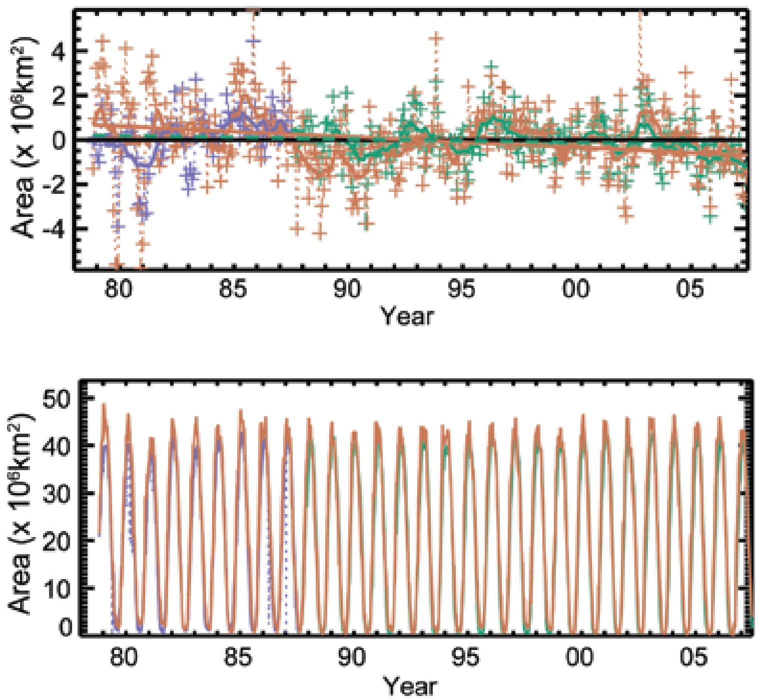

Fig. 5.15. (top) Time series of Northern Hemisphere SCA derived from passive microwave (purple/green) and NOAA snow charts (orange), and (bottom) SCA departures from monthly means, 1978–2007.

to use changes in the areal extent of glaciers as a straightforward indicator of changes in climatic conditions. Mass balance measurements, or the difference between the accumulation and ablation, are a more direct method to determine the year-to-year "health" of a glacier. Changes in mass balance correspond to changes in glacier volume. These measurements are typically obtained from less than about 0.2% of the world's glaciers. Researchers have measured mass balance on more than 300 glaciers since 1946, with a continuous record for about 40 glaciers since the early 1960s (e.g, Cogley 2005; Kaser et al. 2006).

These results indicate that in most regions of the world, glaciers are shrinking in mass. From 1961 to 2005, the thickness of "small" glaciers decreased approximately 12 m, or the equivalent of more than 9,000 km^3 of ice (Dyurgerov and Meier 2005; online at http://nsidc.org/sotc/glacier_balance.html). Recent mass loss of glaciers, ice caps, and ice sheets is estimated to be 0.58 mm SLE per year between 1961 and 2005 and 0.98 mm SLE per year between 1993 and 2005 (Dyurgerov and Meier 2005; online at http://nsidc.org/sotc/sea_level.html). In contrast to the two major ice sheets, Greenland and Antarctica, the network of small glaciers and ice caps, although making up only about 4% of the total land ice area or about 760,000 km^3, may have provided as much as 60% of the total glacier contribution to sea level change since the 1990s. This acceleration of glacier melt may cause 0.1 to 0.25 m of additional sea level rise by 2100 (Meier et al. 2007). The greatest mass losses per unit area are found in Patagonia, Alaska, and northwest United States/southwest Canada. However, because of the corresponding large areas, the biggest contributions in total to sea level rise come from Alaska, the Arctic, and the Asian high mountains.

