JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. D3, PAGES 4039-4046, FEBRUARY 16, 2000

Interannual variations of snow accumulation on the Greenland Ice Sheet (1985-1996): new observations versus model predictions

Joseph R. McConnell,[1] Ellen Mosley-Thompson,[2] David H. Bromwich,[2] Roger C. Bales,[3] and Jay D. Kyne[4]

Abstract. Newly measured time series of net water-equivalent accumulation from ice cores are reported for 11 sites located near the 2000-m contour of the Greenland Ice Sheet. Many of these sites are located in regions where accumulation has not been previously measured. We compared these new time series of annual accumulation with previously reported modeled precipitation covering the same time range. Because ice core accumulation records include both regional and local accumulation components, we used adjacent ice core records at six multiple-core sites to estimate the local component and extrapolated these results to the five single-core sites. We investigated the impact of this short-scale spatial variability in accumulation on statistical comparisons between the observed accumulation and model precipitation. Although scalers were required to match the ~12-year mean modeled precipitation to the mean observed accumulation, a high degree of correspondence between observed interannual accumulation and scaled modeled precipitation was found at 7 of 11 locations. The need for scaling and the low correspondence between model simulations and observations at some sites clearly indicate that model improvements are needed. Although very encouraging, a more spatially distributed array of ice core accumulation measurements, spanning the same time period as the precipitation modeling, is necessary for continued model improvement and validation. In agreement with earlier studies, the large temporal variability in snow accumulation predicted by modeling and confirmed by ice cores indicates that the ice sheet elevation varies by tens of centimeters from year to year simply because of changing accumulation.

1. Introduction

Understanding the mass balance of the Greenland Ice Sheet is central to predicting future sea level change and requires an accurate understanding of snow accumulation throughout the interior of the island. However, accumulation rates vary strongly from region to region and on all timescales, and large uncertainties persist in our knowledge of net water-equivalent accumulation across the ice sheet. A number of field-based studies to measure net snow accumulation on the ice sheet have been reported [*Ohmura and Reeh*, 1991]. Many of these investigations were conducted before 1965 and/or included snow pit observations spanning only 1 or 2 years of accumulation and therefore have a high degree of uncertainty. Moreover, new compilations of field data do not support many of the previously reported accumulation features (e.g., the extent of the large accumulation ridge in west-central Greenland [*Bromwich et al.*, 1998]).

As part of NASA's Program for Arctic Regional Climate Assessment (PARCA) [*Abdalati et al.*, 1998], 4 deep ice cores and 32 shallow firn cores have been collected at widely distributed locations to improve understanding of the temporal and spatial variability of net water-equivalent accumulation over the ice sheet. Net water-equivalent accumulation is the combined result of snow precipitation minus sublimation, together with the net effects of snow redistribution by wind. A closely related component of PARCA is to improve models for precipitation prediction over Greenland but such models require contemporaneous measurements of net water-equivalent accumulation for validation. Here we report newly measured annual time series of net water-equivalent accumulation (nominally 1985-1996) at 11

[1]Desert Research Institute, Reno, Nevada.

[2]Byrd Polar Research Center and Department of Geography, Ohio State University, Columbus.

[3]Department of Hydrology and Water Resources, University of Arizona, Tucson.

[4]Polar Ice Coring Office, University of Nebraska, Lincoln.

Paper number 1999JD901049.
0148-0227/00/1999JD901049$09.00

Table 1. Measured Accumulation and Modeled Precipitation

Site[a,b]	Latitude/Longitude, °N/°W	Mean Annual Accumulation[c]	Correlation Coefficient[d]	Chi-Square Probability [e]	Model Scaler a[e]
1A	63.2/44.8	68.9	0.44(0.27)	6.6×10^{-19}	2.66
1B		67.1	0.62(0.48)	1.5×10^{-11}	2.63
2A	66.0/44.5	44.1	0.33(0.55)	7.0×10^{-17}	1.97
2B		44.9	0.16(0.42)	2.1×10^{-20}	1.99
3	66.5/42.5	64.1	0.66(0.64)	7.7×10^{-11}	1.53
4A	69.8/35.0	47.5	0.69(0.66)	1.0×10^{-6}	2.16
4B		48.4	0.94(0.90)	1.1×10^{-1}	2.23
4C		48.2	0.87(0.88)	1.6×10^{-6}	2.22
5A	75.0/30.0	13.0	0.46(0.40)	5.2×10^{-1}	1.65
5B		12.4	−0.35(−0.30)	4.1×10^{-3}	1.49
6	71.1/47.2	42.5	0.80(0.89)	2.6×10^{-2}	1.71
7	71.9/47.5	42.8	0.86(0.80)	5.4×10^{-3}	1.24
8A	73.8/49.5	31.4	0.86(0.83)	6.8×10^{-3}	1.65
8B		31.7	0.90(0.76)	4.7×10^{-1}	1.65
8C		31.0	0.76(0.79)	4.5×10^{-2}	1.61
9	75.0/51.0	30.5	0.47(0.13)	6.5×10^{-3}	1.60
10	76.0/53.0	36.4	0.44(0.50)	2.2×10^{-6}	1.17
11A	78.5/56.8	16.1	−0.17(−0.21)	6.9×10^{-2}	1.37
11B		12.6	0.03(0.02)	5.7×10^{-1}	1.08
11C		15.0	0.47(0.41)	3.7×10^{-1}	1.32
11D		14.4	0.04(0.19)	3.5×10^{-1}	1.24
11E		12.2	0.40(0.33)	5.7×10^{-1}	1.06

