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Annual net snow accumulation over southern Greenland from 1975 to 1998

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Abstract. As part of NASA's Program for Arctic Regional Climate Assessment (PARCA), extensive ice core measurements of annual net water-equivalent accumulation have been made recently around the southern Greenland ice sheet. Analysis of these measurements demonstrates that annual and seasonal accumulation patterns are sometimes regional, with temporal variability in accumulation correlated over large areas. Using this unique, widely distributed set of contemporaneous accumulation measurements, as well as available previously published observations, we developed maps of annual net snow accumulation south of ~73°N for each year from 1975 to 1998. Here net snow accumulation is defined as snow accumulation minus ablation. In order to achieve a more consistent spatial distibution of core measurements for each of the 24 years in the study period, some of the observed records were extrapolated up to 5 years using empirical relationships between monthly precipitation measured at coastal stations and the observed ice core net accumulation records. Initial comparisons between the maps of annual net snow accumulation and similar maps of net accumulation derived from meteorological model simulations show excellent agreement in the temporal variability of accumulation, although significant differences in the magnitude of accumulation remain. Both measurements and model simulations indicate that annual net accumulation, averaged over all higher-elevation regions (above 2000 m) of the southern ice sheet, varies significantly from one year to the next. The maximum year-to-year change during the 24-year study period occurred between calendar years 1995 and 1996, when the average annual net snow accumulation increased by 101 and 172 kg m^{-2} yr^{-1}, or 37% and 57%, for observations and model simulations, respectively. Taken alone, this 1-year change in average net snow accumulation corresponds to a drop in sea level of ~0.16 and ~0.28 mm yr^{-1}.

1. Introduction

Understanding the current mass balance of the Greenland ice sheet is critical for predicting future sea level. The deposition and accumulation of water as snow on the ice sheet are key components of mass balance. Mass balance can be inferred from changes in ice sheet thickness with time; efforts to use satellite and aircraft altimetry are ongoing. Recently reported radar [*Davis et al.*, 1998; *Zwally et al.*, 1998] and laser [*Krabill et al.*, 1999] altimetry studies of the southern ice sheet show little change in overall mass, although some areas show significant thinning and thickening during the past few decades. However, multiple factors determine ice sheet elevation change over annual to decadal timescales. A study of firn densification, when driven by contemporaneous ice core measurements of net annual snow accumulation, suggested that the bulk of the reported pattern in ice sheet elevation change from 1978 to 1988 [*Davis et al.*, 1998] is predominantly the result of spatial and temporal variability in snow accumulation [*McConnell et al.*, 2000a; *Davis et al.*, this issue]. At higher elevations this accumulation-driven elevation change may mask any thickening and thinning associated with long-term changes in mass balance. If available, independent estimates of spatially distributed, an-

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nual net snow accumulation could be used to model the elevation change that results from short-term variability in accumulation [*Arthern and Wingham*, 1998], although such estimates of accumulation must be both accurate and contemporaneous with the altimetry measurements [*McConnell et al.*, 2000b]. This accumulation-driven component could be subtracted from the observed elevation change to reveal any long-term elevation change associated with ice sheet imbalance or changes in ice flow behavior without the need for very long duration altimetry measurements to mitigate the impact of snow accumulation variability.

Meteorological models of precipitation and net accumulation have been developed to simulate accumulation on the Greenland ice sheet [*Chen et al.*, 1997; *Bromwich et al.*, 1998; *Hanna et al.*, 2001]. These models are based on climate analyses such as the European Centre for Medium-Range Weather Forecasts (ECMWF) and U.S. National Centers for Environmental Prediction/National Center for Atmospheric Research. Validations between model-simulated accumulation and contemporaneous ice-core point measurements [*McConnell et al.*, 2000b; *Hanna et al.*, 2001] indicate that the models may approximately replicate the observed temporal variability in accumulation but not necessarily the magnitude of accumulation. For example, *McConnell et al.* [2000b] confirmed earlier observations by *Bromwich et al.* [1998] that these models generally underpredict accumulation in the interior of the ice sheet and overpredict accumulation near the coasts. However, it is also clear that using measurements of accumulation from ice cores to validate regional-scale meteorological models is problematic because they represent rather different temporal and spatial scales. While ice core measurements provide information representative of a small area and are generally at no better than annual temporal resolution, meteorological models simulate regional accumulation and are at daily to weekly timescales.

In the past, ice core accumulation measurements have been concentrated either along linear traverse routes or near particular locations such as Summit. Such limited spatial representation of snow accumulation has precluded development of time-specific, regional maps of net annual accumulation for meteorological model development and validation. As part of the Program for Arctic Regional Climate Assessment (PARCA), a large number of firn cores spanning at least the past few decades were collected at locations widely distributed around Greenland, with particular effort focused on the higher elevation regions south of ~73°N. Here we present annual maps of net snow accumulation from 1975 to 1998 for the region of the ice sheet above the equilibrium line and south of ~73°N. Net snow accumulation is defined here as snow accumulation minus ablation and is expressed in water equivalence. Net snow accumulation is zero at the equilibrium line. These maps were developed using 24 new PARCA records of net annual accumulation in combination with the few previously published, contemporaneous records of net annual accumulation in this region. To allow optimal spatial constraints on the maps of annual accumulation, we extrapolated the observed accumulation records in time using empirical relationships between the time series of observed accumulation and continuous monthly measurements of accumulation at a number of stations around the coast of Greenland.

