A Satellite-Derived Climate-Quality Data Record of the Clear-Sky Surface Temperature of the Greenland Ice Sheet

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ABSTRACT

The authors have developed a climate-quality data record of the clear-sky surface temperature of the Greenland Ice Sheet using the Moderate-Resolution Imaging Spectroradiometer (MODIS) ice-surface temperature (IST) algorithm. Daily and monthly quality-controlled MODIS ISTs of the Greenland Ice Sheet beginning on 1 March 2000 and continuing through 31 December 2010 are presented at 6.25-km spatial resolution on a polar stereographic grid along with metadata to permit detailed accuracy assessment. The ultimate goal is to develop a climate data record (CDR) that starts in 1981 with the Advanced Very High Resolution Radiometer (AVHRR) Polar Pathfinder (APP) dataset and continues with MODIS data from 2000 to the present, and into the Visible Infrared Imager Radiometer Suite (VIIRS) era (the first VIIRS instrument was launched in October 2011). Differences in the APP and MODIS cloud masks have thus far precluded merging the APP and MODIS IST records, though this will be revisited after the APP dataset has been reprocessed with an improved cloud mask. IST of Greenland may be used to study temperature and melt trends and may also be used in data assimilation modeling and to calculate ice sheet mass balance. The MODIS IST climate-quality dataset provides a highly consistent and well-characterized record suitable for merging with earlier and future IST data records for climate studies. The complete MODIS IST daily and monthly data record is available online.

1. Introduction

Enhanced melting of the Greenland Ice Sheet has been documented in recent literature along with surface temperature increases measured using infrared (IR) satellite data (Comiso et al. 2003; Wang and Key 2003, 2005a,b; Comiso 2006) over the last decade or more. Enhanced melting has also been reported using passive-microwave data (Mote 2007; Tedesco 2007). Mass loss of the Greenland Ice Sheet during the last decade has also been documented (Luthcke et al. 2006; Zwally et al. 2011; Rignot et al. 2011). The overall ice sheet mass balance is controlled by the surface temperature, accumulation, ice sheet thickness, geothermal flux, and the basal stress regime; varying any of these parameters will change the net melt rate (Bell 2008). A large percentage

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of the mass loss of the Greenland Ice Sheet comes from surface melt (Rignot and Kanagaratnam 2006), which is controlled in part by air temperature through sensible heat transfer but also through absorption of solar radiation, particularly at near-infrared (NIR) wavelengths. Thus detailed monitoring of the surface temperature of the ice sheet can provide important information on mass loss. Surface temperature measurements of the ice sheet can also be used to study temperature and melt trends, lapse rate as a function of slope and elevation, and may be used for validation of surface temperature in data-assimilation modeling.

Near-daily IR satellite data (1 km) have been available from Advanced Very High Resolution Radiometer (AVHRR) sensors since August 1981. Decadal-scale surface temperatures of the Arctic from the AVHRR, including the AVHRR Polar Pathfinder (APP) and Extended APP (APP-x) datasets, have been developed and used to study 30-yr trends in surface temperature (Maslanik et al. 1998; Fowler et al. 2002; Comiso et al. 2003; Wang and Key 2003, 2005a). To ensure consistent climate modeling, there is a need to extend these IST records using AVHRR, and also using independent algorithms from the Moderate-Resolution Imaging Spectroradiometer (MODIS) (http://modis.gsfc.nasa.gov/), which has more channels and can therefore provide enhanced cloud masking relative to what is possible with the AVHRR.

A climate data record (CDR) is a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change (National Research Council 2004). Characteristics of a CDR include knowledge and documentation of uncertainties, demonstration of rigorous validation, and inclusion of metadata. The CDR may incorporate several data sources that are merged to create a single record and, when this occurs, the existence of an overlap period between datasets is important, if not mandatory, and similar data and algorithms must be used to create the long-term record.

In this paper, we present a data record of the ice-surface temperature (IST) (skin or radiating temperature) developed using the MODIS instrument and describe the features that make the record worthy of becoming a CDR when a sufficient number of years are available to study climate trends—that is, two or more decades. We also compare APP and MODIS IST data records, and results from validation efforts are described. Plans to lengthen the record using the APP dataset, which started in 1981, and also to extend the dataset forward into the Visible Infrared Imager Radiometer Suite (VIIRS) era (http://www.nasa.gov/mission_pages/NPP/main/index.html), are presented.

2. Background

Surface and air temperatures on the Greenland Ice Sheet have been studied on the ground using automatic weather station (AWS) data (Steffen and Box 2001; Box 2002; van den Broeke et al. 2008, 2011) and using satellite data (see for example, Key and Haefliger 1992; Haefliger et al. 1993; Stroeve and Steffen 1998; Shuman et al. 2001; Comiso et al. 2003; Wang and Key 2005a,b; Comiso 2006; Hall et al. 2008a,b; Lampkin and Peng 2008; Hall et al. 2009). Many other ground-based and satellite temperature measurements have also been made but they often do not span a very long time period. Modeling results are also available (e.g., see van den Broeke et al. 2011).

Several products provide a time series of hemispheric-scale surface temperature and employ IR channels on various satellites. The primary instruments for which such IR data are available are the AVHRR and MODIS. The clear-sky limitation of satellite-derived IR temperatures precludes the measurement of the surface under all-weather conditions. The surface temperature of the ice sheet beneath clouds can be very different (usually higher) from that under clear skies (see, for example, Miller 1956; Stroeve and Steffen 1998; Hudson and Brandt 2005; Koenig and Hall 2010) especially in the winter when there is an inversion in the lower atmosphere. Thus a time series of satellite-derived (clear sky) surface temperatures can be significantly different from the all-sky surface temperature (Liu et al. 2009).

Cloud masking and cloud cover trends are important factors in interpreting surface-temperature measurements from space (Wang and Key 2005b). The AVHRR has five bands: visible bands 1 (0.58–0.68 μm) and 2 (0.725–1.00 μm), solar IR band 3B (3.53 to 3.93 μm), and thermal–IR bands 4 (10.30–11.30 μm) and 5 (11.50–12.50 μm), while MODIS has 36 bands, spanning the visible through IR (http://modis.gsfc.nasa.gov/about/specifications.php). MODIS provides additional spectral information that is particularly useful for polar cloud detection, superseding the more-limited capability of AVHRR. MODIS NIR bands at 1.6 and 2.2 μm are useful for the detection of clouds over snow and ice, while the 1.6-μm NIR channel (3A) on the AVHRR is only available for part of the time series. AVHRR channels 1, 2, 3B, 4, and 5 are used for daytime cloud detection; channels 3B, 4, and 5 are used at night. Additionally, AVHRR has no absorptive channels, whereas MODIS has water vapor bands that peak low in the troposphere (7.3 and 6.7 μm), as well as carbon dioxide bands.

