

MODIS snow-cover products

Dorothy K. Hall^{a,*}, George A. Riggs^b, Vincent V. Salomonson^c,
Nicolo E. DiGirolamo^b, Klaus J. Bayr^d

^aHydrological Sciences Branch, NASA/Goddard Space Flight Center, Code 974, Greenbelt, MD 20771, USA

^bScience Systems and Applications, Inc., Lanham, MD 20706, USA

^cNASA/Goddard Space Flight Center, Code 900, Greenbelt, MD 20771, USA

^dDepartment of Geography, Keene State College, Keene, NH 03431, USA

Received 1 April 2001; received in revised form 20 December 2001; accepted 1 February 2002

Abstract

On December 18, 1999, the Terra satellite was launched with a complement of five instruments including the Moderate Resolution Imaging Spectroradiometer (MODIS). Many geophysical products are derived from MODIS data including global snow-cover products. MODIS snow and ice products have been available through the National Snow and Ice Data Center (NSIDC) Distributed Active Archive Center (DAAC) since September 13, 2000. MODIS snow-cover products represent potential improvement to or enhancement of the currently available operational products mainly because the MODIS products are global and 500-m resolution, and have the capability to separate most snow and clouds. The MODIS snow-mapping algorithms are automated, which means that a consistent data set may be generated for long-term climate studies that require snow-cover information. Extensive quality assurance (QA) information is stored with the products. The MODIS snow product suite begins with a 500-m resolution, 2330-km swath snow-cover map, which is then gridded to an integerized sinusoidal grid to produce daily and 8-day composite tile products. The sequence proceeds to a climate-modeling grid (CMG) product at 0.05° resolution, with both daily and 8-day composite products. Each pixel of the daily CMG contains fraction of snow cover from 40% to 100%. Measured errors of commission in the CMG are low, for example, on the continent of Australia in the spring, they vary from 0.02% to 0.10%. Near-term enhancements include daily snow albedo and fractional snow cover. A case study from March 6, 2000, involving MODIS data and field and aircraft measurements, is presented to show some early validation work.

© 2002 Elsevier Science Inc. All rights reserved.

1. Introduction

Snow-cover maps of the Northern Hemisphere have been available since 1966 from the National Oceanic and Atmospheric Administration (NOAA). These maps have continually been improved as new satellite data have become available. These maps, however, are not global and they rely on analysts to fine-tune the maps. For operational use, this is an advantage. However, for long-term climate studies, it is imperative to have a data set that is developed using an objective technique for snow mapping so that the data from the maps can be consistent when used as input to climate models.

On December 18, 1999, the Earth Observing System (EOS) Terra spacecraft was launched with a complement

of five instruments, one of which is the Moderate Resolution Imaging Spectroradiometer (MODIS). MODIS data are now being used to produce snow-cover products from automated algorithms at Goddard Space Flight Center in Greenbelt, MD. The products are transferred to the National Snow and Ice Data Center (NSIDC) in Boulder, CO, where they are archived and distributed via the EOS Data Gateway (EDG).

The MODIS snow-cover maps represent a potential improvement relative to hemispheric-scale snow maps that are available today mainly because of the improved spatial resolution and snow/cloud discrimination capabilities of MODIS, and the frequent global coverage. Their accuracy, however, has not yet been established, nor has the accuracy of existing operational maps. The difficulty in establishing the accuracy of any of these maps is that it is not known which map is the “truth” (if any) and the techniques used to map snow cover in the various maps are different, resulting in different products. The improved spatial resolution of the

* Corresponding author.

E-mail address: dhall@glacier.gsfc.nasa.gov (D.K. Hall).

MODIS snow maps (500 m), relative to snow maps derived from other available sensors, e.g. NOAA's Advanced Very High Resolution Radiometer (AVHRR) at 1.1-km resolution, should benefit hydrologists for snow-cover mapping. In this paper, we describe the MODIS snow products, and discuss a case study of early validation efforts from a field and aircraft experiment near Keene, NH, in March 2000, and field measurements in December 2000.

2. Background

2.1. Instrument descriptions

2.1.1. MODIS

MODIS is an imaging spectroradiometer that employs a cross-track scan mirror, collecting optics, and a set of individual detector elements to provide imagery of the Earth's surface and clouds in 36 discrete, narrow spectral bands from approximately 0.4 to 14.0 μm (Barnes, Pagano, & Salomonson, 1998). Key land-surface objectives are to study global vegetation and land cover, global land-surface change, vegetation properties, surface albedo, surface temperature, and snow and ice cover on a daily or near-daily basis (Justice et al., 1998). The spatial resolution of the MODIS instrument varies with spectral band, and ranges from 250 m to 1 km at nadir.

2.1.2. MODIS Airborne Simulator (MAS)

The MAS is a spectroradiometer designed to acquire calibrated radiances. The spectral coverage and radiometric response of an existing multichannel instrument were modified to approximate the narrow spectral bands of the MODIS for measuring scientific parameters of cloud and terrestrial surface targets (King et al., 1996). The MAS, with 50 spectral bands in the wavelength range from 0.55 to 14.2 μm , is flown aboard a NASA ER-2 research aircraft at an altitude of about 20 km. Data from MAS channels 1–10, in the visible, near-infrared and short-wave-infrared parts of the spectrum, are discussed in this paper. The MAS views 43° on either side of nadir with an Earth swath width of 37.25 km. The 15-cm aperture spatial instantaneous field-of-view is 2.5 mrad, or 50-m spatial resolution at nadir from the nominal aircraft height.

2.1.3. The Landsat Enhanced Thematic Mapper Plus (ETM+)

The ETM+ was launched on April 15, 1999, on the Landsat-7 satellite (<http://www.landsat.gsfc.nasa.gov/project/satellite.html>). The ETM+ has eight discrete bands ranging from 0.45 to 12.5 μm , and the spatial resolution ranges from 15 m in the panchromatic band, to 60 m in the thermal-infrared band. All of the other bands have 30-m resolution. ETM+ data can be accessed as browse products and ordered from the USGS EROS Data Center in Sioux Falls, SD from the following Web address: [\[edcsns17.cr.usgs.gov/EarthExplorer/\]\(http://edcsns17.cr.usgs.gov/EarthExplorer/\). ETM+ data provide a high-resolution view of snow cover that can be compared with the MODIS and operational snow-cover products. However, ETM+ data are only acquired once every 16 days and are therefore not frequent enough for mapping changing snow-cover conditions operationally.](http://www.</p>
</div>
<div data-bbox=)

2.2. Snow maps

2.2.1. NOAA operational snow maps

2.2.1.1. *National Environmental Satellite, Data and Information Service (NESDIS)*. The Satellite Analysis Branch of NOAA's NESDIS began to generate Northern Hemisphere Weekly Snow and Ice Cover analysis charts derived from NOAA's GOES and POES visible satellite imager, in November 1966. Maps were manually constructed and the spatial resolution of the charts was 190 km. However, since 1997, a new Interactive Multi-Sensor Snow and Ice Mapping System (IMS) is used by analysts to produce products daily at a spatial resolution of about 25 km, and utilizes a variety of satellite data to produce the maps (Ramsay, 1998). NOAA also produces a daily product, developed by automated techniques, which uses visible, near-infrared and passive-microwave data to map snow cover, and agrees in 85% of the cases studied, with the IMS product (Romanov, Gutman, & Csiszar, 2000).

2.2.1.2. *The National Operational Hydrologic Remote Sensing Center (NOHRSC) maps*. NOHRSC snow-cover maps, generated by National Weather Service NOHRSC hydrologists, are distributed electronically in near real time, to local, state and federal users during the snow season (Carroll, 1995). The NOHRSC 1-km maps are generated primarily from the NOAA polar-orbiting satellites and the Geostationary Orbiting Environmental Satellite (GOES) satellites to develop daily digital maps depicting the areal extent of snow cover for the coterminous United States, and Alaska, and portions of southern Canada.

2.2.2. Description of the MODIS snow-mapping products and algorithms

The MODIS snow products are provided as a sequence of products beginning with a swath product, and progressing, through spatial and temporal transformations, to an 8-day global-gridded product. For a more complete description, see Riggs, Barton, Casey, Hall, and Salomonson (2000). The MODIS maps provide global, daily coverage up to 500-m spatial resolution. The climate-modeling grid (CMG) products are at 0.05° resolution, which is ~ 5.6 -km resolution at the Equator. Quality-assessment (QA) information is included in the products. In the future, percent snow cover or fractional snow cover in each pixel will be provided along with daily snow albedo in the 500-m products. Fractional snow cover for each pixel (from 40%

