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Accumulation Map for the Greenland Ice Sheet: 1971-1990

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Abstract. An updated accumulation map for the Greenland Ice Sheet for the period 1971-1990, based on kriging of accurate point estimates developed during the past decade at over 40 points plus over 200 historical points, shows an average water accumulation of 30 g $cm^{-2}yr^{-1}$. Average uncertainty (standard deviation) in estimates of point accumulation for the interior part of the ice sheet, where the kriging drift surface is well constrained, is approximately 7 g $cm^{-2}yr^{-1}$, or 24% of mean accumulation. 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. There are still many areas on the ice sheet, including northwest and southern Greenland, where annual accumulation remains poorly constrained.

Introduction

Accurate spatial estimates of accumulation (precipitation minus evaporation) on the Greenland Ice Sheet are a central ingredient in studies of changes in ice sheet mass and elevation. Using over 250 point accumulation estimates, *Ohmura and Reeh* [1991] found two main areas of high accumulation: i) the southern and southeastern region below about 2500 m, and ii) the western region between about 2000 and 3000 m elevation. Three key concerns with the maps from their analyses are: i) the point estimates span a 70-year period and represent many different time windows, ii) a majority of the points are only 1-2 year averages, and iii) the annual point estimates used different approaches (density changes, visible stratigraphy, $\delta^{18}O$), many of which have considerable uncertainty.

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 are based on shallow ice cores that were dated with near zero uncertainty [*Anklin et al.*, 1998] in recent decades, and cover at least 10 years; 4 cores cover more than 200 years.

In the current analysis we have developed an accumulation map for a recent 2-decade period for which the most complete data are available, 1971-1990. Our primary aim was to develop improved accumulation estimates for the region above ~2000 m elevation, where our data were collected.

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Methods

Cores up to 30-m depth were retrieved using a mechanically assisted hand auger [*McConnell et al.*, 2000b], while deeper cores were recovered using an electromechanical drill [*Zagorodnov et al.*, 2000]. Methods used to analyze cores, and results for three of the deeper cores have been reported elsewhere [*Anklin et al.*, 1998; *Bales et al.*, 2001*a*]. All the cores were dated using a combination of seasonally varying parameters (dust, $\delta^{18}O$, hydrogen peroxide, calcium, nitrate, ammonium and electrical conductivity). Where possible, absolute dating was confirmed using 1963 beta horizons resulting from the 1961 and 1962 atmospheric atomic tests, and using volcanic horizons. Annual "firn" thicknesses were converted to water equivalent using a depth-density model derived from the density measured on each core section at the time of drilling.

The data used to estimate ice-sheet-wide accumulation were a combination of published historical data, and our PARCA data. Where multiple records were available for the same site, we used the more-recent or longer record, which more accurately reflected accumulation in the period of interest. If there were replicate estimates we used an average. We selected historical data based on the length of record, methods used and documentation. In particular, data from some earlier studies that relied on accumulation estimated from density changes, measured by ramming a rod into the snow, and from single-year visual observations of stratigraphy, were not used.

Most points compiled by *Ohmura and Reeh* [1991] were also in *Bender* [1984]; to facilitate cross-referencing, we adopted their notation to identify points. More recent data (98 points) were compiled from: *Bolzan and Strobel*, [1994]; *Anklin et al.*, [1994]; *Fischer*, [1997]; *Fischer et al.*, [1995]; *Jung-Rothenhäusler*, [1998]; *Ohmura et al.*, [1999], *Anklin et al.*, [1998]; and *Mosley-Thompson et al.*, [2001]. *Ohmura et al.* [1999] and *Bromwich et al.*, [1998] used some of the preliminary (unpublished) PARCA values in developing their accumulation maps; however, several of our point estimates have been considerably revised since that time. The full compilation can be found in *Bales et al.*, [2001*a*]. We used data from 17 coastal points in addition to the 253 points on the ice sheet. Although our main goal was to improve accumulation estimates in the region of the ice sheet with data, above about 1800-2000 m elevation, we found that including the coastal points in the interpolation procedure was necessary in order to constrain