The MODIS IST and AVHRR APP datasets were selected to create a CDR to span a time period from 1981 to the present. These datasets are described below.

a. MODIS surface temperature time series

IST can be mapped at 1-km resolution using MODIS data from nearly identical instruments that are currently in orbit on both *Terra* and *Aqua* satellites, launched in 1999 and 2002, respectively. MODIS IST of Greenland was developed and is produced as a special product at Goddard Space Flight Center in Greenbelt, Maryland, using the algorithm developed for the MODIS sea ice product, MOD29 or MYD29. MOD refers to *Terra* MODIS products and MYD refers to *Aqua* MODIS products. Information on the MODIS IST product may be found in Hall et al. (2004) and Riggs et al. 2006 (http://modis-snow-ice.gsfc.nasa.gov/?c=userguides). The MODIS IST algorithm derives its heritage from the algorithm of Key and Haefliger (1992) and Key et al. (1997), which was also used to develop the APP and APP-x IST datasets (Maslanik et al. 2001; Fowler et al. 2002). As with the corresponding AVHRR product, the MODIS IST is a skin temperature. Skin temperature is the temperature of the surface at radiative equilibrium, at the interface between the snow/ice surface and the atmosphere. The estimated depth affecting the satellite-derived temperature is a few millimeters but this can vary as the near surface of the ice sheet changes during the year. For example, if snow cover is present, the grain size and liquid water content of the overlying snow will affect the dielectric properties of the snow cover and hence the penetration depth slightly.

The MOD29 IST Greenland products employ the standard MODIS 1-km resolution cloud mask (MOD35) that uses up to 14 spectral bands and multiple spectral and thermal tests to identify clouds (Ackerman et al. 1998, 2008; Liu et al. 2004). MOD35 uses several cloud-detection tests to indicate a level of confidence that a pixel is clear or cloudy. For MODIS Collection 5, changes were implemented resulting in improvement in cloud masking during the polar night over snow and ice targets; when processing polar night scenes, two spectral cloud tests were modified, two were added, and one clear-sky test was added (Frey et al. 2008). These tests reduced the misidentification of cloud as clear from 44.2% to 16.3% (at two Arctic stations) but did not change the misidentification of clear as cloud, which remained at 8% (Liu et al. 2004; Frey et al. 2008). Furthermore, Liu et al. (2010) showed that the MODIS cloud-detection method performs better over open (unfrozen) water than over sea ice, when compared to *CloudSat* and Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) cloud amounts. For the Greenland IST MOD29 product, the conservative cloud tests in MOD35, called "confident clear," are used but generally considered to be overly conservative over snow and ice targets (Stroeve et al. 2006).

b. AVHRR surface temperature time series

A time series of satellite-derived surface temperatures for the Arctic has been developed by Comiso et al. (2003) and Comiso (2006). This technique has also been employed by Vincent et al. (2008) for the retrieval of surface temperatures in the polar regions. The atmospheric humidity is much lower in polar regions and use of the window channels (e.g., channel 4 and channel 5 of AVHRR) may not work well because of the lack of correlation of the difference of these channels with water vapor and humidity in these regions. Moreover, the calibration of the channels may not be consistent from one AVHRR instrument to another and the absolute value may not be reliable. Thus, in situ observations are used to adjust the satellite-derived observations. The technique used to develop this dataset uses in situ observations to take into account atmospheric effects and is thus fundamentally different from that reported used by Key and Haefliger (1992).

APP DATA RECORD

Because consistency in the IST algorithm is required, we selected the APP data record to explore for use in development of the CDR. The APP 5-km Equal-Area Scalable Earth-Grid (EASE-Grid) composites (available at http://www.nsidc.org/data/nsidc-0066.html) are part of a collection of products for both poles, consisting of twice-daily geolocated and calibrated radiances and derived parameters including the five AVHRR channel brightness temperatures or reflectances, clear-sky surface broadband albedo and skin (radiating) temperature, solar zenith angle, satellite elevation angle, sun–satellite relative azimuth angle, surface-type mask, cloud mask, and coordinated Universal Time (UTC) of acquisition (Meier et al. 1996; Maslanik et al. 1998, 2001; Fowler et al. 2002). APP data extend poleward from 48.4° north and 53.2° south latitudes and are available beginning in July 1981; the APP record is currently being updated through 2010 (http://nsidc.org/data/nsidc-0094.html). APP products are available at 0400 and 1400 local solar time. The IST algorithm used to develop the APP skin temperature was derived from Key and Haefliger (1992) and Key et al. (1997).

Cloud masking for the APP product is accomplished using the Cloud and Surface Parameter Retrieval (CASPR) System (Key 2002). CASPR is a toolkit for analysis of data from the AVHRR satellite instruments (Key 2002, and http://stratus.ssec.wisc.edu/caspr/userman.pdf) and can be used to retrieve a variety of surface and cloud parameters.

3. Methodology and results

The MOD29 IST product of Greenland, described above, is used to create the data record. The time series presented here employs *Terra* MODIS clear-sky swath data acquired within ±3 h of 1400 local solar time (1700 UTC) to facilitate continuity with the APP data record. *Aqua* MODIS ISTs are used to fill in gaps caused by instrument outages in the months of December 2003 and 2008 as described later. The swath data are projected onto a polar stereographic grid at 6.25-km resolution. This is the same projection used by the APP IST dataset (and other polar datasets), thus use of this projection facilitates accurate comparisons between the MODIS and Polar Pathfinder datasets.

The relative uncertainty of each mean-monthly map may be assessed based on coverage. Maximum coverage would result if there is a measurement of IST in each grid cell on each day of a given month. Coverage is reduced by cloud cover and instrument outages. Ideally, in a month having 31 days, 31 days of ISTs would be available to calculate the mean-monthly IST for the grid cell; however, because of cloud cover and the occasional instrument outages, it rarely if ever happens that all of the days in a given month are available for any given grid cell. Thus we provide coverage maps to accompany the mean-monthly IST maps. Additionally, to study the possibility of extending the data record back in time to create a CDR, we analyzed differences between APP and MODIS IST maps obtained within ±1 h of each other.

We also compared ISTs with in situ data from Summit, Greenland, during the winter of 2008/09 and compared the ISTs with modeled data, which is described in van den Broeke et al. (2011). Details of these comparative studies are discussed in a later section.

a. MODIS IST maps and climate-quality data record

The 2010 mean-monthly IST climate-quality data record color-coded maps are provided in Fig. 1a along with accompanying maps showing the number of days of IST data that were available to calculate the value in each cell (Fig. 1b). All data are available to download from the National Aeronautics and Space Administration through the MODIS Snow/Ice Project Web site (http://modis-snow-ice.nasa.gov).

