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.

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.

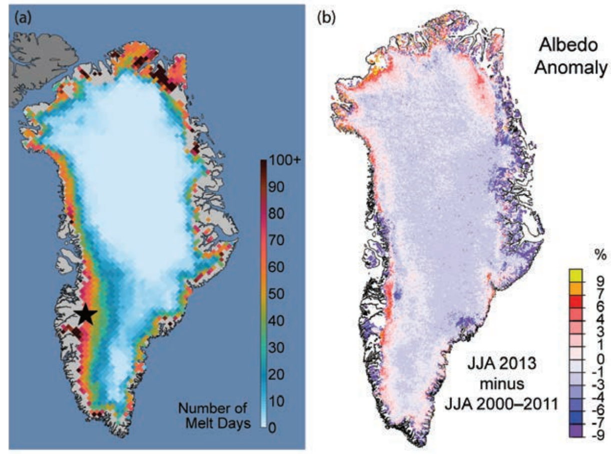

Fig. 5.22. (a) Cumulative number of melting days on the Greenland Ice Sheet between 1 Jan and 23 Sep 2013. (Source: National Snow and Ice Data Center) (b) Greenland Ice Sheet albedo anomalies in summer 2013 relative to the 2000–11 average derived from MODIS (Moderate-resolution Imaging Spectroradiometer).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

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).

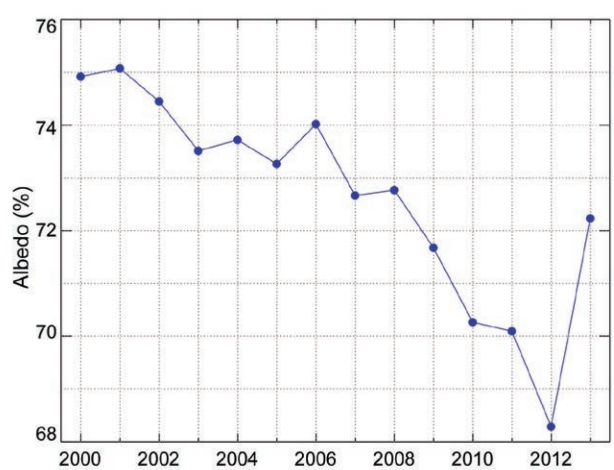

Fig. 5.23. Area-averaged albedo of the Greenland Ice Sheet in summer since 2000 derived from MODIS data.

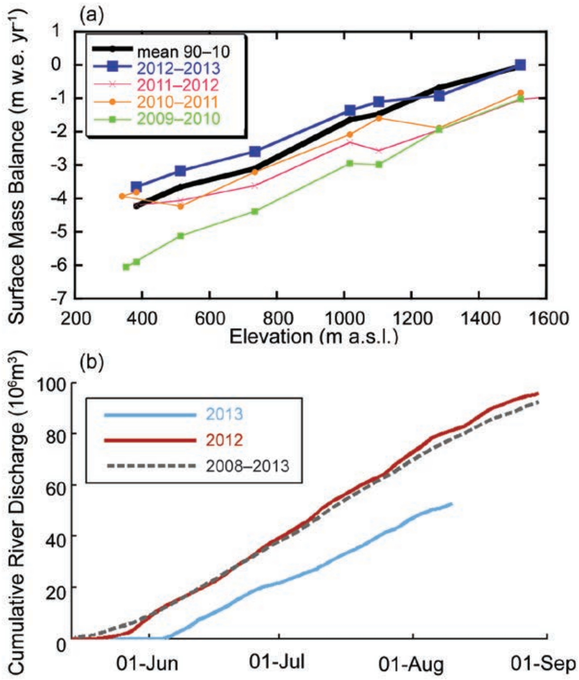

Fig. 5.24. (a) Surface mass balance (meters of water equivalent per year) as a function of elevation along the K-transect for four years since 2009/10, and the long-term average for 1990–2010. (b) Cumulative river discharge from the AK4 catchment (~20 km east of Kangerlussuaq) in southwest Greenland (see Fig. 5.22a) in 2013 compared with 2012 and the 2008–13 average.

The 2013 estimated equilibrium line altitude on the transect was near the long-term average position of 1500 m a.s.l., in strong contrast to its upslope migration to ~2700 m during the very warm summer of 2012 (e.g., Tedesco et al. 2013c).

