Greenland surface melt trends 1973–2007: Evidence of a large increase in 2007

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[1] A time series of surface melt extent, frequency and onset has been updated to include data from Electrically Scanning Microwave Radiometer (ESMR) (1973, 1974 and 1976), Scanning Multichannel Microwave Radiometer (SMMR) (1979–1987) and the Special Sensor Microwave/Imager (SSM/I) (1987–2007). The seasonal melt departure (SMD), the sum from 1 June to 31 August of the departure from average of each day's melt extent, is a new metric used to describe the amount of melt. Results show a large increase in melt in summer 2007, 60% more than the previous high in 1998. During summer 2007, some locations south of 70°N had as many as 50 more days of melt than average. Melt occurred as much as 30 days earlier than average. The SMD is shown to be significantly related to temperatures at coastal meteorological stations, although 2007 had more melt than might be expected based on the summer temperature record.

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1. Introduction

[2] Satellite observations have pointed to decreasing sea ice [*Comiso*, 2002, 2006a; *Fetterer et al.*, 2007] and snow cover [*Robinson and Estilow*, 2007] across the Northern Hemisphere since 2000 compared to the 1980s. The decrease in sea ice and snow cover has focused attention on the role of the cryosphere as both an important indicator of climate change and a feedback in the climate system. This most recent Intergovernmental Panel on Climate Change assessment report concludes that changes in surface melting have contributed to a loss of mass in Greenland, which in turn is "very likely" a contributor to global sea level rise [*Lemke et al.*, 2007].

[3] Passive microwave satellite sensors have been used to map the spatial extent and frequency of melting on the Greenland ice sheet, and the data have been a useful indicator of changing melt given the continuous time series of data available since October 1978 [*Mote et al.*, 1993; *Mote and Anderson*, 1995; *Abdalati and Steffen*, 1997, 2001; *Mote*, 2003; *Steffen et al.*, 2004; *Tedesco*, 2007a, 2007b]. Infrared instruments also have been used to assess ice sheet temperature and melt, including the Advanced Very High Resolution radiometer (AVHRR) [*Comiso*, 2006b] and the Moderate Resolution Imaging Spectroradiometer (MODIS) [*Hall et al.*, 2007]. Furthermore, surface melt as measured by satellite is not only a useful indicator of climate, but plays a role in the surface mass balance [e.g., *Hanna et al.*, 2002, 2005, 2007; *Box et al.*, 2004] and may play an important role in basal lubrication and ice sheet dynamics [*Zwally et al.*, 2002].

[4] This study extends the existing passive microwave time series of surface melting on the Greenland ice sheet back to 1973 and updates the record to 2007. In order to account for the effect of missing data, this research applies a new metric for melt, the seasonal melt departure (SMD). This measure is the sum of all daily departures of the areal extent of melt from the daily mean. Finally, this research compares the melt time series with temperature records from coastal meteorological stations on Greenland. The objectives are (1) to develop an improved measure of surface melt, (2) to develop an extended time series of surface melt, updated to include 2007, and (3) to assess how well the melt data compares with available meteorological data.

2. Data and Methods

[5] Measurements of snowpack melt were made using data obtained from three satellite microwave radiometers, the Nimbus-5 Electronically Scanning Microwave Radiometer (ESMR), the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I). The Nimbus-5 ESMR recorded radiation at one channel, 19.35 GHz [*Parkinson et al.*, 1999]. Data are available from December 1972 to December 1976, but the 1975 summer season was not included due to an insufficient number of days with data. The SMMR recorded radiation every other day in 10 channels [*Gloersen et al.*, 1990], including both polarizations for 6.6, 10.7, 18.0, 21.0, and 37.0 GHz, from October 1978 to August 1987. The SSM/I, which began operation in July 1987, records radiation daily in seven channels, the vertical polarization for 22.2 GHz and both polarizations for 19.35, 37.0, and 85.5 GHz [*Gloersen and Barath*, 1977]. The 18 and 19.35 GHz horizontally polarized channels were used for this research to build the longest possible time series of microwave data.

[6] The ESMR, SMMR and SSM/I data were obtained from the National Snow and Ice Data Center (NSIDC) archive of brightness temperatures in a 25 $\times$ 25 km grid on a polar stereographic projection [*Maslanik and Stroeve*, 2007]. Any data sample that was located within a given grid cell on a given day, beginning at 0 UTC, was averaged into the daily value for that grid cell. Isolated grid cells with missing data were filled by averaging the adjacent grid cells.