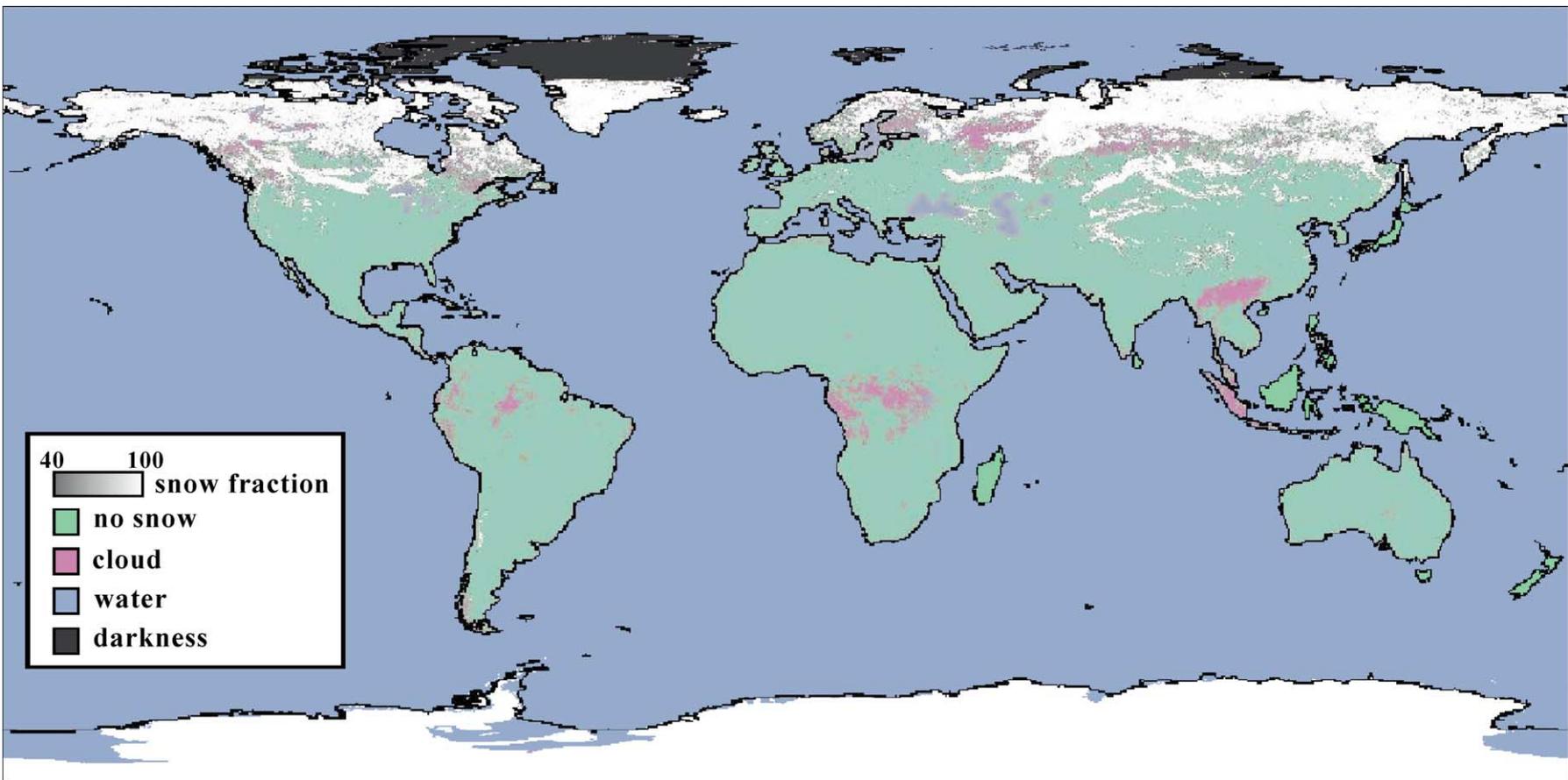


Fig. 1. Eight-day composite global MODIS snow-cover map—October 24–31, 2001.

to 100%) is already available in the CMG products. Because cloud cover often precludes the acquisition of snow cover using visible and near-infrared sensors, the daily maps are composited, and 8-day composite products are available. The CMG product is specifically designed for use by climate modelers. It provides a global view of the Earth's snow cover in a geographical projection (Fig. 1).

The automated MODIS snow-mapping algorithm uses at-satellite reflectances in MODIS bands 4 (0.545–0.565 μm) and 6 (1.628–1.652 μm) to calculate the normalized difference snow index (NDSI) (Hall, Riggs, & Salamonson, 1995):

$$NDSI = \frac{\text{band 4} - \text{band 6}}{\text{band 4} + \text{band 6}} \quad (1)$$

A pixel in a non-densely forested region will be mapped as snow if the NDSI is ≥ 0.4 and reflectance in MODIS band 2 (0.841–0.876 μm) is >11%. However, if the MODIS band 4 reflectance is <10%, then the pixel will not be

mapped as snow even if the other criteria are met. This prevents pixels containing very dark targets such as black spruce forests, from being mapped as snow. This is required because very low reflectances cause the denominator in the NDSI to be quite small, and only small increases in the visible wavelengths are required to make the NDSI value high enough to classify a pixel, erroneously, as snow.

Changes that occur in the spectra of a forest stand as it becomes snow-covered can be exploited to map snow cover in forests. The primary change in reflectance occurs in the visible wavelengths as snow has a much higher visible reflectance than soil, leaves or bark. A fundamental change that snow cover causes in the spectral response of a forest, which can be used in a global algorithm, is that the reflectance in the visible will often increase with respect to the near-infrared reflectance. This behavior is captured in the normalized difference vegetation index (NDVI), as snow will tend to lower the NDVI. MODIS bands 1 (0.620–0.670 μm) and 2 (0.841–0.876 μm) are used to calculate the NDVI. The NDVI and NDSI are used together to improve snow mapping in dense forests. If the NDVI = ~ 0.1, the

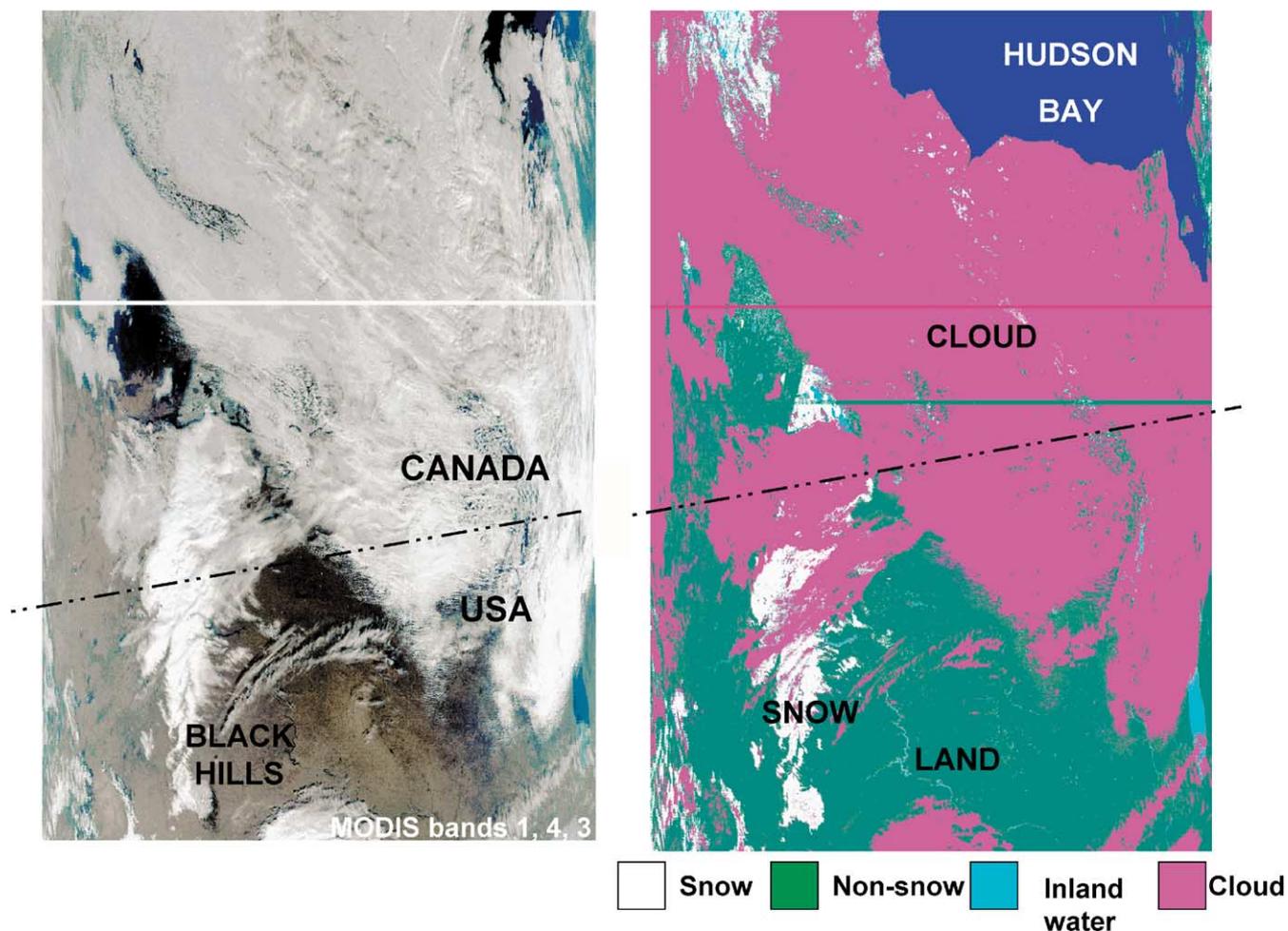


Fig. 2. MODIS image (left) and snow map (right)—November 3, 2000.

pixel may be mapped as snow even if the NDSI is < 0.4 (Klein, Hall, & Riggs, 1998).

