balance (annual net balance and its summer/winter components) measures how climate affects the health of Arctic glaciers. As most 2007–08 measurements are not yet available, we report results for the 2006–07 balance year (Svalbard: 4 glaciers, Iceland: 6, Alaska: 3, Arctic Canada: 4). Annual surface balances were negative for 14 glaciers, positive for 2 (1 each in Iceland and Alaska), and zero for 1 (in Svalbard) (WGMS 2009).

Summer (JJA 2008) 700-hPa air temperature and winter (September 2007–May 2008) precipitation data from the NCEP–NCAR reanalysis serve as climatic indices for regions centered over each of the Arctic's major glaciated regions (excluding Greenland) (Table 5.1). Sixteen discrete regions form four groups (Alaska, Arctic Canada, Iceland, and the Eurasian Arctic) based on correlations between 1948 and 2008 NCEP summer temperature series. These indices suggest that the 2008 annual mass balance was likely extremely negative in Arctic Canada, due to unusually high summer air temperatures, and positive in Alaska due to strong positive winter precipitation anomalies (confirmed by GRACE satellite gravimetry; S. Luthcke 2009, personal communication). Annual balance was likely near zero or slightly positive in the Eurasian Arctic (relatively cool summers and generally high winter precipitation) and negative in Iceland (higher-than-average summer temperatures and below-average winter precipitation).

Melt onset and freeze-up dates and 2008 melt season duration were determined from temporal backscatter variations measured by QuikSCAT's SeaWinds (Table 5.1). In Arctic Canada, melt duration anomalies (relative to 2000–04 climatology) on the North Ellesmere, Agassiz, and Axel Heiberg ice caps ranged from +17.6 to +22.5 days, largely due to late freeze-up. Here, summer 2008 was the longest melt season in the 2000–08 record. Melt duration anomalies were also strongly positive on northern Prince of Wales Icefield and Severnaya Zemlya, and positive in central and southern Arctic Canada, Franz Josef Land, and Iceland. The melt season in southwest Alaska was the shortest in the 9-yr record, with strongly negative melt duration anomalies, mostly due to early freeze-up.

The total ice shelf area in Arctic Canada decreased by 23% in summer 2008 (Mueller et al. 2008). The Markham ice shelf disappeared completely and the Serson ice shelf lost 60% of its area. In the past century, 90% of the Arctic ice shelf area has been lost. Several fjords on the north coast of Ellesmere Island are now ice free for the first time in 3,000–5,500 years (England et al. 2008).

f. Greenland—J. E. Box, L.-S. Bail, R. Benson, I. Bhattacharya, D. H. Bromwich, J. Cappelen, D. Decker, N. DiGirolamo, X. Fettweis, D. Hall, E. Hanna, T. Mote, M. Tedesco, R. van de Wal, and M. van den Broeke

1) Summary

An abnormally cold winter across the southern half of Greenland led to substantially higher west coast sea ice thickness and concentration. Even so, record-setting summer temperatures around Greenland, combined with an intense melt season (particularly across the northern ice sheet), led the 2008 Greenland climate to be marked by continued ice sheet mass deficit and floating ice disintegration.

2) Regional surface temperatures

Temperature anomalies were mixed and exhibited seasonal variability (Fig. 5.17). Annual mean temperatures for the whole ice sheet were +0.9°C, but were not abnormal, given a rank of 23 of 51 years over the 1958–2008 period (Box et al. 2006). Persistent warm anomalies were evident over the northern ice sheet in all seasons. Temperatures were abnormally cold over the southern ice sheet in winter. Coastal meteorological stations around Greenland with a consistent 51-yr period (1958–2008) (Cappelen 2009) indicate a record-setting warm summer in 2008. The Upernavik (Nuuk) summer temperature was the warmest (second warmest) on record since 1873, respectively.