[a]Period 1985-1996, except sites 8, 11 (1985-1992), 1B (1986-1996) and 4B, 4C (1988-1996).
[b]See Table 2 for multiple core locations.
[c]Units cm^3 H_2O yr^{-1}.
[d]Correlations computed parametrically (nonparametrically) using Pearson's r (Spearman rank order).
[e]$C = aM$, M is modeled precipitation and C is observed accumulation.

sites located near the 2000-m contour. Many sites are located in regions of the ice sheet where accumulation has not been measured previously. We compare these newly measured annual time series of accumulation to previously reported modeled precipitation [*Chen et al.*, 1997; *Bromwich et al.*, 1999] covering the same time range, with the focus more on comparison of interannual variability rather than on mean accumulation and precipitation rates.

2. Methods

2.1. Ice Cores

Shallow ice cores (5 to 25 m) were recovered from sites widely distributed around the ice sheet during the 1997 and 1998 field seasons (Table 1 and Figure 1). Multiple cores were collected at some sites to evaluate the impact of small-scale spatial variability in snow accumulation. The shallow cores typically span the last 10 to 30 years and were collected using a 10-cm (4-inch) hand auger with a power drill attachment. This device allows a small field team to collect a 20 m core in 2 to 5 hrs.

Each core was analyzed for four seasonally varying chemical species (hydrogen peroxide (H_2O_2), ammonium ion, calcium ion, nitrate) and liquid conductivity using the continuous melter system described by *Anklin et al.* [1998]. The seasonally varying concentrations of dust and oxygen isotopic ratios ($\delta^{18}O$) were analyzed for discrete samples cut continuously along each core. Beta radioactivity was measured in selected samples targeted to identify known time-stratigraphic horizons associated with atmospheric thermonuclear testing in the 1950s and 1960s. Annual layers were identified as illustrated by *Anklin et al.* [1998]. The annual firn thicknesses were converted to annual water equivalent using a depth-density model function consisting of a polynomial (of order varying between 3 and 5 for different cores) fit to the measured density data. Core densities were measured in the field and, for some cores, again in the laboratory with good agreement. Water equivalent accumulation for each year was calculated as the difference in water equivalent depth between appropriate annual markers. Annual water accumulation values for the deeper cores at sites 8 and 11 have been previously reported [*Anklin et al.*, 1998].

2.2. Precipitation Retrieval Method

A dynamic precipitation retrieval method using European Centre for Medium-Range Weather Forecasts (ECMWF) operational analyses has been developed and is described in detail by *Chen et al.* [1997] and *Chen and Bromwich* [1999]. The method efficiently and accurately computes vertical air motion over high mountain regions such as Greenland using the equivalent geopo-

