**Table 5.2. 2009 Greenland station surface air temperature anomalies by season, relative to 1971–2000.**

| Station (Region) Latitude N. Longitude W, time range | Winter | Spring | Summer | Autumn | Annual |
|---|---|---|---|---|---|
| Thule AFB/Pituffik, 76.5 N. 68.8 W, 1961-2009 | **3.7** | 1.0 | **2.6*** | -1.4 | **1.6** |
| Upernavik (NW), 72.8N, 56.2 W 1958-2009 | **5.1** | 1.0 | **2.7** | 0.9 | **2.3** |
| Aasiaat (W), 68.7N 52.8, 1958-2009 | **4.5** | 0.6 | **2.0** | 0.3 | 2.1 |
| Nuuk (SW), 64.2 N, 43.2 W, 1958-2009 | 2.3 | 0.1 | 1.1 | **-0.6** | 1.1 |
| Prins Christian Sund (S), 60.0 N, 43.2 W, 1958-2009 | 1.4 | 0.6 | 0.7 | 0.4 | 1.0 |
| Tasiilaq (SE) 65.6 N, 22.0 W, 1958-2009 | 1.8 | 1.6 | **1.2** | 0.1 | **1.3** |
| Illoqqortoormiut (E), 70.4 N, 22.0 W, 1958-2009 | 1.4 | 0.1 | 1.2 | -0.1 | 0.5 |
| Danmarkshavn (NE), 76.8N 18.8 W, 1958-2009 | 1.1 | 0.6 | 0.0 | 0.8 | 0.5 |

*Anomalies are in °C, with respect to the 1971–2000 base period. Bold values indicate values that meet or exceed 1 standard deviation from the mean. Underlined values exceed 2 standard deviations from the mean. The * symbol indicates a record setting year. The winter value takes December from the previous year.

Canada (four), Iceland (nine) and Svalbard (four). Sixteen of the glaciers had a negative annual balance and four had a positive balance (two in Alaska and two in Svalbard). In addition, satellite gravimetry measurements reveal a regional annual net balance of -9 ± 20 Gt $yr^{-1}$ for Gulf of Alaska glaciers. Here, two glaciers located close to the coast had positive annual balances, reflecting heavy winter snowfall in winter 2007/08, while Gulkana Glacier in the Alaska Range had a slightly negative annual balance. In Arctic Canada, annual net balances were among the three most negative balances recorded in the 43–48 year record, likely due to the very warm summer in 2008, extending the period of very negative balances that began in 1987. The annual balances recorded in Iceland were slightly more negative than average (16–17 years of record), while those in Svalbard were more positive than average (20–42 years of record).

Summer (JJA 2009) air temperature data (700 hPa level) and winter (September 2008–May 2009) precipitation data from the NCEP/NCAR Reanalysis provide indications of climatic conditions over the major glaciated regions of the Arctic in the 2008/09 mass balance year (Fig. 5.20; Table 5.1). Winter precipitation anomalies were positive (relative to the 1948–2008 mean) in Iceland and over the Alaska panhandle and adjacent areas to the north, and negative in southwest Alaska and southwest Svalbard. Summer temperature anomalies were strongly positive over southern Alaska, the Canadian Arctic and Svalbard, and very negative over Novaya Zemlya and Severnaya Zemlya.

Melt season duration, and the dates of melt onset and freeze-up, on Arctic glaciers and ice caps were determined from 2009 backscatter time-series measured by the SeaWinds scatterometer on QuikScat (Fig. 5.21; Table 5.1). In Arctic Canada, melt duration anomalies (relative to the 2000–04 average) were positive on all ice caps in the Queen Elizabeth Islands, with the largest anomalies occurring on the northernmost ice caps (N Ellesemere, Agassiz, and Axel Heiberg) despite later-than-average melt onset dates. Melt duration anomalies were also positive on Svalbard and slightly positive in southwest Alaska, mainly due to both early melt onset and late freeze-up in the eastern Alaska Range. Melt duration anomalies were strongly negative on north and south Baffin Island, due to very negative (early) freeze-up anomalies, and on Novaya Zemlya, due to both very positive (late) melt onset and negative (early) freeze-up anomalies. Melt duration anomalies were also negative on Iceland and Franz Josef Land, and slightly negative on Severnaya Zemlya despite exceptionally positive (late) freeze-up anomalies.