(v) River discharge

Overall, the twenty-first century to date is characterized by an increased level of river discharge to the Arctic Ocean (www.R-ArcticNet.sr.unh.edu). The mean 2000–06 discharge from six of the largest Eurasian rivers (North Dvina, Pechora, Ob, Yenisei, Lena, and Kolyma) was 127 km^3 (7%) higher than long-term mean over the period 1936–99 (Fig. 5.16). The largest Siberian rivers, Yenisey and Lena, provided more than 70% of this increase. Preliminary 2007 estimates of annual discharge to the Arctic Ocean from the Russian rivers have been made using near-real-time data (http://RIMS.unh.edu). These estimates indicate a relatively high annual discharge for the six largest Eurasian rivers, possibly achieving a new historical maximum in 2007 for total discharge to the Arctic Ocean over the 1936–2007 observational period.

The mean annual discharge to the ocean over 2000–06 from the five largest North American rivers was about 6% (30 km^3) greater than the long-term mean over 1973–99. The historical annual maximum was observed for the summary discharge in 2005 (Fig. 5.16). However, the relatively short discharge time series for North America (37 yr) and the significant unmonitored land area does not support conclusions with the same reliability as for Eurasia.

6) Greenland—J. Box, J. Cappelen, D. Bromwich, L.-S. Bai, T. Mote, B. Veenhuis, N. Mikkelsen, and A. Weidick

(i) Synopsis

Greenland experienced regional warming in 2007, with statistically significant positive (warm) annual temperature anomalies in the 1.3° to 2.7°C range for coastal stations and 1.3°C for the inland ice sheet with respect to the 1971–2000 averages. Seasonal temperature anomalies were largest in winter but not positive in every season. Upper air temperatures indicate lower- to midtropospheric warm anomalies in all seasons above sounding stations surrounding Greenland. Noteworthy are western and southern locations where midtropospheric anomalies exceed those observed at the surface. Ice sheet surface melt duration anomalies were up to 53 days longer than the 1973–2000 average, based on passive microwave remote sensing. MODIS-derived surface albedo anomalies in 2007 versus the 2000–07 period were persistently negative, consistent with extensive surface melting. Greenland's largest glacier continued its recession, with ice flushing out from an embayment thought to have been ice filled since at least the onset of the Little Ice Age. The overall ice sheet mass budget was likely in mass deficit by at least 100 $km^3 yr^{-1}$.

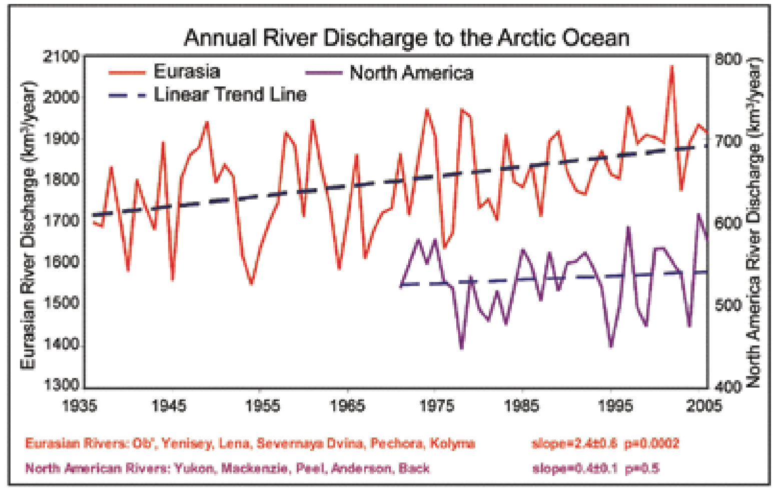

Fig. 5.16. Total annual discharge to the Arctic Ocean from the six largest rivers in the Eurasian pan-Arctic for the observational period 1936–2006 (updated from Peterson et al. 2002) (red line) and from the five largest North American pan-Arctic rivers over 1973–2006 (purple line). The least squares linear trend lines are shown as dashed blue.

(ii) Coastal surface air temperatures

Warm (positive) anomalies predominated in 2007, relative to the last 50-yr period (1958–2007), when con-

Table 5.1. Greenland station surface air temperature anomalies by season, 2007 vs 1971–2000. Anomalies are in K. Bold values indicate values that meet or exceed 1 *Z*-score.