The introduction of a “thermal mask,” (e.g., see Romanov et al., 2000 for an example of a thermal mask) on October 3, 2001 has improved the algorithm by eliminating much of the spurious snow cover that was found in many parts of the globe in the earlier MODIS snow maps. Possible causes of the spurious snow cover were confusion with cloud cover, aerosol effects and snow/sand confusion on coastlines. To improve the snow-mapping results, and remove most of the spurious snow cover, we instituted a thermal mask in the fall of 2001, which has greatly reduced the errors of commission. Using MODIS infrared bands 31 (10.78–11.28 μm) and 32 (11.77–12.27 μm), a split-window technique (Key, Collins, Fowler, & Stone, 1997) is used to estimate ground temperature. If the temperature of a pixel is > 277 K, then the pixel will not be mapped as snow. Results in snow-covered areas have not changed much, but results in warm areas have improved dramatically. It is anticipated that the temperature of the thermal mask will be increased to 280 °K, or 283 °K as in Romanov et al., 2000.

2.2.2.1. Quality assurance (QA) information. The quality assurance (QA) information should help the user determine the usefulness of the snow-cover data. QA information in the data products provides additional information on algorithm results for each pixel. The QA data are stored as bit flags. The information content of the QA data varies by product, but all contain common settings in the first two bits with additional bits used to indicate the occurrence of specific conditions. Common QA settings indicate where nominal or abnormal results occurred. Additional bits may be set to indicate certain situations that are specific to each snow algorithm and data product, e.g. suspect radiance data, extreme viewing angle. Additional details concerning the QA may be found in Riggs et al. (2000).

2.2.2.2. The MODIS cloud-mask product. The current version of the MODIS snow algorithm reads the unobstructed field-of-view quality flag from the MODIS cloud-mask algorithm (Ackerman et al., 1998). If that flag is set to ‘certain cloud,’ then cloud is set in the snow-mapping algorithm. Any other setting of that flag is interpreted as a clear view of the surface and the pixel is analyzed for the presence of snow. Several revisions were implemented in the cloud-mask algorithm since MODIS began collecting science data on February 24, 2000. In September 2000, a new version of the cloud mask was inserted in the data product production system. Even with the new version of the cloud mask, there are still circumstances where snow and cloud confusion persist, and the cloud mask is overly conservative in mapping cloud cover in snow-covered areas. Thus a more liberal cloud mask is undergoing testing (Riggs & Hall, in press).

The snow algorithm is not applied when the surface viewed is in darkness. Determination of darkness comes

from the cloud-mask product, and is defined when the solar zenith angle is $\geq 85^\circ$.

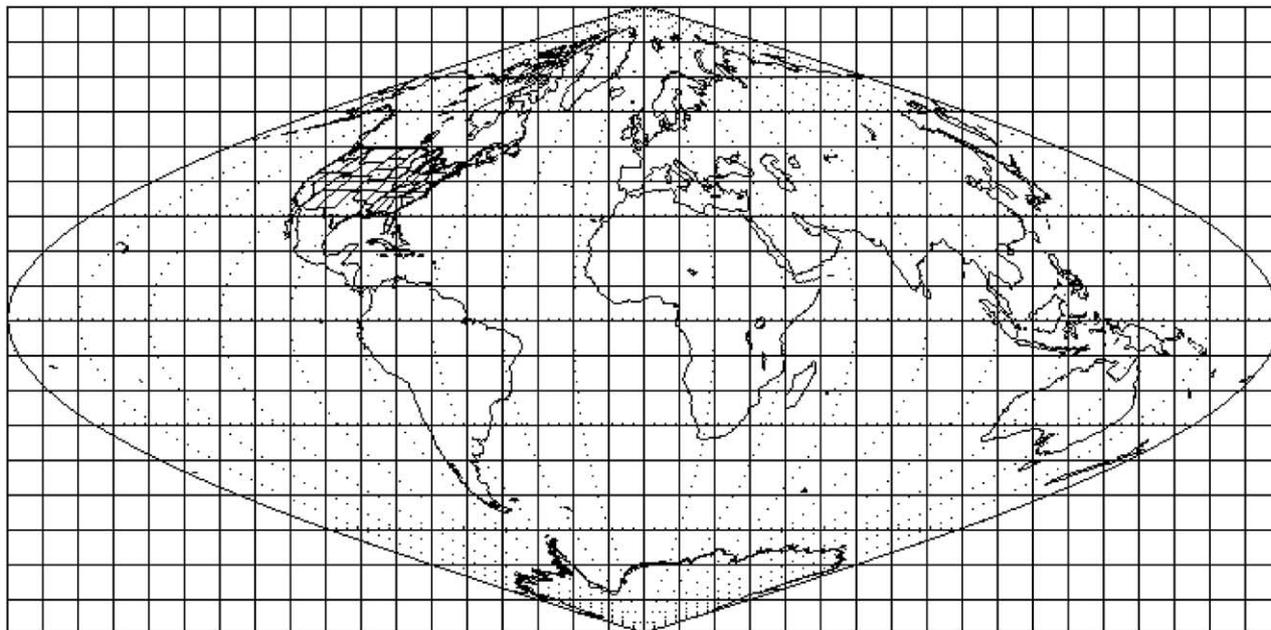
Masking of oceans and inland waters is done with the 1-km resolution land/water mask contained in the MODIS geolocation product. The 1-km data of the land/water mask is applied to the four corresponding 500-m resolution pixels in the snow algorithm. The snow-mapping algorithm is not run on ocean waters, but is implemented for inland water bodies (i.e., the Great Lakes).

2.2.2.3. Swath product. The snow data-product sequence begins with a 5-min swath segment (granule) (Fig. 2) at a nominal pixel spatial resolution of 500 m and a nominal swath coverage of 2330 km (cross track) by 2030 km (along track) (Fig. 2). Gridded latitude and longitude values are stored as separate data layers in the product. Inputs to the swath snow-cover product are: the MODIS (Level 1B) radiance data (Guenther et al., 1998), the MODIS cloud mask (Ackerman et al., 1998), and a land/water mask. Analysis for snow in a MODIS swath is constrained to pixels that: (1) have nominal Level 1B radiance data, (2) are on land or inland water, (3) are in daylight, and (4) are unobstructed by clouds according to the cloud-mask product. The constraints are applied in the order listed.

2.2.2.4. Daily and 8-day composite tile products. The second product in the sequence is created by mapping pixels from the swath product to their Earth locations on the integerized sinusoidal projection (Wolfe, Roy, & Vermote, 1998) (Fig. 3a). The projection is divided into tiles of approximately $10^\circ \times 10^\circ$ (lat./long.) and daily products are made for each tile. This daily product is an intermediate product in which all the observations (pixels) in the snow swath product are geolocated onto the projection. This results in a three-dimensional data array in which the observations are “stacked.” The third product, the daily snow product, is generated by selecting the observation acquired nearest nadir and having the greatest coverage of the grid cell from the many observations acquired during a day (Fig. 3b). This product also has 500-m resolution. An 8-day composite maximum snow-cover product is produced for each tile by compositing 8 days of the daily 500-m resolution products. Eight-day periods begin from the first day of each year. An example of the daily CMG map (as a special product) is shown in Fig. 4a, with the corresponding 8-day CMG composite map shown in Fig. 4b. (Snow maps shown in Fig. 4 are 0.25 (~ 25 km) resolution special, early products have been superseded by the 0.05° resolution CMG).

In selecting the compositing technique for the 8-day composites, we decided that it would be most useful to use maximum snow cover. In other words, if snow were present on any day in any location on the daily tile product, it will show up as snow-covered on the 8-day composite. Maximum snow cover is a more useful parameter than minimum or average snow cover. Using either minimum

(a)



(b)

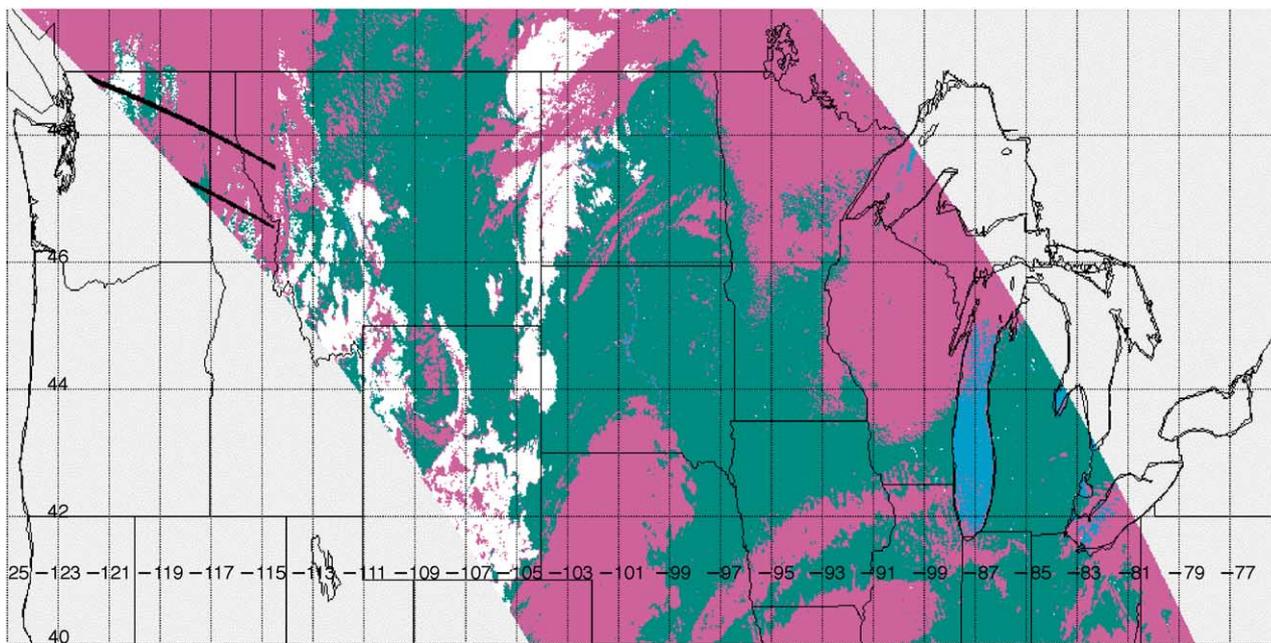


Fig. 3. (a) Location of tiles on the integerized sinusoidal grid. (b) Daily tile snow-cover product showing snow cover in the Black Hills, South Dakota. Snow is white, clouds are pink and non-snow-covered areas are green. Inland water is blue/green.