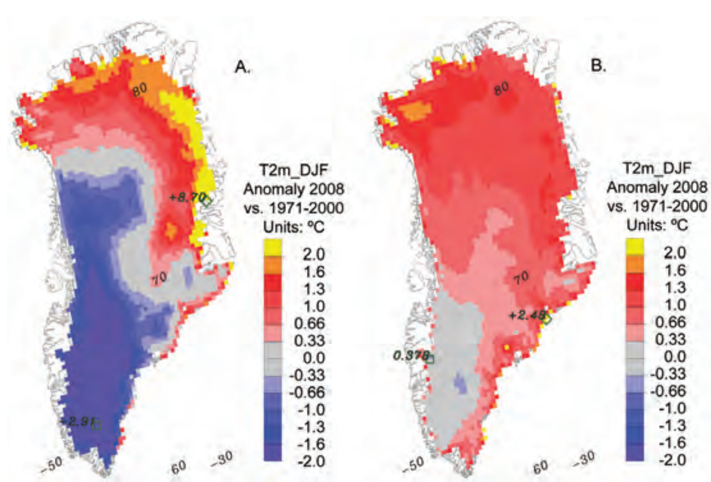

Fig. 5.17. 2008 (a) winter and (b) summer near-surface (2 m) air temperature anomalies with respect to the 1971–2000 base period, simulated by Polar MM5 after Box et al. (2006).

Table 5.1. 2008 Summer 700-hPa temperature and winter precipitation anomalies (relative to 1948–2008 NCEP reanalysis means) for glaciated regions of the Arctic (excluding Greenland). Inferred sign of surface mass balance is based on comparison of historical mass balance records for each region with NCEP reanalysis temperature and precipitation anomalies. Anomalies in melt duration and the timing of melt onset and freeze-up (relative to 2000–04 climatology) derived from QuikSCAT data. For timing, negative anomalies indicate an earlier-than-normal date.

Region	Sub-region	Latitude (°N)	Longitude (°E)	JJA 700-hPa T Anomaly	2008 Rank	Sep–May Ppt Anomaly	2008 Rank	Inferred Surface Balance	Melt Onset Anomaly	Freeze-up Anomaly	Melt Duration Anomaly
				(°C)	(*N* = 60)	(mm)	(*N* = 60)		days	days	days
Arctic Canda	North Ellesmere Island	80.6–83.1	267.7–294.1	2	4	12.3	10	––	−1.8	9.8	19.3
	Axel Heiberg Island	78.4–80.6	265.5–271.5	1.67	5	0	30	––	−2.9	11.4	17.6
	Agassiz Ice Cap	79.2–81.1	278.9–290.4	2.11	3	−9.2	44	––	5.4	24.0	22.5
	Prince of Wales Icefield	77.3–79.1	278–284.9	1.77	7	−11.4	42	––	2.1	7.8	10.2
	Sydkap	76.5–77.1	20.7–275.8	1.53	6	−58.5	59	––	3.0	3.8	1.4
	Manson Icefield	76.2–77.2	278.7–282.1	1.71	7	−62.5	56	––	6.4	5.7	0.0
	Devon Ice Cap	74.5–75.8	273.4–280.3	1.47	6	−8	33	––	0.8	−0.8	5.8
	North Baffin	68–74	278–295	1.97	2	12.4	17	––	−26.9	−14.4	4.9
	South Baffin	65–68	290–300	2.39	1	5.9	25	––	−2.8	−1.6	−1.1
Eurasian Arctic	Severnaya Zemlya	76.25–81.25	88.75–111.25	−0.36	41	38.9	17	+	−0.2	13.4	10.6
	Novaya Zemlya	68.75–78.75	48.75–71.25	0.29	24	78	6	+	21.5	−5.3	−4.2
	Franz Josef Land	80–83	45–65	−0.77	46	110	3	++	8.4	−2.4	6.1
	Svalbard	76.25–81.25	8.75–31.25	0.13	31	58.5	7	+	−6.6	−2.8	−0.8
Iceland		63–66	338–346	0.13	27	−29.3	46	–	−4.2	−14.4	6.5
Alaska	SW Alaska	60–65	210–220	−0.33	40	117.4	14	+	3.5	−15.6	−17.7
	SE Alaska	55–60	220–230	−0.91	50	237	5	++	*	*	*

3) Upper-air temperatures

Upper-air sounding data available from the Integrated Global Radiosonde Archive (Durre et al. 2006) indicate a continued pattern of lower tropospheric warming and lower stratospheric cooling 1964-onward (Box and Cohen 2006). Lower tropospheric warm anomalies in all seasons, particularly in spring along western Greenland, were accompanied by relatively small midtropospheric cool anomalies. Winter tropopause temperatures (200 hPa) were above normal. Lower stratospheric (above 100 hPa) temperatures were lower than normal.