Station (Region), latitude N, longitude W, time range	Winter	Spring	Summer	Autumn	Annual
Pituffik/Thule AFB (NW), 76.5°N, 68.8°W, 1961–2007	**−2.9**	1.4	**1.2**	0.4	0.1
Upernavik (NW), 72.8°N, 56.2°W, 1958–2007	5.3	9.0	−1.8	2.8	1.9
Ilulissat (W), 69.2°N, 51.1°W, 1958–2007	**5.4**	1.6	**1.4**	0.0	**2.1**
Aasiaat (W), 68.7°N, 52.8°W, 1958–2007	**5.5**	2.9	**1.9**	0.3	**2.7**
Nuuk (SW), 64.2°N, 51.8°W, 1958–2007	1.4	2.8	**−3.1**	−0.4	−0.1
Prins Christian Sund (S), 60.0°N, 43.2°W, 1958–2007	1.5	0.4	**1.8**	**1.2**	**1.3**
Tasiilaq (SE), 65.6°N, 22°W, 1958–2007	2.0	1.6	1.6	1.2	1.6
Danmarkshavn (NE), 76.8°N, 18.8°W, 1958–2007	1.0	0.5	0.4	1.7	0.9

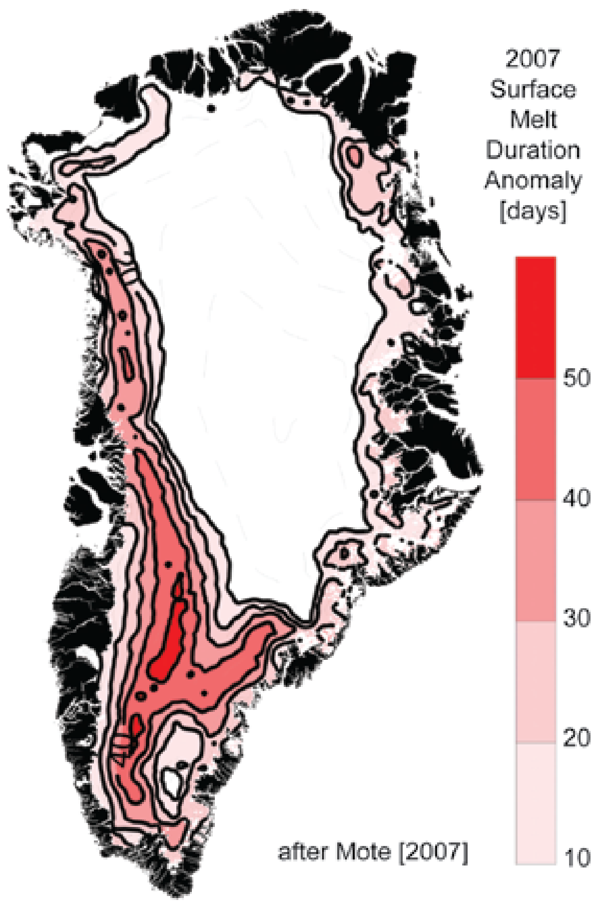

Fig. 5.17. Surface melt duration departure from average for summer (Jun–Aug) 2007 from SSM/I; units are days. The average is based on the summers from 1973 to 2000 (excluding 1975, 1977, and 1978). Only departures >10 days are included. (Figure after Box et al. 2006 and Mote 2007.)

tinuous surface air temperature records are available from a collection of stations around the island (Cappelen et al. 2007, 2008). Exceptions included an anomalously cold winter at Pittufik (northwest), an unusually cold summer and autumn at Nuuk (southwest), and an anomalously cold summer at Upernavik. The *Z*-scores exceeding ±1.0 or ±2.0 indicate anomalies exceeding the most common 66% or 95% of the observed cases, respectively (Table 5.1). At Upernavik (northwest) the spring temperature was the warmest in the past 50 yr, and at Nuuk (southwest) the summer temperature was the coldest in the past 50 yr. The only anomalies that were significant annually, that is, with *Z*-scores ≥1.0, were warm anomalies for 2007 annual means.