Consistent with surface mass balance estimates, river discharge observations of a small basin of the Kangerlussuaq catchment, which includes much of the K-transect (Rennermalm et al. 2012, 2013a,b), reveal a later melt season onset in 2013 and lower flow conditions compared to previous years. Cumulative river discharge in 2013 (Fig. 5.24b) was the lowest recorded during the instrumental record beginning in 2008, confirming that meltwater runoff from the ice margin in this area of southwestern Greenland was below previous years (Tedesco et al. 2013a).

3) Surface air temperature observations

Near surface air temperature (NSAT) data recorded at long-term meteorological stations (Cappelen 2013; http://www.dmi.dk/fileadmin/Rapporter/TR/tr13-04.pdf) indicate that the outstanding surface temperature feature in 2013 was a consistent warm anomaly along the west Greenland coast during March (see Fig. 5.2a). A record warm March was recorded at Pituffik/Thule AFB, where the NSAT anomaly relative to 1981–2010 baseline was +7.7°C, the warmest on record since 1948. Similarly, the Upernavik and Kangerlussuaq March NSAT anomalies were +7.7° and +8.6°C, respectively. In contrast, during the summer months (June–August) NSAT values were generally near or below one standard deviation of anomalies relative to the 1981–2010 average, indicating that summer 2013 NSATs were normal with respect to that period. Wide-area air temperature anomalies are broadly consistent with the data for individual stations (Tedesco et al. 2013a).

In contrast to the previous six summers, characterized by negative North Atlantic Oscillation (NAO) phases, summer 2013 was characterized by persistent positive NAO phases, inducing lower-than-normal 500-hPa geopotential heights over Greenland. Consequently, warm, southerly air masses were diverted eastward from Greenland and northerly airflow in west Greenland (see Fig. 5.4b) promoted cooler, wetter, and cloudier weather than normal, and less melting than in recent years, as reported above.

4) Satellite observations of ice mass and marine-terminating glaciers

Based on GRACE satellite measurements, the cumulative ice sheet loss was 570 ±100 Gt between the end of April 2012 and the end of April 2013, which corresponds to the period between the beginning of the 2012 and 2013 melt seasons. The mass loss was more than twice the average annual loss rate of 260 ±100 Gt during 2003–12 (Fig. 5.25). The 2012/13 mass loss is the largest annual loss rate for Greenland in the GRACE record, mostly reflecting the large mass loss during the summer of 2012 (Tedesco et al. 2013c).

LANDSAT and ASTER images of 41 of the widest marine-terminating glaciers in summer 2013 indicate a net cumulative area change of –20 km^2 since summer 2012 (after Box and Decker 2011). This is the second smallest area change on record and 118 km^2 less than the average annual area change (–138 km^2) since 2000. The largest local increases in area between 2012 and 2013 occurred at Petermann (+16 km^2), Ryder (+4 km^2), Nioghalvfjerdsbrae/79 (+3 km^2) glaciers. The largest local area decreases occurred at Zachariae (–16 km^2), Humboldt (–10 km^2), and Helheim glaciers (–4 km^2).

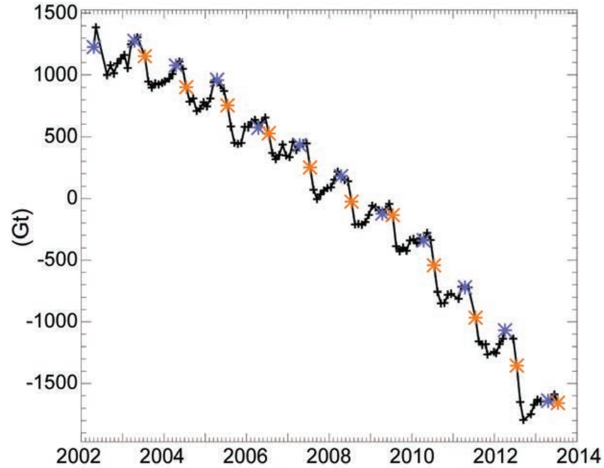

Fig. 5.25. Monthly changes in the total mass (Gt) of the Greenland Ice Sheet estimated from GRACE measurements since 2002. Blue and orange asterisks denote Apr and Jul values, respectively. Black asterisks denote all other months. Total ice mass change estimates from GRACE for summer 2013 are unavailable because the K-band ranging system was switched off during Aug and Sep to preserve battery life. The uncertainty in the mass loss estimate between Apr 2012 and Apr 2013, ±100 Gt yr^{-1}, is due to scatter in the data; estimates of leakage from imperfectly modeled signals external to the ice sheet; errors in the correction for glacial isostatic rebound; and uncertainty in the scaling factor used to correct for the limited horizontal resolution of GRACE. Velicogna and Wahr (2013) discuss uncertainties in GRACE estimates of polar ice sheet mass.

