HYDROLOGICAL PROCESSES
Hydrol. Process. **23**, 7–30 (2009)

Hydrologic response of the Greenland ice sheet: the role of oceanographic warming

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Abstract:

The response of the Greenland ice sheet to ongoing climate change remains an area of great uncertainty, with most previous studies having concentrated on the contribution of the atmosphere to the ice mass-balance signature. Here we systematically assess for the first time the influence of oceanographic changes on the ice sheet. The first part of this assessment involves a statistical analysis and interpretation of the relative changes and variations in sea-surface temperatures (SSTs) and air temperatures around Greenland for the period 1870–2007. This analysis is based on HadISST1 and Reynolds OI.v2 SST analyses, *in situ* SST and deeper ocean temperature series, surface-air-temperature records for key points located around the Greenland coast, and examination of atmospheric pressure and geopotential height from NCEP/NCAR reanalysis. Second, we carried out a novel sensitivity experiment in which SSTs were perturbed as input to a regional climate model, and document the resulting effects on simulated Greenland climate and surface mass balance. We conclude that sea-surface/ocean temperature forcing is not sufficient to strongly influence precipitation/snow accumulation and melt/runoff of the ice sheet. Additional evidence from meteorological reanalysis suggests that high Greenland melt anomalies of summer 2007 are likely to have been primarily forced by anomalous advection of warm air masses over the ice sheet and to have therefore had a more remote atmospheric origin. However, there is a striking correspondence between ocean warming and dramatic accelerations and retreats of key Greenland outlet glaciers in both southeast and southwest Greenland during the late 1990s and early 2000s. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS Greenland ice sheet; climate change; global warming; sea surface temperature; air temperature

Received 28 January 2008; Accepted 6 May 2008

INTRODUCTION

Much recent research indicates increased mass loss of the Greenland ice sheet (GrIS) during the past 15–50 years, with new summer temperature, melt and runoff records within the past 5 years noted for this timeframe (Hanna *et al.*, 2008). Although longer climate records indicate that Greenland was at least as warm during the 1920s to the 1940s as in the last few years (Hanna *et al.*, 2007), there are major concerns and uncertainties relating to enhanced current and future mass losses due to ongoing global warming. The GrIS contains about a tenth of the world's freshwater, is vulnerable to mass loss by climate warming, and has a potential contribution of $\sim$7 m to global sea-level rise (Hanna and Braithwaite, 2003; Dowdeswell, 2006). The ice sheet covers an area of $\sim 1{\cdot}7 \times 10^6$ km^2, equal to $\sim$82% of the total area of Greenland (Ohmura *et al.*, 1999; Dowdeswell, 2006). It is a huge ice dome with two main peaks: one at 3220 m at Summit (about 72 °N, 29 °W), and the other at 2850 m in the south at about 64 °N, 44 °W (Hanna and Braithwaite, 2003). The ice sheet is up to about 3 km thick in the middle, and its great weight depresses the underlying crust, which assumes the concave shape of a saucer. The ice sheet has waxed and waned in response to natural climatic-forcing factors (e.g. changes in solar radiation) or internal variability over millennia: during the last Ice Age, which peaked about 20 000 years ago, it expanded to the continental shelf break and shortly connected with the Laurentide ice sheet that covered much of North America, while more recently it has receded significantly from a 'high stand' during the Little Ice Age (Boggild and Podlech, 2006). Given the huge store of freshwater locked up in Greenland ice, it is essential to improve understanding both of (1) oceanographic and atmospheric factors controlling its mass-balance sensitivity and hydrologic response to ongoing climate change, and (2) the implications of changing freshwater runoff from the ice sheet on oceanographic/climatic conditions—most notably the thermohaline circulation and North Atlantic climate change. Owing to limitations of space, we will not explore the second factor except to briefly report that recent modelling studies give mixed results concerning the possible influence of GrIS melt on the thermohaline circulation projected for the 21st century, with one coupled general circulation model (GCM)–GrIS model

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experiment suggesting an abrupt and rather strong weakening of the thermohaline circulation by 2100 (Fichefet *et al.*, 2003), while other experiments suggest a more limited impact (Jungclaus *et al.*, 2006; Driesschaert *et al.*, 2007; Mikolajewicz *et al.*, 2007). However, knowledge of the second factor ultimately depends on achieving a better understanding of the first, so in the remainder of this study, we present a review and original data analysis directly addressing the first factor.

Observational evidence of recent hydrological changes of GrIS

Observational studies have provided many insights into recent GrIS hydrological/mass balance changes. Airborne and satellite laser-altimetry data analyses indicate a volume loss of about 60 km^3 per year in the 1993/1994 to 1998/1999 period, that increased to about 80 km^3 per year in 1997–2003 (Krabill *et al.*, 2000, 2004; Thomas *et al.*, 2006). Various recent analyses of gravimetric (GRACE) satellite data suggest greater mass (volume) losses in the 101–226 Gt per year (111–248 km^3 per year) range within the recent few years, that is, 2002–2006 (Chen *et al.*, 2006; Luthcke *et al.*, 2006; Ramillien *et al.*, 2006; Velicogna and Wahr, 2006): the largest mass losses are generally indicated as being from low elevations ($< \sim 2000$ m) and especially in southeast (SE) Greenland, with partly compensating mass gains at higher elevations (>2000 m) (Luthcke *et al.*, 2006). Other altimetry data indicate substantial growth of the GrIS interior from 1992 to 2003 (Johannessen *et al.*, 2005; Thomas *et al.*, 2005; Zwally *et al.*, 2005), which may be partly attributable to increased atmospheric moisture and precipitation and/or shifting storm tracks forced by greenhouse gases (Trenberth *et al.*, 2007).

Satellite radar interferometry (InSAR) reveals widespread acceleration of Greenland glaciers, a pattern progressing northward since 1996, with an accompanying doubling of the ice sheet's volume deficit from approximately 90–220 km^3 per year (Rignot and Kanagaratnam, 2006), although it is as yet too early to say just how exceptional are these changes. The recent accelerations of Kangerdlugssuaq and Helheim (outlet) glaciers appear to be driving the recent (2001–2006) concentration of mass loss in SE Greenland (Luckman *et al.*, 2006; Stearns and Hamilton, 2007); however, the velocities of these glaciers appear to have decreased again in 2006 to near their previous rates (Howat *et al.*, 2007). Some of these margin changes may signal a response to recent climatic warming through infiltration of surface meltwater in a basal dynamic positive feedback mechanism (Zwally *et al.*, 2002; Parizek and Alley, 2004; Das *et al.*, 2008; Joughin *et al.*, 2008). Alternatively, thinning and breakup of Jakobshavn Glacier's SW Greenland floating ice tongue and acceleration of the glacier itself (e.g. Luckman and Murray, 2005)—as well as that of Helheim Glacier in SE Greenland—may have been induced, or at least influenced, by ocean forcing. (Thomas *et al.*, 2003; Howat *et al.*, 2005; Bindschadler, 2006).

Taking all approaches together, the general consensus is an accelerating mass loss of the GrIS over the past decade 1995–2005 (Lemke *et al.*, 2007); a recent survey concludes that the GrIS is currently losing ~100 Gt per year (Shepherd and Wingham, 2007). However, there remains considerable discrepancy among these pioneering observational estimates. Most of the observational studies have data spans of less than a decade, which also means that the interpretation of their results may be seriously affected by large year-to-year variability in GrIS mass turnover, e.g. sudden glacier accelerations (Rignot and Kanagaratnam, 2006). Since the Helheim and Kangerdlugssuaq glaciers have been shown to accelerate and decelerate over just a few years (Howat *et al.*, 2007), these 'speed-ups' may just represent flow variability on interannual time scales and therefore represent the 'weather' rather than the 'climate' of the GrIS (Howat *et al.*, 2007; Shepherd and Wingham, 2007).On the whole, we cannot be certain that the apparently accelerating GrIS mass loss and unexpected rapid changes in its outlet glaciers, represent a profound change in ice-sheet behaviour (Murray, 2006). The above studies alone, therefore, have yet to provide a convincing broad temporal perspective on how the GrIS might be responding to long-term climatic change, most notably the evident global and regional warming since the 1970s (IPCC, 2007).

Enhanced hydrological cycling of GrIS

Surface mass balance (SMB), essentially net snow accumulation minus meltwater runoff, time series are available, e.g. Hanna *et al.* (2005, 2007, 2008); Box *et al.* (2006); Fettweis (2007), which can help place the remotely sensed results into a longer, multi-decadal, climatic perspective. These series are based on meteorological models that assimilate observations for calibration and verification. Hanna *et al.* (2005, 2008) modelled runoff and hence SMB 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 European Centre for Medium-Range Weather Forecasts (ECMWF)/ERA-40 meteorological (re)analysis data and Greenland weather-station data. (The year 1958 marks the start of the ECMWF ERA-40 climate reanalysis and hence the Hanna *et al.* (2005, 2008) modelled SMB series.) Box *et al.* (2006) used the regional climate model (RCM) Polar MM5, driven by ECMWF operational analysis (meteorological) data (http://www.ecmwf.int/products/data/archive/descriptions/od/oper/index.html), and a network of automatic weather-station data, to estimate precipitation, surface-air energy fluxes and hence SMB of the GrIS for 1988–2004. Fettweis (2007) used the RCM Modèle Atmosphérique Régional (MAR) forced at its boundaries by ECMWF analysis to derive SMB for 1970–2006 (see Section on Sensitivity Experiments for more details). There is good agreement of respective annual SMB values from these independently derived SMB series for the period of published overlap (1970–2006 for the Hanna *et al.* (2008) and Fettweis (2007) modelled SMB, and 1988–2004 for all three series) (Figure 1(a)). However, by definition, none of these SMB series takes into account the mass losses from iceberg calving and basal melting, for which—due to difficulties of their observation and modelling—only crude estimates can currently be given. Iceberg calving is roughly equivalent to the amount of annual runoff, whereas basal melting, both below the ice sheet proper and the few ice shelves in the north (with relatively small total ice-shelf area), is probably relatively small for Greenland (Reeh *et al.*, 1999).

The longest (50-year; 1958–2007) currently available published GrIS SMB series reveals an upward trend of 123·0 km^3 or 55·1% in annual runoff from 1958–2007—which is statistically significant in view of the standard deviation of the annual values $\sigma = 70{\cdot}2\ km^3$; moreover, 6 of the 10 highest runoff years have occurred since 2001 inclusive (Hanna *et al.*, 2008, updated) (Figure 1(b)). On the basis of the updated Hanna *et al.* (2008) GrIS SMB series, GrIS precipitation follows a significantly increasing trend of 88·7 km^3 or +15·7% over this 50-year period, compared with $\sigma = 69{\cdot}0\ km^3$ or 11·3% (Figure 1(b)). Additional precipitation, mainly in the form of snow accumulation, therefore largely (about three quarters) offsets rising Greenland runoff in terms of the SMB. There is a relatively small and insignificant negative trend in SMB of $-34{\cdot}2\ km^3$ per year ($\sigma = 104{\cdot}9\ km^3$) from 1958 to 2007, highlighting the sensitive balance between increased snow accumulation in the interior of the ice sheet and increased runoff around

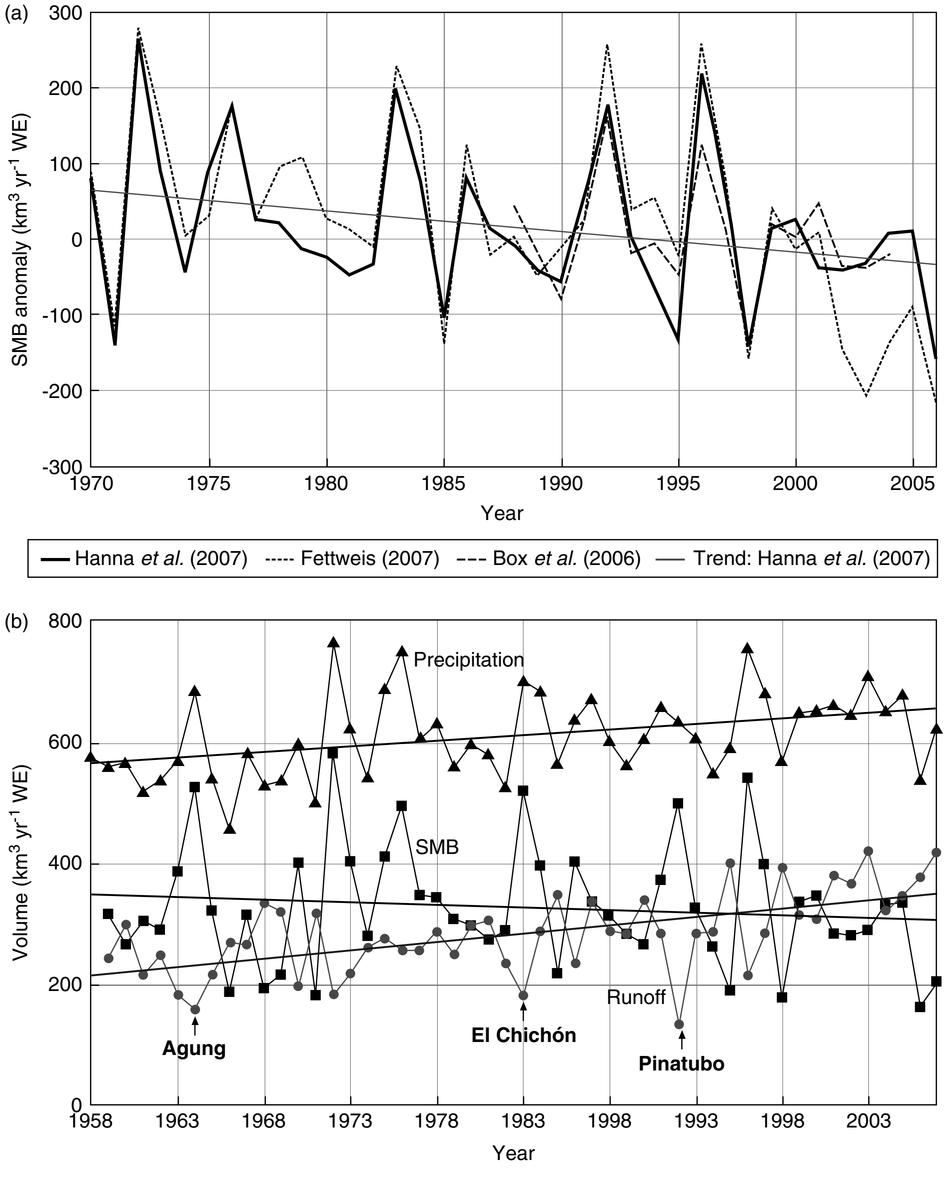


Figure 1. (a) Greenland ice-sheet surface mass balance (SMB) annual series from three independent studies: Fettweis (2007); Hanna *et al.* (2008) and Box *et al.* (2006); (b) Greenland ice-sheet precipitation, surface meltwater runoff and surface mass balance (SMB = solid precipitation minus evaporation minus runoff) series for 1958–2007 (updated series from Hanna *et al.*, 2007, 2008). Note significantly increasing precipitation and runoff trends but negligible SMB change. We may conclude from the trend analysis that the hydrological system of the ice sheet has become more vigorous, i.e. with more mass turnover at the surface. The dynamic response to the increased turnover remains critical to understand

the edges. The further mass loss from ice dynamics due to accelerated flow of outlet glaciers was at least several times larger for the recent few warmest years (Rignot and Kanagaratnam, 2006).