2. Methods

Shallow (5-25 m) and deeper cores (50-130 m) were recovered during the 1997, 1998, and 1999 field seasons (Figure 1) from 24 sites widely distributed around the ice sheet south of ~73°N above ~1800-m elevation. Multiple cores were collected at some sites in order to evaluate the impact of short-scale spatial variability in snow accumulation [*McConnell et al.*, 2000b]. Core locations and basic accumulation statistics are given in Table 1. Details of the collection methods and dating procedures are given by *Mosley-Thompson et al.* [this issue]. While the full suite of glaciochemical records (hydrogen peroxide (H_2O_2), nitrate, calcium, ammonia, dust, and $\delta^{18}O$) were used in dating the cores, the individual annual layer thickness was determined as the difference between successive minima in H_2O_2 so the accumulation values correspond to approximately the calendar year total.

Previously published annual accumulation data on southern Greenland are relatively sparse for the period from 1975 through 1998. Included in this study are an-

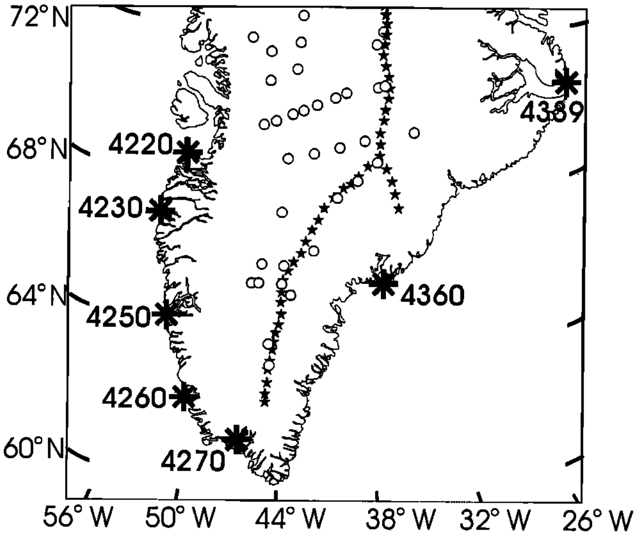

Figure 1. Locations of ice core accumulation (circle) and coastal precipitation measurements (asterisk) used in this study. Also shown is the approximate location of the ice divide (star). Stations identified as 4220, 4230, 4250, 4260, 4270, 4339, and 4360 correspond to Asiat, Sisimiut, Godthaab, Paamiut, Narsarsuaq, Scoresbysund, and Ammasalik, respectively. Not shown is the coastal station at Danmarkshavn (76.77°N, 18.77°W).

Table 1. Results of Empirical Extrapolation of Ice Core Accumulation Measurements

Latitude, °N/ Longitude, °W	Time Span	Number of Years	Number of Coastal Sites	Core Model Correlation Coefficient[a]	Average Accumulation, kg m^{-2} yr^{-1}	Extrapolation Uncertainty, kg m^{-2} yr^{-1}
63.2/44.8	1978 – 1995	18	6	0.85(0.77)	663	76
63.8/45.0	1977 – 1996	20	7	0.96(0.96)	324	27
65.2/43.9	1970 – 1986	17	6	0.92(0.81)	487	95
65.4/46.5	1976 – 1997	22	7	0.92(0.90)	351	48
65.5/44.5	1970 – 1997	28	8	0.70(0.67)	474	61
65.5/46.1	1976 – 1997	22	7	0.90(0.84)	350	58
66.0/44.5	1976 – 1995	20	7	0.98(0.97)	442	18
66.0/46.0	1970 – 1996	27	7	0.78(0.75)	378	96
66.5/42.5	1981 – 1996	16	5	0.78(0.73)	613	99
67.5/45.0	1984 – 1996	13	4	0.96(0.87)	361	31
68.0/41.0	1987 – 1996	10	3	0.95(0.90)	476	34
68.5/39.5	1985 – 1996	12	4	0.94(0.85)	385	37
69.0/38.0	1983 – 1996	14	5	0.97(0.97)	357	20
69.0/45.0	1977 – 1996	20	7	0.91(0.70)	447	56
69.2/43.0	1977 – 1996	20	7	0.95(0.94)	404	37
69.4/41.0	1985 – 1996	12	4	0.97(0.99)	384	25
69.6/39.0	1982 – 1996	15	5	0.95(0.87)	327	18
69.8/35.0	1976 – 1995	20	7	0.92(0.88)	469	47
69.8/47.2	1983 – 1989	7	3	0.95(0.86)	467	26
70.0/46.3	1982 – 1989	8	3	0.96(0.86)	419	31
70.2/45.0	1983 – 1989	7	3	0.97(0 93)	467	21
70.4/44.1	1982 – 1989	8	3	0.99(0.90)	446	13
70.5/43.0	1982 – 1989	8	3	0.94(1.00)	437	29
70.8/41.5	1983 – 1989	7	2	0.97(0.96)	402	23
70.9/40.6	1981 – 1989	9	3	0.89(0.88)	349	25
71.1/37.3	1970 – 1989	20	8	0.95(0.94)	255	14
71.1/37.9	1979 – 1989	11	4	0.97(0.94)	249	8
71.1/47.2	1974 – 1995	22	7	0.88(0 68)	422	43
71 5/45.0	1986 – 1996	11	4	0.95(0.94)	426	28
71.9/47.5	1974 – 1995	22	7	0.94(0.92)	423	29
72.2/45.0	1984 – 1996	13	4	0.72(0 75)	360	40
72.2/49.4	1986 – 1996	11	4	0.90(0.85)	542	49
72.3/38.0	1970 – 1996	27	8	0 80(0.74)	218	20
72.6/37.6	1970 – 1989	20	7	0.93(0 93)	201	18

[a] Correlations computed parametrically (nonparametrically) using Pearson's r (Spearman rank-order).

nual net accumulation values reported by *Anklin et al.* [1994] for 10 shallow cores collected in 1990 along the Expedition Glaciologique International au Groenland flow line in west Greenland (69.7°N, 48.1°W to 71.1°N, 37.3°W). In addition, we used published discrete measurements of H_2O_2 [*Sigg and Neftel*, 1991] to develop an accumulation record at Dye-3 (65.2°N, 43.9°W) extending from 1975 to 1986.

