averaged over the entire ice sheet was 68%. Albedo in July 2015 was as much as 15%–20% below average along the northwestern ice sheet and along the west coast, where a large increase in melting days was observed in 2015. Over the entire summer, however, the albedo anomaly along the southwestern ice sheet margin coast was positive, consistent with a relatively shorter melt season and with the presence of summer snow accumulation.

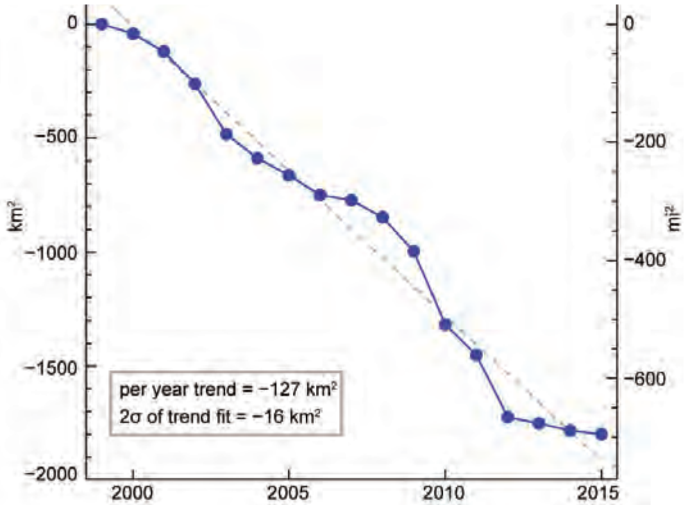

Fig. 5.11. Cumulative net area change (km², left *y*-axis and square miles, right *y*-axis) of 45 of the widest and fastest-flowing marine-terminating glaciers of the Greenland Ice Sheet (Box and Hansen 2015; Jensen et al. 2016). The linear regression is dashed.

GRACE satellite data (Velicogna et al. 2014) are used to estimate monthly changes in the total mass of the Greenland Ice Sheet, including mass gain due to accumulation and summer losses due to runoff and calving (Fig. 5.10). Between the beginning of September 2014 and the beginning of September 2015 GRACE recorded a 174 ± 45 Gt (Gt ≡ 10^9 tons) mass loss, versus an average September-to-September loss of 278 ± 35 Gt for the 2002–15 period. As a comparison, the 2013–14 September-to-September loss was 236 ± 45 Gt (7% of the total loss of ~ 3500 Gt since the beginning of the GRACE record in 2002) and that for 2011–12 was 638 ± 45 Gt (18% of the total loss). The relatively modest loss for the 2014–15 period is consistent with reduced melting over the southwest portion of the ice sheet and increased summer snowfall.

Glacier front classification in LANDSAT and ASTER imagery (after Jensen et al. 2016) reveals that 45 of the widest and fastest flowing marine-terminating glaciers retreated at a slower rate in 2013–15 than in the 1999–2012 period (Fig. 5.11). Between the end of the 2014 melt season and the end of the 2015 melt season, 22 of the 45 glaciers retreated, but the advance of 9 relatively wide glaciers resulted in the lowest annual net area loss in the 16-year period of observations (1999–2015), being –16.5 km² or 7.7 times lower than the annual average area change trend of –127 km² yr⁻¹ (Fig. 5.11). Specifically, Petermann Glacier advanced by 0.68 km across a width of 17.35 km, and Kangerdlugssuaq Glacier advanced by 1.68 km across a width of 6.01 km.