By comparing 2009 summer temperature, winter precipitation, and melt season anomaly patterns with both the anomaly patterns and measured mass balances for 2007/08, we predict another very negative mass balance year in Arctic Canada (but probably not

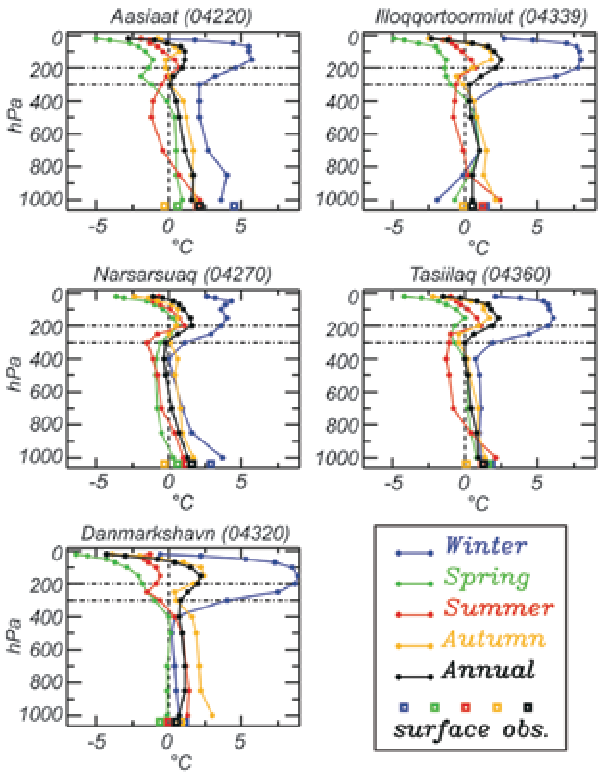


**Fig. 5.22. Upper-air and surface seasonal and annual mean temperature anomalies in 2009, with respect to the 1971–2000 average. The station WMO ID number is indicated beside the location name. See Table 5.2 for site coordinates.**

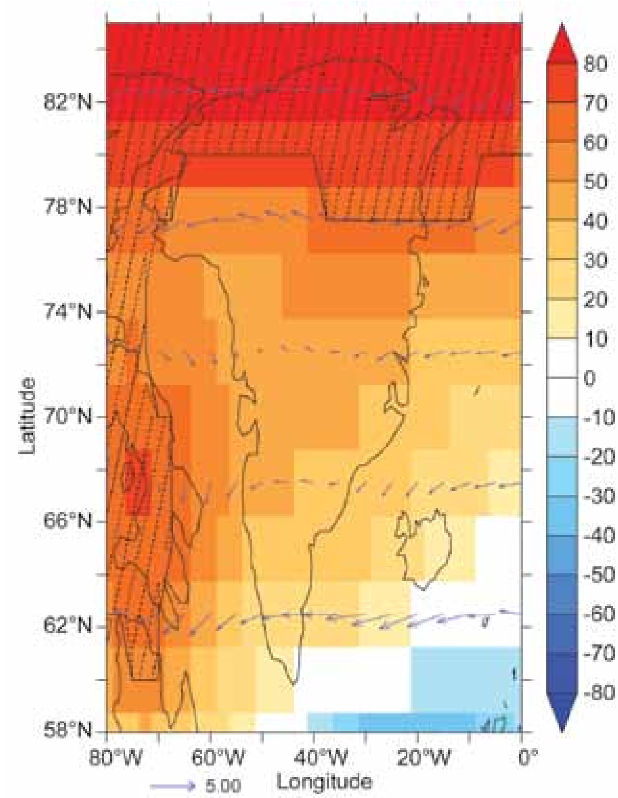


**Fig. 5.23. The geopotential height and wind anomalies for JJA 2009 (referenced to the 1960–2009 mean) at 500 hPa from the NCEP/NCAR Reanalysis. The blue arrows represent wind vector anomalies. Areas where anomalies were at least twice the 1960–2009 standard deviation are hatched.**

as negative as 2007/08), and annual balances more negative than in 2007/08 in Alaska, Svalbard and Franz Josef Land, and more positive than in 2007/08 in Iceland, Novaya Zemlya and Severnaya Zemlya.

