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Variability in the surface temperature and melt extent of the Greenland ice sheet from MODIS

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[1] Satellite-derived moderate-resolution imaging spectroradiometer (MODIS) ice-surface temperature (IST) of the Greenland ice sheet shows a positive trend and two major melt events from 2000 to present. IST increased by ~0.55 ± 0.44°C/decade, with the greatest increase (~0.95 ± 0.44°C/decade) found in northwestern Greenland where coastal temperatures and mass loss are also increasing and outlet glaciers are accelerating. IST shows the highest rates of increase during summer (~1.35 ± 0.47°C/decade) and winter (~1.30 ± 1.53°C/decade), followed by spring (~0.60 ± 0.98°C/decade). In contrast, a decrease in IST was found in the autumn (~−1.49 ± 1.20°C/decade). The IST trends in this work are not statistically significant with the exception of the trend in northwestern Greenland. Major surface melt (covering 80% or more of the ice sheet) occurred during the 2002 and 2012 melt seasons where clear-sky measurements show a maximum melt of ~87% and ~95% of the ice sheet surface, respectively. In 2002, most of the extraordinary melt was ephemeral, whereas in 2012 the ice sheet not only experienced more total melt, but melt was more persistent, and the 2012 summer was the warmest in the MODIS record (−6.38 ± 3.98°C). Our data show that major melt events may not be particularly rare during the present period of ice sheet warming. **Citation:** Hall, D. K., J. C. Comiso, N. E. DiGirolamo, C. A. Shuman, J. E. Box, and L. S. Koenig (2013), Variability in the surface temperature and melt extent of the Greenland ice sheet from MODIS, *Geophys. Res. Lett.*, *40*, 2114–2120, doi:10.1002/grl.50240.

1. Introduction and Background

[2] Accelerated warming of the Arctic has been documented by many scientific studies [e.g., *Chen et al.*, 2006; *Hanna et al.*, 2008], and mass loss of the Greenland ice sheet has accelerated in the last decade due to increases in both ice discharge and surface meltwater runoff [*van den Broeke et al.*, 2009; *Velicogna*, 2009; *Rignot et al.*, 2011]. Meltwater from the Greenland ice sheet alone has a potential contribution to sea level rise in excess of 7 m [*Gregory et al.*, 2004]. However, in situ measurements of the average air and surface temperature of the entire ice sheet are difficult to obtain due, at least in part, to the low density of meteorological stations on the ice sheet.

[3] The only way to measure the surface temperature at a good temporal resolution and with extensive spatial coverage over the ice sheet is by satellite; however, clouds typically preclude our ability to capture the entire ice sheet surface at the same time using infrared (IR) sensors. Accurate determination of surface temperature will permit improved measurement and modeling of surface mass balance (SMB) and ice sheet processes. SMB is equal to the mass input, through net snow accumulation minus the net seasonal runoff of surface meltwater [*Hanna et al.*, 2011]. Surface temperature is an integral component of the ice sheet radiation budget and mass balance. Runoff is controlled, in large part, by surface temperature, and even basal melt and internal temperature of the ice sheet are affected by surface temperature [*Bell*, 2008], though the time scale may be quite long (e.g., decades to centuries).

[4] Near-daily IR satellite data have been available since the advent of advanced very high resolution radiometer (AVHRR) digital data in 1981, providing a multidecadal surface temperature record. Based on AVHRR data, *Comiso and Parkinson* [2004] reported an increase in average Arctic surface temperature (north of 60° latitude) of ~0.50 ± 0.2°C/decade and an average increase in the surface temperature of Greenland of 0.85 ± 0.2°C/decade between 1981 and 2003, while *Wang and Key* [2005] reported that the Arctic (north of 60° latitude) warmed by ~0.57°C/decade between 1982 and 1999. Additionally, surface and near-surface (~2 m) air temperatures have been studied using meteorological station data and automatic weather station (AWS) data at various locations on the Greenland ice sheet [*Steffen et al.*, 1996; *Shuman et al.*, 2001; *Hanna et al.*, 2008, 2012].

[5] Recently, a climate-quality data record of the clear-sky surface temperature, or ice-surface temperature (IST), of the Greenland ice sheet was developed [*Hall et al.*, 2012]. We use this record to show seasonal and annual variability and trends in the IST of the ice sheet as a whole and of the six major drainage basins. We then report on 13 years of maximum surface melt extent, with a focus on major melt events that occurred in 2002 and 2012.

2. Data and Methodology

2.1. Moderate-Resolution Imaging Spectroradiometer Climate-Quality Data Record

[6] The Greenland IST record extends from March 2000 through the present, providing daily and monthly average

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IST maps on a polar-stereographic grid at 6.25 × 6.25 km resolution, representing a temporally consistent measurement of clear-sky surface temperature [*Hall et al.*, 2012]. The moderate-resolution imaging spectroradiometer (MODIS) IST algorithm, based on an algorithm developed by *Key et al*. [1997], employs the standard MODIS 1 km resolution cloud mask [*Ackerman et al.*, 2008]. The IST measurement represents the temperature at the surface of the snow/ice (~<2 μm) [see *Warren and Brandt*, 2008] and is very sensitive to detection of surface melt and **re**freeze.

