MODIS Snow-Cover Products

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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. These 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 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 is generated for long-term climate studies that require snow-cover information. Extensive quality assurance (QA) information is stored with the product. The snow product suite starts with a 500-m resolution swath snow-cover map which is gridded to the Integerized Sinusoidal Grid to produce daily and eight-day composite tile products. The sequence then proceeds to a climate-modeling grid product at 5-km spatial resolution, with both daily and eight-day composite products. A case study from March 6, 2000, involving MODIS data and field and aircraft measurements is presented. Near-term enhancements include daily snow albedo and fractional snow cover.

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. Currently NOAA has operational snow maps which provide snow-cover information on a daily basis. 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. Such 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. The products are transferred to the National Snow and Ice Data Center (NSIDC) in Boulder, CO, where they are archived and distributed. These products should represent improved input to hydrologic and general-circulation models, however, their accuracy has not yet been established.

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. In this paper, we describe the MODIS snow products, and discuss a case study of early validation efforts from a field and aircraft experiment in Keene, New Hampshire, in March 2000, and field measurements in December of 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. It 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 eight 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 accessed as browse products and ordered from the USGS EROS Data Center in Sioux Falls, SD from the following Web address: http://edcsns17.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.

Snow Maps

Operational snow maps

The National Operational 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 **(Carroll, 1995).** The NOHRSC 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.

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) produces 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).**

Description of the MODIS snow-mapping products and algorithms

The MODIS snow products are created as a sequence of products beginning with a swath (scene) and progressing, through spatial and temporal transformations, to an eight-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, in the future, at 5-km spatial 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 products. Because cloudcover often precludes the acquisition of snow-cover information from visible and near-infrared sensors, the daily maps are composited, and eight-day composite products are available. The 5-km resolution snow map is known as the climate modeling grid (CMG) product, and is specifically designed for use by climate modelers. It provides a global view of the Earth's snow cover (**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**):

$$NDSI = band\ 4 - band\ 6\ /\ band\ 4 + band\ 6 \qquad [1]$$

A pixel 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 make a pixel be classified, 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 a 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. Used together, the NDVI and NDSI provide a strong signal that can be exploited to classify snow-covered forests (**Klein et al., 1998**). MODIS bands 1 (0.620-0.670 μm) and 2 (0.841–0.876 μm) are used to calculate the NDVI.

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 persists.

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 $\geq 85°$.

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). The land/water mask will be discussed further in the *Issues and Limitations* section of this paper.

Swath product. The snow data-product sequence begins as a swath (scene) (**Figure 2**) at a nominal pixel spatial resolution of 500 m and a nominal swath coverage of 1354 km (cross track) by 2030 km (along track) (**Figure 2**). The swath product is produced from five minute segments of each MODIS orbit. Latitude and longitude data are stored 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 eight-day composite tile products. The second product 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° x 10° 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 eight-day composite maximum snow-cover product is produced for each tile by compositing eight days of the daily 500-m resolution products. If snow were present on any day in any location on the daily tile product, it

will show up as snow covered on the eight-day composite. Eight-day periods begin from the first day of a year.

Daily and 8-day composite climate-modeling grid product. The climate-modeling grid (CMG) products are currently produced as special products, and are not yet available. They should be available by the beginning of the 2001-2002 snow season. The daily global snow-cover CMG product will be 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-km spatial resolution of the CMG cells. The initial 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 5-km cell. Interpretation of fractional snow extent data can be difficult because of the extent of clouds in a cell. Other work (Hall et al., submitted) has shown that generating a binary 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 may overestimate snow cover as compared to operational maps.

The eight-day composite map shown in **Figure 1** is a special product at $\frac{1}{4}° \times \frac{1}{4}°$ resolution, produced from the eight days of the daily product. Maximum snow extent and minimum cloud obscuration is shown during the period. All eight 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. The planned eight-day composite CMG will be produced from the eight-day composite maximum snow-cover product tiles. The procedure is identical to that described for the daily global snow-cover CMG product.

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) that provides uniform support for data management across the DAACs, and the EOS Data Gateway (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. There are several unresolved issues in the MODIS snow-cover products. Two of particular importance are the usage of the MODIS cloud mask, and spurious detection of snow. These are described below.

