Observed and Modeled Greenland Ice Sheet Snow Accumulation, 1958–2003, and Links with Regional Climate Forcing

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ABSTRACT

Annual and monthly snow accumulation for the Greenland Ice Sheet was derived from ECMWF forecasts [mainly 40-yr ECMWR Re-Analysis (ERA-40)] and further meteorological modeling. Modeled accumulation was validated using 58 ice core accumulation datasets across the ice sheet and was found to be 95% of the observed accumulation on average, with a mean correlation of 0.53 between modeled and observed. Many of the ice core datasets are new and are presented here for the first time. Central and northern interior parts of the ice sheet were found to be ~10%–30% too dry in ERA-40, in line with earlier ECMWF analysis, although too much (>50% locally) snow accumulation was modeled for interior southern parts of Greenland. Nevertheless, 47 of 58 sites show significant correlation in temporal variability of modeled with observed accumulation. The model also captures the absolute amount of snow accumulation at several sites, most notably Das1 and Das2 in southeast Greenland. Mean modeled accumulation over the ice sheet was 0.279 (standard deviation 0.034) m yr^{-1} for 1958–2003 with no significant trend for either the ice sheet or any of the core sites. Unusually high accumulation in southeast Greenland in 2002/03 leads the authors to study meteorological synoptic forcing patterns and comment on the prospect of enhanced climate variability leading to more such events as a result of global warming. There is good agreement between precipitation measured at coastal meteorological stations in southern Greenland and accumulation modeled for adjacent regions of the ice sheet. There is no significant persistent relation between the North Atlantic Oscillation index and whole or southern Greenland accumulation.

1. Introduction

Meteorologists and ice sheet modelers have eagerly been awaiting the production of the new 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40). This reanalysis consists of a global climatological time series of model-consistent data generated by a numerical weather prediction model run retrospectively, feeding in all available observations to a three-dimensional variational data assimilation (3DVAR) system (Simmons and Gibson 2000; Kållberg et al. 2004). ERA-40 covers the period 1957–2001 and can be used, in principle, to study climatic characteristics, variability, and change for the past few decades over hitherto inaccessible parts of the earth's surface, where, for example, traditional meteo-

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rological observations may be relatively few or records unreliable and/or broken. This is subject to some caveats—most notably that in the same regions where the reanalysis model is least constrained by observations, any shortcomings—weaknesses and biases in the model—will be most revealed.

Here we investigate Greenland snow accumulation (here defined as snowy precipitation minus evaporation and sublimation), which is the main mass input to the Greenland Ice Sheet (GrIS). Variations in snow accumulation are critical for governing surface mass balance of the GrIS (Hanna et al. 2002). We focus on accumulation in southeast (SE) and southwest (SW) Greenland, because these are two key regions of largest annual accumulation (Bales et al. 2001; Hanna et al. 2001; Ohmura et al. 1999) at the forefront of interaction of their ice surfaces and mass budgets with the atmosphere and ocean. We focus on winter 2002/03, as this was an unusually high accumulation year in SE Greenland (section 4a). We consider possible influences of changes in atmospheric circulation, denoted by the North Atlantic Oscillation (NAO) index (Hurrell 1995), on Greenland accumulation, which may be enlightening on processes affecting ice sheet mass balance and possibly prove useful for helping predict the GrIS likely future behavior based on the results of general circulation model (GCM) output. The main mass-loss process, surface meltwater runoff, is treated in a separate paper (Hanna et al. 2005). Modeled snow accumulation depends principally on precipitation and surface air temperature. How accurate and reliable is ERA-40-modeled snow accumulation? The best way of determining this is by validation with independent in situ data. Many meteorological observations are already fed into ERA-40 to help produce its forecast snowfall, but in Greenland observations are rather sparse and come almost entirely from Danish Meteorological Institute (DMI) stations around the coast, which may well experience a different climate compared to the interior of the ice sheet. Moreover, precipitation data from the DMI stations cannot strictly be used to validate modeled accumulation because, through their use in ERA-40, they are not a truly independent measure. However, they can still reasonably be used as a basis for comparison, as is done later. Newly available ice core data from sites well distributed around the ice sheet are fully independent and therefore extremely useful for helping validate/tune ERA-40-based simulations of the ice sheet's mass balance.

2. ERA-40-derived snow accumulation

Two-meter surface air temperature (SAT2), snowfall (i.e., snowy precipitation that reaches the surface), and surface latent heat flux from ERA-40 reanalysis, 1958–2001, and later ECMWF operational analyses from 2002 and 2003, were obtained from the British Atmospheric Data Center (BADC) on a 0.5° latitude by 0.5° longitude Greenland area grid. Gridpoint values were bilinearly interpolated from the original N80 reduced Gaussian grid (http://www.ecmwf.int/products/data/technical/gaussian/n80FIS.html). Geopotential or surface heights in the ECMWF model are based on the definitive Ekholm orography (Ekholm 1996), but this is typically several hundred meters in error over large parts of outer Greenland due to relatively low model resolution and spectral ripples in the model. SAT2 and snow accumulation are greatest in outermost parts of Greenland, so any errors are most significant here. In line with earlier work, we adjusted SAT2 for orography errors using the height difference between the ECMWF model orography and a definitive digital elevation model (DEM) and an assumed lapse rate of -8 K km^{-1} (Hanna et al. 2001, 2002). Here we used empirically derived lapse rates[1] and an updated DEM provided by P. Huybrechts (an improved version of the Ekholm orography, provided on an ~5 km × 5 km polar stereographic grid). Moreover, in the current work we compared heights and adjusted SAT2 at the DEM resolution, effectively downscaling the SAT2 fields to a resolution of 5 km × 5 km. This allows much better for variations in topography around the edges of the GrIS, so corrected temperature fields should be more accurate.

Snowfall was taken directly from ERA-40 and later ECMWF analysis forecast fields but, in line with SAT2, was extrapolated using fuzzy interpolation to the ~5 km × 5 km polar stereographic grid. The ECMWF calculates snowfall using an explicit equation for cloud condensate and the fraction of ice and water in the latter, which depends on cloud temperature (http://www.ecmwf.int/research/ifsdocs_old/PHYSICS/Chap6_Clouds2.html#959602). Tiedtke (1993) and Gregory et al. (2000) discuss the representation of clouds and convection in the ECMWF analyses. Snow can then melt and evaporate as it falls through lower model levels to reach the surface. Melt rates depend on layer temperature (depending on the vertical temperature profile, surface snowfall is possible with a positive surface air temperature if the intensity of melting in the atmosphere is not high enough). Surface latent heat flux was used together with the latent heats of vapor-

[1] Regression fitting of ERA-40 − surface station SAT2 differences vs ERA-40 − surface station height differences yielded -8 K km^{-1} at elevations >1000 m and -6 K km^{-1} ≤ 1000 m.

FIG. 1. Locations of ice core sites used in the study. Note the Greenland Ice Sheet (shaded) and elevation contours in meters.

ization and sublimation to calculate evaporation and sublimation where SAT2 was, respectively, >0° or ≤0°C. Evaporation and sublimation were then deducted from snowfall to derive a "net" snow accumulation (Hanna et al. 2001, 2002). This was done on a 6-hourly basis from which monthly and annual-mean snow accumulation were calculated. Modeled annual accumulation should be directly comparable with annual accumulation retrieved from ice cores.

