tic snow melt season was characterized by a strongly negative North Atlantic Oscillation (NAO) which reached a low of -2.25 in June (see section 5b). A negative NAO is associated with enhanced southerly air flow into the Arctic which contributes to warm temperature anomalies and rapid ablation of the snowpack. The only other year since 1950 to have a June NAO value lower than -2.0 was 1998 (Atkinson et al. 2006), when warm temperature anomalies were also present across Arctic land areas.

f. *Glaciers and ice caps (outside Greenland)*—G. Wolken, M. Sharp, M-L. Geai, D. Burgess, A. Arendt, and B. Wouters. With data contributions from J. G. Cogley and I. Sasgen.

Mountain glaciers and ice caps cover an area of over 400 000 km^2 in the Arctic, and are a major contributor to global sea level change (Meier et al. 2007; Gardner et al. 2011; Jacob et al. 2012). They gain mass by snow accumulation, and lose mass by surface melt and runoff, and by iceberg calving where they terminate in water (ocean or lake). The climatic mass balance (B_{clim}, the difference between annual snow accumulation and annual runoff) is a widely used index of how glaciers respond to climate variability and change.

As B_{clim} measurements for the 2011/12 balance year are not yet available, we summarize measurements of 24 Arctic glaciers for 2010/11 (World Glacier Monitoring Service 2013). The glaciers are located in Alaska (three), Arctic Canada (four), Iceland (six), Svalbard (four), Norway (two), and Sweden (five) (Table 5.1). All but three of the glaciers (Dyngjujökull, Brúarjökull, and Eyjabakkajökull in eastern Iceland) had a negative annual balance (i.e., loss of ice mass). Mass balances of glaciers in Svalbard and northern Scandinavia were very negative in 2010/11. In the Canadian Arctic, the 2010/11 balances were the most negative on record for all four glaciers. In this region, between five and nine of the most negative mass balance years in the 49–52 year record have occurred since 2000. The mean annual mass balance for the period 2000/11 is between three (Melville South Ice Cap) and eight (Meighen Ice Cap) times as negative as the 1963–99 average for each ice cap. This is a result of strong summer warming over the region that began around 1987 (Gardner and Sharp 2007) and accelerated significantly after 2005 (Sharp et al. 2011). For the monitored Arctic glaciers as a whole, mass balance year 2010/11 continues a trend of increasingly negative cumulative balances (Fig. 5.10).

Trends of increasingly negative cumulative balances are also evident in regional total mass balance estimates (ΔM, which includes mass losses by iceberg

TABLE 5.1. Measured annual climatic mass balances (B_{clim}) of glaciers in Alaska, the Canadian Arctic, Iceland, Svalbard, Norway, and Sweden for 2009/10 and 2010/11. Mass balance data for all glaciers are from the World Glacier Monitoring Service (2013).

Region	Glacier	Length of Record (yr)	Net Balance 2009/10 (kg m^{-2} yr^{-1})	Net Balance 2010/11 (kg m^{-2} yr^{-1})
Alaska	Wolverine	46	-85	-1070
	Lemon Creek	59	-580	-720
	Gulkana	46	-1832	-1290
Arctic-Canada	Devon Ice Cap	51	-417	-683
	Meighen Ice Cap	50	-387	-1310
	Melville S. Ice Cap	49	-939	-1339
	White	49	-188	-983
Iceland	Langjökull S. Dome	15	-3800	-1279
	Hofsjökull E	21	-2830	
	Hofsjökull N	22	-2400	
	Hofsjökull SW	21	-3490	
	Köldukvislarjökull	19	-2870	-754
	Tungnaarjökull	20	-3551	-1380
	Dyngjujökull	14	-1540	+377
	Brúarjökull	19	-1570	+515
	Eyjabakkajökull	20	-1750	+525
Svalbard	Midre Lovenbreen	44	-200	-920
	Austre Broggerbreen	45	-440	-1004
	Kongsvegen	25	+130	-434
	Hansbreen	23	-14	-280
Norway	Engabreen	42	-520	-910
	Langfjordjøkulen	21	-760	-1257
Sweden	Marmaglaciaren	22	-500	-1450
	Rabots Glaciar	30	-1080	-2110
	Riukojietna	25	-960	-1080
	Storglaciaren	66	-690	-1060
	Tarfalaglaciaren	17	-1060	-1820

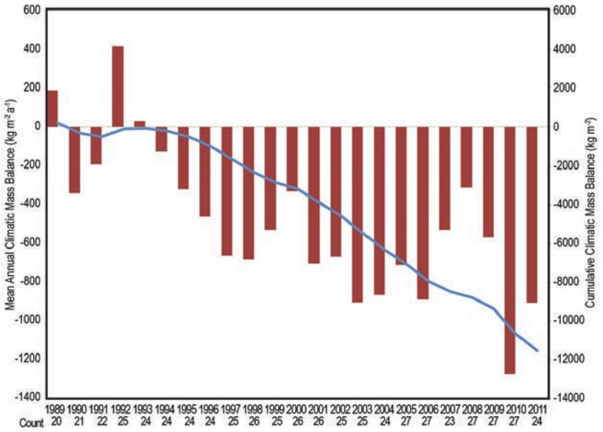

Fig. 5.10. Mean annual climatic mass balance (B_{clim}) from 1989 to 2011 (red) and cumulative climatic mass balance relative to 1989 (blue) based on available annual measurements (count) for 24 glaciers monitored in the Arctic (World Glacier Monitoring Service 2013).