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, while **Figure 5B**, of the same area on the same date, shows the snow cover, but without the cloud mask. On **Figure 5B**, all non-snow-covered areas are shown as green, including the clouds, and 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 **Figure 5B**, without the cloud mask, is a more realistic depiction of the actual snow cover than is shown in **Figure 5A**. The snow algorithm is not applied when the surface viewed is in darkness. 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 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. In the near future, we will investigate other spectral tests with the intention of implementing tests or combinations of tests that are better suited to snow mapping. In other words, we will be looking for other tests of the cloud mask that allow us to map fewer clouds and more snow cover.

The MODIS cloud mask errs in identifying clouds along coastlines and other water bodies when there are no clouds present. Also, on edges of snow-covered regions, a halo of "cloud," one-to-three pixels wide is often mapped when no clouds are observed in the region (see, for example, snow in **Figure 4A**). That observation appears to be related to a fuzzy boundary between snow cover and non-snow-covered land. Confusion of cloud over snow has also been observed in regions of rugged snow-covered terrain, e.g., the Sierra Nevada in California.

Spurious snow cover is detected along some coastlines (e.g., the west coast of Florida and the California coast and the northeastern coast of South America) (**Figure 1**). These areas consist of a few pixels that are mapped as snow cover, however no snow exists there on the ground. Initial analysis indicates that there is a mismatch between the land/water mask and the MODIS image data. In some cases the land/water mask, which is 1-km resolution, does not accurately map the coastline at least at the 500-m resolution of the snow maps. In addition, some beaches are misidentified as snow as shown in **Figure 6** which shows an area just south of San Francisco. The snow-mapping algorithm is mapping some pixels as snow just inland from the ocean. If the land/water mask were perfectly registered to the snow map, these beaches (erroneous snow pixels) would be on

the coastline. They probably represent mixed pixels (water and beach). The mixed pixels may have the reflectance characteristics similar to snow.

Furthermore, some small inland water bodies are not mapped by the land/water mask. The snow-mapping algorithm may map these water bodies as snow covered especially if they contain shallow water, which often has a relatively high reflectance. Additional work is needed in order to characterize the cause of misidentified snow and then to eradicate it in an objective way.

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 (**Figure 7**). 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 7**). A third site, Spofford Lake, was not safe for in-situ measurements due to the thin ice. 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 7** 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 7**. 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. MODIS data from the same day also show patchy snow near Keene as shown in the MODIS snow map in **Figure 8**. 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 8**). 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 primary area of disagreement among 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 8**) 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, e.g., 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).

The NESDIS IMS product shows some snow in the Catskills, as do ETM+ images from March 8, 2000, in which some snow can be seen through cloudcover. Combined with analysis of individual bands of Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and MODIS, the conclusion is that the NOHRSC map overestimates the snow cover, but the MODIS snow map, though closer to reality, may underestimate the snow cover somewhat. The exact amount of snow cover is unknown.

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. An algorithm is under development to map percent snow cover at the subpixel scale (**Barton et al., in press; Kaufman et al., submitted**).

DISCUSSION AND CONCLUSION

A sequence of MODIS snow-cover products is presented. The orbital 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-km resolution and will consist 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.

Comparison of different snow-cover maps reveals a discrepancy in the amount of snow mapped in a forested area in south-central New York on March 6, 2000. It was determined that the NOHRSC map overestimated the snow cover there and the MODIS map, while it may have underestimated the snow cover somewhat, appeared reasonable when the meteorological and other satellite data were considered. The actual snow cover was not known. Other work shows that the MODIS snow-cover maps compare well with current operational maps, and are superior to passive-microwave-derived snow-cover maps **(Hall et al., submitted).**

Near-term future enhancements to the MODIS snow maps include daily snow albedo **(Klein et al., 2000),** which should be available in the summer of 2001, fractional snow cover **(Barton et al., in press; Kaufman et al., submitted)** and production of a climate-modeling grid that will permit global studies and will provide consistent input to climate models.