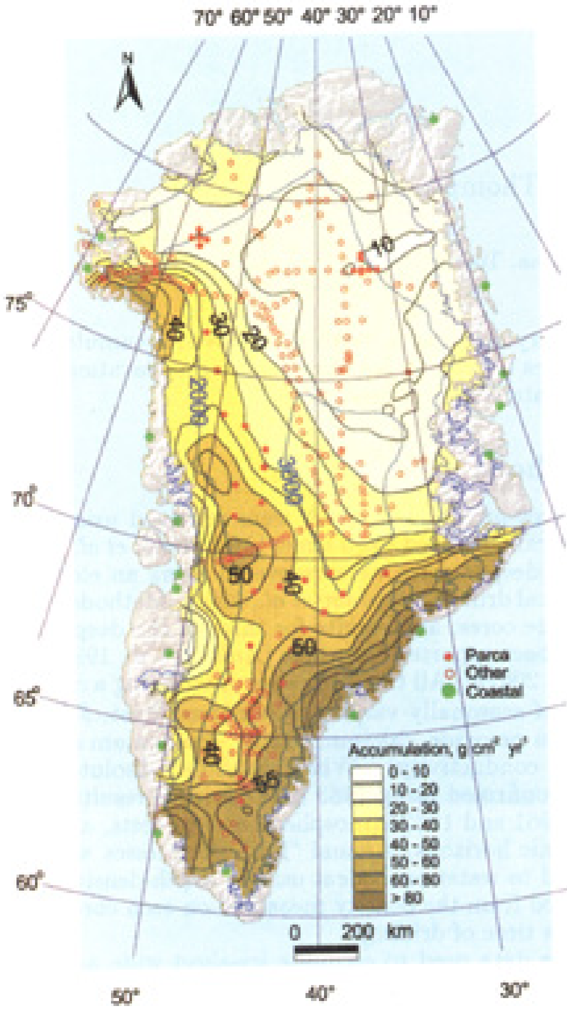

Figure 1. Accumulation map based on kriging. Shades of yellow show results for the entire island, with the accumulation contours shown just for the Greenland Ice Sheet. Contour and shading are accumulation in mm water equivalent. Also shown for reference are the 1000, 2000 and 3000 m elevation contours.

the map boundaries. Accumulation was estimated from the coastal precipitation data reported by *Ohmura et al.* [1999] by subtracting their evaporation estimates from the precipitation data.

For the northwest and west-central parts of the ice sheet, point estimates for times other than 1971-90 were multiplied by a factor representing the ratio of average accumulation for the period of the estimate to average accumulation for 1971-90. Factors were developed from analysis of six 200-year records in these parts of the ice sheet, and are reported elsewhere [*Bales et al.*, 2001*b*]. For other parts of the ice sheet, the longer records failed to give a consistent indication of regional-scale decadal variability so no corrections were made.

Interpolation was done using kriging. A quadratic surface (2nd order drift) was fit to the data, and residuals between the surface and data kriged; accumulation was then 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 $(\mathrm{g\ cm^{-2}y^{-1}})^2$, a sill of 55 $(\mathrm{g\ cm^{-2}y^{-1}})^2$, and a range of 200 km was estimated from the semivariogram. The kriged values are sensitive to: i) the ratio of the nugget to the sill, where a large ratio will weight sites further away more heavily and increase smoothing, and ii) the magnitude of the range, where a longer range will also increase smoothing. A larger nugget or sill also gives higher kriging variances; a longer range decreases the kriging variance. Some sites with short records and high uncertainty were dropped after examining the contribution of individual data points to the semivariogram. Because of the highly non-uniform distribution of data, 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 in areas with fewer data.

Results

The median length of record in the 253 points used is 10 years, with most of the data falling into the period 1940-present. The mean accumulation for all 253 points, as adjusted, is 29.1 g $\mathrm{cm^{-2}yr^{-1}}$, and 31.7 g $\mathrm{cm^{-2}yr^{-1}}$ for the 17 coastal points. The kriged map (Figure 1) shows high accumulation areas (> 40 g $\mathrm{cm^{-2}yr^{-1}}$) in the south, southeast and west, and much lower accumulation in the northeast (< 20 g $\mathrm{cm^{-2}yr^{-1}}$).