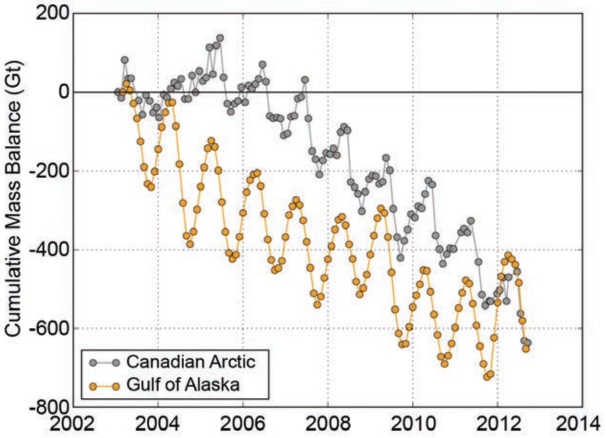

Fig. 5.11. Cumulative mass balances of Canadian Arctic Archipelago (CAA) and Gulf of Alaska region (GoA) glaciers, determined from the GRACE satellites. CAA data are unpublished estimates derived from monthly Stokes coefficients from the Center for Space Research fifth release (CSR RL5) and processed following methods in Gardner et al. (2011) and Wouters and Schrama (2007). The GoA data are unpublished estimates updated from Sasgen et al. (2012) and derived from a composite of monthly Stokes coefficients from the CSR, the Jet Propulsion Laboratory, and the German Research Center for Geosciences processing centers.

calving), derived using GRACE satellite gravimetry (Fig. 5.11). Available for the 2011/12 balance year, estimated ΔM of all the glaciers and ice caps in the Canadian Arctic Archipelago (CAA) was -106 ± 27 Gt, while in the Gulf of Alaska region ΔM was +51.9 ± 16.3 Gt. The CAA estimate matches the record negative value of the previous year (2010/11), and the Gulf of Alaska region estimate is the most positive for the region during the GRACE observation period, 2003–12 (Fig. 5.11). The higher rates of mass loss in the CAA (Fig. 5.11), and the strongly negative B_{clim} values reported in the previous paragraph, confirm the growing importance of glaciers and ice caps in this region as contributors to global sea level rise (Gardner et al. 2011).

Variability in mean summer temperature accounts for much of the interannual variability in B_{clim} in cold, dry regions like the Canadian high Arctic while, in more maritime regions, like Iceland and the Gulf of Alaska region, variability in winter precipitation is also a factor. Land surface temperature (LST) over ice in summer may serve as a proxy for B_{clim} of glaciers across the Arctic. Moderate to large positive LST anomalies over glaciers and ice caps occurred throughout the Arctic during summer 2012, particularly in the Canadian high Arctic (Fig. 5.12). Summer mean LSTs in 2012 were the warmest in the 13-year record on northern Ellesmere and Agassiz ice caps—exceeding the record set the previous year—and the second warmest on the Axel Heiberg Island, Prince of Wales (eastern Ellesmere Island), and Penny (southern Baffin Island) ice caps. Elsewhere in the Arctic, summer mean LSTs in 2012 equaled the 2011 record on Franz Josef Land, and were the second and fourth warmest in Severnaya Zemlya and Novaya Zemlya, respectively. In contrast, 2012 summer mean LSTs were only the eighth warmest in the 13-year long record in Iceland and the tenth warmest in southern Alaska (Fig. 5.12), where B_{clim} and ΔM, respectively, were positive.

Data from the NCEP/NCAR R1 reanalysis were also used as indicators of climatic conditions over the major glaciated regions of the Arctic during the 2011/12 mass balance year. Relative to the 1948–2008

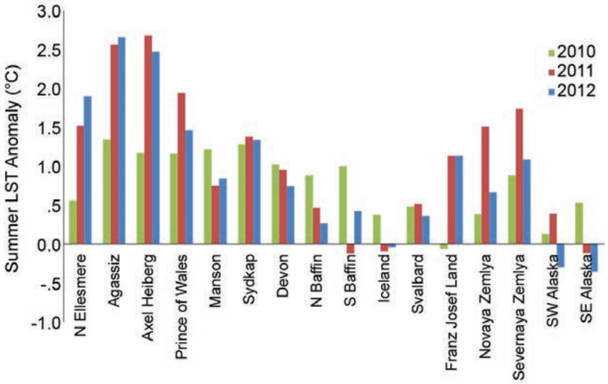

Fig 5.12. Comparison of 2010, 2011, and 2012 summer mean land surface temperature (LST) anomalies (relative to 2000–10) for 16 glaciated regions of the Arctic based on the MODIS MOD11A2 LST product (ORNL DAAC 2010).

mean, winter (September 2011–May 2012) precipitation was significantly above normal in southern Alaska and Iceland (see Fig. 5.9) and near normal elsewhere in the Arctic. Summer air temperature anomalies (JJA 2012 mean at 700 hPa geopotential height, relative to the 1948–2008 mean) were again strongly positive (+1.4°C to +3.6°C) over the Canadian Arctic Islands (including Baffin Island), and positive over Severnaya Zemlya (+0.41°C) and Franz Josef Land (+0.48°C). They were close to normal in Svalbard, Iceland, and southern Alaska. These patterns are broadly consistent with the pattern of summer LST anomalies and glacier mass balance.