3. Validation of modeled accumulation

Figure 1 shows the sites of 58 ice cores collected by National Aeronautics and Space Administration's (NASA's) Program in Arctic Regional Climate Assessment (PARCA) since 1995. These sites are quite well distributed across the GrIS and include 12 cores collected during the summer 2003 field season. Some of the other core data used here were previously reported in McConnell et al. (2001). Table 1 summarizes ice core location, elevation, and period of records. Annual accumulation observed in the cores is generally selected based on the H_2O_2 winter minima within the ice cores, or else the winter sea salt maximum, both of which probably occur within about a month of 1 January. To evaluate small-scale variability of snow accumulation, multiple cores were collected at Humboldt (five total), Nasaea (two total), Nasau (three total), Saddlea (two total), Sandya/Summit (three total), Sdomea (two total), and Stunua (three total) (McConnell et al. 2000). Glaciological noise adds a random uncertainty with ~0.031 m yr^{-1} standard deviation to a measurement of accumulation for a single year in an ice core, shown by recent ice core collections from Greenland, the South Pole, and Siple Dome (West Antarctica) (McConnell et al. 2000).

Table 2 shows mean annual accumulation (MAA) from the cores and our ERA-40-based model and, also, standard deviations and trends for observed and modeled accumulation for common comparison periods. Nearly all sites are >2000 m elevation, so it is a reasonable assumption that there is no significant runoff (export of melt water) at these sites (Janssens and Huybrechts 2000).

We spatially depict the results of direct comparison of modeled and observed accumulation in Fig. 2. This figure shows model/core ratios and model-core–correlation coefficients at each of the core sites. There was an average model/core ratio of 0.95, and an average correlation of $r = 0.53$ between modeled and observed accumulation. Mean accumulation for all sites was 0.431 m yr^{-1} (modeled) and 0.456 m yr^{-1} (observed). This means that on average our accumulation model

TABLE 1. Location, elevation, and period of record of Greenland ice cores used in this study. Elevations interpolated from J. Bamber's very high spatial resolution digital elevation model (DEM; Bamber et al. 2001).

Site	Lat (°)	Lon (°)	Elevation (m)	Period of record
6345	63.8	−45	2729	1977–97
6642	66.5	−42.5	2384	1982–97
6745	67.5	−45	2200	1984–97
6839	68.5	−39.5	2782	1985–97
6841	68	−41	2636	1987–97
6938	69	−38	2944	1983–97
6939	69.6	−39	2949	1982–97
6941	69.4	−41	2758	1985–97
6943	69.2	−43	2492	1977–97
6945	69	−45	2147	1977–97
7145	71.5	−45	2621	1986–97
7147	71.1	−47.2	2182	1974–96
7245	72.2	−45	2748	1984–97
7247	71.9	−47.5	2363	1974–96
7249	72.2	−49.4	2166	1991–7
7345	73	−45	2810	1975–97
7551	75	−51	2224	1965–96
7653	76	−53	2158	1977–96
Basin 1	71.8	−42.4	2916	1976–2002
Basin 2	68.3	−44.8	2171	1980–2002
Basin 4	62.3	−46.3	2300	1969–2002
Basin 5	63.9	−46.4	2472	1964–2002
Basin 6	67	−41.7	2416	1983–2002
Basin 7	67.5	−40.4	2443	1983–2002
Basin 8	69.8	−36.4	2970	1958–2002
Basin 9	65	−44.9	2599	1958–2002
cnp1	73.2	−32.1	2951	1958–98
cnp2	71.9	−32.4	2749	1960–98
cnp3	70.5	−33.5	2923	1964–98
cp1	69.8	−47.1	1913	1984–98
crawpt	69.8	−47.1	1913	1982–94
d1	64.5	−43.5	2580	1958–98
d2	71.8	−46.2	2534	1958–98
d3	68.9	−44	2433	1958–98
d5	68.5	−42.9	2469	1970–2002
das1	66	−44	2499	1958–2002
das2	67.5	−36.1	2967	1958–2002
dye2b	66	−46	2238	1958–97
dye3	65.2	−43.9	2481	1976–98
gits	71.1	−61	1877	1958–95
humboldt	78.5	−56.8	1961	1958–94
jav2	72.6	−47.1	2608	1968–98
jav3	70.5	−46.1	2256	1981–98
kul1	67.5	−39	2409	1975–98
kul2	66.8	−40.1	2103	1989–98
kul3	66.1	−41	1947	1989–98
nasaea	75	−30	2601	1964–96
nasau	73.8	−49.5	2327	1958–94
saddlea	66	−44.5	2451	1976–96
sandya	72.5	−38.3	3209	1958–2002
sdo2	63.1	−46.4	2662	1980–98
sdomea	63.2	−44.8	2862	1978–96
stunua	69.8	−35	2871	1976–96
uak1	65.5	−44.5	2516	1958–98
uak2	65.5	−43.5	2351	1984–98
uak3	65.5	−42.6	2109	1989–98
uak4	65.5	−46.1	2344	1977–98
uak5	65.4	−46.5	2266	1978–98

TABLE 2. MAA (m yr^{-1}) from ice cores and ECMWF-based modeling. Note the random uncertainty of ~0.03 m yr^{-1} in ice-core-measured accumulation. Also shown are standard deviations and, for records ≥30 yr, underlying least squares linear regression trend line changes. See Table 1 for details of comparison periods.

	Mean	Mean	Std dev	Std dev	Trend	Trend
Site	Core	ECMWF	Core	ECMWF	Core	ECMWF
6345	0.325	0.682	0.066	0.117		
6642	0.635	0.658	0.128	0.132		
6745	0.361	0.335	0.085	0.065		
6839	0.385	0.361	0.091	0.069		
6841	0.475	0.386	0.099	0.072		
6938	0.359	0.304	0.062	0.063		
6939	0.334	0.267	0.055	0.047		
6941	0.384	0.297	0.072	0.050		
6943	0.402	0.338	0.087	0.059		
6945	0.445	0.351	0.104	0.070		
7145	0.429	0.354	0.072	0.057		
7147	0.425	0.364	0.076	0.066		
7245	0.361	0.310	0.048	0.050		
7247	0.428	0.352	0.074	0.061		
7249	0.952	0.313	0.208	0.059		
7345	0.289	0.251	0.047	0.040		
7551	0.326	0.307	0.054	0.055	−0.068	0.015
7653	0.348	0.325	0.067	0.057		
basin 1	0.363	0.271	0.057	0.042		
basin 2	0.378	0.337	0.114	0.066		
Basin 4	0.411	0.678	0.154	0.107	0.042	−0.030
Basin 5	0.346	0.499	0.082	0.078	−0.040	−0.008
Basin 6	0.657	0.601	0.096	0.119		
Basin 7	0.650	0.522	0.078	0.104		
Basin 8	0.353	0.262	0.072	0.060	0.052	0.041
Basin 9	0.359	0.513	0.078	0.090	−0.004	0.015
cnp1	0.145	0.112	0.048	0.032	0.017	0.018
cnp2	0.223	0.147	0.062	0.043	−0.014	0.029
cnp3	0.269	0.251	0.053	0.064	0.059	0.037
cp1	0.358	0.331	0.136	0.071		
Crawpt	0.473	0.331	0.156	0.071		
d1	0.766	0.938	0.136	0.193	−0.035	0.046
d2	0.450	0.344	0.078	0.057	0.002	0.019
d3	0.414	0.343	0.068	0.065	−0.003	0.038
d5	0.383	0.342	0.077	0.061	0.045	0.012
das1	0.604	0.574	0.091	0.107	0.024	0.034
das2	0.809	0.804	0.188	0.209	0.076	0.037
dye2b	0.358	0.359	0.120	0.065	0.183	0.069
dye3	0.489	0.737	0.070	0.146		
Gits	0.346	0.340	0.078	0.064	−0.074	0.066
Humboldt	0.148	0.139	0.047	0.031	0.028	0.041
jav2	0.388	0.318	0.061	0.055	0.012	−0.005
jav3	0.396	0.365	0.084	0.067		
kul1	0.520	0.597	0.161	0.130		
kul2	0.840	0.743	0.183	0.164		
kul3	1.111	0.923	0.370	0.215		
nasaea	0.142	0.094	0.035	0.032	−0.022	0.024
nasau	0.344	0.296	0.074	0.055		
saddlea	0.447	0.506	0.082	0.090		
sandya	0.230	0.154	0.054	0.023	0.031	0.018
sdo2	0.533	0.622	0.155	0.096		
Sdomea	0.671	0.796	0.119	0.117		
stunua	0.476	0.297	0.099	0.078		
uak1	0.474	0.572	0.079	0.105	−0.034	0.055
uak2	0.684	0.751	0.127	0.155		
uak3	1.040	0.886	0.347	0.197		
uak4	0.363	0.386	0.117	0.067		
uak5	0.382	0.377	0.118	0.068		

