i. *Glaciers and ice caps (outside Greenland)*—M. Sharp, G. Wolken, M-L. Geai, D. Burgess, A. Arendt, B. Wouters, J. Kohler, L. M Andreassen, and M. Pelto

Mountain glaciers and ice caps cover an area of over 400 000 km^2 in the Arctic and have been a major contributor to global sea level change in recent years (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. Snow accumulation minus mass losses by iceberg calving and runoff gives the total mass balance (ΔM).

Since many B_{clim} measurements for the 2012/13 mass balance year are not yet available, we begin by summarizing measurements from 24 Arctic glaciers in 2011/12 (World Glacier Monitoring Service 2014). These glaciers are located in Alaska (three), Arctic Canada (four), Iceland (six), Svalbard (four), Norway (two), and Sweden (five) (Fig. 5.19; Table 5.2). For the monitored Arctic glaciers as a whole, B_{clim} in 2011/12 was negative (Fig. 5.20), although 2011/12 was the eighth least negative year since 1989.

All but seven of the glaciers (Wolverine and Lemon Creek in coastal southern Alaska, Kongsvegen in Svalbard, Engabreen in northern Norway, and Rabotsglaciären, Storglaciären, and Tarfalaglaciären in northern Sweden) had a negative B_{clim}, i.e., loss of ice mass. For the four Scandinavian glaciers with positive B_{clim} in 2011/12, the recorded values were among the 5–7 most positive in the period of record for each glacier. This is most likely a result of anomalously cool temperatures over the region in summer 2012 (see Figs. 5.2c, 5.4a). In the Canadian Arctic, however, the 2011/12 climatic balances were each among the four most negative in their 50–52-year records, extending the unusually high mass loss rates from that region since 2006/07 (Sharp et al. 2011). This is consistent with the extensive surface melting and mass loss recorded in Greenland in summer 2012, which was a result of advection of warm southerly air masses (Tedesco et al. 2013a). B_{clim} was negative in interior Alaska (Gulkana Glacier) and positive in coastal southern Alaska (Wolverine and Lemon Creek glaciers), where winter snowfall was unusually high. In coastal southern Alaska, the 2011/12 balances were among the 5–10 most positive ever recorded at the glaciers sampled. The mass balance of Hansbreen in southern Spitsbergen, Svalbard, was the second most negative in the 24-year record.

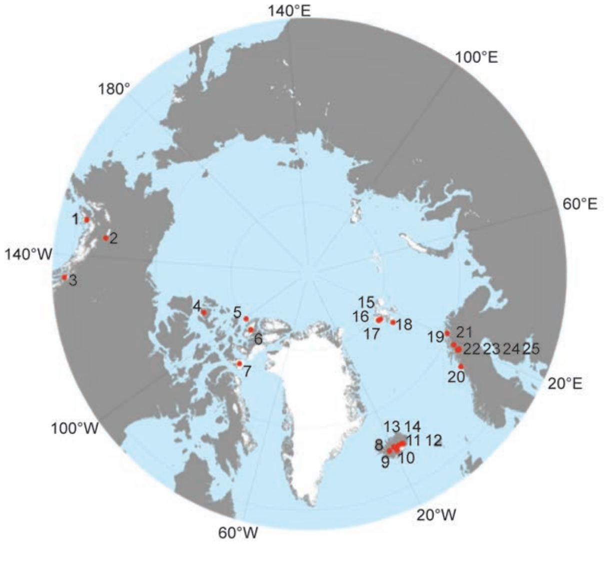

Fig. 5.19. Locations of 25 Arctic glaciers with long-term records of annual climatic mass balance (B_{clim}). See Table 5.2 for glacier names.