[7] A land mask digitized from the Quaternary map of Greenland published by the Geologic Survey of Greenland (1:2500000 scale) [*Weidick*, 1971] was used in conjunction

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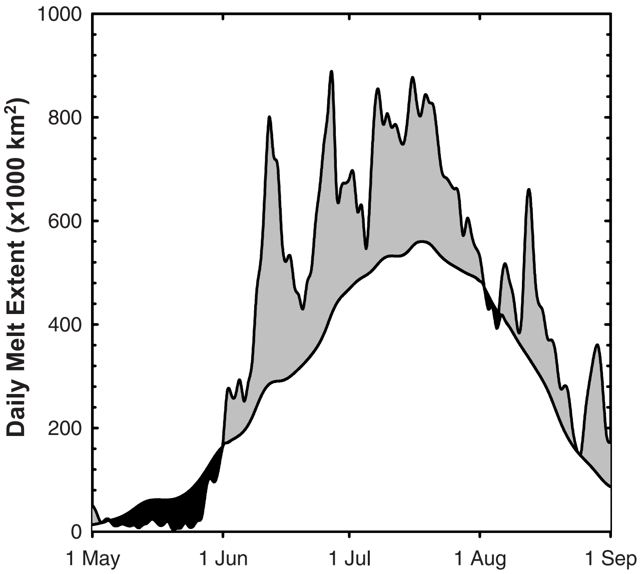

Figure 1. Illustration of the calculation of the melt departures on a daily basis for 2007. Areas in light grey show periods when the 2007 melt extent exceeded the 1973–2007 average. Areas in black show periods when the 2007 melt extent was less than average. The seasonal melt departure (SMD) was calculated by summing the daily departures from 1 June to 31 August in a given year.

with NSIDC's SMMR and SSM/I water and coastline masks to eliminate all grid cells not covered by at least 50 percent ice or grid cells with any permanently standing water. The unmasked grid cells available for analysis covered a total area of 1.648 million km^2, including parts of ice caps separate from the ice sheet. The ice sheet covers approximately 1.701 million km^2 and ice caps cover another 65,000 km^2 [*Weidick*, 1985].

2.1. Melt Determination

[8] Passive microwave sensors may be used to estimate the frequency with which melt occurs due to the increase in emissivity as liquid water forms in previously dry snow. The emissivity of snow changes rapidly as melt occurs. Because of the high dielectric constant of liquid water, wet snow results in an increase in absorption relative to volume scattering, which reduces the scattering albedo and enhances emission. Changes in melt duration and extent on the Greenland ice sheet have been mapped using the seasonal change in emissivity [*Mote et al.*, 1993; *Mote and Anderson*, 1995], the frequency dependence of emissivity, such as the cross polarized gradient ratio (XPGR) of *Abdalati and Steffen* [1997] and *Steffen et al.* [2004], and the diurnal change in emissivity [*Tedesco*, 2007a]. They have also been mapped using the MODIS thermal-infrared channels by *Hall et al.* [2007], and using QuikSCAT scatterometer data by *Nghiem et al.* [2001].

[9] A microwave emission model was employed to determine the 19 GHz, horizontally polarized, T_Bs associated with 1% volumetric water content for each grid cell, each year on the Greenland ice sheet. This study uses an approach following *Mote and Anderson* [1995], where the emission model is described in detail. The emission model uses scattering coefficients that are empirically derived from the T_Bs before the onset of melt each year. The model is then used to simulate the brightness temperature associated with melt for each grid cell, each year. These T_Bs are used as threshold values to distinguish melt from non-melt during the summer of a given year. While *Mote and Anderson* [1995] used the 37 GHz frequency, this study used the 18 GHz (SMMR) and 19.35 GHz (SSM/I and ESMR) channels in order to include the available ESMR data.

[10] The three sensors differ slightly in frequency (18 GHz versus 19.35 GHz), in view angle, radiometric resolution and calibration and swath width. However, because the approach derives a new set of threshold T_Bs each year, and because the model explicitly accounts for the sensor frequency and view angle, the impact of using three different sensors is minimized. The one exception is August to December 1987, when the model used pre-melt T_Bs from SMMR to create threshold T_Bs that were applied to SSM/I. (In that instance, a linear regression of SMMR to SSM/I brightness temperatures from the dry snow zone of the ice sheet was produced from T_Bs during the crossover period of the two instruments in 1987. The regression was used to adjust the SMMR brightness temperatures. The result is that two sets of threshold T_Bs were created for 1987, one for SMMR from January to July, and one for SSM/I from August to December.)

