

# Greenland Ice Sheet

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## Highlights

- A persistent and strong negative North Atlantic Oscillation (NAO) index was responsible for southerly air flow along the west of Greenland, which caused anomalously warm weather in winter 2010-11 and summer 2011.
- The area and duration of melting at the surface of the ice sheet in summer 2011 were the third highest since 1979.
- The lowest surface albedo observed in 12 years of satellite observations (2000-2011) was a consequence of enhanced surface melting and below normal summer snowfall.
- The area of marine-terminating glaciers continued to decrease, though at less than half the rate of the previous 10 years.
- *In situ* measurements revealed near record-setting mass losses concentrated at higher elevations on the western slope of the ice sheet, and at an isolated glacier in southeastern Greenland.
- Total ice sheet mass loss in 2011 was 70% larger than the 2003-09 average annual loss rate of  $-250 \text{ Gt y}^{-1}$ . According to satellite gravity data obtained since 2002, ice sheet mass loss is accelerating.

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## Meteorological station records (J. E. Box and J. Cappelen)

Surface air temperatures from Greenland long-term meteorological stations are characterized by a record-setting warm winter, unusually cold spring (March-May) and a record-setting warm late summer in the northwest of the island (Table HTC3). At Upernavik, summer 2011 was the warmest since the Beginning of Records (BR) in 1873. Similarly, at Thule AFB, July 2011 and the summer season (June-August) was the warmest on record since BR 1961. At Kangerlussuaq, April 2011 was the coldest on record since BR 1949. April 2011 cold anomalies exceeding 2 standard deviations below the 1971-2000 normal were observed at west Greenland

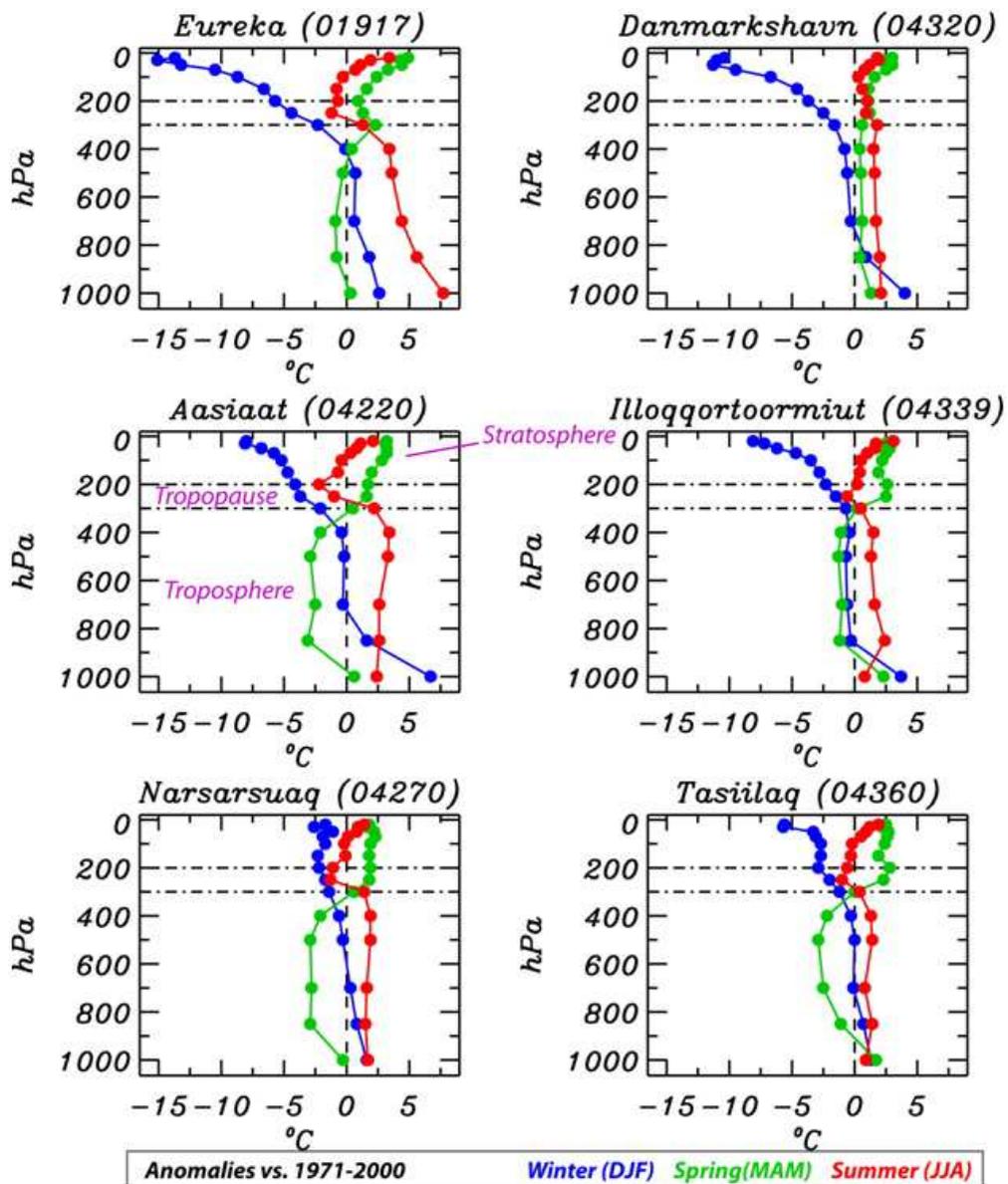
stations Nuuk and Paamiut. Surface air temperatures at the ice sheet Summit station since BR 1987 were below normal during March-June.

Table HTC3. Greenland station air temperature anomalies in the 12-month period before September 2011 relative to 1981-2010.