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1) Coastal surface air temperatures

Warmer-than-normal winter and summer air temperatures prevailed along the northwest Greenland coast in 2009, compared to the 1971–2000 average, according to surface air temperature data recorded at operational meteorological stations (Table 5.2). Summer air temperatures at Thule AFB/Pituffik were the warmest on record since 1961. Aasiaat summer temperatures were second warmest on record since 1950. At stations with records beginning in 1873, the only outstanding anomaly was summer at Upernavik ranking second warmest. In contrast, autumn surface temperatures anomalies along west Greenland were relatively cool.

2) Upper-air temperatures

Seasonally-averaged 2009 upper-air temperature data, available from twice-daily balloon sounds at the Integrated Global Radiosonde Archive (http://www.ncdc.noaa.gov/oa/climate/igra/) (Durre et al. 2006), indicate a pattern of warm atmospheric anomalies below ~5 km (Fig. 5.22). This is consistent with a warming trend prevailing since reliable records began in 1964 and especially since the mid-1980s (Box and Cohen 2006). A number of sites were outstanding. These included Danmarkshavn and Illoqqortoormiut, with record-setting warm anomalies in the winter in the lower stratospheric between 50 and 200 hPa, and Aasiaat, where the summer was the warmest on record since 1964 at 1000 hPa. The averaged total column (1000 hPa–20 hPa) temperatures in winter ranged between the fourth and second warmest on record among the sampling sites. In the spring, these sites were among the second/third coolest, making the annual total column mean temperature near normal. Surface air temperature anomalies (Table

| Table 5.3. Greenland ice sheet surface mass balance anomalies, after Fettweis et al. (2010). | | | | |
|---|---|---|---|---|
| **2009 anomaly referenced to** | **Toptal SMB (Gt)** | **Total Snowfall (Gt))** | **Total Runoff (Gt)** | **JJA Air Temperature (°C)** |
| 1971-2000 | -280 | -150 | 110 | 0.72 |
| 1991-2000 | -230 | -140 | 84 | 0.52 |
| 2001-2009 | -85 | -100 | -37 | -0.71 |

5.2) are broadly consistent with the lowest level of the upper-air observations. The main exception is a consistent pattern of surface observations indicating a cool autumn season, while the lowest upper-air level (1000 hPa) indicates warming.

3) Atmospheric circulation anomaliesPersistent 500 hPa geopotential height anomalies drew more warm air than normal across northern Greenland

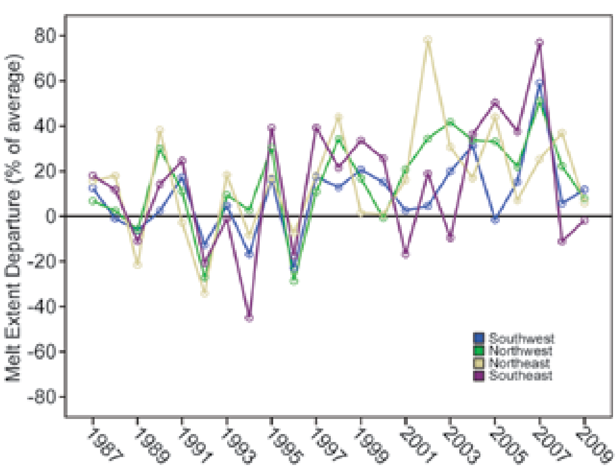


**FIG. 5.24. Time series of Greenland regional melt extent anomalies derived from passive microwave remote sensing, after Mote (2007).**

(Fig. 5.23, see also Fig. 5.3). The pattern was very similar to that of 2008 (Fettweis et al. 2010). Consistent with the geopotential height anomaly, passive microwave satellite data indicate a higher number of melting days than normal at the north of the ice sheet and along the eastern margin.