2.2. Seasonal Melt Departure

[11] Values of the 18 or 19.35 GHz, horizontally polarized brightness temperatures for each day of available data were compared to the simulated melt brightness temperatures for the given year. The simulated values for each year were used as threshold values to identify whether the snowpack in a given grid cell was experiencing melt. The spatial coverage of the grid cells identified as experiencing melt each day was summed to quantify the areal extent of melt on a given day. These values can be averaged to produce an average melt extent. The average melt extent for a season is analogous to the average frequency of melt occurrence of all grid cells for the season. This is identical to the average daily melt extent produced by *Mote and Anderson* [1995] and is functionally similar to the "melt index" produced by *Tedesco* [2007b].

[12] Periods of missing data could bias the monthly or seasonal average melt extent if the missing days were clustered during periods of more or less extensive melt. In order to account for the effect of missing days, daily departures from the mean daily melt extent for 1973–2007 were calculated from the melt-extent time series. The departures from average of each day's melt extent were then totaled to yield the SMD for June–August. (See Figure 1 for an illustration of this calculation.)

[13] On average, 89% of all grid cells identified with melt were between 1 June and 31 August. Comparisons of time series of SMD using seasons of April–September and June–August showed almost no difference in the interannual variability. Furthermore, a correlation of SMD calculated for April–September against June–August for 1979–2006 yields a correlation coefficient of 0.999. Therefore, June–August SMD is used in this study.

2.3. Total Area With Melt

[14] The total area with melt (TAM), or the area including any cells that experienced melt at least one day in any

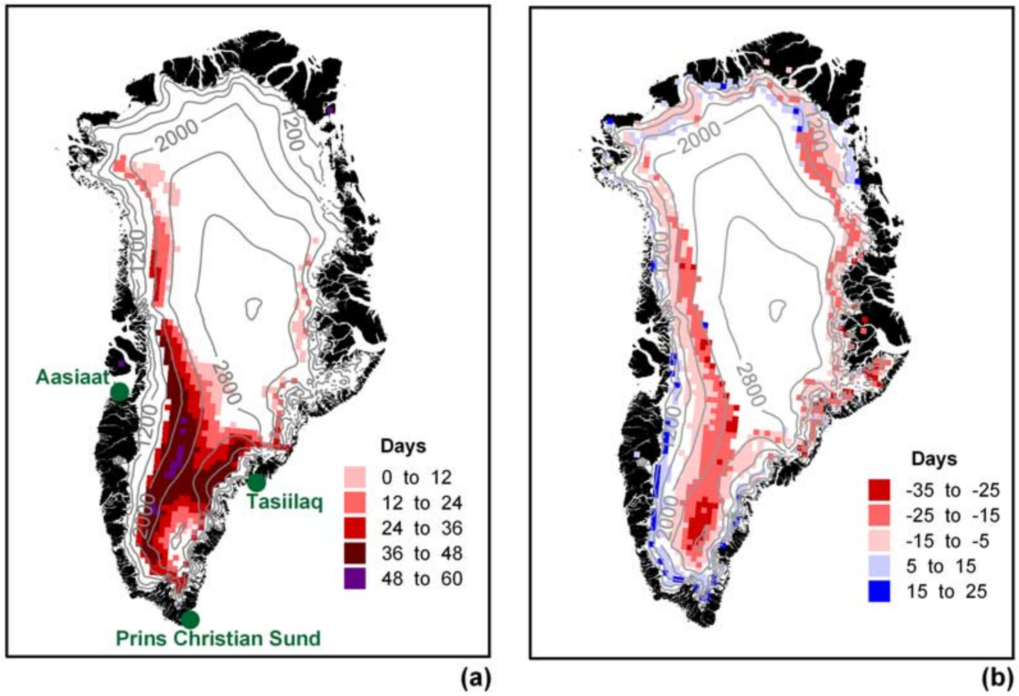

Figure 2. (a) Departure from the 1973–2007 mean of melt frequency (days) shaded, where only significant departures (p = 0.10) are shown, and (b) departure of the date of melt onset (days) shaded. Onset departures smaller than ±5 days are not shown. Elevation contours are shown in grey, and black indicates the land area. Sites of coastal meteorological stations used in the study are also shown in Figure 2a.

season, was also calculated for comparison with other studies though the total area with melt is a less useful metric than the SMD. This metric is similar to the total melt area extent of *Tedesco* [2007a]. Even a few days of melt at high elevation locations may produce a high TAM, even during a year with a relatively low frequency of melt at lower elevations.

2.4. Melt Frequency and Onset

[15] The annual melt frequency, the number of days with melt, was calculated for each grid cell for June–August each year. To account for missing days, the melt frequency was first calculated as a percentage of the total number of days with available data. The melt frequency as a percentage was multiplied by 123 days to express the maps in units of days. An average melt frequency map was created for 1973–2007 and annual maps of frequency departures were calculated.

