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Published in:
Journal of Climate

DOI:
10.1175/2007JCLI1964.1

Publication date:
2008

Citation for published version (APA):
Hanna, E., Huybrechts, P., Steffen, K., Cappelen, J., Huff, R., Shuman, C., Irvine-fynn, T., Wise, S., & Griffiths, M. (2008). Increased Runoff from Melt from the Greenland Ice Sheet: A Response to Global Warming. *Journal of Climate*, *21*(2), 331-341. https://doi.org/10.1175/2007JCLI1964.1

Increased Runoff from Melt from the Greenland Ice Sheet: A Response to Global Warming

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(Manuscript received 20 March 2007, in final form 10 May 2007)

ABSTRACT

The authors attribute significantly increased Greenland summer warmth and Greenland Ice Sheet melt and runoff since 1990 to global warming. Southern Greenland coastal and Northern Hemisphere summer temperatures were uncorrelated between the 1960s and early 1990s but were significantly positively correlated thereafter. This relationship appears to have been modulated by the North Atlantic Oscillation, whose summer index was significantly (negatively) correlated with southern Greenland summer temperatures until the early 1990s but not thereafter. Significant warming in southern Greenland since ~1990, as also evidenced from Swiss Camp on the west flank of the ice sheet, therefore reflects general Northern Hemisphere and global warming. Summer 2003 was the warmest since at least 1958 in coastal southern Greenland. The second warmest coastal summer 2005 had the most extensive anomalously warm conditions over the ablation zone of the ice sheet, which caused a record melt extent. The year 2006 was the third warmest in coastal southern Greenland and had the third-highest modeled runoff in the last 49 yr from the ice sheet; five of the nine highest runoff years occurred since 2001 inclusive. Significantly rising runoff since 1958 was largely compensated by increased precipitation and snow accumulation. Also, as observed since 1987 in a single composite record at Summit, summer temperatures near the top of the ice sheet have declined slightly but not significantly, suggesting the overall ice sheet is experiencing a dichotomous response to the recent general warming: possible reasons include the ice sheet's high thermal inertia, higher atmospheric cooling, or changes in regional wind, cloud, and/or radiation patterns.

1. Introduction

The Greenland Ice Sheet (GrIS) contains ~7.4-m global sea level equivalent and is vulnerable to ongoing anthropogenic climate change (Gregory et al. 2004). Therefore, it is essential to establish its current state of mass balance and climatic sensitivity, and detect any warning signs that might be a guide to its future response. Observationally based studies have provided intriguing insights into recent mass balance changes of the GrIS. Airborne and satellite laser-altimetry data analyses were used to derive an overall volume loss of 60 $\mathrm{km^3\ yr^{-1}}$ in 1993/4–1998/9; that increased to 80 $\mathrm{km^3\ yr^{-1}}$ in 1997–2003 (Krabill et al. 2000, 2004; Thomas et al. 2006). Various recent analyses of Gravity Recovery and Climate Experiment (GRACE) satellite data suggest much greater mass (volume) losses of the order of 101–226 Gt $\mathrm{yr^{-1}}$ (111–248 $\mathrm{km^3\ yr^{-1}}$) within the last few years (2002–2006; Chen et al. 2006; Luthcke et al. 2006; Ramillien et al. 2006; Velicogna and Wahr 2006), but there is considerable scatter and uncertainty in and between these pioneering estimates.

Satellite radar interferometry (InSAR) was used to observe acceleration of several Greenland outlet glaciers, which appear to have been progressing northward since 1996, with an accompanying apparent doubling of the ice sheet's volume deficit from 90 to 220 $\mathrm{km^3\ yr^{-1}}$

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DOI: 10.1175/2007JCLI1964.1

(Rignot and Kanagaratnam 2006). Recent dramatic changes in some Greenland margin glaciers are a likely response to recent climatic warming through either a meltwater percolation dynamic feedback mechanism (Zwally et al. 2002; Parizek and Alley 2004) or oceanic erosion of calving fronts (Howat et al. 2005; Thomas 2004). On the other hand, altimetry data (Johannessen et al. 2005; Thomas et al. 2005; Zwally et al. 2005) suggest that there appears to have been significant ($\sim$2–5 cm yr^{-1}) growth of the GrIS interior above 2000-m elevation from 1992 to 2003/4, which may be attributed to increased atmospheric moisture and precipitation and/or shifting storm tracks (Hanna et al. 2006). However, because of short data spans (around one decade), such studies have yet to provide a more convincing multidecadal perspective on how the GrIS might be responding to long-term climatic change, most notably the evident global warming since the 1970s (Alley et al. 2007).

Here we analyze updated summer temperature records from various Greenland stations and meteorological reanalyses, and conduct a comparative analysis of Greenland summer temperatures with Northern Hemisphere temperatures and the North Atlantic Oscillation. This is to provide a multidecadal climatic context for—and therefore help assess the significance of—recent changes in GrIS precipitation, runoff, and surface mass balance, as we also update and reanalyze records for the latter in this paper. Through our synthesis of various key Greenland meteorological and glaciological datasets and model output, we statistically assess the significance of recent (last few years') warm and/or high snowmelt and/or meltwater runoff summers and relate them to general Greenland and hemispheric climatic trends.

2. Recent significant Greenland warming and record high temperatures

Monthly air temperature records from eight Danish Meteorological Institute (DMI) synoptic stations around the coast of Greenland (located mainly in the southwest but including Tasiilaq in the southeast) show pronounced warming since the early 1990s (Figs. 1 and 2). The warming follows an overall regional cooling trend between 1958 and 1992, concentrated in winter in the 1960s to 1980s (Hanna and Cappelen 2003). Hereafter in this paper, we present results of significance testing of temperature (and other) time series, highlighting p, the probability of the observed temperature (or other) trend over time occurring by chance rather than indicating a significant relationship: if p is less than a constant threshold ($\alpha = 0.05$), the trend relationship is deemed significant; n is number of years in the sample. Trend-line changes greater than the standard deviation, σ, in the sample are also likely to be significant, so we make this comparison too. Summer trends of the 7-station DMI average (i.e., excluding Kangerlussuaq because of its relatively short record) indicate significant warming for 1991–2006 of 1.7°C ($\sigma = 0.8^{\circ}\mathrm{C}$, $p = 0.025$, $n = 16$) compared with insignificant cooling for 1961–90 of $-0.5^{\circ}\mathrm{C}$ ($\sigma = 0.7^{\circ}\mathrm{C}$, $p = 0.28$, $n = 30$) and significant annual warming for 1961–2006 of 0.9°C ($\sigma = 0.8^{\circ}\mathrm{C}$, $p = 0.023$, $n = 46$). The DMI data are the most comprehensive meteorological records available for Greenland's coastal region and have been homogenized—most notably the original observations have been checked and the data compared with time series of related climatic elements for the same stations—with the specific purpose of studying long-term climatological trends (Cappelen et al. 2001). Fortunately for our purposes, the DMI data also reflect changing meteorological conditions on the adjacent low-lying marginal ablation zone of the ice sheet, where much of the seasonal melt and subsequent runoff occurs.