2.2. Methodology

[7] For the present study, we improved the Greenland IST data record after finding instances in which the internal (automated) cloud mask erroneously identified the ice surface as cloud free on many days during the summers (June, July, and August (JJA)). We determined this by manually inspecting each daily IST map. In many of these cases, the algorithm was detecting cloud top temperature which was much lower than clear-sky surface temperature (up to 30°C lower). These erroneous ISTs were removed from the record for the present analysis, though we cannot guarantee that the automated and manual cloud masking has masked every cloud.

[8] To construct maps of surface melt, we used a threshold of −1°C such that any grid cell with an IST ≥ −1°C is considered to be "melt" as long as one pixel within the cell (6.25 × 6.25 km) was classified as melt. Several studies have shown that there may be a cold bias in the MODIS-derived surface temperature [*Wan et al.*, 2002; *Hall et al.*, 2008; *Koenig and Hall*, 2010].

[9] It is difficult to find in situ surface-temperature data that can be used to assess the accuracy of the MODIS IST; such data, acquired from well-planned field experiments, are important to gather in future field work. Nevertheless, to augment the previous validation studies referenced above, we compared each of the 112 cloud-free Terra MODIS IST swaths containing Summit Station (72.58°N, 38.45°W) (~3216 m) for JJA of 2012 with 2 m temperatures from the National Oceanic and Atmospheric Administration (NOAA) station at Summit. The mean difference was 1.04 ± 1.23°C, with the ISTs being 1–3°C lower than the 2 m temperatures. Though a 2 m air temperature over snow and ice often does not agree with the surface temperature, this comparison shows that the mean difference, at least in summer, is similar to results of previous studies.

3. Results

3.1. Trends in IST

[10] Figure 1 is a plot of monthly IST anomalies using 154 months of the data record (March 2000 to December 2012). There is a trend toward higher IST over the study period of 0.55 ± 0.44°C/decade, though it is not statistically significant. In Figure 2, we see large positive IST anomalies for 2010, a warm year (−22.09 ± 5.70°C), and negative anomalies for spring and autumn 2011, a cool year (−25.15 ± 5.74°C) (Table 1).

[11] The only year during the study period that is anomalously warm in all seasons is 2010 (Figures 1 and 2). Declining albedos caused additional melt and reduced summer snowfall which maximized surface solar heating and thus positive albedo feedback [*Tedesco et al.*, 2011; *Box et al.*, 2012]. The persistent negative summer North Atlantic Oscillation (NAO) index contributed to the warm summer and declining albedos in 2010 [*Box et al.*, 2012]. This may be considered in the context of work by *Wang and Key* [2005] who noted a decline in albedo of −1.5%/decade over the Arctic between 1982 and 1999. The greater negativity of the NAO index since ~2000 is associated with more blocking high pressure over Greenland and a higher frequency of advection from southerly airflow (warm air onto the ice sheet) along the western part of the ice sheet [*Hanna et al.*, 2013], as occurred in June/July 2012 (to be discussed later).

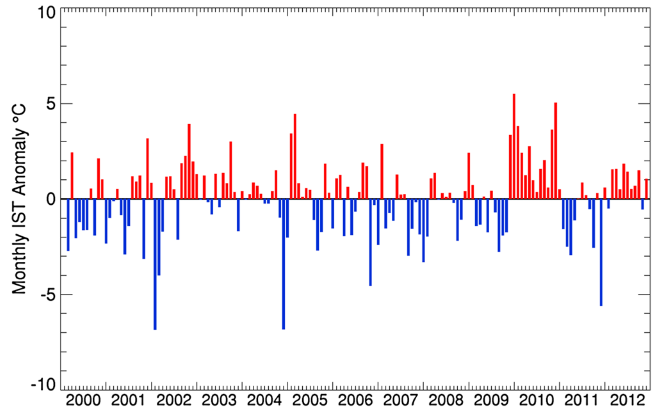

Figure 1. Monthly IST anomalies for the Greenland ice sheet (154 months).

[12] Seasonal ISTs (Table 2) and IST trends were also calculated. They are positive in winter (December, January, and February (DJF)) at 1.30 ± 1.53°C/decade, spring (March, April, and May (MAM)) at 0.60 ± 0.98°C/decade, and summer (JJA) at 1.35 ± 0.47°C/decade, and negative in autumn (September, October, and November (SON)) at −1.49 ± 1.20°C/decade. The observed warming during winter is consistent with results from *Box* [2002], *van As* [2011], and *Hanna et al.* [2012] showing enhanced winter warming of Greenland, with *Hanna et al*. [2012] also showing autumn cooling during 2000–2011.

