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 that were judged to be high quality estimates 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 about 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 about 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 about 20-25%. In these regions further sampling will be required to reduce uncertainty in both regional and ice-sheet wide accumulation.

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 [*IPCC*, 1995]. 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, 2000b*; Mosley-Thompson et al.*, 2000*; Davis et al.*, 2000].

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 *Ohmura et al.* [1999] updated these compilations with selected published and unpublished data developed over the past two decades, and did a more thorough analysis of coastal precipitation data.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*., 2000c*; Mosley-Thompson et al.*, 2000].

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 two decades and for more than 250 additional points prior to that time. In the current analysis we used the recent points plus more than half of those 250 historical point estimates to develop ice-sheet-wide accumulation maps.

Data and Methods

We divided the analysis of point accumulation data into two parts: i) a review of historical data from field studies carried out prior to about 1981, and ii) data from field studies carried 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 multi-decadal 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 both by 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 to 5 cm of water each year (standard deviation) for a 1-year accumulation measurement from an ice core [*McConnell et al.,* 2000c]. In addition, regional precipitation varies significantly from year to year, especially in southern Greenland [*McConnell et al.,* 2000b]. Thus estimates of accumulation based on 1-2 years of record are highly uncertain. Both the recent and historical data include replicate and duplicative 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.

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 based on 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 about 50 points include or exceed more than 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 1950's and early 1960's 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 (CRREL) in 1961. The 3 L-D (Lead Dog; shown as USACE [U.S. Army Corp of Engineers] in Figure 2) points in Table 1 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. Dropping the three points with fewer than five 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 seven 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 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 five years. Annual layers were identified from visual stratigraphy, with snow-pit density profiles measured by weighing SIPRE tubes. Detailed profiles are 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 due to short record lengths and availability of other, better data in the vicinity; 3 co-located points were averaged. Updated compilations are in *Bender* [1984] and a recent reprint of the original *Benson* report [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]. These data were derived from pits 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 record, 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 GISP 1 (Greenland Ice Sheet Project) activities in the 1970's. Average accumulation for 14 points, designated GISP(C) are reported in *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 in *Clausen et al.* [1988] are for the period 1943-73. Accumulation was determined from annual cycles of ?^{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 [*Personal communication, S. Johnsen and H. Clausen,* 2000]. Sixteen points reported as *Clausen et al*., personal communication, in *Bender* [1984] were from 11-m cores, with no details available. Because some were replicate cores from the same location, or 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 co-located with the Koide point reported by *Ohmura and Reeh* [1991], so the two were averaged. The three DANS-ETAL points in the Dye 3 vicinity reported by *Dansgaard et al.* [1985], represent 9-year averages, and are based on ?^{18}O and visual stragriphy 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 given in *Bender* [1984]. Accumulation was based on ?^{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 GISP(O) in Table 1 were only reported in the *Ohmura and Reeh* [1991] tabulation and referred to a table in a report by Radok [1982], and are assumed to be based on analysis of 10-m cores as described above for GISP(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 lab. Cores were dated based on annual variations in ?^{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 ?^{18}O records. Two replicate cores were averaged, giving the 8 GISP-OHIO points in Table 1. Five cores that were collected as part of related field efforts are labeled WHILLANS in Table 1 [*Whillans,* 1987]. Methods are the same as for the GISP-OHIO cores. The average record length for the 13 cores is about 21 years. Some additional sites that were identified in the *Whillans* [1987] report 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 *Paterson* [1955]; however 7 of these points were dropped due to their proximity to points with longer records and 2 other co-located points were merged, giving the 14 points listed in Table 1. We retained these 14 points in our tabulation 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 *Quervain* [1969]; however, as several were close together, we eliminated 6 and averaged 2 others with nearby records, resulting in 4 points (Table 1). Average record length is about 7 years, based on stratigraphic analysis in pits.

A few points came from very local investigations that reported only a few data. The single Carrefour point [*Ambach*, 1977], 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 based on shallow cores and pits. As two points were very close, we averaged them giving the two locations in Table 1.

The Henrickson [Schuster, 1954], Koch-Wegener [1930] and Merc-Quervain [1920] 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 1912-13, 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 in the *Ohmura and Reeh* [1991] tabulation. Therefore the total number of what we consider good quality accumulation estimates developed prior to 1981 is 177.

Data developed after 1981. PARCA data are based on multi-parameter analysis of ice cores, most of which were about 20 m in length; four sites had deeper cores [*Anklin et al.*, 1998*; McConnell et al*., 2000b, 2000c*; Mosley-Thompson et al*., 2000]. The median record length is 21 years. Besides PARCA, there are 3 other recent reports of accumulation on the ice sheet: i) the North GRIP traverse [*Fischer et al*., 1998; *Friedmann*, 1995; *Fischer*, 1997], ii) EGIG line [*Anklin et al.*, 1994*; Fischer et al.*, 1995], and iii) 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 (?^{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 atmospheric nuclear testing, and volcanic horizons (mainly Laki in 1783 or Tambora in 1815). Preliminary values are reported for 3 of the 1999 cores (UAK1, UAK4, UAK5), with others still being analyzed. Details of the PARCA cores have been published elsewhere [*Anklin et al*., 1998; *McConnell*, 2000b, 2000c; *Bales et al*., 2000; *Mosley-Thompson et al*., 2000]. There may be minor differences between accumulation values in those references and those in Table 1 due to preliminary dating of the records, and reporting averages for different time periods, and in a few cases unresolvable dating uncertainties of ±1 year.

The North Greenland traverse (NGT), done in 1993-95, involved 13 shallow cores (100-175 m depth) at about 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 due to 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, based on the 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 *Fisher* [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. ?^{18}O and Ca^{2+}), with volcanic reference horizons for absolute dating, and are very good; although 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, done by the Institut für Vermessungkunde, Technische Universität Braunschweig, Germany in 1990-92, repeated the east-west line located at about 70ºN traversed about 30 years earlier [*Fischer et al.*, 1995]. It involved multi-parameter analysis (?^{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 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 ?^{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 GISP2 program to assess spatial variability of accumulation in central Greenland.

In summary, since 1981 these four major investigations (GISP2, 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 1-2.

Kriging. Interpolation to develop an ice-sheet-wide estimate of accumulation was accomplished using kriging. Because there were few data below about 1800 m in elevation (Figure 3), we used 17 coastal points [*Bales et al.*, 2000; *Ohmura et al.*, 1999] to constrain estimates at lower elevations in addition to the data in Tables 1-2. 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 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 non-uniform 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 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.