Station (Region), Latitude, Longitude	First Year	Statistic	SEP	OCT	NOV	Autumn	DEC	JAN	FEB	Winter	MAR	APR	MAY	Spring	JUN	JUL	AUG	Summer
Eureka 80.0 85.9	1948	Anomaly	-0.1	-0.6	3.8	1.1	<b>7.4</b>	5.6	-1.4	<b>4.0</b>	4.4	-3.5	1.8	0.9	<b>2.5</b>	<b>3.5</b>	0.0	<b>3.1</b>
		Rank	24	30	5	13	<b>1</b>	5	44	<b>1</b>	3	49	14	14	<b>1</b>	<b>1</b>	0	<b>1</b>
		Z-score	0.4	0.0	1.5	0.9	<b>2.3</b>	1.7	-0.3	<b>2.1</b>	1.8	-0.9	0.7	0.6	1.9	<b>3.3</b>	0.0	<b>3.2</b>
		warmest year	1998	2006	2009	1998	<b>2010</b>	1977	1978	<b>2011</b>	1962	1953	1967	2010	<b>2011</b>	<b>2011</b>	1960	<b>2011</b>
		coldest year	1979	1978	1982	1978	1972	1975	1979	1973	1977	1987	1995	1987	1974	1964	2000	1979
Pituffik/Thule AFB 76.5 68.8	1961	Anomaly	0.8	-0.1	<b>4.6</b>	2.8	5.3	5.9	-1.8	4.6	-1.1	<b>-5.0</b>	-0.5	-1.2	0.8	<b>3.5</b>	2.0	<b>2.1</b>
		Rank	12	18	<b>1</b>	3	4	3	22	2	19	<b>33</b>	16	37	3	<b>1</b>	3	<b>1</b>
		Z-score	0.4	0.0	<b>2.0</b>	1.4	1.2	1.5	-0.4	1.4	-0.2	<b>-2.0</b>	0.1	-0.7	1.2	<b>2.6</b>	1.4	<b>2.2</b>
		warmest year	1978	2004	<b>2010</b>	2000	1978	1977	1963	1963	1980	1968	1965	2010	1996	<b>2011</b>	<b>2009</b>	<b>2011</b>
		coldest year	1997	1964	1978	1986	2007	2004	1979	1984	1961	<b>2011</b>	1999	1992	1980	1972	1996	1972
Upernavik 72.8 56.2	1873	Anomaly	1.3	2.1	5.8	<b>3.1</b>	6.9	10.5	7.0	8.2	1.4	-4.1	-0.6	-1.1	1.8	3.7	1.8	2.4
		Rank	20	18	2	<b>1</b>	3	4	13	3	52	132	94	98	5	<b>1</b>	11	<b>1</b>
		Z-score	1.1	1.3	<b>2.4</b>	<b>2.3</b>	1.9	<b>2.1</b>	1.4	<b>2.3</b>	0.3	-1.4	-0.4	-0.6	1.9	<b>3.0</b>	1.5	<b>2.7</b>
		warmest year	1928	1960	1878	<b>2010</b>	1873	1929	1947	1947	1916	1905	1932	1932	2008	<b>2011</b>	1960	<b>2011</b>
		coldest year	1997	1986	1917	1917	1898	1983	1984	1983	1887	1896	1964	1896	1894	1916	1873	1873
Kangerlussuaq 67.0 50.7	1949	Anomaly	2.7	2.8	6.9	4.1	10.5	5.2	2.9	6.3	-0.2	<b>-8.6</b>	-1.7	-3.5	1.4	1.7	1.0	1.4
		Rank	2	10	2	<b>1</b>	1	15	24	7	33	<b>59</b>	47	54	9	3	15	4
		Z-score	1.7	1.0	<b>2.1</b>	<b>2.5</b>	<b>2.4</b>	0.8	0.3	1.4	-0.1	<b>-2.3</b>	-0.7	-1.3	1.1	1.6	0.7	1.5
		warmest year	2003	1960	1995	<b>2010</b>	<b>2010</b>	1963	1986	1986	2005	2000	2010	2005	1997	1968	1960	2010
		coldest year	1982	1989	1978	1982	1974	1983	1984	1983	1993	<b>2011</b>	1984	1993	1978	1973	1983	1983
Ilulissat 69.2 51.1	1873	Anomaly	2.8	1.9	5.2	3.3	6.2	4.6	5.5	5.5	2.2	-5.7	-1.3	-1.6	0.0	2.2	0.0	0.7
		Rank	2	24	3	<b>1</b>	3	24	24	7	56	127	108	109	37	2	47	17
		Z-score	<b>2.2</b>	1.0	<b>2.4</b>	<b>2.8</b>	<b>2.1</b>	1.1	1.0	1.6	0.3	-1.6	-0.7	-0.7	0.6	<b>2.3</b>	0.4	1.4
		warmest year	1915	1960	1878	<b>2010</b>	1978	1929	1986	1929	1916	1905	1933	1932	1997	1960	1960	1960
		coldest year	1884	1874	1986	1884	1898	1983	1984	1884	1993	1896	1875	1887	1918	1972	1884	1972
Aasiaat 68.7 52.8	1951	Anomaly	<b>2.6</b>	2.2	3.6	2.8	6.0	6.5	7.3	6.7	3.2	-4.6	-0.6	-0.7	1.1	2.3	1.8	1.7
		Rank	<b>1</b>	4	<b>1</b>	<b>1</b>	2	5	5	3	14	57	43	41	12	2	4	2
		Z-score	<b>3.1</b>	1.7	<b>2.2</b>	<b>2.9</b>	1.9	1.2	1.2	1.7	0.7	-1.6	-0.4	-0.3	1.1	<b>2.0</b>	1.6	1.9
		warmest year	<b>2010</b>	1960	<b>2010</b>	<b>2010</b>	1978	1980	1986	2010	2005	2000	2010	2010	2003	1960	1960	1960
		coldest year	1989	1986	1978	1986	1971	1983	1984	1984	1993	1984	1984	1993	1992	1972	1983	1972
Nuuk 64.2 51.8	1873	Anomaly	<b>3.1</b>	3.1	4.7	3.6	5.9	1.7	1.1	2.9	-0.1	-4.7	-0.9	-1.9	0.4	0.8	0.1	0.4
		Rank	<b>1</b>	3	2	<b>1</b>	1	38	61	15	91	137	106	127	55	31	71	43
		Z-score	<b>2.9</b>	<b>2.5</b>	<b>2.8</b>	<b>3.8</b>	<b>2.4</b>	0.6	0.2	1.2	-0.3	<b>-2.3</b>	-0.8	-1.4	0.3	0.9	0.0	0.5
		warmest year	<b>2010</b>	1960	1878	<b>2010</b>	<b>2010</b>	1917	1901	2010	1916	1953	2010	1932	1947	2008	2010	2010
		coldest year	1879	1884	1913	1898	1883	1984	1984	1984	1993	1949	1992	1993	1922	1955	1884	1914
Paamiut 62.0 49.7	1958	Anomaly	2.0	<b>3.9</b>	<b>5.4</b>	<b>3.8</b>	<b>6.1</b>	3.6	1.9	3.9	0.2	-4.0	-1.3	-1.7	-0.2	0.9	0.1	0.3
		Rank	2	<b>1</b>	<b>1</b>	<b>1</b>	<b>1</b>	9	22	6	29	52	43	46	23	11	24	18
		Z-score	1.9	<b>2.6</b>	<b>2.8</b>	<b>3.4</b>	<b>2.3</b>	1.0	0.3	1.4	0.0	<b>-2.0</b>	-0.8	-1.0	0.1	0.9	0.1	0.4
		warmest year	2003	2010	2010	<b>2010</b>	2010	2010	1986	2010	2005	2005	2010	2005	1987	1958	2010	2010
		coldest year	1982	1963	1986	1982	1974	1983	1984	1984	1993	1984	1992	1993	1972	1969	1969	1969
Narsarsuaq 61.2 45.4	1961	Anomaly	<b>2.5</b>	3.8	<b>5.6</b>	<b>4.0</b>	6.9	3.2	2.6	4.3	0.6	-3.6	-1.5	-1.5	0.9	1.1	0.4	0.8
		Rank	<b>1</b>	2	<b>1</b>	<b>1</b>	2	13	19	7	27	47	43	40	11	8	19	7
		Z-score	<b>2.3</b>	<b>2.1</b>	<b>2.1</b>	<b>3.1</b>	1.8	0.6	0.3	1.1	0.0	-1.4	-0.8	-0.8	1.0	1.3	0.4	1.2
		warmest year	<b>2010</b>	2003	<b>2010</b>	<b>2010</b>	1978	2003	1986	2010	1962	1998	2010	2010	1991	1991	1987	2003
		coldest year	1969	1963	1982	1963	1974	1983	1984	1984	1995	1990	1992	1989	1992	1969	1983	1983
Quaqortoq 60.7 46.0	1880	Anomaly	<b>2.8</b>	3.2	4.5	3.5	6.0	3.1	1.7	3.7	5.7	-3.7	-1.5	0.2	-0.4	1.2	1.0	0.6
		Rank	<b>1</b>	3	1	<b>1</b>	3	19	46	10	6	126	123	74	90	13	18	37
		Z-score	<b>2.9</b>	<b>2.2</b>	<b>2.5</b>	<b>3.3</b>	<b>2.4</b>	1.2	0.4	1.6	1.6	-1.9	-1.3	-0.1	-0.4	1.4	1.0	0.7
		warmest year	<b>2010</b>	1960	<b>2010</b>	<b>2010</b>	1978	2010	1901	2010	1932	1881	1935	1932	1929	2003	1960	1929
		coldest year	1969	1884	1920	1898	1914	1983	1883	1884	1882	1984	1992	1989	1922	1969	1884	1884
Danmarkshavn 76.8 18.8	1949	Anomaly	<b>1.1</b>	1.4	-2.7	0.0	2.4	0.7	5.6	3.0	2.3	0.2	1.3	1.3	1.3	-0.2	1.1	0.7
		Rank	9	13	47	27	9	20	3	4	13	16	15	9	6	26	7	5
		Z-score	1.2	0.7	-0.8	0.2	1.0	0.3	<b>2.2</b>	1.8	0.9	0.4	0.8	1.1	1.3	0.1	1.3	1.3
		warmest year	2002	2002	1972	2002	1956	1990	2008	2005	1976	2006	1967	1976	2006	1958	2003	2008
		coldest year	1968	1966	1971	1971	1975	1978	1970	1967	1966	1969	1956	1966	2006	1955	1999	1955
Illoqortoormiut 70.4 22.0	1948	Anomaly	<b>1.5</b>	2.1	-2.0	0.5	3.6	2.1	6.0	4.0	0.9	1.1	0.4	0.8	-0.4	-0.8	0.0	-0.4
		Rank	5	6	44	14	6	13	2	2	15	11	15	14	21	26	14	22
		Z-score	1.7	1.2	-0.4	0.8	1.5	0.9	<b>2.2</b>	<b>2.1</b>	0.7	0.9	0.9	1.0	0.5	0.5	0.8	0.6
		warmest year	2002	2002	2002	2002	1984	1974	2005	2005	1996	2004	2009	1996	1995	1991	2004	2004
		coldest year	1956	1968	1951	1951	1965	1959	1978	1966	1969	1951	1956	1956	1956	1953	1952	1955
Tasiilaq 65.6 37.6	1895	Anomaly	<b>1.9</b>	2.2	-0.1	1.3	4.3	0.6	3.1	2.8	-2.4	0.8	0.4	-0.4	0.8	0.9	0.4	0.7
		Rank	5	9	44	10	4	43	11	5	98	39	57	74	35	33	34	28
		Z-score	1.7	1.6	0.4	1.4	<b>2.0</b>	0.4	1.3	1.7	-1.0	0.5	0.0	-0.3	0.4	0.6	0.6	0.7
		warmest year	1939	1915	2002	1941	1933	1987	1932	1929	1929	1926	1933	1929	1932	1939	2010	2003
		coldest year	1982	1917	1917	1917	1917	1918	1919	1918	1899	1919	1979	1990	1998	1983	1983	1983
Prins Christian Sund 60.0 43.2	1951	Anomaly	<b>2.7</b>	1.9	2.1	<b>2.2</b>	<b>4.9</b>	1.9	0.9	2.7	-0.3	-1.7	0.3	-0.6	0.2	0.6	0.0	0.3
		Rank	<b>1</b>	2	2	<b>1</b>	<b>1</b>	6	21	2	40	57	20	47	23	12	26	18
		Z-score	<b>2.6</b>	<b>2.0</b>	1.8	<b>2.7</b>	<b>3.3</b>	1.2	0.4	<b>2.0</b>	-0.3	-1.6	0.3	-0.8	0.4	0.7	0.1	0.5
		warmest year	<b>2010</b>	2003	2002	<b>2010</b>	2010	2010	2005	2010								