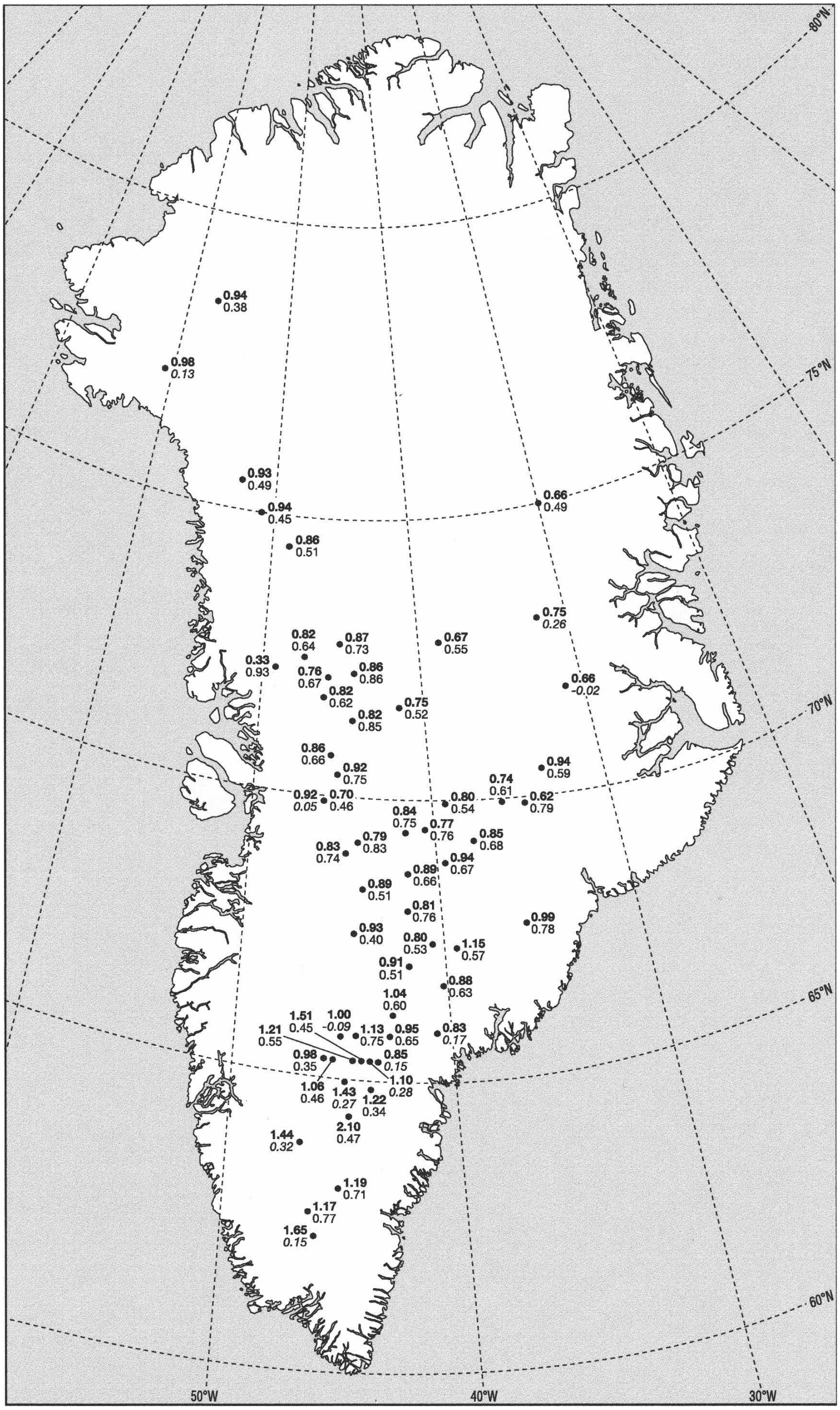


Fig. 2. (top) MAA ratios (ECMWF modeled/core) and (bottom) model–core annual accumulation correlation coefficients at the sites shown in Fig. 1. Nonsignificant correlations for 11 core sites are italicized.

slightly underestimates accumulation across the GrIS, but we regard being within 5% as a quite good result since it is no greater than the uncertainty expressed in the Intergovermental Panel on Climate Change estimates of GrIS accumulation (Church et al. 2001). However, the model tends to overestimate accumulation by 17%–65% in interior southern Greenland [but by 110% at site 6345 (near South Dome)]. On the other hand, the model yields 67%–92% of observed accumulation for more central Greenland areas (including 67% of observed MAA at Summit). Essentially, our ERA-40-based accumulation shares a common feature with earlier ECMWF-based models in being too dry for much of the interior plateau, except in the south where it is too wet. Misrepresentation of the Ekholm orography in the ECMWF model may be partly responsible here, although it is very difficult to correct for and it is probably not the full answer. Mean standard deviations were 0.102 and 0.084 m yr^{-1} for observed and modeled accumulation, respectively, probably reflecting greater spatial variability inherent in the core measurements, which are almost all representative of a much smaller area than an ECMWF grid point.

The mean model–core interannual accumulation correlation of 0.53 is statistically highly significant (1% significance level) given the average core record length (therefore a core–model comparison period) of ~26 yr. There is quite a large variation between individual core sites, with no apparent correlation at a few sites (e.g., $r = -0.02$ at *cnp2* in central eastern Greenland) but 47 of 58 sites are significantly correlated ($p < 0.05$). Sites with poor modeled–observed accumulation correlation are concentrated in southern Greenland, in east-northeast (ENE) and in northwest (NW) Greenland. Higher-correlation sites tend to be in more central areas. Comparative modeled–observed 1958–2003 annual accumulation histories for three well-separated core sites—Das1 (central southern Greenland), Das2 (in the near-coastal SE mountains), and Sandya (central Greenland)—are shown in Fig. 3. They reveal excellent agreement between observed and modeled accumulation for these three newly drilled cores. We can be fairly certain that common peaks in modeled and observed accumulation in these graphs in particular are due to real meteorological events, not artifacts in the model.

