Satellite-derived, melt-season surface temperature of the Greenland Ice Sheet (2000–2005) and its relationship to mass balance

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Received 28 March 2006; revised 27 April 2006; accepted 2 May 2006; published 8 June 2006.

[1] Mean, clear-sky surface temperature of the Greenland Ice Sheet was measured for each melt season from 2000 to 2005 using Moderate-Resolution Imaging Spectroradiometer (MODIS)–derived land-surface temperature (LST) data-product maps. During the period of most-active melt, the mean, clear-sky surface temperature of the ice sheet was highest in 2002 (−8.29 ± 5.29°C) and 2005 (−8.29 ± 5.43°C), compared to a 6-year mean of −9.04 ± 5.59°C, in agreement with recent work by other investigators showing unusually extensive melt in 2002 and 2005. Surface-temperature variability shows a correspondence with the dry-snow facies of the ice sheet; a reduction in area of the dry-snow facies would indicate a more-negative mass balance. Surface-temperature variability generally increased during the study period and is most pronounced in the 2005 melt season; this is consistent with surface instability caused by air-temperature fluctuations. **Citation:** Hall, D. K., R. S. Williams Jr., K. A. Casey, N. E. DiGirolamo, and Z. Wan (2006), Satellite-derived, melt-season surface temperature of the Greenland Ice Sheet (2000–2005) and its relationship to mass balance, *Geophys. Res. Lett.*, *33*, L11501, doi:10.1029/2006GL026444.

1. Introduction

[2] Extensive, perhaps historically unprecedented melt has occurred on the Greenland Ice Sheet in the last 25 years as determined from ground, aircraft and satellite data [*Abdalati and Steffen*, 1995, 2001; *Krabill et al.*, 2000; *Nghiem et al.*, 2001; *Comiso et al.*, 2003; *Steffen et al.*, 2004; *Rignot and Kanagaratnam*, 2006] (see also K. Steffen and R. Huff, http://cires.colorado.edu/science/groups/steffen/greenland/melt2005/). Analysis of snow-melt extent using passive-microwave satellite data showed that the maximum melt area increased 16% from 1979–2002 [*Steffen et al.*, 2004]. Both surface and subsurface melt are detected with passive-microwave data and while both are important in meltwater production, most of the subsurface melt refreezes close to where it was formed [e.g., see *Joshi et al.*, 2001]. However surface melt, which is directly related to surface temperature, may contribute more directly to accelerated disintegration of the ice sheet because of its rapid movement to the base of the ice sheet where it can allow accelerated ice flow, leading to sea-level rise [*Zwally et al.*, 2002].

[3] The importance of monitoring surface temperature is highlighted by recent modeling studies showing that summer temperature increases of only ∼2–5°C are required to double melt rates and thus increase runoff from the Greenland Ice Sheet [*Hanna et al.*, 2005]. To assess interannual surface-temperature variability across Greenland, we analyze clear-sky surface temperature of the ice sheet derived from Moderate-Resolution Imaging Spectroradiometer (MODIS) land-surface temperature (LST) standard-data product maps for six melt seasons (2000–2005), and relate the results to ice-sheet mass balance.

2. Background

[4] Carl Benson's pioneering work on the Greenland Ice Sheet led to his classification of the ice sheet into an ablation area and an accumulation area, separated by the equilibrium line where the net mass balance equals zero [*Benson*, 1962]. Various facies exist within the accumulation area, the approximate boundaries of which may sometimes be identified by their unique spectral signatures [*Hall et al.*, 1989; *Williams et al.*, 1991; *Fahnestock et al.*, 1993; *Abdalati and Steffen*, 1995; *Long and Drinkwater*, 1999]. The facies boundaries change over time with changes in the ice-sheet mass balance. For example, the dry-snow area may shrink if the mass balance becomes more negative over a period of years.

[5] Surface-temperature conditions on the Greenland Ice Sheet have been studied extensively [e.g., *Key and Haefliger*, 1992; *Haefliger et al.*, 1993; *Shuman et al.*, 2001; *Steffen and Box*, 2001; *Comiso et al.*, 2003]. Using Advanced Very-High Resolution Radiometer data, *Stroeve and Steffen* [1998] derived surface temperatures over Greenland from 1989 to 1993. Monthly mean summer ice-sheet temperatures showed little variation between years, though they cited 1992 as having lower monthly-mean temperatures than the other years due to the worldwide cooling related to the eruption of Mt. Pinatubo. *Comiso et al.* [2003] measured increased AVHRR-derived surface temperatures in the Arctic poleward of 60°N, beginning in 1981.

3. Data and Methodology

[6] MODIS LST data products consist of daily and 8-day composite 1-km and 0.05°-resolution map products, with quality-control information in each 1-km pixel or 0.05° cell. We selected the 8-day composite 0.05°-resolution product (MOD11C2) to use for this work because the maps provide an 8-day average LST for each cell (cloud-cover permitting). MOD11C2 is derived from the 1-km and 0.05°-resolution daily products [*Wan et al.*, 2002].

