Greenland

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Summary

Greenland climate in 2010 is marked by record-setting high air temperatures, ice loss by melting, and marine-terminating glacier area loss. Summer seasonal average (June-August) air temperatures around Greenland were 0.6 to 2.4°C above the 1971-2000 baseline and were highest in the west. A combination of a warm and dry 2009-2010 winter and the very warm summer resulted in the highest melt rate since at least 1958 and an area and duration of ice sheet melting that was above any previous year on record since at least 1978. The largest recorded glacier area loss observed in Greenland occurred this summer at Petermann Glacier, where 290 km^2 of ice broke away. The rate of area loss in marine-terminating glaciers this year (419 km^2) was 3.4 times that of the previous 8 years, when regular observations are available. There is now clear evidence that the ice area loss rate of the past decade (averaging 120 km^2/year) is greater than loss rates pre-2000.

Coastal surface temperatures

A clear pattern of exceptional and record-setting warm air temperatures is evident at long-term meteorological stations around Greenland (Table GL1). For instance:

- Nuuk (64.2°N along Greenland's west coast): Year 2010 summer, spring, and winter 2009/2010 were the warmest on record since record keeping began in 1873.
- Aasiaat (69.0°N along Greenland's west coast): It was the warmest month of May and August, and the warmest winter, spring, 2nd warmest summer and the warmest year (July 2009-August 2010) since record keeping began in 1951.
- Narsarssuaq (61.2°N in southern Greenland): It was the warmest month of May, and the warmest winter, spring and the warmest year (July 2009-August 2010) since record keeping began in 1951.
- Thule AFB, Pituffik (76.5°N along Greenland's west coast): It was the warmest spring (March-May) on record, which began in 1961.

Table GL1. 2010 Greenland station surface air temperature anomalies by season, relative to 1971–2000.