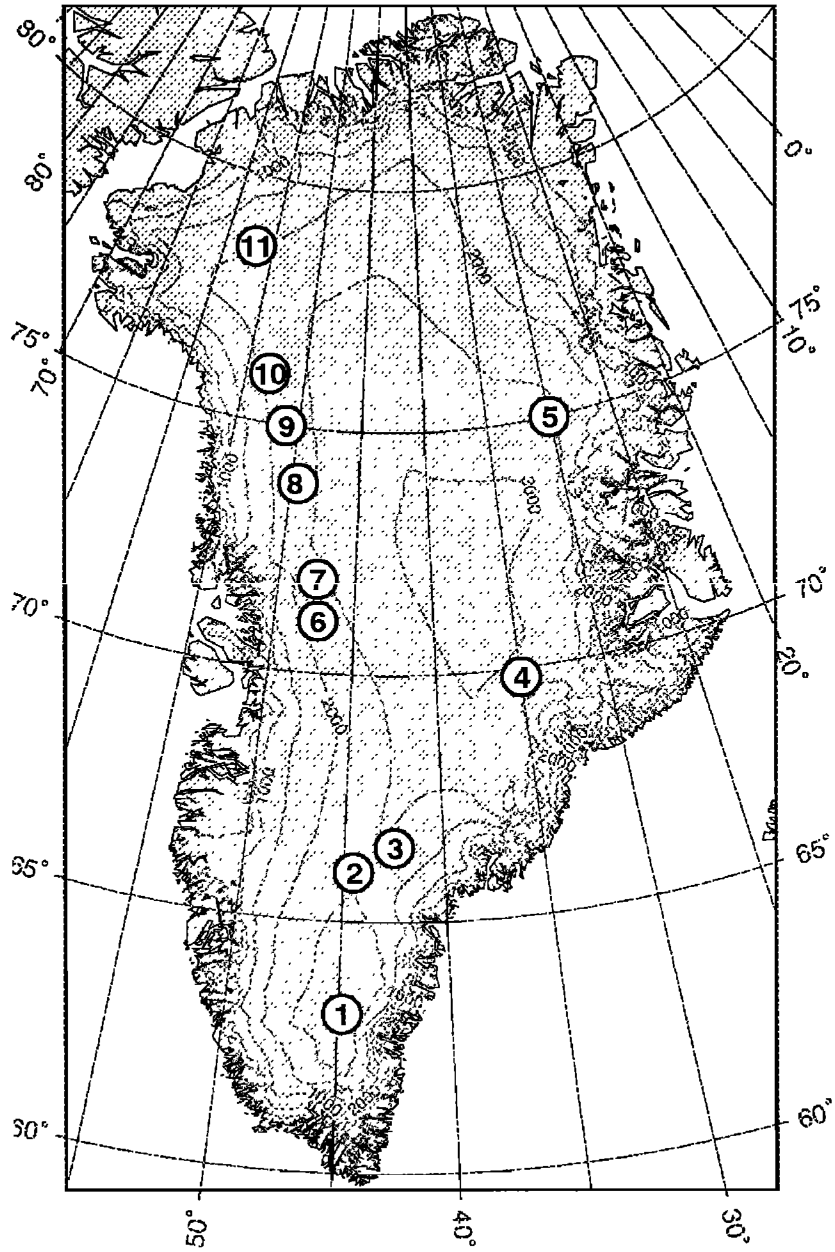

Figure 1. Elevation map of the Greenland Ice Sheet showing ice core locations along the 2000-m elevation contour.

tential in σ coordinates. The precipitation rate is derived based on the ECMWF-analyzed atmospheric data every 12 hours. A horizontal grid size of 50 km by 50 km is used, and the simulation period is currently 1985-1996. The grid-scale condensation is assumed to begin at a critical relative humidity of 85% [*Chen et al.*, 1997]. Choice of this threshold was based on comparisons of the modeled precipitation with accumulation analyses for the entire ice sheet or over large regions [e.g., *Ohmura and Reeh*, 1991; *Bender*, 1984; *Bolzan and Strobel*, 1994] and with observed winter precipitation amounts during 1987 and 1988 over Canada and the northern part of the United States. However, these large-scale accumulation syntheses for Greenland were based on accumulation data from many different time periods and regions. There is ample evidence that accumulation rates have varied substantially over recent decades and centuries and that rates are changing differently around the ice sheet [*Clausen et al.*, 1988; *Anklin et al.*, 1998]. Hence model development and validation requires accumulation measurements that are contemporaneous with the modeling and that are widely distributed around the ice sheet.

The timescale of accumulation variations from cores is long (year, decade, century) but the horizontal scale is small (e.g., 10 km). By contrast, the current meteorological model is developed for weather forecasting purposes, so that its timescale is short (day, week, month) but its horizontal scale is relatively large (hundreds of kilometers). For model enhancement, it is thus preferable to compare the modeled precipitation with areally averaged accumulation from ice cores distributed widely around the ice sheet. In this study, we emphasize interannual precipitation/accumulation variations that have relatively large length scales and defer the detailed (and much smaller scale) comparisons of modeled precipitation amounts with observed accumulation values to a subsequent analysis.

3. Results

Newly measured annual accumulation and previously reported modeled annual precipitation are shown in Figure 2. Simulated precipitation values from the model grid points closest to the core location were used [*Bromwich et al.*, 1998]. Parametric and nonparametric correlation coefficients between the model predictions and observations are given in Table 1 [*Press et al.*, 1992]. Note that in using linear correlation coefficients to com-