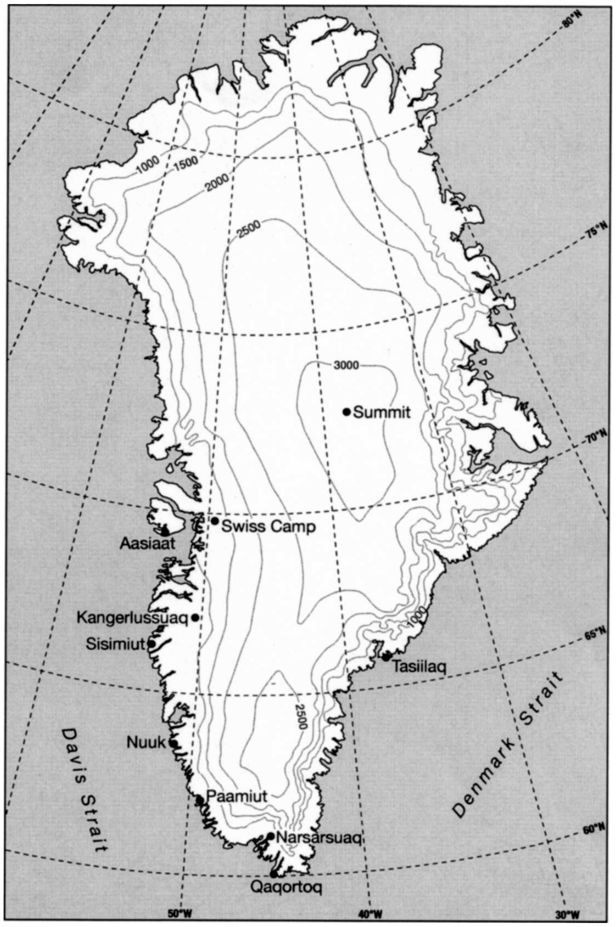

FIG. 1. Location map showing the Greenland climate stations used in study.

For the DMI station average, 2003 was the warmest

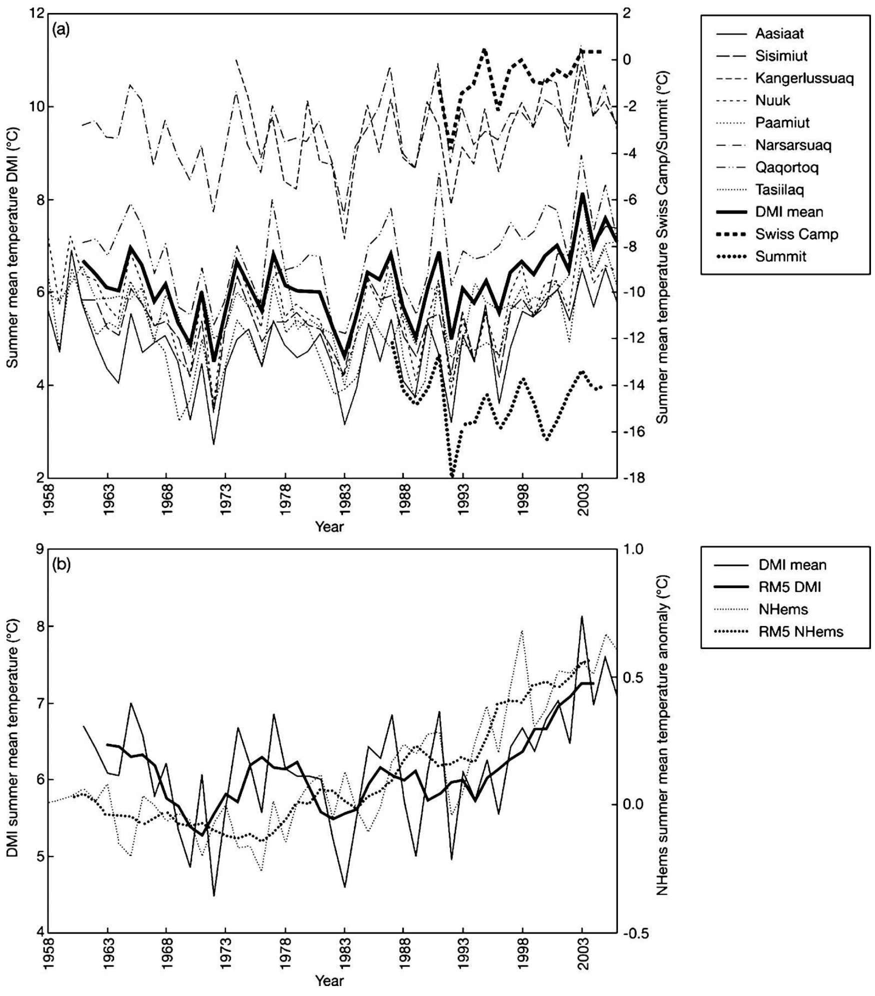

FIG. 2. (a) JJA mean temperature 1958–2006 at Greenland climate stations (their locations are shown on Fig. 1). (b) Greenland summer mean temperature from mean of 7 DMI stations (Fig. 1, except Kangerlussuaq) compared with Northern Hemisphere summer mean temperature, with 5-yr running means of both series. Note some early years in Greenland/Northern Hemisphere antiphase (e.g., 1965, 1971, 1983), as highlighted by the disparate running means, but the post-Pinatubo (1992 onward) period shows much better agreement in terms of interannual variability, correlation, and strong upward trends.

summer [June–August (JJA)] on record, with a mean temperature of 8.1°C at 3.3σ above the most recent climatological "normal" period (1971–2000) mean (Table 1, Fig. 2). The second warmest summer was 2005 (7.6°C) at 2.5σ above the 1971–2000 mean. 2005 was more than half a degree warmer than the third warmest summer 2006 (7.07°C), which was closely followed by 2001 (7.02°C), 1965 (7.00°C), and 2004 (6.97°C). The four warmest summers on record were within the last six years. Since about half the annual runoff from the GrIS occurs in July, we separately examined the DMI July temperature series (not shown). This analysis also revealed 2003 and 2005 as the joint warmest years at 8.7°, and both were 2.3σ above the long-term (1971–2000) mean.