Mapping algorithms are influenced by the underlying spatial distribution of the data, and this is particularly true when the measurements are few and poorly distributed. To improve the spatial distribution of accumulation values, we developed an empirical method to extrapolate the measured time series of net accumulation using continuous measurements of monthly precipitation from 1970 to 1999 at eight locations along the coast of Greenland (Figure 1). Extrapolation was limited to no more than 5 years prior to or subsequent to the period of measurement in the ice core record. Coastal precipitation data were obtained from the Danish Meteorological Institute [*Frich et al.*, 1996]. While accurate measurements of solid precipitation are difficult at best, we assume only that the uncertainties in each month's total precipitation are approximately constant from year to year. That is, it is assumed that the relationship between the measured, though somewhat uncertain, monthly coastal precipitation and net accumulation at a point on the ice sheet is stationary in time. The method assumes that a time series of annual net snow accumulation, M_t, at a site on the ice sheet can be approximated using a linear combination of normalized monthly precipitation measurements, $C_{t,i}$, from some number of coastal locations, n. Rapid variations of density with depth, as well as difficulties in shipping and handling firn core from very shallow depths, lead to uncertainty in accumulation measurements in the shallowest part of the core. Thus the most recent 1.5 years of each measured accumulation record was eliminated from the time series, M_t, used in the empirical modeling. The n weights, W_i, were determined by solving

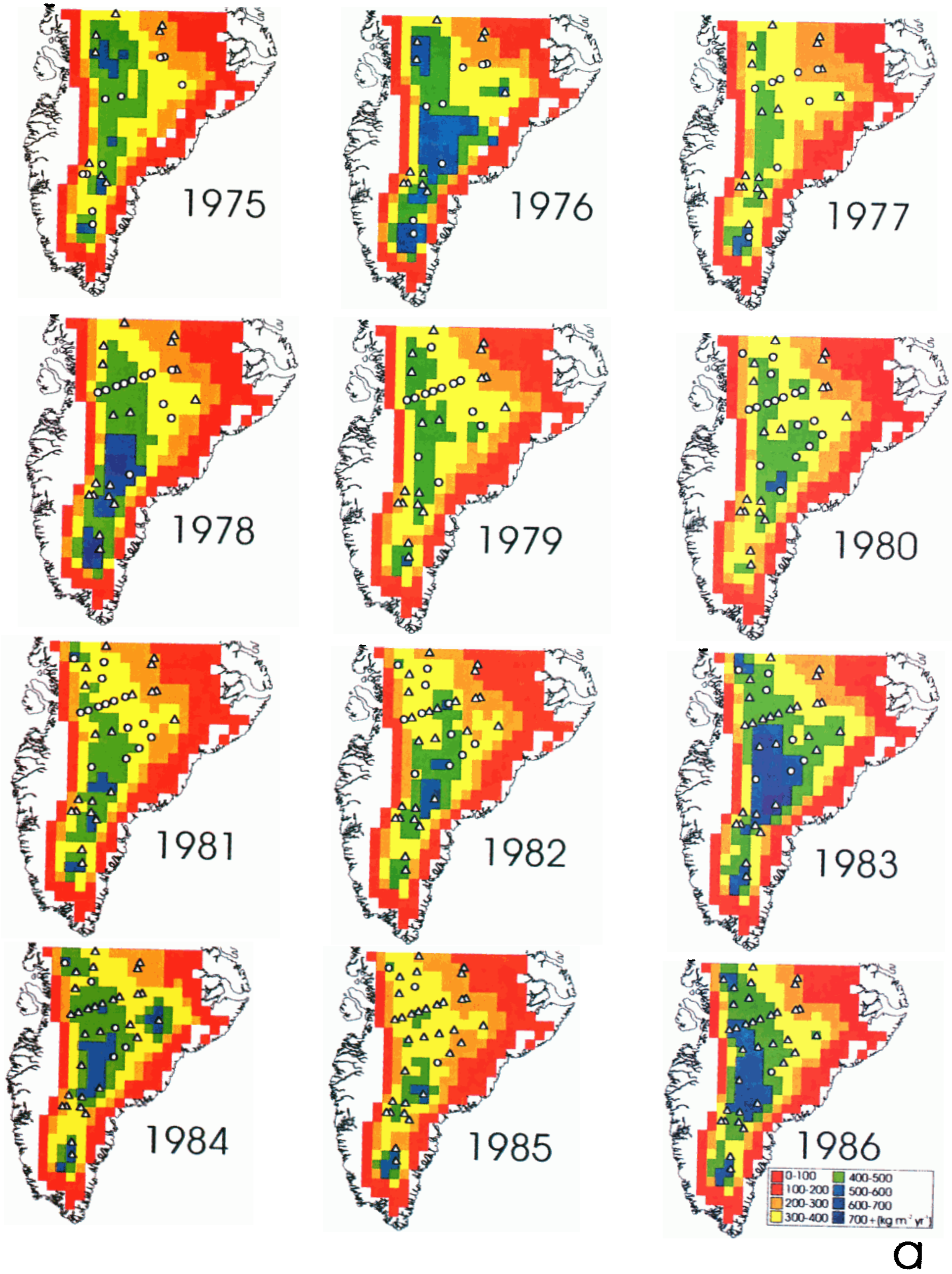

Plate 1. Net snow accumulation each year from 1975 to 1998 in southern Greenland above the equilibrium line. Net snow accumulation is expressed as $\mathrm{kg_{water}\ m^{-2}\ yr^{-1}}$. Locations of ice core measurements (triangles) and extrapolated measurements (circles) are shown for each year.