or average snow cover would result in failure to map some snow cover. Since the daily data will also be available, it should be relatively easy to find out when and where a storm deposited new snow cover. The compositing technique also minimizes cloud cover.

2.2.2.5. Daily and 8-day composite climate-modeling grid product. The 8-day composite climate-modeling grid

(CMG) products are available to download from http://www.snowmelt.gsfc.nasa.gov/MODIS_Snow/modis.html and from NSIDC. The daily global snow-cover CMG product has been available since early 2002 through NSIDC, and is presented in a geographic projection, by assembling MODIS daily data tiles (approximately 320) to include all land areas, of the daily 500 m snow product and binning the 500-m cell observations into the 0.05° CMG

cells. The binning technique in use creates a fractional snow-cover array based on the number of snow observations in a grid cell, a fractional cloud data array based on the number of cloud observations in a grid cell, a confidence index and a QA field. Percentages of snow and clouds in a cell are determined based on a count of all input observations, including non-snow and non-cloud observations. The confidence index provides a relative measure of how much of the land surface in a cell was viewed under clear sky conditions. The QA field provides an indication of the quality of the 500-m data within each cell. Interpretation

of fractional snow extent data can be difficult because of clouds in a cell. Other work (Hall, Kelly, Riggs, Chang, & Foster, *in press*), using a special product as shown in Fig. 4a and b, has shown that generating a maximum snow extent map by defining, as snow-covered, all cells in the fractional snow array that contain 1% or more fractional snow, provides a useful measure of snow extent, but overestimates snow cover as compared to operational maps and Landsat ETM+ data.

The 8-day composite map shown in Fig. 1 is produced at 0.05° resolution, produced from the 8 days of the daily

(a)

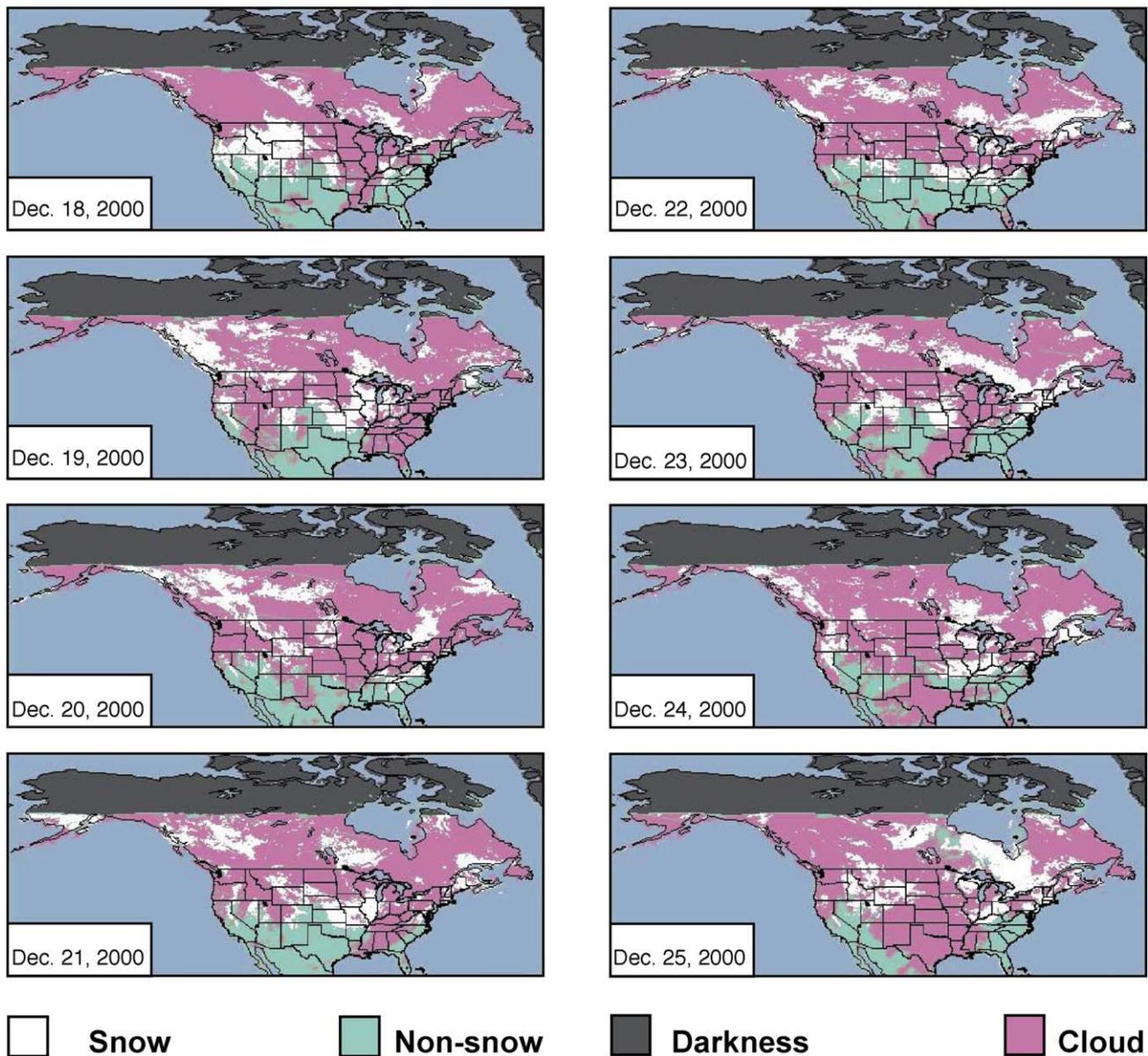


Fig. 4. (a) Daily MODIS snow maps of North America—December 18–25, 2000. (b) Eight-day composite MODIS snow map of North America—December 18–25, 2000.