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FIGURES

1. Eight-day composite global MODIS snow-cover map – December 18-25, 2000. Snow is white, clouds that persisted for all eight 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 Eight-day composite MODIS snow map of North America – December 18-25, 2000. Snow is white, clouds that persisted for eight days are pink and non-snow covered areas are light green; grey areas represent areas not imaged by MODIS due to darkness (SZA≥85°).
5. MODIS snow map of the Eastern United States (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. A natural-color MODIS reflectance image (bands 1,4,3) is shown on the left. The box outlines an area south of San Francisco, California. At right the MODIS snow map of the area in the box is shown with spurious snow and cloud pixels. A portion of the snow map is overlain on the natural-color image below it, showing the mismatch of the land/water mask and the snow map.
7. MAS image (left) and snow map (right) showing field sites near Keene, New Hampshire – March 6, 2000.
8. 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.
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.
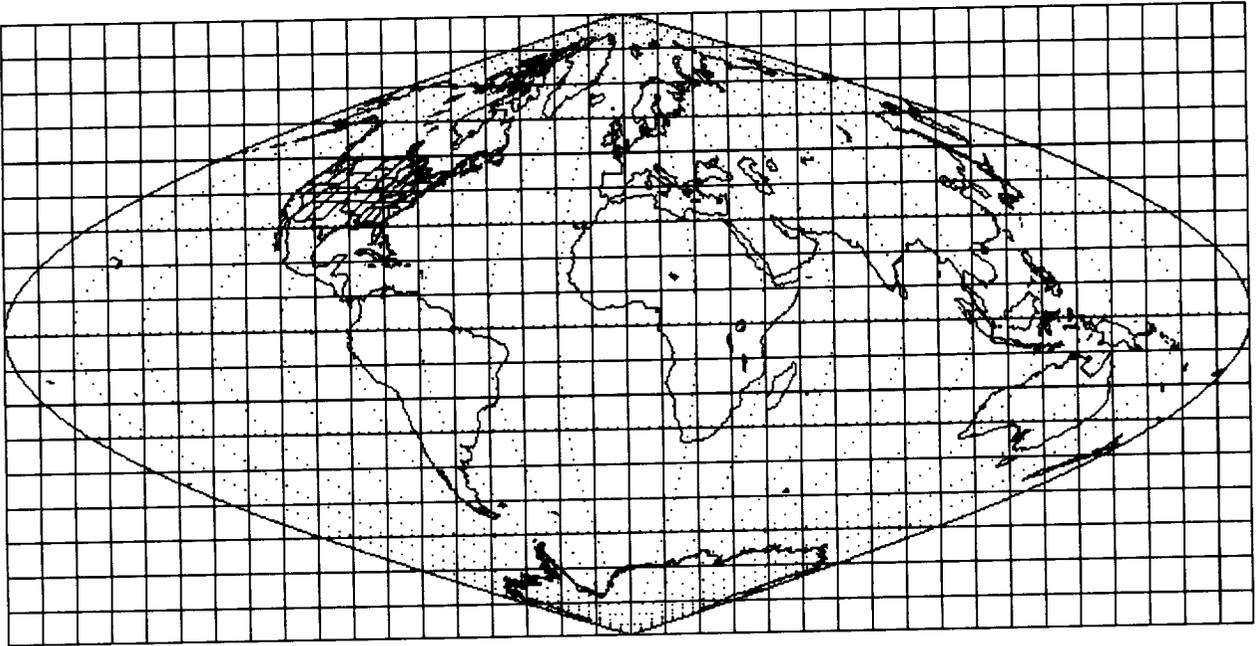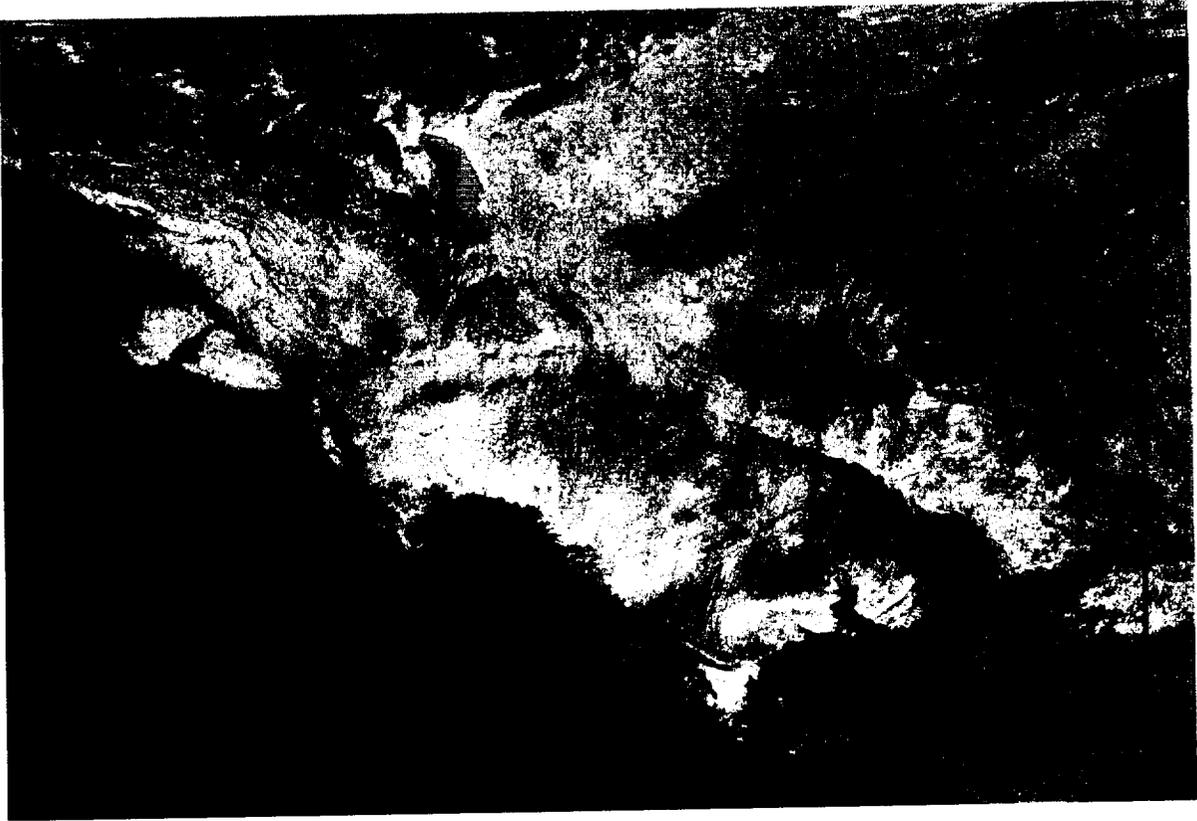
Snow ☐   Non-snow ▦   Darkness ▪   Cloud ▪