The region of strongly positive summer 700 hPa air temperature anomalies in 2012 over south and west Greenland, Baffin Island, and Canada's Queen Elizabeth Islands is associated with a region of anomalously high geopotential height at all levels of the troposphere that was centered over Greenland and Baffin Bay. (Figure 5.3b shows the anomalously high pressure in this region.) This is a feature that has persisted during summers of the last six years (Box et al. 2012a; Sharp et al. 2011). These positive anomalies point to another strong melt season on these ice caps in 2012, and it is worth noting that the extreme warm temperature event of 8–12 July 2012 that produced record melt extent on the Greenland Ice Sheet (Box et al. 2012a; section 5g) also affected the ice caps in Arctic Canada. In contrast, the near-normal summer air temperatures in Iceland and southern Alaska (where summer LST anomalies were negative), followed heavy winter precipitation in 2011/12, and may therefore have resulted in relatively low summer melt in those regions in 2012.

g. *Greenland Ice Sheet*—M. Tedesco, P. Alexander, J. E. Box, J. Cappelen, T. Mote, K. Steffen, R. S. W. van de Wal, J. Wahr, and B. Wouters

1) SATELLITE OBSERVATIONS OF SURFACE MELTING AND ALBEDO

Melting at the surface of the Greenland Ice Sheet set new records for extent and melt index (i.e., the number of days on which melting occurred multiplied by the area where melting was detected) for the period 1979–2012, according to passive microwave observations (e.g., Tedesco 2007, 2009; Mote and Anderson 1995). Melt extent reached ~97% of the ice sheet surface during a rare, ice-sheet-wide event on 11–12 July (Fig. 5.13a; Nghiem et al. 2012). This was almost four times greater than the average melt extent for 1981–2010. The 2012 standardized melting index (SMI, defined as the melting index minus its average and divided by its standard deviation) was +2.4, almost twice the previous record of about +1.3 set in 2010 (Fig. 5.13b).

According to satellite observations, melting in 2012 began about two weeks earlier than average at low elevations, and lasted as much as 140 days (20–40 days greater than the mean value) in some areas of southwest Greenland (section 5e). Melting day anomalies (i.e., the number of melting days in 2012 minus the 1980–2010 average) were as much as +27 days in the south and +45 days in the northwest. Areas in northwest Greenland between 1400 m and 2000 m above sea level (a.s.l.), where melting is expected to be negligible or sporadic, experienced nearly two months longer melt duration in 2012 than the 1981–2010 reference period.

The area-averaged albedo of the ice sheet, estimated from spaceborne observations (MODIS), set a new record in 2012 (Fig. 5.14a). Negative albedo anomalies were widespread across the ice sheet, but were particularly low along the western and northwestern margins (Fig. 5.14b). The lowest albedo values occurred in the upper ablation zone and overlapped with the regions of extended melt duration.

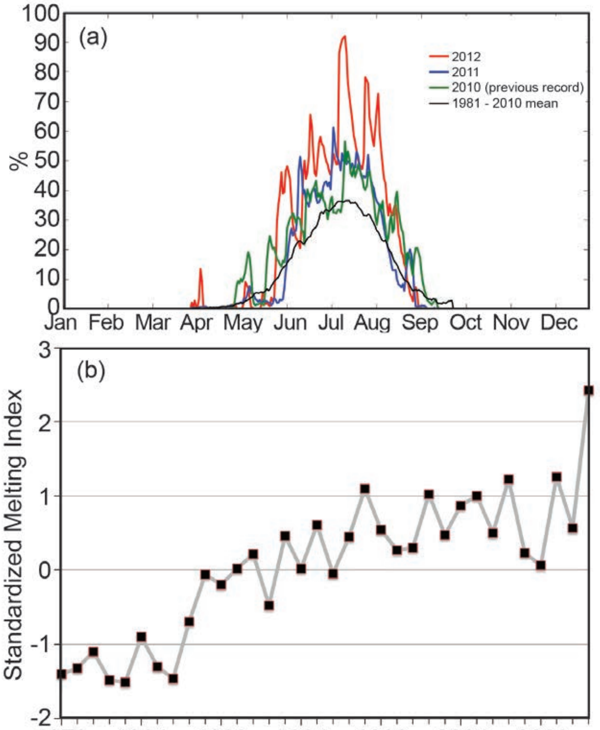

Fig. 5.13. (a) Surface melt extent, detected by the SSM/I passive microwave sensor, expressed as % of the total area of the Greenland Ice Sheet. (b) Standardized melt index (SMI) for the period 1979–2012 using the Tedesco (2009) algorithm.