The IST data record consists of daily and monthly IST maps; each file (flat binary, floating point) has an accompanying color-coded image map. A land mask was modified manually through visual analysis from an Albers conical equal-area land mask and a polar stereographic land mask to create an "optimal" mask that was reprojected to the 6.25-km polar stereographic projection. We include noncontiguous ice caps found along the Greenland coast in our "ice sheet" analysis.

Accompanying each monthly map is another map giving the number of days that were available to calculate the mean-monthly IST in each grid cell to allow a user to assess the validity of the IST map. This is important because an IST decision is not made for cells that are mapped as cloud or if data were not obtained for some other reason (see discussion below on *Terra* MODIS instrument outages).

Metadata are included to provide swath identification numbers in an ASCII file for each grid cell having a valid mean-monthly IST: the date, pixel location, and the swaths that were used to calculate the mean-monthly IST are provided. (The swath data can easily be ordered and downloaded once the identification numbers are known.) The Bamber et al. (2001) digital-elevation model (DEM) is also provided on the same grid to enable a user to overlay the DEM onto the IST maps.

1) Evaluation of coverage of the mean-monthly maps

Since MODIS swaths within ±3 h of 1700 UTC do not cover Greenland fully each day, coverage of the ice sheet is uneven for the daily maps from which the monthly maps are created. Furthermore, clouds can be present on part, but not all, of a swath and instrument outages can further reduce coverage. For example, a grid cell on a mean-monthly map may show a mean IST of −2°C, which might have been calculated from an average of 25 out of a possible 31 days, and a nearby cell may also show a mean IST value of −2°C but it might be based on only 20 days of data. Thus the number of days used to calculate the mean-monthly IST is provided (Fig. 1b) to give the user a guideline for determining the uncertainty of each grid-cell value. The user may then decide to study the coverage further by downloading the daily binary data or by investigating the swath data.

There are numerous time periods during which the *Terra* MODIS instrument experienced brief (<1 day) outages, and there are also several time periods during which the instrument was not operational for more than one day. The periods when the outages lasted more than one day are shown in Table 1. The most notable periods during which the instrument was not obtaining scientific data are relevant because these longer outages affect the quality of the data record. The MODIS Characterization and Support Team provides details on data gaps related to spacecraft or instrument issues at the following Internet site: http://mcst.gsfc.nasa.gov/index.php?section=15.

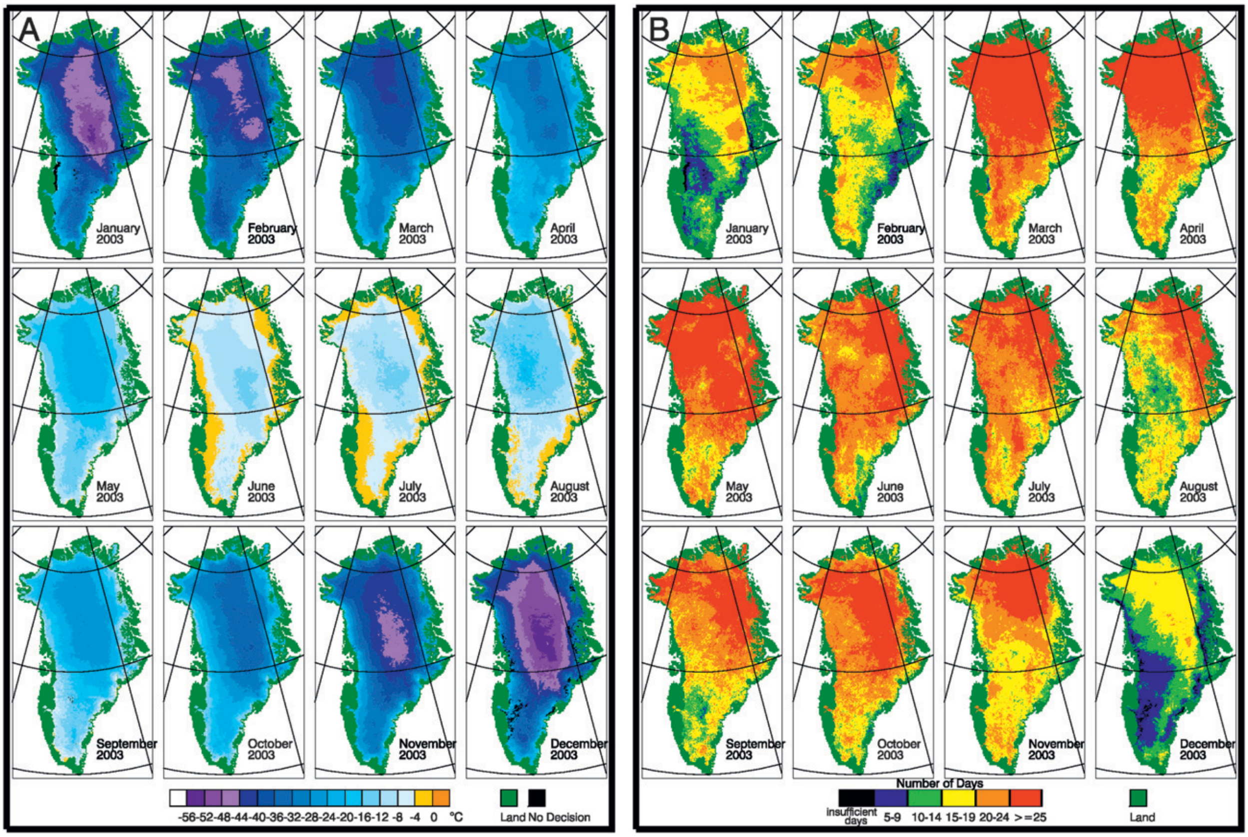

FIG. 1. (a) Mean-monthly ice-surface temperature (IST) color-coded maps for 2010 and (b) number of days of data available to create the maps shown in (a).

The average number of days available to create each monthly IST map was calculated by taking the average coverage reported for each grid cell and determining an average coverage number for the entire ice sheet so that there is one number per cell for each month as seen (along with the standard deviation) in Fig. 2. Note that some of the months that show low average coverage are months in which there were extended (>1 day) instrument outages. These include August 2000, December 2003, and December 2008. Furthermore, there was not enough data to create a mean-monthly map for June of 2001 because of an extended instrument outage.

For the December 2003 and 2008 instrument-outage periods listed in Table 1, we used *Aqua* IST data to replace the *Terra* IST data to fill in those data gaps. Comparison of December *Terra* and *Aqua* ISTs for swaths acquired ±1 h apart shows that the ISTs agree to within <±1°C.

There is a pronounced seasonality to coverage that is caused primarily by cloud cover. Figure 3 shows the average number of days available to create the monthly maps by month. Clouds are more prevalent in the months of November through February and less prevalent in the months of March through May.