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 for all 256 points was 29 g cm^{-2} yr^{-1}, 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 (Figure 5) 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 two-decade period (1971-90) [*Bales et al.,* 2000]

We evaluated co-kriging as a means of capturing the elevation dependence of accumulation, but it failed to improve the result, due in part to 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 km. 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.

Discussion

Over much of the central and northern parts of the ice sheet the kriged result gives an accumulation pattern that retained features of the map published previously by *Ohmura and Reeh* [1991] (Figure 6**)**. Our mean ice-sheet accumulation value is about 30 g cm^{-2} yr^{-1}, versus 31 reported by *Ohmura and Reeh* [1991], and *Ohmura et al*. [1999].

However, the actual difference for the ice sheet is only about 0.3 g cm^{-2} yr^{-1}, based on 30.5 g cm^{-2} yr^{-1} for PARCA from Figure 5 versus 30.8 g cm^{-2} yr^{-1} for the digitized *Ohmura and Reeh* [1991] map on Figure 6. Note that in these figures 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 on the Figures. 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] (Figure 7). First, the new PARCA data show much lower accumulation in the west-central region around 2500 m elevation, between 68ºN and 75ºN; and between 1500-2000 m elevation up to 77ºN. This difference is based on the 1995-98 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 about 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 about 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 about 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 on Figure 5 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. 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 (Figure 8) indicates that areas with lower uncertainty are centered around field measurement points, versus 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 about 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: i) the northeastern quadrant of the ice sheet, which is less accessible for ice coring due to its greater distance from the logistics base; ii) the far north, which is also distant, iii) the west central area and iv) the east central area. In those four areas the standard deviation is about 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 (67-69ºN and 73-76ºN), and east central regions (67-71ºN).

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 9). Sampling single years from the record gives one standard deviation of $\pm$25-30% of the mean; sampling 10-year records from the 200-year time series, the standard deviation drops off to $\pm$7%, and for 20 years it is about

±6%. Note that the standard deviation drops off slowly after about 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.

Combining Figures 1 and 8 illustrates the uncertainty associated with the points used for the spatial interpolation (Figure 10). The mean uncertainty relative to the 200-year mean for the pre-1981 dataset compiled by *Ohmura and Reeh* [1991], is about ±28% (standard deviation), versus about ±7% for the dataset 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 on Figure 6 (Figure 11). 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.

Conclusions

Of the more than 360 point accumulation estimates that have been developed over the Greenland ice sheet, there are only about 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 have an uncertainty (standard deviation) of about ±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 about 1800 m elevation, has an average accumulation of about 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: i) there are few data below the dry snow zone on the ice sheet, ii) there are few coastal data that are representative of ice-sheet versus ocean precipitation, and iii) 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 sub-annually 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 about 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, due to 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 multi-parameter identification of annual layers should reduce the overall uncertainty in the upper elevations to well under 20%.

Acknowledgements

This research was supported by grants NAG5-5031 and 6779 to the University of Arizona and grants NAG5-5032 and 6817 to the Ohio State University. We acknowledge C. Kim and T. House for help in compiling data; D. Belle-Oudry, B. Snider, J. Burkhart, Z. Li, M. Davis and P-N. Lin for analyzing cores; and R. Brice, G. Lamorey, J. Abraham and T. Albert for data analysis.