Least squares linear regression line changes (modeled and observed accumulation) were calculated for 21 sites with ≥30 yr ice core records (Table 2). These reveal no evidence of statistically significant underlying trends at any of the 21 core sites. This suggests that there has been no significant change in accumulation of the GrIS over the past few decades.

4. Snow accumulation over the Greenland Ice Sheet, 1958–2003

Mean annual snow accumulation from ECMWF-based modeling for various periods for the GrIS is shown in Table 3. Corresponding values for $P - E$, total precipitation (large-scale plus convective) minus evaporation and sublimation, are also shown. The main difference why these values are greater is that they include rain as well as snowfall. Our overall MAA estimate of 0.279 m yr^{-1} for the ice sheet is very close to a previous estimate of 0.287 m yr^{-1} from a precursor modeling study using ECMWF operational analyses (Hanna et al. 2002). However, that study used a considerably lower resolution and poorer ice mask. Our present estimate is also reassuringly close to accumulation estimates based on analysis of ice core records of 0.297 (Ohmura et al. 1999) and 0.300 m yr^{-1} (Bales et al. 2001).

Interannual variability in modeled accumulation and $P - E$ is best defined by the respective standard deviations, which work out at 0.033 and 0.041 m yr^{-1} or ~13% and 12%, respectively. Therefore, on the basis of the values presented in Table 3, there has been no significant trend in GrIS accumulation or $P - E$ over the past few decades. There is no significant statistical relation between whole Greenland winter [December–March (DJFM)] precipitation or accumulation and the winter NAO index ($r = 0.13$); the same is true of smoothed (5-yr running mean) versions of these series.

a. SE Greenland

Accumulation rates in SE Greenland tend to be high due to prevailing easterly winds, frequent cyclogenesis in and around Fram Strait, the relatively low latitude, relatively high moisture availability from source air often originating over a warm ocean, and most importantly orographic enhancement against the steep near-coastal mountains, which steeply rise to >2000 m. Mean annual precipitation may commonly reach ≥1–2 m yr^{-1} in the southeast Greenland mountains (Cappelen et al. 2001; Ohmura et al. 1999) (Fig. 4a). Our SE Greenland model domain (latitude <67°N, longitude <45°W; latitude 67°–70°N, longitude <40°W) (Fig. 1) has 0.675 m yr^{-1} MAA (1958–2003), with a standard deviation of 0.136 m yr^{-1} or 20%. Actual values range from 0.357 m yr^{-1} in 1966 to 1.033 m yr^{-1} in 1972 (Fig. 5a). Mean monthly modeled accumulation ranges from 0.018 m yr^{-1} in July to 0.091 m yr^{-1} in January, reflecting the more active winter midlatitude jet stream and vigorous winter cyclones clipping SE Greenland.

Southeast Greenland winter accumulation is significantly correlated with 04360 Tasiilaq (Ammassalik)

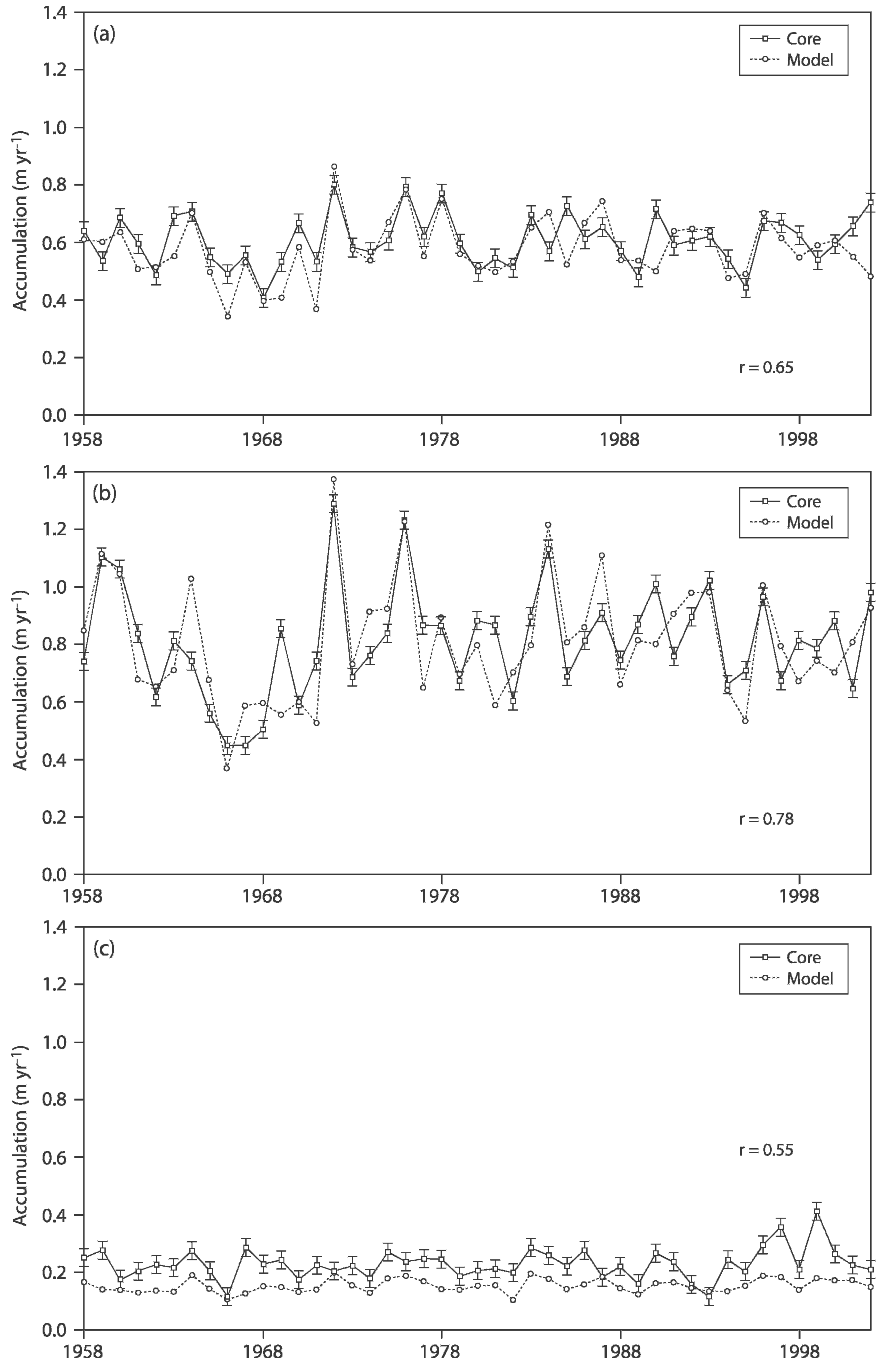


Fig. 3. Accumulation for (a) Das1, (b) Das2, and (c) Sandya from ice core and ECMWF analyses.