Recent high snow accumulation events occurred in winter 2004/2005, concentrated in West Greenland (Nghiem *et al*., 2007), and winter-spring 2002/2003 in SE Greenland (Krabill *et al*., 2004; Box *et al*., 2005; Hanna *et al*., 2006a). Huybrechts *et al.* (2004) hypothesized that such events may become more frequent in Greenland as storm tracks intensify or shift position with future climate change. On the other hand, 2006 was the 6th lowest precipitation year in the 50-year ECMWF Greenland record, which—together with the high 2006 runoff—resulted in the second-lowest annual ice-sheet net mass input (SMB) since 1958 (Hanna *et al*., 2007, 2008). Enhanced climate variability may also be an artefact of global warming (IPCC, 2007).

Notably, the existing published long-term (multi-decadal) SMB series (e.g. Hanna *et al*., 2005, 2008) do not fully bear out model predictions, which suggest that increased Greenland accumulation may be significantly outweighed by rising runoff in a warmer climate (Huybrechts *et al*., 2004). However, according to the mechanism proposed by Zwally *et al.* (2002), the so-called 'Zwally effect', the additional meltwater that we observe may already be more readily reaching the bed of the GrIS and prompting accelerated flow of Greenland outlet glaciers—which could contribute to the enhanced flow detected by Rignot and Kanagaratnam (2006), although this is far from certain (Hanna *et al*., 2007). Such amplification might explain the significant increases in overall mass loss strongly suggested by the consensus of GrIS mass balance estimates for the past decade (Lemke *et al*., 2007) but is far from proven. However, since some recent key glacier accelerations in East Greenland have already subsided (Howat *et al*., 2007), the sustainability of the enhanced flow is questionable. If the Zwally effect is dominant (which very much remains to be shown), then flow variability should be directly connected to surface-runoff variability but there is no evidence that this is the case on the glaciers that discharge most of the Greenland ice; however, this could be interpreted as being due to other mechanisms, including hydrofracturing from increased meltwater percolation into crevasses that may contribute to ice-front retreat (Joughin *et al*., 2008).

Climatic interpretation

Southern Greenland summer warming since the early 1990s reflects general Northern Hemisphere and global warming (Hanna *et al*., 2008). We may thus link significantly increased GrIS melt and runoff during that time to global climate warming. However, there was less apparent linkage between Greenland and the Northern Hemisphere average during a Greenland warming phase between 1918 and 1947 (Hanna *et al*., 2007). According to a composite record of seven coastal Greenland stations south of 70°N latitude (updated from Hanna and Cappelen, 2003), summer (JJA) 2003 was the warmest since 1958, while the second warmest summer 2005 had the most extensive anomalously warm condition over the ablation zone of the ice sheet, which caused a record melt-area extent according to calculations by Hanna *et al.* (2008). Summer 2006 was the fifth warmest in coastal southern Greenland since 1958, and 2006 had the third highest runoff in the last 49 years from the ice sheet according to the Hanna *et al.* (2008) SMB model.

Significant increases 1958–2006 in Greenland margin summer temperatures and runoff, record-high 2003 summer temperature and 2005 snowmelt records, and a highly significant correlation of recent Greenland with Northern Hemisphere temperatures, collectively suggest that an expected signal of the GrIS to global warming may be emerging (Hanna *et al*., 2008). This signal now appears to be distinct from natural/regional climatic fluctuations, such as those related to changes in the North Atlantic Oscillation (e.g. Hanna and Cappelen, 2003).

Our initial analysis of updated meteorological data from Greenland reveals summer 2007 as the second warmest of the last 50 years, while July 2007 was marginally the warmest July of the last 50 years, in southern coastal Greenland. Preliminary results from a simulation made with the RCM MAR forced with ECMWF re/analysis data, show a record surface melt (592 km^3 per year) of the GrIS during summer 2007 compared with 1979–2006 (Fettweis, 2007, updated). This record melt is associated with very low snowfall (361 km^3 per year) during the first three quarters of 2007, suggesting a very low SMB rate for the end of 2007 (Fettweis, 2007, updated). This model result should be considered in combination with two further recently published observation-based studies using passive-microwave satellite data. First, a Greenland surface-melt index (melting area times number of melting days) compiled by Tedesco (2007) reached record high levels at high elevations (>2000 m) in 2007, although the overall snowmelt extent and melt index for the whole ice sheet were not exceptional, compared with the previous 18 years. Tedesco's result is indicative of unusually high temperatures at high elevations of Greenland in the 2007 summer melt season. Second, Mote (2007) found that although the total GrIS area with melt was not remarkable in summer 2007, there was a 60% greater seasonal melt departure this past summer than the previous record in 1998 (out of a data series spanning 1973/1974, 1976 and 1979–2007).

The new Greenland summer warmth and snowmelt records are consistent in timing with recent increased losses of summer Arctic sea-ice (e.g. Comiso, 2006; Shein *et al*., 2006; Richter-Menge *et al*., 2007). Indeed, reduced extent and duration of winter sea-ice should expose Greenland to enhanced warm air advection from surrounding seas, lengthening snowmelt and runoff seasons and possibly enhancing snow accumulation—the latter a negative feedback for ice-sheet response to climate warming. The feedback will be accentuated by increased SSTs around Greenland in a warming climate. Moreover, higher sea temperatures are linked with enhanced ice-shelf/floating ice tongue basal melt rates and—probably more importantly in Greenland but still to be proven—the unpinning of outlet glaciers leading to at least temporarily accelerated ice flow and hence mass loss. Mass, momentum and energy exchanges between the ocean and atmosphere can partly be defined by analysing relative temperature differences between the two media (e.g. Bigg, 2003). Hanna *et al.* (2006b) recently studied such differences for several new pan-Icelandic SST records. Although Iceland is situated in a climatically crucial area of the North Atlantic, Greenland is the world's largest island and has an ice sheet similarly sensitive to changes in climate and heat from the surrounding seas. SSTs are an important aspect of Greenland climate (and hence glaciological) variability—an aspect that has not been systematically studied before to the authors' best knowledge, but which we address in this paper.

DATA/METHODOLOGY

Monthly air-temperature series to the end of 2006 from four key long-term climatological stations situated around the coast of southern Greenland (Table I; Figure 2), were obtained from a recent DMI technical report (Cappelen *et al.*, 2007) and updated through summer 2007 for the purposes of this study. The four stations are representative of conditions around the marginal zone of the southern GrIS, where much surface meltwater runoff and calving occurs each summer season.

For each of the four stations, monthly SST data representative of the nearby open ocean were extracted from the HadISST1 dataset (Rayner *et al.*, 2003), as a basis for air temperature–SST comparisons (see Table I and Figure 2 for locations of HadISST1 pixels used in the present study). HadISST1 is a state-of-the-art monthly SST analysis covering the period 1870–2007, is updated each month in near-real time, and is a standard SST database for climatological studies. HadISST1

Table I. Geodetic information about HadISST1 grid cells and neighbouring DMI Greenland climate stations used in study

HadISST1 grid cell	DMI station/s			
	Name/s	Lat (°N)	Lon (°W)	Elevation (m)
69 °N, 55 °W	04 216/04 221 Ilulissat	69·23	51·07	29
64 °N, 53 °W	04 250 Nuuk	64·17	51·75	80
59 °N, 45 °W	04 262 Ivigtut/04 270 Narsarsuaq	61·17	45·42	27
65 °N, 38 °W	04 360 Tasiilaq	65·60	37·63	50

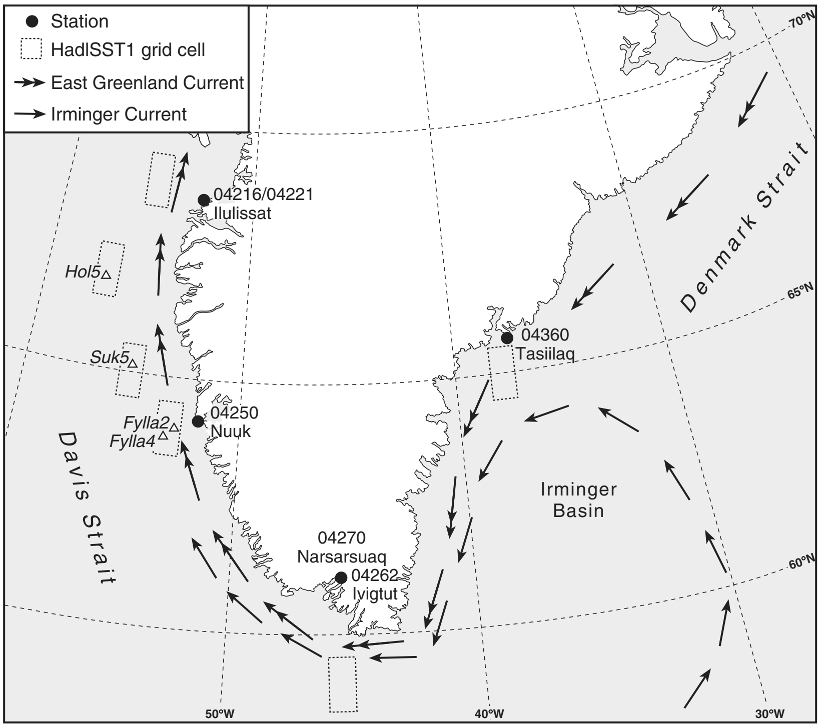


Figure 2. Map showing location of HadISST1 grid cells, DMI Greenland climate stations and ocean stations used in this study. Produced by Paul Coles, University of Sheffield

was produced using a two-stage reduced-space optimal interpolation, quality controlled gridded *in situ* (ship and buoy) and satellite observations, homogenized sea-ice data and an empirically tuned algorithm to interpolate SST in the marginal ice zone (MIZ; important for high-latitude regions such as around Greenland) (Rayner *et al.*, 2003). The inevitable limitations of this kind of interpolation in data-poor regions, including most probably the high-latitude areas currently under consideration, necessitate caution when using HadISST1 in climatological studies; however, HadISST1 is considered to provide a good record of changing Northern Hemisphere sea-ice extent for the past century, and its smoothed long-term series agrees well with those of other major SST analyses for both the Greenland and other regions (Rayner *et al.*, 2003). Although the HadISST1 dataset is on a nominal 1° latitude × 1° longitude resolution, SST anomaly data were prepared (pre-processed) based on a 2° area resolution (from 1949; 4° before then) with anomalies weighted according to the number of observations in each 1° area cell; it is therefore not well suited to resolving small-scale SST features such as eddies in and around the Gulf Stream (Rayner *et al.*, 2003). It is nevertheless one of the best available SST datasets for examining long-term climate change over the past century.

HadISST1 data were supplemented by higher resolution (in both space and time) OI.v2 analysis (Reynolds *et al.*, 2002) for the purpose of creating maps of pan-Greenlandic SST anomalies for the past few years. OI.v2 is a weekly optimum interpolation of SST data from both *in situ* and satellite sensors onto a 1° latitude × 1° longitude grid, incorporates corrections for data bias, and uses a similar SST scheme to HadISST1 for the marginal ice zone; nevertheless some significant differences remain in the two SST analyses at high latitudes (Reynolds *et al.*, 2002). The main disadvantage is that OI.v2 analyses are only available for the period since November 1981. With both OI.v2 and HadISST1, sparse SST data in the MIZ limit analysis accuracy (Reynolds *et al.*, 2002), making comparison of results from these analysis with independent *in situ* SST time series (where available) highly desirable.

We therefore present an extended version of the Fylla Bank station 2 (Fylla2) measured ocean-temperature series, mean depth 0–40 m, off southwest (SW) Greenland (Figures 2 and 3). This is probably the best representation for the ocean (near-) surface temperature back in time for the West Greenland area. The basic Fylla Bank time series is for mid-June and extends back to 1950 (updated from Ribergaard, 2007); it is normally used when describing hydrographical conditions off West Greenland using a single time series, for example when looking at physical changes in relation to fisheries. Here, we extend this time series further back in time using monthly Smed-data SST anomalies, also for June (Smed, 1978). These anomaly data are based on whatever data Smed could find for a large area off SW Greenland. Nevertheless, the overlapping period (1950–1975) shows that the Smed data seem to be representative for Fylla2 ($r = 0{\cdot}70$), and thus the Fylla2 series has been extended—with an appropriate adjustment for the offset between the two series—back to 1875. These time series were first presented together by Buch and Hansen (1988), who used different running means for the two series, but these authors did not attempt to merge the means. There is reasonable qualitative, and significant quantitative, agreement of the new extended Fylla2/Smed series with HadISST1 data from the nearby pixel centred on 64°N, 53 °W (Figure 3). The Fylla2/Smed data (and other DMI sea-temperature profiles highlighted below) are thought not to have been assimilated into the HadISST1 analysis (Rayner, personal communication, 2007), so are therefore useful for independent verification purposes. Detrended correlation coefficients of June Fylla2/Smed SST against HadISST1 are $r = 0{\cdot}53$ for June HadISST1, $r = 0{\cdot}50$ for July HadISST1, $r = 0{\cdot}63$ for June/July/August

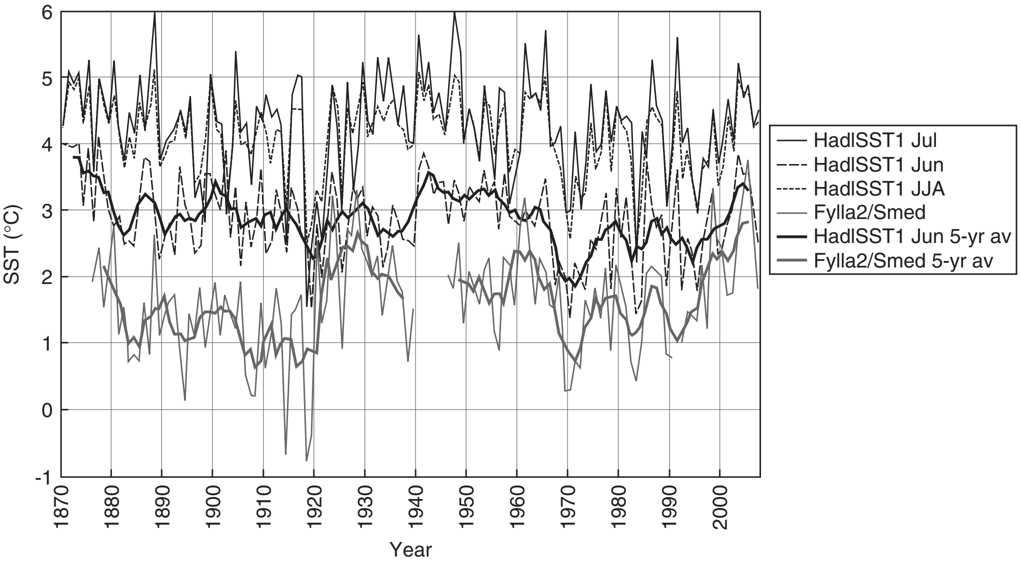


Figure 3. Comparison of HadISST1 at 64°N, 53 °W with *in situ* Fylla2/Smed summer SST

(= Northern Hemisphere summer) HadISST1, and $r = 0{\cdot}66$ for annual HadISST1; these are all highly significant ($p < 0{\cdot}01$) given the long time series. The main apparent difference between the series is the 41% greater amplitude in the Fylla2/Smed series, which may reflect more local-scale or coastal variations that tend to get averaged out in the (gridded) HadISST1 analysis.