MODIS bands 1, 4, 3
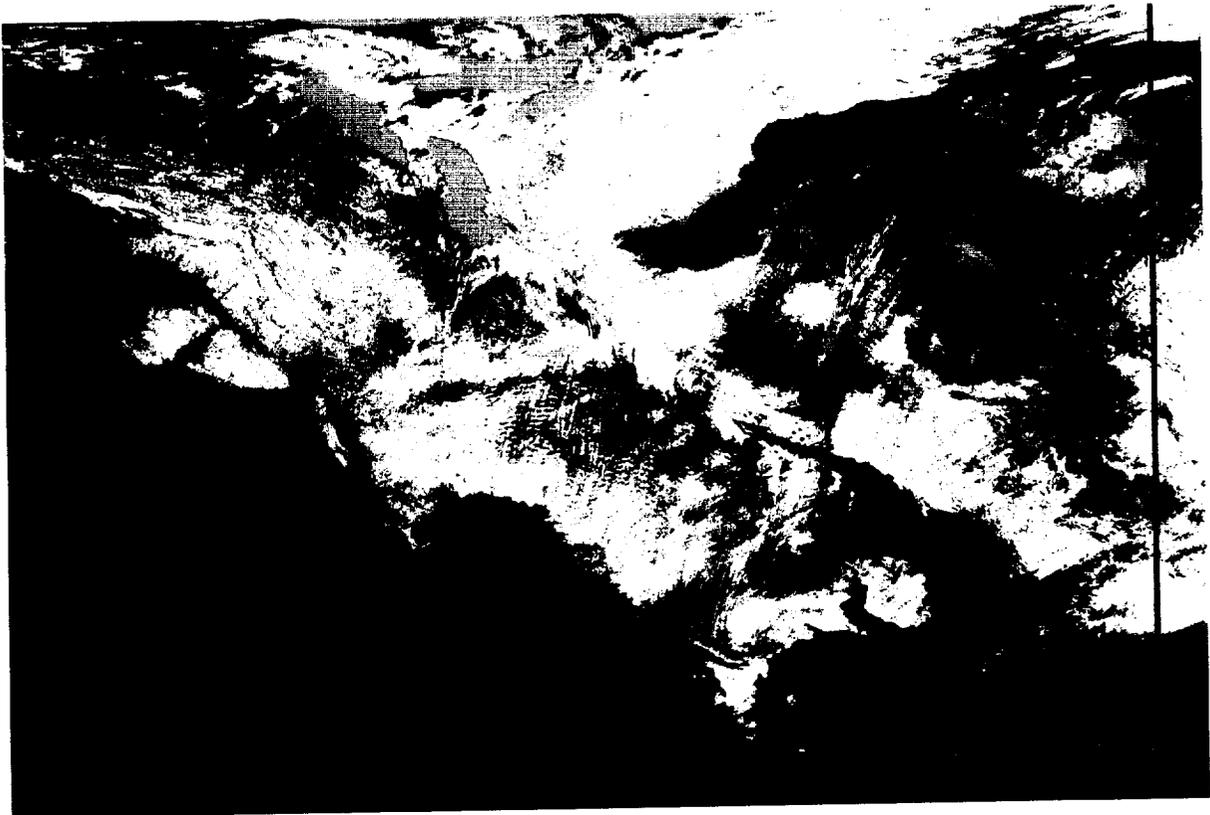
CANADA

A

HUDSON
BAY

Snow

Non-snow

Inland
water

Cloud

46

44

42

25 —123 —121 —119 —117 —115 —1⎵3 —111 —109 —107⎵1   79 —77 —

40

Dec. 21, 2000

Dec. 20, 2000

Dec. 19, 2000

Dec. 18, 2000

Dec. 25, 2000

Dec. 24, 2000

Dec. 23, 2000

Dec. 22, 2000

☐ Snow

■ Non-snow

■ Darkness

■ Cloud