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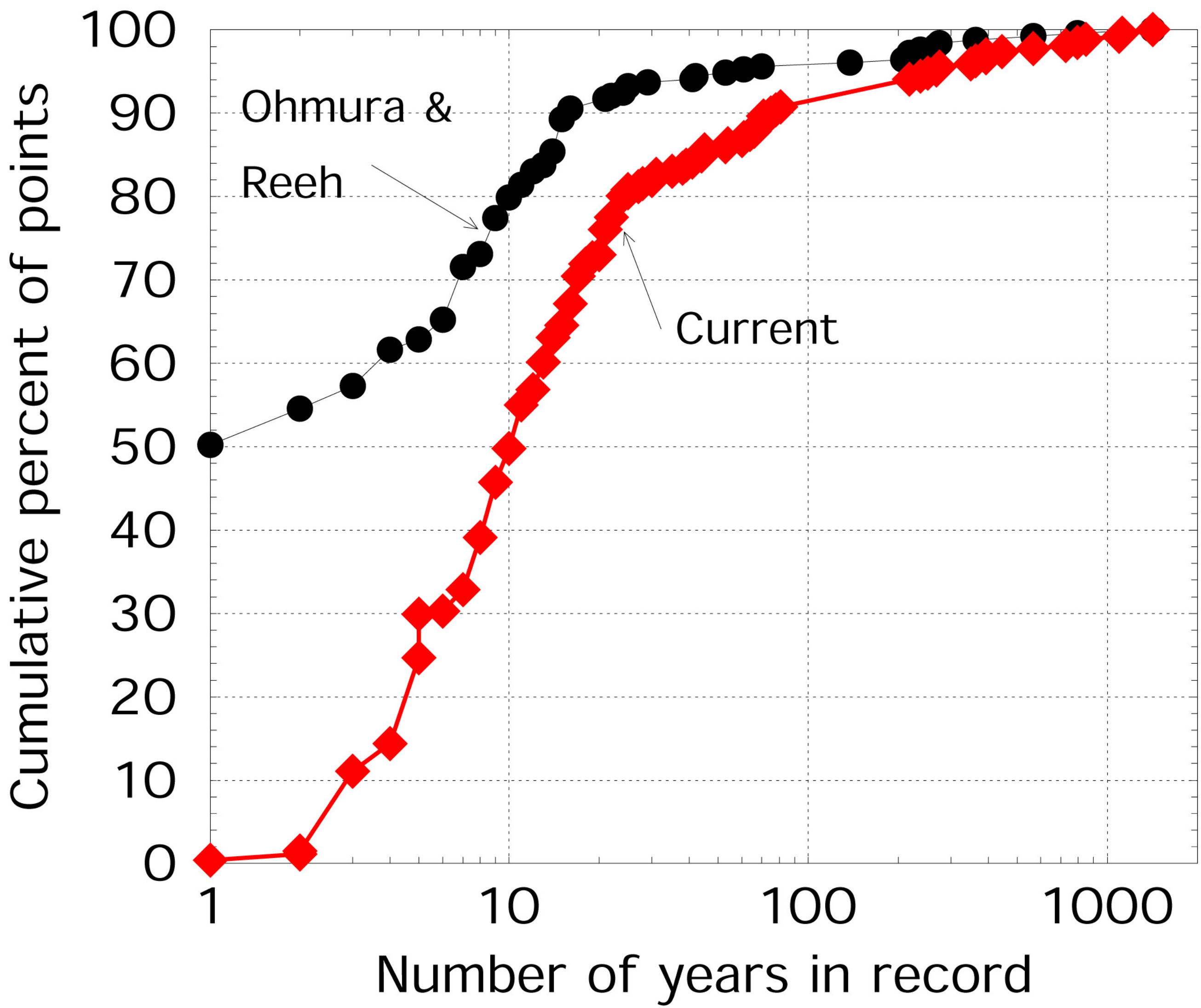
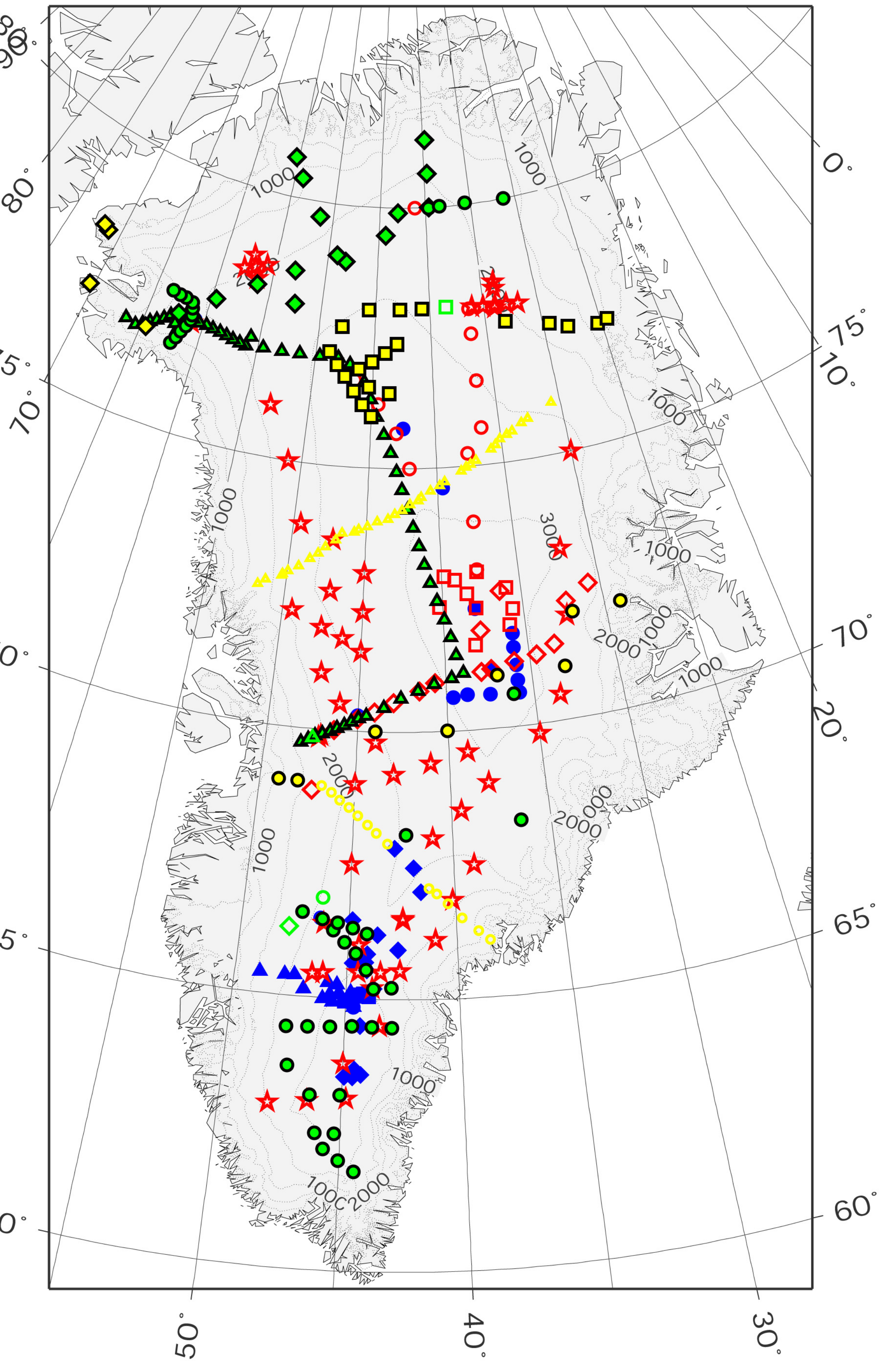
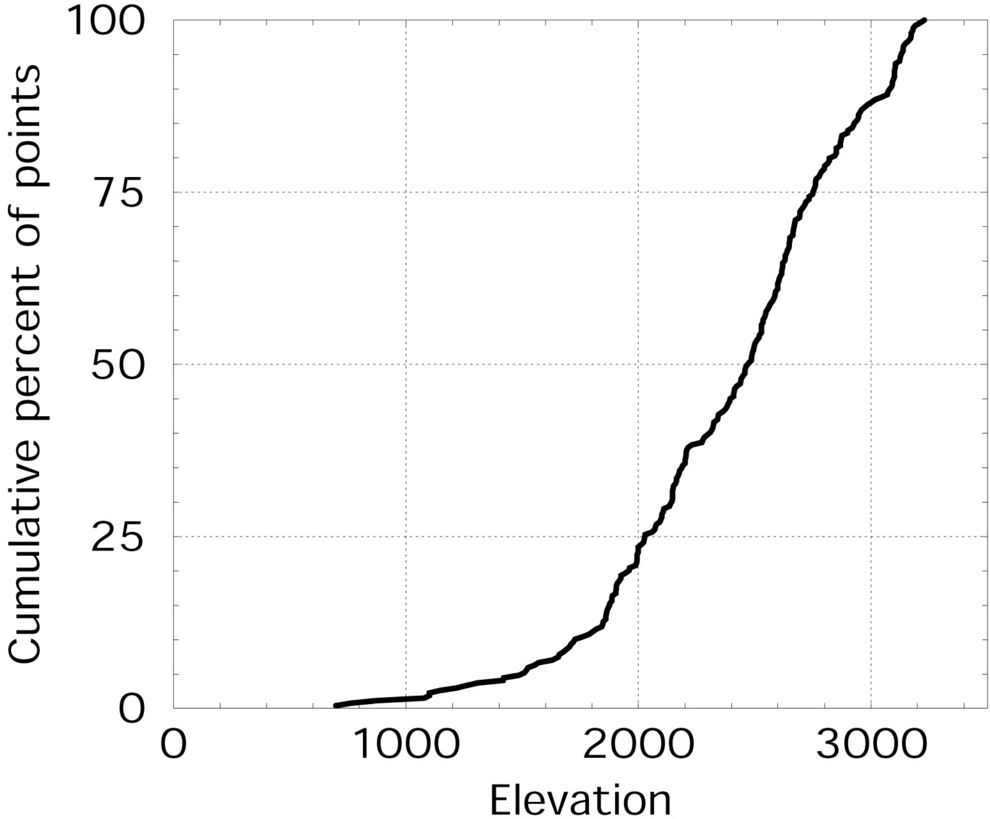
List of Figures