[13] Because we can only obtain IST values under clear skies, a trend in cloud cover could affect the IST trend results. Using the MOD35 cloud mask product [*Ackerman et al.*, 2008], we plotted monthly cloud cover percentage for the study period. No statistically significant trend in the percentage of cloud cover was found, though we noted an overall decrease (−3.77 ± 2.01%/decade) of cloud cover that was most pronounced in autumn (−7.35 ± 3.66%/decade). The higher rate of cloud cover decline could be a factor in the negative IST anomaly trend in SON since clouds tend to retain heat close to the ground over snow-covered areas. Low clouds may have a different effect from high clouds; however, low versus high clouds are not differentiated in the cloud mask.

3.2. IST Trends in Drainage Basins

[14] IST trends in the six major drainage basins [*Zwally et al.*, 2005] of the ice sheet (Table 3) were also investigated (see maps in Figure 3 for location of the basins.) IST trends (for the entire year) calculated using monthly data are all positive, though generally not statistically significant, and strongest in the northwestern part of the ice sheet, Basin 1, where the trend is 0.95 ± 0.44°C/decade and is statistically significant at the 95% confidence level. Other research

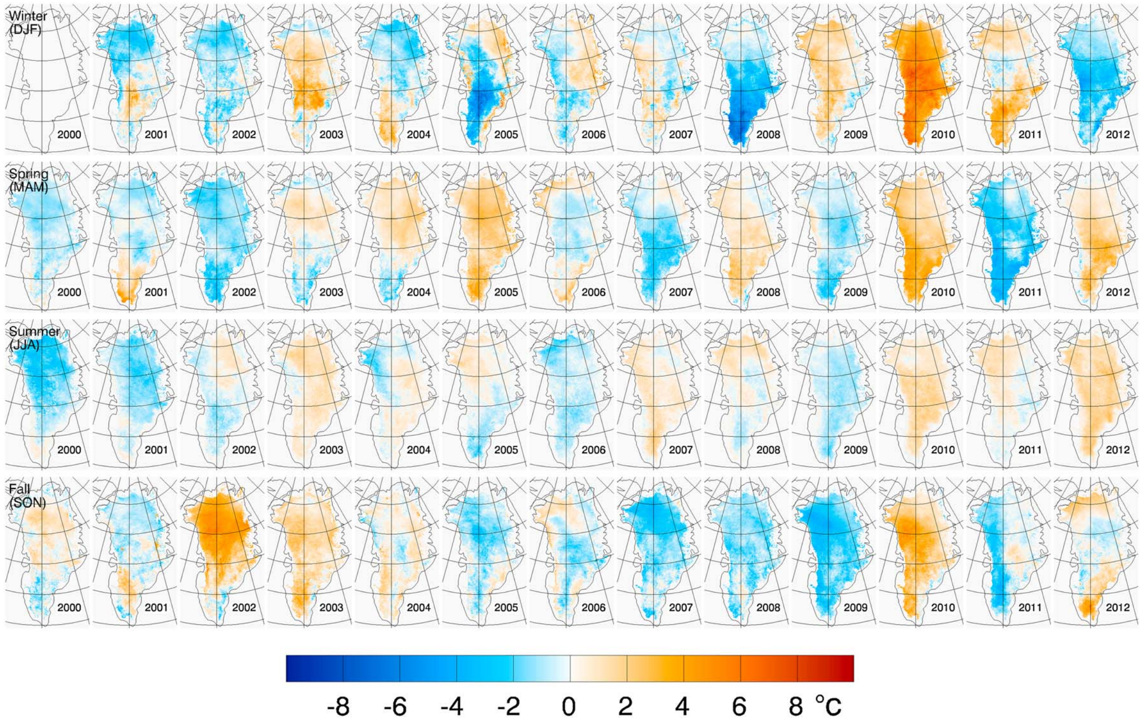

Figure 2. Seasonal IST anomalies calculated from monthly IST anomaly data (March 2000 to November 2012). For winter (DJF), the December data for each year were derived from the previous year.

Table 1. Mean Annual ISTs of the Greenland Ice Sheet with Standard Deviation (°C)

Year	Mean IST
2001	-24.65 ± 6.28
2002	-24.05 ± 5.27
2003	-23.32 ± 5.81
2004	-23.72 ± 5.71
2005	-22.94 ± 5.69
2006	-24.62 ± 5.97
2007	-24.78 ± 5.98
2008	-24.37 ± 5.83
2009	-24.97 ± 5.72
2010	-22.09 ± 5.70
2011	-25.15 ± 5.74
2012	-23.62 ± 6.24

Table 2. Mean Seasonal ISTs of the Greenland Ice Sheet with Standard Deviation (°C)

