

MODIS Snow-Cover Products

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Popular Summary

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. Much of the western part of the country relies on snowmelt runoff and thus knowledge of the areal extent and depth of snow cover is important. 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. MODIS snow-cover products are available for basin-scale studies at 500-m spatial resolution, and as global products at about 5.6-km resolution. The global products are useful as input to climate models.

Significant Findings

The significance of this paper is that it describes in detail the current state of the MODIS snow products so that potential users will be informed about their availability and utility. Additionally, there is a discussion of the validation activities so users can determine the usefulness of the products, and associated errors.

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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. Also the 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 ~5.6-km spatial resolution, with both daily and 8-day composite products. Each pixel of the CMG contains fraction of snow cover from 40 – 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 – 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.

KEY WORDS: snow cover, snow mapping, remote sensing

INTRODUCTION

Snow-cover maps of the Northern Hemisphere have been available since the late 1960s 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. But 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 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, Maryland. The products are transferred to the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, 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 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, New Hampshire, in March 2000, and field measurements in December 2000.

BACKGROUND

Instrument descriptions

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 et al., 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.

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.

The Landsat Enhanced Thematic Mapper Plus (ETM+)

The ETM+ was launched on April 15, 1999, on the Landsat-7 satellite (<http://landsat.gsfc.nasa.gov/project/satellite.html>). The ETM+ has 8 discrete bands ranging from 0.45 – 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: <http://edcns17.cr.usgs.gov/EarthExplorer/>. ETM+ data provide a high-resolution view of snow cover that can be used to compare with the MODIS and operational snow-cover products. But ETM+ data are only acquired once every 16 days and are therefore not frequent enough for mapping changing snow-cover conditions operationally.

Snow Maps

NOAA Operational snow maps

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, that 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 et al., 2000).

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.

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 et al. (2000). The MODIS maps provide global, daily coverage at 500-m and, at ~5.6-km resolution at the equator. The climate-modeling grid (CMG) products are at 1/20°th resolution which is ~5.6-km resolution. 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 40-100%) is already available in the CMG products. Because cloudcover often precludes the acquisition of snow cover from visible and near-infrared sensors, the daily maps are composited, and 8-day composite products are available. The climate modeling grid (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 (Figure 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 et al., 1995):

$$\text{NDSI} = \frac{\text{band 4} - \text{band 6}}{\text{band 4} + \text{band 6}} \quad [1]$$

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 pixel may be mapped as snow even if the NDSI is < 0.4 (Klein et al., 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 cloudcover, 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 et al., 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.

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)**.

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 cloudcover in snow-covered areas.

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 where 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. Since the land/water mask is only 1-km resolution, 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).

Swath product. The snow data-product sequence begins with a 5-minute swath segment (granule) (**Figure 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) (**Figure 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.

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 et al., 1998**) (**Figure 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 (**Figure 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. 8-day periods begin from the first day of a year. An example of the daily CMG product (as a special product) is shown in **Figure 4A**, with the corresponding 8-day CMG composite "special" product shown in **Figure 4B**. (Snow maps shown in Figure 4 are ~25-km resolution special, early products and are no longer produced.)

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 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 go find out when and where a storm deposited new snow cover. Also, the compositing technique minimizes cloud cover.

Daily and 8-day composite climate-modeling grid product. The eight-day composite climate-modeling grid (CMG) products are available to download from http://snowmelt.gsfc.nasa.gov/MODIS_Snow/modis.html, and from the National Snow and Ice Data Center (NSIDC). The daily global snow-cover CMG product will be available in 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 ~5.6-km spatial resolution of the 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 the extent of clouds in a cell. Other work (**Hall et al., in press**), using a special product as shown in **Figures 4A & 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. Therefore, the $1/20^\circ \times 1/20^\circ$ resolution CMG map products show snow-cover percentages only from 40-100% snow cover.

The 8-day composite map shown in **Figure 1** is produced at $1/20^\circ \times 1/20^\circ$ resolution, produced from the 8 days of the daily product from 24-31 October 2001, showing maximum snow extent and minimum cloud obscuration during the period. All 8 days of observations for a cell are examined. 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 0.02-0.10%.

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://nsidc.org/imswelcome>), and can access information about the MODIS snow products with links to related MODIS web pages <http://nsidc.org/NASA/MODIS/>.