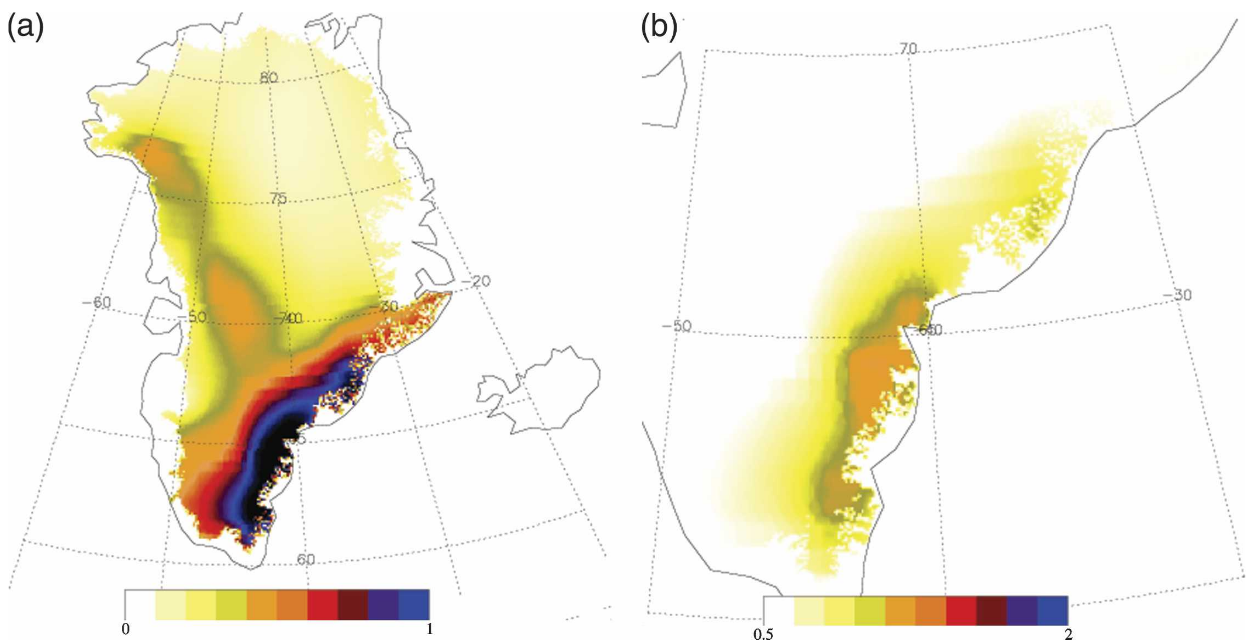
(65.60°N, 37.63°W) winter precipitation (r = 0.75) and with 04360 Tasiilaq winter air temperature (r = 0.73) (Fig. 6). Because 04360 lies between the ice sheet and the ocean, this suggests that, during relatively mild, wet winters on the SE Greenland coast, mild air is advected over the SE part of the ice sheet, and this in turn enhances orographic precipitation and snow accumulation. The excellent agreement between high/low accumulation/precipitation years also provides an invaluable additional check of our accumulation–model results. This is despite the caveat regarding nonindependent validation data mentioned in section 1.

We present an extended winter (DJFM) accumulation series, which we compare with the NAO winter index; the r value of −0.09 indicates no significant correlation (Fig. 6). Correlation coefficients between the

TABLE 3. Mean annual snow accumulation (m yr^{-1}) from ECMWF-based modeling for various periods for the Greenland Ice Sheet.

Period	Accumulation	$P - E$
1958–2003	0.279	0.341
1961–90	0.275	0.335
1993–98	0.284	0.349
1998–2003	0.292	0.366

NAO winter index and winter precipitation ($r = -0.22$) and air temperature ($r = -0.20$) measured at 04360 Tasiilaq on the SE Greenland coast are also low. This is unsurprising, as SE Greenland lies relatively near the Icelandic node of the NAO, so its climate appears to be relatively insensitive to changes in the NAO index (Box 2002; Hanna et al. 2004). However, subdividing our accumulation record reveals a nonsignificant positive $r = 0.31$ early on in the record 1958–78 and a significant ($p < 0.05$) negative $r = -0.56$ for later on 1979–98, so the two periods reverse and practically cancel in terms of accumulation–NAO relations. The later period is presented for comparison with Hanna et al. (2001), who found a significant negative relation of precipitation and NAO in southern Greenland. There ap-



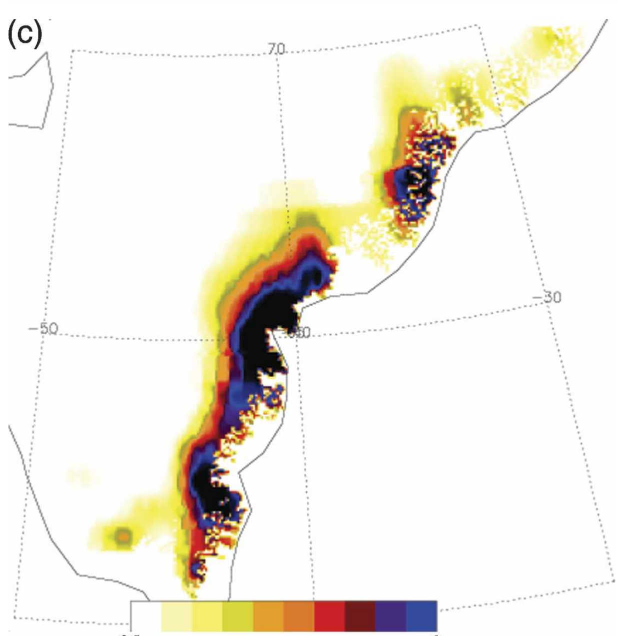


FIG. 4. (a) Greenland Ice Sheet 1958–2003, (b) south Greenland Ice Sheet 1961–90, and (c) south Greenland Ice Sheet 2002–03 MAA. Scale bars are in m yr^{-1}.

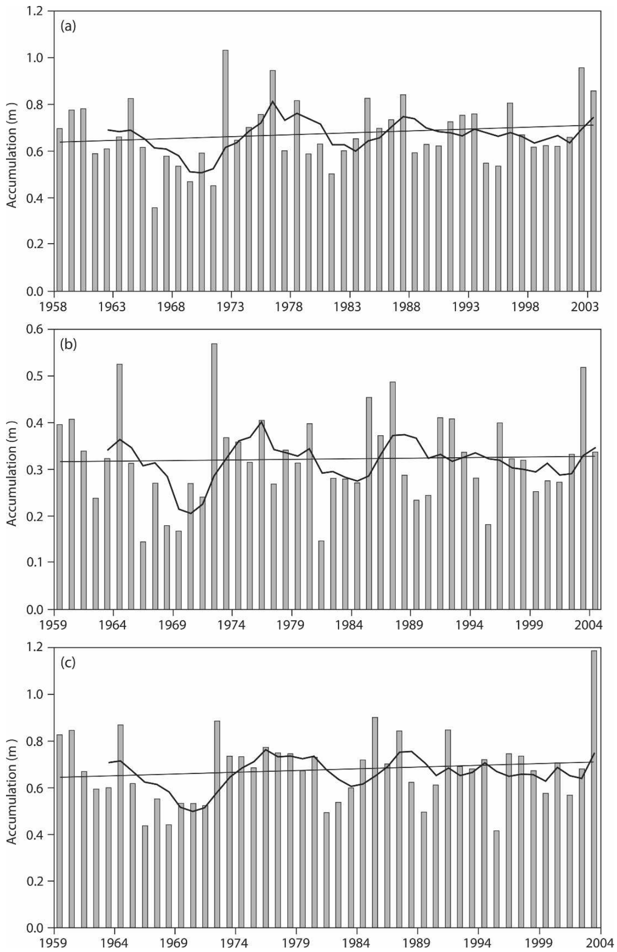


FIG. 5. (a) Annual snow accumulation in SE Greenland, (b) winter (December–March) snow accumulation in SE Greenland, and (c) annual (June–May) snow accumulation in SE Greenland.

pears to be some quasi-decadal periodicity in snow accumulation, with the early 1960s, mid-1970s, and mid-1980s being quite "snowy" periods. Least squares linear regression shows no significant underlying trend in accumulation, either annual or for any of the months.