4) Surface melt extent and duration

Passive (SMMR and SSM/I, 1979–2008) and active (QuikSCAT, 2000–08) microwave remote sensing (Bhattacharya et al. 2009, submitted to *Geophys. Res. Lett.*; Liu et al. 2005) indicate abnormally high melt duration over the north and northeast ice sheet and along the east and west coasts above Greenland's most productive three outlet glaciers in terms of ice discharge into the sea: Kangerlussuaq; Helheim; and Jakobshavn (Fig. 5.18). Lower-than-normal melt duration is evident over much of the upper elevations of the ice sheet. New records of the number of melting days were observed over the northern ice sheet, where melting lasted up to 18 days longer than previous maximum values. Anomalies near the west coast are characterized by melting up to 5–10 days longer than the average (Tedesco et al. 2008).

The average daily melt extent, after Mote and Anderson (1995) and Mote (2007), for 2008 was 424,000 km^2, about 2.4% greater than the 1989–2008 average of 414,000 km^2, representing the lowest average melt extent since 2001. Significantly more melt occurred in 2008 in the northeast (45.6% greater than the 1989–2008 average) and northwest (29.7%), but less occurred in the two east-central regions (–16.8% and –25.4%) and in the southeast (–21.1%). Melt extent in 2008 was also above the 1979–2007 average. The trend in the total area of melt during 1979–2008 is approximately +15,900 $km^2\ yr^{-1}$ and is significant at the 95% confidence interval ($p < 0.01$).

5) Precipitation anomalies

Annual PT anomalies in 2008, determined using Polar MM5 data assimilation modeling (Bromwich et al. 2001; Cassano et al. 2001; Box et al. 2006), were positive (negative) up to 750 mm (–250 mm) over the eastern (western) ice sheet, respectively. More PT than normal occurred in isolated areas in extreme southeast, east, north, and northwestern Greenland. The overall anomaly indicated approximately 41 Gt more PT than normal for the 1971–2000 standard normal period.