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 **Figure 5**. **Figure 5A**, is a MODIS swath product of the East Coast of the United States, acquired on December 23, 2000. **Figure 5B**, of the same area on the same date, shows the snow map, but without the cloud mask. On **Figure 5B**, 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 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 due to its 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 that contain ice which 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 are under investigation.

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.

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 and Li, 1998). There has been much work undertaken to develop methods to map fractional snow cover (e.g., Rosenthal and Dozier, 1996; Nolin et al., 1993) 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. At least two algorithms are under development for mapping fractional snow cover using MODIS data (Barton et al., in press; Kaufman et al., submitted). 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. More work is needed to develop an automated algorithm that is effective globally to map fractional snow cover.

Cloudcover 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 (Robinson et al., 1984; Chang et al., 1987; Grody et al., 1996; Armstrong and Brodzik, 1999). The Advanced Microwave Scanning Radiometer (AMSR) will be launched on the Aqua satellite in 2001. The AMSR <http://198.122.199.205/AMSR/> will have improved spatial resolution relative to the Special Sensor Microwave/Imager (SSM/I) data that are currently available. 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 should be possible.

There are instances where 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. This is an error of omission and has not been estimated yet, but appears to be rather minor.

CASE STUDY

Northeastern United States

March 6, 2000. Shortly after the MODIS instrument began acquiring data, a one-day field and aircraft experiment was undertaken on March 6, 2000, in the area surrounding Keene, New Hampshire. 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 (Figure 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 350-420 g cm⁻³ at both sites. On

Figure 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 37-51%. 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 **Figure 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 x 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 m² and 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.

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 (**Figure 7**). The Keene, New Hampshire, 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 ~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 error when the NOHRSC image was registered to the MODIS image 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 **Figure 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).

Figure 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 **Figure 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 cloudcover. 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. Unfortunately an ETM+ scene from March 8, 2000, was cloudy. 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. Snow was also visible on the IMS product as seen in **Figure 8**. Since none of the snow maps agree, 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 ~6-8 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 registered to the ETM+ map, showed nearly continuous snow cover (**Figure 9**). The binary MODIS snow-mapping algorithm will map snow cover if ~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.

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 climate-modeling grid (CMG) product will be produced at ~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 field work 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 overestimation of snow cover as compared to the ETM+-derived map for the same day, as confirmed by field measurements.

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 wet snow causes the current passive-microwave snow-mapping algorithms not to map snow that is known to be there.

Future enhancements to the MODIS snow maps include daily snow albedo (**Klein et al., 2000**), which should be available in early 2002 and, fractional snow cover at 500-m spatial resolution (**Barton et al., in press; Kaufman et al., submitted**). Future re-processing will allow all of the MODIS snow maps to be processed in a consistent manner beginning with the September 13, 2000 data.

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FIGURES

1. 8-day composite global MODIS snow-cover map – December 18-25, 2000. Snow is white, clouds that persisted for all 8 days are pink and non-snow covered areas are light green; grey areas represent areas not imaged by MODIS due to darkness.
2. MODIS image (left) and snow map (right) – November 3, 2000. Snow is white, clouds are pink and non-snow covered areas are green; water is either dark blue (oceans or bays) or light blue (inland waters).
3. 3A. Location of tiles on the integerized sinusoidal grid; 3B 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.
4. 4A Daily MODIS snow maps of North America – December 18-25, 2000; 4B 8-day composite MODIS snow map of North America – December 18-25, 2000. Snow is white, clouds that persisted for 8 days are pink and non-snow covered areas are light green; grey areas represent areas not imaged by MODIS due to darkness ($SZA \geq 85^\circ$).
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. Snow is white, clouds are pink and non-snow-covered areas are green. Inland water is blue/green.
6. MAS image (left) and snow map (right) showing field sites near Keene, New Hampshire (at arrow) – March 6, 2000.
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.
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 IMS map in Canada, was removed in order to facilitate the comparison with the NOHRSC map.
9. Landsat-7 ETM+ (left) and MODIS (right) false-color images (top row) of Keene, New Hampshire and the surrounding areas; ETM+ (left) and MODIS (right) snow maps of the same area (bottom row) – December 23, 2000.