## Upper air temperatures (J. E. Box)

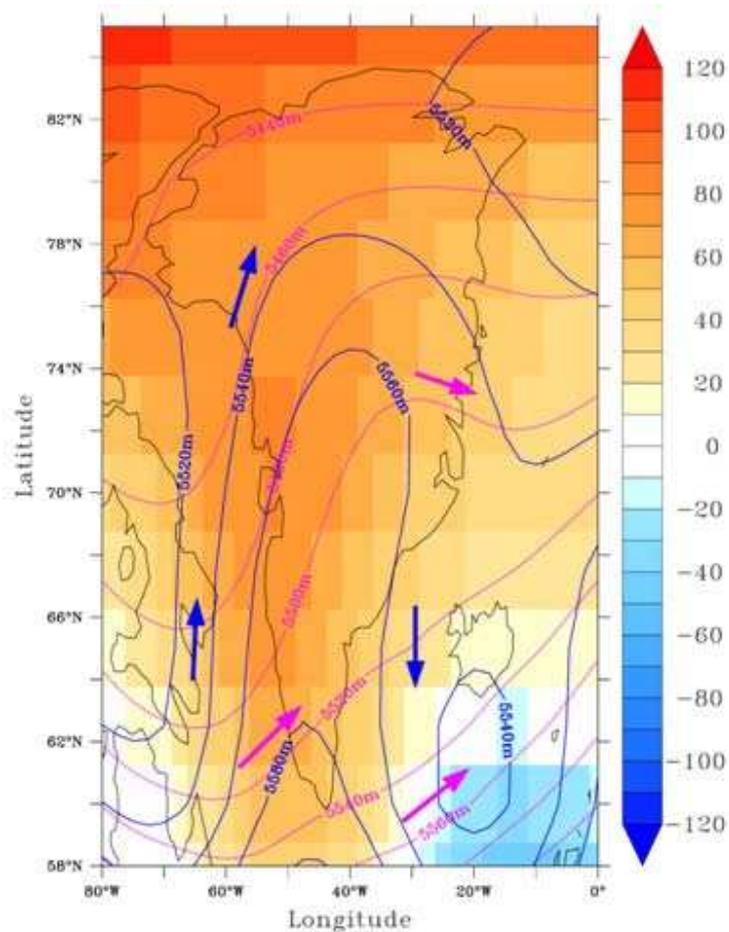
Seasonally-averaged 2011 upper air temperature data available from twice-daily radiosonde observations (Durre et al. 2006) in the vicinity of Greenland (see Table HTC4 for site locations) indicate anomalous tropospheric warmth in summer and winter and mid-tropospheric cold anomalies in spring (Fig. HTC8). The typical asymmetry between the tropospheric and stratospheric anomalies is most evident in winter, when record-setting cold anomalies were observed above 100 hPa. Mid-stratospheric atmospheric mass is low and prone to extremes. The overall warm pattern near the surface at 1000 hPa is consistent with a warming trend prevailing since reliable records began in 1964 and which has been most pronounced since the mid-1980s (Box and Cohen 2006).



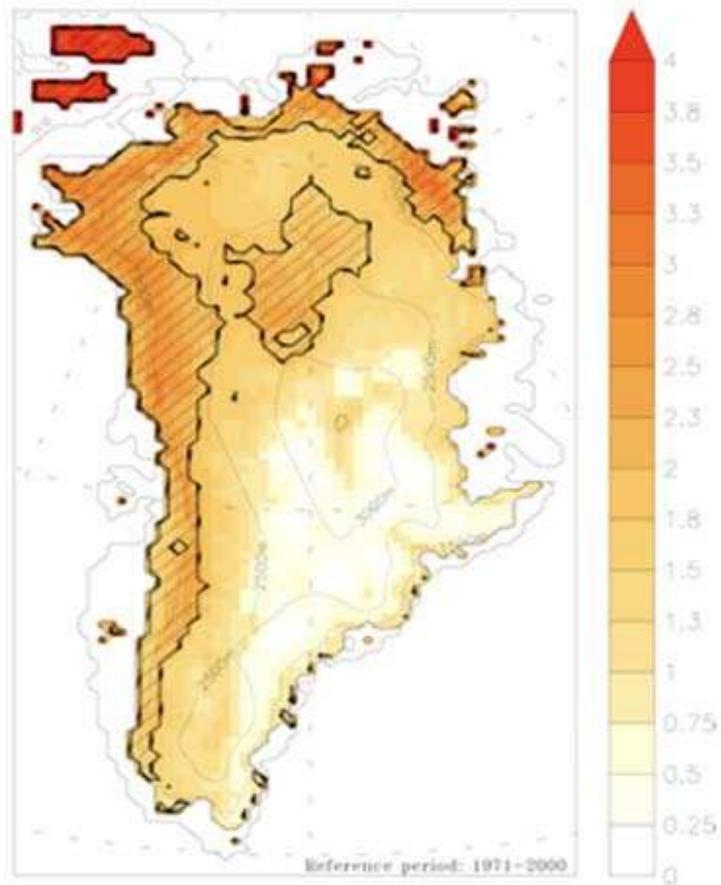
**Fig. HTC8.** Upper air temperature anomalies relative to the 1981-2010 baseline in winter, spring and summer of 2011.

## Atmospheric circulation and air temperature (X. Fettweis)

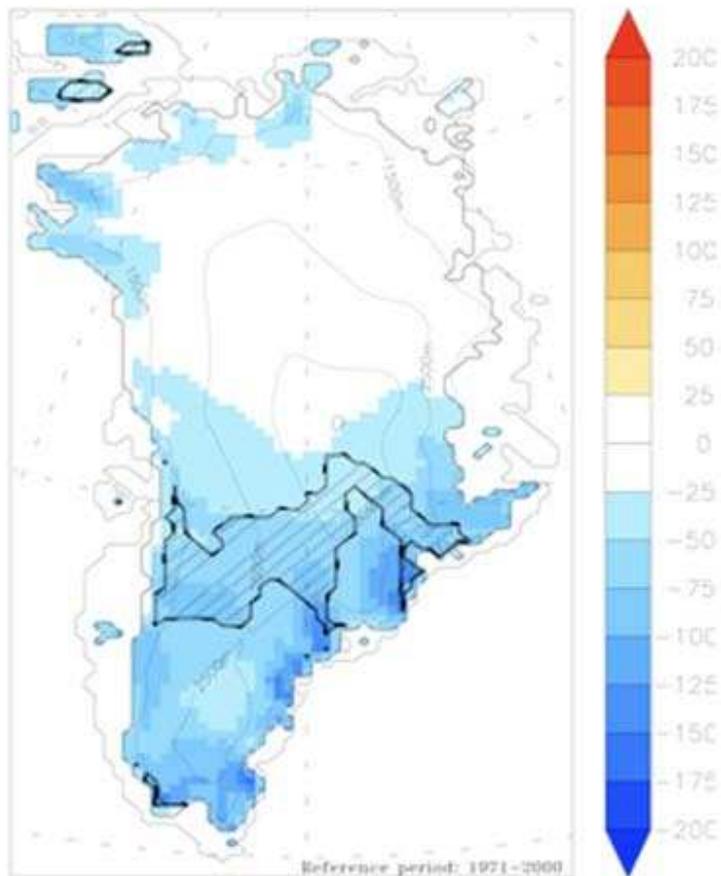
Summer 2011 was characterized by a constant negative North Atlantic Oscillation (NAO) index for the entire season; a -2.4 standard deviation anomaly in comparison with the 1971-2000 JJA NAO average. Consequently, the 2011 atmospheric flow was characterised by warm air advection from the south along the western coast (Fig. HTC9). The circulation anomaly (Fig. HTC9) caused significant summer temperature departures from normal (Fig. HTC10) and drier conditions than normal at the south of the ice sheet (Fig. HTC11). The effects of the circulation anomaly also extended into the Canadian Arctic Islands, where there were strong positive temperature anomalies and negative glacier mass balances (see the essay on [Glaciers and Ice Caps](#)).



**Fig. HTC9.** Geopotential height anomalies for summer (JJA) 2011 (referenced to the 1981-2010 mean) at 500 hPa from the NCEP/NCAR Reanalysis. The blue and magenta lines plot the summer (JJA) mean geopotential height at 500 hPa in 2011 and during 1971-2000, respectively. The arrows show the direction of the main air flows.



**Fig. HTC10.** Summer (JJA) mean 2011 near-surface temperature (Kelvin) anomalies simulated by MAR (Fettweis et al., 2011) relative to the period 1981-2010. Areas where temperature anomalies were at least twice the 1981-2010 standard deviation are hatched.



**Fig. HTC11.** Summer (JJA) snowfall anomaly (mm water equivalence) simulated by MAR (Fettweis et al., 2011) relative to the period 1981-2010. Areas where temperature anomalies were at least twice the 1981-2010 standard deviation are hatched.