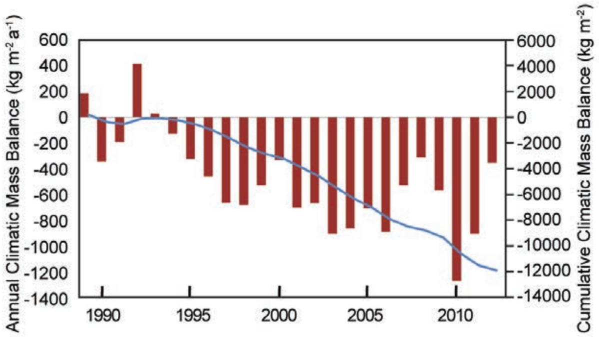

Fig. 5.20. Average annual (red bars) and cumulative (blue line) climatic mass balance (B_{clim}) of 24 Arctic glaciers (see Fig. 5.19) monitored during the period 1988/89–2011/12.

Trends of increasingly negative cumulative balances are evident in regional total mass balance estimates (ΔM) for Arctic Canada and Alaska derived using GRACE satellite gravimetry (Fig. 5.21). However, GRACE estimates of ΔM for the 2012/13 mass balance year are incomplete at the time of writing. Nevertheless, available measurements of ΔM for all the glaciers and ice caps in the Canadian Arctic Archipelago (CAA) suggest that the region gained mass between the ends of the summer 2012 and 2013 melt seasons, while mass accumulation in the Gulf of Alaska region over winter 2012/13 was significantly less than in winter 2011/12 (Fig. 5.21). It is not yet possible, however, to determine the sign of the mass balance in the Gulf of Alaska region in 2012/13 because the glaciers were still losing mass at the end of the available GRACE record.

In summer 2013, near-surface summer air temperatures over Greenland and Arctic Canada were up to 3.5°C cooler than in the period 2007–12 (see section 5j, Figs. 5.2c, 5.4a). The relatively low mass loss measured in summer 2013 by GRACE in Arctic Canada (Fig. 5.21), and the lower melt extent and less negative surface mass balance on the Greenland ice sheet compared to 2012 (see section 5j), are consistent with the air temperature observations for these cold, dry regions, where variability in average summer temperature accounts for much of the interannual variability in B_{clim}. This contrasts with more maritime regions, e.g., Iceland and the mountains adjacent to the Gulf of Alaska, where variability in winter precipitation is also a factor.

By contrast, summer 2013 was very warm over some glaciated regions of the Arctic, including southern Alaska, Novaya Zemlya, Svalbard, northern Scandinavia, and eastern Iceland (see Figs. 5.2c, 5.4a). In northwest Svalbard and northern Norway, this warm summer followed a winter with unusually low snowfall. For northwest Svalbard, this resulted

Table 5.2. Measured annual climatic mass balance (B_{clim}) of 24 glaciers in Alaska, the Canadian Arctic, Iceland, Svalbard, and northern Scandinavia for 2009/10, 2010/11, and 2011/12 (data from the World Glacier Monitoring Service). Additional 2012/13 data for glaciers in Svalbard and Norway were provided by J. Kohler and L. Andreassen. Numbers in the far left column identify glacier locations in Fig. 5.19.

Region	Glacier (Length of record in years)	Climatic Balance (kg m^{-2} yr^{-1})			
		2009/10	2010/11	2011/12	2012/13
Alaska					
1	Wolverine (47)	-85	-1070	510	
3	Lemon Creek (60)	-580	-720	450	
2	Gulkana (47)	-1832	-1290	-790	
Arctic Canada					
7	Devon Ice Cap (52)	-417	-683	-503	
5	Meighen Ice Cap (51)	-387	-1310	-1118	
4	Melville S. Ice Cap (50)	-939	-1339	-1556	
6	White (50)	-188	-983	-951	
Iceland					
8	Langjökull S. Dome (16)	-3800	-1279	-542	
9	Hofsjökull E	-2830			
9	Hofsjökull N	-2400			
9	Hofsjökull SW	-3490			
14	Köldukvislarjökull (20)	-2870	-754	-289	
10	Tungnaarjökull (21)	-3551	-1380	-1294	
13	Dyngjujökull (15)	-1540	+377	-975	
12	Brúarjökull (20)	-1570	+515	-759	
11	Eyjabakkajökull (21)	-1750	+525	-954	
Svalbard					
17	Midre Lovenbreen (45)	-200	-920	-260	-940
16	Austre Broggerbreen (46)	-390	-1010	-180	-1090
15	Kongsvegen (26)	+130	-440	210	-610
18	Hansbreen (24)	-14	-280	-150	
Norway					
20	Engabreen (43)	-520	-910	1140	-1780
19	LangfjordjØkulen (22)	-760	-1257	-760	-2610
Sweden					
21	Marmaglaciaren (23)	-500	-1450	-90	
22	Rabots Glaciar (31)	-1080	-2110	20	
23	Riukojietna (26)	-960	-1080	-90	
24	Storglaciaren (67)	-690	-1060	680	
25	Tarfalaglaciaren (18)	-1060	-1820	830	