Year	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
2000	N/A	-26.5 ± 6.68	-8.93 ± 4.78	-28.19 ± 7.44
2001	-39.38 ± 7.98	-25.85 ± 6.77	-8.36 ± 4.54	-27.78 ± 7.77
2002	-40.12 ± 8.08	-25.68 ± 6.74	-8.02 ± 4.26	-25.53 ± 7.20
2003	-38.07 ± 7.55	-25.24 ± 6.45	-6.75 ± 4.10	-27.31 ± 7.66
2004	-39.49 ± 8.00	-24.70 ± 6.24	-7.88 ± 4.21	-27.36 ± 7.79
2005	-39.94 ± 8.01	-23.20 ± 6.62	-7.91 ± 4.17	-29.20 ± 7.61
2006	-39.06 ± 7.95	-25.52 ± 7.00	-8.62 ± 4.40	-28.38 ± 7.83
2007	-38.64 ± 8.01	-26.38 ± 6.51	-7.24 ± 4.37	-30.11 ± 8.04
2008	-41.12 ± 7.24	-24.78 ± 6.91	-7.30 ± 4.21	-29.72 ± 7.79
2009	-37.51 ± 7.73	-26.23 ± 6.46	-8.36 ± 4.39	-30.95 ± 7.75
2010	-34.48 ± 8.40	-23.40 ± 6.88	-6.73 ± 4.24	-26.86 ± 7.75
2011	-37.53 ± 8.75	-26.29 ± 6.16	-7.44 ± 4.12	-29.78 ± 7.41
2012	-41.16 ± 8.00	-23.94 ± 6.32	-6.38 ± 3.98	-28.47 ± 7.83
Mean	-38.85 ± 7.98	-25.21 ± 6.60	-7.67 ± 4.28	-28.46 ± 7.68

Table 3. IST Trends in the Six Major Drainage Basins of the Greenland Ice Sheet (March 2000 to December 2012)[a]

Basin Number	Trend (°C/Decade)
1	0.95 ± 0.44
2	0.49 ± 0.45
3	0.32 ± 0.46
4	0.55 ± 0.45
5	0.47 ± 0.55
6	0.54 ± 0.53

[a]The trend in Basin 1 is statistically significant at the 95% significance level; trends in the other basins are not statistically significant.

[*van As*, 2011; *Hanna et al.*, 2012] shows that the northwestern part of the ice sheet is undergoing acceleration of outlet glaciers [*Moon et al.*, 2012] and accelerated mass loss [*Kjaer et al.*, 2012]. *van As* [2011] reported that air temperatures along the northwestern coast are rising rapidly at a rate of ~2.0°C/decade with the greatest temperature rise in winter, consistent with our observations that show an IST increase of ~2.51 ± 1.02°C/decade in Basin 1 in winter.

3.3. Melt Extent

[15] We examine surface melt to understand summer conditions because the temperature of the ice sheet surface does not rise above 0°C since the ice/snow surface cannot exist as ice/snow above the freezing point of water. Maps of annual maximum surface melt extent derived from the MODIS IST data record are shown in Figure 3a. (Areas classified as "no melt" may have been cloud covered during one or more days when melt occurred and thus