[16] The annual melt onset was determined by calculating the first date when two consecutive observations of a given grid cell indicating that melt had occurred.

2.5. Station Data

[17] Average daily maximum and minimum temperatures for three coastal meteorological stations were examined: Aasiaat along the west coast, Prins Christian Sund along the south coast, and Tasiilaq along the southeast coast (Figure 2). Data for each station were available from 1973 through August 2007 from the National Climatic Data Center's World Summary of the Day dataset. June–August daily maximum and maximum temperature departures from the average were calculated for each station.

3. Findings

[18] The duration of melt and the onset of melt both indicated more melt than average in 2007 for large parts of the Greenland ice sheet. The frequency of melt was as much as 50 days above the average for some locations south of 70N, particularly between 2000 and 2400 m a.s.l. along the western side of the South Dome and in the region between the North Dome and South Dome (Figure 2a). Large areas in the interior of the North Dome had no melt in the summer of 2007, but those areas that experience any melt average only 0.5 to 2 days per year (Figure 2a). Only those areas with a significant departure from normal in melt frequency (p = 0.10) are displayed in Figure 2a. Many of these same areas saw melt commence 10–20 days earlier than average, while areas above 2400 m a.s.l. of the South Dome saw melt start as much as 30 days earlier than average in 2007 (Figure 2b). All departures from the mean melt onset date are shown in Figure 2b, but the only locations with significant departures (p = 0.10) were near the summit of the South Dome.

[19] The SMD data show a series of years of above average melt beginning in 1997 and a clear upward trend since the 1970s (Figure 3a). All but two of the above average years were 1990 or later, while all but three of the below average years were before 1990. The trend in SMD is +367,000 km^2 y^{-1} (+259,000 to +474,000 km^2 y^{-1} at the 95% confidence interval). The trend is not due to the

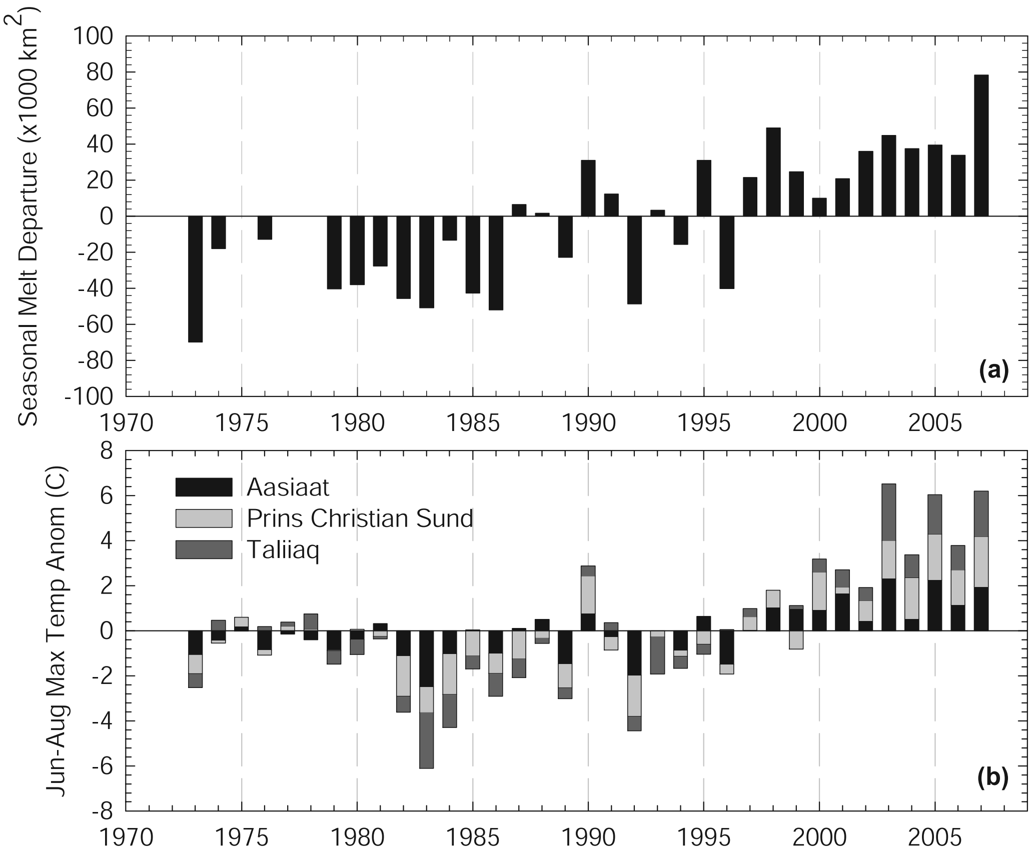

Figure 3. (a) Seasonal melt departure (SMD) for June–August and (b) seasonal maximum daily temperature anomalies at three coastal meteorological stations for June–August from 1973 to 2007. No SMD data are available for 1975, 1977 and 1978.