2) CLOUD COVER "TRENDS" AS DETERMINED FROM THE *TERRA* MODIS CLOUD MASK

In addition to mapping clouds, the standard *Terra* MODIS cloud mask, MOD35, used to mask clouds in the MOD29 IST product, can provide information on cloud cover trends over the IST data record (Fig. 4). The plots in Fig. 4 demonstrate the variability in cloud cover over the time series. No statistically significant trends at the 95% or higher level were found. The influence of

TABLE 1. *Terra* MODIS instrument outages lasting >1 day from 1 March 2000 through 31 December 2010.

Date	Reason
5–18 Aug 2000	Earth View door was closed to minimize contamination
26–30 Oct 2000	No reason provided
15 Jun–2 Jul 2001	Instrument experienced a power supply shutdown
19–28 Mar 2002	Spacecraft was in "safe mode"
16–24 Dec 2003	Spacecraft was in "safe mode"
20–23 Dec 2008	Science formatting equipment anomaly occurred

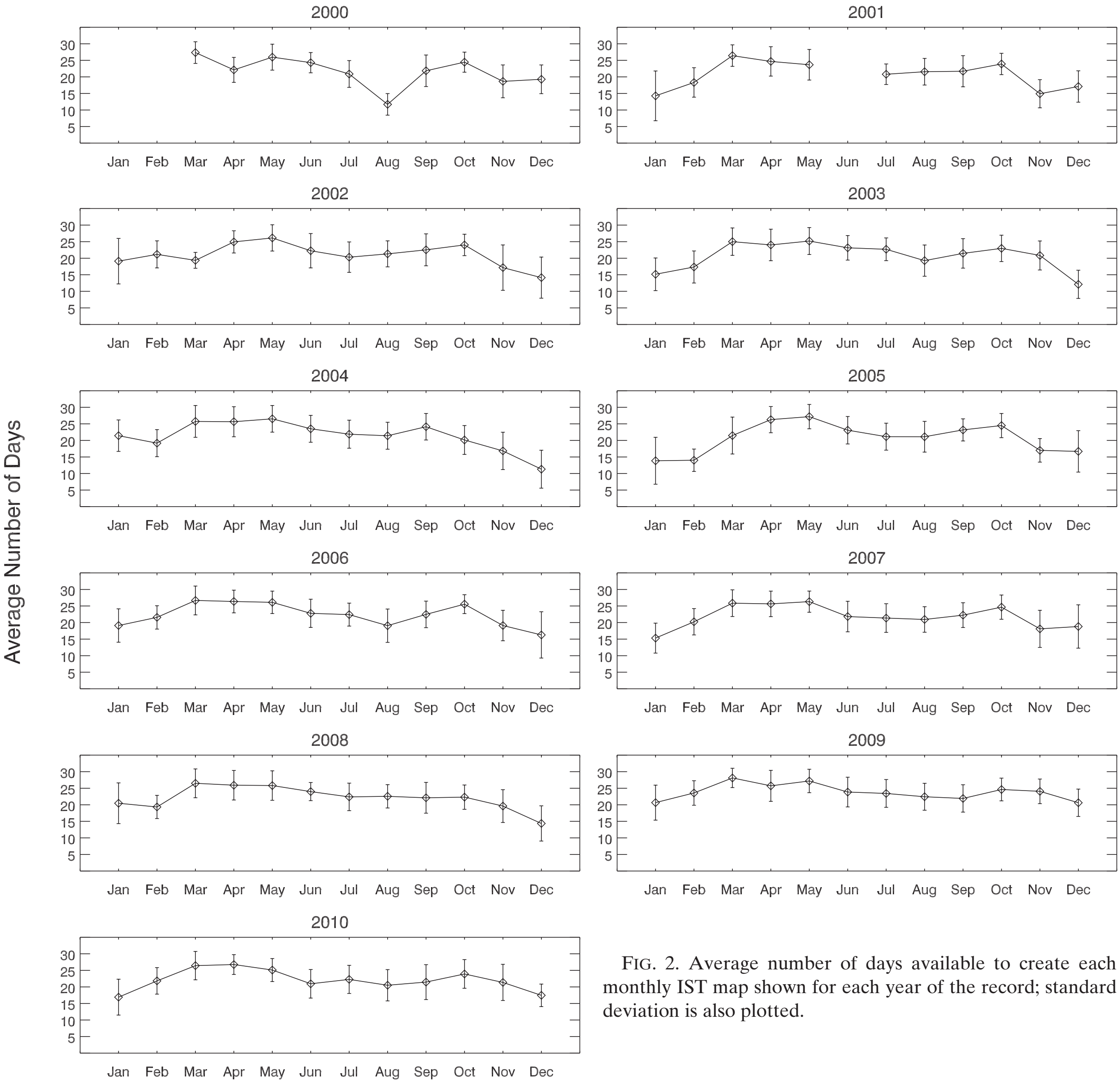

FIG. 2. Average number of days available to create each monthly IST map shown for each year of the record; standard deviation is also plotted.

cloud cover on surface temperature is important when studying a time series of IST data (see for example, Wang and Key 2005a,b; Liu et al. 2010). The time series of data shown in Fig. 4 is affected by the same instrument outages described earlier. To create the cloud cover plots, we used only days for which the total MODIS swath coverage of the ice sheet was 80% or greater. This excluded only 135 days of data for the ~130 month record. In addition, the selection of swaths is slightly biased toward clear skies. When developing the daily maps using individual swaths, if one swath is cloudy and the other is clear [on the same day within 3 h of 1400 local solar time (1700 UTC)], we selected the clear swath to obtain the IST value.

3) VALIDATION OF THE MODIS IST RECORD

To study the uncertainties of the MODIS climate-quality data record, the IST maps can be compared with in situ data, and MODIS-derived ISTs at cells corresponding with the location of weather stations can be compared with air temperatures (even though air and surface temperatures are not the same—see, for example, Hudson and Brandt 2005). ISTs can also be compared

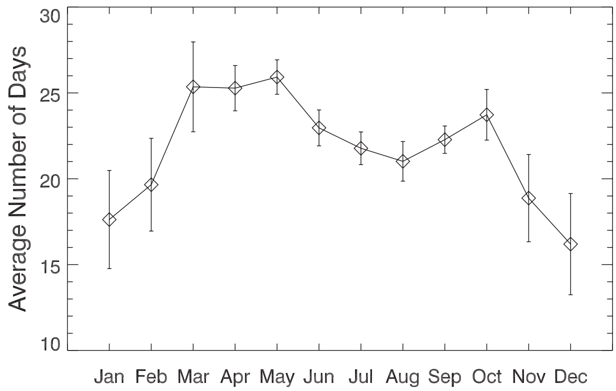

FIG. 3. Average number of days (2000–10) available to create the mean-monthly IST maps, shown by month.