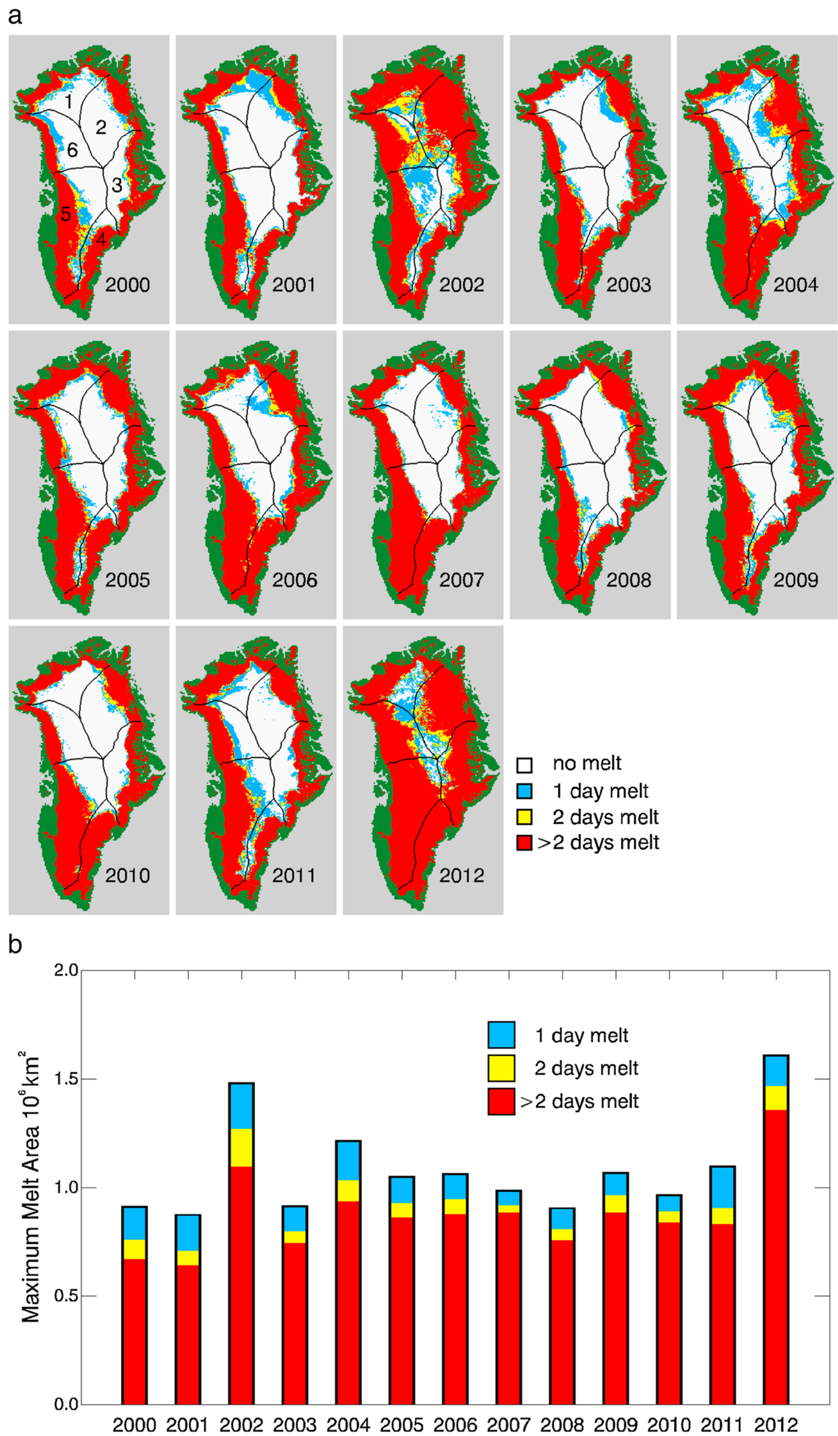

Figure 3. (a) Maps of annual maximum melt extent constructed from MODIS IST data of the Greenland ice sheet for the study period (March 2000 to August 2012). The non–ice-covered land surrounding the ice sheet is shown in green. The boundaries of the six major drainage basins of the Greenland ice sheet [after *Zwally et al*., 2005] are superimposed on the maps. (b) Extent of maximum melt in each melt season as derived from the MODIS IST data record; colors relate to those shown in Figure 3a. Note the large amount of melt in 2012 that lasted for >2 days. The melt extent in 2002 is also notably large.

would not be detected as melt by the IST algorithm.) In the following paragraphs, we discuss and compare the 2002 and 2012 melt seasons which show the greatest melt extent of the MODIS record. We define an annual maximum melt extent that covers 80% or more of the ice sheet surface as "major."

3.3.1. Major Melt Events in 2002 and 2012

[16] In early July 2012, a high-pressure system was stranded over Greenland bringing clear skies, southerly winds, and a warming across the ice sheet, contributing to the surface melting [*Nghiem et al*., 2012; *Hanna et al*., in press]. In a related paper, *Nghiem et al*. [2012] describe

the melt event in detail which was captured by melt maps from three different satellite instruments including from the MODIS data described here.

[17] The 2012 melt season has the most extensive surface melt in the MODIS IST record (Figures 3a and 3b). A time series of surface melt maps from MODIS, from 9–16 July, is shown in Figure 4. The melt was more extensive than in any other year even compared to the passive-microwave satellite record extending back to 1979 [*Mote*, 2007, as discussed in *Nghiem et al.*, 2012].

[18] Hourly mean air temperatures from the NOAA instrument at Summit Station reached 0°C or higher on 11 July 2012 for several hours and almost reached 0°C on 12 July. The ice sheet surface at Summit would likely have been melting during the warmest parts of both days, especially where the solar radiation was intense. There are many known problems with station measurements of near-surface temperature [e.g., see *Genthon et al.*, 2011; *YongFeng et al.*, 2011]; however, the NOAA instrument used at Summit is actively ventilated and serviced daily, and thus more accurate than nearby AWS that are passively ventilated and are not serviced as frequently.

[19] The relatively low albedo in July 2012 [*Box et al.*, 2012] contributed to the unusual warmth and to the extensive melt. We tracked the albedo using the MODIS MOD10 daily snow albedo product [*Klein and Stroeve*, 2002]. As the air temperature rose to 0°C, melting occurred and showed an albedo drop of 12.5% from 9 to 11 July 2012 at 73.31°N, 46.86°W, 2640 m mean sea level elevation (for location, see plus (+) sign in Figure 4). This location was selected because it provided cloud-free observations before, during, and after the major melt event. After 12 July, the ice sheet surface temperature dropped and the albedo gradually increased over the next few days.