Interestingly, 2002 and 2003, with 0.956 and 0.856 m yr^{-1}, respectively, are the second and fourth highest snow accumulation years in the 46-yr series (Fig. 5a). The extended winter SE Greenland accumulation series has 2002/03 as having had 0.518 m, or the third greatest, snow accumulation out of 1958/59–2003/04 (after 1971/72 and 1963/64) (Fig. 5b). These were the only three (four-month) winters with >0.5 m snow accumulation, compared with a mean winter snow accumulation of 0.322 m, and the standard deviation of 0.098 m suggests that they are significantly high snow accumulation winters. The high 2002/03 snow accumulation is spatially well shown by comparative MAA maps for 1961–90 (the climatological "normal") and 2002/03 for south Greenland (Figs. 4b,c). These show a relatively small, well-concentrated area of maximum MAA, ~1.25 m yr^{-1}, at ~64°N, 42°W (Fig. 4b). In 2002/03 MAA peaked at >2 m yr^{-1} in three distinct clusters: one at the same approximate location (centered a little farther north) and two others farther south and north along the East Greenland margin (Fig. 4c). Our ECMWF-based accumulation maps for the GrIS for individual months during winter 2002/03 (not shown) reveal the highest anomalies (+50%–>+100%) persistently located in a band down the eastern and southeastern sides, sometimes highest near the margin (as in November and December 2002), although January 2003 anomalies were not as great as in the other winter months. The winter (December 2002–March 2003) mean temperature of −2.9°C at 04360 Tasiilaq is >1 K above the next highest winter temperature value for the past 46 years. All months from May 2002 to April 2003 inclusive had above-average snow accumulation in SE Greenland, with December 2002 having 2.3 standard deviations above average and April 2003 a remarkable 4.0 σ above the mean. June 2002–May 2003 annual accumulation was 1.187 m yr^{-1}, which was the only June–May ≥0.9 m yr^{-1} in the 46-yr series compared with a mean June–May SE Greenland accumulation of 0.678 m yr^{-1} and a standard deviation of 0.146 m yr^{-1} (Fig. 5c). This period was coincident with the June–May survey sampling period of W. B. Krabill et al.'s annual airborne laser surveys around the edges of Greenland (concentrating on prominent outlet glaciers) (Krabill et al. 2000, 2004). These surveys, normally carried out in May each year since 1991, are designed to monitor ongoing changes in elevation of the GrIS and have detected a general and accelerating thinning of typically 0.5–1 m yr^{-1} around the edges of the ice sheet since 1993 (Krabill et al. 2004). However, this trend was bucked in SE Greenland in 2002/03, with regionally strong thickening of up to 2–4 m yr^{-1} measured by the airborne surveys that year. This thickening signal could only be explained by near doubling of long-term snow accumulation, as we have seen above; this more than compensated for any increased melt produced during that somewhat warmer-than-average year (Krabill et al. 2004).

What caused this unusually large amount of snow to be deposited in SE Greenland? There is some correlation of monthly accumulation anomalies with 2-m air temperature anomalies from the ECMWF analysis; large areas ≥5 K above normal (the 1958–2002 average in the analysis) suggest advection of relatively warm air over much of Greenland. An enormous "blocking" anticyclone became established over Scandinavia in November 2002 and remained in that position, or a bit to

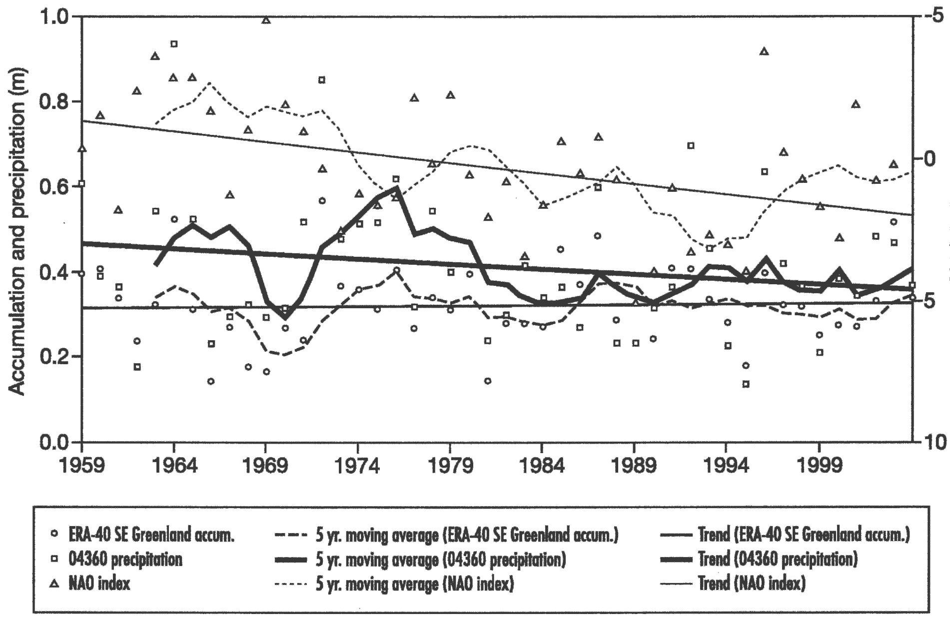


FIG. 6. Comparison of ERA-40-derived accumulation over SE Greenland with precipitation measured at 04360 and with NAO index: winter (DJFM).

the east, until February 2003 (as revealed by mean sea level pressure charts in *Weather Log,*[2] Royal Meteorological Society). The Northern Hemisphere midlatitude atmospheric circulation was therefore fairly stationary with a three-wave pattern. The upper-level midlatitude jet stream tended to be bifurcated with one branch going over the Mediterranean and North Africa and the other branch extending over Iceland/SE Greenland. The Icelandic low was persistently ~4 hPa deeper and situated farther west than normal (Fig. 7). Mean sea level pressure (MSLP) anomalies were typically −5 to −10 hPa over southern Greenland from November 2002 to March 2003 with a huge −16 hPa anomaly centered over SE Greenland in February 2003. Also in that month, Reykjavik had some 223% of its mean February precipitation, with Reykjavik precipitation, November 2002–March 2003, ~138% of average (*Weather Log*, Royal Meteorological Society). The synoptic pattern was anomalous with monthly mean temperatures about 3 K below normal in Helsinki, Finland, and 3–4 K above normal in Reykjavik from November 2002 to January 2003. Depressions were dragged up over SE Greenland, dumping a lot of snow there.