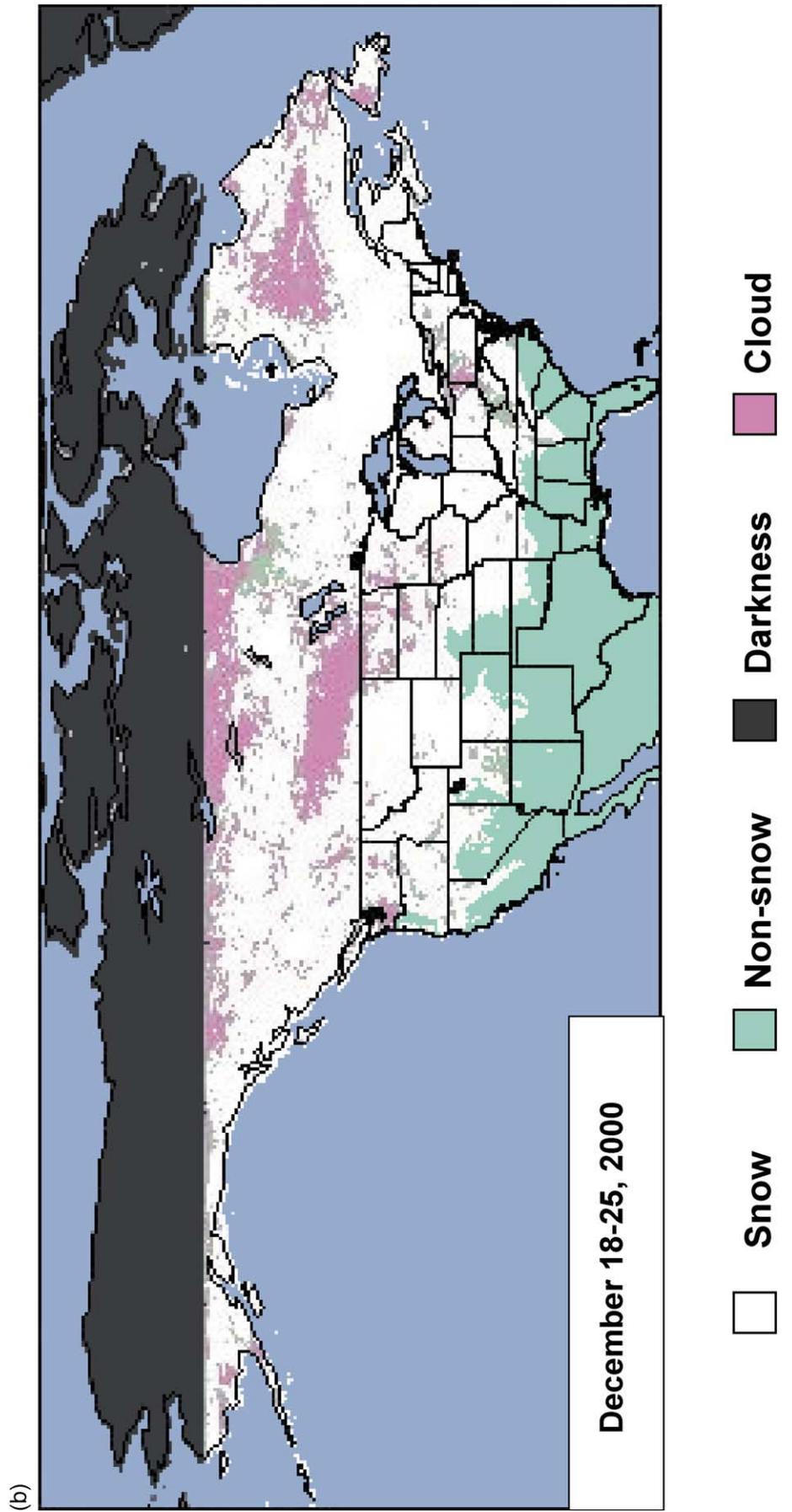


Fig. 4 (continued).

product from 24 to 31 October 2001, showing maximum snow extent and minimum cloud cover during the period. Maximum observable snow extent is reported as the highest fraction of snow observed in a cell during the period. This results in the clearest view of snow cover used to represent the snow extent in the period. Persistent clouds are reported for cells in which cloud cover was 80% or greater for all days of the period. Errors of commission in the 8-day composite global maps have been very low. For example, errors of commission in Australia on three separate 8-day composite snow maps ranged from 0.02% to 0.10%.

2.2.2.6. Data archiving and distribution. The NSIDC is one of eight NASA Data Active Archive Centers (DAACs), and is part of the Earth Observation System Data and Information System (EOSDIS). The EOSDIS utilizes the EOSDIS Core System (ECS) for data management across the DAACs, and the EDG, which facilitates online Web-

based user access to data (Scharfen et al., 2000). Users can search and order data via the EDG client at NSIDC (<http://www.nsidc.org/imswelcome>), and can access information about the MODIS snow products with links to related MODIS web pages <http://www.nsidc.org/NASA/MODIS/>.

2.2.2.7. Issues and limitations. The cloud mask (Ackerman et al., 1998), as it is used currently in the MODIS snow and ice algorithms, tends to overestimate cloud cover as seen in Fig. 5. Fig. 5 (left) is a MODIS swath product of the East Coast of the United States, acquired on December 23, 2000. Fig. 5B, of the same area on the same date, shows the snow map, but without the cloud mask. In Fig. 5 (right), all non-snow-covered areas are shown as green, including the clouds; 18% more snow cover is mapped versus when the cloud mask is used. Comparison of this image with the true-color MODIS image reveals that it is a more realistic depiction of the

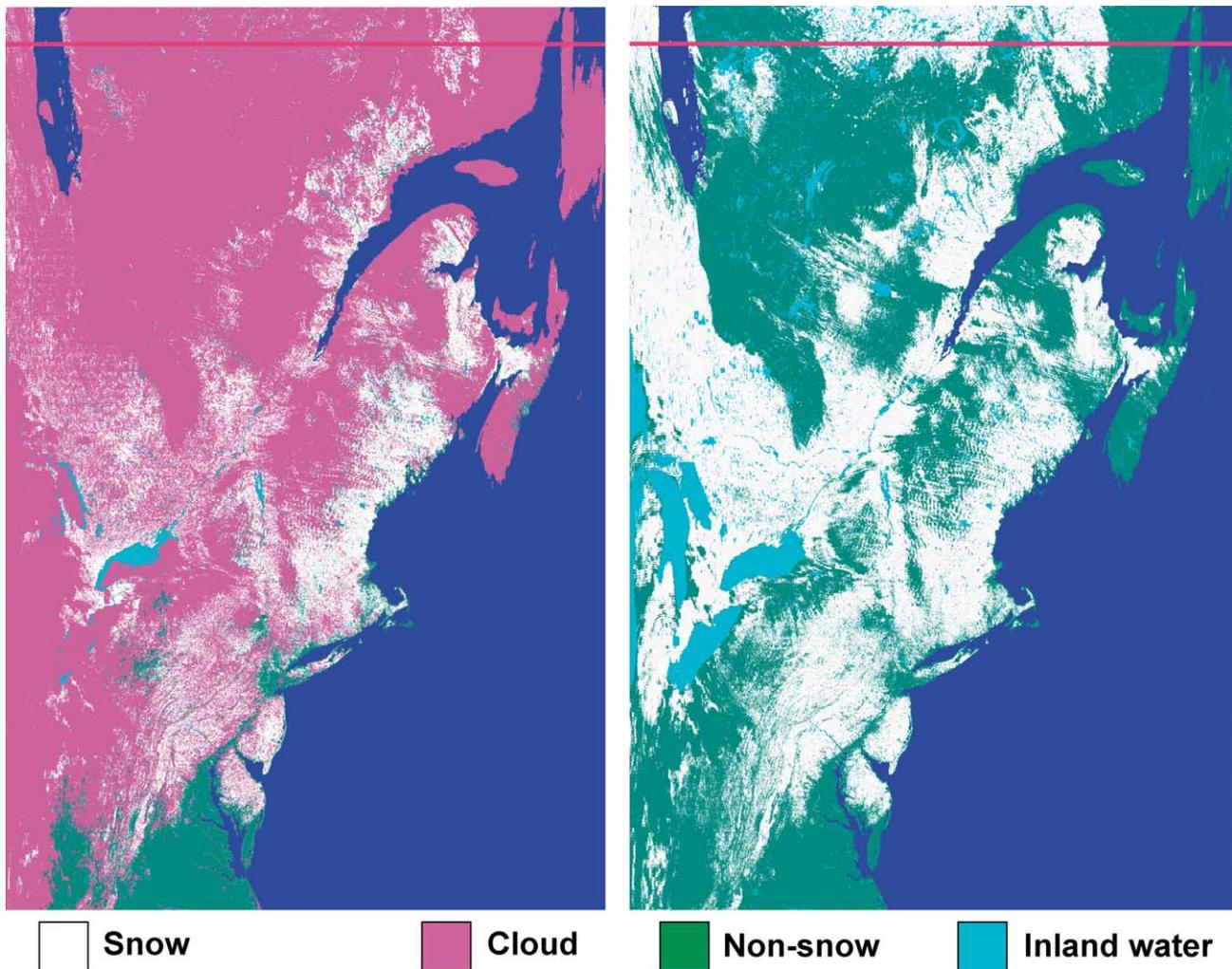


Fig. 5. MODIS snow map product of the eastern United States—December 23, 2000 (left); MODIS snow map processed without the MODIS cloud mask of the same area (right)—December 23, 2000.

actual snow cover than is provided in the current product with our current use of the cloud mask. The snow-mapping algorithm does some cloud screening through the use of MODIS band 6. In the short-wave infrared part of the spectrum, the reflectance of most clouds remains high while the reflectance of snow drops to near-zero values. The NDSI (Eq. (1)) component of the MODIS snow-mapping algorithm filters out most clouds effectively, with the exception of high clouds, which contain ice that may often be mapped erroneously as snow.

The initial version of the snow algorithm uses only the cloud mask “unobstructed field-of-view” flag as the cloud mask. There are many spectral tests built into the MODIS cloud-mask product. Identification of other spectral tests provided in the current cloud-masking product that may be better suited to snow mapping have been identified (Riggs & Hall, *in press*).

Confusion in the identification of cloud over snow has also been observed in high-elevation regions, e.g., the Sierra Nevada in California and the Southern Alps of New Zealand and is under investigation.

Another limitation of the MODIS snow-mapping algorithm, as it is designed at 500-m spatial resolution, is that it is a binary algorithm (snow or no snow). This limitation is especially significant in mountainous areas (Shi & Li, 1998). There has been much work undertaken to develop methods to map fractional snow cover (e.g., Nolin, Dozier, & Mertes, 1993; Rosenthal & Dozier, 1996) using Landsat data. Rosenthal and Dozier (1996) reported good results when their spectral mixture modeling-derived results were compared with aerial photography. However, it is extremely rare to find data to validate such algorithms. Several algorithms are under development for mapping fractional snow cover using MODIS data (Barton, Hall, & Riggs, 2000; Kaufman, Kleidman, Hall, Martins, & Barton, *in press*; Appel & Salomonson, 2002). Due to a lack of validation of the results of these algorithms, we have not provided a fractional snow-cover product to users at 500-m resolution. Work is ongoing to develop an automated algorithm that is effective globally to map fractional snow cover.