Fig. 5.10. Cumulative change in the total mass (Gt) of the Greenland Ice Sheet between Apr 2002 and Sep 2015 estimated from GRACE measurements. The square symbols denote Apr values for reference.

f. Glaciers and ice caps outside Greenland—G. Wolken, M. Sharp, L. M Andreassen, A. Arendt, D. Burgess, J. G. Cogley, L. Copland, J. Kohler, S. O'Neel, M. Pelto, L. Thomson, and B. Wouters

Mountain glaciers and ice caps cover an area of over 400 000 km² in the Arctic and are a leading contributor to global sea level change (Gardner et al. 2011, 2013; Jacob et al. 2012). They gain mass by snow accumulation and lose mass by surface melt runoff, and by iceberg calving where they terminate in water (ocean or lake). The total mass balance (ΔM) is defined as the difference between annual snow accumulation and annual mass losses (by iceberg calving plus surface melt runoff). Of the 27 glaciers currently monitored, however, only three (Kongsvegen, Hansbreen, and Devon Ice Cap NW) lose any mass by iceberg calving into the ocean. For all glaciers discussed here, the climatic mass balance is reported (B_{clim}, the difference between annual snow accumulation and annual runoff). B_{clim} is a widely used index of how glaciers respond to climate variability and change.

B_{clim} measurements for mass balance year 2014/15 are available for only 9 of the 26 glaciers that are monitored across the Arctic (three each in Alaska and Svalbard, and one in Norway), and some of these are still provisional. Therefore, we focus on the 2013/14 B_{clim} measurements, which are available for 21 glaciers (WGMS 2015b). These glaciers are located in Alaska (three), Arctic Canada (four), Iceland (seven), Svalbard (three), Norway (three), and Sweden (one; Fig. 5.12; Table 5.1). For these glaciers as a group, the mean B_{clim} in 2013/14 was negative. However, five glaciers [one each in Arctic Canada (Meighen Ice Cap) and Iceland (Dyngjujökull) and three in Svalbard (Midre Lovenbreen, Austre Broggerbreen, and Kongsvegen)] had positive balances.

For the Arctic as a whole, 2013/14 was the 17th most negative mass balance year on record (the first record dates from 1946) and the 12th most negative year since 1989 (i.e., the median for the 25-year period), when annual measurements of at least 20 glaciers began. This balance year continues the increasingly negative trend of cumulative regional climatic mass balances, calculated by summing the annual mean mass balances for all glaciers in each reporting region of the Arctic (Fig. 5.13). For Svalbard, 2013/14 was among the least negative mass balance years on record, and the climatic balances of each of its three glaciers were among the 3–9 most positive since 1987. Local meteorological observations suggest that the positive balances in Svalbard were attributable to high winter (October–May) precipitation, especially at low elevations, that was followed by a relatively cool summer (June–August). Melt suppression over Svalbard, as well as the Russian Arctic Archipelagos and the northernmost islands of Arctic Canada, was likely linked to negative 850-hPa air temperature anomalies in June–September. In contrast, in 2013/14 the mean measured climatic balance of glaciers in Alaska was the fifth most negative since 1966, with Lemon Creek and Wolverine glaciers registering their third and fourth most negative years on record, respectively. The negative balances of Alaska, Iceland, and northern Scandinavia glaciers in 2013/14 were most likely linked to melt increases caused by positive air temperature anomalies at the 850-hPa level in July–September that exceeded +2.5°C in northern Norway and Sweden (data from NCEP–NCAR reanalysis). Indeed, in 2014, many locations in northern Scandinavia reported their highest summer air temperatures since records began (Overland et al. 2015).

Among the nine glaciers for which 2014/15 B_{clim} measurements have been reported, the balances of glaciers in Alaska, Svalbard, and northern Norway