We use satellite-derived velocity data of Greenland outlet glaciers to assess the sensitivity of these glaciers to SST variations around Greenland.

Regression and variance analyses were used to determine the level and significance of trend changes of data for various time periods, while lead/lag correlation analysis was used to compare air-temperature and SST variations, which might yield insights into physical mechanisms. In addition, we explore the sensitivity of a RCM of Greenland to perturbations in SST.

RESULTS

Long-term SST observations and comparison with air temperature

Long-term variations in pan-Greenland HadISST1 are shown for annual, summer (JJA) and July series in Figure 4. Detrended correlation coefficients between the series are all significant at the $p < 0{\cdot}01$ level, with several correlation coefficients exceeding $r = 0{\cdot}60$, and the highest correlations of $r = 0{\cdot}75$ ($r = 0{\cdot}65$) between annual SST for the points south and southwest (south and southeast) of Greenland (Table II). July SST series are less well correlated than the annual or summer (JJA) series, which we attribute to more predominant local/regional variations in the higher time- frequency (monthly) SST data causing more frequent divergence between the series.

SST series are compared with the neighbouring Greenland air-temperature series in Figure 5 and Tables III, IV and V. Good qualitative agreement is apparent, especially for 64 °N, 53 °W and Nuuk. SST–air temperature detrended correlation coefficients for long-term and standard climatological 'normal' periods are shown in Tables III and IV, and are mainly significant—although lower and often non-significant for the 1931–1960 normal period, suggesting either dataset problems (which might be exacerbated by a brief lack of data during World War Two) or a possible decoupling of conditions in the ocean and atmosphere around Greenland during this period (Figure 6). However, the fact that SST–air

Table II. Detrended correlation coefficients (r values) between HadISST1 long-term (1870–2007) sea-surface temperature for four key grid cells surrounding southern Greenland

	69 °N, 55 °W	64 °N, 53 °W	59 °N, 45 °W	65 °N, 38 °W
69 °N, 55 °W	1·00	0·68	0·57	0·47
64 °N, 53 °W	0·62(0·58)	1·00	0·75	0·46
59 °N, 45 °W	0·49(0·36)	0·59(0·45)	1·00	0·65
65 °N, 38 °W	0·51(0·42)	0·39(0·30)	0·61 (0·44)	1·00

Annual [summer (July)] values above (below) central diagonal.
All r values are significant at the $p < 0.01$ significance level. http://secamlocal.ex.ac.uk/people/staff/dbs202/cat/stats/corr.html.

Table III. Detrended correlation coefficients between contemporaneous and lead/lag summer (JJA) HadISST1 pan-Greenland sea-surface temperature and summer air-temperature series for neighbouring Greenland (near-)coastal stations (see Table I for details) for long-term and standard climatological 'normal' periods

Period ↓	69 °N, 55 °W	69 °N, 55 °W	69 °N, 55 °W	64 °N, 53 °W	64 °N, 53 °W	64 °N, 53 °W	59 °N, 45 °W	59 °N, 45 °W	59 °N, 45 °W	65 °N, 38 °W	65 °N, 38 °W	65 °N, 38 °W
SST lag →	0	−1	+1	0	−1	+1	0	−1	+1	0	−1	+1
All	**0·46**	0·07	0·13	**0·65**	**0·32**	**0·28**	**0·52**	*0·21*	0·05	**0·30**	0·15	0·07
1901–50	**0·56**	*0·36*	0·09	**0·62**	*0·28*	0·07	**0·48**	0·22	−0·14	0·19	0·22	0·08
1951–2000	**0·39**	−0·23	0·13	**0·60**	0·08	*0·28*	**0·59**	0·23	*0·28*	**0·51**	0·20	0·19
1871–1900	0·17	0·06	0·00				**0·66**	0·01	0·01			
1881–1910	0·14	0·02	−0·23				*0·41*	0·04	−0·19			
1891–1920	*0·39*	*0·40*	0·00	**0·52**	0·21	−0·17	**0·54**	0·11	−0·25	0·12	0·33	−0·06
1901–30	**0·58**	*0·41*	0·12	**0·73**	0·25	0·02	**0·51**	0·25	−0·21	0·16	0·35	0·12
1911–40	**0·65**	0·35	0·06	**0·68**	0·27	0·04	**0·73**	0·32	−0·05	0·28	*0·37*	0·06
1921–50	**0·58**	0·16	−0·03	**0·56**	0·30	0·03	**0·62**	0·36	−0·06	*0·46*	0·14	0·22
1931–60	0·20	−0·20	0·02	0·17	0·31	−0·02	**0·50**	−0·05	−0·24	0·13	−0·03	0·02
1941–70	0·15	−0·33	0·08	*0·46*	0·28	0·12	*0·37*	0·12	−0·05	0·13	0·02	0·05
1951–80	0·21	*−0·39*	0·05	**0·54**	0·21	0·20	**0·51**	0·20	0·04	*0·42*	0·27	0·12
1961–90	**0·57**	−0·29	0·09	**0·76**	0·20	*0·44*	**0·56**	0·33	0·34	**0·52**	0·30	0·02
1971–2000	**0·65**	−0·14	0·14	**0·67**	−0·07	0·29	**0·69**	0·14	0·29	**0·62**	0·14	0·08
1977–2006	**0·72**	−0·19	0·16	**0·76**	0·03	*0·38*	**0·63**	0·09	0·33	**0·65**	−0·10	0·08

Contemporaneous = 0; SST leading air temperature by 1 summer season (1 year) = −1; SST lagging air temperature by 1 summer season (1 year) = +1.
Significant r values are in italics for $p < 0{\cdot}05$ and bold for $p < 0{\cdot}01$.

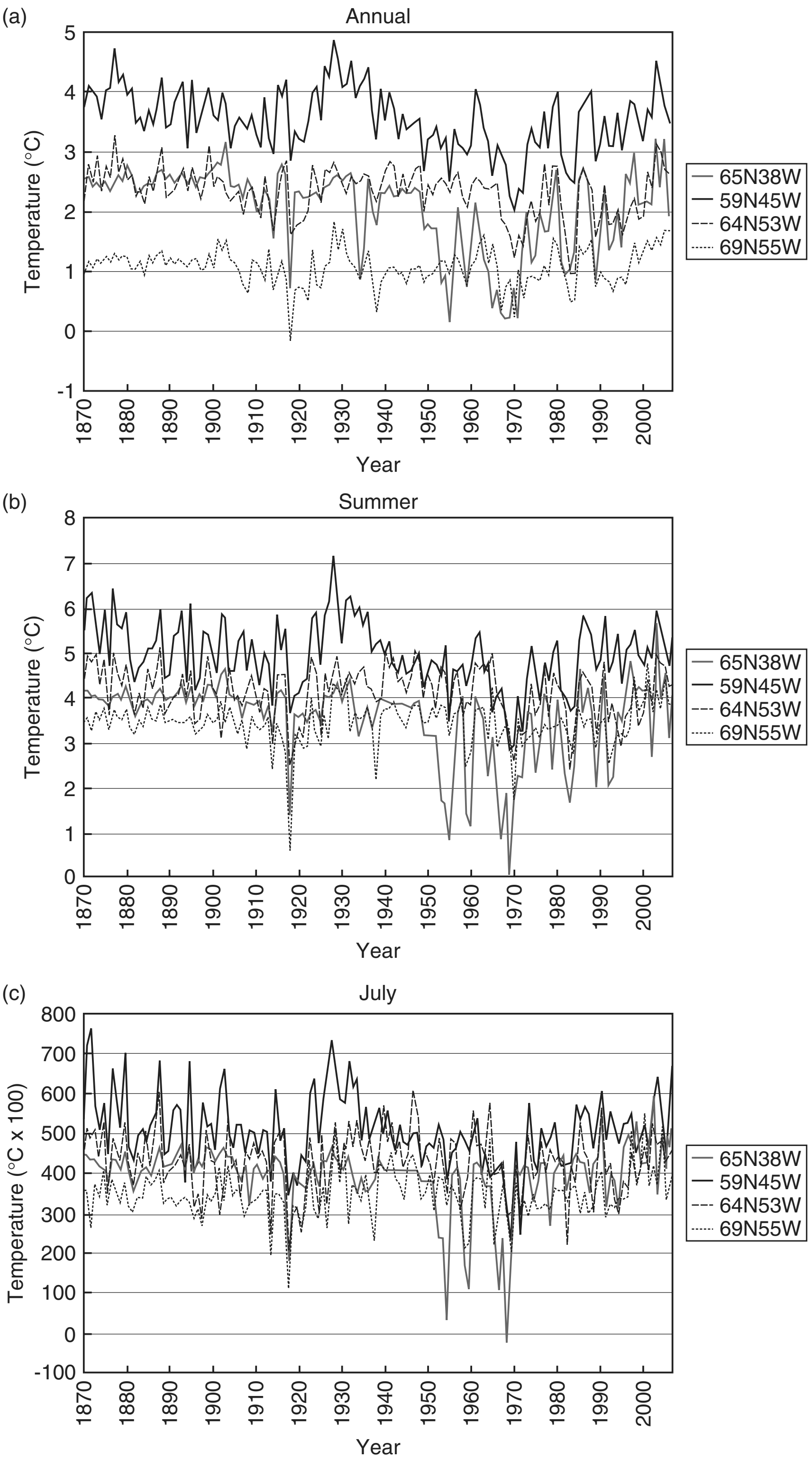


Figure 4. Long-term variations in pan-Greenland HadISST1 sea surface temperature at four key locations, shown in Figure 2, surrounding Greenland ice sheet: (a) annual; (b) summer (JJA); (c) July

temperature correlation coefficients are almost as high for the earlier 20th century as for the recent few decades (Tables III and IV; Figure 6), the long-term homogeneity tests already applied to the Greenland air-temperature series (Cappelen *et al.*, 2007), and the increasing number of observations fed into the HadISST1 dataset during this timeframe, leads us to favour the latter explanation.

SST/air temperature correlation coefficients are generally lower for 65°N, 38 °W/04 360 Tasiilaq (SE Greenland) than for south or southwest Greenland (Tables III and IV). This is presumed to be the result of the particularly vigorous East Greenland Coastal Current advecting different conditions from further upstream (Dickson *et al.*, 2007), and the periodic entrainment of heavy ice floes, which can act as a thermal barrier between sea and air.

Lead/lag correlations were also derived for monthly air temperature leading and lagging July SST by 1 and 2 months, and by summer (JJA) air temperature leading and lagging summer SST by one summer season (i.e. 1 year). From the results of these calculations, we infer the greatest overall statistical association between contemporaneous SST and air-temperature changes (Tables III and IV). This is especially evident in the case of the summer/annual data (Table III) but is also true of the July/monthly data too (Table IV). This finding suggests there may be a common response of both ocean and atmosphere to forcing from widespread changes in atmospheric circulation, as may be inferred from earlier analyses of recent air/sea temperature changes in SW Greenland and association with the North Atlantic Oscillation (NAO) index (Hanna and Cappelen, 2003; Buch *et al.*, 2004). This hypothesis is not inconsistent with some significant correlations for July SST lagging air temperature by 1 month, which are sometimes higher than correlations for contemporaneous SST/air temperature (Table IV). This may implicate atmospheric-circulation variations as a short-term (monthly-timescale) driver of air temperature and subsequent SST variability in summer (through air-sea heat exchange in the boundary layer) but needs further investigation. On the other hand, summer (JJA) SST is sometimes significantly correlated with air temperature of the following summer but not the other way round (Table III). This may be related to the high thermal inertia of sea water, which gives the climate system a long memory regarding SSTs. The main derivation of this part of the analysis shows that SST/air-temperature relations may work either way, and indicates the complexity of the Greenland climate system.

Trend-line changes for the whole, 50-year and climatological normal periods are not entirely consistent between the SST and air-temperature series (Table V). In fact, none of the overall (1901–2006) trends for (any of) the SST and air-temperature series are statistically significant (Table V). This is partly a reflection of relatively high SST during the 1870s, prior to a 30–40-year period of suppressed SST, which would seem to be a real feature (at least off SW Greenland) as it is present in the Fylla2/Smed as well as the HadISST1 series (Figures 3–5).

Significant warming of 04 250 Nuuk (SW Greenland) air temperature and adjacent SST occurred in 1901–1950 in both summer (JJA) and July—the only station/region to show such a feature. Although summer air temperature rose significantly for the same period at 04 262/02 470 Narsarsuaq, there was no significant trend in contemporaneous neighbouring SST (near southern tip of Greenland).