Cloud cover and darkness preclude mapping snow cover using MODIS data alone. In the future, passive microwave data will be combined with the MODIS data to achieve improved snow maps that will not be restricted by weather conditions, and that will contain some information on snow depth (Armstrong & Brodzik, 1999; Chang, Foster, & Hall, 1987; Grody & Basist, 1996; Robinson, Kunzi, Kukla, & Rott, 1984). The Advanced Microwave Scanning Radiometer (AMSR) was launched on the Aqua satellite in May 2002. The AMSR <http://www.198.122.199.205/AMSR/> has improved spatial resolution relative to the Special Sensor Microwave/Imager (SSM/I) data. The best resolution of the AMSR will be 5 km. There have been many studies employing both passive microwave and visible data to

study snow cover, and following the launch of Aqua, a great leap of progress in this regard is now possible.

A limitation to the 8-day composite product occurs when snow cover is deposited and melts while the region is cloudy. If the clouds clear after the snow has melted, the MODIS 8-day composite maps will not show that there was any snow cover during that 8-day period.

3. Case study

3.1. Northeastern United States

3.1.1. March 6, 2000

Shortly after the MODIS instrument began acquiring data, a field and aircraft experiment was undertaken in the area surrounding Keene, NH. On March 6th, there was an overflight of the NASA ER-2 aircraft with the MAS on-board. Field measurements consisted of: snow depth, extent, temperature, density, sky conditions and tree-canopy density. Two primary sites were studied: Bretwood Golf Course and Tenant Swamp, both northwest of Keene (Fig. 6). Sky conditions were almost completely clear for the entire day over Keene on March 6, 2000.

Snow conditions at Bretwood Golf Course were patchy while at Tenant Swamp the snow cover was continuous, with 3–10 cm snow depths and snow densities ranging from 350 to 420 g cm⁻³ at both sites. In Fig. 6, Bretwood Golf Course can be seen clearly on both the MAS image and the MAS-derived snow map, because more snow is visible than in the surrounding areas, including Tenant Swamp, which are forested and therefore the snow cover underneath is partially obscured. A spherical densiometer was used to measure the tree-canopy density at Tenant Swamp. Results showed that the percent of open canopy ranged from 37% to 51%. Because the tree canopy is obstructing the view of the ground from above, the MODIS and MAS snow maps do not show 100% snow cover on and near Tenant Swamp.

A snow map was derived from MAS data using a prototype MODIS snow-mapping algorithm and is also shown in Fig. 6. Patchy snow cover is evident at the site of the field measurements with the Bretwood Golf Course showing as snow-covered even though field measurements reported patchy snow cover. The smaller patches can be estimated as 4 × 8 m in size. The total snow-covered area at the golf course site was ~ 60%. Patches range from very small—less than 1 m²—to large continuous patches of several hundred square meters and the snow was almost totally continuous toward the NW part of the golf course near the river. MODIS data from the same day also show patchy snow near Keene. Though the snow cover at Tenant Swamp was continuous, according to ground measurements because of the forests, not all of the snow on the ground is visible.

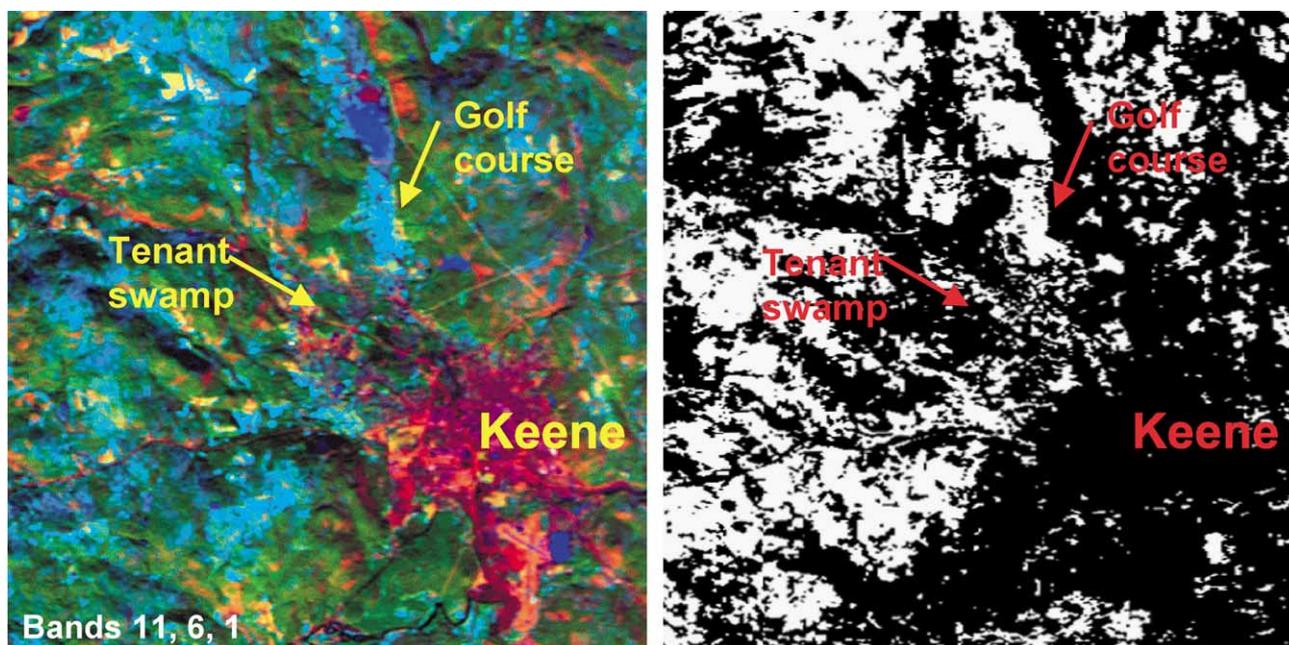


Fig. 6. MAS image (left) and snow map (right) showing field sites near Keene, NH (at arrow)—March 6, 2000.

The MODIS snow map and the NOHRSC operational snow map were compared for an area that included part of Maine, all of New Hampshire and Vermont, Massachusetts, and part of New York, Rhode Island and Connecticut on March 6, 2000 (Fig. 7). The Keene, NH, study area is included in this map. Though there was general agreement between the MODIS and NOHRSC maps during the day of the field work on March 6, there is only $\sim 73\%$ agreement in the area of New York, and parts of New England when the MODIS and NOHRSC maps are digitally registered. The 2nd order RMS registration error was 0.65 pixel.

The primary area of disagreement between the snow maps is in south-central New York where the NOHRSC snow map shows complete snow cover in the Catskill Mountains, and the MODIS map shows patchy snow cover. In south-central New York, 26 meteorological stations that are located in the area in question (see Fig. 7) were found (NOAA, 2000). Of these stations, only three reported measurable snow on the ground, six reported a trace of snow and the rest of the stations showed no snow was on the ground. The stations that had snow on March 6th tended to be located at the higher elevations; all of the stations (except for one) that reported any snow were over 350 m in elevation. In this forested area, it is hard to detect all of the snow on the ground, especially if the sensor is not ‘looking’ straight down (nadir).

Fig. 8 shows part of the NOAA NOHRSC and IMS operational maps for the area. The IMS map also shows snow cover in Canada, but that was deleted for Fig. 8 to facilitate comparison with the NOHRSC map, which does

not show snow in this part of Canada. Though at different resolutions, the IMS map shows less snow in the Catskills than does the NOHRSC map.

ETM+ images from March 8, 2000 show some patchy snow cover through cloud cover. Combined with analysis of images in visible bands of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and MODIS, the conclusion is that the NOHRSC map overestimates the snow cover, in the Catskills, on March 6, 2000, but the exact amount of snow cover is unknown.

To summarize, four different data sets were studied to reveal the extent of snow cover in south-central New York. A SeaWiFS image was available, and some snow was present as determined from analysis of the visible bands. A rather large area of snow cover was mapped on the NOHRSC snow maps contrasting with a rather small area mapped by the MODIS map for March 6, 2000. A small amount of snow was also visible on the IMS product as seen in Fig. 8. Since none of the snow maps agrees, the accuracy of the MODIS snow map is impossible to determine.

On December 23, 2000, field work was again performed at the same sites near Keene, and although there was no aircraft overflight, there was a Landsat-7 ETM+ acquisition on that day. According to ground measurements, the snow cover was continuous and snow depths varied from ~ 6 to 8 cm at all of the sites. The MODIS snow map was registered to a snow map that was developed from ETM+ data (using the MODIS snow-mapping algorithm as modified for use with ETM+ data). While the 30-m resolution ETM+-derived snow map showed patchy snow cover, the MODIS map, digitally