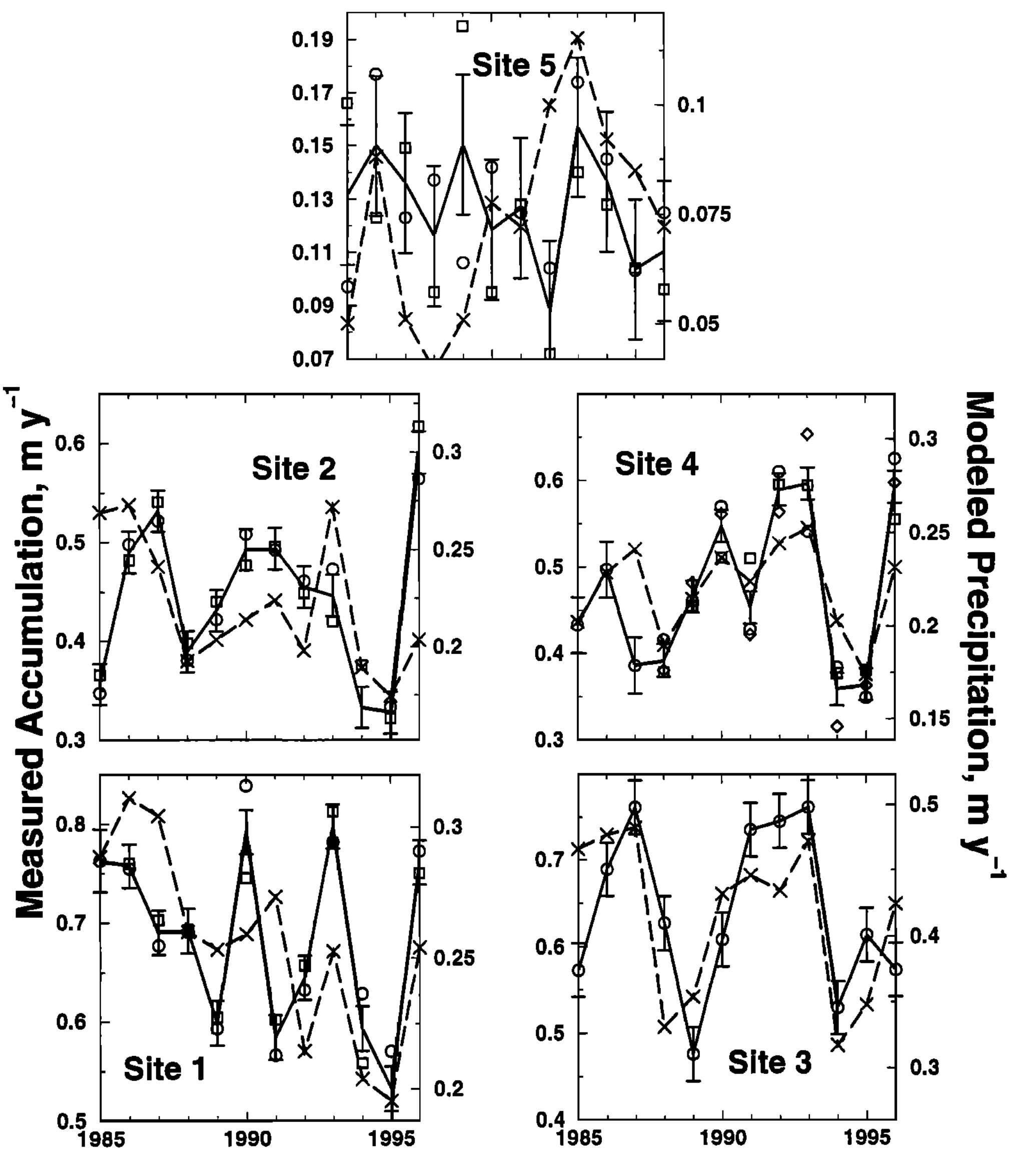

Figure 2. Modeled (dashed) precipitation and measured (solid) annual accumulation at (a) five southern and eastern locations and (b) six northern and western locations. At sites where multiple cores were collected (Table 1), individual core measurements are shown as symbols and the average as a line. Error bars represent 1 standard deviation of the expected short-scale spatial variability in accumulation (Table 2) and are scaled by $(\sqrt{n})^{-1}$ where n is the number of independent core accumulation measurements included in the annual accumulation estimate. Spatial variability at single-core site 3 was extrapolated from multiple-core sites 2 and 4. Similarly, the measured spatial variability from site 8 was assumed at single-core sites 6, 7, 9, and 10. The left and right vertical scales are proportional to the model scalers given in Table 1.