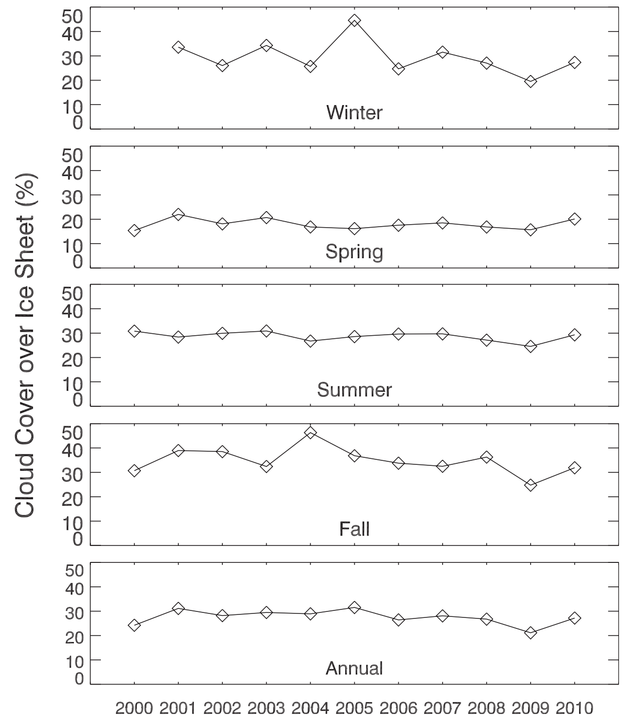

FIG. 4. Mean percent cloud cover over the Greenland Ice Sheet as determined from the MOD35 Cloud Mask standard MODIS product. Mean percent cloud cover was calculated from the daily MODIS IST maps, which slightly favor clear-sky conditions based on our selection of swath data. None of these plots is statistically significant at the 95% or higher level.

with modeled data. In this section, we will describe preliminary efforts to validate the MODIS IST data record by comparing ISTs with a time series of in situ–derived surface temperatures acquired at Summit, Greenland, during the winter of 2008/09, and by comparing the ISTs with modeled surface temperatures.

(i) In situ measurements

During the winter of 2008/09 at Summit one of the authors (LSK) obtained detailed surface temperature measurements of the ice sheet using thermochrons as well as air temperature and other measurements, including cloud cover (Koenig and Hall 2010). A thermochron is a small (1.5 cm), programmable temperature sensor and datalogger that is highly accurate for typical midwinter ice sheet temperatures (Koenig and Hall 2010). Thermochrons were positioned on the ice sheet surface and checked daily so that they were always on top of the snow-covered ice sheet surface.

Surface temperatures from Summit were compared with ISTs from the MOD29 IST product for 59 ''clear-sky'' observations between 17 November 2008 and 12 February 2009 (Fig. 5). This was done in a similar manner to that reported in Koenig and Hall (2010) in which land surface temperature (LST) data were used in a location where a point measurement was representative of at least a 1 km × 1 km area. Only ISTs and thermochron measurements acquired within 30 min of each other were compared. The MODIS ISTs were ~3°C lower than the thermochron-derived surface temperatures, which is consistent with the findings of Koenig and Hall (2010) who found that LSTs (from the MODIS standard LST product) were ~3°C lower than the thermochron-derived surface temperatures, and Hall et al. (2008a) who found a cold bias of ~2°C for the MODIS LSTs as compared to surface temperatures determined from 2-m AWS-derived air temperatures.

What can explain the ~3°C cold bias of the IST measurements? The satellite cell is 1 km × 1 km and the thermochron measurement is a point measurement; however, the area around Summit Camp, even ~1 km away, is homogeneous and surface temperatures were found to be consistent (Koenig and Hall 2010), so it is very unlikely that the difference in temperatures is due to changes in surface temperature related to topographic variations. Different satellites using different bands and different algorithms to calculate LST are in very good agreement (LSTs from different IR sensors agree to within ~0.5°C) according to Hall et al. (2008a). The IR sensors are consistently measuring lower surface temperatures than measured on the ground: thus we may conclude that the satellites may be measuring something slightly different from what the thermochron is measuring. This difference may be due, at least in part, to inadequacies of atmospheric correction of the satellite-derived skin temperature and needs to be explored further. Hudson and Brandt (2005) also found that 2-m air temperatures, during the polar night in

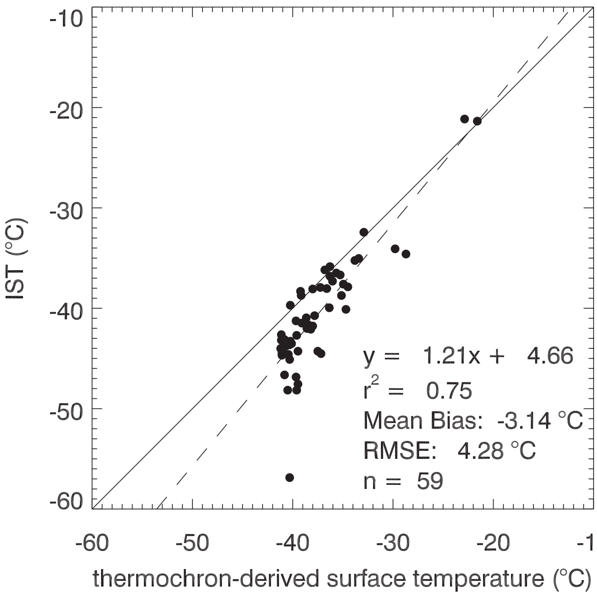

FIG. 5. Relationship between IST and in situ–derived snow/ice surface temperature (from thermochron data) at Summit, Greenland, Site 1, 17 Nov 2008–12 Feb 2009; thermochron temperatures were derived from Koenig and Hall (2010).

Antarctica, were always lower than the surface temperature (see their Fig. 14), and most of the time the difference is >1°C, and can be as great as 4°C. However the Hall et al. (2008a) and Koenig and Hall (2010) temperatures are actual surface temperatures and not 2-m air temperatures.

Note in Fig. 5 that most of the 59 measurements were acquired when temperatures ranged from ~ −50°C to −35°C. The two values at ~ −20°C corresponded within ±1°C of the thermochron measurements. When storms occurred and cloud cover was present, the surface warmed but MODIS-derived IST data were not available. So we do not know if the ±3°C bias just applies to very cold surface temperatures (<−35°C) or the full range of possible surface temperatures over snow and ice, up to 0°C. There is some evidence (see Hall et al. 2008a; Wan et al. 2002) that at higher temperatures there is closer correspondence between MODIS-derived surface temperatures and snow/ice surface temperature, but more data at temperatures near 0°C are needed to confirm this.