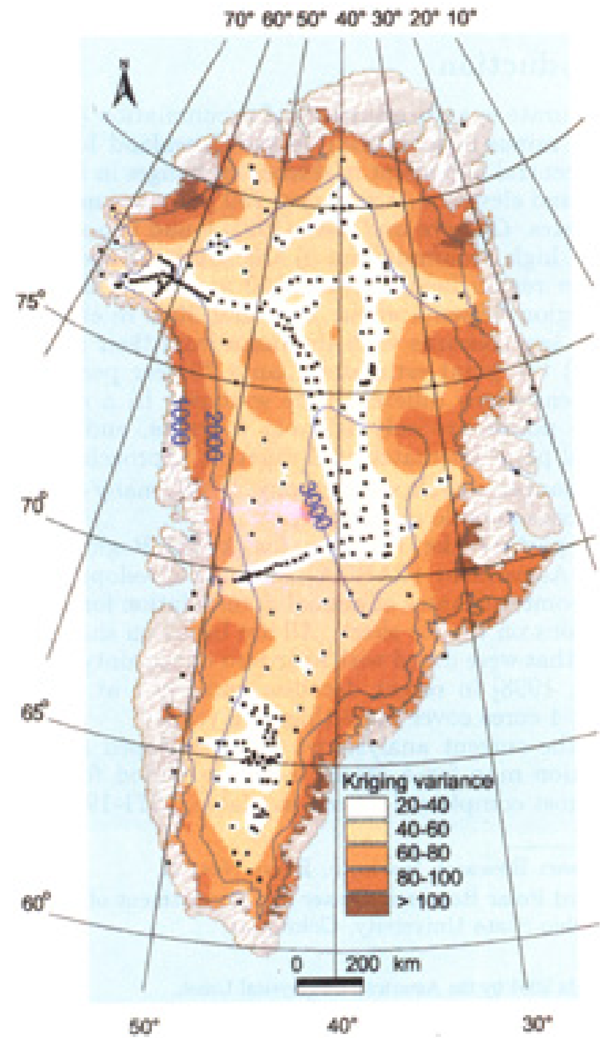

Figure 2. Kriging variance, shown with the points used to develop the kriged surface.

The mean accumulation value for the ice sheet is 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. 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. As there are no ice sheet data in the regions in question, below about 1800-2000 m in elevation, we did not impose a specific elevational gradient to accumulation. 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 area with data. Since our main objective was to develop estimates for the ice sheet, we felt that using a higher order surface was not warranted. 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 a 5-10 g $cm^{-2}y^{-1}$ change 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

The kriging variance (Figure 2) 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 $cm^{-2}y^{-1}$. The maximum would be ~7 g $cm^{-2}y^{-1}$. 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 part of the ice sheet in the south, where the standard deviation is 5-7 g $cm^{-2}yr^{-1}$. The greatest opportunities to reduce total 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).

Over much of the central and northern part of the ice sheet, the kriged result gives an accumulation pattern that retains features of the map published previously by *Ohmura and Reeh* [1991]. Our mean ice-sheet accumulation value is 30 g $cm^{-2}y^{-1}$, versus 29 for *Ohmura and Reeh* [1991], and *Ohmura et al.* [1999]. Above 2000 m elevation our kriged value is 30 g $cm^{-2}yr^{-1}$, similar to that reported by *Ohmura and Reeh* [1991]. The large differences between our map and that of *Ohmura and Reeh* [1991] in the area below 2000 m are due in part to differences in interpolation methods (i.e., kriging versus hand contouring).

There are four distinct regional differences between the two maps. 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 1995-98 PARCA cores from the region where few ice-core data had been collected previously. Second, this new map shows greater accumulation along much of the western part of the ice sheet, below about 2000 m elevation; this is below the elevation of the accumulation observations, and estimated accumulation is sensitive to the interpolation method. Third, the new map indicates higher accumulation in the east-central part of the ice sheet, which is again based on new shallow cores. Fourth, in the southern part of the ice sheet there are broad regional differences between the two maps that result mainly from the addition of the new PARCA data, although accumulation details are also sensitive to the interpolation methods used.

Conclusions

The part of the ice sheet from which most of the point accumulation estimates come, the inland area above 1800-2000 m elevation, has an average 1971-1990 accumulation of about 30 g $cm^{-2}yr^{-1}$ and an average uncertainty (standard deviation) in point estimates of accumulation of no more than 7 g $cm^{-2}yr^{-1}$, or 24%. Strategic sampling using shallow cores could reduce this uncertainty to well under 20%. Over the whole ice sheet, the uncertainty is up to 8 g $cm^{-2}yr^{-1}$ (upper limit), with lower values applying to the lower accumulation regions.

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