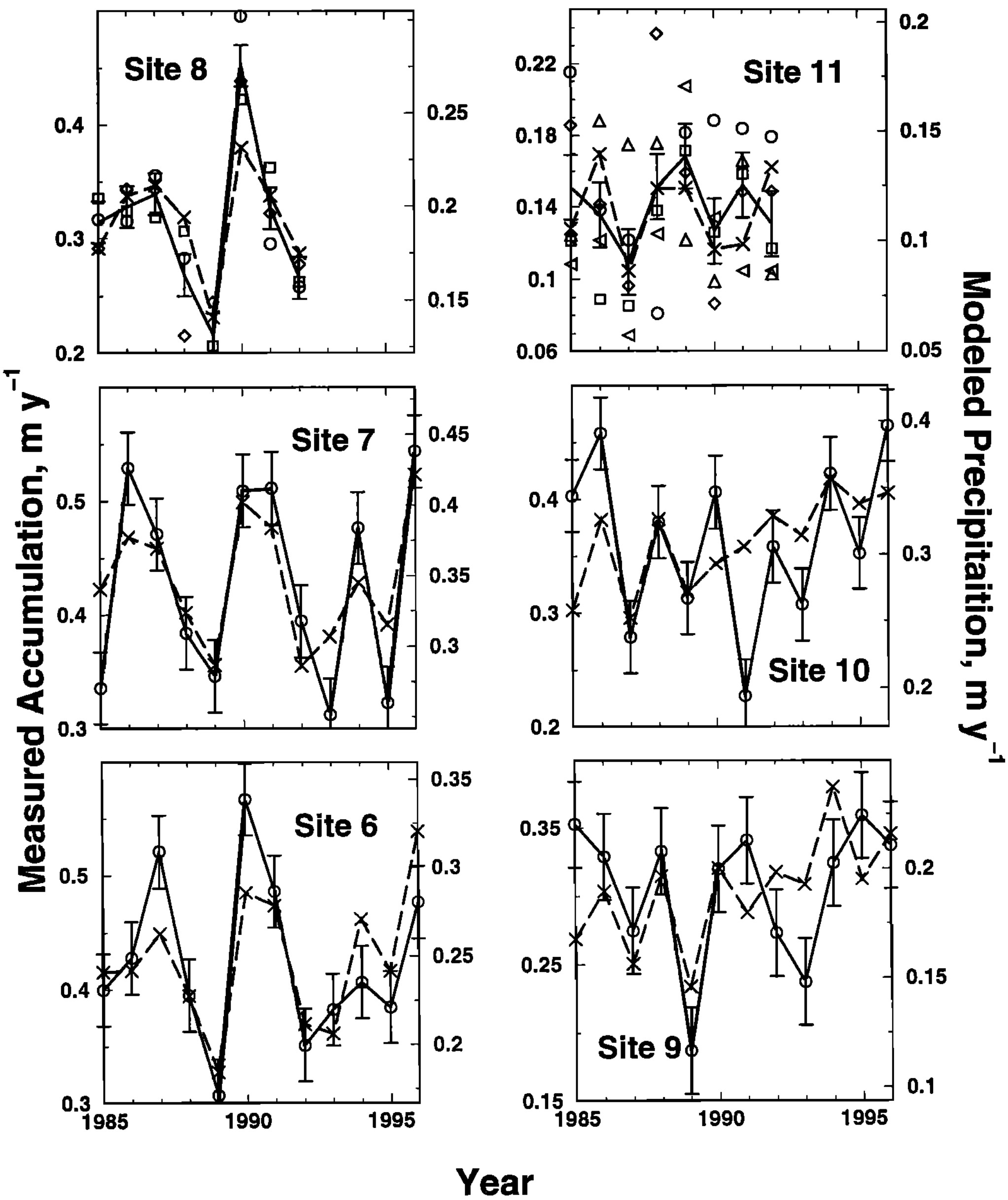

Figure 2. (continued)

pare model simulations of precipitation (M) to observations of net water-equivalent accumulation (C), we implicitly make use of a linear fitting function of the form $C = aM + b$ where a and b are free parameters. The primary focus of this study is on interannual variability so we evaluate agreement between the modeled precipitation and measured accumulation using a chi-square "goodness of fit" analysis of the form $C = aM$ with one free scaling parameter a (Table 1). At all core sites, a is greater than 1.0 (i.e., mean modeled precipitation was always lower than mean measured accumulation). Chi-square "goodness of fit" results (Table 1) show the probability that chi-square would exceed the measured value by chance. Probabilities greater than $\sim 1\times10^{-3}$ suggest agreement between the scaled model precipitation and the observed accumulation [*Press et al.*, 1992]. For the chi-square analysis, required estimates of uncertainty in the measured accumulation were derived from analyses of short-scale spatial variability in snow accumulation using adjacent core accumulation records as discussed below (Table 2). Error bars shown in Figure 2 represent one standard deviation of this expected short-scale spatial variability and are scaled by $(\sqrt{n})^{-1}$ where n is the number of independent core accumulation measurements included in the annual accumulation estimate. Note that the vertical scales in Figure 2 are proportional to the model scalers given in Table 1.

