multiple cores in most regions, the regional uncertainty in accumulation should be considerably lower than the 7 g cm^{-2} yr^{-1} average uncertainty at a point. However, there are still many areas on the ice sheet where both point and regional accumulation rates are highly uncertain. This uncertainty arises largely for three reasons: 1) there are few data below the dry snow zone on the ice sheet, 2) there are few coastal data that are representative of ice sheet versus ocean precipitation, and 3) there is undersampling at all elevations in some parts of the ice sheet.

Future ice-coring research should be designed to significantly reduce the uncertainty of spatial and temporal accumulation patterns, and while it should address the spatial and temporal properties of accumulation over all of Greenland, particular emphasis should be given to near-coastal parts of the ice sheet. The approach to addressing the accumulation variability will necessarily continue to involve a synthesis of coastal precipitation and ice sheet accumulation values to give annually to subannually resolved estimates over all of Greenland. Some of the required information can be developed by recovering and analyzing existing data. However, selective, but significant, augmentation of existing data will also be critical. Three areas on the ice sheet where accumulation is still highly uncertain are parts of northwestern, southeastern, and southern Greenland, particularly below ~1800-2000 m in elevation. Also, we have few data at any elevation in northeastern Greenland. In general, uncertainty is greater below the dry snow zone, because of the lack of data.

Continued analysis and development of historical accumulation records offers the possibility of making small reductions in the uncertainty of average accumulation by reducing uncertainty in point data. In particular, examination of previously unpublished primary data for several sites reported only in secondary references should yield more defensible values. Temporal variability can also be reduced by more detailed analysis of historical data, which can be important regionally. This is because secondary references only report average values, whereas examination of primary data will yield year-by-year values. Further analysis of archived cores and the strategic collection of additional shallow to intermediate depth cores along with multiparameter identification of annual layers should reduce the overall uncertainty in the upper elevations to well under 20%.

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