[20] The maximum melt extent in 2002 [*Steffen et al.*, 2004; *Nghiem et al.*, 2005] and 2012 was similar as seen in Table 4, showing that the maximum melt extent in JJA of 2002 covered 87.2% of the ice sheet, while it covered 94.8% in JJA of 2012. (Note that this differs from the >98% for 2012 reported by *Nghiem et al.* [2012] because they used microwave instruments in addition to MODIS to "see" through the clouds and were thus able to capture more melt.) Most of the ephemeral melt (defined herein as melt occurring only on 1–2 days during the summer) in 2002 occurred between 29 June and 2 July, and was associated with a parcel of warm air brought in from the southeast by a low-pressure system in the North Atlantic that lingered for a few days, resulting in sunny skies and higher air temperatures over Greenland [*NCEP*, 2002]. Ephemeral melt accounted for 22.5% of the total surface melt in 2002, and only 14.5% in 2012 (Table 4).

[21] Ephemeral melt, as depicted by the blue and yellow colors in Figures 3a and 3b, was more prevalent in 2002 than in 2012, while the melt persistence was much greater in 2012,

Table 4. Percentage of Total Melt and Ephemeral Melt (Melt That Occurred on Only 1 or 2 Days During the Melt Season), as Derived from MODIS IST Data Record

Year	Total Melt (%)	Ephemeral Melt (%)
2000	53.5	14.0
2001	51.3	13.4
2002	87.2	22.5
2003	53.7	9.8
2004	71.4	16.1
2005	61.6	10.7
2006	62.4	10.7
2007	57.9	5.6
2008	53.1	8.4
2009	62.8	10.5
2010	56.7	7.1
2011	64.4	15.2
2012	94.8	14.5

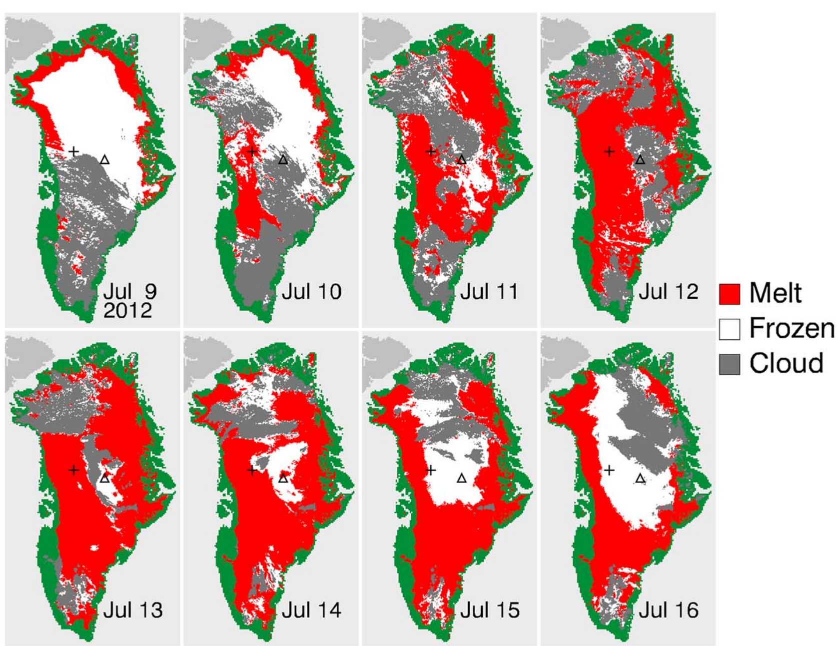

Figure 4. MODIS-derived melt maps from 9 to 16 July 2012. The non–ice-covered land surrounding the ice sheet is shown in green. The plus (+) sign on the left marks the spot of the albedo measurement, discussed in the text, and the triangle on the right marks the location of Summit Station.

though the total melt was greater by only 7.6 percentage points. The 2012 summer was the warmest in the MODIS record (Table 2) at about $-6.38 \pm 3.98°C$ (compared to $-8.02 \pm 4.26°C$ for JJA of 2002). It is also noteworthy that the 2012 melt occurred at very high elevations on the ice sheet including at Summit Station where melt had not occurred since 1889 (123 years ago) according to ice core records [*Nghiem et al.*, 2012]. So, the 2012 summer melt was clearly more persistent and severe than the 2002 summer melt.

4. Discussion and Conclusions

[22] Using the MODIS IST data record, we observed large variability in the surface temperature of Greenland and two major melt events during the 2000–2012 study period. The annual average IST increased over the study period at a rate of ~$0.55 \pm 0.44°C$/decade, with the greatest increases observed during summer ($1.35 \pm 0.47°C$/decade), followed by winter ($1.30 \pm 1.53°C$/decade) and spring ($0.60 \pm 0.98°C$/decade), and a cooling was observed in autumn ($-1.49 \pm 1.20°C$/decade). All six major drainage basins show increasing IST during the MODIS era, with the greatest rate ($0.95 \pm 0.44°C$/decade) in northwestern Greenland (Basin 1) where other research shows acceleration of outlet glaciers and mass loss, and increasing coastal air temperatures. The IST trend in Basin 1 is the only trend reported in this paper that is statistically significant (at the 95% level).