1. Distribution of record lengths for point accumulation estimates.
2. Locations of historical and recent point estimates of accumulation
3. Elevational distribution of accumulation estimates from Tables 1-2.
4. Time periods covered by data used in kriging analysis.
5. 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 mm water equivalent. Also shown for reference are the 1000, 2000 and 3000 m elevation contours. [*National Snow and Ice Data Center*, 1992. Digital SAR Mosaic and Elevation Map of the Greenland Ice Sheet. Digital data available from nsidc@kryos.colorado.edu. Boulder, Colorado: NSIDC Distributed Active Archive Center, University of Colorado at Boulder]
6. 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.
7. 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.
8. Kriging variance, shown with the points used to develop the kriged surface.
9. 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.
10. Uncertainty of how well the data points used in the spatial interpolations on Figures 5-6 represent the 200-year mean accumulation for those locations.
11. Point-by-point comparison of PARCA core locations versus accumulation on Figure 6. Also shown is a 1:1 line, to facilitate visual comparisons.

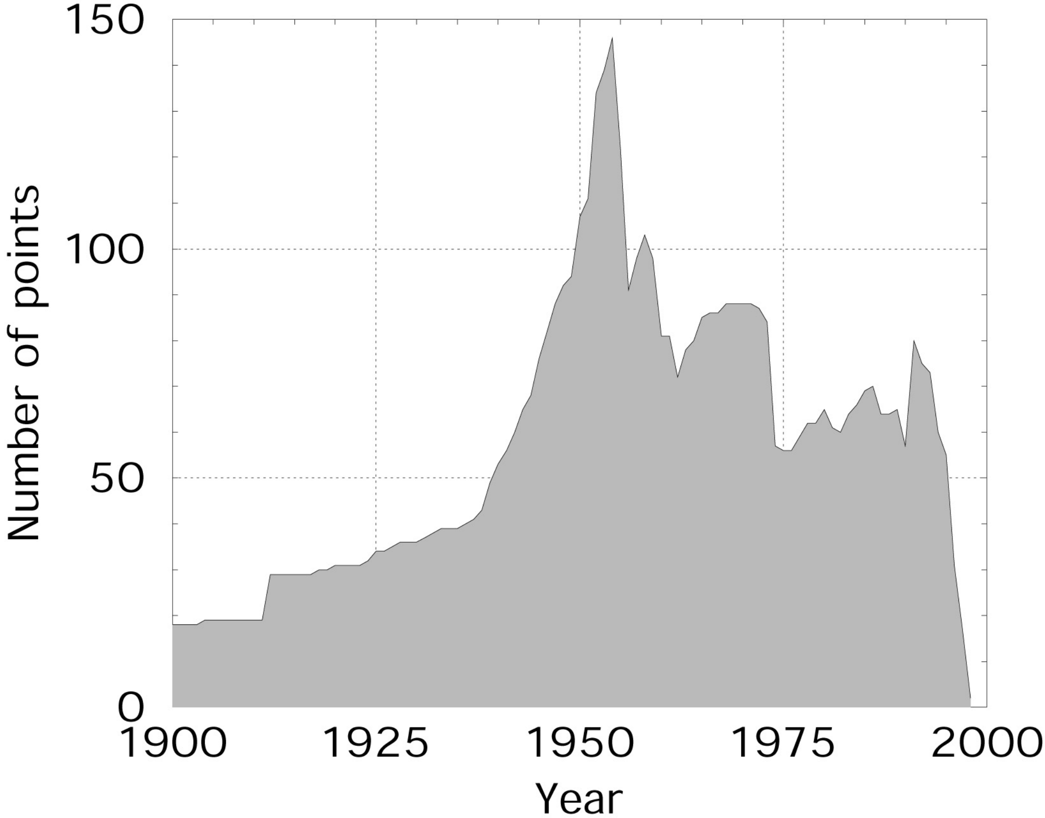

Cumulative percent of points
Number of years in record
Ohmura &
Reeh
Current
0
10
20
30
40
50
60
70
80
90
100
1
10
100
1000