4. Discussion

Two aspects of the agreement between modeled precipitation and measured accumulation should be considered: average values and interannual variability. Visual inspection of the results shown in Figure 2 indi-

Table 2. Analysis of Small-Scale Spatial Variability

Site	Number of Cores	Years	Accumulation, cm yr^{-1}	Var(X), cm^2 yr^{-2}	Cross Correlation	Var(P), cm^2 yr^{-2}	Var(e), cm^2 yr^{-2}
1	2[a]	1986 – 1996	67.7	82.9	0.879	72.8	10.0
2	2[a]	1978 – 1996	45.3	67.8	0.870	59.0	8.8
4	3[a]	1988 – 1996	48.4	95.8	0.891	85.4	10.4
5	2[a]	1968 – 1996	14.6	16.9	0.183	3.1	13.8
8	3[b]	1965 – 1992	33.4	43.2	0.767	33.1	10.0
11	5[c]	1929 – 1992	14.1	17.1	0.049	0.9	16.2

[a]Cores located ~ 10 m apart.
[b]Core 8B located ~ 50 m from Core 8A, Core 8C ~ 2 km from Core 8A.
[c]Cores 11B, 11C, 11D, and 11E located ~ 25 km north, east, south, and west of Core 11A respectively.

cates that the model simulation is capturing much of the short-term temporal variability observed in the ice cores. The disagreement between annual average accumulation and simulated precipitation is consistent with previous comparisons between computed precipitation amounts and (noncontemporaneous) accumulation syntheses [*Bromwich et al., 1998*]. These revealed that precipitation is overpredicted in the southwest and southeast coastal regions and underpredicted in the inner region of Greenland, but with the island averages agreeing to within 10%. The cores from the 11 sites near the 2000-m contour reside within the inner region of Greenland. Preliminary analyses have shown that the elevation distribution of predicted precipitation can be improved by a refined choice of the threshold for the onset of grid-square condensation. In addition to the general underestimate of precipitation in the ice sheet interior, the accumulation-precipitation comparisons are influenced by precipitation and accumulation gradients that are often locally offset from one another, particularly near coastlines and ice divides. This leads to the large variability in model scalars and is clearly illustrated by *Bromwich et al.* [1998] for sites 6 and 7 by comparing the simulated precipitation map using the *Chen et al.* [1997] approach with the accumulation analysis. In order to quantify the regional biases in simulated precipitation, contemporaneous analyses of precipitation and accumulation are needed for the entire ice sheet. The present analysis is designed to examine the interannual variability of precipitation and accumulation that are characterized by large spatial scales.

Measurement errors increase uncertainty in the year-to-year results, but our multiparameter approach leaves little doubt as to the number of years in the shallow core records. Poor understanding of the timing of chemical and dust transport to a core site and transfer to the snow, and the sometimes low resolution of the annual cycle in core chemistry (e.g., a broad winter minimum in H_2O_2 and $\delta^{18}O$), can result in "years" of unequal length. That is, while every effort is made to identify the depths in the record that correspond to the same part of the year for each annual cycle, uncertainties in picking these depths may result in accumulation "years" of slightly different lengths. Errors in density measurements can have small effects on both the average and interannual accumulation estimates, particularly at shallow depths where core quality is often poor and density varies rapidly with depth.

Both parametric and nonparametric methods were used to determine correlations between the observed year-to-year accumulation and the modeled year-to-year precipitation (Table 1). Both methods produced similar correlation coefficients and for most cores were significant at the 70% to 90% probability level. However, spatial variability in snow accumulation at scales from centimeters to kilometers is superimposed upon the regional year-to-year variability [*McConnell et al.*, 1997; *Van der Veen*, 1993] and has perhaps the greatest effect on how well the measured accumulation values represent regional accumulation. One impact of spatial variability is a reduction in the degree to which a single firn or ice core record will reflect modeled regional accumulation (i.e., result in lower correlations between model results and observations).

To explore the potential effect of small-scale variability on annual accumulation records, adjacent cores were collected at 6 of the 11 sites (Table 2). Following *Fisher et al.* [1985], we assumed that variability in ice core accumulation record is caused both by a regional precipitation signal P(t) and a local, psuedo-random component e(t) from small-scale spatial variability in snow accumulation. For time series from two adjacent cores, $X(t)$ and $Y(t)$, $X(t) = P(t) + e_x(t)$ and $Y(t) = P(t) + e_y(t)$. Given the correlation coefficient between X and Y, r_{xy}, then the total variance can be separated into signal and noise components by $Var(P) = r_{xy}Var(X)$ and $Var(e_x) = (1-r_{xy})Var(X)$. Note that this separation of variance differs from the case where one time series contains a noise-free signal [*Fisher et al.*, 1985]. Estimates of temporal and spatial variability at those sites where multiple cores were collected are given in Table 2. Where more than two cores were collected, all possible r_{xy} values were averaged and used to compute $Var(P)$ and $Var(e)$ from the average of the individual core variances. At four of the sites (1, 2, 4, and 5), the cores were located about 10 m apart so the computed spatial variability, $Var(e)$, represents only very local spatial variability in snow accumulation.

At site 11, however, shallow cores were collected 25 km to the north, east, south, and west of the deep drill site so the computed spatial variability is more representative of the variability expected within the 50 km by 50 km precipitation model grid cell. Note that except for site 11, these estimates are limited by the relatively short periods of record and small numbers of cores at each site.