TABLE 1. The 10 warmest summers (JJA) of the 7-station DMI average representing coastal southern Greenland during 1958–2006 (see Fig. 1 for station locations).

Rank	Year	Temperature (°C)	Anomaly (σ with respect to 1961–2006 mean)
1	2003	8.14	2.61
2	2005	7.60	1.89
3	2006	7.07	1.20
4	2001	7.02	1.13
5	1965	7.00	1.11
6	2004	6.97	1.07
7	1991	6.89	0.96
8	1997	6.86	0.92
9	1987	6.85	0.91
10	2000	6.78	0.82

The Greenland Climate Network (GC-Net) automatic weather station (AWS) Swiss Camp (1169 m masl) record (Steffen and Box 2001) was used to gauge observed temperature changes on the western flank of the GrIS, where extensive seasonal melt and relatively high runoff from this relatively low-elevation zone contribute a large proportion of the total GrIS runoff (Box et al. 2006; Hanna et al. 2005). This record, by far the longest GC-Net series, spans 15 yr (1991–2005), and its interannual variability is significantly correlated with that of the mean of the 7 DMI coastal stations (detrended series $r = 0.65$, $p < 0.01$; Fig. 2a). Similar to the positive (7-station mean) DMI temperature trend, Swiss Camp summer mean temperatures increased significantly by 2.2°C ($\sigma = 1.2$, $p = 0.017$, $n = 15$; corrected for 25-m-vertically down-glacier movement of the station) since 1991. The recent three summers 2003–05 were almost equally record warm years (mean temperatures 0.3°, 0.3°, and 0.35°C) at Swiss Camp, alongside 1995 (0.5°C). The latter season has been previously noted for its relatively high modeled runoff compared with most other years 1958–2003 (Hanna et al. 2005).

A reprocessed and updated 1987–2005 near-surface (~1–1.5-m) air temperature series for Summit (3205-m elevation; Shuman et al. 2001) shows slight but insignificant overall −0.3°C ($\sigma = 1.4$°C, $p = 0.81$, $n = 19$) cooling in summer, in contrast to all the other Greenland temperature records (all from much lower elevations and generally around the margins; Fig. 2a). This new Summit series is a reanalyzed composite primarily of University of Wisconsin and ongoing GC-Net AWS data supported by Special Sensor Microwave/Imager (SSM/I) brightness temperature data (Shuman et al. 1995, 1996, 2001). We apply a −0.8°C temperature correction to the pre-1996 Summit summer series to compensate for inferred greater summer solar warming of the older-style University of Wisconsin AWS (Shuman et al. 2001). There is a highly significant correlation between individual years' fluctuations in the detrended DMI and Summit series (detrended $r = 0.78$, $p < 0.01$; Fig. 2a). Three hypothesized possible causes for the disparate trends are 1) continued relative suppression of more regional climatic change by thermal inertia of the huge central Greenland ice mass as noted for Arctic Ocean sea ice (Serreze and Francis 2006); 2) a differential response of the high-elevation zones of the GrIS in accordance with the well-known lower-tropospheric warming/higher atmospheric cooling response to increased greenhouse gases (Stott et al. 2006), which has been demonstrated specifically for Greenland in a recent analysis of radiosonde data spanning 1964–2006 (Box and Cohen 2006); and/or 3) regional changes in wind, cloud cover, or radiation patterns over the GrIS. Notably, this observed pattern (coastal/marginal warming combined with little change or slight cooling in the high interior) is opposite to the output of simulations from atmosphere–ocean general circulation models (AOGCMs): in all high-resolution temperature changes studied for the present century, Huybrechts et al. (2004) and Gregory and Huybrechts (2006) found that modeled summer warming is actually largest over the Greenland interior and smallest along the coast. The reason for this discrepancy is as yet unclear but further analysis of the Summit composite temperature time series is anticipated.

High-resolution (5 km × 5 km) surface air temperature (SAT) data were bilinearly interpolated from the 0.5°-resolution 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) and corrected for ECMWF terrain errors using empirically derived ice sheet surface lapse rates, as explained in Hanna et al. (2005). These SAT data provide corroborating evidence for anomalously (3°–5°C) high summer temperatures around the Greenland margins during recent noted warm/high melt summers, which occurred most widely within the ice sheet's southern and western marginal ablation zones—therefore potentially affecting the largest swath of the GrIS—in July 2005 (Fig. 3). However, the accumulation zone of the GrIS (>2000-m elevation) had apparently cold summer anomalies in 2003 and 2006, in contrast to warm anomalies in more outer lying areas, in line with the Summit temperature results discussed above.

Comparison of Greenland summer temperatures with combined Hadley Centre and Climatic Research Unit temperature data (HadCRUT3v) Northern Hemisphere summer temperatures (Brohan et al. 2006; Jones et al. 1999; Rayner et al. 2003, 2006) reveals a nonsignificant correlation (e.g., detrended $r = 0.25$ for 1961–81 and detrended $r = -0.12$ for 1971–91; $p \gg 0.05$) for much of the record, followed by a significant positive correlation since the early 1990s (e.g., detrended $r = 0.72$, $p < 0.01$ for 1992–2006; Fig. 2b and Fig. 4). All correlation values are based on detrended data. Thus 1995, 1998, 2003, and 2005 were unusually warm both in Greenland and hemispherically, whereas 1996 and 1999 were relatively cool years. Both Greenland and Northern Hemisphere summer temperatures exhibit common strongly rising trends since the early 1990s, although the earliest part of this period (1992/3) marks the general temperature recovery following cooling after the 1991 Mount Pinatubo volcanic eruption (Robock and Mao 1995).