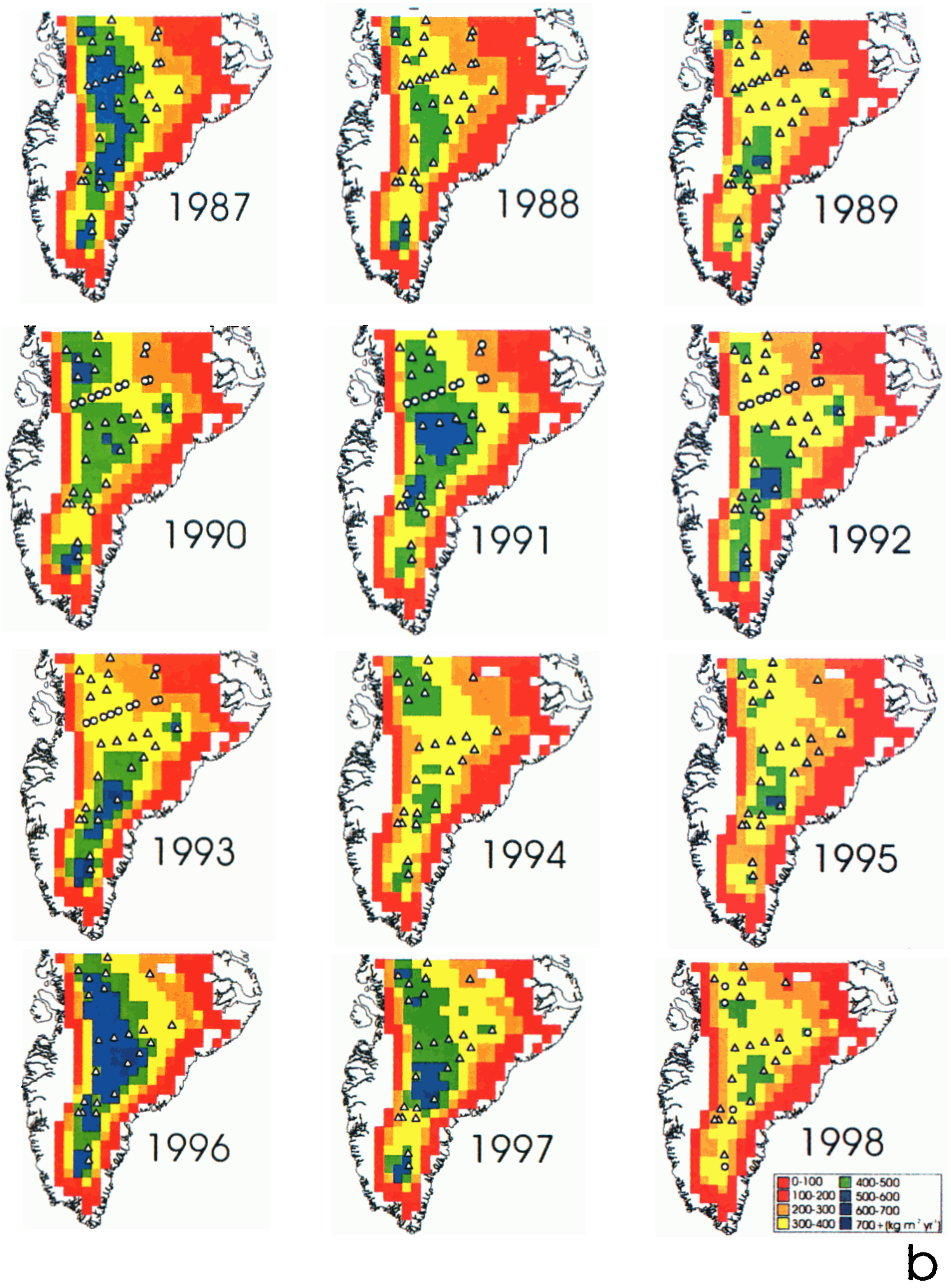

Plate 1. (Continued)

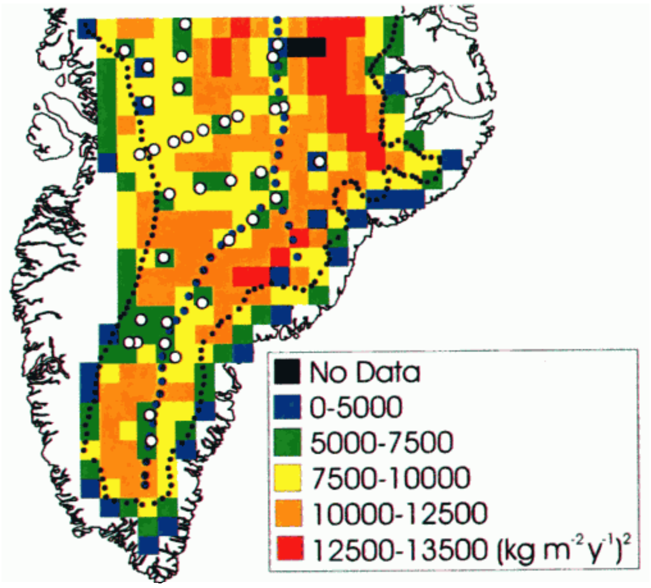

Plate 2. Kriging variance averaged over the 24 maps of annual net snow accumulation shown in Plate 1. Ice core locations are shown as open circles. Also shown are the approximate locations of the 2000-m elevation contour (asterisk) and the ice divide (solid circle).