(ii) Modeled IST data

We also compared ISTs with modeled surface temperatures derived from measured air temperatures at three AWS stations (S5, S6, and S9) operated in the ablation area of the Greenland Ice Sheet by the University of Utrecht and described in van den Broeke et al. (2011). These stations are located from west to east along the *K* transect in southwest Greenland at increasing elevations (van den Broeke et al. 2011). All clear-sky AWS surface temperatures were compared with the MODIS IST (also clear sky) values for each full year of available AWS data (2004–09 for stations S5 and S9 and 2004, 2005, 2006, and 2009 for S6). The results showed excellent agreement, with r^2 values of 0.928 (S5), 0.923 (S6) and 0.944 (S9). A few outlier points were present in each year, and without them the agreement would be even higher. We strongly suspect that the consistently ''cold'' outlier IST points (relative to AWS surface temperatures) are unmasked clouds.

4) COMBINING THE IST RECORDS FROM APP AND *TERRA* MODIS

At the time of this work, APP and MODIS data were both available for most days for the years 2000–04. This period of overlap between datasets is essential for assessing the validity of combining or merging the APP and MODIS data records.

The APP ISTs are generally lower than the MODIS ISTs. Monthly difference maps (see Figs. 6a,b for the year 2003) are based on comparisons between APP maps acquired at 1700 UTC and MODIS IST maps constructed using swath data acquired within ±1 h of 1700 UTC. In Fig. 6a, there are differences in the APP and MODIS IST maps in all months, with the greatest differences in the cold months of November, December, and January when differences can be >5°C. This is also when the cloud cover is greatest (see Fig. 3). The smallest differences between the APP and MODIS ISTs occur in the spring and fall months.

The main reason for the differences between the APP and MODIS IST values is because different cloud masks are used in each product. When we combine the APP and MODIS cloud masks and only show grid cells that are mapped as cloud free on *both* maps, there is much closer agreement between the APP and MODIS IST maps as seen in Figs. 6b and 7b as described below.

Plots showing the relationship between APP and MODIS IST were developed for all months of the overlap period and are shown for 2003 in Figs. 7a and 7b. The plots in Fig. 7a correspond to the 2003 difference maps in Fig. 6a. The agreement between APP and MODIS and ISTs is good with R^2 values of 0.67–0.95 when the APP and MODIS IST individual cloud masks were employed (Fig. 7a). However, when a common cloud mask was used, the agreement is much better, ranging from 0.87 to 0.98 (Fig. 7b).

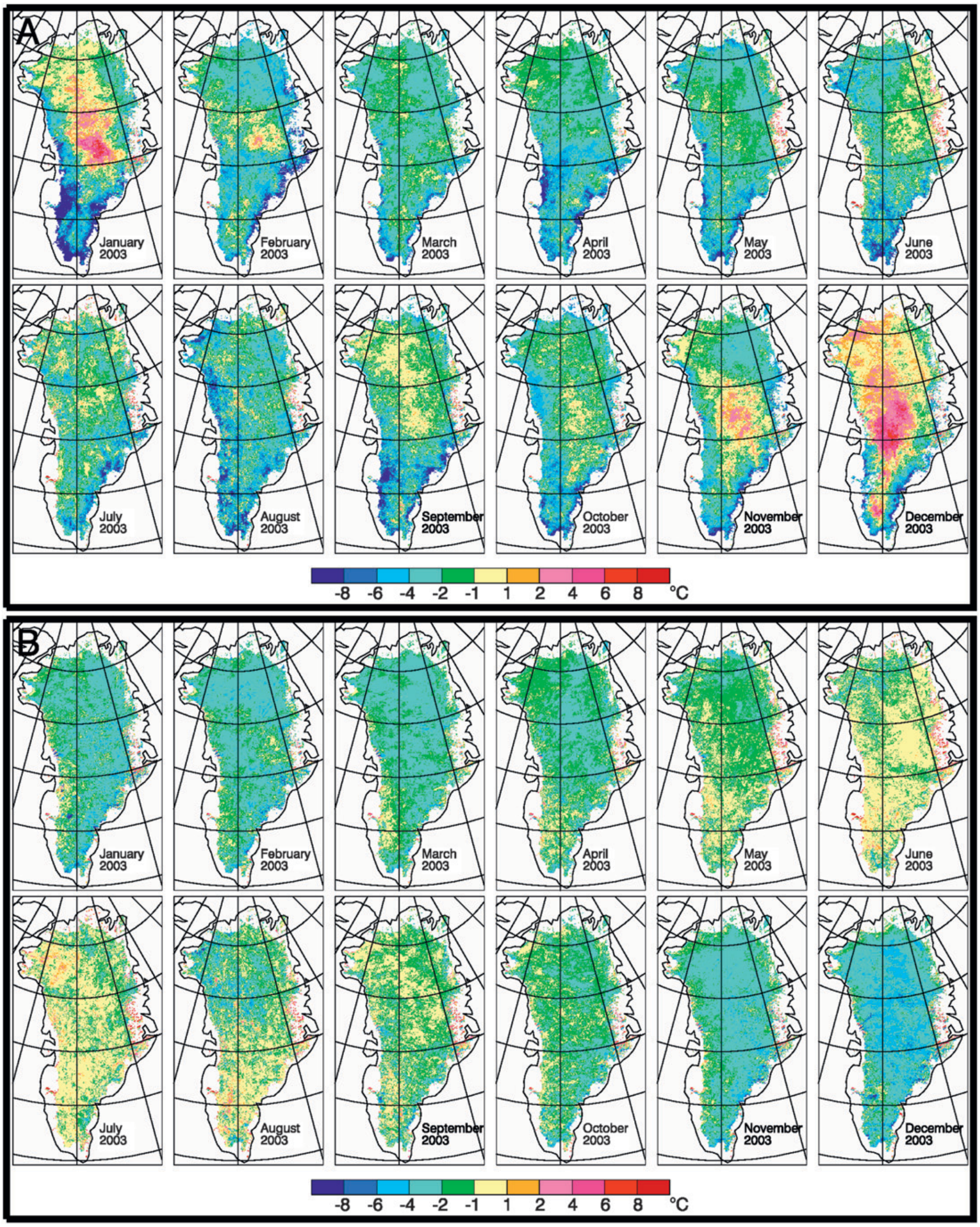

FIG. 6. (a) Monthly difference maps showing APP IST values minus *Terra* MODIS IST values for 2003. The data were obtained within ±1 h of the time of acquisition of the APP data. Each mean-monthly map used its own cloud mask for this analysis. (b) Monthly difference maps showing APP IST values minus *Terra* MODIS IST values for 2003. The MODIS data were obtained within ±1 h of the time of acquisition of the APP data. The respective cloud masks were combined and the combined cloud mask was used to develop each mean-monthly map.