4) Surface melt extent and duration

Passive microwave measures of melt extent (Mote 2007) indicate that the seasonally-averaged melt extent (JJA) in 2009 was near the 1979–2009 average and was also the lowest since 1996 (Fig. 5.24). There was less-extensive-than-average melt from mid-June through the first week of July and much more extensive-than-average melt during the remainder of July. August was near normal. Late June corresponded to periods of temperatures at 850 hPa averaging 1°C–3°C below normal over most of the ice sheet in the North American Regional Reanalysis, while 850 hPa temperatures were above normal during July across the northern half of the ice sheet. Passive (SMMR and SSM/I, 1979–2009) and active (QuikSCAT, 2000–09) microwave remote sensing indicate substantially less melt duration in areas below ~1800 m elevation compared to recent years of high melt duration. More melting than normal is evident above ~800 m elevation in the north and eastern ice sheet.

5) Precipitation and Surface Mass Balance

The balance between ice mass gain from snowfall and the loss from meltwater runoff is positive for any healthy ice mass. The 2009 surface mass balance anomaly was 25% to 50% less positive than normal (Fig. 5.25). This condition usually reflects a heavy melt year. However, in 2009 melt was below-normal (Table 5.3). The source of the relatively low surface mass balance was the below normal snow accumulation for Greenland, especially evident along the western slope (Fig. 5.26). For the ice sheet as a whole snowfall was 25% (150 Gt) below normal, resulting in below normal mass input to the ice sheet. The temperature and precipitation anomalies are very likely the result of regional circulation anomalies that deserve more attention.

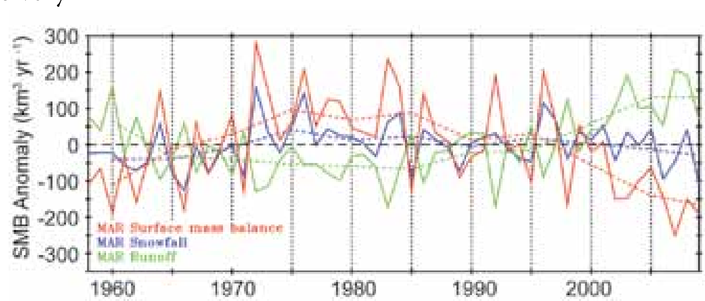


**FIG. 5.25. Time series of surface mass balance component anomalies simulated by the regional climate MAR model (Fettweis et al. 2010).**

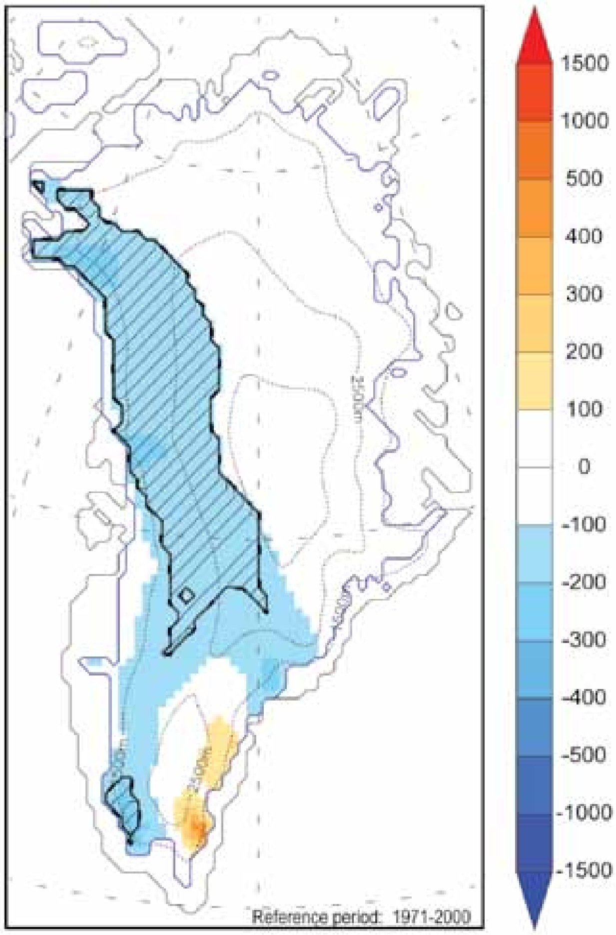


**FIG. 5.26. Year 2009 snowfall anomalies simulated by the regional climate MAR model (Fettweis et al. 2010). Hatched areas indicate an anomaly that is twice or more the 1971–2000 standard deviation.**