We also report a significant inverse correlation for much of the period (e.g., $r = -0.52$, $p < 0.05$ for 1961–81 and $r = -0.69$, $p < 0.01$ for 1971–91) between Greenland summer temperatures and a summer (JJA),

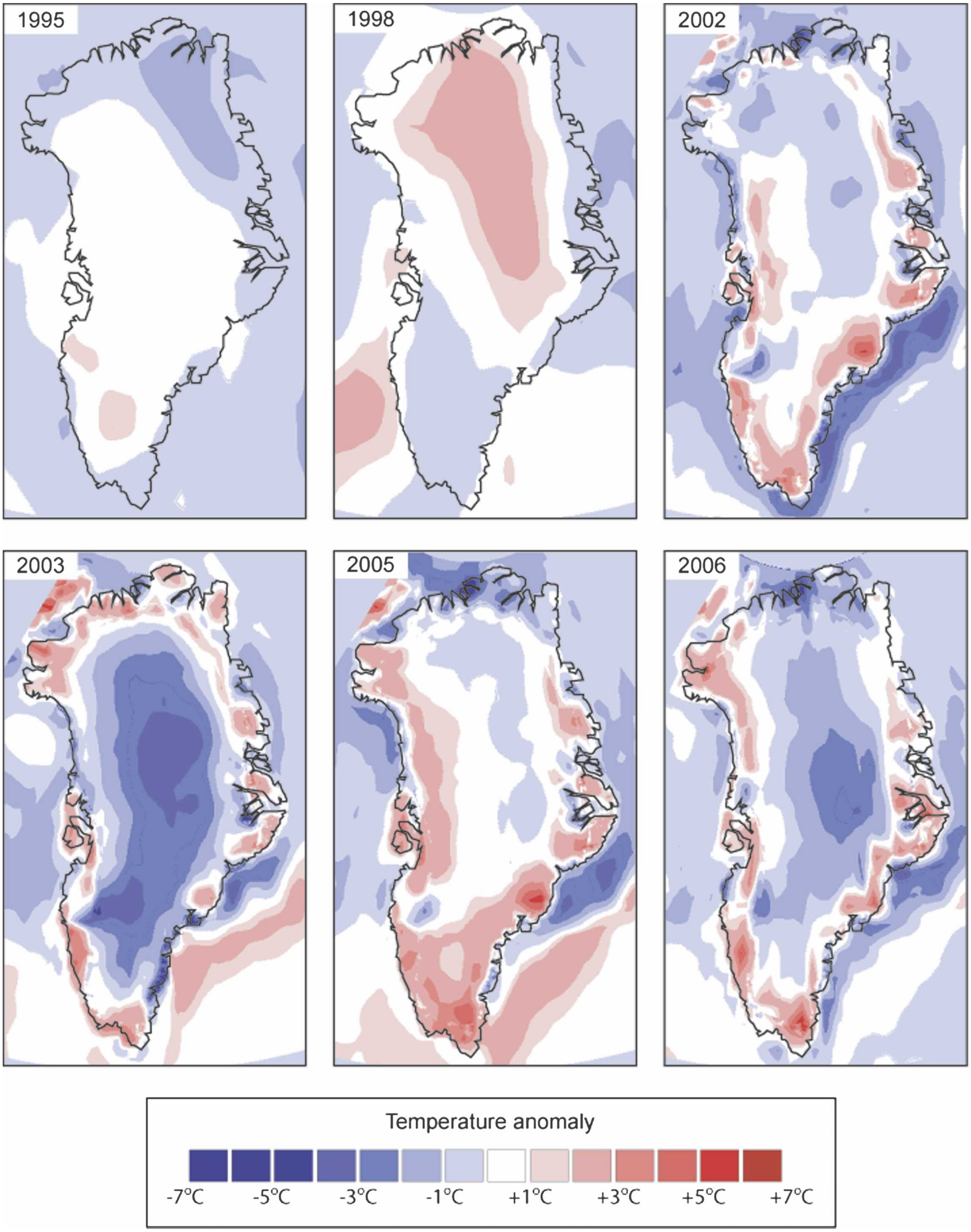

FIG. 3. July near-surface (2-m) air temperature anomalies, with respect to mean July 1971–2000 temperature, for noted recent warm summers (1995, 1998, 2002, 2003, 2005, and 2006) in Greenland from downscaled, orography-corrected ECMWF analyses.

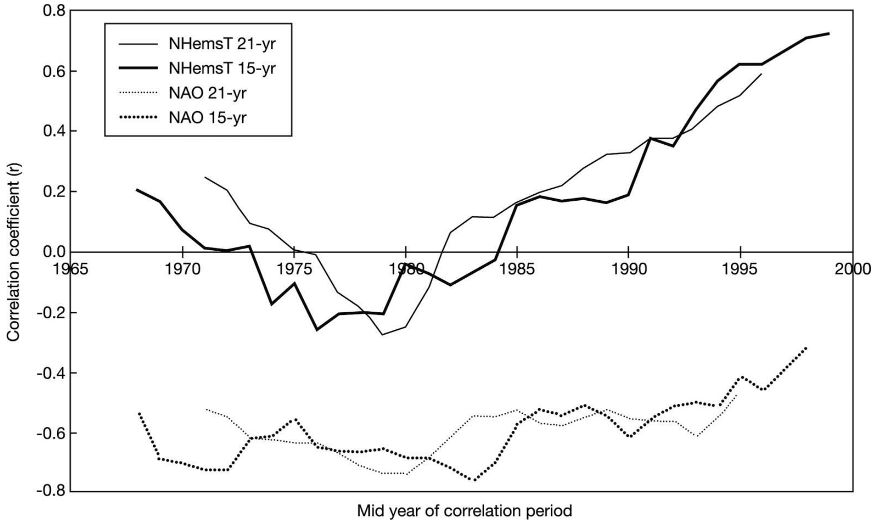

FIG. 4. Statistical relationship (15- and 21-yr correlations of detrended series) of JJA Greenland coastal temperatures with JJA Northern Hemisphere temperatures and JJA NAO index.

principal-component-based North Atlantic Oscillation (NAO) index (the leading empirical orthogonal function of sea level pressure anomalies over 20°–80°N latitude, 90°W–40°E longitude; Hurrell 1995). However, the Greenland summer temperature–summer NAO (inverse) relationship breaks down after the early 1990s.

We infer from our statistical analysis that the reason for the recent strong Greenland–Northern Hemisphere relation is the changes in atmospheric circulation depicted by the NAO, which became positive between the 1960s and 1980s before switching to a less positive or more neutral state from the mid-1990s (Hanna and Cappelen 2003; Overland and Wang 2005). We hypothesize that a less positive NAO may have reduced the insularity of Greenland by encouraging advection of warmer air masses over the ice sheet.