Historical and Recent Accumulation Estimates

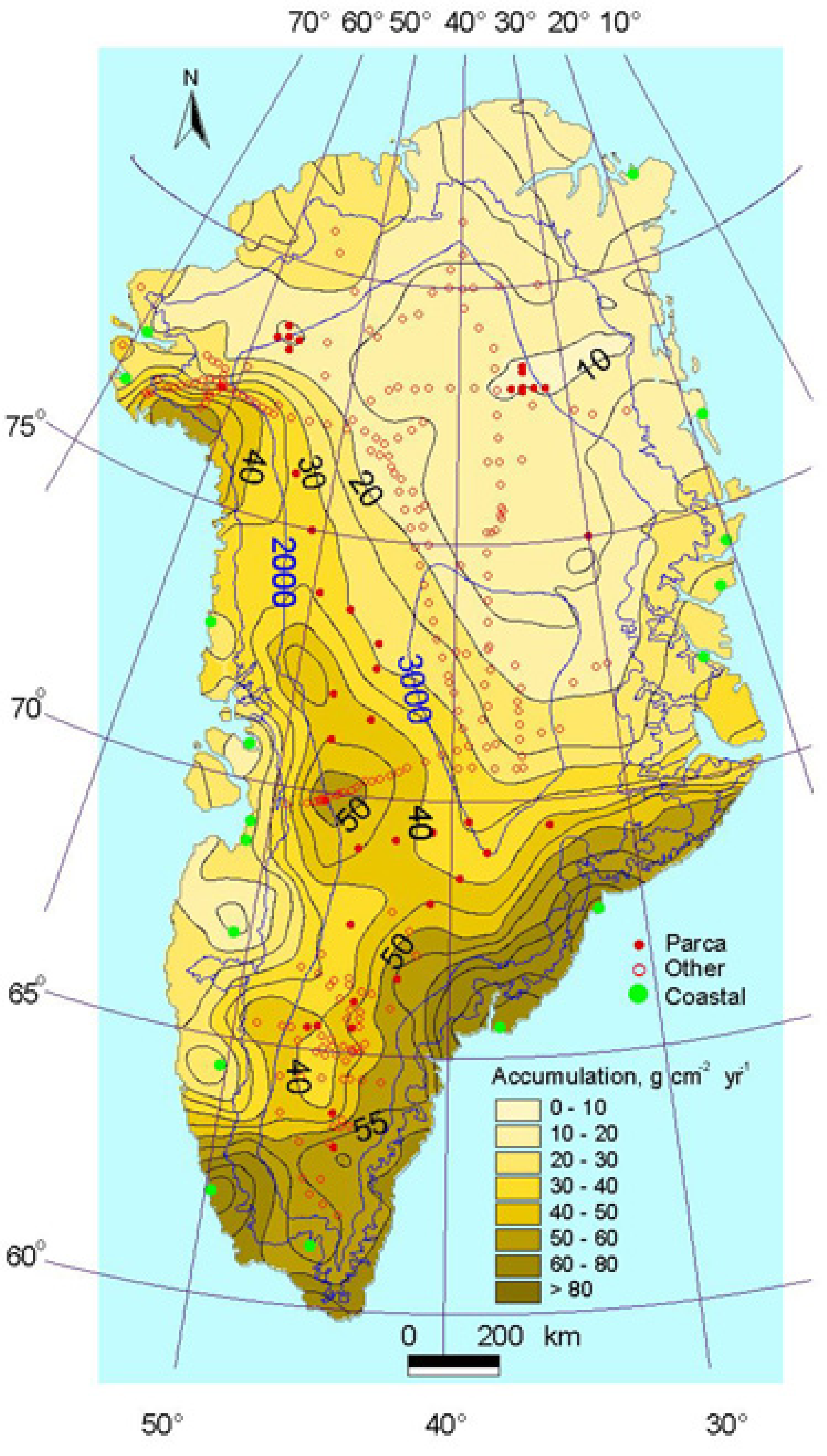




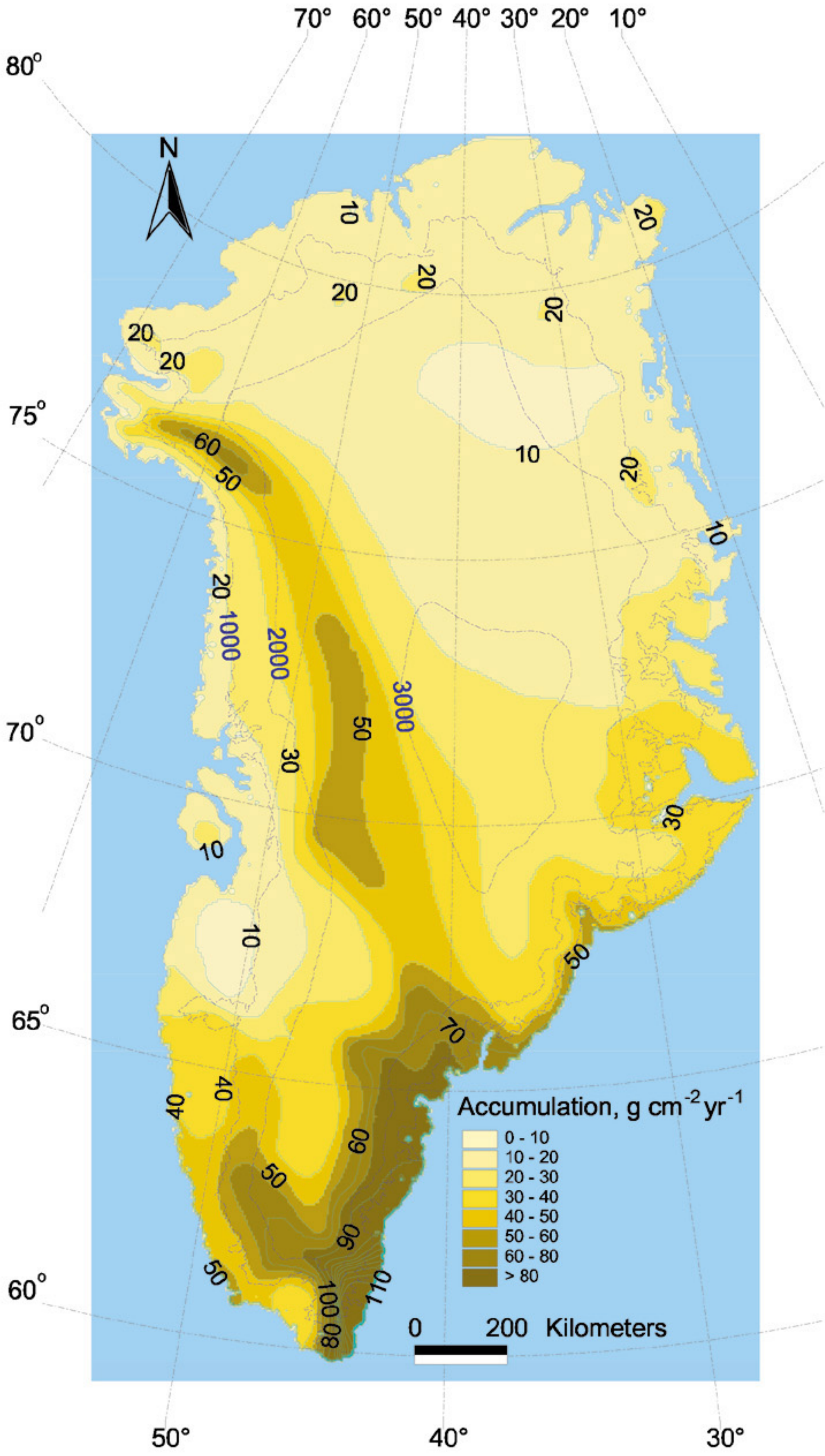
Cumulative percent of points
100
75
50
25
0
0
1000
2000
3000
Elevation