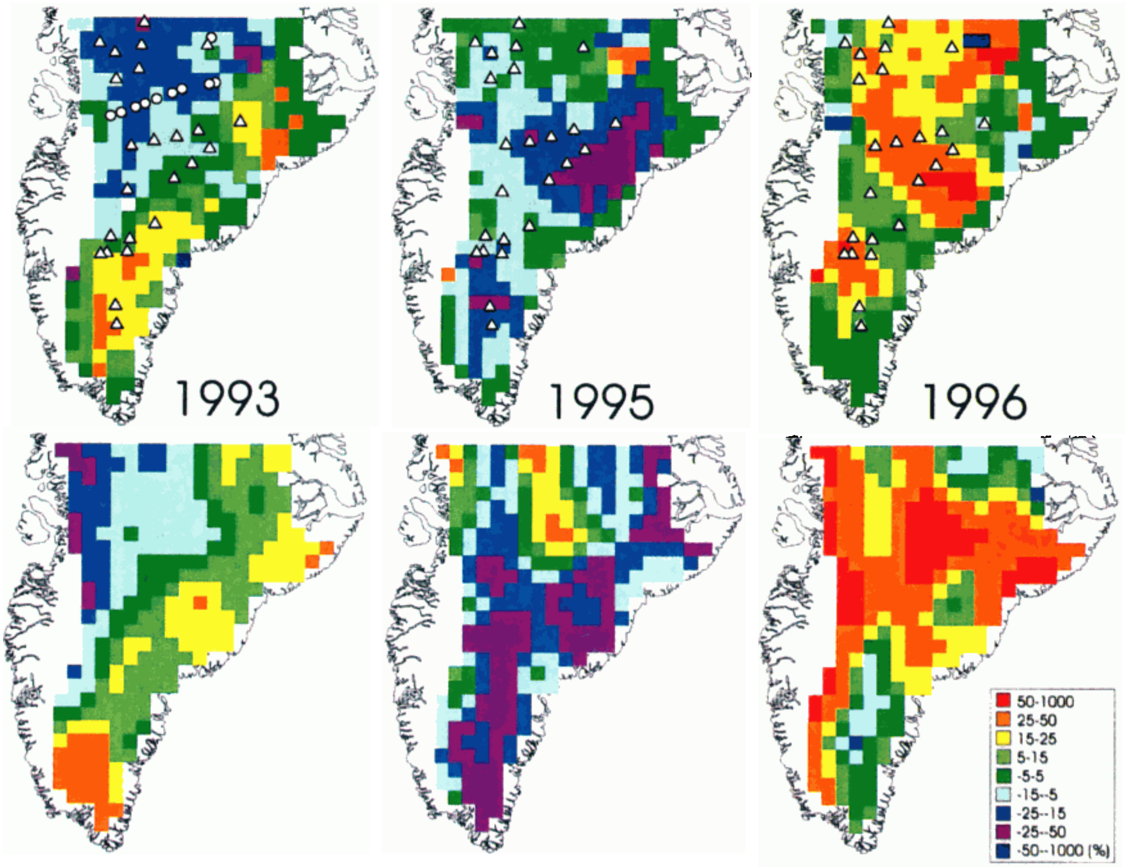

Plate 3. (top) Maps of the percentage difference between annual net snow accumulation and the 1979-1998 mean for the years 1993, 1995, and 1996. (bottom) Similar percentage differences for net accumulation model simulations reported by *Hanna et al.* [2001]. Locations of ice core measurements (triangles) and extrapolated measurements (circles) are shown for each year.

the overdetermined set of m linear equations, where m is the number of years in the annual accumulation time series. By overdetermined, we mean that m is larger than n:

$$M_t = C_{t,i} W_i. \qquad (1)$$

The classical least squares solution to (1) is [*Lines and Treitel*, 1984]

$$W_i = (C^T_{t,i} C_{t,i})^{-1} C^T_{t,i} M_t. \qquad (2)$$

To avoid instabilities in the inversion of the matrix ($C^T_{t,i}$ $C_{t,i}$), a white noise or damping factor can be added to the diagonal so (2) is rewritten as

$$W_i = (C^T_{t,i} C_{t,i} + kI)^{-1} C^T_{t,i} M_t, \qquad (3)$$

where k is a constant and I is the identity matrix.

Because rates of snow accumulation on the ice sheet and precipitation along the coast are not uniform during the year, a search over the monthly accumulation was used to find those months of contiguous precipitation at each coastal site that yielded the best fit to the measured accumulation time series. In order to minimize the impact of possible time-variable error in the monthly precipitation data as well as any highly anomalous monthly accumulation measurements on the empirical extrapolation, we restricted the monthly optimization to include at least three contiguous months of measured precipitation at any particular coastal site. Note that uncertainty in the empirically extrapolated annual accumulation was estimated by first dropping 1 year from the measured accumulation record M_t, then optimizing the weights on the remaining accumulation data, and, finally, modeling the accumulation for the missing year. This was repeated for each year for which an ice core accumulation measurement was made.

The damping factor, k, was set to 5% of the diagonal value to diminish the influence of any highly anomalous monthly precipitation measurements at the coastal sites. Because we imposed the limitation that (3) was overdetermined by a factor of 3 or more, modeled accumulation was relatively insensitive to the choice of k. In addition, the relationship between coastal precipitation and snow accumulation on the ice sheet may change with time, so the period of comparison for deriving the empirical model weights between coastal and ice core sites was restricted to 1970-1999. Finally, because glaciological noise is inherent in any ice core accumulation measurement [*van der Veen and Bolzan,* 1999], particularly at annual timescales, the number of coastal sites used in the model was restricted to be no more than about one third of the number of years in the annual accumulation measurements. When necessary, the original optimized weights were evaluated, and the coastal site with the lowest weight was dropped. The empirical model was optimized again with the new subset of coastal data in an iterative loop until the one-third criterion was reached.