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0094-8276/06/2006GL026444$05.00

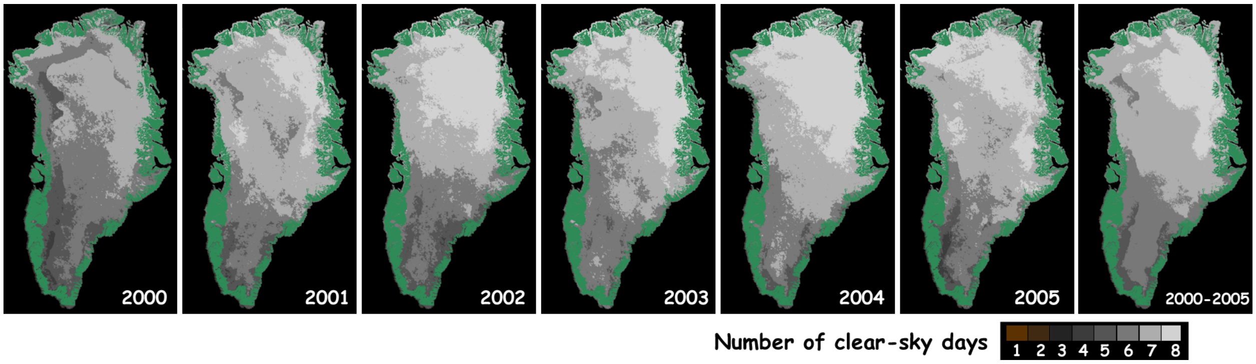

Figure 1. Maps showing average number of clear-sky days within each 8-day period during the melt season of each year, derived from the MOD11C2 land-surface temperature (LST) map product on a cell-by-cell basis. The melt season is defined to extend from April 30 or May 1 to September 28 or 29 (days 121–272).

[7] Temperatures derived from the daily, 1-km LST product have been compared with in-situ measurements using multiple thermal-infrared radiometers in field campaigns including one in a snow field, where the error was generally <1°C [*Wan et al.*, 2002], but could get up to 2°C. Furthermore, the LST is relatively constant, between −2° and 0°C, in the exposed ice region within the ablation area of the Greenland Ice Sheet, and the LST does not exceed 0°C over ice with surface melt. 0°C represents the upper boundary of LST for the glacier ice and is consistent with the expected temperature of melting ice. The automatic weather-station (AWS) data on the Greenland Ice Sheet [*Steffen and Box*, 2001] are useful in checking the trend of seasonal variations in MODIS LST data with surface air temperature or upper-level snow temperature profile data, however it is difficult to use these data to compare directly with the values in the LST product because there is no accurate radiometric measurement of snow-surface temperature in the AWS data.

[8] The major uncertainty in the LST product is the effect of cloud contamination because it is often difficult to discriminate cloud-contaminated from clear-sky LSTs over snow and ice in cold regions, especially in the case of thin clouds or fog that may not be detected by the MODIS cloud mask. The MODIS LST algorithm uses a cloud mask derived from MODIS data [*Ackerman et al.*, 1998] to determine whether or not to calculate LST. The cloud mask tends to be conservative, generally mapping more clouds than are actually present over snow and ice.

[9] MODIS maps provide LST only when the sky is clear, causing a bias because surface temperatures are generally warmer under clouds, especially low clouds (K. Steffen, personal communication, 2005). (The air temperature difference between an overcast and clear day can be several °C.) Thus the "mean" clear-sky LSTs represent a likely underestimation of the actual mean-surface temperatures.

[10] In some cases there is only one clear day available to create the 8-day LST map for any given cell, thus the LST of each cell may not represent a true mean for the 8-day period. Figure 1 shows the average number of clear-sky days for each 8-day period during the entire melt season [defined as extending from April 30 or May 1 (depending on whether or not it was a leap year) (day 121) to September 28 or 29 (day 272) of each year]. Data used in Figure 1 were derived from the MODIS LST MOD11C2 product, and provide an indication of the relative cloudiness among the years.

[11] Nineteen 8-day-mean LST maps of Greenland were averaged on a cell-by-cell basis for the entire melt season (between days 121 and 272), to develop one map of mean-surface temperature along with a standard deviation (SD) map for each melt season. (Only 17 and 18 maps were used for 2001 and 2004, respectively, due to missing and/or suspected-bad data.) In addition, we also studied the period of most-active melt in each year, May through mid-August [days 121 to 225 (August 12 or 13)]. Because freezeup can begin around mid-August, we consider days 121–225 to be the period of most-active melt for the purpose of this work. Surface temperatures during the most-active part of the melt season are more relevant to surface melt on the ice sheet than those derived from the entire melt season, during which time subsurface melt may play a significant role.

5. Discussion and Concluding Remarks

[18] Higher ice-sheet surface temperatures can lead to enhanced ice-sheet disintegration when surface water percolates through great thicknesses of the ice sheet leading to an acceleration of ice-sheet flow [*Zwally et al.*, 2002]. We observed a general expansion of increasing surface-temperature variability from 2000 to 2005 on the Greenland Ice Sheet, being greatest in 2005, a year cited as being anomalously warm over Greenland by other investigators, and according to our LST data. The SDs are consistent with surface instability caused by air-temperature fluctuations.

[19] We also found that the two warmest years (2002 and 2005) are the same years that experienced the most-extensive melt of the six-year period. *Steffen et al.* [2004] showed that there was a very large melt extent in 2002, extending over 690,000 km^2 of the ice sheet compared to a 1979–1999 average of 455,000 km^2 [*Abdalati and Steffen*, 2001], and 2005 has been cited by Steffen and Huff (http://cires.colorado.edu/science/groups/steffen/greenland/melt2005/) as experiencing melt equal or greater in area than occurred in 2002. This is consistent with the average melt-season LSTs presented herein, and findings by *Comiso* [2006] showing that those same two years were unusually warm using AVHRR data of the Arctic since 1981.

[20] MODIS-derived LST provides a quantitative assessment of the mean surface temperature and surface-temperature change on the Greenland Ice Sheet. Because the location of the glacier-facies boundaries reflects the ice sheet mass balance, a sustained increase in surface temperature would cause the glacier-facies boundaries to migrate to higher elevations.