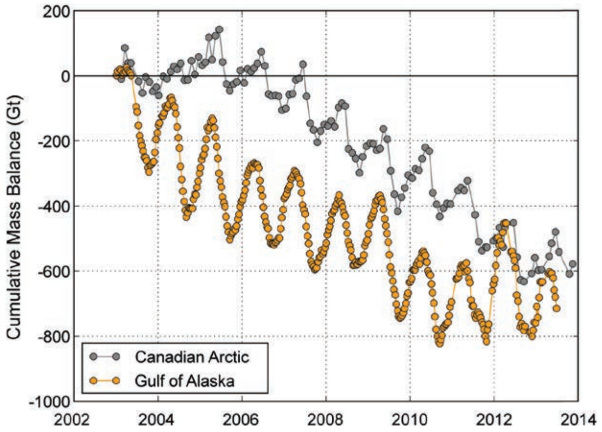

FIG. 5.21. Cumulative total mass balance (Gt) of glaciers in the Canadian Arctic and the Gulf of Alaska region for the period 2003–13. Note that available measurements for the Gulf of Alaska do not cover the full 2012/13 mass balance year. The total uncertainty from 2003 to 2010 in the Gulf of Alaska and Canadian Arctic mass trends was ±11 Gt yr^{-1} (Luthcke et al. 2013) and ±7 Gt yr^{-1} (update of Gardner et al. 2013), respectively. Uncertainties in the GRACE time series result from different approaches used to process the raw Level 1B satellite observations, signal leakage in and out of the solution domain, and different methods for modeling non-glacier sources of mass variability.

in the second or third most negative annual climatic balances on record in 2012/13, while for northern Norway it resulted in the single and second most negative annual climatic balances (Table 5.1). In Alaska, final values for the annual climatic mass balance have not yet been determined, but measurements in late summer 2013 suggest that 2012/13 may have been the most negative balance year on record at coastal Wolverine Glacier and the fifth most negative at Gulkana Glacier in the Interior (preliminary data provided by the United States Geological Survey). In southeastern Alaska, both Lemon Creek and Taku Glaciers had above-average equilibrium line altitudes of 1050 and 1115 m, respectively, at the end of summer 2013, which suggests a moderately negative annual climatic balance (B_{clim}) in that region.

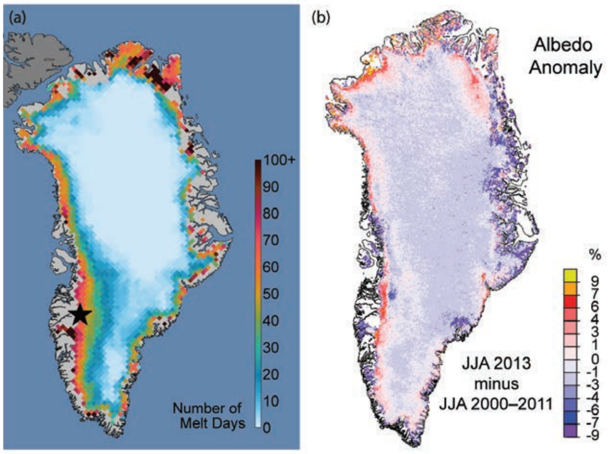

Fig. 5.22. (a) Cumulative number of melting days on the Greenland Ice Sheet between 1 Jan and 23 Sep 2013. (Source: National Snow and Ice Data Center) (b) Greenland Ice Sheet albedo anomalies in summer 2013 relative to the 2000–11 average derived from MODIS (Moderate-resolution Imaging Spectroradiometer). The black star on the west coast of Greenland in (a) marks the location of Kangerlussuaq and the K-transect to its east.