(iii) Upper air temperatures

Upper air sounding data available from the Integrated Global Radiosonde Archive (Durre et al. 2006) indicate for Greenland in 2007 a continued pattern of lower- to midtropospheric warming and lower-stratospheric cooling, consistent with trends since 1964 (Box and Cohen 2006). In the lower troposphere at the 850-hPa level (1.1–1.5-km altitude), for example, annual temperature anomalies were between +0.6° and +1.5°C at sites surrounding the island, relative to the 1971–2000 average. Seasonal anomalies were largest in winter with +8.1°C at 1,000 hPa at the Aasiaat/Egedesminde sounding site, with smaller positive anomalies elsewhere in almost all seasons. At the upper limit of mandatory observational levels, (20 hPa, in the lower–mid stratosphere), –11.6°C anomalies are evident. Large lower-stratospheric temperature anomalies are not necessarily abnormal given the relatively large observed temperature variability due in part to much lower atmospheric mass (e.g., Christy and Drouilhet 1994). Summer anomalies above southern Greenland balloon launching sites at the 850 and 600-hPa levels were between 0.2° and 1.3°C.

(iv) Greenland ice sheet melt extent

Passive microwave observations indicate summer 2007 (June–August) SMD was greater than any other observed summer since records began in 1973 (Mote 2007). The ice sheet area undergoing surface melt was 60% greater in 2007 than the next highest year (1998). Summer 2007 had 20 days more melt than average (1973–2000) across nearly all of the regions that exhibit melting. Up to 53 more days of melting than average was observed for elevations in the 2,000- to 2,400-m above sea level range between the north and south domes of the ice sheet (Fig. 5.17).

(v) Ice sheet precipitation, evaporation, and meltwater runoff

Polar MM5 climate data assimilation model runs spanning 50 yr (1958–2007), 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 year 2007 precipitation and accumulation was not abnormal despite a +10 km^3 decade^{-1} positive total precipitation trend over the 1958–2007 period. Surface water vapor fluxes were within an insignificant inter-annual range. In accordance with a +1.3°C year 2007 annual mean temperature anomaly, the fraction of precipitation that fell as rain instead of snow, surface meltwater production, and meltwater runoff were well above the 1971–2000 mean (Table 5.2). Due to abnormally large mass loss by meltwater runoff despite normal snow accumulation,

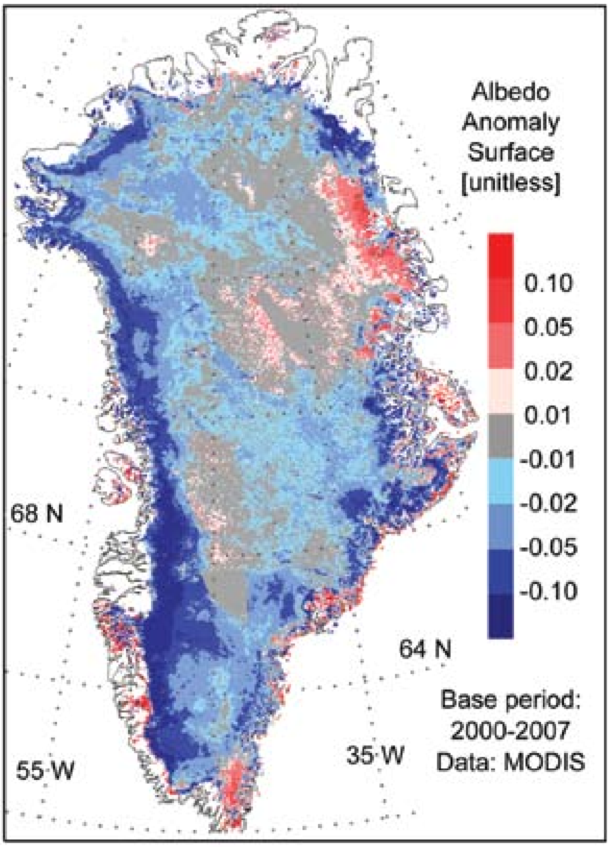

Fig. 5.18. Albedo anomaly (unitless) for 8–23 Aug (days 220–235) 2007 vs the 2000–07 average (from algorithm based on Liang et al. 2005).

the net surface mass budget was 46% below normal, corresponding with a –156 $km^3\ yr^{-1}$ anomaly. The 2007 surface mass budget anomaly was a significant fraction of the accumulation rate of 613 $km^3\ yr^{-1}$ for the 1971–2000 period.