The focus of the current study is on annual net snow accumulation on the southern ice sheet, where net snow accumulation is defined as snow accumulation minus ablation. At the equilibrium line, net snow accumulation is zero because snow accumulation is balanced by ablation and no snow is preserved from year to year. To constrain the maps, zero snow accumulation points were added to the ice core accumulation measurements, with the zero points located every 50 km along a time-invariant equilibrium line specified as a function of elevation, latitude, and longitude (adapted from *Zwally and Giovinetto* [2000]). Measurements of net annual snow accumulation (expressed as $\mathrm{kg_{water}\ m^{-2}\ yr^{-1}}$) at the 35 ice core sites were kriged to develop maps of net annual accumulation. To provide as much spatial constraint as possible, 249 accumulation values (multiyear averages of net accumulation from ice core measurements) reported by *Bales et al.* [2001] for the entire ice sheet and 132 zero accumulation points along the equilibrium line were used to develop a drift surface. The drift surface was determined using a weighted least squares fit of a polynomial basis function in universal transverse Mercator coordinates. Note that the observed accumulation values were assigned a weight of 1.0 and the zero points were assigned a weight of 0.5. After investigating various orders for the polynomial fit, a fifth-order polynomial was selected because it appeared to best capture the large-scale accumulation patterns over the southern ice sheet, thus yielding residuals with little or no spatial trend. The same drift

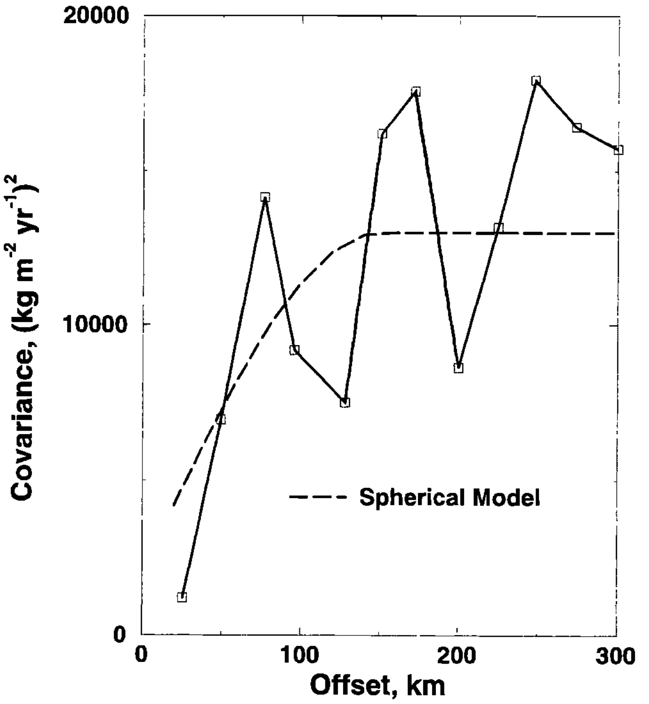

Figure 2. Stacked semivariogram (solid line with squares) and spherical model approximation (dashed line) developed from 1975-1998 annual accumulation data.

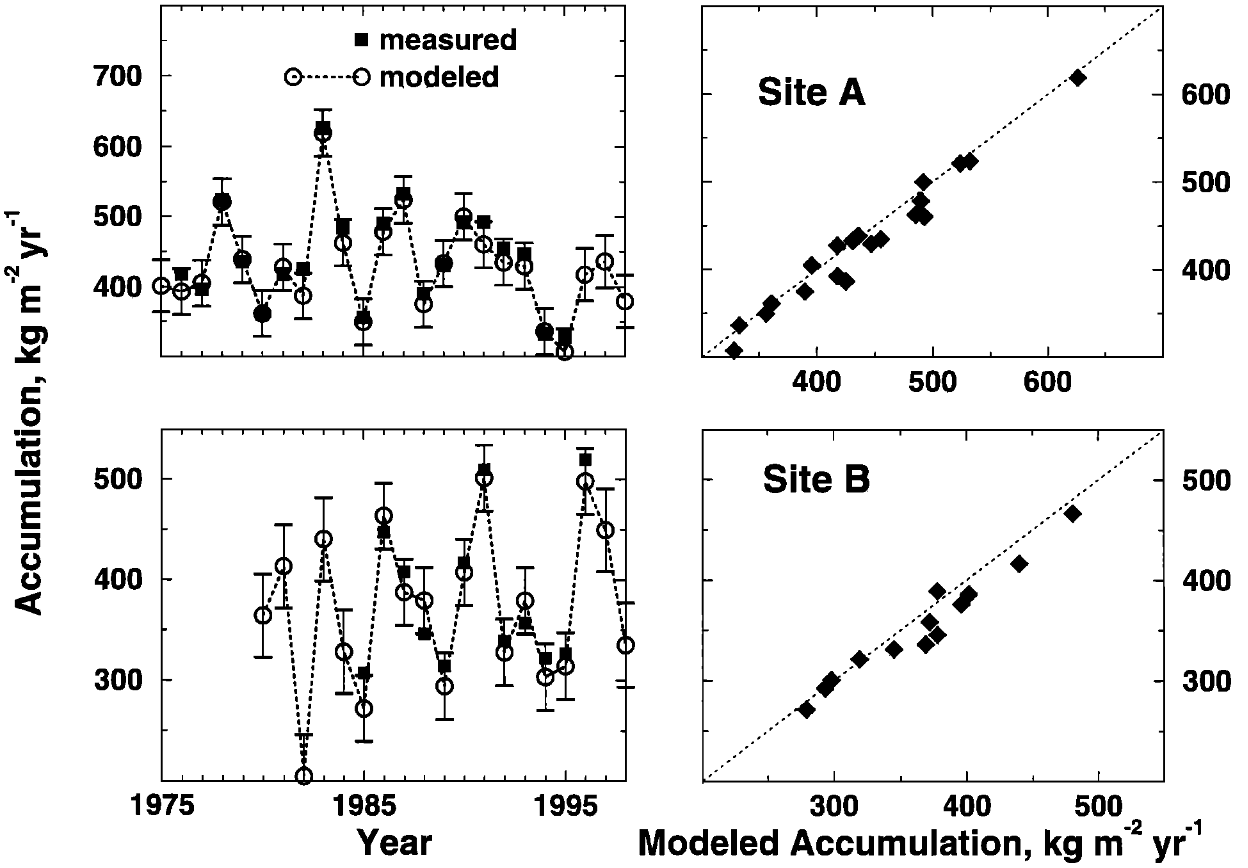

Figure 3. Measured (square) and empirically modeled (circle) net water-equivalent accumulation for core accumulation records at the Site A (66.0°N, 44.5°W) and Site B (69.4°N, 41.0°W) PARCA shallow core sites. Error bars reflect one standard deviation in the combined uncertainty caused by short-scale spatial variability in accumulation [*McConnell et al.*, 2000b] and the estimated uncertainty in the empirical extrapolation. Correlation coefficients between observed and modeled accumulation, along with estimates of the uncertainty associated with the empirical extrapolation, are listed in Table 1 for each core location.

surface was used for each year in the 24-year study period.