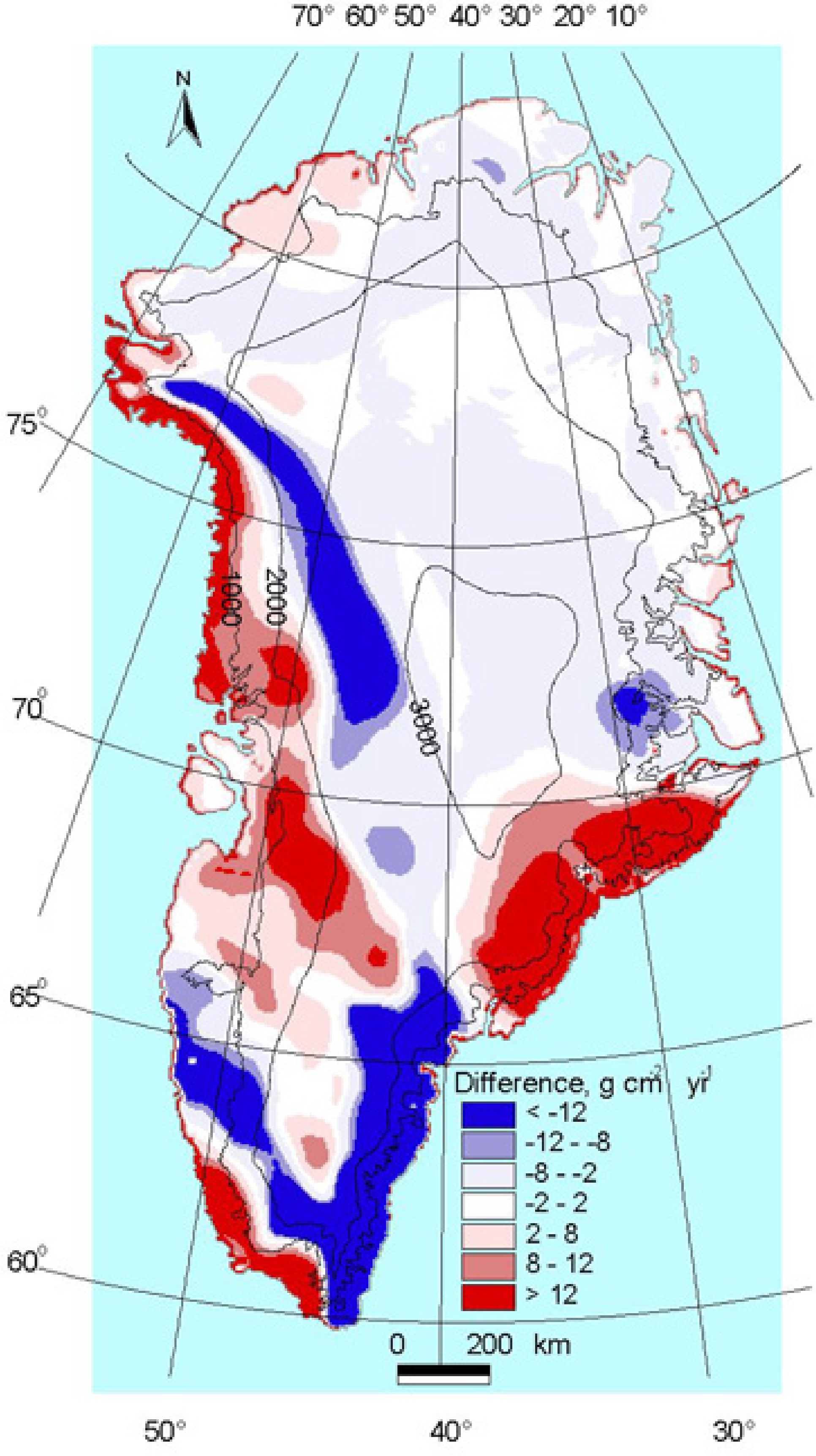
150
100
50
0
Number of points
1900
1925
1950
1975
2000
Year