(vi) Ice sheet albedo

Surface solar radiation reflectance, referred to as albedo, decreases in response to surface melting. Melt season surface albedo anomalies were calculated using the Liang et al. (2005) algorithm for the 2000–2007 period in 15-day intervals that provided sufficient cloud-free viewing of the surface. Negative surface albedo anomalies were widespread beginning in early June, when melting normally begins, through late August when abnormal melt and more frequent rainfall darkened the snow and ice surface (Fig. 5.18).

(vii) Glacier changes

The terminus of Greenland's largest glacier, the Jakobshavn's Isbrae near Ilulissat, moved 0 to 500 m in 2007 (Fig. 5.19), continuing a retreat that began in 2001 with a dramatic 11-km floating ice collapse (Weidick and Bennike 2007). The large ice lagoon called Tissarissoq at the south side of the fjord was flushed of ice by the end of the summer, ice-free probably for the first time since at least the onset of the Little Ice Age (ca. 0.4–0.1 ky BP). It is possible that Tissarissoq was ice-free before that time during the medieval warm period (ca. 1.1–0.5 ky BP).

b. Antarctic

1) Overview—T. A. Scambos

The Antarctic climate system is distinctly different from the Arctic, governed more strongly by the high degree of symmetry of both land and ocean surrounding the pole. The continent's high plateau anchors a strong polar vortex of westerly winds, and is the source of a near-constant katabatic airflow from a frequent inversion layer near the ice sheet surface. Along its coastline, a narrow zone of easterly flow occurs south of the girdling westerlies. (Captain James Cook noted in 1796 that if he were to try to approach the continent again, he might take advantage of this high-latitude shift in the prevailing winds.) Variations in this westerly flow, and in the relative air pressure between the vortex interior and the encircling regions is the primary oscillation of the far southern climate system, the so-called SAM (Marshall 2003). Another recognized pattern is zonal wave 3 (Raphael

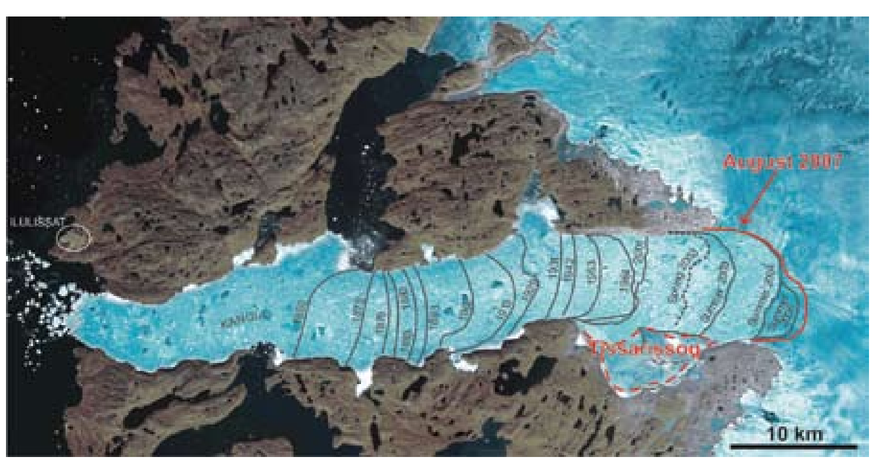

Fig. 5.19. Front position of the Ilulissat (Jakobshavn Isbrae) glacier in 2007 and earlier years, based on Weidick and Bennike (2007). The image mosaic is from Jun 2003 Landsat and ASTER images.