**Greenland coastal precipitation** (S. H. Mernild, J. Cappelen, B. V. Jørgensen, W. H. Lipscomb, J. E. Box, and E. Hanna)

Changes in Greenland precipitation over time are of interest for understanding fluctuations in glacier and ice sheet mass balance and freshwater runoff to the ocean. Long-term changes are difficult to quantify, however, because Greenland meteorological stations are sparsely and non-uniformly distributed. Here, observed precipitation data (uncorrected for gauge catch efficiency and type) from eight DMI (Danish Meteorological Institute; DMI 2000, 2010) synoptic stations are examined, from Kangerlussuaq (continental west) to Qaqortoq in southwest Greenland and from Tasiilaq (maritime east) to Station Nord in the northeast (Table HTC4).

**Table HTC4.** Greenland station precipitation (uncorrected) anomalies by season for 2011 relative to 1981-2010.

Station (Region), Latitude, Longitude	First year	Statistic	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	Winter (DJF)	Spring (MAM)	Summer (JJA)	SEP - AUG
Kangerlussuaq (W)	1976	Anomaly	-7	18	-2	-8	-8	-13	-11	-10	15	-18	-34	-55
67° 01' N		Rank	34	1	25	36	32	34	22	21	4	35	32	34
50° 42' W		Z-score	-1.2	4.5	-0.7	-1.0	-0.9	-1.1	-0.6	-0.5	1.5	-1.3	-1.4	-1.6
		driest year	1990	1989	2006	2011	1995	2000	1999	1977	1990	1995	1980	1980
		wettest year	2000	2011	1991	2005	2005	1994	1997	1991	2004	2005	1983	2005
Nuuk (SW)	1890	Anomaly	17	-4	46	-22	-48	-28	-7	16	51	-24	-21	-116
64° 10' N		Rank	13	37	10	58	99	71	43	38	14	43	58	44
51° 45' W		Z-score	0.5	-0.1	1.4	-0.7	-1.0	-0.8	-0.1	0.3	0.7	-0.4	-0.3	-0.6
		driest year	1939	1933	1909	1902	1911	1913	1933	1966	1939	1930	1903	1949
		wettest year	1953	1890	1968	2006	1928	1979	1983	1984	1954	2005	1915	2005
Narsarsuaq (SW)	1961	Anomaly	-8	-19	-4	-34	-18	-48	-4	19	-14	-56	-33	-208
61° 10' N		Rank	19	24	20	43	27	47	24	17	23	38	35	41
45° 25' W		Z-score	-0.2	-0.3	-0.1	-1	-0.5	-1.3	-0.1	0.4	-0.2	-1.0	-0.5	-1.1
		driest year	1966	2010	1962	1989	1974	2008	1992	1966	1976	1983	1983	1976
		wettest year	1996	1993	1998	1999	1987	1983	1966	1984	1966	1962	2009	1985
Qaqortoq (SW)	1961	Anomaly	-31	-4	-29	-23	-5	-62	-57	23	-25	-56	-97	-293
60° 43' N		Rank	27	13	31	29	14	38	35	13	20	31	33	35
46° 03' W		Z-score	-0.6	-0.1	-0.5	-0.6	-0.1	-1.4	-1.0	0.4	-0.2	-0.7	-1.0	-1.1
		driest year	2004	1982	1994	1989	1985	1974	1992	1980	2010	1985	2010	2010
		wettest year	2005	1993	1983	1975	1987	1997	1982	1984	1992	1983	1984	1996

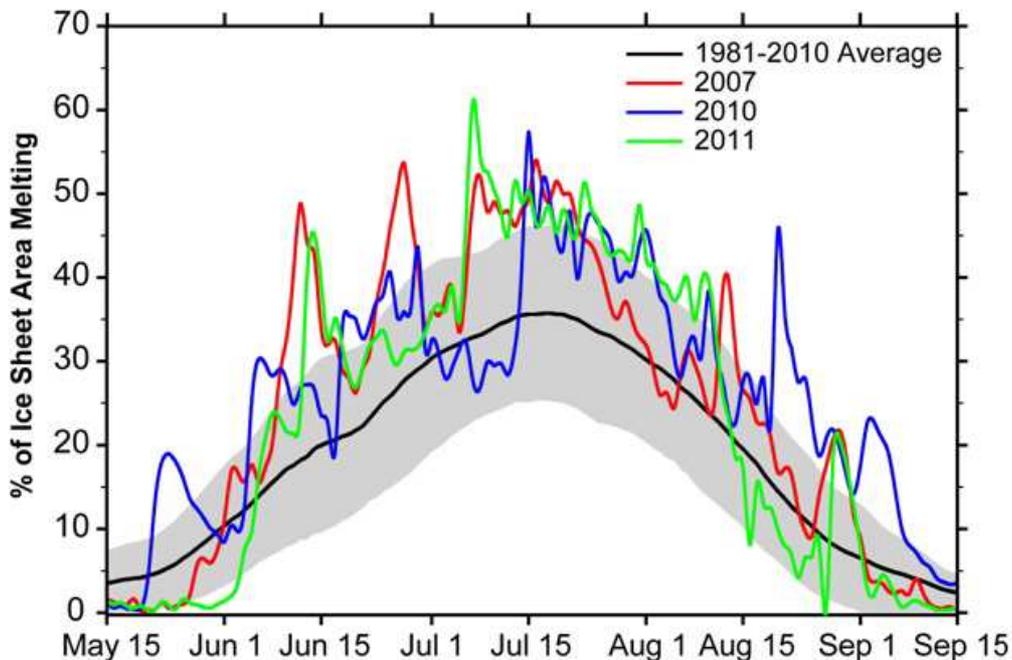
Station (Region), Latitude, Longitude	First year	Statistic	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	Winter (DJF)	Spring (MAM)	Summer (JJA)	SEP - AUG
Tasiilaq (SE)	1898	Anomaly	-24	12	50	53	-26	-31	-14	1	-80	76	-44	-34
65° 36' N		Rank	47	31	19	11	76	108	63	42	67	19	80	53
37° 37' W		Z-score	-0.3	0.2	1.0	1.2	-0.6	-1.1	-0.4	0.0	-0.7	1.1	-0.7	-0.2
		driest year	1948	1957	1940	1950	1941	1991	1954	1943	1931	1915	1924	1931
		wettest year	1972	1932	1964	1909	1903	1953	1901	1947	1972	1964	1901	1903
Illoqqortoormiut (E)§	1950	Anomaly	18	112	4	36	49	3			160	89		
70° 29' N		Rank	13	2	21	5	2	23			2	3		
21° 57' W		Z-score	0.4	3.1	0.2	1.7	4.1	0.2			1.7	2.5		
		driest year	1955	1965	1992	1988	1958	1982	2001	1977	1986	1953	1950	1952
		wettest year	2008	1982	1976	2004	1970	1953	1970	1982	2008	1976	1969	2008
Danmarkshavn (NE)	1949	Anomaly	0	5	24	17	5	-5	-11	27	-6	46	11	36
76° 46' N		Rank	16	14	3	7	8	56	39	4	23	1	13	10
18° 40' W		Z-score	0.0	0.4	1.8	1.3	1.0	-0.8	-0.7	1.6	-0.2	2.4	0.4	0.6
		driest year	1975	2010	1962	1962	1997	2011	2010	1973	1951	1962	2010	1951
		wettest year	2006	2008	1982	2006	2009	1954	1986	1990	2006	2011	1998	2006
Station Nord (NE)	1961	Anomaly	-5	-1	9	0	4	-4	4	18	34	23	36	134
81° 36' N		Rank	16	14	5	14	9	19	10	6	11	11	9	12
16° 39' W		Z-score	-0.3	-0.1	0.5	0.0	0.3	-0.4	0.2	1.1	1.1	0.5	1.1	1.2
		driest year	1997	1994	1986	1986	1980	1990	1993	1988	1988	2006	1996	2006
		wettest year	2006	2010	2010	2010	1988	1994	1995	1999	2010	2010	1995	2010

§Anomalies are in mm water equivalent (w.e.), with respect to the 1981-2010 base period. No precipitation data exist from July and August 2011 for Illoqqortoormiut. In cases when the monthly precipitation is zero for two or more months, the next highest year is mentioned in the table. Bold values indicate values that meet or exceed 2 standard deviations from the base period. Red characters indicate record-setting values. The winter values include December from the previous year.

In 2011, a clear pattern of below-average annual (September through August) precipitation is evident at the west, southwest and southeast stations, with the largest anomalies in the south (above one standard deviation). In east and northeast Greenland, precipitation was above average. Overall, precipitation in 2011 was less extreme than in 2010, when annual precipitation reached a record low since BR 1961 in Qaqortoq and a record high since 1961 at Station Nord. No annual precipitation records were set in 2011. Remarkable extremes occurred; Kangerlussuaq had the wettest February and driest April on record (RB 1976) and Danmarkshavn had the wettest spring (March to May) and the driest June on record (RB 1949).