The winter 2002/03 synoptic airflow and accumulation over SE Greenland are unusual, based on the past few decades, but they may not be unique. The most recent, subsequent, winter (2003/04) had lower, near-normal accumulation of 0.336 m yr^{-1}. The highest overall annual and winter modeled accumulations of 1.033 and 0.568 m yr^{-1} were in 1972, although the June 1971–May 1972 accumulation of 0.885 m yr^{-1} was unremarkable. Ongoing climate change in the form of anthropogenic global warming may bring with it more interannual variability (Houghton et al. 2001), including a greater frequency of higher-accumulation years. GCM time slice integrations also suggest that Greenland precipitation will increase by ~25%–45% during the present century due to greater levels of available moisture and slightly higher-latitude polar lows/storm tracks in a warmer atmosphere (Huybrechts et al. 2004). This includes a "hotspot" of >50% enhanced precipitation farther up the eastern side of Greenland. However, greater projected accumulation on the (largely) high-lying mountains of SE Greenland is unlikely to offset enhanced melt for the ice sheet as a whole, with GrIS mass balance changes predicted to cause a +0.02 to +0.07 m contribution to global sea level between 1975 and 2100 (Huybrechts et al. 2004).

b. SW Greenland

Southwest Greenland is much drier on the whole than SE Greenland because the high topography of central southern Greenland (the region encompassing South Dome) shelters the SW from prevailing easterly winds. Our SW Greenland model domain (latitude ≤70°N, longitude >45°W) (Fig. 1) has 0.383 m yr^{-1} MAA (1958–2003), with a standard deviation of 0.067 m yr^{-1} or 17%. The individual annual values range

[2] A monthly supplement published by the Royal Meteorological Society.

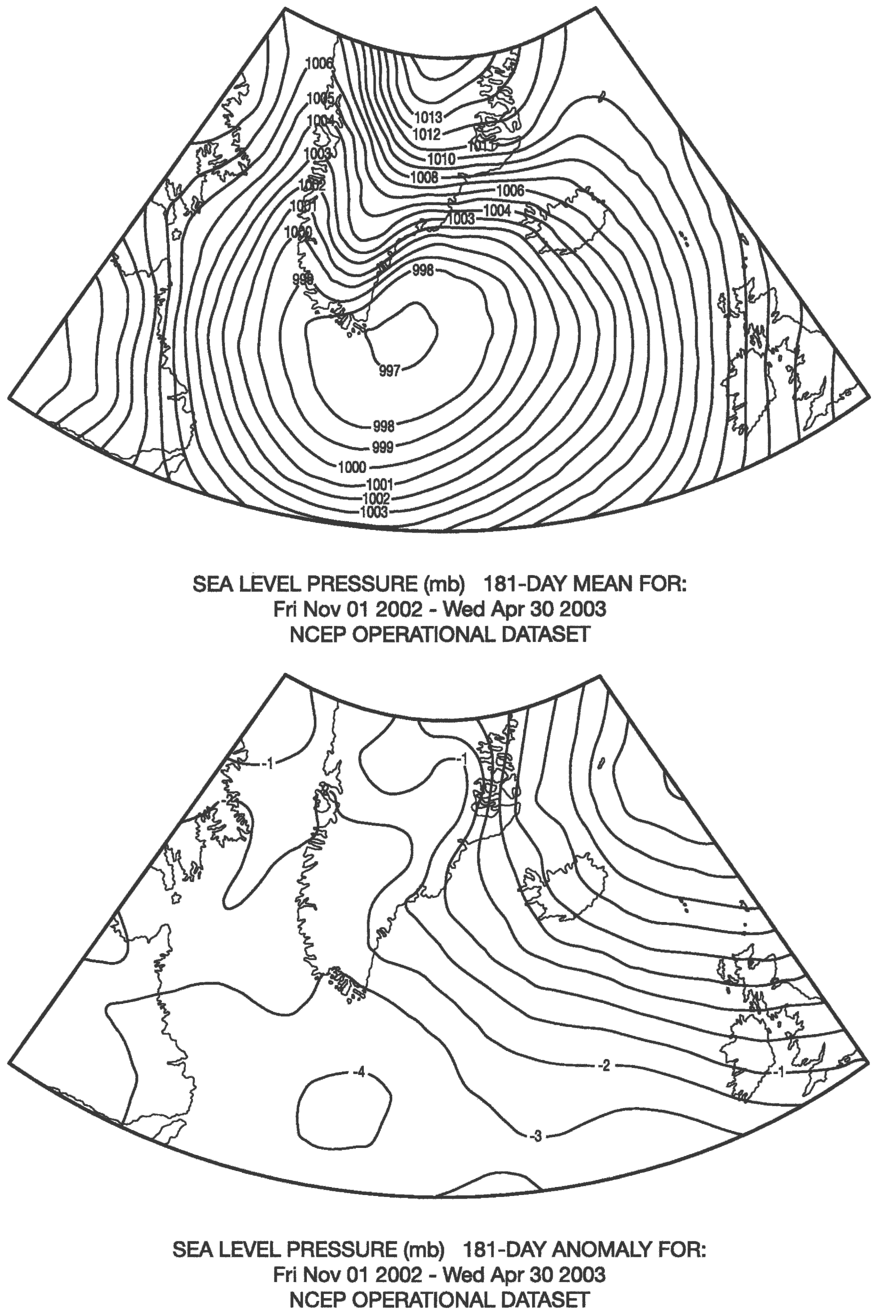


FIG. 7. (a) MSLP chart for November 2002 to April 2003 and (b) MSLP anomaly chart for November 2002 to April 2003 w.r.t. November–April 1979–95 mean. Charts provided by the National Oceanic and Atmospheric Administration–Cooperative Institute for Research in Environmental Sciences (NOAA–CIRES) Climate Diagnostics Center, Boulder, CO, from their Web site (http://www.cdc.noaa.gov).

from 0.268 m yr^{-1} in 1985 to 0.571 m yr^{-1} in 1983 (Fig. 8a). Again, there is no underlying trend in the series. Mean monthly modeled accumulation ranges from 0.014 m yr^{-1} in July to 0.050 m yr^{-1} in November.

The SW Greenland extended winter (DJFM) accumulation series is significantly correlated with 04250 Nuuk (Godthåb) (64.17°N, 51.75°W) winter precipitation ($r = 0.72$) (Fig. 9) but not with 04250 Nuuk winter air temperature ($r = -0.02$). Again, the very good agreement between high/low accumulation/precipitation years is reassuring for our accumulation–model results. However, unlike for SE Greenland, air tem-

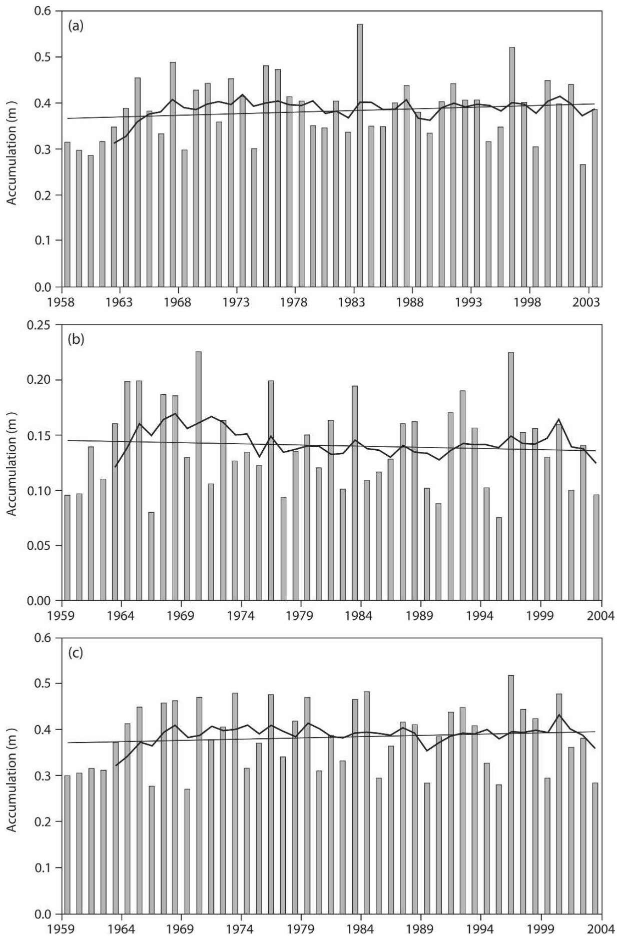


FIG. 8. (a) Annual snow accumulation in SW Greenland, (b) winter (DJFM) snow accumulation in SW Greenland, and (c) annual (June–May) snow accumulation in SW Greenland.

perature does not seem to be a significant factor in air circulation changes affecting snow accumulation on the SW corner of the ice sheet. We propose that this may be because prevailing northeast winds come off of the ice sheet, for example, 04250 Nuuk has prevailing north and northeast winds (Cappelen et al. 2001).