3. Significantly increased Greenland Ice Sheet runoff and record 2005 melt extent

Here we link the updated results of modeled annual runoff and observed surface melt time series including summer 2006 (Fig. 5) to observed Greenland and global temperature changes. Hanna et al. (2005) published the first multidecadal GrIS runoff and surface mass balance (SMB = net snow accumulation minus meltwater runoff) record, 1958–2003, and an independently derived but shorter (1988–2004) GrIS SMB series is presented in Box et al. (2006), with good agreement of the respective annual runoff values for overlapping years (detrended $r = 0.86$, $p < 0.01$). Hanna et al. (2005) modeled runoff using a positive degree-day model and retention scheme to allow for seasonal meltwater refrozen into the snowpack (Janssens and Huybrechts 2000), in conjunction with downscaled ECMWF meteorological (re)analysis data and empirically derived ice sheet surface lapse rates. Hanna et al. (2005) showed substantial variability of snow accumulation and surface meltwater runoff (respective standard deviations 12% and 25% of mean annual values), as well as a statistically significant increasing trend in runoff since the early 1990s. In the 46-yr record, the four highest runoff years—1998, 2003, 2002, and 1995—were within the last decade.

In our present 49-yr series (1958–2006), updated and recalibrated from Hanna et al. (2005), 1998, 2003, and 2006 were respectively the first-, second-, and third-highest runoff years (Table 2; Fig. 5). The underlying trend-line increase in runoff from 1958 to 2006 is 113.0 km^3 (40.0% of mean 1958–2006 runoff), compared with a standard deviation of the annual runoff values of 68.7 km^3 (24.3%), and is a significant increase ($p = 0.000\,351$, $n = 49$). The five highest runoff years have all occurred since and including 1995, and five of the nine highest runoff years since 2001 inclusive (Table 2), supporting the significantly rising trend found from regression analysis. The GrIS annual runoff and Greenland coastal JJA temperature series are significantly correlated (detrended $r = 0.51$, $p < 0.01$). A high degree of correlation would be expected from our use of a degree-day model, but it importantly confirms a close correspondence between Greenland coastal temperatures and modeled conditions on the GrIS on a monthly basis.

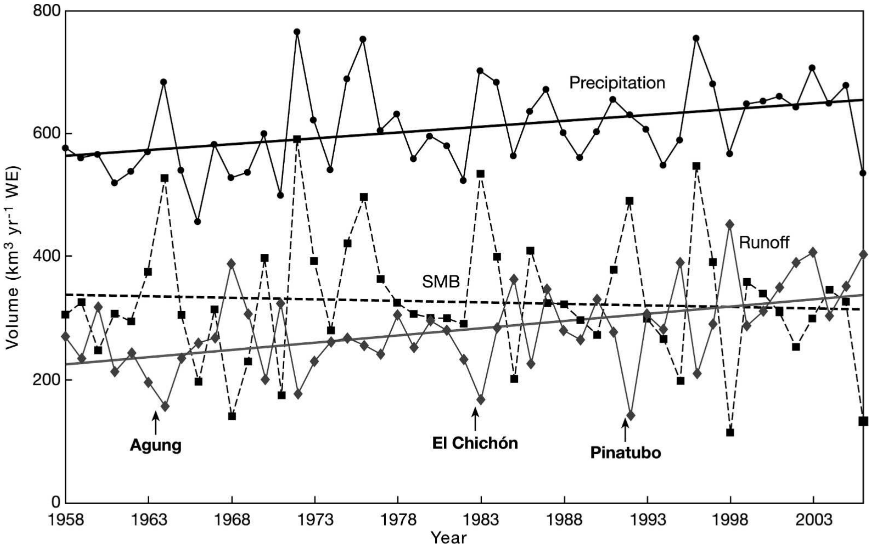

FIG. 5. Greenland Ice Sheet precipitation, runoff, and surface mass balance (SMB = solid precipitation minus evaporation minus runoff) series for 1958–2006, recalibrated and updated. Note significantly rising trends in precipitation and runoff but negligible change in SMB.

Annual GrIS runoff is highly significantly correlated (detrended $r = 0.69$, $p < 0.01$) with annual GrIS snowmelt area derived from passive microwave satellite data (Abdalati and Steffen 1997; Fig. 6). The annual mean daily snowmelt area shows a peak value for 2005 slightly, but not significantly, greater than the previous maximum melt years of 1998 and 2002 (Fig. 6). Note that satellite snowmelt data are only available since the summer of 1979 as the Scanning Multichannel Microwave Radiometer (SMMR) sensor was launched in late October 1978. The maximum melt extent over this period reached a new record of 43% of the total ice sheet area in 2005, compared with a 1979–2005 mean maximum melt extent of 29% and a standard deviation of 6%. Similarly, an unequivocal new record melt area for 2005 was found from infrared satellite GrIS annual melt data 1982–2005 (Comiso 2006). Rather than directly implying increased runoff, this measure demonstrates that warmer air masses reached higher elevations during summer 2005. Surprisingly, 2005 was only the eighth-highest runoff year, despite being the record high melt-area year (out of 1979–2006): this may be attributed to relatively high GrIS precipitation/accumulation in 2005 (Table 2). The 2005 analysis highlights the significance of variable accumulation and associated water retention and storage within the Greenland snowpack.

TABLE 2. Rank-ordered Greenland Ice Sheet runoff, precipitation, and SMB data for 1958–2006; all units are km^3 yr^{-1} water equivalent. Values greater than two standard deviations from the mean annual value of that parameter are in bold.

Rank	Runoff	Precipitation	SMB
1	**1998 (452.7)**	**1972 (767.2)**	**1972 (590.0)**
2	2003 (407.2)	**1996 (755.5)**	**1996 (547.1)**
3	2006 (403.1)	**1976 (752.3)**	**1983 (533.9)**
4	1995 (390.9)	2003 (707.1)	1964 (527.7)
5	2002 (390.6)	1983 (701.8)	1976 (496.1)
6	1968 (388.2)	1975 (689.0)	1992 (490.1)
7	1985 (363.2)	1964 (684.6)	1975 (421.1)
8	2005 (351.7)	1984 (684.1)	1986 (410.5)
9	2001 (349.8)	1997 (680.8)	1984 (399.5)
10	1987 (346.8)	2005 (678.3)	1970 (397.9)
40	1973 (229.9)	1974 (541.1)	2002 (253.2)
41	1986 (226.1)	1965 (540.4)	1960 (248.0)
42	1961 (213.1)	1962 (538.7)	1969 (229.3)
43	1996 (208.4)	1969 (535.9)	1985 (200.5)
44	1970 (200.3)	2006 (535.6)	1995 (198.6)
45	1963 (195.9)	1968 (528.5)	1966 (197.2)
46	1972 (177.2)	1982 (524.1)	1971 (175.1)
47	1983 (168.0)	1961 (519.9)	1968 (140.3)
48	1964 (156.9)	1971 (499.4)	2006 (132.5)
49	**1992 (141.1)**	**1966 (456.8)**	**1998 (114.5)**