The accumulation residuals (annual ice core observations of accumulation minus the drift surface value at that location) were kriged to a 50-km grid. For some years, ice-core-based observations of accumulation were sparse. Thus a stacked semivariogram was constructed by pairing all accumulation values within a year and then combining all 24 individual years into one semivariogram (Figure 2). Interpretation of the stacked semivariogram resulted in spherical model parameters that included a nugget of 2000 (kg m^{-2} yr^{-1})^2, a sill of 11,000 (kg m^{-2} yr^{-1})^2, and a range of 150 km. Because of the highly nonuniform distribution of the observations a search radius of 150 km using three to nine points was used in areas with more densely distributed observations, and a search radius of 200 km using two to three points was used in areas with few observations. When kriging from the zero accumulation points along the equilibrium line, the search radius was limited to half the standard search ranges. These same spherical model parameters were used in kriging each year's accumulation.

3. Results

Examples of measured and empirically modeled annual net accumulation at two core locations are shown in Figure 3. Note that monthly precipitation records from seven and four coastal stations were used in the empirical model for ice core sites A (66.0°N, 44.5°W) and B (69.4°N, 41.0°W), respectively. Because (3) is overdetermined by approximately a 3 to 1 ratio in this application and because of the use of the damping factor, k, the modeled accumulation is slightly less variable from year to year than the measurements. Scatterplots of empirically modeled versus measured accumulation show that the model simulates the variability over nearly the full range of observations at these core sites. Table 1 summarizes the results, including parametric and nonparametric correlation coefficients between the ice core measurements of accumulation and the empirically modeled estimate of accumulation, as well as the estimated uncertainty in the accumulation values extrapolated using the empirical model. While the correlation coefficients in Table 1 are quite high, we emphasize that net accumulation (and the underlying temporal variability) is large over much of the southern ice sheet. Thus strong correlations between the empirically modeled accumulation and the observed ice core measurements do not preclude significant uncertainty in the core-based measurements from short-scale spatial variability in accumulation as discussed by *McConnell et al.* [2000b] and *van der Veen and Bolzan* [1999].

Maps of net annual accumulation above the equilibrium line from 1975 to 1998 are shown in Plate 1. For clarity, the locations of the measured (triangles) and extrapolated (circles) accumulation observations used in creating each annual map are shown. Note the large year-to-year variability in snow accumulation, with particularly high accumulation years over much of the ice sheet in 1976, 1983, 1987 and 1996. Anomalously low accumulation years include 1985, 1988-1989, 1995, and 1998. For a few grid cells in some years, there were not enough accumulation measurements (or specified zero accumulation points) within the search range for kriging.

4. Discussion

Even though the PARCA ice cores undoubtedly comprise the most extensive and widely distributed contemporaneous measurements of accumulation ever assembled for the southern Greenland ice sheet, uncertainty in point accumulation remains high in some areas. The kriging variance averaged over 24 years for each grid cell is shown in Plate 2. Kriging variance in the estimated annual net snow accumulation at a point, which provides an indication of the uncertainty that arises from the spatial mapping or kriging of the point measurements, is ~10,000 (kg m^{-2} yr^{-1})^2, with low values of ~5000 (kg m^{-2} yr^{-1})^2 for grid cells located near one or more ice core sites and high values up to 13,000 (kg m^{-2} yr^{-1})^2 for grid cells well away from any core measurements. Note that the very low kriging variance near the coastlines results from forcing the net snow accumulation to zero at the equilibrium line.

Hanna et al. [2001] developed a 1979-1998 record of net snow accumulation (defined as precipitation minus sublimation for simulated air temperatures 2 m above the snow surface below 0°C and zero minus evaporation above 0°C) over Greenland using an ECMWF-driven meteorological model. They found good agreement in point comparisons of mean 1985-1996 modeled and measured net snow accumulation reported by *McConnell et al.* [2000b] for 11 widely distributed ice core locations above ~2000-m elevation. Note that measurements from 6 of these 11 core sites (those south of ~73°N) are incorporated in the accumulation maps in Plate 1. Maps of the percentage difference ((individual year - 1979-1998 mean)/1979-1998 mean) for the *Hanna et al.* model results are shown in Plate 3 (bottom) and for the observations (Plate 3, top) for the years 1993, 1995, and 1996. These years were selected as examples of years with intermediate, low, and high net accumulation, respectively. The meteorological model used a 1.125° by 1.125° grid cell. For comparison with the kriged maps of net annual accumulation, the model results were kriged to the same grid. Note both the general agreement in the overall variation from the 1979-1998 mean accumulation and the similarity in the spatial distribution in accumulation variation for these years.