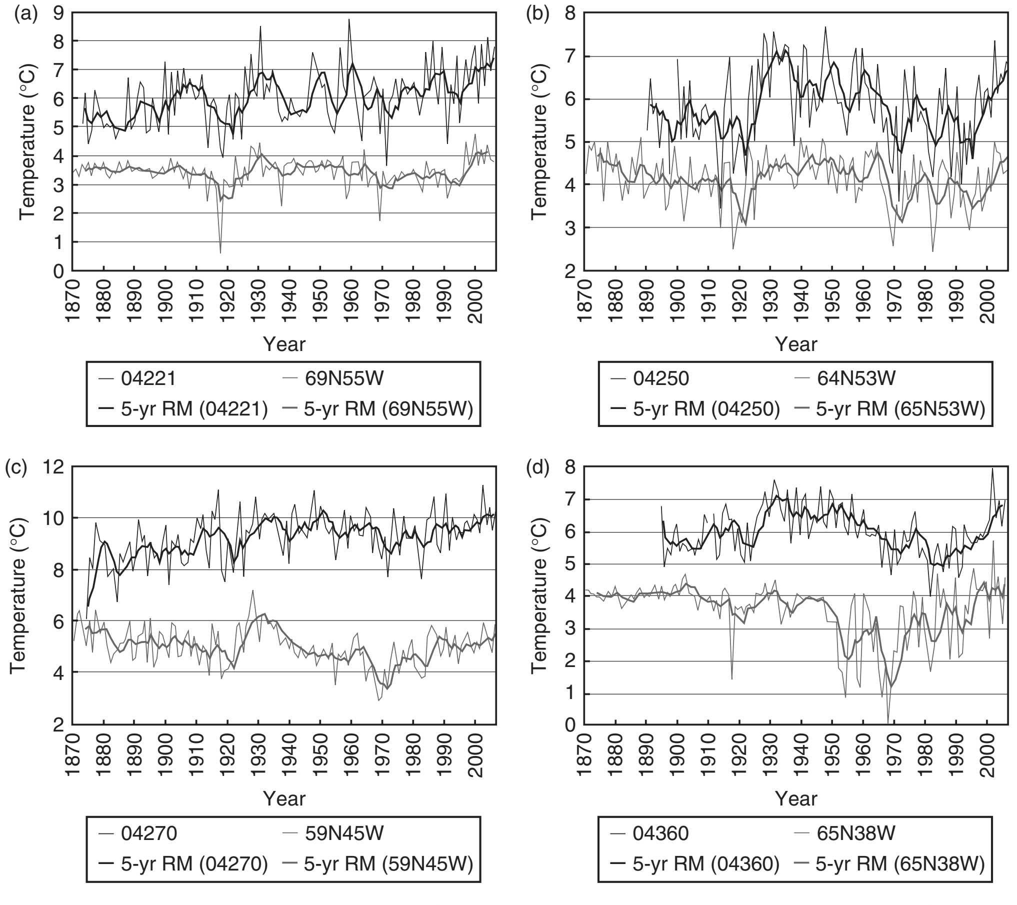


Figure 5. Comparison between summer (JJA) HadISST1 sea-surface temperature and neighbouring Greenland station air temperature: (a) 69 °N, 55 °W and 04 216/04 221 Ilulissat; (b) 64 °N, 53 °W and 04 250 Nuuk; (c) 59N, 45W and 04 262/04 270 Ivigtut/Narsarsuaq; (d) 65 °N, 38 °W and 04 360 Tasiilaq

Table IV. Detrended correlation coefficients between contemporaneous and lead/lag **July** HadISST1 pan-Greenland sea-surface temperature and monthly (May–September) air-temperature series for neighbouring Greenland (near-)coastal stations for long-term and standard climatological 'normal' periods

Period →	Lag	All	1901–50	1951–2000	1871–1900	1881–1910	1891–1920	1901–30	1911–40	1921–50	1931–60	1941–70	1951–80	1961–90	1971–2000	1977–2006
69 °N, 55 °W	0	**0·27**	*0·32*	0·18	0·24	0·31	0·18	*0·37*	**0·53**	0·34	−0·11	0·01	0·08	**0·48**	*0·44*	**0·56**
69 °N, 55 °W	−1	0·16	0·26	−0·01	0·27	**0·50**	*0·40*	0·36	0·28	0·20	−0·10	−0·10	−0·05	0·03	0·11	0·33
69 °N, 55 °W	−2	0·01	0·12	−0·12	−0·06	−0·08	0·23	0·09	0·22	0·09	0·07	−0·20	−0·25	*−0·40*	0·11	0·08
69 °N, 55 °W	+1	**0·31**	**0·44**	0·20	−0·13	−0·17	*0·43*	**0·49**	**0·49**	0·23	0·18	−0·08	−0·07	0·30	*0·44*	*0·38*
69 °N, 55 °W	+2	0·15	*0·29*	0·17	−0·10	0·11	*0·43*	*0·40*	0·30	0·28	0·00	*0·42*	0·28	0·33	0·01	−0·03
64 °N, 53 °W	0	**0·55**	**0·45**	**0·53**			**0·50**	**0·57**	**0·51**	**0·49**	0·16	*0·41*	**0·48**	**0·66**	**0·65**	**0·61**
64 °N, 53 °W	−1	**0·45**	*0·31*	**0·47**			**0·52**	*0·44*	0·32	0·10	−0·06	0·25	*0·41*	**0·61**	**0·56**	**0·67**
64 °N, 53 °W	−2	*0·23*	0·03	*0·31*			0·31	0·13	0·10	−0·07	−0·24	0·16	0·14	0·35	*0·39*	**0·52**
64 °N, 53 °W	+1	**0·47**	**0·50**	*0·28*			*0·44*	**0·57**	**0·58**	*0·43*	0·19	0·33	*0·42*	**0·53**	0·31	0·29
64 °N, 53 °W	+2	**0·29**	0·24	0·12			*0·42*	**0·51**	0·35	0·30	−0·15	0·12	0·30	*0·41*	0·08	0·15
59 °N, 45 °W	0	**0·32**	0·24	**0·44**	*0·37*	0·23	0·23	0·13	0·30	**0·53**	**0·51**	*0·43*	**0·51**	**0·49**	*0·39*	0·16
59 °N, 45 °W	−1	**0·28**	*0·33*	*0·36*	0·33	0·25	0·30	*0·38*	**0·51**	0·30	0·27	0·24	0·28	*0·44*	**0·50**	**0·51**
59 °N, 45 °W	−2	**0·26**	**0·47**	*0·28*	0·09	0·06	*0·39*	*0·45*	*0·46*	*0·42*	0·21	*0·44*	0·21	0·27	0·12	0·16
59 °N, 45 °W	+1	**0·46**	**0·45**	**0·49**	**0·48**	0·33	**0·47**	**0·53**	**0·64**	**0·58**	0·02	0·09	*0·46*	**0·53**	**0·56**	*0·46*
59 °N, 45 °W	+2	**0·33**	**0·41**	*0·30*	*0·44*	0·21	*0·41*	**0·52**	**0·55**	**0·51**	0·12	0·36	*0·41*	**0·47**	0·34	0·20
65 °N, 38 °W	0	0·12	−0·15	0·27			*−0·38*	−0·17	−0·05	−0·31	0·06	0·30	*0·42*	*0·38*	0·14	0·32
65 °N, 38 °W	−1	0·15	0·23	0·23			0·23	0·25	*0·39*	*0·41*	0·24	0·12	0·29	0·11	0·18	0·25
65 °N, 38 °W	−2	0·07	0·14	0·13			−0·05	0·08	0·10	0·21	0·11	0·03	0·23	0·17	0·07	0·08
65 °N, 38 °W	+1	0·00	0·06	−0·03			0·12	0·05	0·10	0·01	−0·12	−0·14	−0·10	0·06	0·13	0·21
65 °N, 38 °W	+2	−0·08	−0·02	−0·04			−0·24	−0·09	−0·03	0·33	−0·21	−0·25	0·04	0·18	0·31	0·24

Contemporaneous = 0; SST leading air temperature by 1 and 2 months = −1 and −2; SST lagging air temperature by 1 and 2 months = +1 and +2.
Significant r values are in italics for $p < 0{\cdot}05$ and bold for $p < 0{\cdot}01$. http://secamlocal.ex.ac.uk/people/staff//dbs202/cat/stats/corr.html.

Table V. Trend-line changes of HadISST1 pan-Greenland sea-surface temperature and air-temperature series for neighbouring Greenland (near-)coastal stations for long-term and standard climatological 'normal' periods: (a) summer (JJA); (b) July

(a) Summer

Period	69 °N, 55 °W	04 221	64 °N, 53 °W	04 250	59 °N, 45 °W	04 262/70	65 °N, 38 °W	04 360
1901–2006	0·23	0·84	−0·12	−0·17	−0·40	0·63	−0·57	
1901–50	0·42	0·33	**0·82**	**1·57**	0·11	**1·30**	−0·23	
1951–2000	−0·11	0·59	**−0·62**	−0·84	**0·72**	0·12	**1·66**	**−1·00**
1873–1900	**−0·18**	0·70	−0·44		−0·43	**1·33**	**0·21**	
1881–1910	−0·05	**1·56**	−0·06		0·17	**1·03**	0·13	
1891–1920	**−0·87**	−0·60	−0·56		−0·86	0·46	**−0·85**	
1901–30	0·03	−0·17	0·24	**0·94**	0·74	0·85	−0·34	
1911–40	**0·78**	0·75	**0·85**	1·70	**1·29**	0·32	0·26	
1921–50	0·21	0·23	0·57	**0·65**	**−1·12**	**0·90**	−0·14	**0·75**
1931–60	−0·26	0·20	−0·36	−0·62	**−1·63**	−0·23	**−1·96**	**−0·61**
1941–70	**−0·69**	0·08	**−0·88**	**−1·23**	**−1·12**	**−0·77**	**−2·42**	**−1·29**
1951–80	**−0·50**	−0·05	−0·52	−0·72	−0·31	−0·53	0·65	**−1·06**
1961–90	−0·13	**1·06**	−0·50	−0·57	0·77	−0·05	0·89	**−0·79**
1971–2000	0·33	0·87	−0·09	−0·04	1·01	**0·83**	**1·20**	0·05
1977–2006	**0·86**	0·82	0·30	**0·90**	**0·68**	**0·84**	**1·20**	**1·27**

(b) July

Period	69 °N, 55 °W	04 221	64 °N, 53 °W	04 250	59 °N, 45 °W	04 262/70	65 °N, 38 °W	04 360
1901–2006	0·29	0·71	0·06	0·09	−0·38	0·65	0·06	
1901–50	0·65	0·27	**1·06**	**1·88**	0·10	**1·21**	−0·12	
1951–2000	0·28	0·72	−0·36	−0·30	**0·81**	0·91	**1·92**	**−0·86**
1873–1900	**−0·49**	0·12	**−0·74**		−0·47	**1·01**	**0·34**	
1881–1910	−0·03	**1·36**	−0·24		0·17	0·33	0·07	
1891–1920	−0·43	−0·51	−0·45	0·28	**−1·07**	**1·21**	**−0·86**	
1901–30	0·01	−0·73	−0·21	**1·17**	0·76	0·46	−0·16	
1911–40	**0·84**	**2·04**	**1·14**	**2·28**	**1·31**	0·54	0·11	
1921–50	0·59	0·30	**1·24**	0·73	**−1·18**	**1·15**	−0·04	
1931–60	**−0·68**	−0·29	**−0·85**	**−1·45**	**−1·44**	**−1·10**	**−1·67**	
1941–70	**−1·13**	0·71	**−0·95**	−0·74	**−1·31**	−0·65	**−2·22**	**−1·48**
1951–80	−0·34	0·65	−0·16	0·26	−0·24	0·31	0·81	−0·66
1961–90	−0·10	0·17	−0·62	−0·46	**1·06**	0·07	**1·34**	**−1·10**
1971–2000	**0·55**	**3·31**	−0·19	−0·32	**0·97**	0·82	0·55	−0·15
1977–2006	**1·03**	−0·42	0·20	0·10	**0·62**	0·35	0·58	**1·08**

Significant trends (defined as $>1\sigma$) are shown in bold type.

Conversely, significant increases in HadISST1 off southern Greenland during 1951–2000 were accompanied by smaller, non-significant increases in air temperature at Narsarsuaq. Although some of these differences may be related to biases in the SST analyses, it should be noted that Narsarsuaq is ~50 km inland well up a long fjord, so has pronounced 'continental' (i.e. ice-sheet) and micro-/meso-meteorological (rather than purely coastal) influences; other factors apart from SST conspire to influence its (summer) climate (e.g. Cappelen *et al.*, 2001).

Note the interesting contrast in significant trends between SE Greenland SST (significantly positive) and 04 360 Tasiilaq air temperature (significantly negative) for both the summers and July months of 1951–2000 (Table V). This could be related to changes in the East Greenland Current, which is influenced by much larger scale forcing factors—notably export of Polar water and sea ice through Fram Strait, sea-ice melt and GrIS runoff—than merely the local climate around Tasiilaq (Dickson *et al.*, 2007). When we break down the analyses into a series of sequential 30-year (climatological normal period) trends for SST and air-temperature data, we find sustained significant cooling of Tasiilaq summer air temperature for 1951–1980 and 1961–1990, accompanied by significant warming of adjacent SST (in July) during 1961–1990, explaining the mixed signal for the 1951–2000 period. However, both the Tasiilaq summer SST and air-temperature series show significant warming for the most recent 30-year period (1977–2006).

Overall there are a greater number of negative trends for 1951–2000 compared with 1901–1950, reflecting general cooling in southern coastal Greenland for much of this period (Hanna and Cappelen, 2003), which was only reversed—with significant warming mirroring general global warming—since the early 1990s (Hanna *et al.*, 2008). Note that trends for the last 30 years (1977–2006) are mainly significantly positive (Table V).

Sensitivity experiments

To help evaluate the possible effects of variations in SST on Greenland climate, sensitivity experiments were conducted using the Modèle Atmosphérique Régional (MAR) model (Figure 7), which is a RCM (Gallée and Schayes, 1994) coupled to the 1-D Soil Ice Snow Vegetation Atmosphere Transfer (SISVAT) scheme (De Ridder and Gallée, 1998). Fettweis (2007) presented a 28-year

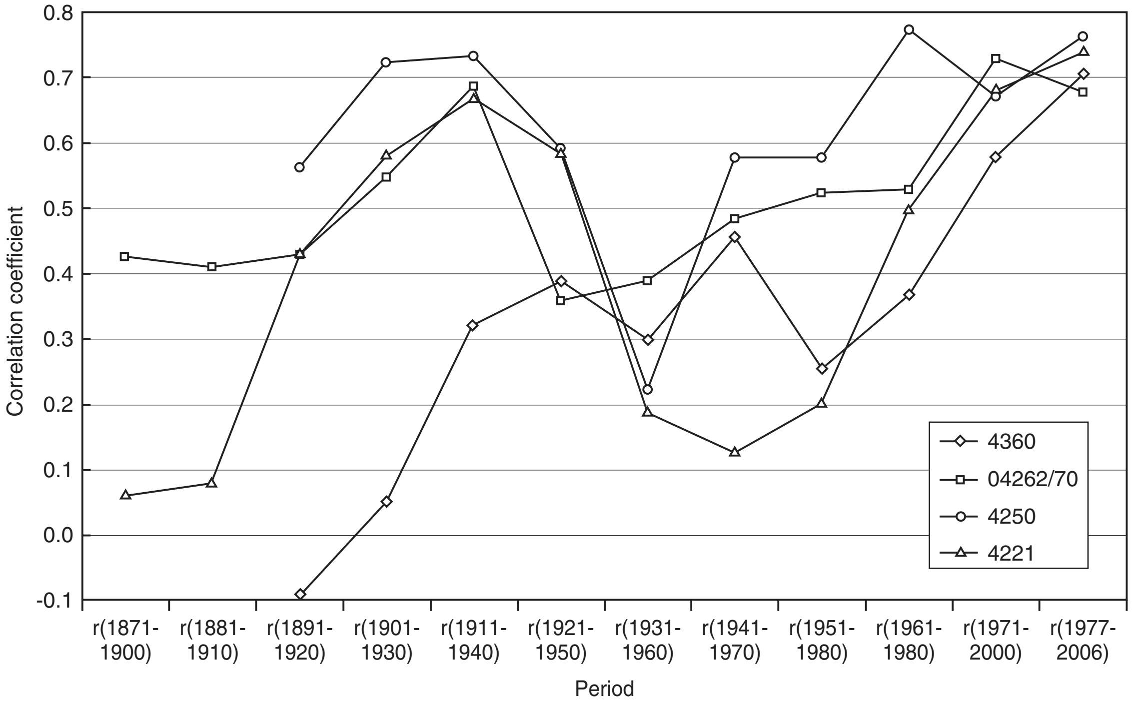


Figure 6. Correlation coefficients between Greenland sea-surface temperature and air temperature for summer (JJA) for sequential simultaneous climatological normal (30-year) periods. This comparison is for the four Greenland synoptic meteorological stations (here identified by their WMO numbers) and adjacent HadISST1 pixels depicted on the Greenland map (Figure 2)