4. Significantly enhanced Greenland Ice Sheet precipitation/accumulation

Greenland Ice Sheet precipitation—downscaled from ECMWF operational analyses and reanalyses (Hanna et al. 2005)—follows a significantly increasing trend of 90.9 km^3 yr^{-1} (14.9%), compared with a standard deviation of 69.7 km^3 yr^{-1} (11.4%), for 1958–2006 ($p = 0.005\,81$, $n = 49$; Fig. 5). Additional precipitation, mainly in the form of snow accumulation, therefore

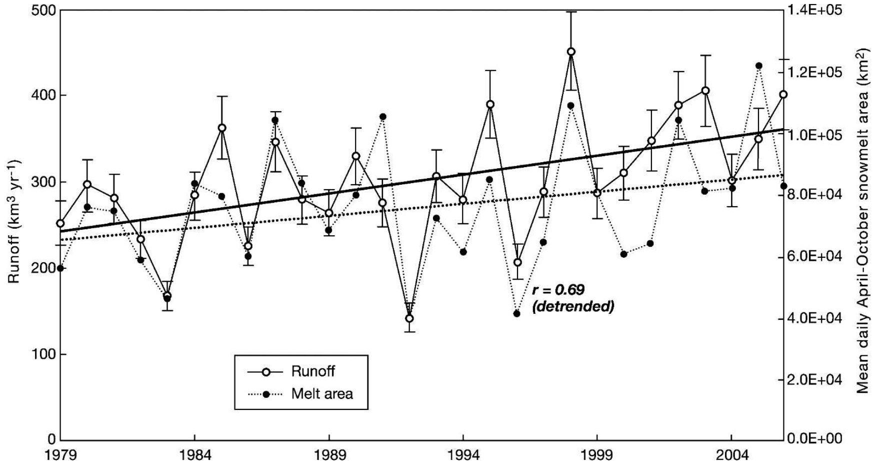

FIG. 6. Comparison of Greenland Ice Sheet annual runoff with satellite-derived snowmelt area, 1979–2006.

largely (~80%) offsets rising Greenland runoff. There is thus an insignificant negative trend in SMB of −22.1 km^3 over 1958–2006, compared with a standard deviation σ of 104.8 km^3 for the annual SMB values. The insignificant SMB trend underlines the sensitive balance between increased snow accumulation in the interior of the ice sheet and increased meltwater runoff around the edges. Additional mass loss from ice dynamics due to accelerated flow of outlet glaciers was probably at least several times larger for the recent few warmest years (Rignot and Kanagaratnam 2006).

Observations and models both indicate the occurrence of recent high snow accumulation events in winter 2004/05, concentrated in west Greenland (Nghiem et al. 2007), and winter–spring 2002/03 in southeast Greenland (Hanna et al. 2006; Krabill et al. 2004). Huybrechts et al. (2004) hypothesized that such events may become more frequent in Greenland as storm tracks intensify or shift position with climate change, for example, future greenhouse gas scenarios. On the other hand, 2006 was the sixth-lowest precipitation year in the 49-yr Greenland record, which, together with the high 2006 runoff, resulted in the second-lowest annual seasonal mass balance on record (Table 2).

Preconditioning of the snowpack and firn is very important for subsequent melt and runoff: in the GrIS 1958–2003 annual SMB series of Hanna et al. (2005), high runoff years (except 2003) are generally synchronous with low precipitation/accumulation and vice versa. More accumulation results in a higher albedo for a longer time, which reduces absorbed energy available for melt; the available surface energy needs to melt any snow first before ice can melt in the ablation region; in addition higher volumes of meltwater are retained in the thicker snowpack, which tends to reduce net runoff. These processes and related surface albedo changes are implicitly taken into account in the different degree-day factors for snow and ice used in our degree-day model, and by the meltwater retention scheme. Low snow accumulation in 2006 (as well as high summer temperatures) may have contributed to the high 2006 runoff (Fig. 5 and Table 2). However, the accumulation–ablation relation is complex, modulated by other factors, including energy balance of the snowpack, and timing, intensity and duration of precipitation and high summer melt events.

Because of conflicting GrIS accumulation/ablation (modeled) trends for the past half century, the GrIS mass contributed by increased accumulation largely (~75%–80%) offsets that lost from enhanced meltwater. Therefore, analysis of our modeled SMB series does not clearly support climate-model predictions suggesting that increased Greenland accumulation may be outweighed by rising runoff, yielding a net mass loss for the ice sheet, in a warmer climate (Huybrechts et al. 2004). However, additional surface meltwater seeping through to the bed of the ice sheet during warmer conditions may prompt increased flow speed of Greenland outlet glaciers (Zwally et al. 2002), as seen in the InSAR results (Rignot and Kanagaratnam 2006).

5. Discussion and concluding remarks

The significant increases in observed Greenland margin summer temperatures and modeled runoff, the new 2003 and 2005 observed temperature and snowmelt records, and highly significant correlation of recent Greenland with Northern Hemisphere temperatures since the early 1990s, collectively suggest that an expected response of the GrIS to global warming may well be emerging. This signal can be set against a background of natural variability, including regional changes in atmospheric circulation related to the NAO. We therefore place the recent studies concerning current GrIS mass balance changes that are typically restricted to a few years or at most a decade or so of observations, in a longer-term (multidecadal) climatic perspective. For example, the thinning of the margins and volume loss of the GrIS derived from laser altimetry (Krabill et al. 2004; Thomas et al. 2006) is based on 11 yr of data and may well at least partly reflect the strong warming trend since the early 1990s, but similar surveys made during the 1970s and 1980s would have obtained quite different results and perhaps even a different sign and pattern of elevation/volume changes.

The new Greenland summer warmth and snowmelt records are also consistent in timing with recent increased losses of summer Arctic sea ice (Comiso 2006; Shein 2006). Indeed, reduced extent and duration of winter sea ice should expose Greenland to more advection from a warmer surrounding ocean, extend its snowmelt and runoff seasons, and possibly lead to enhanced snow accumulation. High sea surface temperature (SST) anomalies around 1°–2°C are evident in the northern North Atlantic surrounding southern Greenland in both the summers (June–August) of 2005 and 2006 (more information is available online at http://iridl.ldeo.columbia.edu/maproom/.Global/.Ocean_Temp/Anomaly.html), although small pools of cool water (0° to −1°C anomaly) interestingly lay immediately adjacent to the southeast Greenland coast, especially in 2006: this could indicate additional injection of relatively cold Greenland meltwater into the East Greenland Coastal Current (Bacon et al. 2002) in these high melt and runoff years.