[23] While winter warming is observed, the ice sheet temperature is still not close to the melting point, with an average winter ice sheet temperature in the MODIS data record of $-38.85 \pm 7.98°C$ (Table 2). The observed spring and summer ice sheet warming is more important because of the possibility of surface melt.

[24] Maps of maximum annual melt extent document a major melt event that occurred in July 2012, causing >98% of the surface of the ice sheet to thaw over a 2 day period (11–12 July) (*Nghiem et al.*, 2012). (The maximum melt measured by MODIS in 2012 was ~95%.) Another major melt event, in June/July 2002, also caused an extensive area of melting of the ice sheet surface (~87% according to MODIS). A comparison of those two melt seasons shows that the total melt was more extensive and more persistent in 2012 versus 2002 and that the mean summer IST was higher in 2012 ($-6.38 \pm 3.98°C$) as compared to 2002 ($-8.02 \pm 4.26°C$). However, our data show that major surface melt events are not rare on the Greenland ice sheet, at least not during the MODIS satellite record. The occurrence of these two events during the satellite era and the warming trend observed for the region may portend a higher frequency of such events in the near future.

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References

Ackerman, S. A., R. E. Holz, R. Frey, E. W. Eloranta, B. Maddux, and M. McGill (2008), Cloud detection with MODIS. Part II: Validation, *J. Atmos. Oceanic Technol.*, *25*, 1073–1086.

Bell, R. E. (2008), The role of subglacial water in ice-sheet mass balance, *Nat. Geosci.*, *1*, 297–304.

Box, J. E. (2002), Survey of Greenland instrumental temperature records: 1873–2001, *Int. J. Climatol.*, *22*, 1829–1847.

Box, J. E., X. Fettweis, J. C. Stroeve, M. Tedesco, D. K. Hall, and K. Steffen (2012), Greenland ice sheet albedo feedback: Thermodynamics and atmospheric drivers, *Cryosphere*, *6*, 593–634, doi:10.5194/tcd-6-593-2012.

Chen, J. L., C. R. Wilson, and B. D. Tapley (2006), Satellite gravity measurements confirm accelerated melting of Greenland ice sheet, *Science*, *313*, 1958–1960.

Comiso, J. C., and C. L. Parkinson (2004), Satellite-observed changes in the Arctic, *Phys. Today*, *2004*, 38–44.

Genthon, C., D. Six, V. Favier, M. Lazzara, and L. Keller (2011), Atmospheric temperature measurement biases on the Antarctic Plateau, *J. Atmos. Oceanic Technol.*, *2*, 1598–1605, doi:10.1175/JTECH-D-11-00095.1.

Gregory, J. M., P. Huybrechts, and S. C. B. Raper (2004), Threatened loss of the Greenland ice-sheet, *Nature*, *428*, 616.

Hall, D. K., R. S. Williams Jr., S. B. Luthcke, and N. E. DiGirolamo (2008), Greenland ice sheet surface temperature, melt and mass loss: 2000–2006, *J. Glaciol.*, *54*(184), 81–93.

Hall, D. K., J. C. Comiso, N. E. DiGirolamo, C. A. Shuman, J. R. Key, and L. S. Koenig (2012), A satellite-derived climate-quality data record of the clear-sky surface temperature of the Greenland ice sheet, *J. Clim.*, *25*(14), 4785–4798.

Hanna, E., P. Huybrechts, K. Steffen, J. Cappelen, R. Huff, C. Shuman, T. Irvine-Fynn, S. Wise, and M. Griffiths (2008), Increased runoff from melt from the Greenland ice sheet: A response to global warming, *J. Clim.*, *21*(12), 331–341, doi:10.1175/2007JCLI1964.1.

Hanna, E., et al. (2011), Greenland Ice Sheet surface mass balance 1870 to 2010 based on Twentieth Century Reanalysis, and links with global climate forcing, *J. Geophys. Res.*, *116*, D24121, doi:10.1029/2011JD016387.

Hanna, E., S. H. Mernild, J. Cappelen, and K. Steffen (2012), Recent warming in Greenland in a long-term instrumental (1881–2012) climatic context: I. Evaluation of surface air temperature records, *Environ. Res. Lett.*, *7*, 045404, doi:10.1088/1748-9326/7/4/045404.

Hanna, E., J. M. Jones, J. Cappelen, S. H. Mernild, L. Wood, K. Steffen, and P. Huybrechts (2013), The influence of North Atlantic atmospheric and oceanic forcing effects on 1900–2010 Greenland summer climate and ice melt/runoff, *Int. J. Climatol.*, *459*(33), 862–880, doi:10.1002/joc.3475. 460.

Hanna, E., X. Fettweis, S. H. Mernild, J. Cappelen, M. Ribergaard, C. Shuman, K. Steffen, L. Wood, and T. Mote (in press), Atmospheric and oceanic climate forcing of the exceptional Greenland Ice Sheet surface melt in summer 2012, *Int. J. Climatol*.

Key, J., J. Collins, C. Fowler, and R. S. Stone (1997), High-latitude surface temperature estimates from thermal satellite data, *Remote Sens. Environ.*, *61*, 302–309.