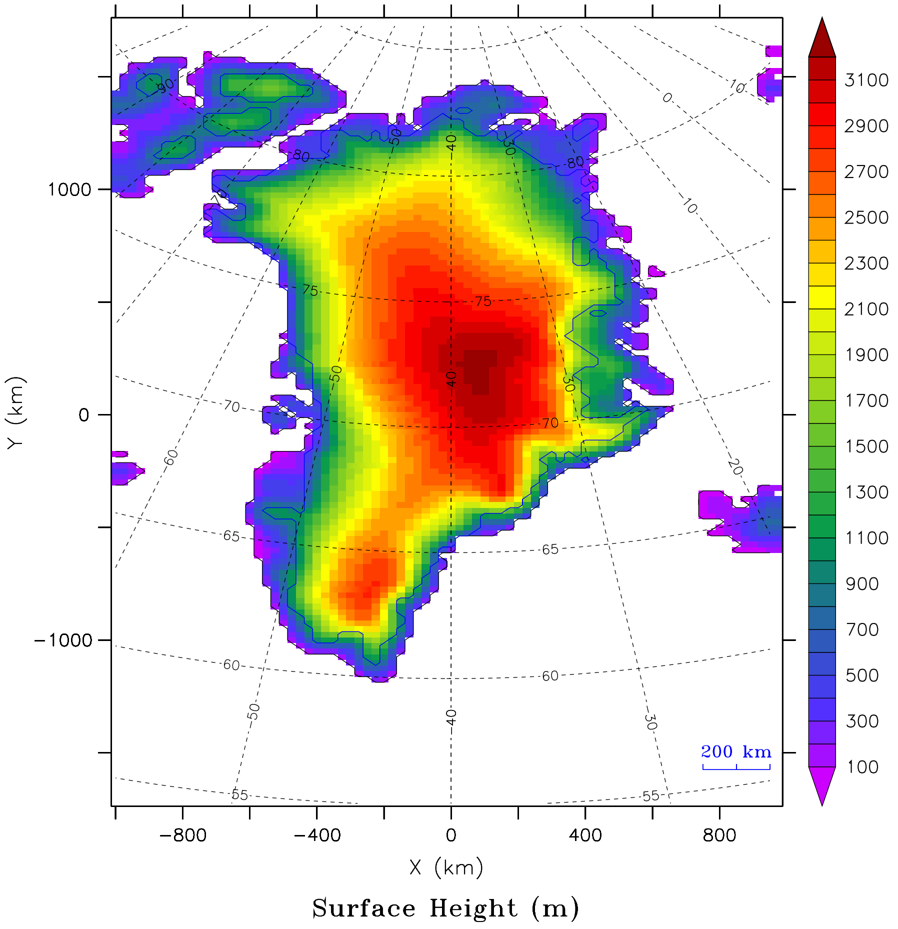


Figure 7. The MAR spatial domain, indicating region of adjusted SSTs around southern Greenland

SMB simulation (1979–2006) over the GrIS made with the MAR model at a resolution of 25 km. This simulation is extended here to the end of September, 2007. The ERA-40 reanalysis (1977–2002) and ECMWF operational analysis (2002–2007) were used to initialize the meteorological fields at the beginning of the simulation and to force the lateral boundaries every 6 h during the simulation. The SST and sea-ice extent in the SISVAT module were also prescribed by the re-analysis. In turn, ERA-40 SST and sea ice were originally prescribed using HadISST1 until 1981 and OI.v2 thereafter, which ensures some consistency with the SST analyses described above (Section on Long-term SST Observations and Comparison with Air Temperature).

The control run (CTRL) in Figure 8 are the results presented in Fettweis (2007). The setup used in the sensitivity experiments ($\mathrm{SST}+2$, $\mathrm{SST}-2$, ...) was unchanged except for SST (Figure 7). SST, prescribed by the re-analysis every 6 h in SISVAT as a boundary forcing, was decreased and increased by 2 °C only for all ocean pixels across the Greenland domain where the reanalysis did not prescribe sea-ice. No change occurred on MAR grid points with sea-ice.

The main impact of the forced SST changes on the SMB components occurs on precipitation and meltwater production. Higher SSTs result in more evaporation above the ocean and more precipitation simulated over Greenland. Also with higher SSTs, more warm ($>0\,^{\circ}\mathrm{C}$) air of oceanic origin is advected into the continent by the atmospheric part of MAR, so that more energy is available to melt snow in summer.

The impact of a SST change of $\pm 2\,^{\circ}\mathrm{C}$ on precipitation/runoff over the GrIS is $\sim \pm 2$–3% of the total precipitation/runoff (Table VI), which is small compared with the viable range of SST variations (no more than 2–3 °C) and standard deviations of ~11 and 24% for snow accumulation and runoff variations, respectively, of the GrIS for the past ~50 years (Hanna *et al.*, 2005, 2007). The main changes obviously occur in southern Greenland and around the coast/ice-sheet margin (Figure 8). For temperature, the change above the ice sheet is due to changes in cloudiness resulting from the evaporation increase (decrease) above the ocean for $+2\,^{\circ}\mathrm{C}$ ($-2\,^{\circ}\mathrm{C}$). The overall impact on SMB (already negative) is $\sim +(-)10\ \mathrm{km}^3\ \mathrm{yr}^{-1}$ for a $+(-)2\,^{\circ}\mathrm{C}$ change in SST. Similar sensitivity experiments for previous noted Greenland warm years, 1998 and 2003, give similar results (Table VI).

These sensitivity experiments do not take into account the impact of a SST change on the sea-ice extent because the sea-ice extent (and temperature above the sea-ice) is kept the same as in the control experiment. Moreover, only the SST in the simulated domain (Figure 7) is changed, and not the atmospheric temperature at the boundaries of the model. Therefore, we only test the impact of a SST change in the model domain here. A global SST change would also change the atmospheric temperature/humidity and consequently the boundary forcing in the model. Therefore, bearing in mind possible feedbacks between ocean, atmosphere and sea-ice, the effect of changing SST in our experiments should be taken as a lower limit, and the overall effect could be considerably greater than suggested by these experiments.

SST as a forcing of recent Greenland summer warmth and mass loss?

As noted above (Section on Climatic Interpretation), several recent studies highlight the exceptional amount and/or spatial extent of melt on the GrIS during summer 2007; however, the sensitivity experiment described above suggests that these cannot be wholly explained by local/regional SST variations. The higher resolution OI.v2 analysis (as mentioned above in the Section on Data/Methodology) was used to derive summer (JJA) SST anomaly maps (Figure 9). These maps qualitatively show that while summer 2007 had anomalously ($\sim +1{\cdot}5$–$2\,^{\circ}\mathrm{C}$) warm SSTs around southern Greenland, these anomalies are not exceptional in the context of other recent warm Greenland summers—defined by Hanna *et al.* (2008) on the basis of Greenland instrumental temperature records—such as 2003 and 2005.

However, it has been suggested that increased melting by a generally warmer ocean may have caused the recently observed, near-synchronous, rapid fluctuations of several key Greenland outlet glaciers of the past few years (e.g. Luckman *et al.*, 2006; Howat *et al.*, 2007; Truffer and Fahnestock, 2007). The ocean-temperature change at the depth of the calving front/grounding line, the peculiarities of the fjord basin (especially differences in local bathymetry) and its sill depth governing contact with the open ocean are likely to be factors more important than SST for influencing any such relationship (Figure 10). In order to gain insights into these factors, we compared summer (June/July) temperature profiles for a range of depths 0–50, 50–150, 150–400 and 400–600 m at Fylla Bank station 4 (Fylla4) and for two other profiles, Sukkertoppen/Maniitsoq st. 5 (Suk5) and Holsteinsborg/Sisimiut st. 5 (Hol5) further north in the West Greenland waters, both with each other and with HadISST1 nearest-pixel SSTs (Figures 2 and 11). These three profiles are all over the continental shelf break west of the fishing banks, where the currents are strongest. Ocean-temperature measurements from 1989 were derived from CTD data, while bottles were used before that date; All data were checked, calibrated, quality controlled and included in the ICES database (Ribergaard, 2007). There is a significant correlation of $r = 0{\cdot}55$ between near-surface (0–40/50 m = SST) variations of Fylla4 west of the bank and Fylla2 over the bank (the latter used previously; Section on Data/Methodology). Cold polar water is mainly found near the surface in these waters, with a core at ~50–100 m depth (Ribergaard, 2007) below the surface-mixed layer, and is evident from its relatively low temperatures (Figure 11). Relatively warm Irminger (Atlantic) waters occupy the 400–600 m depth range, with mixed waters between 150 and 400 m (Figure 11). Most fjords in Greenland are sill-fjords, with sill depths ranging from more than 500 to almost 0 m. For the

Table VI. Sensitivity of whole-Greenland ice sheet climate and surface mass balance parameters to simulated variations in sea-surface temperature for three recent warm Greenland summers for non-sea-ice pixels surrounding Greenland

Year/ scenario	SMB km^3	Available melt-water km^3	Meltwater runoff km^3	Meltwater runoff %	Snowfall km^3		Rainfall km^3	Precip %	3-m summer (JJA) temperature (°C)
1998	**01/05 – >30/09**	**01/05 – >30/09**	**01/05 – >30/09**			**01/05 – >30/09**	**01/05 – >30/09**	**01/06 – >31/08**	
SST − 2°	−187·00	819·31	426·85	*97·04*		228·78	21·25	*99·14*	−8·06
CTRL	−197·17	832·27	439·85	***100·00***		229·47	22·72	***100·00***	−8·04
SST + 2°	−209·25	850·39	456·85	*103·86*		232·52	24·93	*102·08*	−7·96
2003	**01/05 – >30/09**	**01/05 – >30/09**	**01/05 – >30/09**			**01/05 – >30/09**	**01/05 – >30/09**	**01/06 – >31/08**	
SST − 2°	−256·69	826·05	522·90	*97·42*		253·47	25·18	*99·51*	−8·43
CTRL	−268·43	840·44	536·74	***100·00***		253·23	26·79	***100·00***	−8·36
SST + 2°	−285·18	859·19	557·70	*103·91*		255·39	29·32	*101·67*	−8·33
2007	**01/01 – >30/09**	**01/05 – >30/09**	**01/05 – >30/09**		**01/01 – >30/09**	**01/05 – >30/09**	**01/05 – >30/09**	**01/06 – >31/08**	
SST − 2°	−211·96	948·45	580·07	*97·94*	355·29	194·38	22·24	*98·42*	−7·73
SST − 1°	−212·46	954·54	584·28	*98·65*	358·44	195·77	22·74	*99·28*	−7·69
CTRL	−215·91	965·09	592·27	***100·00***	361·21	196·73	23·37	***100·00***	−7·64
SST + 1°	−217·39	972·10	599·61	*101·24*	367·16	199·22	24·18	*101·50*	−7·64
SST + 2°	−225·94	991·29	613·32	*103·55*	370·20	202·27	25·76	*103·61*	−7·54

Table VIII. Detrended correlation coefficients between different station pairs of DMI (June/July) ocean temperatures for each depth range, for period ~1950–2007

Depth range (m)	Fylla4, Suk5	Fylla4, Hol5	Suk5, Hol5
0–50	**0·53**	**0·40**	**0·66**
50–150	**0·64**	**0·67**	**0·62**
150–400	**0·59**	**0·65**	**0·70**
400–600	**0·68**	**0·51**	**0·43**

Significant r values are in italics for $p < 0{\cdot}05$ and bold for $p < 0{\cdot}01$. http://secamlocal.ex.ac.uk/people/staff//dbs202/cat/stats/corr.html.

west and SE Greenland fjords this means, that (with the exception of the shallowest fjord with sill depths below ~100 m) they are affected by heavily mixed, relatively warm Atlantic waters from outside at depths about the sill depths, which is drawn in at depth to compensate for the seaward-directed flow near the surface due to runoff and entrainment (Figure 10) (Ribergaard, 2007). This process may be enhanced by internal waves or upwelling. Therefore the 150–400 m depth water from the deeper shelf-break sections might be most typically representative of water that ultimately finds its way either directly beneath a floating ice tongue or against a grounded ice wall.

There are significant correlations, nearly all with $r > 0{\cdot}5$, between both the temperature of adjacent (and sometimes non-adjacent) ocean-depth sections for any given station (Table VII), and the temperature at all three stations within each depth range (Table VIII). Correlations between DMI station and (corresponding-pixel) HadISST1 ocean temperatures are also mainly significant for Fylla4 and Suk5 but, surprisingly, more so for the 50–150 m layer than the 0–50 m, and almost as much at 150–400 m as at 0–50 m depth; however, correlations are mainly not significant when comparing Hol5 with HadISST1, which may be due to its more northerly position near the sea-ice edge, where HadISST1 is less reliable (Table IX). Moreover, the surface-mixed layer is directly affected by heating by solar radiation, i.e. more variation is expected especially because the observations represent a 2-month window in June/July. We surmize from this analysis that, away from the main seasonal sea-ice margin, HadISST1 is a reasonable proxy of water temperatures down to 400-m depth in this part of offshore Greenland.

Table VII. Detrended correlation coefficients between different depth ranges of DMI (June/July) ocean temperatures for the following stations: Fylla4 above right, and Suk 5 (Hol 5 in brackets) below left, of main diagonal. Period ~1950–2007

	0–50 m	50–150 m	150–400 m	400–600 m
0–50 m	1·00	0·68	**0·58**	*0·31*
50–150 m	**0·75(0·67)**	1·00	**0·84**	**0·51**
150–400 m	0·29 (0·20)	**0·58(0·54)**	1·00	**0·74**
400–600 m	0·03 (0·08)	0·23 (*0·35*)	**0·60(0·80)**	1·00

Significant r values are in italics for $p < 0{\cdot}05$ and bold for $p < 0{\cdot}01$. http://secamlocal.ex.ac.uk/people/staff//dbs202/cat/stats/corr.html.