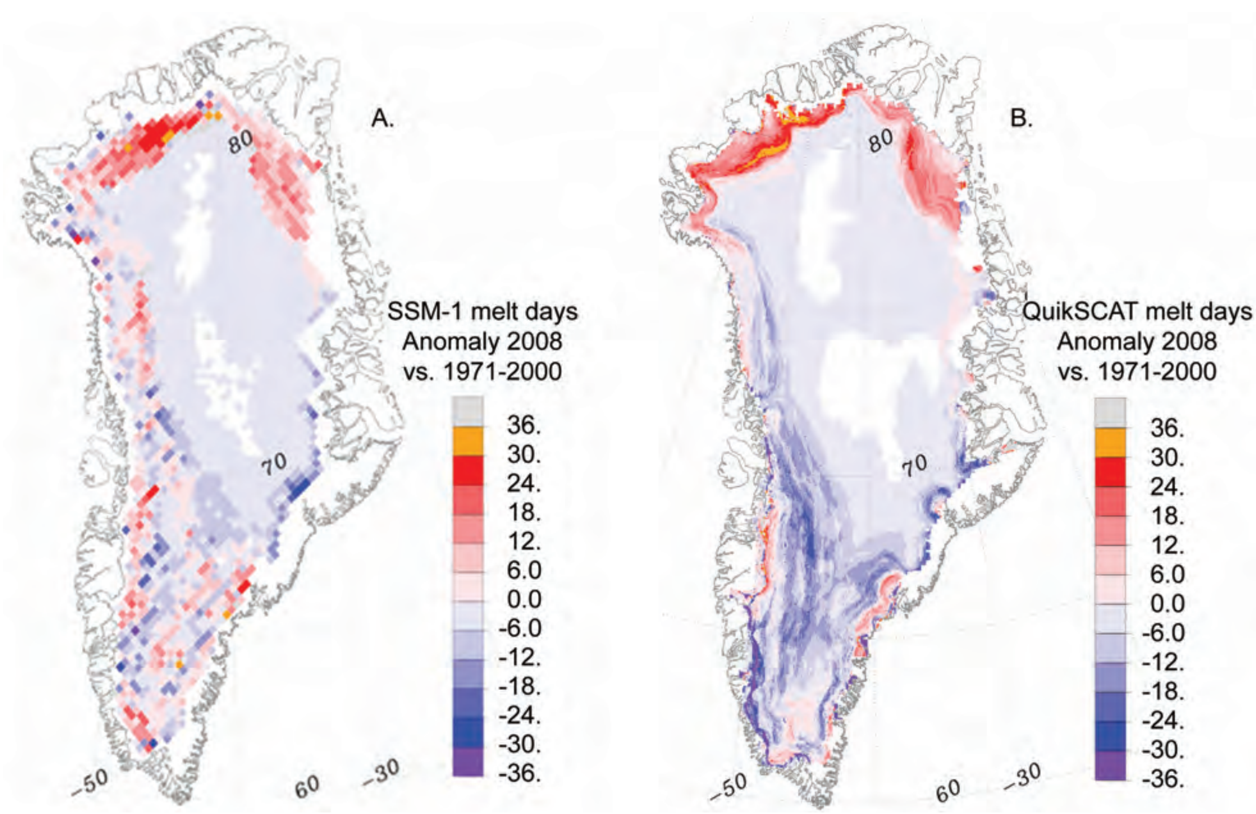

Fig. 5.18. 2008 Greenland ice sheet surface melt duration anomalies relative to the 1989–2008 base period based on (a) SSM/I and (b) QuikSCAT (2000–08 base period), after Bhattacharya et al. (2009, submitted to *Geophys. Res. Lett.*).

Table 5.2. Greenland ice sheet surface mass balance parameters: 2008 departures from 1971–2000 average (adapted from Box et al. 2006). Estimates by Hanna et al. (2008) are included for comparison.

	Box			Hanna		
	Mean (1971–2000)	% of normal	2008 Anomaly (Gt)	Mean (1971–2000)	% of normal	2008 Anomaly (Gt)
Total Precipitation	710.7	105%	38.5	624.16	108%	52
Liquid Precipitation	16.8	142%	7.1	27.01	147%	13
Surface Water Vapor Flux	66.7	100%	−0.2	40.59	74%	−11
Blowing Snow Sumblimation	39.6	99%	−0.3			
Snow Accumulation	604.5	106%	39.0	556.56	109%	50
Meltwater Volume	330.1	159%	194.1	333.95	133%	110
Meltwater Runoff	214.9	186%	184.3	277.91	142%	116
Surface Mass Balance	389.6	63%	−145.3	305.66	83%	−53
Mean T	−19.0		0.9	−21.4		1.1
AAR	0.920	0.905%	−0.087	0.859	0.933%	−0.007

6) Surface albedo

Melt season (day 92–274) surface albedo anomalies, derived using the Liang et al. (2005) algorithm applied to daily cloud-free MODIS imagery, indicate a lower surface albedo around the ablation zone (except the east ice sheet) (Fig. 5.19) resulting from the combined effect of the positive summer surface melt intensity anomaly and, in most areas, less winter snow coverage. A positive albedo anomaly is evident for the ice sheet accumulation zone and is consistent with above-average solid precipitation and/or less-than-normal melting/snow grain metamorphism.

7) Surface mass balance

Polar MM5 climate data assimilation model runs spanning 51 years (1958–2008), calibrated by independent in situ ice-core observations (Bales et al. 2001; Mosley-Thompson et al. 2001; Hanna et al. 2006) and ablation stakes (van de Wal et al. 2006), indicate that 2008 total precipitation and net snow accumulation was slightly (6%–8%) above normal (Table 5.2). In accordance with a +0.9°C 2008 annual mean surface temperature anomaly, the fraction of precipitation that fell as rain instead of snow, surface meltwater production, and meltwater runoff were 142%–186% of the 1971–2000 mean. Consequently, and despite 6%–9% (39–50 Gt) more snow accumulation than normal, the surface net mass balance was substantially (145 Gt) below normal. 2008 surface mass balance ranked ninth-least positive out of 51 years (1958–2008).

Surface mass balance anomalies indicate a pattern of increased marginal melting with noteworthy departures in excess of 1-m water equivalence per year from normal across the northern ice sheet (Fig. 5.20). The pattern of steepening mass balance profile is consistent with observations from satellite altimetry (Zwally et al. 2005) and airborne altimetry (Krabill et al. 2000); satellite gravity retrievals (e.g., Luthcke et al. 2006); and climate projections (Solomon et al. 2007).