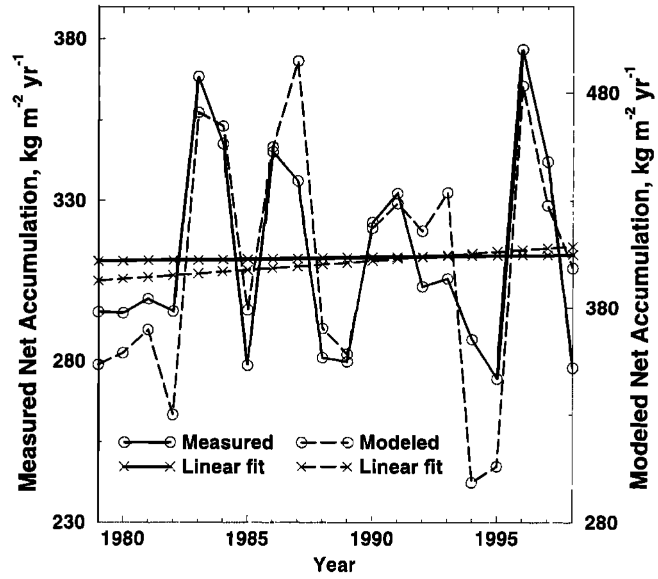

Figure 4. Measured and modeled net accumulation [*Hanna et al.*, 2001] averaged over ~230 map grid cells south of ~73°N and above 2000-m elevation.

The measured net annual snow accumulation for each year from 1979 to 1998, averaged over the ~230 map grid cells (each cell is 50 km by 50 km) below ~73°N and above the 2000-m elevation contour, is shown in Figure 4. Accumulation above 2000 m was selected because most of the ice core measurements are from this region. The average for the southern ice from 1979 to 1998 was 312 kg m^{-2} yr^{-1}. Also shown is the average accumulation above 2000 m for similar maps kriged from the 1979-1998 *Hanna et al.* [2001] model simulations. The mean for the same 20-year time period for the kriged model simulations was 401 kg m^{-2} yr^{-1}. While the magnitude is different between the model-simulated water accumulation and the observed snow accumulation over the southern ice sheet, the agreement in interannual variability is remarkable. Both model results and observations indicate that total net accumulation over the southern ice sheet varies significantly from year to year. From 1979 to 1998, the standard deviation in average net snow accumulation for the higher-elevation regions of the southern ice sheet was 32 and 58 kg m^{-2} yr^{-1}, or 10% and 14%, for observations and model simulations, respectively. The maximum 1-year change occurred from 1995 to 1996 when the average in the observed net snow accumulation increased ~37% from an unusually low 274 to 376 kg m^{-2} yr^{-1}, as compared with an ~57% increase in the model results.

The spatial distribution of the ice core measurements changed over the 24-year period such that regions of the southern ice sheet are not represented uniformly from year to year. Therefore conclusions about long-term changes in accumulation are tentative. However, a linear fit to the southern ice sheet average of the observations indicates only a small (<5%) increase in annual net accumulation between 1979 and 1998. A similar linear fit to the model-simulated net accumulation above 2000 m also shows a long-term increase of <5% over the same 20-year period (Figure 4). However, within the large interannual variability in accumulation neither trend is significant.

The year-to-year variability in snow accumulation will result in interannual changes in sea level. The ice-core-based maps show a 1979-1998 average accumulation rate of 312 kg m^{-2} yr^{-1} over an area of ~5.83 x 10^5 km^2 south of ~73°N and above 2000-m elevation. This annual accumulation rate corresponds to ~0.50 mm of sea level change, so a standard deviation in annual net accumulation of 10% is equivalent to a similar standard deviation in sea level of ~0.05 mm yr^{-1}. The large 37% increase in observed accumulation over this region from 1995 to 1996 resulted in a drop in sea level of ~0.16 mm yr^{-1}. For comparison, *Krabill et al.* [2000] estimated a total decrease in ice sheet mass of ~47 km^3 (water equivalent) from ~1993 to 1998 using repeat altimetry measurements, corresponding to a rise in sea level of 0.13 mm yr^{-1} during that period. Hence typical year-to-year variability in sea level caused solely by changes in snow accumulation in the higher-elevation regions of the southern ice sheet represents more than one third of the total estimated increase in sea level each year caused by measured changes in mass balance of the whole Greenland ice sheet. The largest year-to-year change in sea level from observed changes in net snow accumulation in this region over the 24-year study period is as large or larger than the average yearly change over the entire ice sheet. Clearly, such large interannual variability in snow accumulation will have a significant impact on annual to decadal changes in ice sheet elevation and will mask any long-term changes in elevation associated with mass imbalance at higher elevations.

5. Conclusions

Because this extensive ensemble of new PARCA ice core measurements of annual net snow accumulation is widely distributed and contemporaneous, it offers the first realistic opportunity to develop time-specific maps of spatial variability in annual accumulation over the southern Greenland ice sheet. Note that the lack of core-based measurements of net accumulation at lower elevations, particularly in the southeast where accumulation rates are very high, and the relatively few measurements extending into the 1970s lead to significant uncertainty in long-term accumulation trends. However, these maps demonstrate that temporal variability in net snow accumulation at annual to multiannual scales is large. This variability undoubtedly drives significant short-term changes in ice sheet elevation in the southern regions above 2000 m which mask any long-term changes in elevation associated with ice sheet mass imbalance. Moreover, accumulation over southern Greenland is highly variable in space, so uncertainty in the derived maps of annual accumulation is still high in many areas. To further reduce these uncertainties using only in situ measurements of accumulation would require a substantial increase in field and laboratory efforts, although significant reductions in the uncertainty of net annual accumulation in specific regions of the ice sheet (notably the southeast) would be achieved through the acquisition of relatively few cores (on the order of 10 to 20) spanning 20-30 years of accumulation. High-resolution meteorological models offer an opportunity to efficiently and significantly improve understanding of the highly variable temporal and spatial patterns of snow accumulation. However, while the comparisons shown here between meteorological model simulations and observations are very encouraging, significant differences remain, and it is clear that validation of future meteorological model simulations will require additional in situ measurements of contemporaneous and strategically located ice core measurements of net annual accumulation.

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