end points. If one eliminates the ESMR record and 2007, there remains a trend of 399,000 km^2 y^{-1} (+270,000 to +527,000 km^2 y^{-1} at the 95% confidence interval). The values represent the sum of the departures over the 123-day season. The SMD trend represents a change in the area of the ice sheet experiencing melt by about +2980 km^2 y^{-1} on an average summer day.

[20] The trend in TAM (not shown) is approximately +17,600 km^2 y^{-1} (+10,800 to +24,000 km^2 y^{-1} at the 95% confidence interval). This trend is smaller than the approximately +40,000 km^2 y^{-1} found by *Tedesco* [2007a] using SSM/I data from 1992–2005.

[21] The trend in melt agrees with an increase in surface temperature of the ice sheet measured by AVHRR since 1981 [*Comiso and Parkinson*, 2004], and an increase measured by MODIS since 2000 [*Hall et al.*, 2007].

[22] The trend in melt since the mid 1970s also agrees with the temperature record presented here and with other studies of Greenland's coastal temperature records [*Box*, 2002; *Hanna et al.*, 2007]. The average maximum daily temperatures from the three coastal stations were all below the average with the exception of two years in the 1980s, and all have been above average each year beginning in 2000 (Figure 3b). The summer temperatures explain approximately 58% of the variance in SMD ($p < 0.01$). SMD in 2007 is higher than one would expect based on a linear relationship between the station temperature and SMD.

[23] Statistically significant temperature trends are observed for various periods since 1873, periods of warming occurred during 1885–1947 and 1984–2001, and cooling during 1955–1984, with the largest trends in winter and spring temperatures [*Box*, 2002]. Significant increases in summer temperatures have been observed at seven coastal meteorological stations during 1961–2006 [*Hanna et al.*, 2007]. Data from the coastal stations used by *Hanna et al.* [2007] show that summer 2007 was the second warmest summer since 1961. Also, July 2007 was the warmest July (8.8°C) since 1961, albeit only slightly warmer than 2005 (8.7°C) and 2003 (8.7°C). The recent warming coincides with a lower tropospheric warming observed in the upper-air data [*Box and Cohen*, 2006].

4. Conclusions

[24] The seasonal melt departure, a sum of the departures from average melt extent each day, was 60% greater in summer 2007 than the next highest year (1998). The most recent 11 summers have all been above the 1973–2007 average. The total area with melt (TAM), while above the 1973–2007 average, was not remarkable in 2007. The large areas of anomalous melt frequency south of 70°N are the reason for the dramatic increase in SMD in 2007. Some locations had as many as 50 days more melt than average. These same areas experienced melt onset as much as 20 days

earlier than average in 2007, while areas along the South Dome experienced melt up to 30 days earlier than average.

[25] Both measures of melt extent, SMD and TAM, show statistically significant positive slopes during 1973–2007. The SMD trend represents a change in melt extent of +2980 km^2 y^{-1} on a daily basis ($p < 0.01$), while the TAM shows a trend of +17,600 km^2 y^{-1} ($p < 0.01$) The trend in total area with melt may be less than results published by *Tedesco* [2007a] because of relative high values during ESMR years that were included in this study. The years of 1974 and 1976 had occasional melt high on the ice sheet, but with lower than average frequency at lower elevations, resulting in a high TAM but low SMD.

[26] The trend in SMD corresponds to a trend in the average daily maximum temperatures for June–August at three coastal meteorological stations, which have recently experienced higher temperatures than any period since the 1940s. While the temperatures at the coastal meteorological stations in summer 2007 were comparable to 2003 and 2005, the melt frequency in 2007 was substantially higher. Perhaps this is an indication that the period of increased melt during 2002–2006 had some effect that would enhance melting in 2007. One such mechanism could be a decrease in surface albedo. Another possible mechanism may be a decrease in the cold content of the snow (and increase in firn temperatures) during the warmer winters of recent years. Finally, changes in winter accumulation can play a large role in the summer melting by altering the surface albedo [*Box et al.*, 2005]. At this time, there is not yet enough evidence to state conclusively why 2007 had such anomalous melting when compared to the coastal temperatures.

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