Station (Region), Latitude, Longitude	First Year	Statistic	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	Winter	Spring	Summer	September-August
Pituffik (NW)	1961	Anomaly									4.8	3.4		
76.5 N		Rank									2	1		
68.8 W		St. Deviations									1.3	1.8		
		warmest year									1963	2010		
		coldest year									1984	1992		
Upernavik (NW)	1874	Anomaly	4.6	**11.7**	6.1	4.1	4.2	2.3	0.6	**3.2**	7.9	4.8	2.1	**3.4**
72.8 N		Rank	30	2	16	16	7	7	32	3	5	5	7	5
56.2 W		St. Deviations	0.9	**2.1**	1.2	1.4	1.6	1.8	0.8	**2.0**	1.9	1.9	1.9	**2.0**
		warmest year	1929	1947	1916	1905	1932	2008	1960	1960	1947	1932	2008	1929
		coldest year	1983	1984	1887	1896	1964	1894	1916	1873	1983	1896	1873	1983
Ilulissat (W)	1873	Anomaly	6.5	11.0	7.1	4.1	4.0	2.1	1.1	2.2	7.5	5.1	**1.8**	3.2
69.2 N		Rank	10	7	19	8	5	9	21	7	4	5	3	3
51.1 W		St. Deviations	1.4	1.8	1.2	1.4	1.8	1.5	1.2	1.9	1.9	1.8	**2.0**	1.9
		warmest year	1929	1986	1916	1905	1933	1997	1960	1987	1929	1932	1960	1929
		coldest year	1983	1984	1993	1896	1875	1918	1972	1940	1884	1887	1972	1984
Aasiaat (W)	1951	Anomaly	8.0	**12.3**	**9.8**	5.9	**4.1**	2.3	1.6	**3.2**	**8.8**	**6.6**	**2.4**	**4.3**
68.7 N		Rank	4	2	3	2	**1**	5	7	**1**	**1**	**1**	2	**1**
52.8 W		St. Deviations	1.3	**2.0**	**2.0**	1.9	**2.0**	1.5	1.2	**2.4**	**2.0**	**2.4**	**2.1**	**2.2**
		warmest year	1980	1986	2005	2000	2010	2003	1960	2010	2010	2010	1960	2010
		coldest year	1983	1984	1993	1984	1984	1992	1972	1983	1984	1993	1972	1984
Nuuk (WW)	1873	Anomaly	4.8	**8.5**	4.9	3.1	**4.7**	2.8	1.5	**3.6**	**6.0**	**4.3**	**2.6**	**2.9**
64.2 N		Rank	11	4	16	10	**1**	3	19	**1**	**1**	2	**1**	2
51.8 W		St. Deviations	1.5	**2.0**	1.2	1.5	**2.8**	1.7	1.3	**2.9**	**2.2**	**2.2**	**2.4**	**2.1**
		warmest year	1917	1901	1916	1953	2010	1947	2008	2010	2010	1932	2010	1929
		coldest year	1984	1984	1993	1949	1992	1922	1955	1884	1984	1993	1914	1884
Narsarsuaq (S)	1962	Anomaly	7.1	9.3	6.3	3.1	**5.7**	2.5	1.2	1.9	6.9	5.1	1.9	3.4
61.2 N		Rank	5	2	5	8	**1**	3	8	3	**1**	**1**	2	**1**
45.4 W		St. Deviations	1.3	1.6	1.3	1.0	**2.8**	1.6	1.1	1.7	1.8	1.9	**2.1**	1.9
		warmest year	1985	1986	1962	1998	2010	1991	1991	1987	2010	2010	2003	2010
		coldest year	1983	1984	1995	1990	1992	1992	1969	1983	1984	1989	1983	1983
Prins Christian Sund (S)	1950	Anomaly			2.2	1.3	**2.5**	**2.1**	1.8	**3.4**	**3.8**	2.0	**2.4**	
60.0 N		Rank			12	7	**1**	2	3	**1**	**1**	2	**1**	
43.2 W		St. Deviations			1.1	1.1	**3.2**	**2.0**	1.6	**3.3**	**2.6**	1.9	**2.8**	
		warmest year			2005	2004	2010	2008	2005	2010	2010	2005	2010	
		coldest year			1989	1969	1982	1993	1969	1992	1993	1989	1970	
Tasiilaq (SE)	1896	Anomaly	5.5	2.6	2.1	0.8	1.3	2.6	1.6	**2.9**	**4.0**	1.4	**2.4**	1.9
65.6 N		Rank	5	21	32	48	30	5	18	**1**	4	29	2	8
22.0 W		St. Deviations	1.9	1.0	0.5	0.3	0.6	1.8	1.1	**2.9**	**2.1**	0.6	**2.5**	1.5
		warmest year	1987	1932	1929	1926	1939	1932	1939	2010	1929	1929	2003	2003
		coldest year	1918	1919	1899	1919	1979	1998	1983	1983	1918	1990	1983	1918
Illoqqortoormiut (E)	1950	Anomaly	2.5	-1.7	-2.7	1.7	1.2	0.2	2.2	1.6	1.8	0.1	1.3	0.6
70.4 N		Rank	15	46	43	15	10	23	8	8	14	24	11	17
22.0 W		St. Deviations	0.8	-0.4	-0.5	0.8	1.0	0.4	1.3	1.2	0.8	0.3	1.1	0.6
		warmest year	1974	2005	1996	2004	2009	1995	1991	2004	2005	1996	2004	2005
		coldest year	1959	1978	1969	1951	1956	1956	1953	1952	1966	1956	1955	1969
Danmarkshavn (NE)	1950	Anomaly	-0.5	-1.2	-1.3	1.5	2.9	0.2	0.0	1.5	1.4	1.0	0.6	0.7
76.8 N		Rank	35	41	37	12	5	25	27	5	15	13	12	13
18.8 W		Z-score	-0.1	-0.4	-0.4	0.8	1.6	-0.1	0.1	1.4	0.6	0.8	0.7	0.7
		warmest year	1990	2008	1976	2006	1967	2008	1958	2003	2005	1976	2008	2005
		coldest year	1978	1970	1966	1969	1956	2006	1955	1999	1967	1966	1955	1969
Eureka (N Canada)	1949	Anomaly	2.5	5.4	5.2	**8.1**	4.4	2.3	0.9	**6.0**	4.4	**5.9**	**3.1**	**3.9**
70.4 N		Rank	15	4	2	3	5	6	13	**1**	2	**1**	**1**	**1**
22.0 W		St. Deviations	0.6	1.4	1.9	**2.4**	1.3	1.3	0.9	**3.6**	1.9	**2.8**	**2.7**	**3.1**
		warmest year	1977	1978	1962	1953	1967	1998	2009	2010	2003	2010	2010	2010
		coldest year	1975	1979	1977	1987	1995	1974	1964	2000	1973	1987	1979	1973