Our finding (from our reanalysis-based model results) that enhanced GrIS runoff is largely balanced by increased snow accumulation, is subject to uncertainties in our SMB model that are very hard to quantify, primarily because of the lack of ablation measurements for validating modeled runoff. However, modeled accumulation has previously been validated against the main Greenland network of shallow ice cores, with generally good statistical agreement of observed and modeled net snow accumulation (Hanna et al. 2006), and we highlight once again the good agreement of our annual runoff values with an independent GrIS runoff series (Box et al. 2006) for the period of overlap. Also, surface mass balance (including accumulation and runoff) trends are less sensitive than absolute values to remaining model biases. Comparison of new higher-resolution (1 km × 1 km) runoff/SMB model results against sparse and localized but available spot historic measurements of ablation should enable reevaluation of this model result.

Southern Greenland was at least as warm during the 1930s/1940s, according to another analysis of annual and summer air temperature data from just two available stations, Nuuk and Tasiilaq (Chylek et al. 2006), so we expect that parallel increases in GrIS melt and runoff then occurred that are comparable with the last decade or so (1995–2006) records. The 1930s/1940s warm phase affected high northern latitudes only, in contrast to the more general global warming since ~1990 (Johannessen et al. 2004). However, the presence of an early twentieth-century warm phase illustrates the sensitivity of the GrIS mass balance to changes in atmospheric circulation that affect the relative dominance of regional versus hemispheric climate. Our statistical analysis suggests that southern Greenland climate is currently responsive to general Northern Hemisphere warming. As a consequence, the GrIS is likely to be highly susceptible to ongoing global warming, in which Greenland temperatures are predicted to increase ~1°–8°C by 2100 with typical model simulations favoring a 4°–5°C increase (Gregory et al. 2004; Huybrechts et al. 2004).

Acknowledgments. We thank the British Atmospheric Data Centre, A. Stephens, and ECMWF for providing (re)analysis data, the Climatic Research Unit and Hadley Centre for Northern Hemisphere temperature data, Dr. J. Hurrell's excellent web site for NAO index data, and the NCEP, Environmental Monitoring Center/University of Columbia for SST data. The Cathy, Kenton, and GISP2 AWS data used for part of the Summit temperature series were enabled by the National Science Foundation and are courtesy of the University of Wisconsin (available online at http://uwamrc.ssec.wisc.edu/greenland.html). G. Aðalgeirsdóttir, G. Bigg, C. Clark, F. Ng, T. Scambos, and M. Serreze kindly provided useful comments on the manuscript, and P. Coles and G. Allsopp drafted figures. P.H. acknowledges support through the Belgian Federal Public Planning Service Science Policy Research Programme on Science for a Sustainable Development under Contract SD/CS/01A. The research carried out at the Cooperative Institute for Research in Environmental Sciences, University of Colorado and also at NASA/GSFC, was supported by NASA's Cryospheric Sciences Program.

REFERENCES

Abdalati, W., and K. Steffen, 1997: Snowmelt on the Greenland ice sheet as derived from passive microwave satellite data. *J. Climate,* **10,** 165–175.

Alley, R., and Coauthors, 2007: Summary for policymakers. *Climate Change 2007: The Physical Science Basis,* S. Solomon et al., Eds., Cambridge University Press, 1–18. [Available online at http://www.ipcc.ch/SPM2feb07.pdf.]

Bacon, S., G. Reverdin, I. G. Rigor, and H. M. Snaith, 2002: A freshwater jet on the east Greenland shelf. *J. Geophys. Res.,* **107,** 3068, doi:10.1029/2001JC000935.

Box, J. E., and A. E. Cohen, 2006: Upper-air temperatures around Greenland: 1964–2005. *Geophys. Res. Lett.,* **33,** L12706, doi:10.1029/2006GL025723.

——, and Coauthors, 2006: Greenland ice sheet surface mass balance variability (1988–2004) from calibrated polar MM5 output. *J. Climate,* **19,** 2783–2800.

Brohan, P., J. J. Kennedy, I. Harris, S. F. B. Tett, and P. D. Jones, 2006: Uncertainty estimates in regional and global observed temperature changes: A new dataset from 1850. *J. Geophys. Res.,* **111,** D12106, doi:10.1029/2005JD006548.

Cappelen, J., B. V. Jørgensen, E. V. Laursen, L. S. Stannius, and R. S. Thomsen, 2001: The observed climate of Greenland, 1958–99—With climatological standard normals, 1961–90. Danish Meteorological Institute Tech. Rep. 00-18, Ministry of Transport, Copenhagen, Denmark, 152 pp.

Chen, J. L., C. R. Wilson, and B. D. Tapley, 2006: Satellite gravity measurements confirm accelerated melting of Greenland ice sheet. *Science,* **313,** 1958–1960.

Chylek, P., M. K. Dubey, and G. Lesins, 2006: Greenland warming of 1920–1930 and 1995–2005. *Geophys. Res. Lett.,* **33,** L11707, doi:10.1029/2006GL026510.

Comiso, J. C., 2006: Arctic warming signals from satellite observations. *Weather,* **61,** 70–76.

Gregory, J. M., and P. Huybrechts, 2006: Ice-sheet contributions to future sea-level change. *Phil. Trans. Roy. Soc. London,* **A364,** 1709–1731.

——, ——, and S. C. B. Raper, 2004: Climatology: Threatened loss of the Greenland ice-sheet. *Nature,* **428,** 616.

Hanna, E., and J. Cappelen, 2003: Recent cooling in coastal southern Greenland and relation with the North Atlantic Oscillation. *Geophys. Res. Lett.,* **30,** 1132, doi:10.1029/2002GL015797.

——, P. Huybrechts, I. Janssens, J. Cappelen, K. Steffen, and A. Stephens, 2005: Runoff and mass balance of the Greenland ice sheet: 1958–2003. *J. Geophys. Res.,* **110,** D13108, doi:10.1029/2004JD005641.

——, J. McConnell, S. Das, J. Cappelen, and A. Stephens, 2006: Observed and modeled Greenland ice sheet snow accumulation, 1958–2003, and links with regional climate forcing. *J. Climate,* **19,** 344–358.