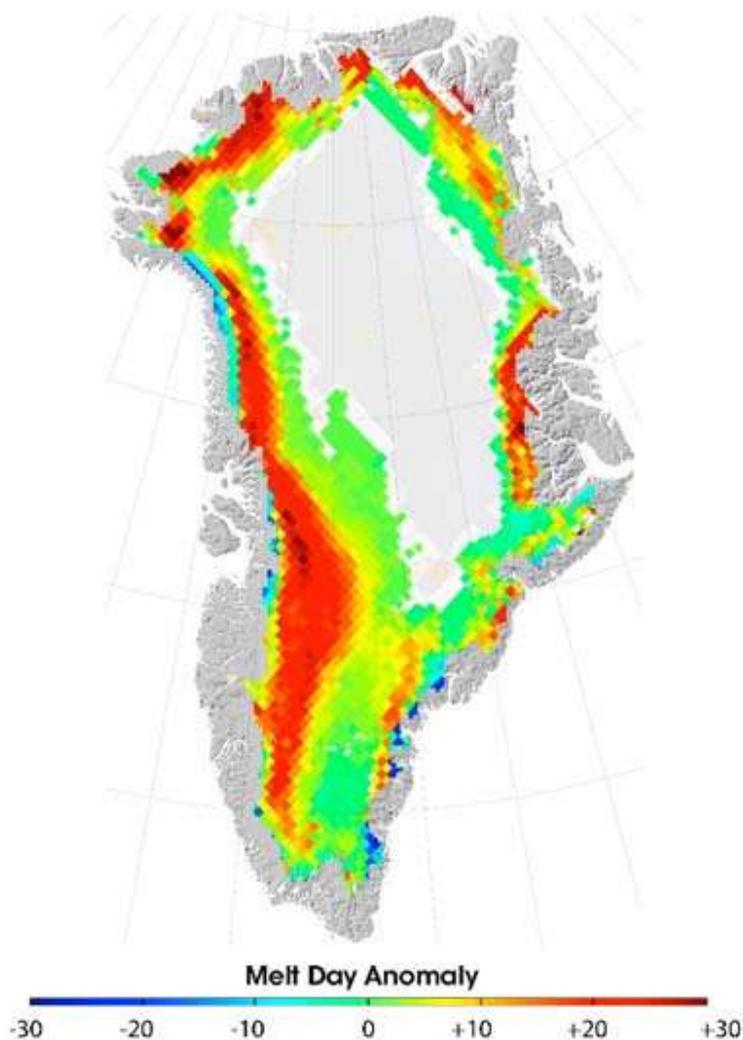
### Surface melting (T. Mote and M. Tedesco)

Greenland ice sheet surface and near-surface melt above ~1% liquid water content is estimated from thresholds in 19 GHz horizontally-polarized brightness temperatures measured by the spaceborne SSM/I instrument (Mote and Anderson, 2005). These data indicated that the melt area for the period June through August 2011 ranked the third greatest since 1979, after 2007 and 2010 in that order. The years were ranked based on the seasonal melt departure (SMD), the sum of the daily melt extent anomalies over each summer (Mote 2007). These annual ranking are sensitive to the length of the selected season. Expanding the season from 15 May to 15 September drops 2011 to the 6th most extensive melt year, following 2010, 2007, 2002, 1998, and 2005, in that order. More extensive than average melt was evident from early June through early August 2011 (Fig. HTC12). An average of 31% of the ice sheet area was melting during June through August 2011, compared to 33% in 2007 and 32% in 2010. No other year since 1979 had an average greater than 30%; the 1981-2010 average was 24.1%.



**Fig. HTC12.** Fractional area (%) of the Greenland Ice Sheet identified as melting from SSM/I. The standard deviation of the 1981-2010 period is shaded.

Melting in Greenland in 2011 was still above the 1979-2010 average and was exceptionally high over the western mid-elevations. The number of melting days in 2011, estimated from spaceborne microwave observations using the approach in (Tedesco, 2007), did not break the previous record set in 2010. Year 2011 is 6th for melting, after 2010, 2007, 1998, 2002, 2005. The updated trend for the area of the ice sheet subject to melting is  $16,800 \text{ km}^2$  per year, close to the trend estimated with 2010 of  $17,202 \text{ km}^2$  per year. The 2011 departure of the number of melting days from the 1979-2010 baseline is illustrated in Fig. HTC13. In 2011, melting at high elevations (above 2500 m) was  $\sim 1$  standard deviation above the 1979-2010 average (versus the  $\sim 2$  standard deviations of 2010). Melting in 2011 was above average over most of Greenland, with large positive anomalies (e.g., longer melting with respect to the average) occurring especially in the west and northwest, with melting lasting up to  $\sim 30$  days longer than the average.

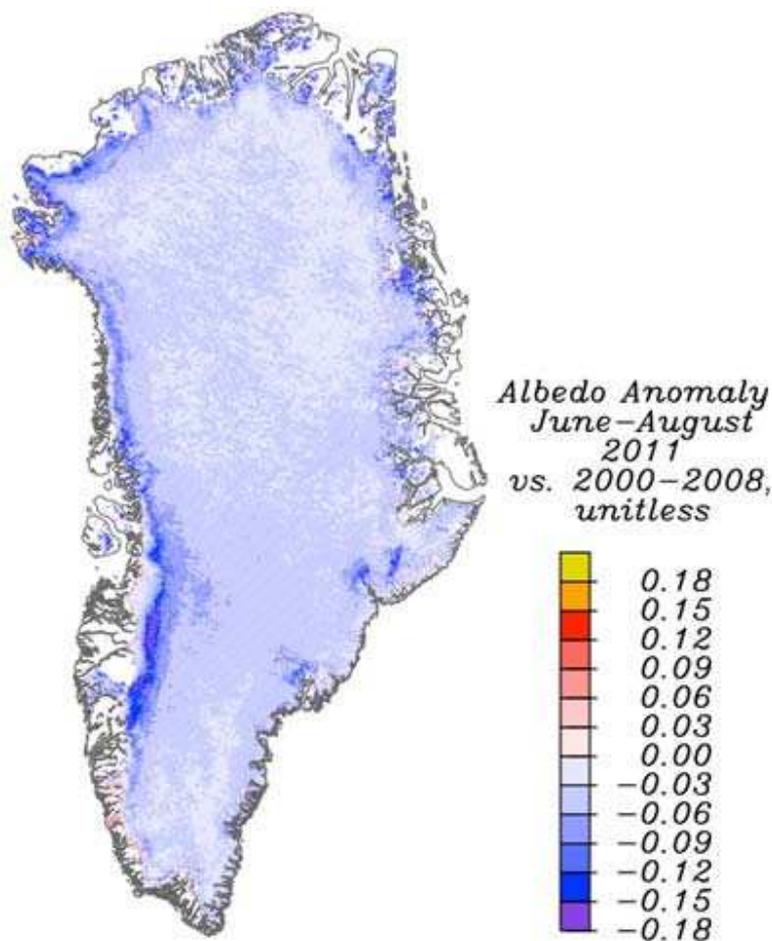


**Fig. HTC13.** Melting degree day anomaly in 2011 relative to the 1979-2010 baseline.

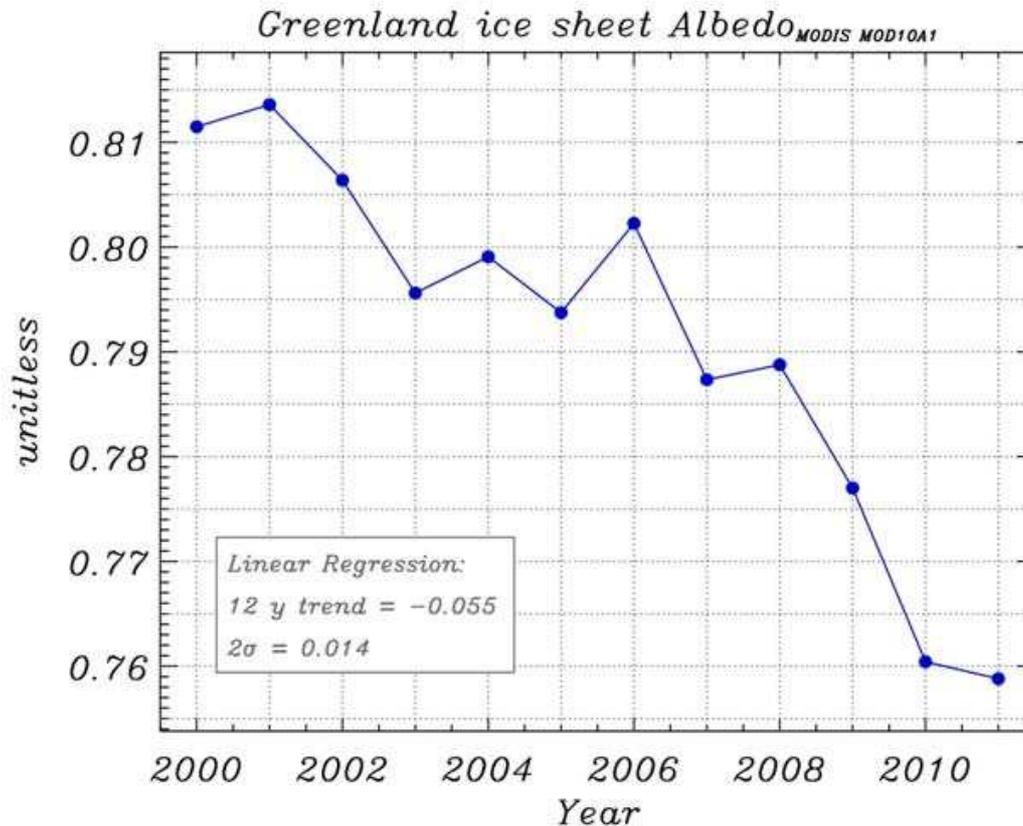
**Albedo** (J. E. Box and D. K. Hall)

A dominant source of energy for melting is absorbed solar irradiance, which depends on the surface solar reflectivity from  $\sim 0.3 \mu\text{m}$  to  $\sim 4 \mu\text{m}$  in wavelength, known as the *albedo*. Freshly fallen snow under clear skies has an albedo of  $\sim 0.84$  (Konzelmann and Ohmura, 1995). Over time, and with increasing temperature, snow grain size increases as crystals metamorphose and grow (Wiscombe and Warren, 1980; Dozier et al., 1981; Warren, 1982) resulting in a decrease in albedo. Melting snow albedo can have values of 0.74 (see measurement summary in Patterson, 1994). Impurity-rich ice sheet albedo retrievals from the MODIS sensor on the NASA Terra platform (the MOD10A1 product; Klein and Stroeve, 2002) can be as low as 0.31 averaged over  $5 \times 5 \text{ km}$  areas, in agreement with the value recommended by Cuffey and Patterson (2011).