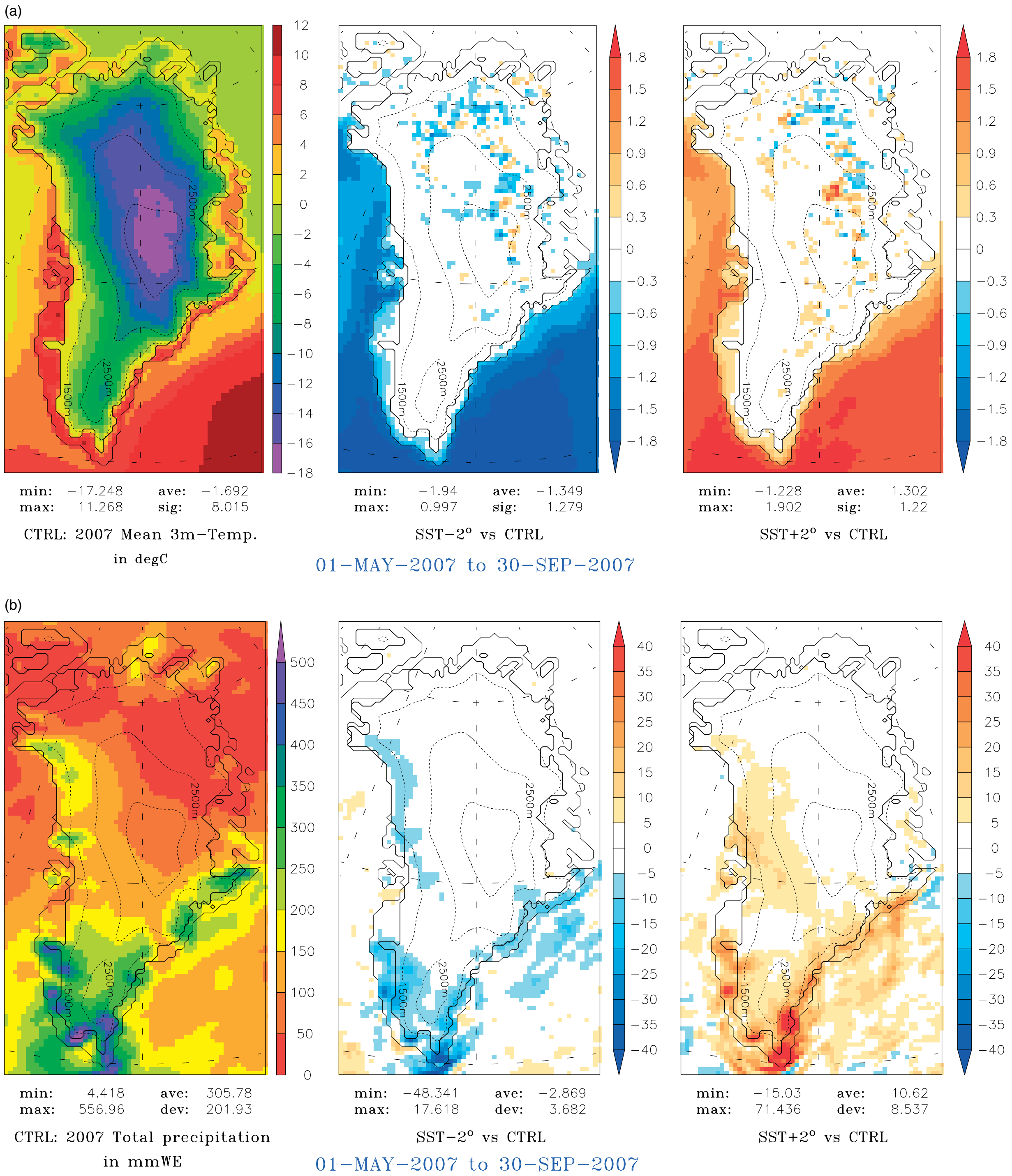


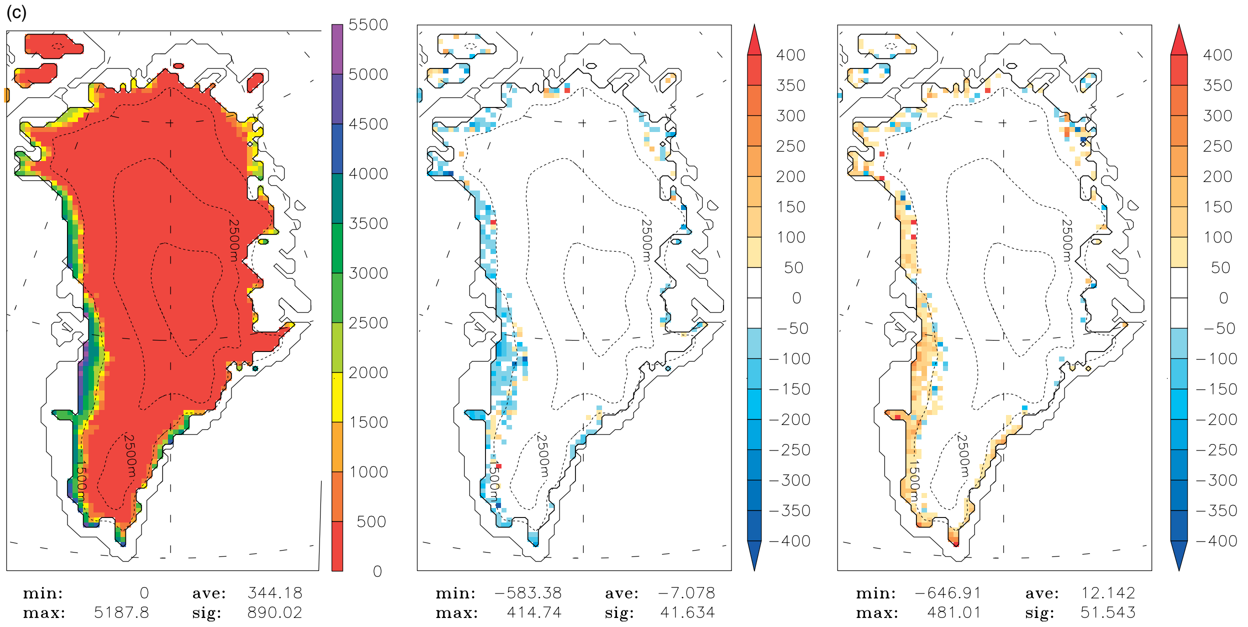
Figure 8. Sensitivity of key climate parameters and runoff simulated by MAR to sea-surface temperature: (a) 3-m air temperature; (b) total precipitation; (c) surface meltwater runoff; (d) 3-m wind vectors

Table IX. Detrended correlation coefficients between DMI (June/July) ocean temperature (for various depth ranges for three sections) and corresponding HadISST1 pixel (June) sea-surface temperature, for period ∼1950–2007

Depth range (m)	Fylla4	Suk5	Hol5
0–50	*0·37*	**0·50**	0·04
50–150	**0·61**	**0·67**	−0·17
150–400	**0·50**	*0·30*	*−0·36*
400–600	**0·41**	0·15	−0·08

Significant r values are in italics for $p < 0.05$ and bold for $p < 0.01$. http://secamlocal.ex.ac.uk/people/staff//dbs202/cat/stats/corr.html.

Pronounced summer warming of the order of 1–2 °C since the early 1990s is evident for all four depth ranges, peaking in 2003 for the deeper ocean water (400–600 m) and in 2005/2006 for the middle/higher sections (0–400 m) of Fylla4 (Figure 11(a)). This pattern is also seen further north at Suk5, where ocean-temperature peaks are evident in 2001 in the 400–600 m layer, 2003 in the 150–400 and 50–150 m layers (with an almost equally high peak in 1999 at 150–400 m), and in 2006—an exceptionally high peak—in the 0–50 m

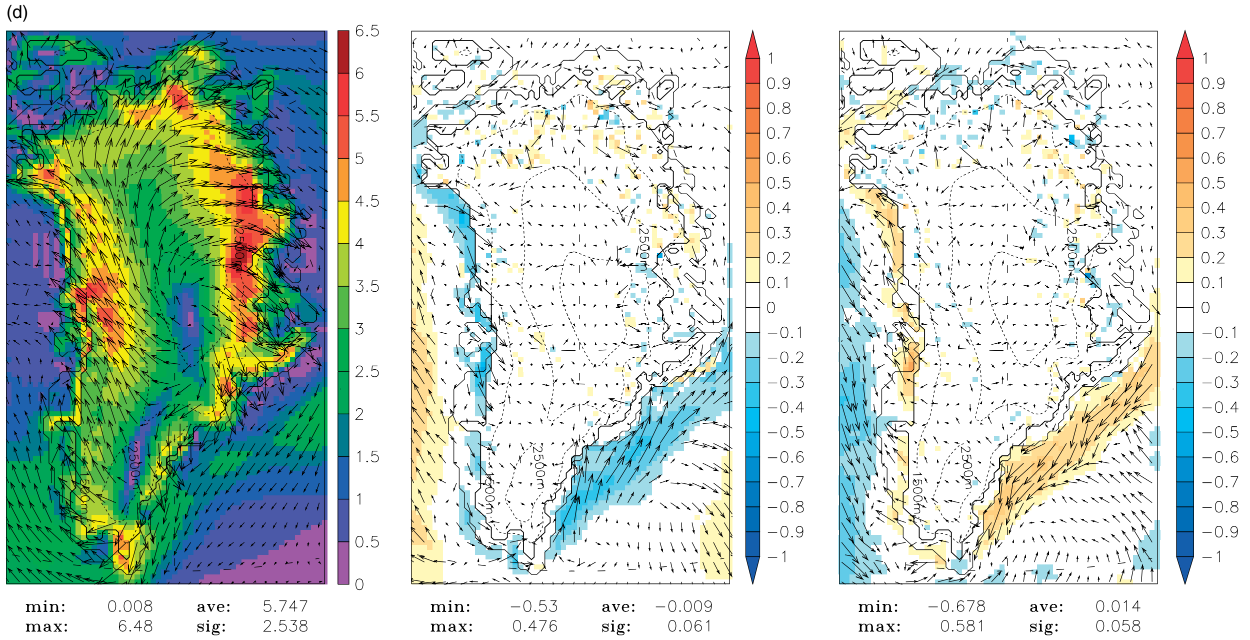


CTRL: 2007 Total runoff in mmWE

SST−2° vs CTRL

SST+2° vs CTRL

01−MAY−2007 to 30−SEP−2007



CTRL: 2007 Mean 3m−Wind speed in m/s

SST−2° vs CTRL

SST+2° vs CTRL

01−MAY−2007 to 30−SEP−2007

Figure 8. (*Continued*)

layer (Figure 11(b)). This largely reflects the Irminger water having become warmer (and saltier) since the mid-1990s (Myers *et al.*, 2007), with warmer conditions closer to the surface in the last few years; less Polar water and/or warmer air temperatures could also have contributed here. Further north still, the Hol5 ocean temperature peaked in 1999, 2001 and 2007 at 400–600 m, and 2001 (with a secondary peak in 1999) at 150–400 m with the latter layer being warm but not unusually so after 2001 (Figure 11(c)). Hol5 50–150 m temperature peaked in 2005, with a secondary peak in 2005—being nearly as warm as the latter in 2006. The Hol5 0–50 m ocean temperature shows an initial peak for 2000 but a much higher peak in 2006. Note that summer 2007 was generally characterized by a return of temperatures above 400 m depth to around the long-term mean, although warm Atlantic waters prevailed in the deepest (400–600 m) layer; a greater presence of Polar water may reflect changes in regional atmospheric/oceanic circulations in winter 2006/2007. However, overall these ocean-temperature depth profiles indicate that over the past decade warmer Atlantic water infiltrated many of

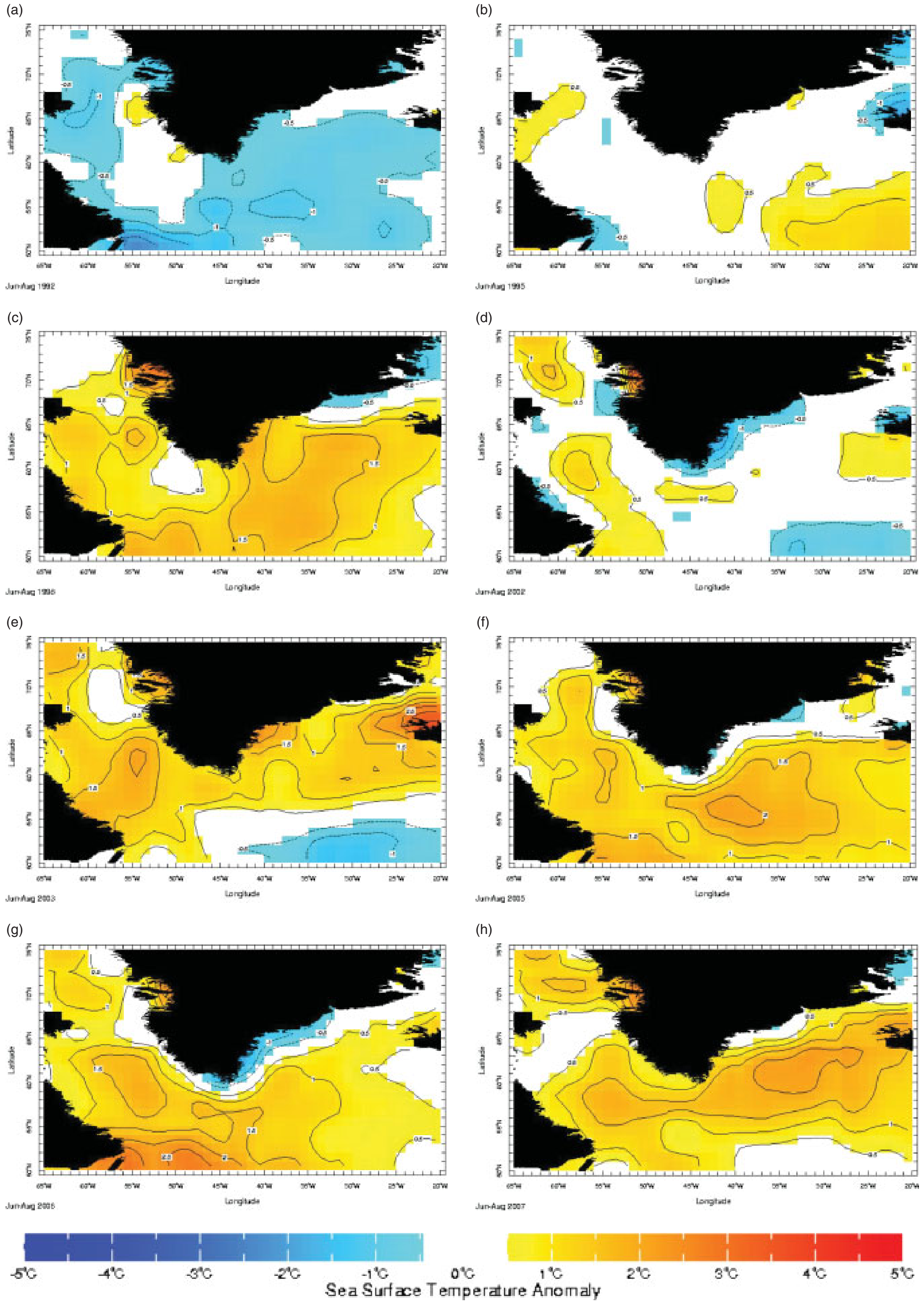


Figure 9. NOAA NCEP EMC CMB global Reyn_SmithOIv2 monthly ssta: sea surface temperature anomaly data (wrt 1971–2000) for recent noted warm and cool summers (JJA) in Greenland. Maps produced using interactive plotting software on: http://iridl.ldeo.columbia.edu/maproom/.Global/.Ocean_Temp/Anomaly.html

the coastal fjords, at least on the western side of southern Greenland, and is very likely to have contributed to enhanced iceberg calving, bottom melting of floating outlet glacier tongues, and erosion of grounded ice.