Southwest Greenland winter accumulation has a low and insignificant correlation coefficient of $r = -0.18$ with the NAO winter index. Winter precipitation from 04250 Nuuk is even more poorly correlated with winter NAO ($r = -0.07$). These results do not contradict Appenzeller et al. (1998), who found significant negative correlations of Greenland precipitation and the NAO index over central western interior Greenland and the Labrador Sea and significant positive correlations over central eastern Greenland, but no significant relation over most of southern Greenland. It also seems likely that their positive and negative correlation areas would tend to cancel for Greenland as a whole. However, their results are based on just 15 years of earlier reanalysis data (1979–93). Redoing the SW Greenland winter accumulation–NAO correlation likewise gives a low and insignificant $r = -0.05$ for 1979–93. However, taking the slightly longer period of 1979–98, compatible with our earlier Greenland precipitation/accumulation study based on ECMWF analyses, gives a significant $r = -0.45$, which agrees with our then conclusion of a "significant correlation of Greenland precipitation in winter with the North Atlantic Oscillation index: negative in the south and west" (Hanna et al. 2001). This is in agreement with our NAO results for SE Greenland presented above. The present results from our longer study show that Greenland accumulation–NAO index relations are highly sensitive to the time period selected, and even intervals that overlap substantially may yield different results. Notwithstanding, winter air temperature at 04250 Nuuk is strongly negatively correlated with winter NAO ($r = -0.71$), in line with recent studies of SW Greenland coastal temperatures and their seeming dependence on the NAO index (Hanna and Cappelen 2003; Chylek et al. 2004).

There are no similar high-accumulation anomalies in 2002/03 or 1971/72 to SE Greenland, and there is a lack of coherence of annual or winter accumulation values between SW and SE Greenland ($r = 0.11$ and 0.23, respectively, both nonsignificant), so we infer quite different climatic forcing mechanisms for the two regions. Both regions experience their greatest snow accumulation in winter, yet are likely to be affected differently by changing atmospheric circulation, synoptic low pressure systems in transit, and smaller-scale mesocyclones. We recommend future detailed study of synoptic forcing fields, possibly using an automatic cyclone detection/tracking algorithm, from ERA-40.

5. Conclusions

This is the first multidecadal study of GrIS accumulation based on weather forecast model (ECMWF) output. We have derived mean annual GrIS accumulation within a few percent of previous (both observational and modeling) studies and found a standard deviation of ~13% in the annual values from 1958 to 2003. Modeled annual accumulation is significantly correlated with observed annual accumulation (mean $r = 0.53$ for a mean period of 26 yr). Also, the agreement at some recent key ice core sites (e.g., Das1 and Das2) is excellent in terms of both temporal correlation and absolute quantity of snow accumulation simulated by the model. The ERA-40-based modeling presented here yields Greenland-wide accumulation that is only slightly (~5%) below that reconstructed from the latest PARCA ice cores.

We have focused on accumulation in SE and SW

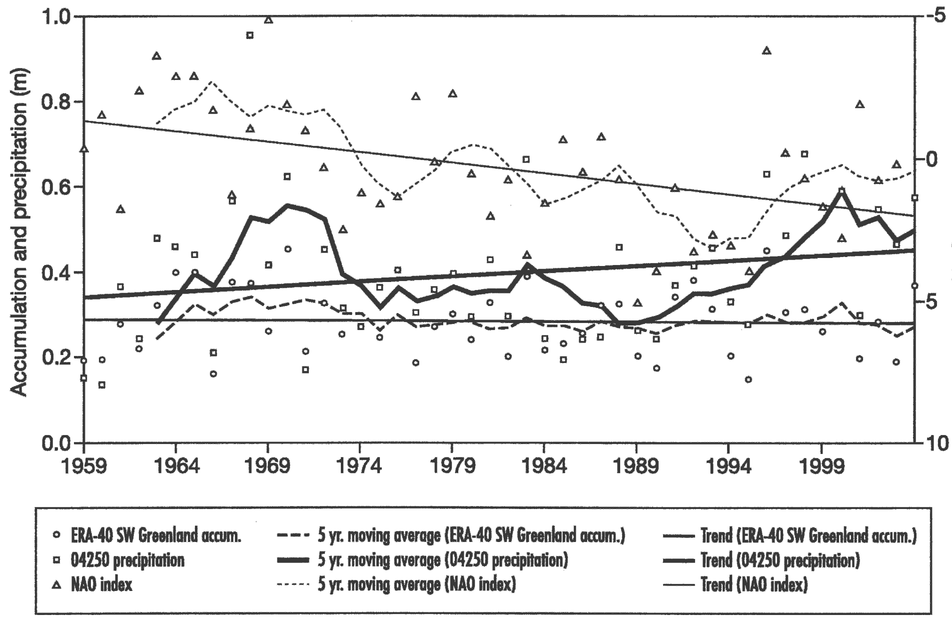


FIG. 9. As in Fig. 6 but over SW Greenland with precipitation measured at 04250.

Greenland because these are two key regions of largest annual snow accumulation at the forefront of interaction of their ice surfaces and mass budgets with the atmosphere and ocean. We have established good agreement between regional accumulation and coastal station precipitation. Both the whole island and regional series show no significant long-term trends, and Greenland accumulation over the past half century or so appears not to be linked with the NAO index. We have highlighted a high-accumulation anomaly in SE Greenland during 2002/03, studied the meteorological dynamic forcing of this extra snow accumulation, and speculated on possible implications of a changing climate on Greenland accumulation.

Our current accumulation model results clearly yield very promising insights into GrIS–climate interactions. However, the ECMWF-based accumulation model evidently needs further refinement. In common with earlier-based ECMWF modeling, the central and northern plateaus are too dry by ~10%–30%, whereas conversely some parts of the interior south seem to be too "wet," in the model. This suggests that significant deficiencies remain in the version of the ECMWF model used to produce ERA-40, partly due to relatively low resolution (~1.125 latitude × 1.125 longitude) originally used by ECMWF to produce their surface climate fields and problems with misrepresentation of the Ekholm orography in the ECMWF model. ERA-40 output can reasonably readily be corrected for resulting surface temperature errors, as done here more thoroughly than previously, but precipitation errors are harder to correct. One possible approach is cokriging of accumulation fields derived from model and core estimates; another is using ERA-40 data as boundary conditions to drive a very high-resolution (less than tens of kilometers) regional climate model over the Greenland area. Both these statistically and physically based approaches are likely to yield significant improvements on existing modeled accumulation.

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