Negative albedo anomalies are widespread over the ice sheet during the 2011 melt period. Figure HTC14 illustrates the 2011 anomalies for summer (June-August), when solar irradiance is highest and the albedo is lowest in magnitude. The albedo anomaly is much larger over the regions where darker bare ice is exposed after the previous winter's snow accumulation has ablated. Fig. HTC15 illustrates the significant albedo decline for the ice sheet.



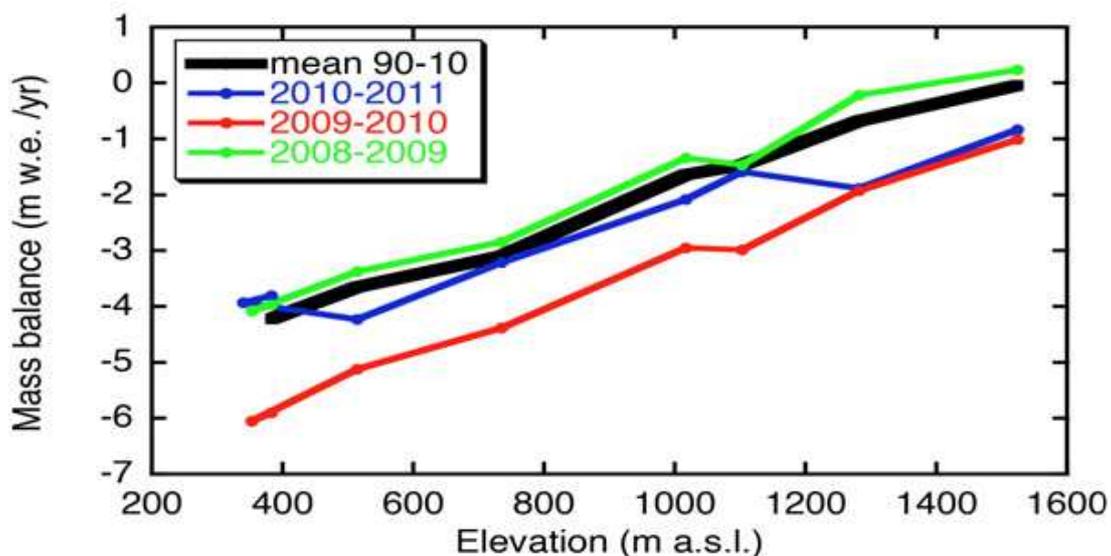
**Fig. HTC14.** Summer (JJA) albedo anomaly in 2011 relative to the 2000-2008 period.



**Fig. HTC15.** Greenland ice sheet albedo from MODIS (Moderate Resolution Imaging Spectroradiometer) observations, 2000-2011.

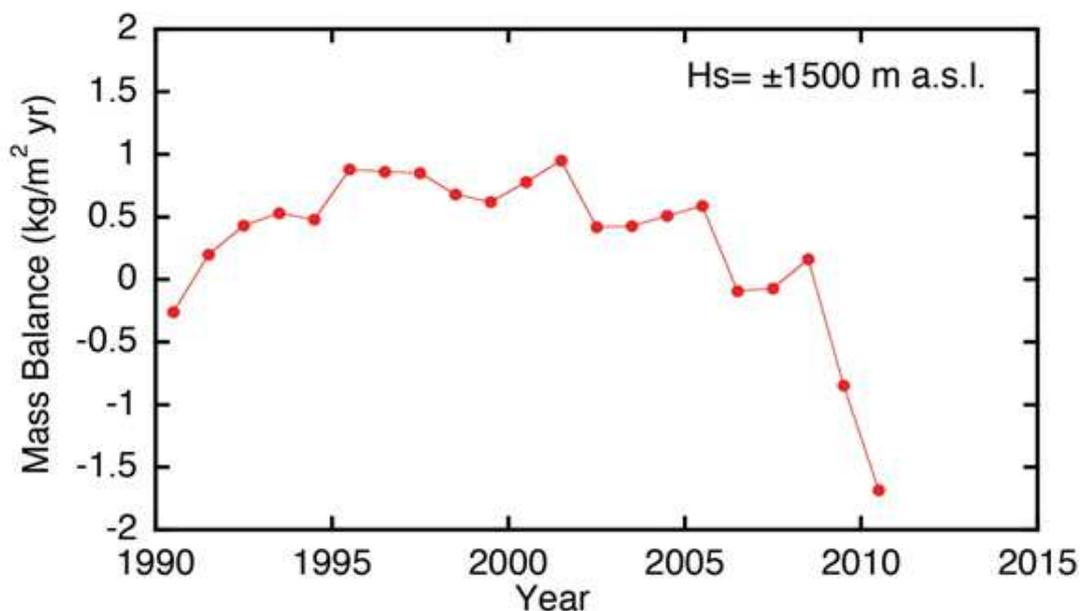
**Surface mass balance along the K-Transect (R. S. W. van de Wal and X. Fettweis)**

The 150 km long K-Transect is located near Kangerlussuaq at 67°N between 340 m and 1500 m above sea level (a.s.l.) on the western flank of the ice sheet (van de Wal et al. 2005). Along the K-transect the surface mass balance (the balance between snowfall (positive mass) and melt water runoff (negative mass) during 2010-2011 was less negative than the previous record-breaking year (2008-2009). Remarkably, only at the two highest sites was the mass balance exceptionally negative like the previous year (2009-2010) (Fig. HTC16). The latter is in agreement with preliminary regional atmosphere simulations. This implies that the weighted-average mass balance over the last year is the second lowest mass balance in 21 years. Sites S8 and S9, the two highest sites in the ablation area, account for approximately 50% of the weighted-average mass balance of the entire transect. The strong ablation just below the equilibrium line in the last two years is likely related to the limited snowfall during the preceding winters.



**Fig. HTC16.** Water equivalent (w.e.) surface mass balance as a function of elevation along the K-Transect during 2010-11, 2009-10 and 2008-09 and for the 20-year average (1990-2010).

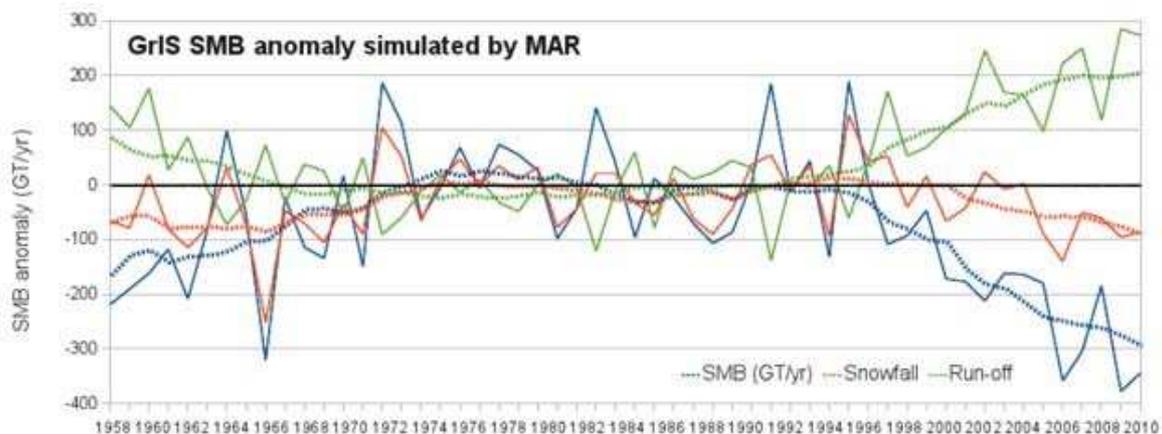
Figure HTC17 illustrates the cumulative surface mass balance around the equilibrium line altitude at 1500 m. a.s.l. From a slightly positive value at the end of the 1990s there has been a change to a clearly negative value, suggesting an upward migration of the equilibrium line altitude. The equilibrium line elevation at the end of summer 2011 is estimated to be 1720 m. a.s.l. Low accumulation rates are followed by stronger ablation rates in summer 2007 and 2010. This is likely also to be the case in 2011, though the accumulation record of 2010-2011 is not yet available.