8) Floating glacier ice changes

Daily surveys of Greenland ice sheet marine terminating outlet glaciers from cloud-free MODIS imagery (http://bprc.osu.edu/MODIS/) indicate that the 32 widest glaciers collectively lost 184.1 km^2 of mostly floating ice between the end of summer 2007 and the end of summer 2008. The 2008 area loss was 3 times that of the previous summer (2006–07 area

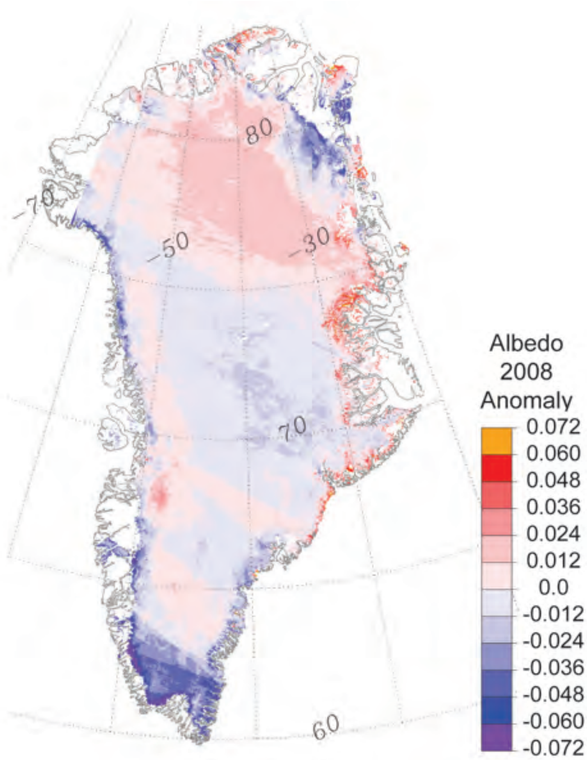

Fig. 5.19. Surface albedo anomaly Jun–Jul 2008 relative to a Jun–Jul 2000–08 base period.

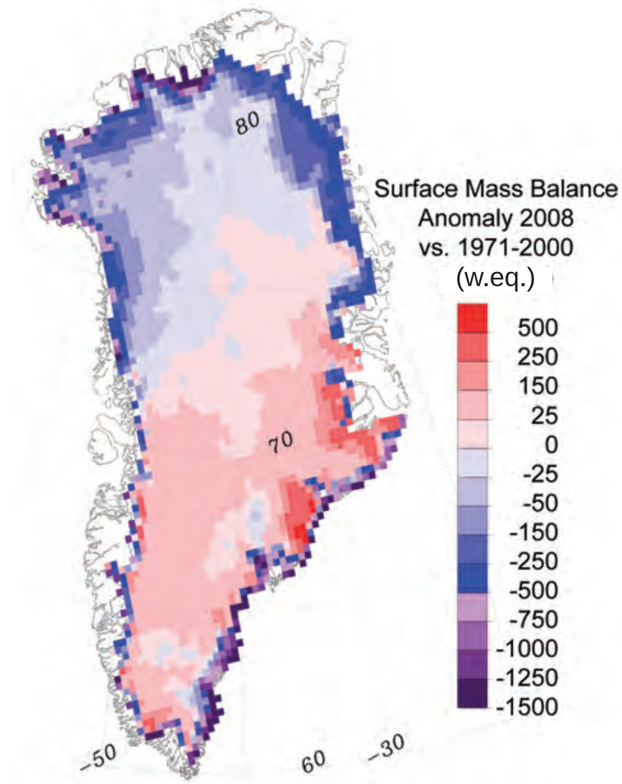

Fig. 5.20. 2008 surface mass balance anomalies with respect to the 1971–2000 base period, simulated by Polar MM5 after Box et al. (2006).

change was −60.8 km^2) and 1.7 times greater than the 8-yr trend, beginning in 2000 when MODIS data became available. In 2008, 18 of the 32 glaciers retreated relative to their end-of-summer 2007 position. The total net effective length change of these glaciers was −9.1 km. These losses marked a continuation of a deglaciation trend of −106.4 km^2 yr^{-1} area change (R = −0.98) since 2000. In other words, between 2007 and 2008, glaciers around Greenland lost an area more than 2 times the size of Manhattan Island, New York. The cumulative area change from end-of-summer 2000 to 2008 is −920.5 km^2, an area loss equivalent to 10 times the area of Manhattan Island.