*Anomalies are in °C, with respect to the 1971–2000 base period. Bold values indicate values that meet or exceed 2 standard deviation2 from the mean. Red characters indicate a record setting year. The winter value takes December from the previous year.

Warming was greatest in Winter (December-February), with temperatures 3.8°C to 8.8°C above the 1971-2000 baseline. The only cooler-than-normal air temperatures were in the winter in east Greenland and are not statistically significant. Winter warming is relevant to increased summer melt because warmed snow or ice volumes require less heat to be brought to the melting point. Under these conditions, melt onset occurs earlier than normal and the snow cover duration is shorter. This leads to a lower average albedo earlier in the summer, allowing for a greater absorption of solar energy, more melting and higher temperatures, especially on land once snow cover is completely melted and exposes bare (dark) land. The "ice-albedo" feedback, responsible for amplified warming in the high latitudes is clearly operating here. A pattern of "polar amplification" of warming has been evident in surface air temperature records for decades (Hansen and Lebedev, 1987).

Atmospheric circulation anomalies

The NCEP/NCAR reanalysis data indicate warm airflow from the south over the southwestern part of the Greenland ice sheet (Fig. GL1).

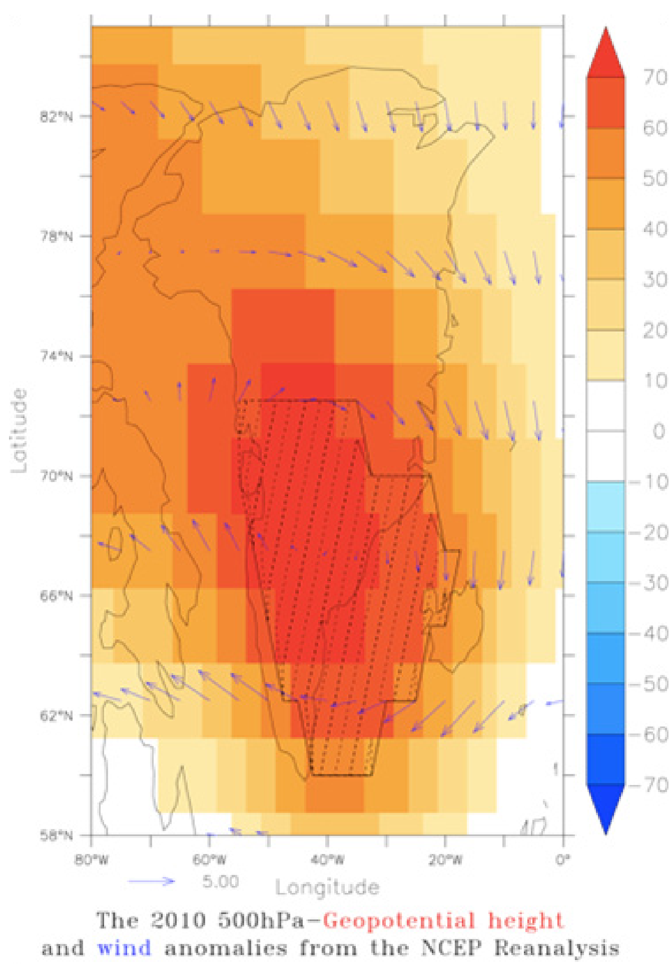

Figure GL1. The geopotential height and wind anomalies for JJA 2010 (referenced to the 1971–2000 mean) at 500 hPa from the NCEP/NCAR Reanalysis. Areas where geopotential height anomalies were at least twice the 1971–2000 standard deviation are hatched. The blue arrows represent wind vector anomalies, with scale indicated by the blue arrow below the plot.