**Fig. HTC17.** The cumulative mass balance in the vicinity of the equilibrium line altitude (67°N, 50°W) along the K-Transect.

### Surface mass balance from MAR simulations (X. Fettweis)

The observationally-constrained Modèle Atmosphérique Régional (MAR) (Fettweis et al., 2011) is coupled with a one-dimensional multi-layered energy balance snow model (Gallée and Schayes 1994; Lefebvre et al. 2003) to simulate surface mass balance over the ice sheet. The skill of MAR has been demonstrated by Fettweis (2007) and Tedesco et al. (2011). The past 51 years of surface mass balance (SMB) components are illustrated in Fig. HTC18. The positive meltwater runoff anomaly in 2011 (Table HTC5) results from a conjunction of warmer conditions along the western coast resulting from anomalies in general circulation and drier conditions (mainly at the south of the ice sheet) allowing low albedo values (enhancing the melt) to be maintained through the whole summer. Although the melt season started late in 2011, at the beginning of June, the dry and warm conditions caused record bare ice exposure, which enhanced the melt. Moreover, at the south of the ice sheet, lower winter accumulation than normal allowed the earlier appearance of the bare ice in the ablation zone. Consequently, the SMB rate simulated by MAR from Sep 2010 to Aug 2011 (Table HTC5) is the second lowest in 50 years after 2010.



**Fig. HTC18.** Greenland ice sheet surface mass balance (GrIS SMB) anomalies in Gt/yr simulated by MAR (Modèle Atmosphérique Régional) relative to 1971-2000.

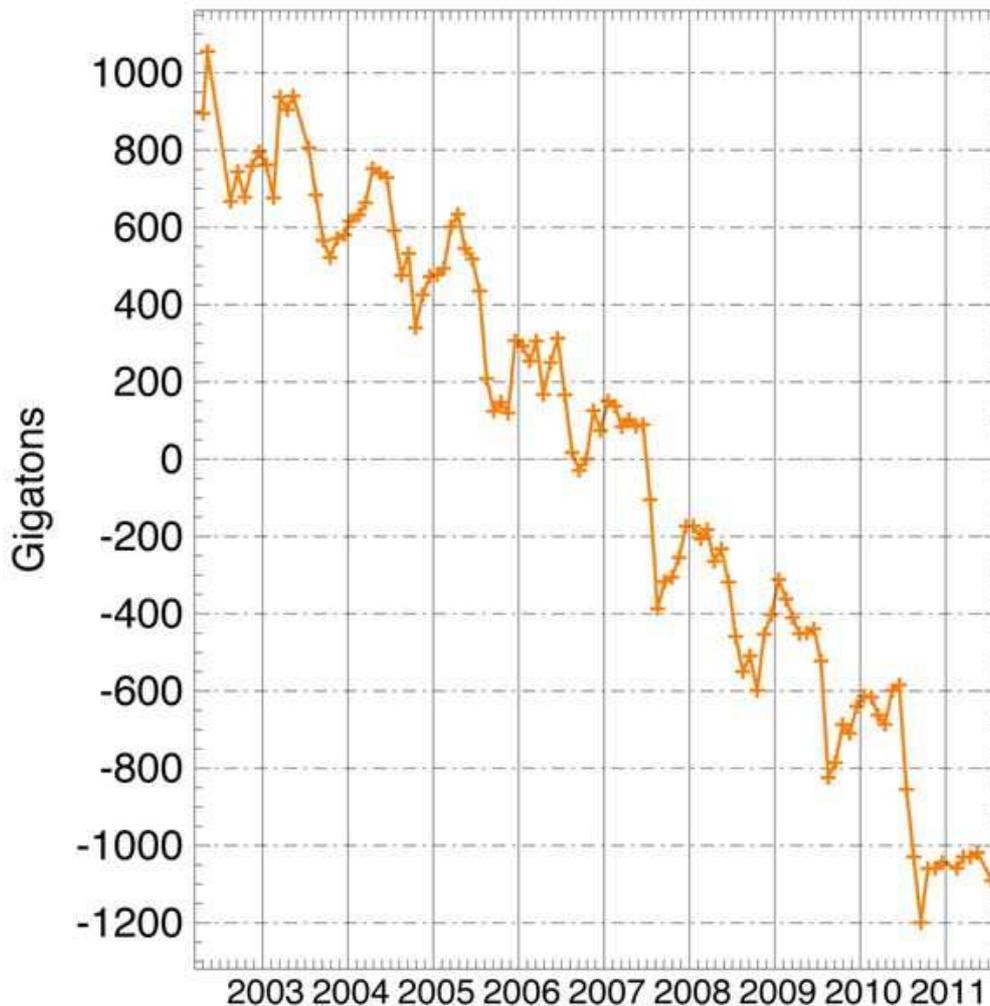
**Table HTC5.** Surface mass balance (SMB), snowfall and runoff anomalies in 2011 relative to the 1971-2000 base period from MAR.

	<b>SMB</b>	<b>Snowfall</b>	<b>Runoff</b>
<b>Gt/year</b>	-344.3	-86.3	-273.1
<b>Normalized value</b>	-3.6	-1.5	4.4

### Greenland mass changes from GRACE (J. Wahr)

GRACE satellite gravity solutions (Velicogna and Wahr 2006) are used to estimate monthly changes in the total mass of the Greenland ice sheet (Fig. HTC19). From the end of April 2010 through the end of April 2011, which roughly corresponds to the period between the beginning of the 2010 and 2011 melt seasons, the ice sheet cumulative loss was -430 Gt, 70% (or 2 standard deviations) larger than the 2003-09 average annual loss rate of -250 Gt y<sup>-1</sup>. This

2010/2011 mass loss is equivalent to a eustatic sea level rise contribution of 1.1 mm, and is the largest annual loss rate for Greenland in the GRACE record (2002-present), 180 Gt more negative than the 2003-09 average. 2005-2006 had almost as much mass loss as 2010-2011, when evaluated between April/May points. Using GRACE data, Rignot et al. (2011) find an acceleration of Greenland ice sheet mass budget deficit during 1979-2010, in close agreement with an independent mass balance model.



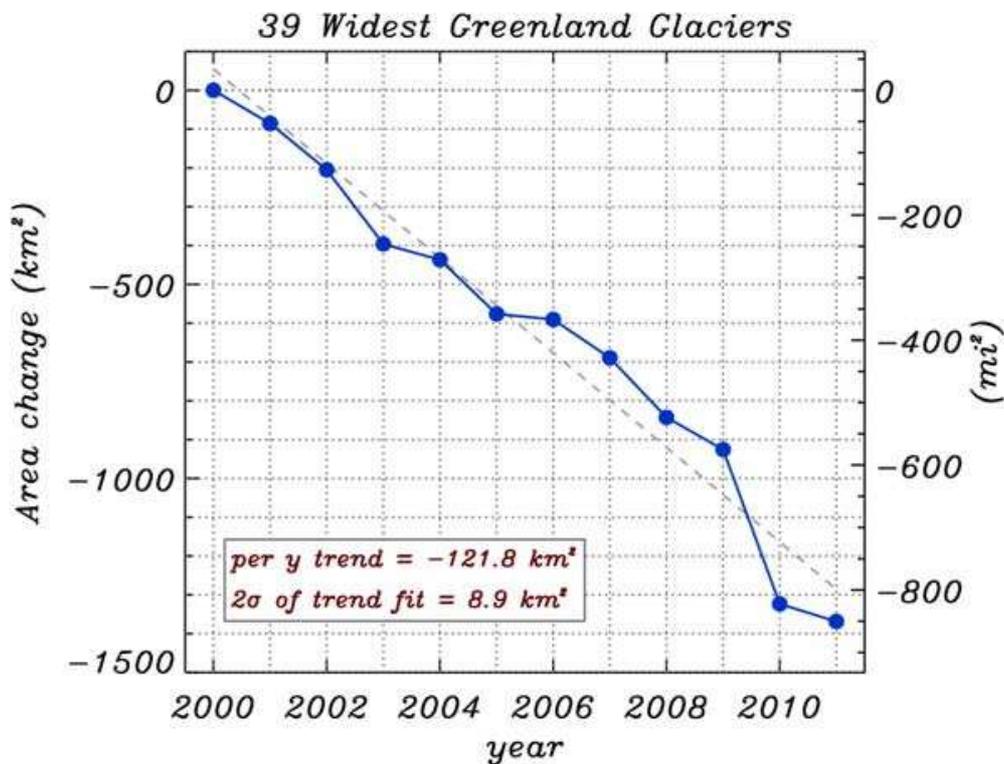
**Fig. HTC19.** Monthly unsmoothed values of the total mass (in Gigatons, Gt), of the Greenland ice sheet from GRACE. On the horizontal axis, each year begins on 1 January. Each small + symbol is a monthly value.

**Marine-terminating glacier area changes** (J. E. Box, D. Decker, C. Chen)

Marine-terminating glaciers are of particular interest because they represent the outlets through which the inland ice can move most quickly and in the largest quantities out to the ocean. Iceberg calving from these glaciers represents an area reduction that can be balanced by

forward motion of the ice by flow. Changes at the fronts of marine-terminating outlet glaciers cause flow speed variations by modulating the balance of driving and resistive stresses (Meier and Post, 1987; Joughin et al. 2008). Generally, retreat leads to flow acceleration and, in turn, mass loss from the ice sheet, which contributes to sea level rise.