**FIG. 5.27. Satellite view of the Nares Strait polynya between Arctic Canada and northwest Greenland. Note the wind-driven "sea smoke" cloud streaks, that is, ice fog condensate from the much warmer ocean surface.**

#### 6) NORTH WATER POLYNYA

Nares Strait, separating Greenland from Ellesmere Island is host to the largest recurring polynya in the Arctic. This "North Water" polynya is formed by some combination of ocean heat and winds. Ecologically, the North Water is known to be a wildlife "bonanza" for marine mammals, including narwhal and beluga whales. Strong winds and large atmosphere-to-surface temperature contrast result in tremendous ocean-to-atmosphere heat transfer, frazil ice, and saline deep water production. The sea ice consolidated into land-fast ice 500 km north of its typical position (Fig. 5.27) in the Lincoln Sea. Nares Strait remained unconsolidated the entire 2008/09 winter. On 7 July 2009, the ice bridge collapsed allowing the normal flow of Arctic Ocean pack ice into the strait that makes ship navigation normally difficult, even for ice breakers. Summer (JJA)-averaged MODIS-derived (MOD28 4.88 km) sea surface temperatures were nearly 2°C warmer in Kane Basin than the 2000–07 average. Passive microwave sea ice concentration indicates an unprecedented low sea ice concentration in Nares Strait during summer 2009, relative to the 1979–2009 average. AMSR-E 12.5 km passive microwave sea ice concentrations were 20% below the 2002–07 base average north of Smith Sound.

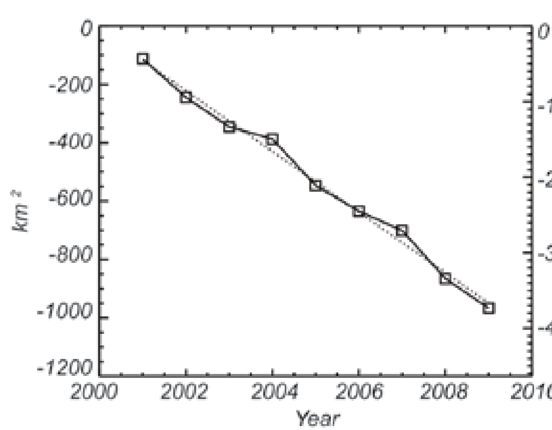


**FIG. 5.28. Cumulative annual area changes for 34 of the widest Greenland ice sheet marine-terminating outlets.**

#### 7) Outlet Glaciers

Daily surveys of Greenland ice sheet marine-terminating outlet glaciers from cloud-free Moderate Resolution Imaging Spectroradiometer (MODIS) visible imagery (http://bprc.osu.edu/MODIS/) indicate that the 34 widest glaciers collectively lost 101 $km^2$ of marine-terminating ice between the end of summer 2008 and the end of summer 2009. Twenty-three of thirty-four of the glaciers retreated in 2009 relative to their end of summer 2008 position. The total net effective length change of these glaciers was -1.2 km. The largest area changes included a 32 $km^2$ loss along the 110 km wide Humboldt Glacier; a 31 $km^2$ loss at the calving front of another north Greenland outlet, the Zachariæ Isstrøm; and 15 $km^2$ ice loss at the Midgard glacier. This marked a continuation of a highly linear (R = -0.99) deglaciation trend (-104 $km^2$ $yr^{-1}$, Fig. 5.28) of the past 10 summers when MODIS data are available. The cumulative area change from end of summer 2000 to 2009 is -967 $km^2$, an area loss equivalent to 11 times the area of Manhattan Island.