Inspection of both OI.v2 and HadISST1 data for pixels closest to Helheim and Kangerdlugssuaq (SE Greenland) and Jakobshavn Isbrae (SW Greenland) glaciers, shows distinct warming of 1–2 °C compared with preceding summers during summer 2003 offshore of Helheim/Kangerdlugssuaq and summer 1998 offshore of Jakobshavn Isbrae (Figure 12), at times when these glaciers underwent dramatic changes. These included

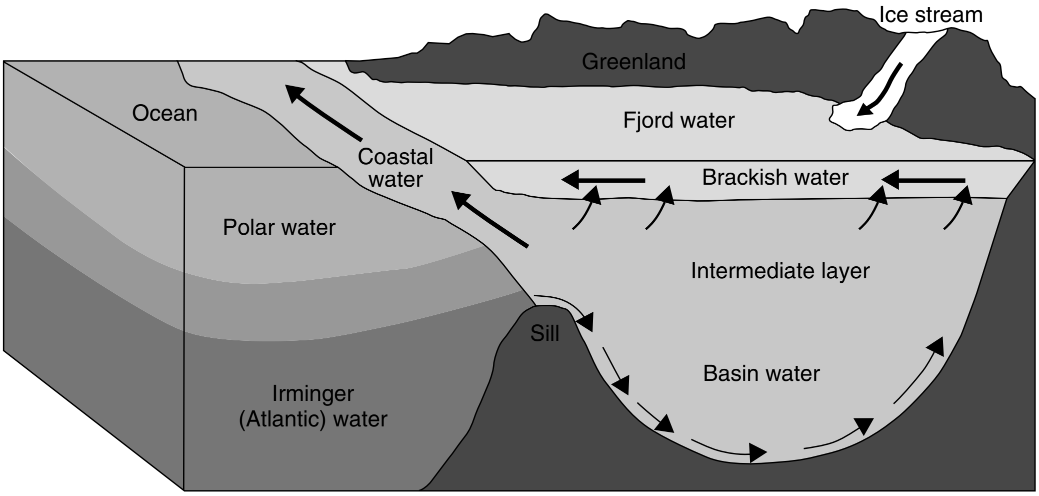


Figure 10. Sketch of the circulation in a West Greenland fjord. Vertical scale is ∼400 m. Adapted from http://www.amap.no/maps-gra/show.cfm?figureId=58

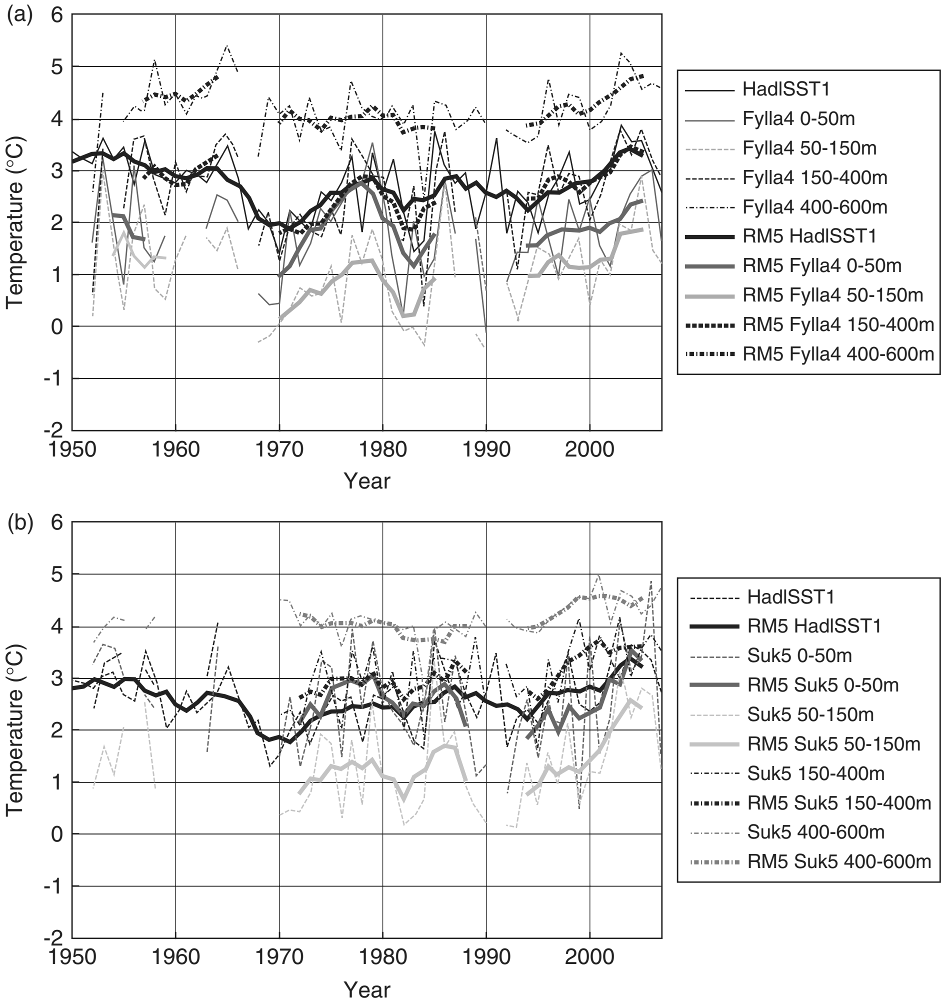


Figure 11. Annual and 5-year running mean (RM5) temperature from HadISST1 (SST) and at (or near) surface and various depths from DMI profiles: (a) Fylla Bank st. 4; (b) Sukkertoppen st. 5; (c) Holsteinsborg st. 5. Positions of stations are shown in Figure 2

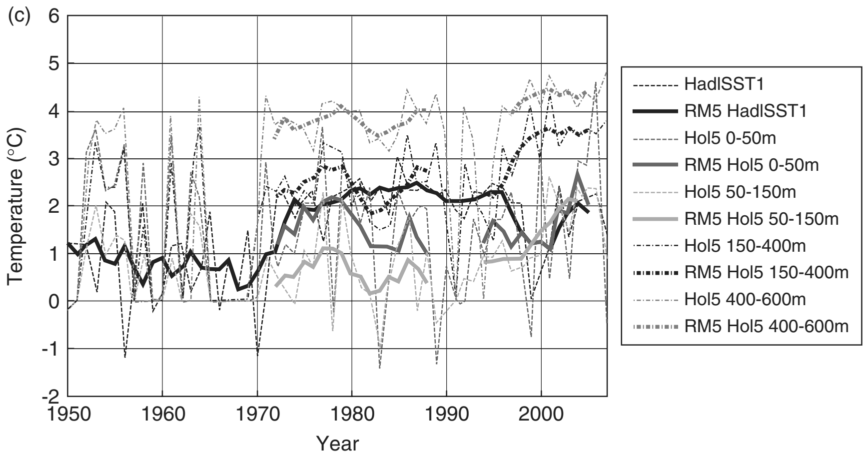


Figure 11. (*Continued*)

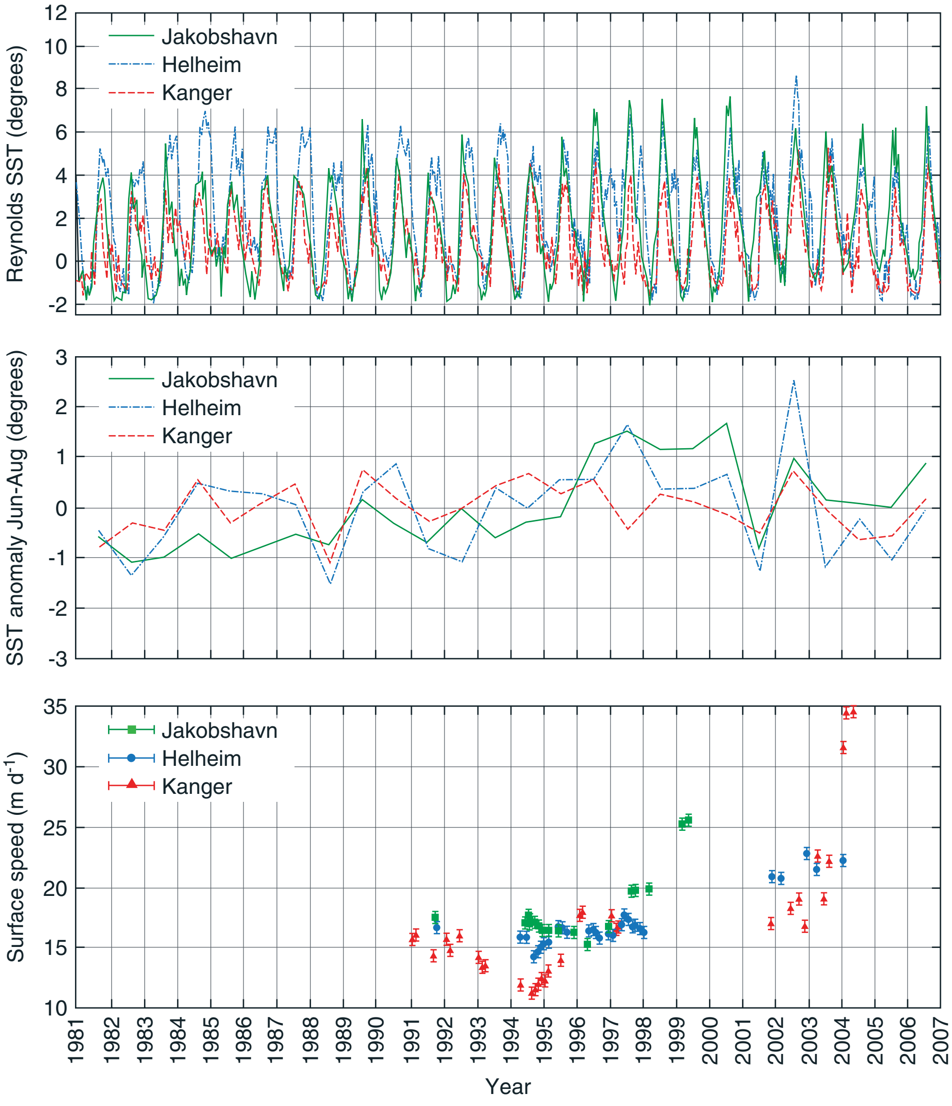


Figure 12. Comparison of sea-surface temperature (SST) and anomalies with ice surface speed over the period of recent dynamic change in three of the largest Greenland outlet glaciers. SST is derived from satellite data and *in situ* measurements (Reynolds *et al*., 2002) and the anomalies are calculated as the annual June-August departure from the long-term June-August mean over the measurement period (1981–2007). Data were first re-sampled to a polar stereographic grid to aid geographic location and points were picked adjacent to glacier fjords. Surface speed is measured by feature tracking between repeat-pass ERS and Envisat SAR images (Luckman *et al*., 2006). Measurement points were chosen close to the calving front and 0·5 m/day error reflects a conservative error based on theoretical considerations. The three outlets have since peaked in velocity (Howat *et al*., 2007)

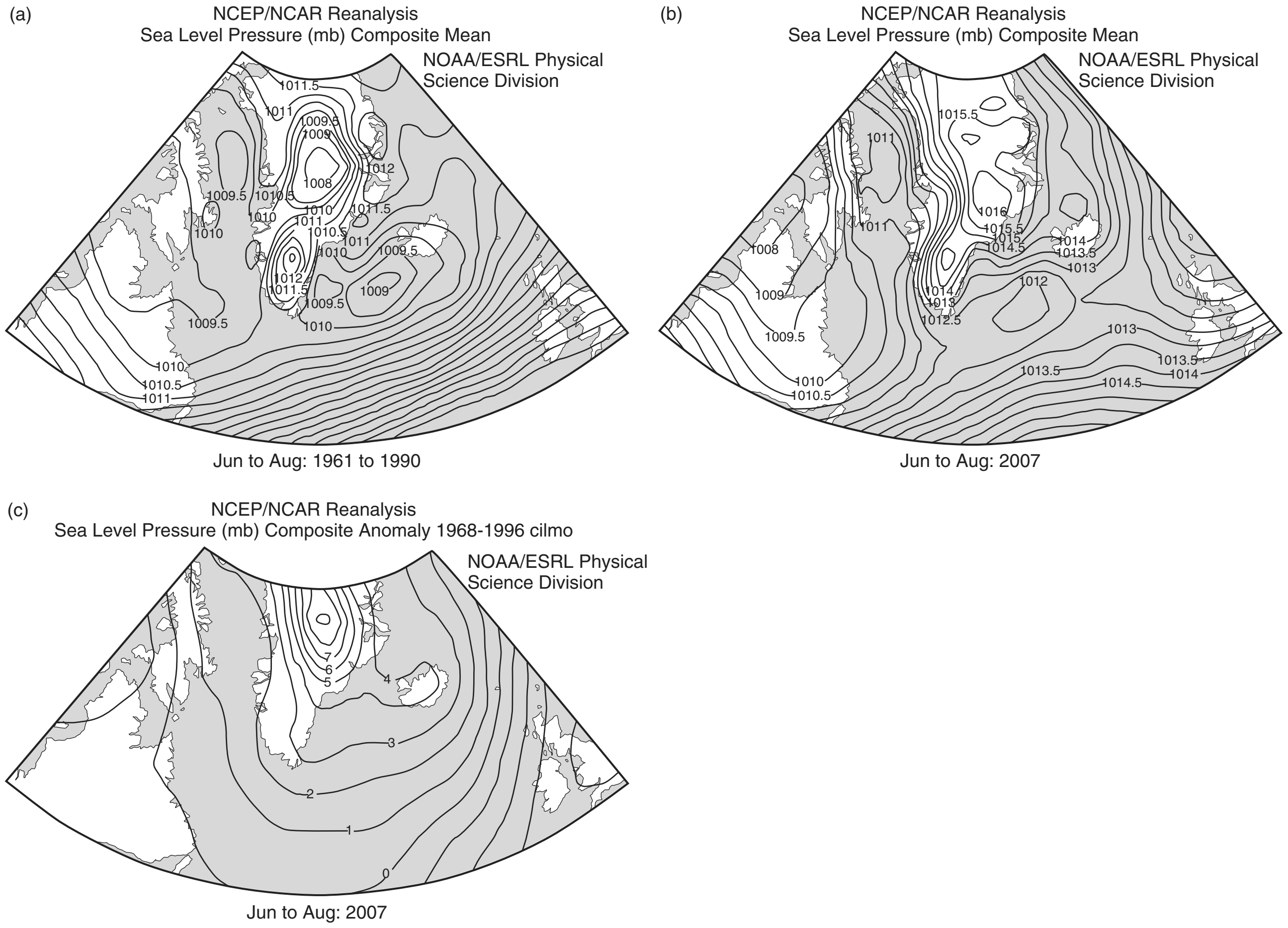


Figure 13. Mean sea-level pressure for summer (JJA) for (a) 1961–90 and (b) 2007; (c) MSLP anomaly for JJA 2007. NCEP/NCAR Reanalysis data obtained and plotted from http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl

synchronous acceleration and retreat of Helheim and Kangerdlugssuaq commencing 2003 (Luckman *et al.*, 2006), and a comparable thinning, acceleration and retreat of Jakobshavn Isbrae in 1998 (Luckman and Murray, 2005). The striking coincidence of marked SST (and likely concomitant ocean-temperature) warming around these major outlet glaciers suggests that the ocean may exert an important influence in forcing ice-dynamical changes that may propagate far inland from the glacier fronts. However, the synchronous SST increase-glacier retreat/acceleration is less apparent for Kangerdlugssuaq than Helheim, possibly because Kangerdlugssuaq lies further north and—with much sea-ice drifting southwestwards in the East Greenland Current—the SST data offshore of Kangerdlugssuaq are either:

1. more strongly subject to vagaries of the sea-ice edge assimilation and interpolation algorithms in the SST analyses or
2. have marine/sea-ice signals more strongly mixed in, effectively decoupling their variations from land ice-based changes.