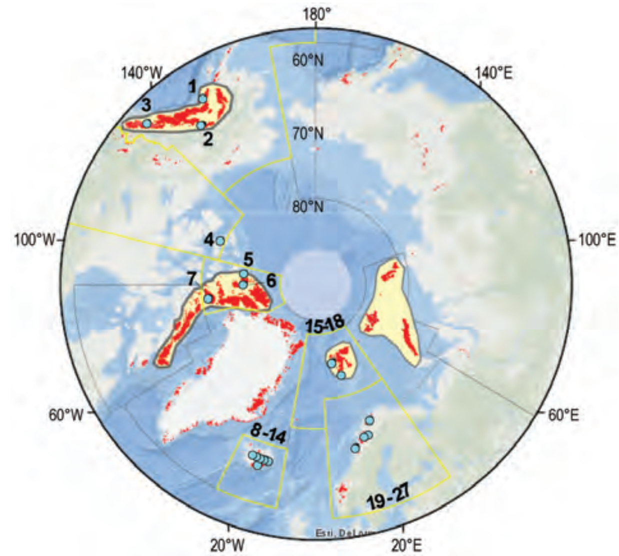

Fig. 5.12. Locations (green circles) of 27 Arctic glaciers with long-term records of annual climatic mass balance (B_{clim}). See Table 5.1 for glacier names. Regions outlined in yellow are the Randolph Glacier Inventory (RGI) regions of the Arctic (Pfeffer et al. 2014). In regions where individual glaciers are located too close together to be identifiable on the map, their numbers are shown at the edge of the RGI region in which they occur. Red shading indicates glaciers and ice caps, including ice caps in Greenland outside the ice sheet. Yellow shading shows the solution domains for regional mass balance estimates for Alaska, Arctic Canada, Russian Arctic, and Svalbard derived using gravity data from the GRACE satellites (see Fig. 5.3).

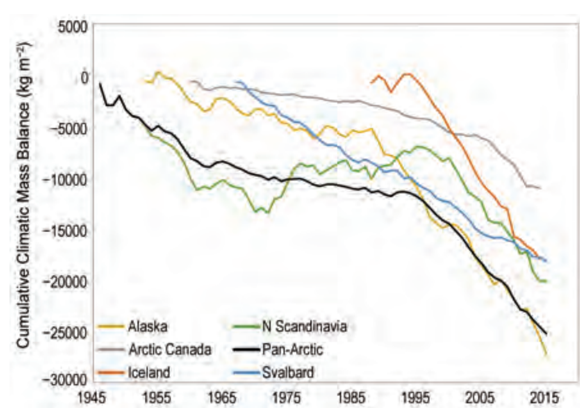

Fig. 5.13. Cumulative climatic mass balances (B_{clim} in kg m^{-2}) for glaciers in five regions of the Arctic and for the Arctic as a whole (Pan–Arctic). Mean balances are calculated for glaciers monitored in each region in each year and these means are summed over the period of record. Note that the period of monitoring varies between regions and that the number and identity of glaciers monitored in a given region may vary between years.

Table 5.1. Measured annual climatic mass balance (B_{clim}) of glaciers in Alaska, the Canadian Arctic, Iceland, Svalbard, and northern Scandinavia for 2013/14 and 2014/15, along with the 1980–2010 mean and standard deviation for each glacier (column 3). Mass balance data are from the World Glacier Monitoring Service (2015; 2016), with corrections to Svalbard data provided by J. Kohler and to Alaska data provided by S. O'Neel, and with updates from the Norwegian Water Resources and Energy Directorate (NVE) database. Numbers in column 1 identify glacier locations in Fig. 5.1. Note that 2014/15 results may be based upon data collected before the end of the 2015 melt season and may be subject to revision.