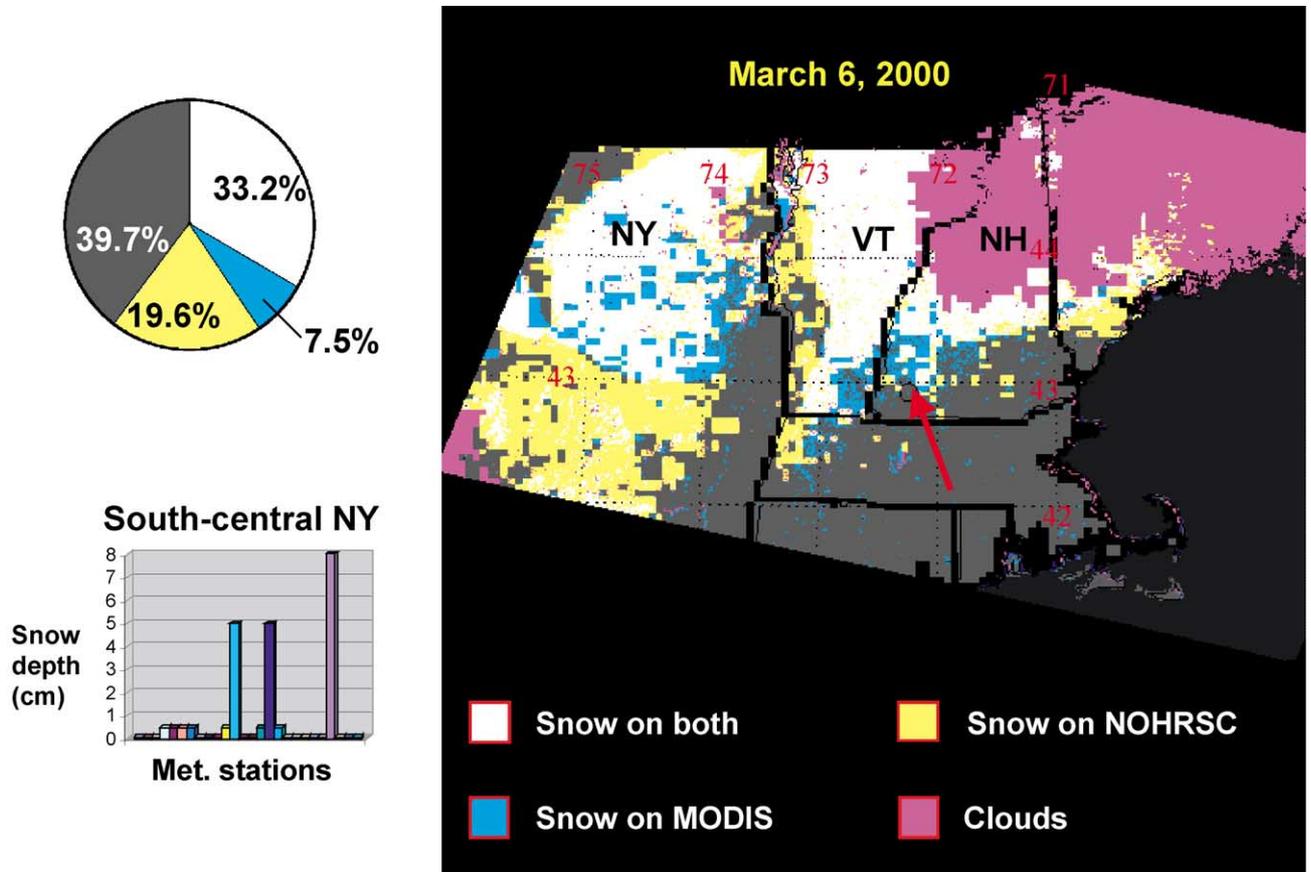


Fig. 7. MODIS/NOHRSC difference map showing differences in the location and amount of snow cover in the eastern United States—March 6, 2000. The MODIS snow map was processed without the MODIS cloud mask in this figure. Graph shows snow depths measured at meteorological stations in south-central New York—March 6, 2000.

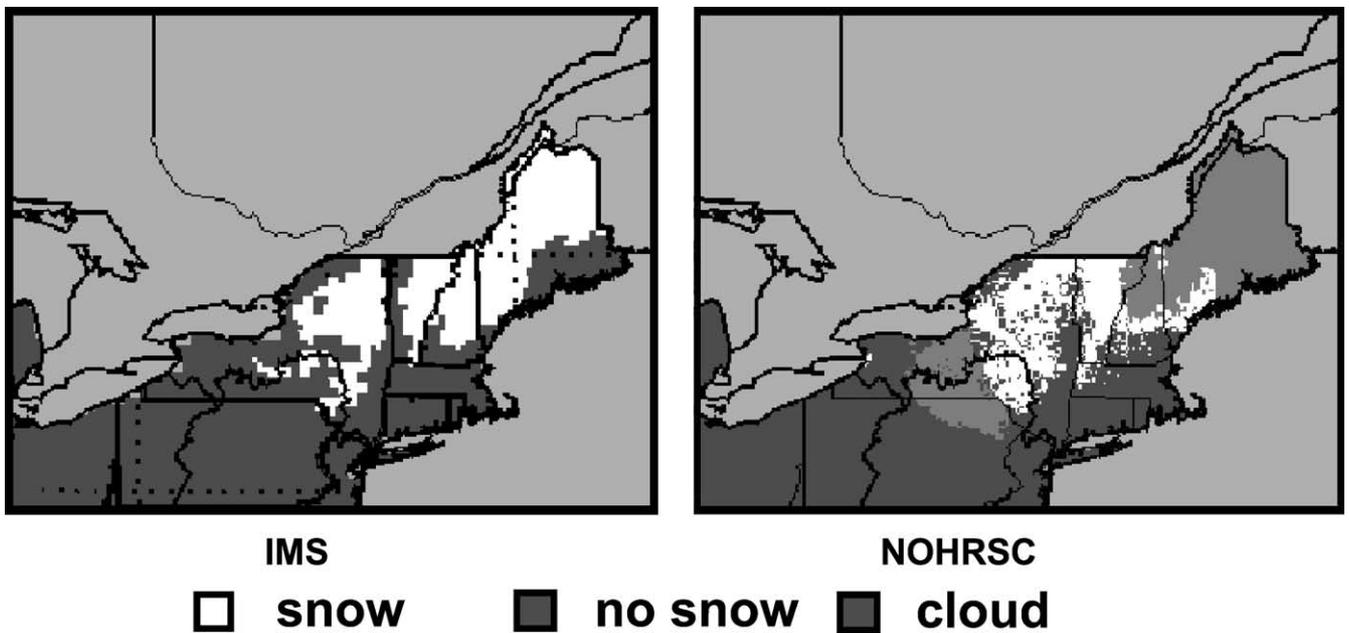


Fig. 8. NOAA Interactive Multisensor Snow and Ice Mapping System (IMS) snow map (left), and NOAA National Hydrologic Remote Sensing Center (NOHRSC) snow map (right) from March 6, 2000 of the northeastern United States. Snow cover, shown on the original IMS map in Canada, was removed in order to facilitate the comparison with the NOHRSC map.

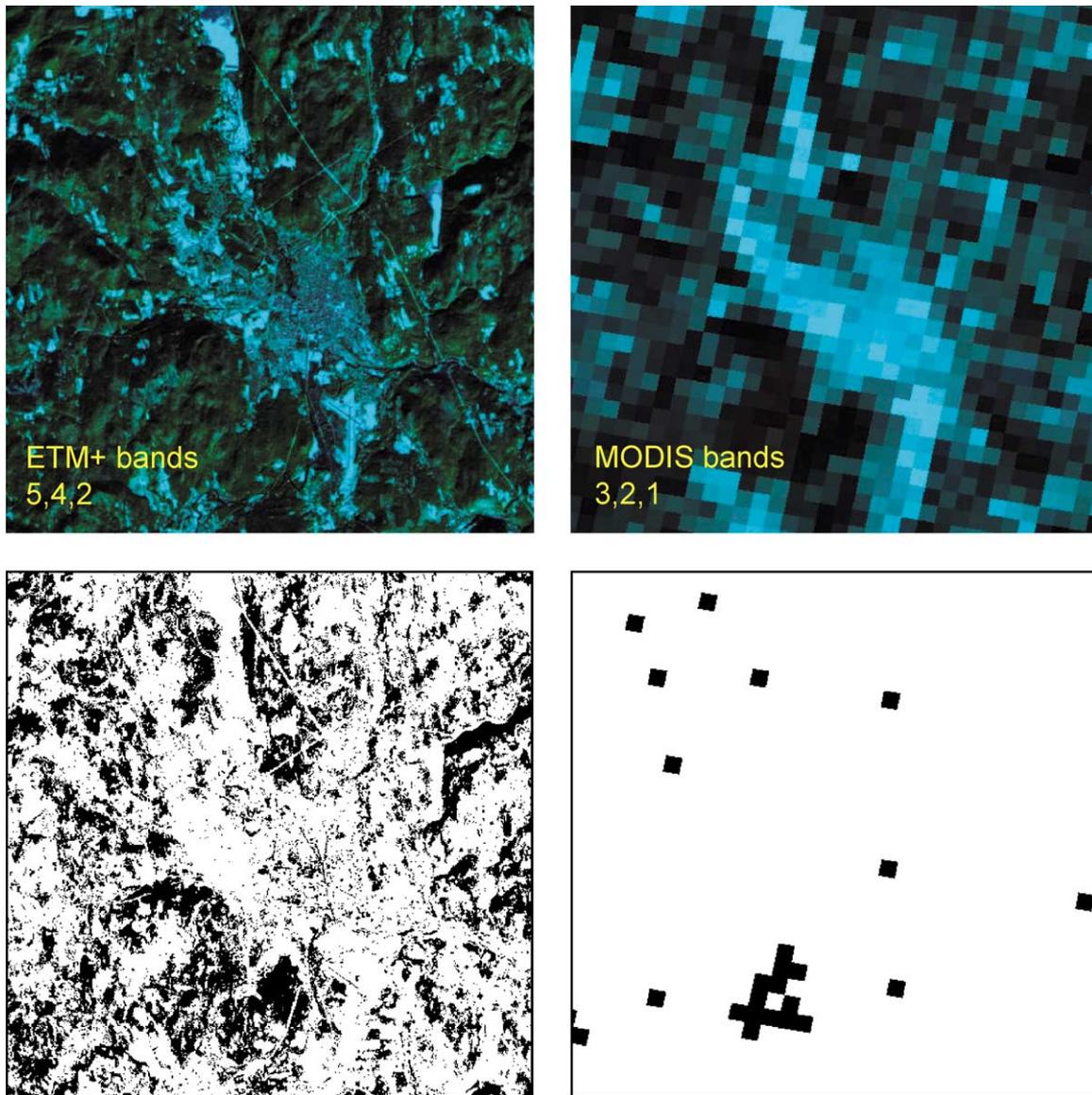


Fig. 9. Landsat-7 ETM+ (left) and MODIS (right) false-color images (top row) of Keene, NH and the surrounding areas; ETM+ (left) and MODIS (right) snow maps of the same area (bottom row)—December 23, 2000.

registered to the ETM+ map, showed nearly continuous snow cover (Fig. 9). The binary MODIS snow-mapping algorithm will map snow cover if $\sim 50\%$ of the 500-m pixel is snow-covered. In this case where the snow is patchy within each 500-m pixel, the MODIS snow map will overestimate the snow cover.