Surface melt extent and duration

The area and duration of melting on the ice sheet continued to expand in 2010, as compared with past years via daily passive microwave satellite remote sensing observations (Mote, 2007). April to mid-September (18 September) 2010 had about an 8% more extensive melt area than 2007, when the previous record maximum melt extent was observed (Figure GL2). The 2010 melt extent through mid September was 38% greater than the 1979-2007 average, and the June to August extent was 26% greater than average. .

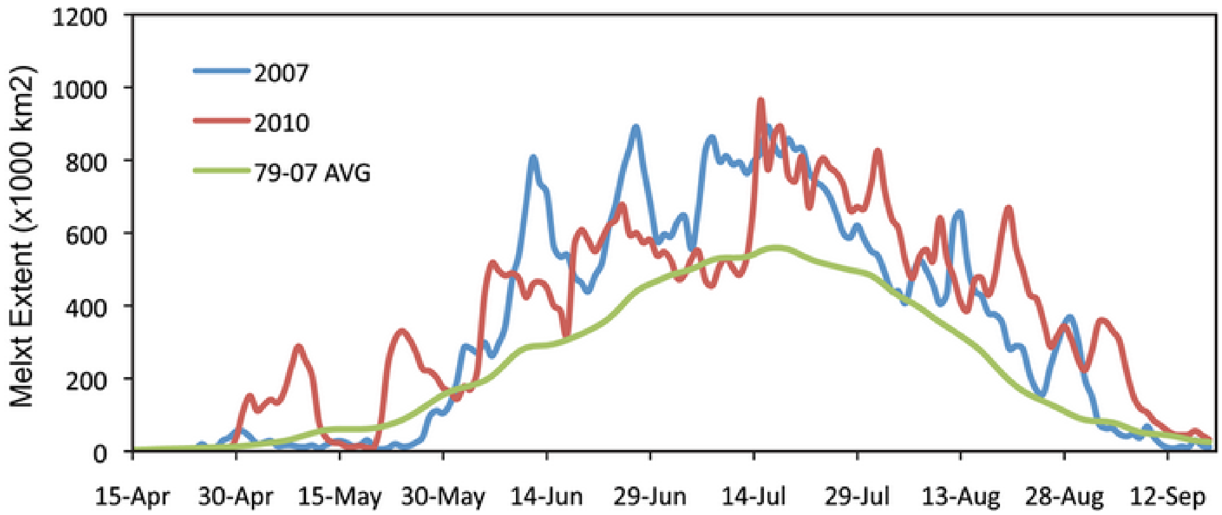

Figure GL2. Time series of Greenland melt extent derived from passive microwave remote sensing from 2010 (red), 2007 (blue) and the 1979-2007 average (green), after Mote (2007).

Abnormal melt duration was concentrated along the western ice sheet (Figure GL3), consistent with anomalous warm air inflow during the summer (Figure GL1) and abnormally high winter air temperatures which led to warm pre-melt conditions. The melt duration was as much as 50 days greater than average in areas of west Greenland that had an elevation between 1200 and 2400 meters above sea level. In May, areas at low elevation along the west coast of the ice sheet melted up to about 15 days longer than the average. NCEP/NCAR Reanalysis data suggest that May surface temperatures were up to 5°C above the 1971–2000 baseline average. June and August also exhibited large positive melting day anomalies (up to 20 days) along the western and southern ice sheet. During August temperatures were 3°C above the average over most of the ice sheet, with the exception of the northeastern ice sheet. Along the southwestern ice sheet, the number of melting days in August has increased by 24 days over the past 30 years.