Snow   Cloud   Non-snow   Inland water

December 18-25, 2000

☐ Snow ■ Non-snow ■ Darkness ■ Cloud

Bands 11, 6, 1

Tenant
swamp

Golf
course

Keene
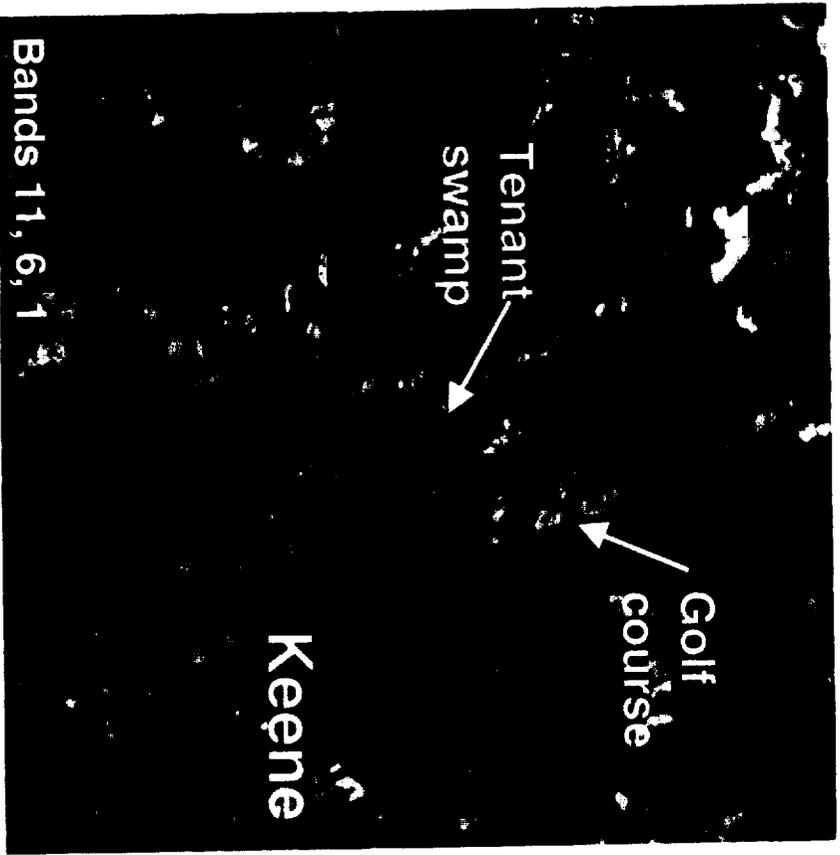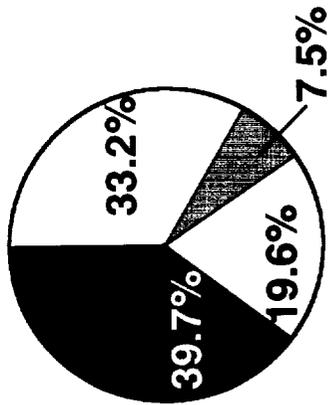
March 6. 2000

Snow on both

Snow on NOHRSC

Snow on MODIS

Clouds

33.2%

7.5%

39.7%

19.6%

South-central NY

Snow
depth
(cm)

8
7
6
5
4
3
2
1
0

Met. stations