4. Discussion and conclusion

A sequence of MODIS snow-cover products is presented. The swath products are mapped to the integerized sinusoidal grid to create the daily tile product. Eight days of the daily tile products are used to produce the 8-day composite tile product. These products are at 500-m resolution. The CMG

product is produced at 0.05° (~ 5.6 -km) resolution and consists of daily and 8-day composite products. Examples of the products are shown, focusing on the site of a field and aircraft experiment from March 6, 2000, and fieldwork on December 23, 2000. The MODIS snow map shows patchy snow cover on March 6th, as confirmed by the field measurements. However, nearly complete snow cover is mapped near Keene on December 23rd, which is an over-estimation of snow cover as compared to the ETM+-derived map for the same day, as confirmed by field measurements but is likely due to the greater resolution of the MODIS image relative to the ETM⁺ image.

Other work shows that the MODIS snow-cover maps compare favorably with current operational maps (Hall et al., *in press*), and perform better than do passive microwave-

derived snow-cover maps during the daytime and in the fall months in the Northern Hemisphere when the snow is still wet.

Future enhancements to the MODIS snow maps include daily snow albedo (Klein et al., 2000), which should be available in the fall of 2002, and fractional snow cover at 500-m spatial resolution. Future re-processing will allow all of the MODIS snow maps to be processed in a consistent manner.

Acknowledgements

The authors would like to thank Janet Chien/GSC, Laurel, MD, for image preparation and processing.

References

- Ackerman, S. A., Strabala, K. I., Menzel, P. W. P., Frey, R. A., Moeller, C. C., & Gumley, L. E. (1998). Discriminating clear sky from clouds with MODIS. *Journal of Geophysical Research*, *103* (D24), 32141–32157.
- Appel, I. L., & Salomonson, V. V. (2002). Estimate of fractional snow cover using MODIS data. *Proceedings of IGARSS'02*, Toronto, Canada, 24–28 June 2002.
- Armstrong, R. L., & Brodzik, M. J. (1999). A twenty year record of global snow cover fluctuations derived from passive microwave remote sensing data. *5th Conference on Polar Meteorology and Oceanography* (pp. 113–117). Dallas, TX: American Meteorological Society.
- Barnes, W. L., Pagano, T. S., & Salomonson, V. V. (1998). Prelaunch characteristics of the Moderate Resolution Imaging Spectroradiometer (MODIS) on EOS-AM1. *IEEE Transactions on Geoscience and Remote Sensing*, *36*(4), 1088–1100.
- Barton, J. S., Hall, D. K., & Riggs, G. A. (2000). Fractional snow cover from the MODIS snow-mapping algorithm. *Proceedings of the 57th Eastern Snow Conference*, 17–19 May 2000, Syracuse, NY (pp. 171–181).
- Carroll, T. R. (1995). Remote sensing of snow in the cold regions. *Proceedings of the First Moderate Resolution Imaging Spectroradiometer (MODIS) Snow and Ice Workshop, 13–14 September, 1995, Greenbelt, MD. NASA Conference Publication, vol. 3318* (pp. 3–14).
- Chang, A. T. C., Foster, J. L., & Hall, D. K. (1987). Nimbus-7 SMMR derived global snow cover parameters. *Annals of Glaciology*, *9*, 39–44.
- Grody, N. C., & Basist, A. N. (1996). Global identification of snowcover using SSM/I measurements. *IEEE Transactions on Geoscience and Remote Sensing*, *34*(1), 237–249.
- Guenther, B., Godden, G. D., Xiong, X., Knight, E. J., Qiu, S., Montgomery, H., Hopkins, M. M., Khayat, M. G., & Hao, Z. (1998). Prelaunch algorithm and data format for the level 1 calibrations products for the EOS-AM1 Moderate Resolution Imaging Spectroradiometer (MODIS). *IEEE Transactions on Geoscience and Remote Sensing*, *36*(4), 1142–1150.
- Hall, D. K., Kelly, R. E. J., Riggs, G. A., Chang, A. T. C., & Foster, J. L. (in press). Assessment of the relative accuracy of hemispheric scale snow-cover maps. *Annals of Glaciology*.
- Hall, D. K., Riggs, G. A., & Salomonson, V. V. (1995). Development of methods for mapping global snow cover using Moderate Resolution Imaging Spectroradiometer (MODIS) data. *Remote Sensing of Environment*, *54*, 127–140.
- Justice, C. O., et al. (1998). The Moderate Resolution Imaging Spectroradiometer (MODIS): land remote sensing for global change research. *IEEE Transactions on Geoscience and Remote Sensing*, *36*(4), 1228–1249.
- Kaufman, Y. J., Kleidman, R. G., Hall, D. K., Martins, V. J., & Barton, J. S. (in press). Remote sensing of subpixel snow cover using 0.66 and 2.1 μm channels. *Geophysical Research Letters*.
- Key, J. R., Collins, J. B., Fowler, C., & Stone, R. S. (1997). High-latitude surface temperature estimates from thermal satellite data. *Remote Sensing of Environment*, *61*, 302–309.
- King, M. D., Menzel, W. P., Grant, P. S., et al. (1996). Airborne scanning spectrometer for remote sensing of cloud, aerosol, water vapor, and surface properties. *Journal of Atmospheric and Oceanic Technology*, *13*, 777–794.
- Klein, A. G., Hall, D. K., & Riggs, G. A. (1998). Improving snow-cover mapping in forests through the use of a canopy reflectance model. *Hydrological Processes*, *12*, 1723–1744.
- Klein, A. G., Hall, D. K., & Nolin, A. W. (2000). Development of a prototype snow albedo algorithm for the NASA MODIS instrument. *Proceedings of the 57th Eastern Snow Conference*, 15–17 May 2000, Syracuse, NY (pp. 143–157).
- NOAA (2000). Climatological Data (New York).
- Nolin, A. W., Dozier, J., & Mertes, L. A. K. (1993). Mapping alpine snow using a spectral mixture modeling technique. *Annals of Glaciology*, *17*, 121–124.
- Ramsay, B. (1998). The interactive multisensor snow and ice mapping system. *Hydrological Processes*, *12*, 1537–1546.
- Riggs, G. A., Barton, J. S., Casey, K. A., Hall, D. K., & Salomonson, V. V. (2000). MODIS Snow Products Users' Guide. http://www.snowmelt.gsfc.nasa.gov/MODIS_Snow/sugkc2.html.
- Riggs, G. A., & Hall, D. K. (in press). Reduction of cloud obscuration in the MODIS snow data product. *Proceedings of the 59th Eastern Snow Conference*, 6–7 June 2002, Stowe, VT.
- Robinson, D., Kunzi, K., Kukla, G., & Rott, H. (1984). Comparative utility of microwave and shortwave satellite data for all-weather charting of snow cover. *Nature*, *312*(5993), 434–435.
- Romanov, P., Gutman, G., & Csiszar, I. (2000). Automated monitoring of snow cover over North America using multispectral satellite data. *Journal of Applied Meteorology*, *39*, 1866–1880.
- Rosenthal, W., & Dozier, J. (1996). Automated mapping of montane snow cover at subpixel resolution from the Landsat Thematic Mapper. *Water Resources Research*, *32*(1), 115–130.
- Scharfen, G. R., Hall, D. K., Khalsa, S. J. S., Wolfe, J. D., Marquis, M. C., Riggs, G. A., & McLean, B. (2000). Accessing the MODIS snow and ice products at the NSIDC DAAC. *Proceedings of IGARSS'00, 23–28 July 2000, Honolulu, HI* (pp. 2059–2061).
- Shi, J., & Li, Z. (1998). Validation of MODIS snow mapping algorithm using AVIRIS image and near-infrared color photo data. *Proceedings of SPIE*, *3502*, 243–250.
- Wolfe, R. E., Roy, D. P., & Vermote, E. (1998). MODIS land data storage, gridding, and compositing methodology: level 2 grid. *IEEE Transactions on Geoscience and Remote Sensing*, *36*(4), 1324–1338.