In short, because of the large differences in IST between the APP and MODIS time series of monthly maps due to cloud-mask differences, we are unable to create a seamless data record that uses both APP and MODIS IST maps at this time. We could adjust for the cloud-mask differences using a common cloud mask for the overlap period, but not for the time period before the overlap period began (during the year 2000), so we await the complete reprocessing of the APP IST data record to attempt again to merge the APP and MODIS IST records.

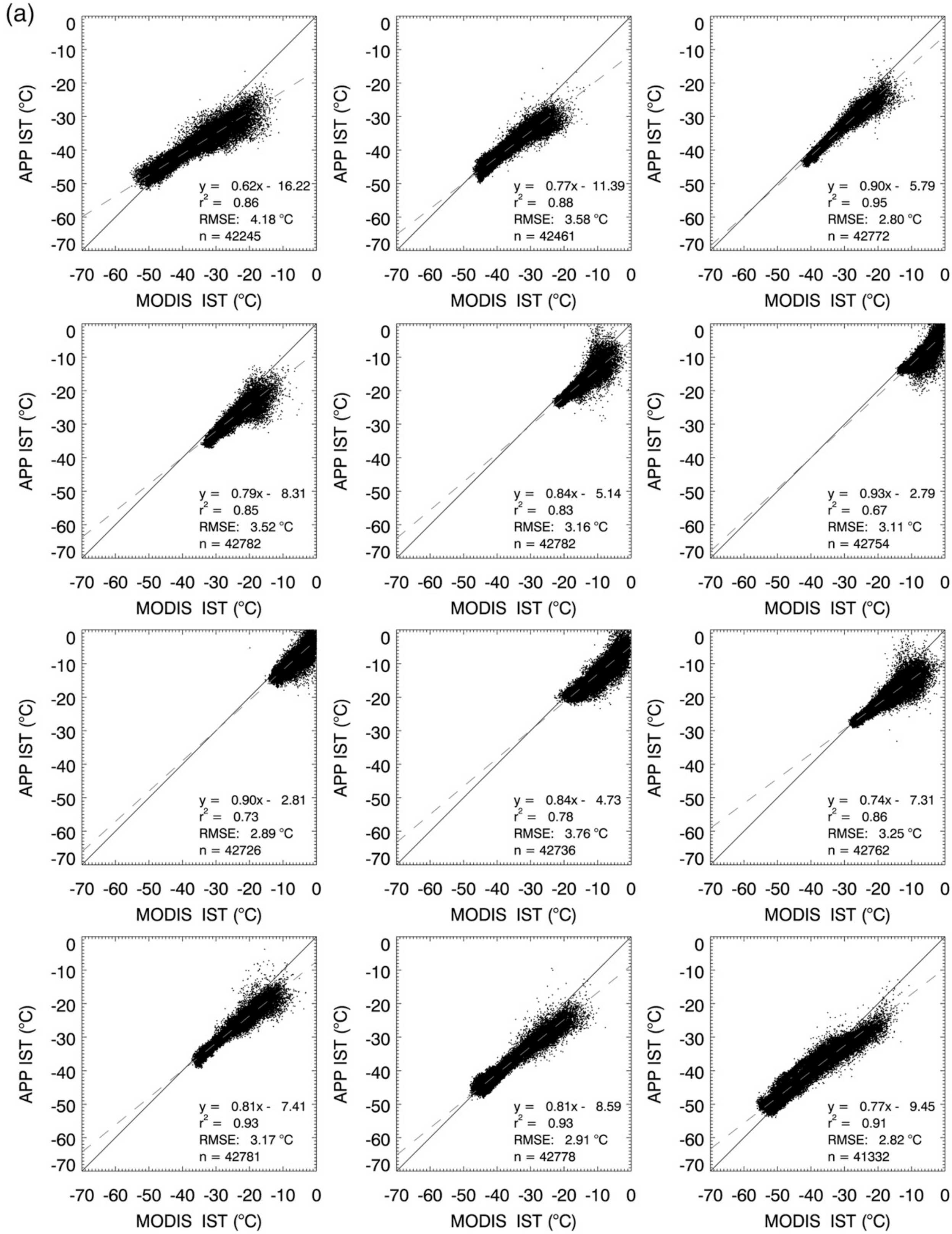

FIG. 7. Relationship between APP ISTs minus *Terra* MODIS ISTs for mean-monthly IST maps for January–December of 2003 when (a) each product used its own separate cloud mask and (b) when an APP–MODIS common cloud mask was employed.