Region	Glacier (Record length, years)	Mean Climatic Balance 1980–2010 (kg m^{-2} yr^{-1})	Standard Deviation of Climatic Mass Balance 1980–2010 (kg m^{-2} yr^{-1})	Climatic Balance 2013/14 (kg m^{-2} yr^{-1})	Climatic Balance 2014/15 (kg m^{-2} yr^{-1})
Alaska					
1	Wolverine (50)	−285	1205	−1950	−1130
3	Lemon Creek (63)	−584	709	−1825	−2270
2	Gulkana (50)	−505	738	−220	−1440
Arctic Canada					
7	Devon Ice Cap (54)	−153	176	−246	
5	Meighen Ice Cap (53)	−173	284	+57	
4	Melville South Ice Cap (52)	−295	369	−159	
6	White (52)	−239	260	−417	
Iceland					
8	Langjökull S. Dome (18)	−1448	817	−1950	
9	Hofsjökull E (24)	−602	1009	−990	
9	Hofsjökull N (25)	−606	787	−950	
9	Hofsjökull SW (24)	−978	947	−990	
14	Köldukvislarjökull (22)	−529	738	−887	
10	Tungnaarjökull (23)	−1170	873	−1535	
13	Dyngjujökull (17)	−133	912	+170	
12	Brúarjökull (22)	−367	660	−34	
11	Eyjabakkajökull (23)	−867	813	−353	
Svalbard					
17	Midre Lovenbreen (48)	−356	305	+30	−450
16	Austre Broggerbreen (49)	−469	342	+10	−610
15	Kongsvegen (29)	−70	378	+140	−160
18	Hansbreen (26)	−431	512	−227	
Nortern Scandinavia					
20	Engabreen (45)	+463	1091	−892	+668
21	Langfjordjøkelen (25)	−927	781	−780	−800
22	Marmaglaciaren (23)	−430	525		
23	Rabots Glaciar (29)	−394	560		
24	Riukojietna (26)	−592	805		
25	Storglaciaren (68)	−113	698	−890	
26	Tarfalaglaciaren (18)	−212	1101		
27	Rundvassbreen (8)	−777		−790	−20

(Langfjordjøkelen) were negative, while those of glaciers in central Norway were near balance (Rundvassbreen) or positive (Engabreen). The pattern of negative balances in Alaska and Svalbard is also captured in time series of regional total stored water estimates (Fig. 5.14), derived using GRACE satellite gravimetry available since 2003. Annual storage changes are proxy for changes in the regional annual glacier mass balance (ΔM) for the heavily glacierized regions of the Arctic (Luthcke et al. 2013). Measurements of ΔM in 2014/15 for all the glaciers and ice caps in Arctic Canada and the Russian Arctic also show a negative mass balance year. The GRACE-derived time series clearly show a continuation of negative trends in ΔM for all measured regions in the Arctic. These measurements of B_{clim} and ΔM are consistent with anomalously warm (up to +1.5°C) June–August air temperatures over Alaska, Arctic Canada, the Russian Arctic, and Svalbard in 2015 (section 5b), and anomalously cool temperatures in northern Scandinavia, particularly in June and July (up to –2°C).

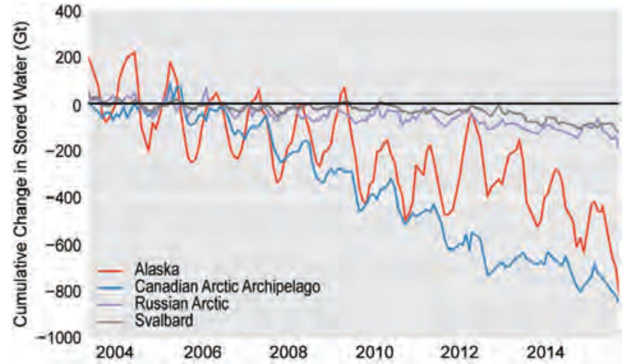

Fig. 5.14. Cumulative changes in regional total stored water for 2003–15 (Gt), derived using GRACE satellite gravimetry. Annual storage changes are proxy for changes in the regional annual glacier mass balance (ΔM). The estimated uncertainty in regional mass changes is 10 Gt yr^{-1} for the Gulf of Alaska, 8 Gt yr^{-1} for the Canadian Arctic, 8 Gt yr^{-1} for the Russian Arctic, and 4 Gt yr^{-1} for Svalbard. These errors include the formal error of the least squares fit and the uncertainties in the corrections for glacial isostatic adjustment, Little Ice Age, and terrestrial hydrology.