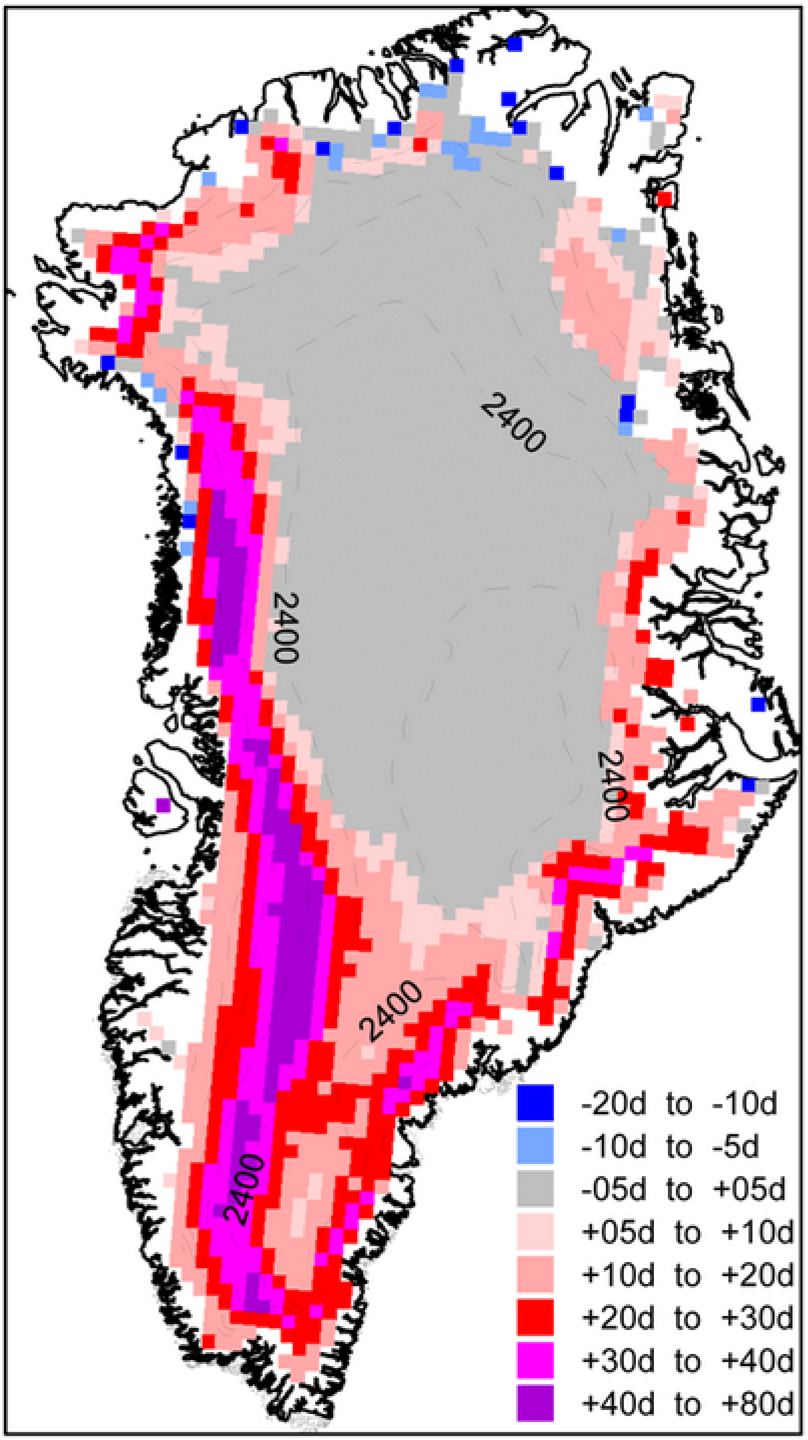

Figure GL3. Difference (days) in summer 2010 melt duration compared to 1979-2007 mean, after Mote (2007). The 2400 m elevation contour is included to illustrate higher elevations of melting over the southern ice sheet.

In May, areas at low elevation along the West coast of the ice sheet melted up to about 15 days longer than the average; June and August also show large positive melting day anomaly values (up to 20 days) along the West and South regions of the ice sheet. NCEP/NCAR Reanalysis data suggest that May surface temperatures were up to 5°C above the average. During August temperatures were 3°C above the average over most of the ice sheet, with the exception of the northeast ice sheet. Along the South-West portion of the ice sheet, the number of melting days in August has increased by 24 days over the past 30 years.