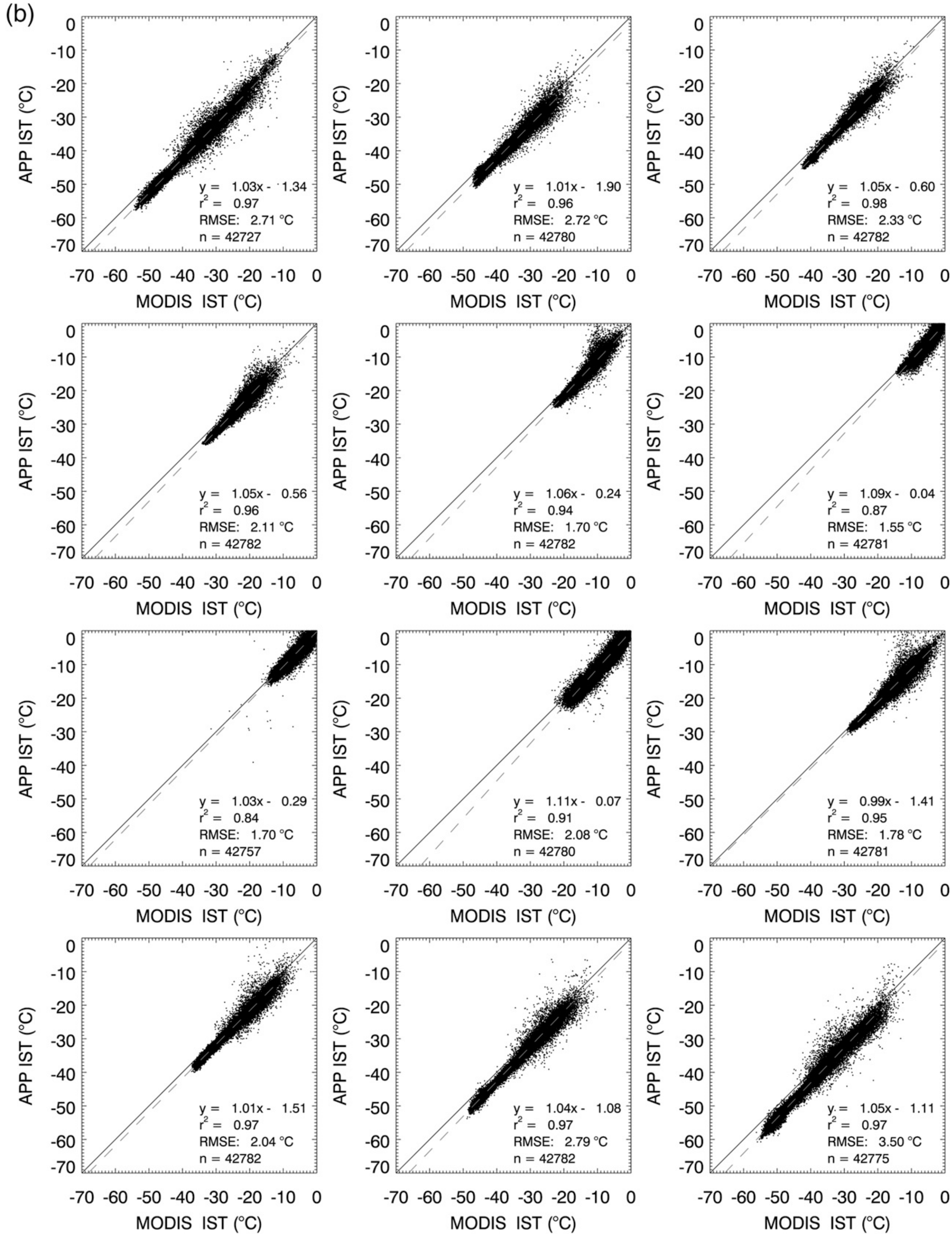

FIG. 7. (*Continued*)

4. Discussion

a. Trend analysis

The length and accuracy of the MODIS climate-quality IST dataset must be sufficient to detect trends if they exist. If we assume a linear trend in surface temperature on a multidecadal scale, systematic biases will have no significant impact because they simply shift the trend line up or down (higher or lower values of the estimated parameter) but do not change its slope. If the bias is temperature dependent, this will affect the trend analysis. At this time we do not know whether the cold bias observed with the MODIS ISTs is the same at low (e.g., −50°C) and high (near 0°C) ice-surface temperatures. Furthermore, if the uncertainties are larger than the trends, then the satellite-derived trends may not be valid. With Arctic surface temperatures changing on the order of ~2°C per decade over the past approximately three decades and an uncertainty in the IST of approximately 1°–1.5°C (e.g., Wang and Key 2005b), a surface temperature trend can, in theory, be detected. However, to have confidence in trend detection, additional validation efforts are necessary to obtain statistically significant estimates of the bias and uncertainty. Furthermore, care must be taken in interpreting IST trends, as changes in other variables can create artificial trends in surface temperature. If, for example, the sensor response changes systematically over time or if a cloud detection algorithm performs poorly for cirrus clouds and cirrus amount exhibits a trend over time, then artificial trends in IST retrievals may be introduced.

While we need a minimum of 20–30 years to assess IST trends over Greenland, even the ~12-yr MODIS IST climate-quality CDR record provides important information on interannual variability. Using this record we can also observe that different parts of the ice sheet can respond to meteorological forcings differently.

If a user wants perfect traceability, the unaltered IST data from the MOD29 standard algorithm will be orderable when the Collection 6 MODIS reprocessing has been completed.

b. Future work

To create a seamless CDR, cloud gaps and instrument-outage gaps should be filled in when possible. A credible statistical technique can be developed to interpolate between data gaps caused by clouds or/and instrument outages that last longer than ~4 consecutive days. One way to fill gaps in the *Terra* IST record is to use *Aqua* MODIS IST data interchangeably with *Terra* data as we did for the instrument-outage periods in December of 2003 and 2008. Future work calls for more extensive comparisons of MODIS *Terra* and MODIS *Aqua* ISTs to determine the feasibility of extending the IST record with *Aqua* data in the event of failure of the MODIS *Terra*. However, it is not likely that *Aqua* data will be useful for filling in long cloud gaps in the *Terra* data record because the *Aqua* MODIS swath data are subject to nearly the same cloud conditions as the *Terra* swath data (±3 h from 1700 UTC).

Plans are under way to reprocess the APP IST data with an improved cloud mask. Using the reprocessed APP data, it may be possible to lengthen the MODIS IST record by merging the APP and MODIS IST data records. Overlap periods between instruments are very important as is use of a common algorithm. The ~4-yr overlap between the APP and *Terra* MODIS IST records allowed us to conduct detailed comparisons of the respective data records and conclude that cloud-mask differences precluded merging the datasets into a seamless record. Following the successful October 2011 launch of the VIIRS, data will become available, probably in early 2012. When this happens, we will compare the MODIS IST maps with maps produced using a similar algorithm for VIIRS to extend the MODIS IST climate-quality data record into the VIIRS era. Detailed studies of differences between the *Terra*/*Aqua* and VIIRS datasets will be conducted during the overlap period between MODIS and VIIRS data acquisition.

In the future when the MODIS IST climate-quality data record is extended to span at least two decades (using future MODIS and/or VIIRS data), it will be useful for detecting climatically significant trends (if any) in IST and melt extent.

5. Conclusions

The MODIS IST climate-quality data record provides daily and mean-monthly ISTs beginning on 1 March 2000 and continuing through 31 December 2010 at 6.25-km spatial resolution on a polar-stereographic grid and is available to download (in 2012, the record will be updated through 31 December 2011).

Cloud-mask differences between the APP and MODIS IST products precluded merging the datasets into a seamless, consistent data record extending from 1981 to the present, but this will be revisited after the planned reprocessing of the APP data record in 2012. The MODIS climate-quality IST data record will be extended using future MODIS data, and VIIRS data after MODIS data are no longer available.

Preliminary validation of the ISTs at Summit Camp, Greenland, during the 2008/09 winter shows that the IST underestimates the surface temperature by ~3°C under clear skies when surface temperatures ranged from approximately −50° to −35°C. The observed cold bias may be lower at ISTs closer to 0°C but more data at surface temperatures near 0°C are needed to confirm this.

ISTs were also compared with modeled data available from the University of Utrecht in The Netherlands. Results show good agreement between the MODIS ISTs and the modeled data at three AWS stations in southwest Greenland.

It will take at least another 8–9 years of MODIS or/and VIIRS data (or reprocessed APP before 2000) to be able to elevate this climate-quality data record of the IST of the Greenland Ice Sheet to the level of a CDR. It will also require that a credible interpolation scheme be devised that will fill in extended instrument or/and cloud gaps. And finally, additional validation (using in situ data) is needed.

Surface-temperature measurements of the ice sheet may be used to study temperature and melt trends and may also be used in data-assimilation modeling. The IST is a key parameter that is needed to calculate ice sheet mass balance. The MODIS IST climate-quality dataset provides a highly consistent and well-characterized data record suitable for merging with earlier and future IST data records for climate studies.

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