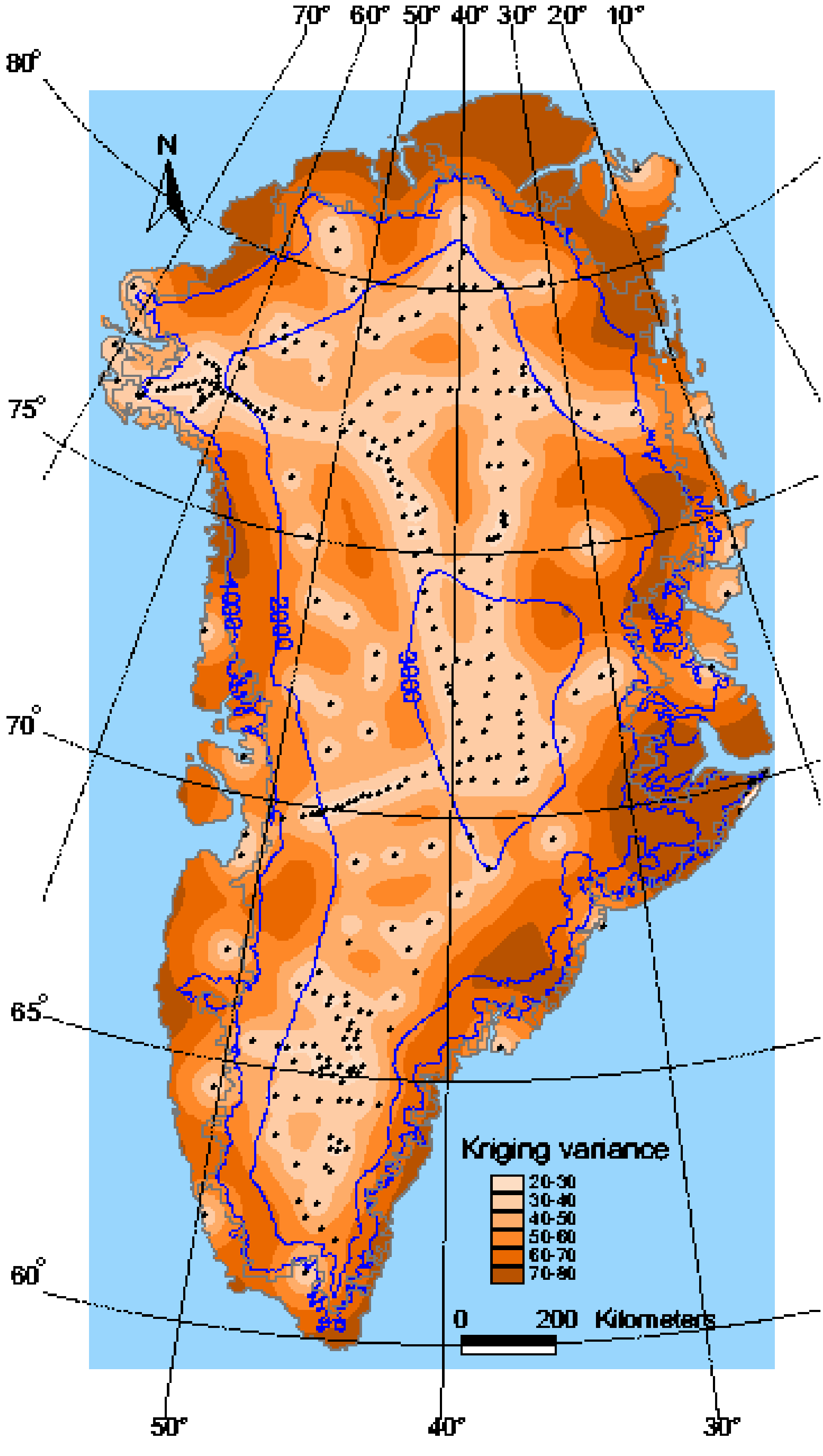


70° 60° 50° 40° 30° 20° 10°
N
75°
70°
65°
60°
10
20
30
40
2000
3000
50
40
50
40
55
Parca
Other
Coastal
Accumulation, g cm⁻² yr⁻¹
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 80
> 80
0 200 km
50°
40°
30°

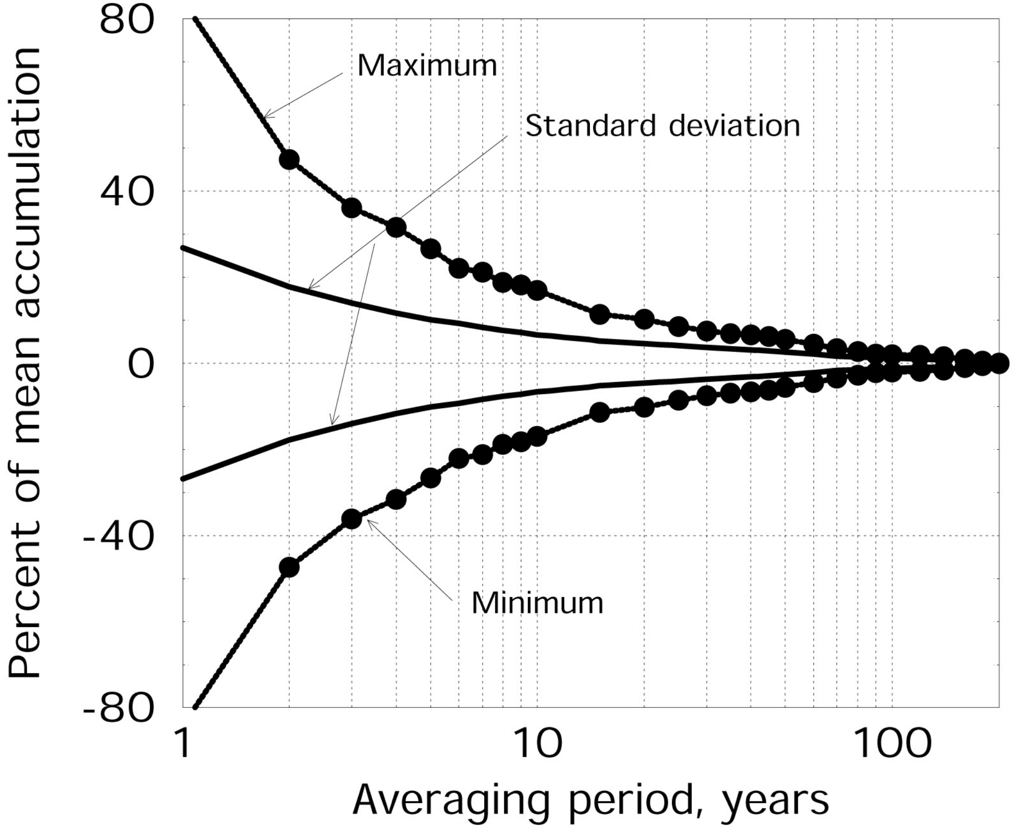


Accumulation, g cm-2 yr-1
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 80
> 80
0 200 Kilometers
N