Table 5.2. Greenland ice sheet surface mass balance parameters: 2007 departures from 1971–2000 average (adapted from Box et al. 2006).

Total	2007 as % of average	2007 minus average ($km^3\ yr^{-1}$)
Total precipitation	97%	−18.9
Liquid precipitation	140%	8.3
Evaporation	97%	−2.1
Blowing snow sublimation	106%	2.1
Snow accumulation	97%	−18.9
Meltwater production	153%	154.9
Meltwater runoff	177%	137.3
Surface mass balance	64%	−156.4
Mean temperature	—	1.3
Accumulation area ratio	93%	−0.064 (%)

and Holland 2006; Raphael 2004), describing the tendency for a trio of fixed high pressure cells, and adjacent low pressure cells, to dominate circulation patterns about the continent.

Several studies have noted the apparent slight cooling trend in near-surface temperature records of Antarctic continental stations over the past several decades (e.g., Chapman and Walsh 2007b). Coupled with this cooling pattern is the warming trend observed in the Antarctic Peninsula, among the fastest-warming regions on Earth. Continental Antarctica is the largest remaining region on our planet with unchanged or cooling climate, and this has occasionally been pointed out by non-scientists as a basis for skepticism about GHG-induced "global" climate warming. Yet the Antarctic system is indeed showing a response over recent decades, in the form of an increasing tendency toward a positive SAM mode, that is, increased westerly wind flow. This pattern is consistent with both GHG forcing of climate (Arblaster and Meehl 2006), and with seasonal ozone reduction in the stratosphere (Thompson and Solomon 2002). This increased tendency toward stronger westerlies tends to isolate the cold continental plateau more, leading to cooling, and drives northwesterly flow over the peninsula, resulting in warming. But, importantly, the stronger westerly flow may be influencing ocean currents as well, moving coastal surface water northeastward via Ekman flow, and as a result drawing a return flow of warmer Antarctic Circumpolar Deep Water onto the continental shelf at depth, thus accelerating basal melt rates of thicker ice masses (e.g., Pine Island glacier; Rignot 2008).

The year 2007 was somewhat anomalous relative to

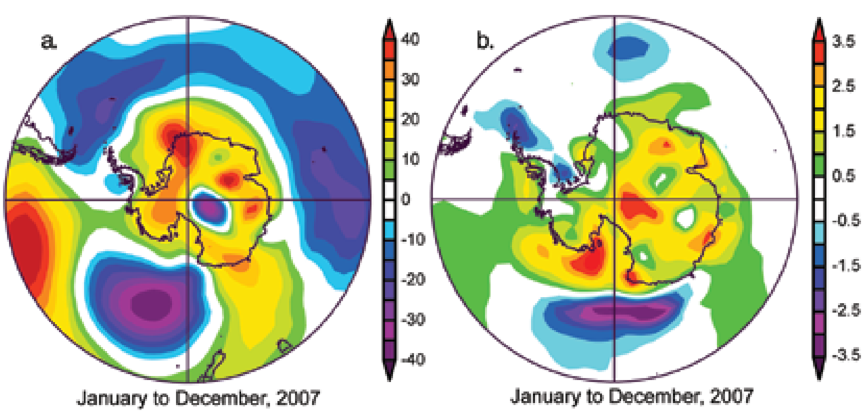

Fig. 5.20. Annual anomaly of (a) 850-hPa geopotential height and (b) surface temperature for 2007 relative to the 1979–2006 period, from NCEP–NCAR reanalysis data. The 850-hPa value is inferred for high-altitude regions of the continent; however, this level best illustrates the near-surface and middle troposphere patterns. These graphs, and climate diagrams shown in Fig. 5.22 (section 5b2), are from the NOAA/ESRL Physical Sciences Division (generated online at www.cdc.noaa.gov). Note that station data for a station near 85°S, 120°E is suspect, particularly for geopotential height, in all NCEP data here.