k. Lake ice—C. R. Duguay, L. C. Brown, K.-K. Kang, and H. Kheyrollah Pour

Lake ice is a sensitive indicator of climate variability and change. Lake ice phenology, which includes freeze-up (ice-on) and break-up (ice-off) dates, and ice cover duration, are largely influenced by air temperature changes and are, therefore, robust indicators of regional climate conditions (Duguay et al. 2006; Kouraev et al. 2007). Long-term trends in ground-based observational records reveal increasingly later freeze-up and earlier break-up dates, closely corresponding to increasing air temperature trends, but with greater sensitivity at the more temperate latitudes (Brown and Duguay 2010; Prowse et al. 2011). Broad spatial patterns in these trends are also related to major atmospheric circulation patterns originating from the Pacific and Atlantic Oceans, e.g., the El Niño-La Niña/Southern Oscillation, the Pacific North American pattern, the Pacific decadal oscillation, and the North Atlantic Oscillation/Arctic Oscillation (Bonsal et al. 2006; Prowse et al. 2011).

Despite the robustness of lake ice as an indicator of climate change, a dramatic reduction in ground-based observations has occurred globally since the 1980s (Lenormand et al. 2002; Duguay et al. 2006; IGOS 2007; Jeffries et al. 2012). Consequently, satellite remote sensing has assumed a greater role in observing lake ice phenology (Latifovic and Pouliot 2007; Brown and Duguay 2012; Kropáček et al. 2013; Surdu et al. 2014).

Freeze-up (FU) in 2012/13 occurred earlier than the 2004–12 average by ~1–3 weeks for most regions of the Arctic (Fig. 5.26a). Notable exceptions include Lakes Ladoga and Onega (western Russia) and lakes of smaller size in southern Norway and adjacent areas of Sweden (~4–5 weeks earlier). Arctic-wide, few lakes experienced later FU than normal (~1–2 weeks later); they were clustered mainly throughout northern Quebec, the northwest Canadian Arctic, northern Finland, and the adjacent areas of Russia, with lakes in a small, localized region of southern Sweden experiencing notably later FU than normal (~2–5 weeks). This is in contrast to the 2011/12 ice season when FU occurred almost a full month later for most lakes located in the southern portion of northern Europe and part of the central portion of Arctic Canada (i.e., Great Slave Lake and Lake Athabasca regions; Duguay et al. 2013).

Break-up (BU) dates in 2013 occurred ~1–3 weeks earlier than the 2004–12 average over much of the Arctic, with the exception of Baffin and Ellesmere Islands in Canada (~1–4 weeks later), consistent with cooler-than-normal spring and summer temperatures in the high Canadian Arctic (see Figs. 5.2b,c), and the southern part of Scandinavia and western Russia (~1–5 weeks later; Fig. 5.26b). Lakes showing the largest BU anomalies with earlier dates (~3–4 weeks earlier) in 2013 are found in Siberia, consistent with spring-time positive air temperature anomalies and early snow cover loss (see sections 5b and 5h). Break-up was also particularly early (by ~2–3 weeks) in the western Hudson Bay and Victoria Island regions of Canada. Earlier BU anomalies of the same magnitude were reported throughout Siberia in 2012 (Duguay et al. 2013). In general, the spatial pattern of ice cover duration (ICD; Fig. 5.26c) anomalies followed closely that of BU anomalies. ICD for 2012/13 was shorter by ~1–4 weeks in regions adjacent to Hudson Bay, as well as in the western section of the Canadian Arctic Archipelago (CAA), northern Alaska, Siberia, and northern Scandinavia. ICD was longer by ~1–4 weeks for Baffin Island, most parts of central to western Arctic Canada, southern Alaska, western Russia, and southern Scandinavia. Exceptions included: (1) Canadian lakes Amadjuak and Nettilling (the largest