g. *Terrestrial snow cover*—C. Derksen, R. Brown, L. Mudryk, and K. Luojus

The Arctic (land areas north of 60°N) is always completely snow-covered in winter and almost snow free in summer, so the transition seasons of autumn and spring are significant when characterizing variability and change. The timing of spring snowmelt is particularly significant because the transition from highly reflective snow cover to the low albedo of snow-free ground is coupled with increasing solar radiation during the lengthening days of the high-latitude spring. The 2015 spring melt season provided continued evidence of earlier snowmelt across the terrestrial Arctic. There is increased awareness of the impact of these changes on the Arctic climate system, the freshwater budget, other components of the cryosphere (such as permafrost and associated geochemical cycles), and Arctic ecosystems (Callaghan et al. 2011).

Snow cover extent (SCE) anomalies (relative to the 1981–2010 reference period) for the 2015 Arctic spring (April, May, June) were computed separately for the North American and Eurasian sectors of the Arctic from the NOAA snow chart Climate Data Record, maintained at Rutgers University (Estilow et al. 2015; http://climate.rutgers.edu/snowcover/). Consistent with nearly all spring seasons of the past decade, both May and June SCE anomalies were strongly negative in 2015 (Fig. 5.15); June SCE in both the North American and Eurasian sectors of the Arctic was the second lowest in the snow chart record, which extends back to 1967.

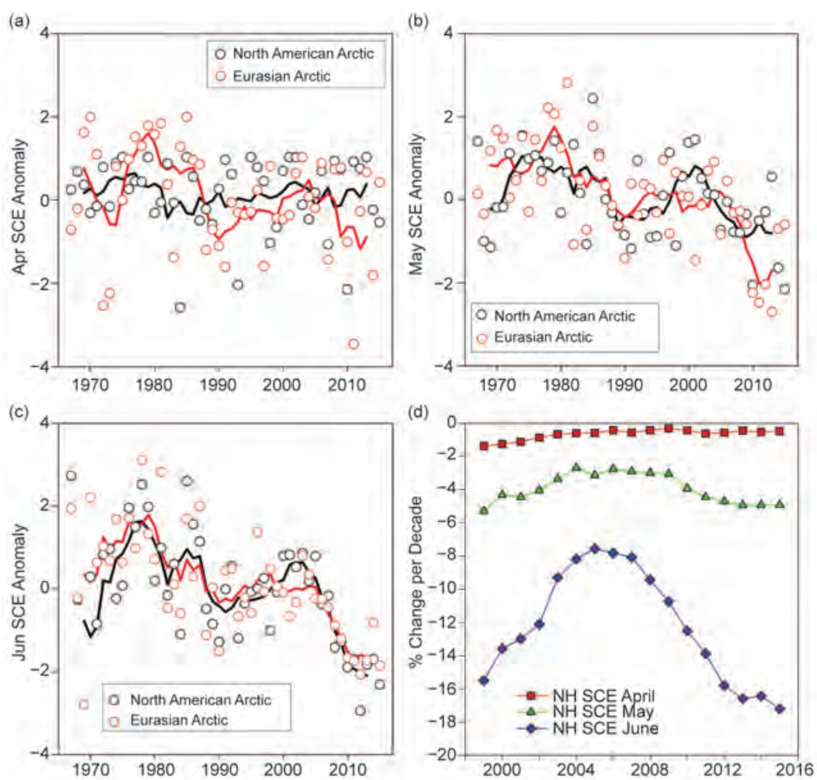

Fig. 5.15. Monthly Arctic snow cover extent standardized (and thus unitless) anomaly time series (with respect to 1981–2010) from the NOAA snow chart Climate Data Record for (a) Apr, (b) May, and (c) Jun 1967–2015 (solid lines denote 5-yr moving average); (d) % change $decade^{-1}$ in spring snow cover extent for running time series starting in 1979 (1979–98, 1979–99, 1979–2000, etc.).