As shown in Table 2, temporal variability is much larger than the computed spatial variability at sites 1, 2, 4, and 8, so correlations between simulated regional precipitation and local observations should be relatively high. Conversely, at the lower accumulation sites (5 and 11), spatial variability is much greater than the temporal variability and correlations should be low. In addition, if comparisons between model simulations and observations are short, then correlations between them will show large variability.

Both spatial variability and the short ~12-year model simulation period impact the comparison of scaled model precipitation and observed accumulation. These effects are indicated by the chi-square "goodness of fit" probabilities (Table 1). For this analysis it was assumed that the scaled precipitation record from the model simulation represents the "true," noise-free regional precipitation. An icecore accumulation record contains both this "true" precipitation component and a psuedo-random spatial variability component, $Var(e)$, estimated from the analysis of adjacent core records Spatial variability values at those sites where only a single core was collected were extrapolated from the nearest multiple-core sites (Table 2). Note that estimated spatial variabilities at multiple-core sites with relatively high accumulation rates (~30-70 cm yr^{-1}) are similar and of the order of 10 cm^2 yr^{-2} so extrapolation to single-core sites with similar accumulation rates is not unreasonable. Chi-square probabilities range from a high of 5.7×10^{-1} at sites 11B and 11E to a low of 2.1×10^{-20} at site 2B. Following *Press et al.* [1992], we assume that probabilities greater than ~ 1×10^{-3} indicate acceptable agreement between the scaled model simulations and observations. Such a relatively low threshold is justified for situations where the expected uncertainties in the accumulation record may not be normally distributed, and non-normal distributions in annual layer thickness and spatial variability in accumulation in Antarctica have been reported [*Hogan and Gow*, 1997; *McConnell et al.*, 1997; *Van der Veen et al.*, 1999]. Chi-square test probabilities indicate agreement between the linearly scaled model results and observations at sites 4, 5, 6, 7, 8, 9 and 11.

We emphasize that the spatial variability estimated at most of the sites is based on analyses of cores located approximately 10 m apart so the spatial variability that is likely to be found over the 50 km by 50 km model grid is undoubtedly larger than estimated. Use of larger spatial variability estimates would increase the reported chi-square probabilities. Comparison of the linearly scaled model results and observations in this way is very stringent. For example, the chi-squared probability at site 3 is 7.7×10^{-11}, well below the threshold of ~ 1×10^{-3}, suggesting that the model is not satisfactorily predicting accumulation. However, as is shown in Figure 2a, the scaled model simulation is clearly capturing most of the temporal variability in the observed accumulation record. The chi-square probability is low because the simulated precipitation record shows very large temporal variability and the spatial variability extrapolated from nearby multiple-core sites is small.

While the scaled model precipitation results are in agreement with observations at some sites, they are not in agreement at other sites. One possible explanation at single-core sites that failed the chi-square test (sites 3 and 10) is that the estimated spatial variability term $Var(e_x)$ is too small, perhaps because of greater windiness at these sites that leads to enhanced spatial variability [*McConnell et al.*, 1997]. Of the sites with multiple core records and so directly measured spatial variabilities (sites 1 and 2), both are on or very near the ice divide where modeling is especially difficult because of large spatial gradients in accumulation that can vary substantially from year to year.

5. Conclusions

Within acceptable statistical limits, good agreement was found at 7 of 11 shallow-core sites in Greenland along the 2000-m elevation contour between interannual variations of measured net water-equivalent accumulation and contemporaneous modeled simulations of precipitation after scaling. As in earlier studies, the precipitation model was found to underpredict accumulation in the interior of the Greenland Ice Sheet, resulting in the need for scalers to match mean simulated precipitation and mean observed accumulation at all core sites. The requirement for these scalers and the low correspondence between simulations and observations at some sites clearly indicates that improvements to the precipitation model are necessary. We emphasize that the time scales and length scales of the precipitation model are not consistent with the time scales and length scales of localized accumulation measurements. Thus, areally averaged, interannual accumulation measurements from many more spatially distributed cores that are contemporaneous with modeling are preferable for continued model improvement and validation. The demonstrated impact of spatial noise on accumulation records reiterates the value of collecting replicate cores. In agreement with earlier studies [*Van der Veen*, 1993], the large temporal variability in snow accumulation predicted by modeling and confirmed by the ice cores (1σ deviation of up to 9 cm yr^{-1} of net water-equivalent accumulation at site 3) indicates that from year to year, the ice sheet elevation varies by tens of centimeters simply from changing accumulation. Estimates of ice sheet thickening or thinning that are based on ice sheet elevation observations with short repeat times [*Thomas et al.*, 1998; *Krabill et al.*, 1999] will have large uncertainty, and trends may be masked unless placed within the context of temporally and spatially varying accumulation. It is hoped that once they are well parameterized and the results validated using contemporaneous and widely distributed ice core accumulation measurements such as those reported here, precipitation models will provide the needed spatial and temporal context in which to interpret ice sheet elevation measurements.