In-situ observations from the K-Transect

Ice sheet surface mass balance from September 2009-2010 was by far the lowest since 1990, when routine measurement began along an elevation transect of in-situ observations located near Kangerlussuaq at 67°N on the western flank of the ice sheet (van de Wal et al. 2005). Averaged over the 150-km long elevation K-transect, from 340 to 1500 meters above sea level, the surface mass balance was highly significant at 2.7 standard deviations below the 1990-2010 average. The altitude of the snow line (the extent of the melt of the winter snow cover) was higher than ever, with a very early onset of the melt season that continued until the beginning of September. Surface albedo values at the weather stations dropped below average and air temperatures in summer were above average.

Marine-terminating glacier area changes

Marine-terminating glaciers are of particular interest because they represent the outlets through which the ice can move most quickly and in the largest quantities out to the sea, contributing to rising average global sea levels and drawing down the inland ice reservoir. Glacier front ice area loss is also of concern because it is associated with reduced flow-resistance, which leads to accelerated ice loss from the inland ice.

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 in the past year Greenland glaciers collectively lost an area of 419 km^2. This is more than 3 times the loss rates of the previous 8 years, 2002-2009, which was 121 km^2/year (Figure GL4). 7/10 of this year's loss came from the 290 km^2 ice island detachment from Petermann glacier in far northwest Greenland (see: http://bprc.osu.edu/MODIS/?p=69). Glacier ice area loss elsewhere (i.e. outside the Petermann Glacier) remained near the 121 km^2/year rate observed during the past decade. There is now clear evidence that the ice area loss rate of the past decade is greater than loss rates pre-2000.