j. *Greenland Ice Sheet*—M. Tedesco, J. E. Box, J. Cappelen, X. Fettweis, T. S. Jensen, T. Mote, A. K. Rennermalm, L. C. Smith, R. S. W. van de Wal, and J. Wahr

1) Satellite observations of surface melting and albedo

Melt estimates over the Greenland Ice Sheet obtained from passive microwave data (Mote and Anderson 1995; Mote 2007) indicate that melting during summer (June–August, JJA) 2013 was near the long-term average for the period 1981–2010. On 26 July, melt area reached a maximum, covering 44.1% of the ice sheet surface. This was much smaller than the record of 97% set in 2012 (Nghiem et al. 2012; Tedesco et al. 2013b,c) and ranked 14th in the 35-year period of record (1979–2013). Moreover, the average melt area (the melting area averaged over the entire summer of 2013) of 16.7%, ranked 16th in the period of record and was the lowest annual value since 2000. For comparison, the average melt area during the record-setting summer of 2012 was 33.5%. The frequency of melting was slightly above the 1981–2010 average along the western and northwestern ice sheet margins, but lower than average in the south and southeast. In terms of number of melting days, surface melting during 2013 occurred for more than 100 days in some southwestern ice sheet margin areas, consistent with the long-term trend (Fig. 5.22a).

The average ice sheet-wide albedo derived from the Moderate-resolution Imaging Spectroradiometer (MODIS; e.g., Box et al. 2012) during summer 2013 was the highest (~0.72) since 2008, interrupting a period of increasingly negative and record albedo values since observations began (Fig. 5.23; Box et al. 2012; Tedesco et al. 2011, 2013b). Albedo for JJA 2013 was above the 2000–11 average along the southwest, northwest, and northeast regions and coasts of the ice sheet and below average for the east and southeast regions (Fig. 5.22b; Tedesco et al. 2013a). Areas of low albedo are generally associated with areas with prolonged melting.

2) Surface mass balance and river discharge

Surface mass balance measurements made ~20 km east of Kangerlussuaq (Fig. 5.22a) between 340 and 1500 m above sea level (a.s.l.) along the 'K-transect' (van de Wal et al. 2005, 2012) indicate that melting along the transect in 2013 was below the 1990–2010 average, particularly near the ice margin (Fig. 5.24a).

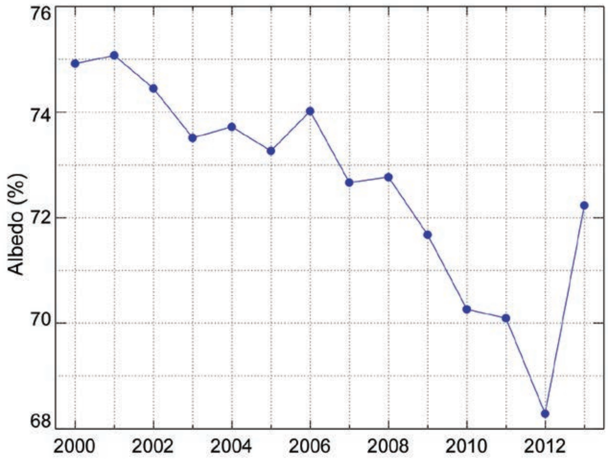

Fig. 5.23. Area-averaged albedo of the Greenland Ice Sheet in summer since 2000 derived from MODIS data.