Howat, I. M., I. Joughin, S. Tulaczyk, and S. Gogineni, 2005: Rapid retreat and acceleration of Helheim Glacier, east Greenland. *Geophys. Res. Lett.,* **32,** L22502, doi:10.1029/2005GL024737.

Hurrell, J. W., 1995: Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science,* **269,** 676–679.

Huybrechts, P., J. Gregory, I. Janssens, and M. Wild, 2004: Modelling Antarctic and Greenland volume changes during the 20th and 21st centuries forced by GCM time slice integrations. *Global Planet. Change,* **42,** 83–105.

Janssens, I., and P. Huybrechts, 2000: The treatment of meltwater retention in mass-balance parameterizations of the Greenland ice sheet. *Ann. Glaciol.,* **31,** 133–140.

Johannessen, O. M., and Coauthors, 2004: Arctic climate change: Observed and modelled temperature and sea-ice variability. *Tellus,* **56A,** 328–341.

——, K. Khvorostovsky, M. W. Miles, and L. P. Bobylev, 2005: Recent ice-sheet growth in the interior of Greenland. *Science,* **310,** 1013–1016.

Jones, P. D., M. New, D. E. Parker, S. Martin, and I. G. Rigor, 1999: Surface air temperature and its changes over the past 150 years. *Rev. Geophys.,* **37,** 173–200.

Krabill, W., and Coauthors, 2000: Greenland ice sheet: High-elevation balance and peripheral thinning. *Science,* **289,** 428–430.

——, and Coauthors, 2004: Greenland Ice Sheet: Increased coastal thinning. *Geophys. Res. Lett.,* **31,** L24402, doi:10.1029/2004GL021533.

Luthcke, S. B., and Coauthors, 2006: Recent Greenland ice mass loss by drainage system from satellite gravity observations. *Science,* **314,** 1286–1289.

Nghiem, S. V., K. Steffen, G. Neumann, and R. Huff, 2007: Snow accumulation and snowmelt monitoring in Greenland and Antarctica. *Dynamic Planet: Monitoring and Understanding a Dynamic Planet with Geodetic and Oceanographic Tools: IAG Symposium, Cairns, Australia, 22–26 August 2005,* P. Tregoning and C. Rizos, Eds., Springer, 31–38.

Overland, J. E., and M. Wang, 2005: The Arctic climate paradox: The recent decrease of the Arctic Oscillation. *Geophys. Res. Lett.,* **32,** L06701, doi:10.1029/2004GL021752.

Parizek, B. R., and R. B. Alley, 2004: Implications of increased Greenland surface melt under global-warming scenarios: Ice-sheet simulations. *Quat. Sci. Rev.,* **23,** 1013–1027.

Ramillien, G., A. Lombard, A. Cazenave, E. R. Ivins, M. Llubes, F. Remy, and R. Biancale, 2006: Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE. *Global Planet. Change,* **53,** 198–208.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Globally complete analyses of sea surface temperature, sea ice and night marine air temperature, 1871–2000. *J. Geophys. Res.,* **108,** 4407, doi:10.1029/2002JD002670.

——, P. Brohan, D. E. Parker, C. K. Folland, J. J. Kennedy, M. Vanicek, T. Ansell, and S. F. B. Tett, 2006: Improved analyses of changes and uncertainties in sea surface temperature measured in situ since the mid-nineteenth century: The HadSST2 dataset. *J. Climate,* **19,** 446–469.

Rignot, E., and P. Kanagaratnam, 2006: Changes in the velocity structure of the Greenland ice sheet. *Science,* **311,** 986–990.

Robock, A., and J. P. Mao, 1995: The volcanic signal in surface temperature observations. *J. Climate,* **8,** 1086–1103.

Serreze, M. C., and J. A. Francis, 2006: The Arctic amplification debate. *Climatic Change,* **76,** 241–264.

Shein, K. A., 2006: State of the climate in 2005. *Bull. Amer. Meteor. Soc.,* **87** (6), S1–S102.

Shuman, C. A., R. B. Alley, S. Anandakrishnan, and C. R. Stearns, 1995: An empirical technique for estimating near-surface air temperature trends in central Greenland from SSM/I brightness temperatures. *Remote Sens. Environ.,* **51,** 245–252.

——, M. A. Fahnestock, R. A. Bindschadler, R. Alley, and C. R. Stearns, 1996: Composite temperature record from the Greenland summit, 1987–1994: Synthesis of multiple automatic weather station records and SSM/I brightness temperatures. *J. Climate,* **9,** 1421–1428.

——, K. Steffen, J. E. Box, and C. R. Stearns, 2001: A dozen years of temperature observations at the summit: Central Greenland automatic weather stations 1987–99. *J. Appl. Meteor.,* **40,** 741–752.

Steffen, K., and J. E. Box, 2001: Surface climatology of the Greenland ice sheet: Greenland climate network 1995–1999. *J. Geophys. Res.,* **106,** 33 951–33 964.

Stott, P. A., G. S. Jones, J. A. Lowe, P. Thorne, C. Durman, T. C. Johns, and J.-C. Thelen, 2006: Transient climate simulations with the HadGEM1 climate model: Causes of past warming and future climate change. *J. Climate,* **19,** 2763–2782.

Thomas, R., 2004: Force-perturbation analysis of recent thinning and acceleration of Jakobshavn Isbrae, Greenland. *J. Glaciol.,* **50,** 57–66.

——, E. Frederick, W. Krabill, S. Manizade, C. Martin, and A. Mason, 2005: Elevation changes on the Greenland ice sheet from comparison of aircraft and ICESat laser-altimeter data. *Ann. Glaciol.,* **42,** 77–82.

——, ——, ——, ——, and ——, 2006: Progressive increase in ice loss from Greenland. *Geophys. Res. Lett.,* **33,** L10503, doi:10.1029/2006GL026075.

Velicogna, I., and J. Wahr, 2006: Acceleration of Greenland ice mass loss in spring 2004. *Nature,* **443,** 329–331.

Zwally, H. J., W. Abdalati, T. Herring, K. Larson, J. Saba, and K. Steffen, 2002: Surface melt-induced acceleration of Greenland ice-sheet flow. *Science,* **297,** 218–222.

——, M. B. Giovinetto, J. Li, H. G. Cornejo, M. A. Beckley, A. C. Brenner, J. L. Saba, and D. Yi, 2005: Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992–2002. *J. Glaciol.,* **51,** 509–527.