Another obvious forcing candidate of the high Greenland melt of summer 2007 is changes in atmospheric circulation, which may have lead to advection of warm air masses over the ice sheet, with concomitant changes in radiation/cloud cover. In order to study this possible effect, we present maps of NCEP/NCAR reanalysis (Kalnay *et al.* 1996) surface pressure patterns and geopotential height/anomalies for two different levels: 700 hPa (~3·5 km altitude) and 500 hPa (~5·5 km altitude) (Figures 13–16). These reveal highly anomalous southerly airflow penetrating up the western flank of the GrIS during summer 2007, with mean JJA 700 (500) hPa geopotential height anomalies of >70 (>80) m over central Greenland, which are unprecedented in the entire 60 years of NCEP/NCAR reanalysis data (1948–2007). A detailed analysis of the causal synoptic conditions is beyond the scope of this paper but these exceptional air pressure/height anomalies lead us to argue that unusual atmospheric, rather than surrounding oceanic, conditions—i.e. conditions consistent with a more remote climatic-forcing origin—may have largely contributed to anomalous GrIS melt—particularly at high elevations (Tedesco, 2007)—in summer 2007.

DISCUSSION/CONCLUSIONS

Our results suggest that, despite modelled influences of SST changes on precipitation/snow accumulation, runoff

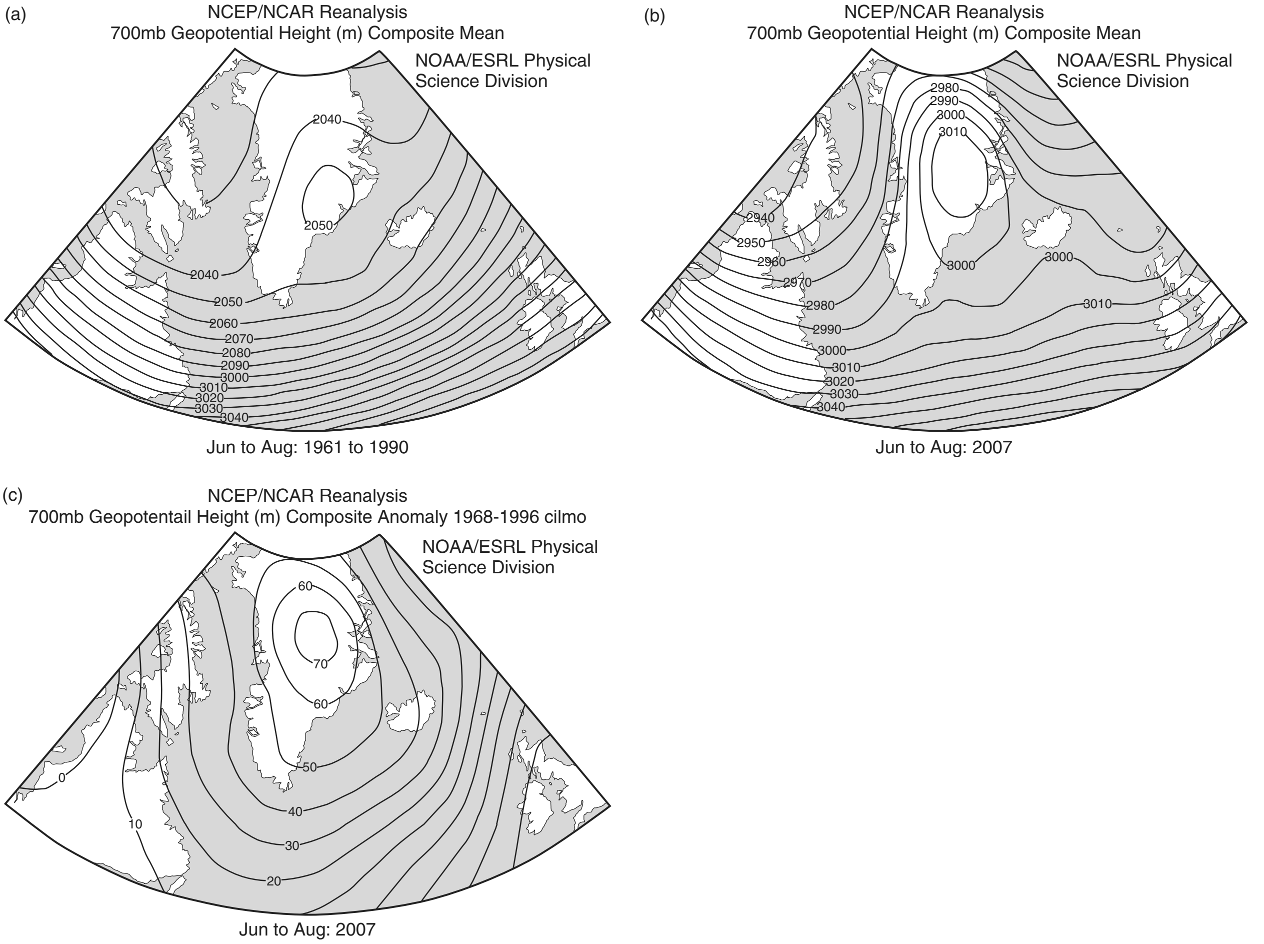


Figure 14. 700 hPa geopotential height for summer (JJA) for (a) 1961–90 and (b) 2007; (c) geopotential height anomaly for JJA 2007. NCEP/NCAR Reanalysis data obtained and plotted from http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl

and SMB, the high Greenland melt anomalies of summer 2007 are more likely to have been mainly forced by anomalous advection of warm air masses over the western flank of the ice sheet and to have therefore had a more remote origin (e.g. related to large-scale changes in the sub-polar jet stream). This is consistent with the finding of Hanna *et al.* (2008) that recent/current Greenland surface-air temperature, since the early 1990s, closely mirrors Northern Hemisphere temperature changes compared with a much more local/regional (largely NAO-type) influence for the several decades prior. Likewise, Johannessen *et al.* (2004) noted that the past century Greenland warming phase (1929–1947) affected high northern latitudes only, in contrast to the broader global pattern of warming since about 1990.

High GrIS melt and runoff in 2006 and 2007 could also be a consequence of lower than normal winter precipitation (accumulation), which may have an impact on SMB via the albedo feedback—as explained, for example, in Fettweis (2007); however, Hanna *et al.* (2005) noted a low (insignificant) correlation between annual runoff and accumulation values for 1958–2003, suggesting that this mechanism is unlikely to be a dominant factor contributing to interannual SMB variability. In agreement, Fettweis (2007) found that thermal factors, rather than precipitation changes, influenced SMB sensitivity during the past 28 years. Nevertheless, the albedo feedback merits further investigation for individual years (such as 2007).

However, there is a striking correspondence between ocean warming and dramatic accelerations and retreats of key Greenland outlet glaciers in both SE and SW Greenland during the late 1990s and early 2000s, which suggests that sea-surface and deeper ocean temperatures may have an important influence on ice-sheet dynamical changes. Such an influence may become increasingly evident within the next 10–50 years due to the delayed response of the North Atlantic Oceans to global warming (e.g. Bigg, 2003, pp.242–243).

Current indications are that the GrIS is likely to be highly susceptible to ongoing global warming, in which Greenland temperatures are predicted to increase ~1–8 (mean 4–5) K by 2100 (Gregory *et al.*, 2004; Gregory and Huybrechts, 2006). The mid range of this estimate yields a negative SMB and the expected eventual demise of the GrIS in the coming millennia (Gregory *et al.*, 2004; Gregory and Huybrechts, 2006). Because surface melt and runoff rates can potentially rapidly far exceed snow accumulation rates, improved meteorological and SMB modelling will be paramount for enhancing understanding of the ice-sheet's ongoing and likely future response to climatic change.

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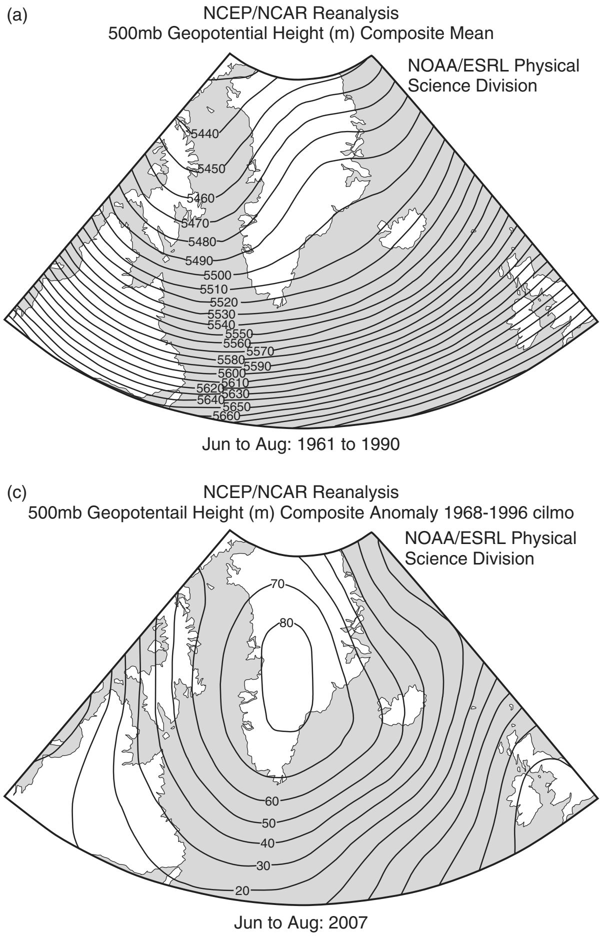

Figure 15. 500 hPa geopotential height for summer (JJA) for (a) 1961–90 and (b) 2007; (c) geopotential height anomaly for JJA 2007. NCEP/NCAR Reanalysis data obtained and plotted from http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl

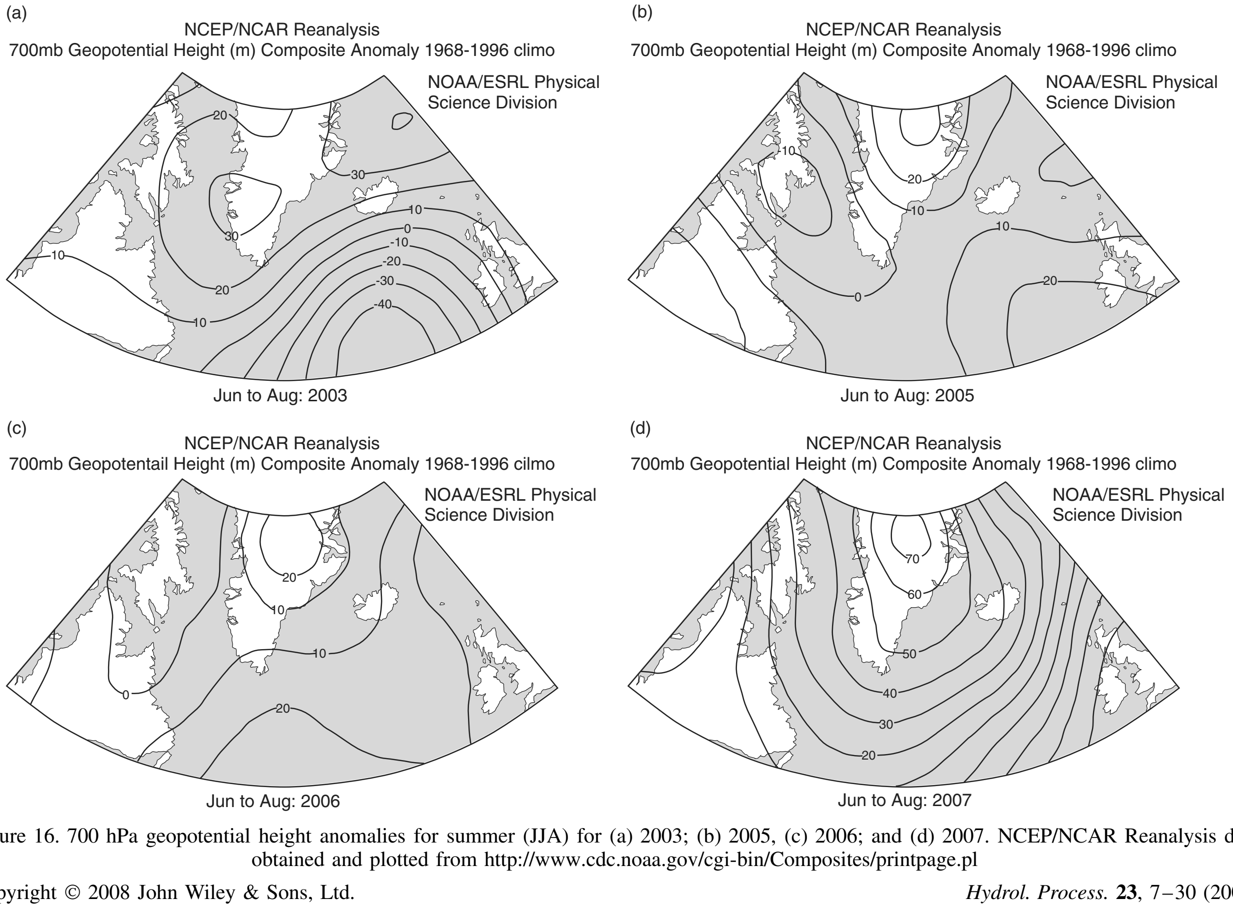

Figure 16. 700 hPa geopotential height anomalies for summer (JJA) for (a) 2003; (b) 2005, (c) 2006; and (d) 2007. NCEP/NCAR Reanalysis data obtained and plotted from http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl

The latest official prediction of 1–13 cm of GrIS contribution to sea-level rise during the current century (Meehl *et al.*, 2007) is based on best estimates of future SMB changes from atmosphere-ocean general circulation models (AOGCMs). However, the effects of dynamic acceleration of ice flow were discussed separately but are not directly included in the IPCC (2007) and Meehl *et al.* (2007) global-sea-level predictions, mainly because ice-flow variability detected during the last few years is too poorly understood to be used as a basis for confident predictions a century ahead. However, we cannot exclude a potentially more rapid response of the ice sheet/outlet glacier dynamics to ongoing climatic change, which like melt/runoff may be subject to strong positive feedback, but at the moment this remains highly speculative. In order to understand the recent rapid changes of GrIS outlet glaciers, future priorities for GrIS studies should also include: (1) the development of new higher resolution full ice-sheet models with full-stress configuration, covering at least the critical margin zones; (2) associated detailed bed elevation and ice-thickness data for GrIS outlet glaciers; and (3) further study of oceanographic changes, which are potentially a predominant forcing factor not currently included in existing ice-sheet models (Steffen *et al.*, 2008).

ACKNOWLEDGEMENTS

Paul Coles redrew many of the figures, and Sorina Hanna drew Figure 10. Figs 13–16 were derived using the interactive website of the NOAA/ESRL Physical Science Division, Boulder, Colorado. PH acknowledges support through the Belgian Federal Public Planning Service Science Policy Research Programme on Science for a Sustainable Development under Contract SD/CS/01A.

EH thanks Dr J.M. Jones for comments on the manuscript.

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