Kjaer, K. H., et al. (2012), Aerial photographs reveal late-20th-Century dynamic ice loss in northwestern Greenland, *Science*, *337*, 569–573.

Klein, A. G., and J. Stroeve (2002), Development and validation of a snow albedo algorithm for the MODIS instrument, *Ann. Glaciol.*, *34*, 45–52.

Koenig, L. S., and D. K. Hall (2010), Comparison of satellite, thermochron and station temperatures at Summit, Greenland, during the winter of 2008/09, *J. Glaciol.*, *56*(198), 735–741.

Moon, T., I. Joughin, B. Smith, and I. Howat (2012), 21st-Century evolution of Greenland outlet glacier velocities, *Science*, *336*, 576, doi:10.1126/science.1219985.

Mote, T. L. (2007), Greenland surface melt trends 1973–2007: Evidence of a large increase in 2007, *Geophys. Res. Lett.*, *34*, L22507, doi:10.1029/2007GL031976.

NCEP (2002), NOAA/National Centers for Environmental Predication (NCEP)/NWS surface analysis maps, SFC/1000 = 500 MB THICKNESS, 27 June–2 July 2002.

Nghiem, S. V., K. Steffen, G. Neumann, and R. Huff (2005), Mapping of ice layer extent and snow accumulation in the percolation zone of the Greenland ice sheet, *J. Geophys. Res.*, *110*, F02017, doi:10.1029/2004JF000234.

Nghiem, S. V., D. K. Hall, T. L. Mote, M. Tedesco, M. Albert, K. Keegan, C. A. Shuman, N. E. DiGirolamo, and G. Neumann (2012), The extreme melt across the Greenland ice sheet in 2012, *Geophys. Res. Lett.*, *39*, L20502, doi:10.1029/2012GL053611.

Rignot, E., I. Velicogna, M. R. van den Broeke, A. Monaghan, and J. Lenaerts (2011), Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, *Geophys. Res. Lett.*, *38*, L05503, doi:10.1029/2011gl046583.

Shuman, C. A., K. Steffen, J. E. Box, and C. R. Stearns (2001), A dozen years of temperature observations at the Summit: Central Greenland automatic weather stations 1987–99, *J. Appl. Meteorol.*, *40*, 741–752.

Steffen, K., J. E. Box, and W. Abdalati (1996), Greenland Climate Network: GC-Net, in CRREL 96-27 Special Report on Glaciers, Ice

Sheets and Volcanoes, Tribute to M. Meier, edited by S. C. Colbeck, pp. 98–103.

Steffen, K., S. V. Nghiem, R. Huff, and G. Neumann (2004), The melt anomaly of 2002 on the Greenland Ice Sheet from active and passive microwave satellite observations, *Geophys. Res. Lett.*, *31*, L20402, doi:10:1029/2004GL020444.

Tedesco, M., X. Fettweis, M. R. van den Broeke, R. S. W. van de Wal, C. J. P. Smeets, W. J. van de Berg, M. C. Serreze, and J. E. Box (2011), The role of albedo and accumulation in the 2010 melting record in Greenland, *Environ. Res. Lett.*, *6*, doi:10.1088/1748-9326/6/1/014005.

van As, D. (2011), Warming, glacier melt and surface energy budget from weather station observations in the Melville Bay region of northwest Greenland, *J. Glaciol.*, *17*(202), 208–220.

van den Broeke, M., J. Bamber, J. Ettema, E. Rignot, E. Schrama, W. J. van den Berg, E. van Meijgaard, I. Velicogna, and B. Wouters (2009), Partitioning recent Greenland mass loss, *Science*, *326*(5955), 984–986. doi:10.1126/science.1178176.

Velicogna, I. (2009), Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE, *Geophys. Res. Lett.*, *36*, L19503, doi:10.1029/2009GL040222.

Wan, Z., Y. Zhang, Q. Zhang, and Z.-L. Li (2002), Validation of the land surface temperature products retrieved from Terra Moderate Resolution Imaging Spectroradiometer data, *Remote Sens. Environ.*, *83*, 163–180.

Wang, X., and J. Key (2005), Arctic surface, cloud, and radiation properties based on the AVHRR Polar Pathfinder data set. Part II: Recent trends, *J. Climatol.*, *18*(14), 2575–2593.

Warren, S. G., and R. E. Brandt (2008), Optical constants of ice from the ultraviolet to the microwave: A revised compilation, *J. Geophys. Res.*, *113*, D14220, doi:10.1029/2007JD009744.

YongFeng, M. A., B. LinGen, and X. CunDe (2011), Impacts of snow accumulation on air temperature measurements by automatic weather stations on the Antarctic ice sheet, *Adv. Polar Sci.*, *22*(1), 17–24, doi:10.3724/SPJ.1085.2011.00017.

Zwally, H. J., et al. (2005), Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea level rise: 1992–2002, *J. Glaciol.*, *51*(175), 509–527.