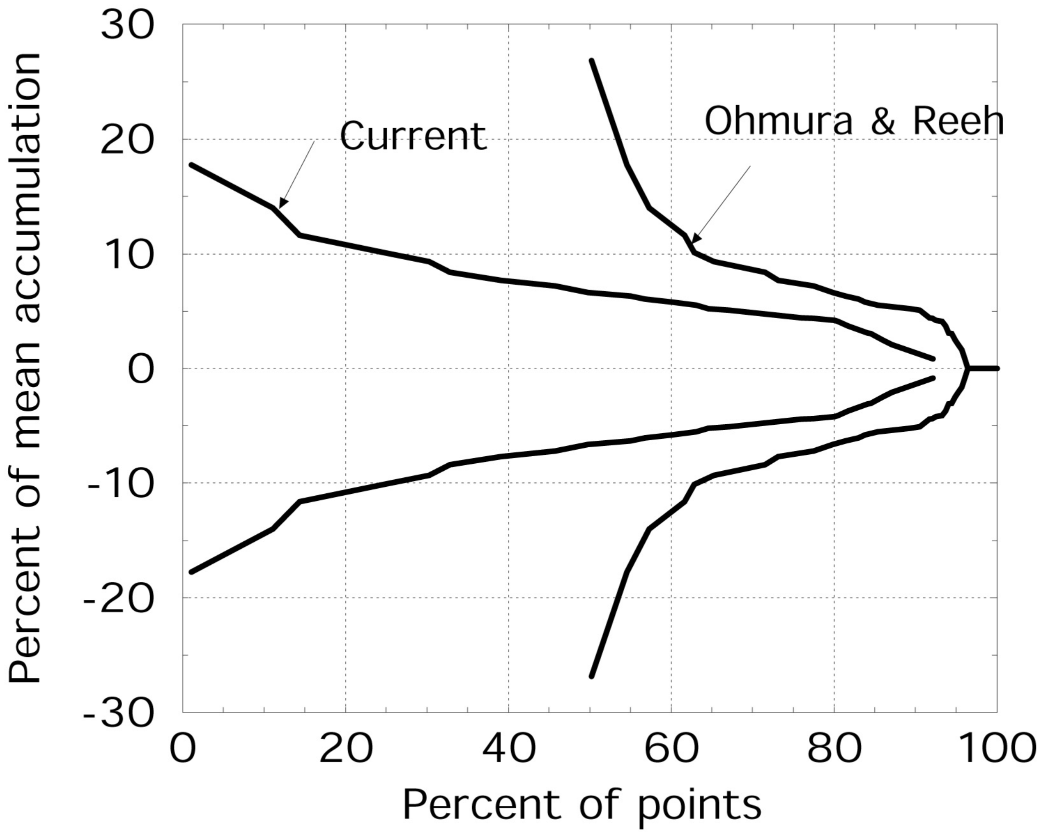

70° 60° 50° 40° 30° 20° 10°
N
75°
70°
65°
60°
1000
2000
3000
Difference, g cm yr
< -12
-12 - -8
-8 - -2
-2 - 2
2 - 8
8 - 12
> 12
0 200 km
50°
40°
30°

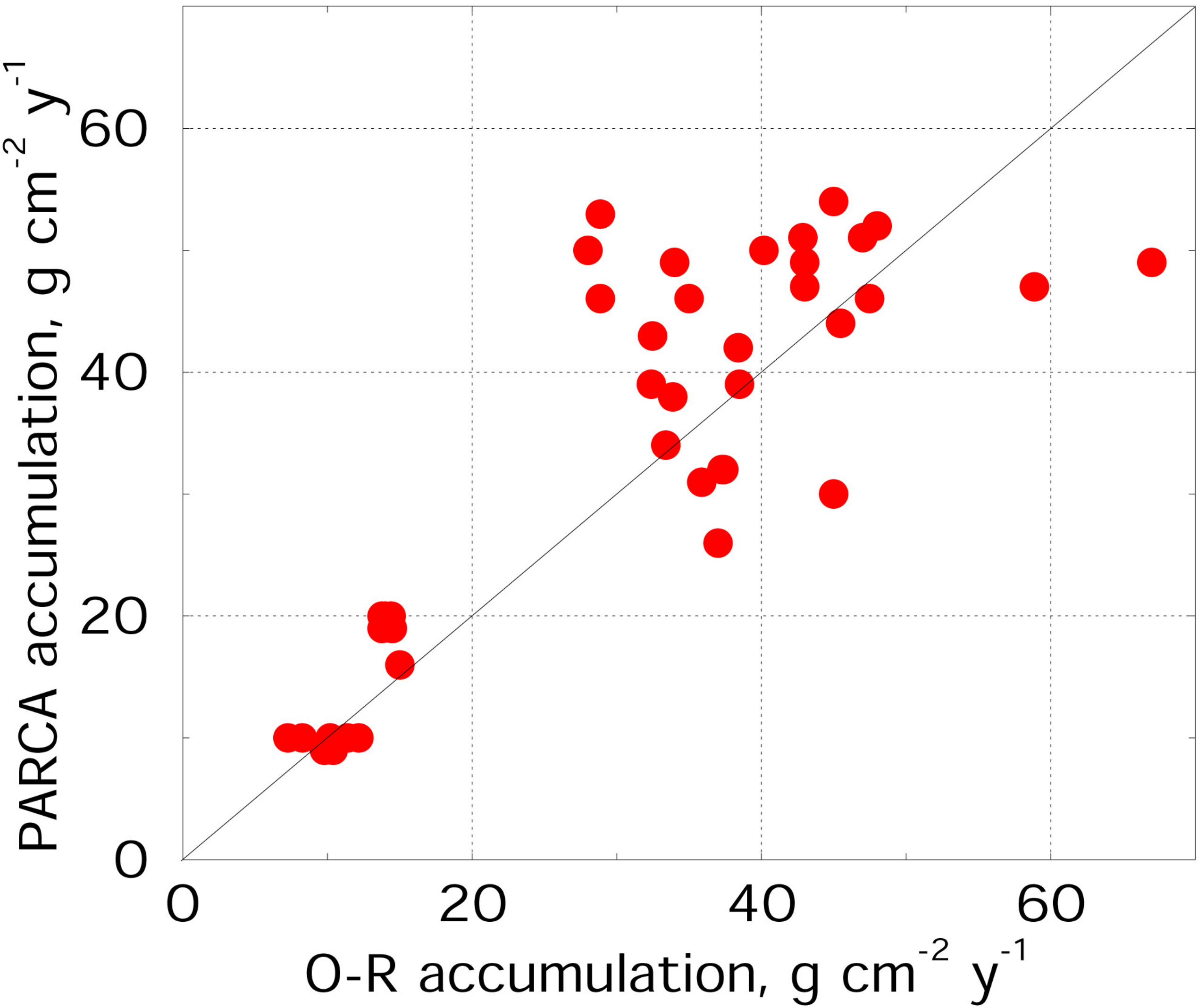


70°
60°
50°
40°
30°
20°
10°
80°
N
75°
70°
65°
60°
2000
2000
2000
3000
Kriging variance
20-30
30-40
40-50
50-60
60-70
70-80
0
200
Kilometers
50°
40°
30°



Maximum
Standard deviation
Minimum
Percent of mean accumulation
80
40
0
-40
-80
1
10
100
Averaging period, years


30
20
10
0
-10
-20
-30
0
20
40
60
80
100
Percent of mean accumulation
Percent of points
Current
Ohmura & Reeh



PARCA accumulation, g cm-2 y-1
O-R accumulation, g cm-2 y-1
0
20
40
60
0
20
40
60