Daily surveys using cloud-free MODIS visible imagery (Box and Decker 2011; <http://bprc.osu.edu/MODIS/>) indicate that in the year prior to end of the 2011 melt season, marine-terminating glaciers collectively lost an area of 45 km<sup>2</sup>. This is 84 km<sup>2</sup> smaller than the average annual loss rate of the previous 10 years (124 km<sup>2</sup> yr<sup>-1</sup>) (Fig. HTC20). Glacier area change measurements from the 1980s and 1990s (Howat and Eddy 2011) indicate an increased rate of ice area loss in the most recent decade.



**Fig. HTC20.** Cumulative net annual area change for the 39 widest marine-terminating glaciers of the Greenland ice sheet (after Box and Decker, 2011). The dashed line is a least-squares regression line.

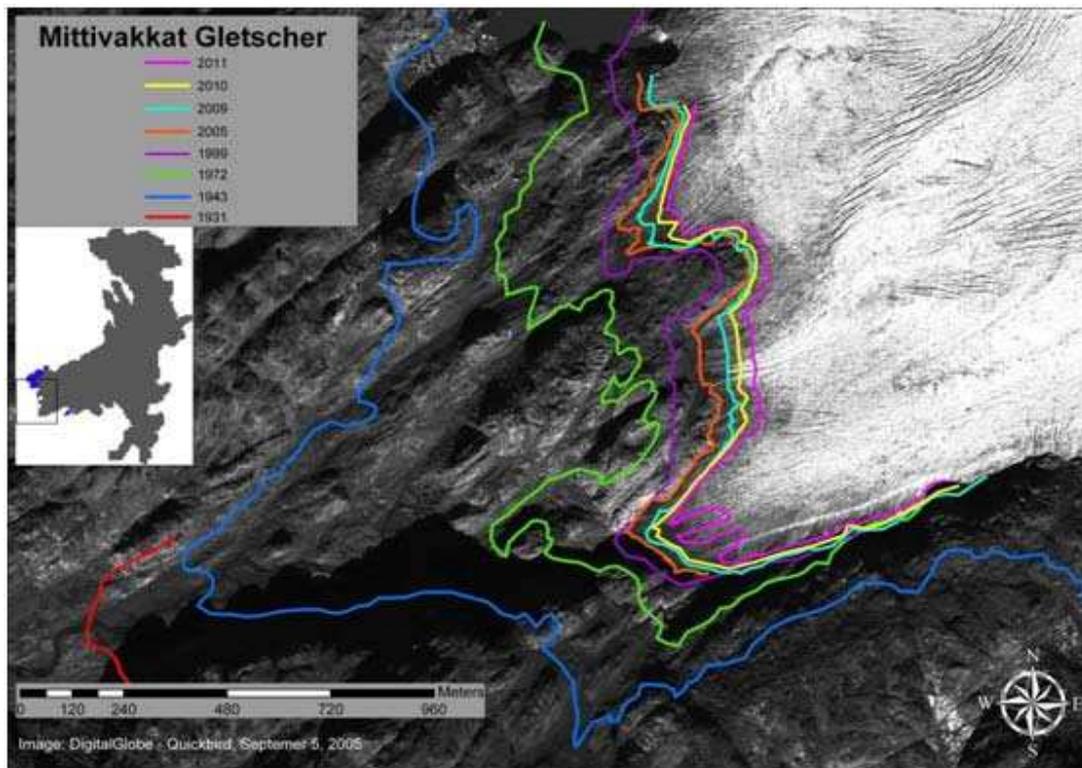
While the overall area change was negative for 2011, 9 of 39 glaciers grew in area relative to the end of the 2010 melt season. These nine include some of the most productive marine-terminating glaciers, in terms of ice volume discharge. The top ice area gainers included Petermann glacier (+13 km<sup>2</sup>), which lost ~275 km<sup>2</sup> in August 2010, Helheim glacier (+8 km<sup>2</sup>) and the "79" glacier (+7 km<sup>2</sup>). One of the most productive east Greenland glaciers, Kangerdlugssauq, increased by +6 km<sup>2</sup>.

The four glaciers with the largest ice loss were: Humboldt (-20 km<sup>2</sup>), Zachariae (-19 km<sup>2</sup>), Steenstrup (-15 km<sup>2</sup>) and Jakobshavn (-9 km<sup>2</sup>). According to the linear regression fit in Fig. HTC20, the average annual loss rate for the 39 Greenland glaciers in the past 11 years is 122

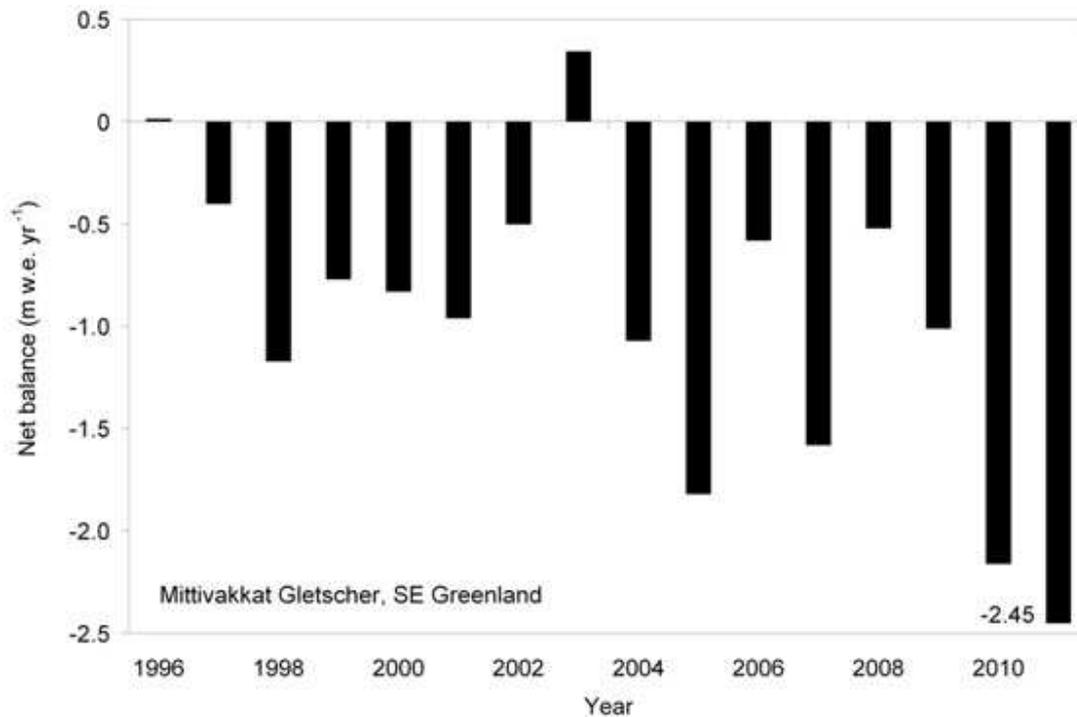
km<sup>2</sup> year<sup>-1</sup>. Since 2000, the net area change of the 39 widest marine-terminating glaciers is - 1369 km<sup>2</sup>, nearly 16 times the size of Manhattan Island, New York.

**Mittivakkat Gletscher: The longest-observed mountain glacier in Greenland** (S. H. Mernild, N. T. Knudsen and E. Hanna)

Mittivakkat Gletscher in southeast Greenland (17.6 km<sup>2</sup>; 65° 41' N, 37° 48' W) has been surveyed for surface mass balance and glacier front fluctuations since 1995 and 1931, respectively (Knudsen and Hasholt 2002, Mernild et al. 2011). The glacier terminus (at the center line) retreated about 22 m (Fig. HTC21) in 2011, 12 m less than the observed record of 34 m in 2010, and approximately 1,600 m in total since the maximum Little Ice Age extension around 1900 and by approximately 1,300 m since 1931. In 2011, net ablation was recorded at all elevations between the summit (930 m a.s.l.) and the terminus (180 m a.s.l.), indicating that the ELA for Mittivakkat was above 930 m a.s.l., and 200 m above the average since mass balance observations began. The total 2011 mass budget loss was 2.45 m water equivalent (w.e.), 0.29 m w.e. higher than the observed record loss in 2010 and significantly greater than the 16-yr average loss of 0.97±0.19 m w.e. yr<sup>-1</sup> (Fig. HTC22).



**Fig. HTC21.** The location of the Mittivakkat Gletscher margin delineated as thick lines for 1931, 1943, 1972, 1999, 2005, 2009, 2010, and 2011 (pink). The 1931, 1943, and 1972 margins were estimated from aerial photographs, the 1999 margin from Landsat 5, and the 2005 margin from Quickbird. The more recent 2009, 2010, and 2011 margins were obtained from topographic surveys (Kern Theodolite observations) and GPS measurements. The Mittivakkat Gletscher outline is shown at left with a black square indicating the photographic area (background photograph: DigitalGlobe, Quickbird 2005 and updated from Mernild et al. 2011).



**Fig. HTC22.** Observed annual water equivalent (w.e.) mass balance of the Mittivakkat Gletscher, southeast Greenland, from 1995 to 2011 (updated from Mernild et al. 2011).

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