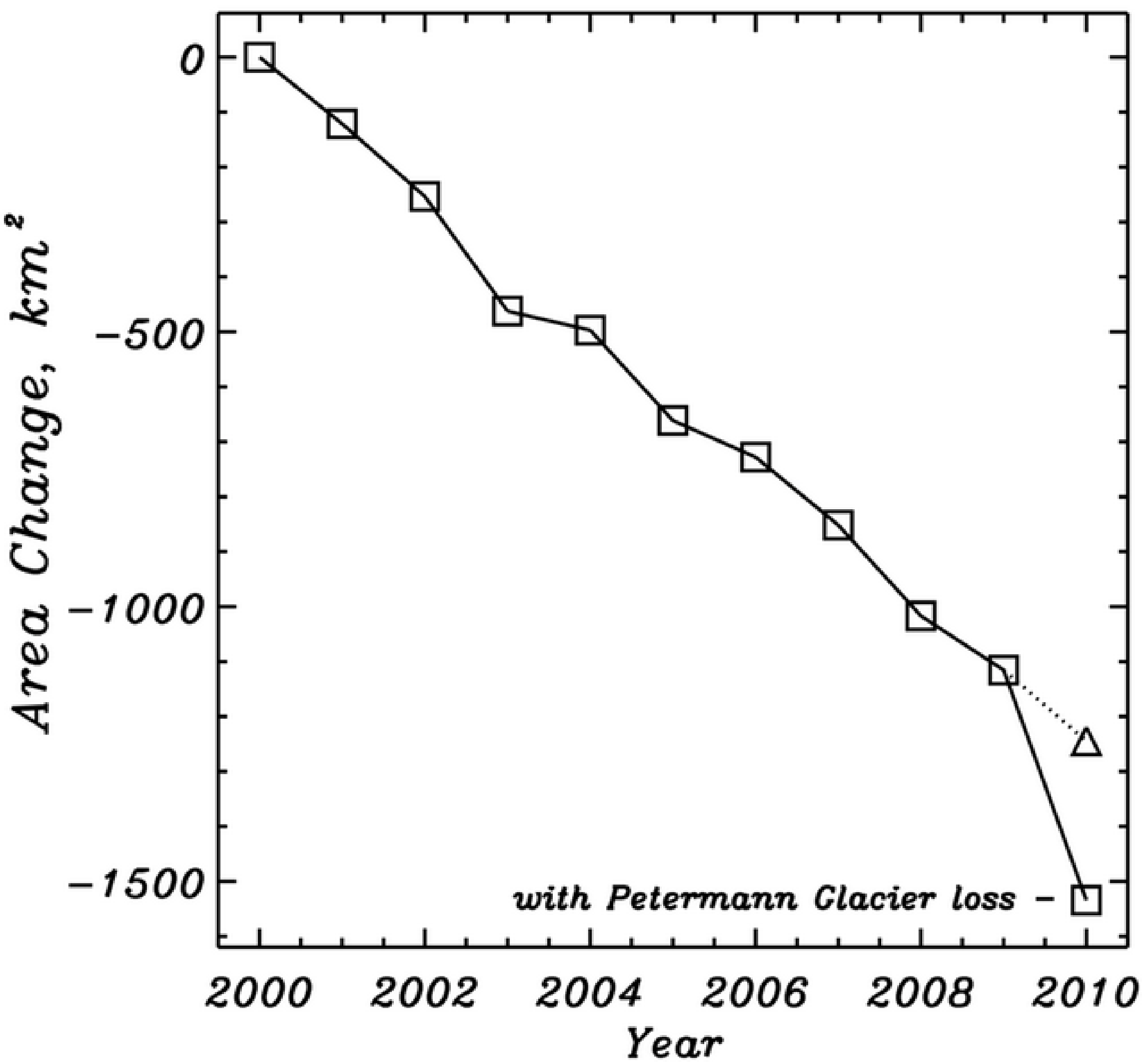

Figure GL4. Cumulative net annual area changes for the 35 widest marine-terminating glacier outlets to the Greenland ice sheet. Year 2010 net area changes are shown with and without the Petermann glacier loss. The trend without the Petermann loss is illustrated by the triangle in year 2010.

A number of other large outlet glaciers also lost significant amounts of ice area: Zachariae Isstrøm in northeast Greenland lost 43 km^2; Humboldt glacier in northwest Greenland lost 20 km^2; Ikertivaq glacier in Southeast Greenland lost 15 km^2; and the 5 glaciers that empty into Upernavik glacier bay in northwest Greenland lost 14 km^2.

Since 2000, the net area change of the 35 widest marine-terminating glaciers is -1535 km^2; equivalent to an ice area loss 17.5 times the size of the 87.5 km^2 Manhattan Island. The total effective glacier length change has been, on average, -1.7 km since year 2000. While the overall area change indicates the largest observed retreat, 7 of 35 glaciers did advanced in 2010 relative to 2009. The largest glacier advances were at Ryder and Storstrømmen glacier, each advancing 4.6 and 4.2 km^2, respectively. Land-terminating glaciers are not part of our survey but most certainly lost a much smaller area because they are so much slower-moving than marine-terminating glaciers.

Precipitation and surface mass balance

The balance between snowfall gain and meltwater loss is positive for any healthy ice mass. In 2010, the MAR regional climate data assimilation model simulated that the ice sheet surface mass balance was 90% less positive than normal (Table GL2); the lowest net mass accumulation rate since 1958 when data to drive the model become available (Figure GL5). This condition reflects a very heavy melt year combined with below normal ice sheet snow accumulation. The high melt rate in 2010 was a consequence of:

- a warmer winter favoring an earlier melt season onset because the snowpack is relatively warm and, thus, can reach its melting temperature more quickly.
- a drier winter favoring less snow pack and thus an earlier appearance of a darker surface (e.g. bare ice or the previous year summer snow surface), which has a lower surface albedo.
- a very warm summer.
- a summer with less snowfall than normal (-20%), impacting the surface albedo which was low during the whole melting season in 2010.

The temperature and precipitation anomalies are very likely the result of regional circulation anomalies illustrated in Figure GL1. The main anomalies occur along the south-western margin where the number of days with bare ice was higher than normal. Compared to Summer 2007, where melt anomalies took place in both ablation and percolation zones (Tedesco et al., 2008), most of melt anomalies of this summer took place in the bare ice zone.