Acknowledgments. This research was supported by the National Aeronautics and Space Administration under grants NAG5-5031 and 6779 to University of Arizona and NAG5-5032, 6817 and 6001 to OSU. We acknowledge the contributions of individuals who participated in field programs. J. Burkhart, M. Davis, Z. Li, and B. Snider assisted in the core analyses. Q.-S. Chen and Y. Li provided the model output.

References

Abdalati, W., R. Bales, and R. Thomas, Program for Arctic Regional Climate Assessment: An improved understanding of the Greenland ice sheet, *Arctic Res. U. S., 12*, 38-54, 1998.

Anklin, M., R. C. Bales, E. Mosley-Thompson, and K. Steffen, Annual accumulation at two sites in northwest Greenland during recent centuries, *J. Geophys. Res., 103*, 28,775-28,783, 1998.

Bender, G., The distribution of snow accumulation on the Greenland Ice Sheet, M.S. thesis, 110 pp., Geophys. Inst., Univ. of Alaska, Fairbanks, 1984.

Bolzan, J. F., and M. Strobel, Accumulation rate variations around Summit, Greenland, *J. Glaciol., 40*, 56-66, 1994.

Bromwich, D. H., R. I. Cullather, Q.-S. Chen, and B. M. Csathó, Evaluation of recent precipitation studies for Greenland Ice Sheet, *J. Geophys. Res., 103*, 26,007-26,024, 1998.

Bromwich, D. H., Q.-S. Chen, Y. Li, and R. I. Cullather, Precipitation over Greenland and its relation to the North Atlantic oscillation, *J. Geophys. Res., 104*, 22,103-22,115, 1999.

Chen, Q.-S., and D. H. Bromwich, An equivalent isobaric geopotential height and its application to synoptic analysis and to a generalized ω-equation in σ-coordinates, *Mon. Weather Rev., 127*, 145-172, 1999.

Chen, Q.-S., D. H. Bromwich, and L. Bai, Precipitation over Greenland retrieved by a dynamic method and its relation to cyclonic activity, *J. Clim., 10*, 839-870, 1997.

Clausen, H. B., N. S. Gundestrup, S. J. Johnsen, R. Bindschadler, and H. J. Zwally, Glaciological investigations in the Crete area, central Greenland: A search for a new deep-drilling site, *Ann. Glaciol., 10*, 10-15, 1988.

Fisher, D. A., N. Reeh, and H. B. Clausen, Stratigraphic noise in time series derived from ice cores, *Ann. Glaciol., 7*, 76-83, 1985.

Hogan, A. W., and A. J. Gow, Occurrence frequency of thickness of annual snow accumulation layers at South Pole, *J. Geophys. Res., 102*, 14,021-14,027, 1997.

Krabill, W., E. Frederick, S. Manizade, C. Martin, J. Sontag, R. Swift, R. Thomas, W. Wright, and J. Yungel, Rapid thinning of parts of the southern Greenland ice sheet, *Science, 283*, 1522-1524, 1999.

McConnell, J. R., R. C. Bales, and D. R. Davis, Recent intra-annual snow accumulation at South Pole: Implications for ice core interpretation, *J. Geophys. Res., 102*, 21,947-21,954, 1997.

Ohmura, A., and N. Reeh, New precipitation and accumulation maps for Greenland, *J. Glaciol., 37*, 140-148, 1991.

Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes, The Art of Scientific Computing, 2nd ed.*, 932 pp., Cambridge Univ. Press, New York, 1992.

Thomas, R. H., B. M. Csathó, S. Gogineni, K. C. Jezek, and K. Kuivinen, Thickening of the western part of the Greenland Ice Sheet, *J. Glaciol., 44*, 653-658, 1998.

Van der Veen, C. J., Interpretation of short-term ice-sheet elevation changes inferred from satellite altimetry, *Clim. Change, 23*, 383-405, 1993.

Van der Veen, C. J., I. M Whillans, and A. J. Gow, On the frequency distribution of net annual snow accumulation at South Pole, *Geophys. Res. Lett., 26*(2), 239-242, 1999.

J. R. McConnell, Desert Research Institute, 2215 Raggio Pkwy, Reno, NV 89512. (jmcconn@dri.edu)

D. H. Bromwich and E. Mosley-Thompson, Byrd Polar Research Center, Ohio State University, 1090 Carmack Rd, Columbus, OH 43210-1002. (bromwich@polarmet1.mps.ohio-state.edu; thompson.4@osu.edu)

R. C. Bales, Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ 85721-0011. (roger@hwr.arizona.edu)

J. D. Kyne, Polar Ice Coring Office, University of Nebraska, 2255 W St., Suite 101, Lincoln, NE 68583-0850. (jkyne@unlinfo.unl.edu)

(Received April 21, 1999; revised August 23, 1999; accepted September 29, 1999.)