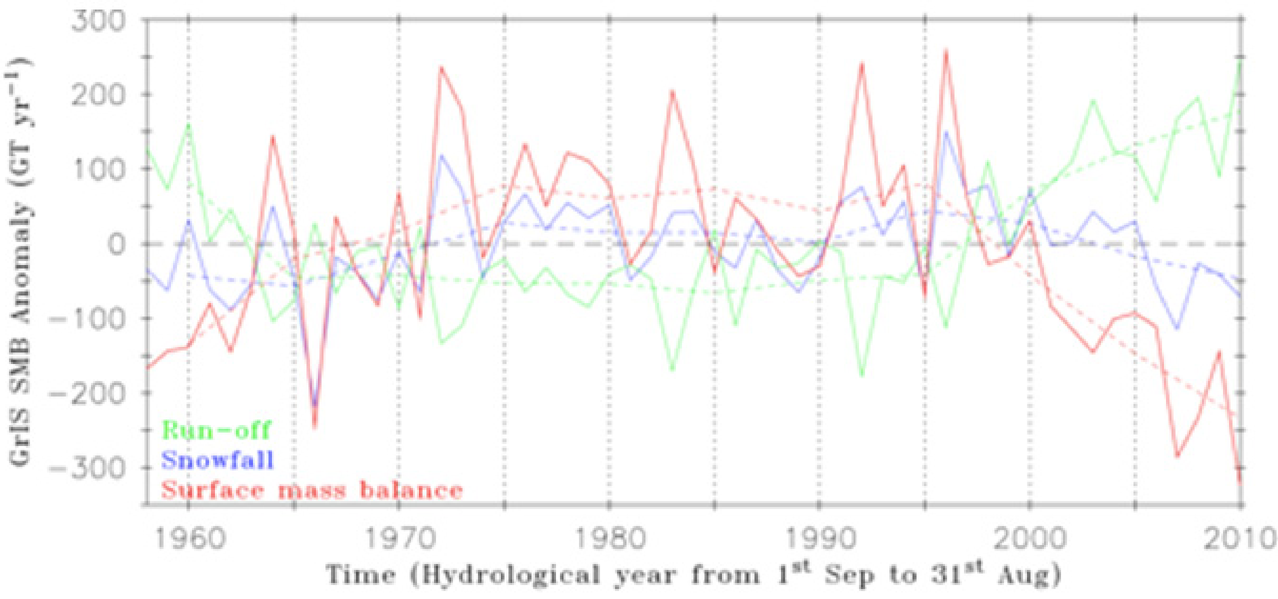

Figure GL5. Time series of hydrological year (1 Sep to 31 Aug) mean surface mass balance (SMB) component anomalies simulated by the regional climate MAR model (Fettweis et al., 2010). The differences between the SMB time series and the snowfall minus run-off time series are attributed to rainfall and sublimation/evaporation.

Table GL2. Greenland ice sheet surface mass balance and near-surface temperature anomalies simulated by the regional climate MAR model.						
2010 anomaly referenced to	Total SMB (GT)	Total Snowfall (GT)	Total Runoff (GT)	Winter Snowfall (GT)	Winter Air Temperature (K)	JJA Air Temperature (K)
Period	1st Sep to 31st August	1st Sep to 31st August	1st Sep to 31st August	1st Sep to 30th April	1st Sep to 30th April	1st Jun to 31st Aug
1971-2000	-383 GT (-93%)	-94 GT (-15%)	290 GT (+124%)	-48 GT (-10%)	2.5	2.4
1991-2000	-392 GT (-93%)	-119 GT (18%)	271 GT (+107%)	-70 GT (-14%)	2.3	2.2
2001-2010	-159 GT (-84%)	-48 GT (-8%)	109 GT (+26%)	-35 GT (-8%)	1.2	1

Anecdotal Data

A long-term resident of Greenland wrote on 4 February, 2010: "we don´t have snow, we don´t have the cold" ... "This weather this year is really different, in 30 years that I live in Ilulissat [69.0°N along Greenland's west coast], that is the first year in this conditions. We have lot of dog sledding tourists, but we cannot do the tour, too much ice on the hills and dangerous to drive by sled." ... "no snow at all". Later, the same source remarked of "10-12 days of" continuous "heat wave" like weather, in June, with "a lot of blue skies".

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