

Algorithm intercomparison for accuracy assessment of the MODIS snow-mapping algorithm

Andrew G. Klein,^{1,2} Dorothy K. Hall² and Klaus Seidel³

ABSTRACT

MODIS, the Moderate Resolution Imaging Spectroradiometer (MODIS), is scheduled for launch in late 1998 or 1999 aboard the first Earth Observing System (EOS) platform. Global, daily snow-cover maps with a spatial resolution of 500 meters will be produced from MODIS data using a fully-automated and computationally-frugal snow-mapping algorithm. Recently, modifications to the original snow-mapping algorithm have been made to improve the accuracy of the MODIS snow-mapping algorithm in forests. To determine if these modifications provide improved snow mapping, and to assess the potential accuracy of MODIS snow maps, an intercomparison with snow maps created from three other snow-mapping algorithms was undertaken. The enhanced MODIS algorithm consistently identifies a higher proportion of pixels as snow than does the original. Comparisons with other snow-mapping algorithms demonstrate the enhanced MODIS algorithm does offer improved snow detection over the original.

INTRODUCTION

In late 1998 or 1999, the Moderate Resolution Imaging Spectroradiometer (MODIS) is scheduled for launch aboard the first NASA Earth Observing System (EOS) platform. MODIS is designed to provide a global view of the Earth – daily at high latitudes, every other day at low latitudes. These global data will provide quantitative measures of numerous geophysical parameters, including snow cover (Salomonson *et al.*, 1992). Compared to currently operational polar-orbiting environmental

satellites such as the Advanced Very High Resolution Radiometer (AVHRR), MODIS offers higher spatial resolution and more spectral bands (**Table I**) which will enable improved snow detection.

Table 1. Properties of the MODIS Land Bands

Band Number	Bandpass (nm)	Nadir Resolution (m)
1	620-670	250
2	841-876	250
3	459-479	500
4	545-565	500
5	1230-1250	500
6	1628-1652	500
7	2105-2155	500

During the past several years, a computationally frugal snow-mapping algorithm has been developed for detecting snow-covered pixels in MODIS images. The algorithm uses at-satellite radiances to map snow globally on a daily basis for the high latitude seasonally snow-covered portions of the earth. Cloud masking will be performed using the MODIS cloud mask that utilizes sophisticated cloud-detection techniques (Ackerman *et al.* 1996).

Since the MODIS sensor is not currently in orbit, the MODIS snow-mapping algorithm was developed using Landsat Thematic Mapper (TM) as a surrogate for MODIS. While the Landsat TM does approximate some of the MODIS spectral bands, it is not perfect MODIS surrogate. In particular, Landsat is a nadir-viewing instrument while MODIS scans $\pm 55^\circ$ off-nadir.

While development of an accurate MODIS snow-mapping algorithm is possible using Landsat TM

¹Department of Geography, MS 3147, Texas A&M University, College Station, TX 77843-3147

²Hydrological Sciences Branch, Code 974 NASA/Goddard Space Flight Center, Greenbelt, MD 20771

³Swiss Federal Institute of Technology (ETHZ), CH 8092, Zürich, Switzerland

data, validating the performance of the algorithm using TM images is difficult. The long repeat cycle (16 days) and the high cost of Landsat data preclude obtaining large amounts of Landsat data for evaluating the performance of the MODIS snow-mapping algorithms for multiple areas over an entire seasonal cycle. Even if extensive Landsat time series were available, validation of the MODIS snow algorithm is hampered by difficulty in obtaining independent measurements of snow-cover extent.

In an effort to overcome these limitations, validation of MODIS snow cover products has been accomplished through intercomparisons with other snow mapping algorithms. Two of these products, one developed at the University of California–Santa Barbara (UCSB) for the Sierra Nevada, California, and another developed at the Swiss Federal Institute of Technology (ETHZ) for the Upper Rhein-Felsberg basin in Switzerland, are area-specific. As such they provide a valuable comparison of a global MODIS algorithm with more complex and presumably more accurate algorithms tailored to a specific area.

The third algorithm is the operational snow-cover algorithm used for portions of the United States and Canada by the National Operational Hydrologic Remote Sensing Center (NOHRSC). Unlike the fully automated processes that is used to produce MODIS snow cover products, NOHRSC products utilize the talents of highly trained operators with considerable experience in mapping North American snow cover. In the post-launch period, NOHRSC products will be a primary dataset for comparison with MODIS snow-cover products. These algorithm intercomparisons, while not exhaustive, provide an initial evaluation of the expected performance of the MODIS snow-mapping algorithm before the MODIS instrument is launched.

MODIS SNOW-COVER MAPPING ALGORITHM DESCRIPTION

Snow has two unique spectral properties in the visible, near and shortwave-infrared portion of the spectrum (0.4 to 2.5 μm) that enable it to be distinguished from other surface covers. These are its high reflectance in the visible wavelengths (MODIS band 4 or Landsat TM band 2 (0.52–0.62 μm)) and its low reflectance in the short-wave infrared (MODIS band 6 or Landsat TM band 5 (1.55–1.75 μm)). The MODIS snow-mapping algorithm makes use of this unique spectral combination in a fully-automated and computationally-frugal approach to snow detection (Hall *et al.*, 1995; Riggs *et al.* 1996). Recently, modifications to the original MODIS snow-

mapping algorithm have been made to improve snow detection in forests (Klein *et al.* in press).

The current version of the MODIS snow-mapping algorithm uses a set of grouped decision tests to detect snow. The primary criterion for determining if a pixel contains snow is the Normalized Difference Snow Index (NDSI). The NDSI owes its heritage to the commonly used Normalized Difference Vegetation Index (NDVI). This index captures the snow's unique combination of a high visible reflectance and a low short-wave infrared reflectance in a single quantity. For MODIS the NDSI is calculated as:

$$NDSI = \frac{(MODIS4 - MODIS6)}{(MODIS4 + MODIS6)}$$

and for Landsat TM:

$$NDSI = \frac{(TM2 - TM5)}{(TM2 + TM5)}$$

Snow is characterized by much higher NDSI values than most other surface covers. In the original MODIS snow-mapping algorithms pixels meeting two criteria were classified as snow. The primary classification criterion was that pixels with an NDSI value greater than or equal to 0.40 were considered to be snow. Secondly, because pixels containing water can also have high NDSI values, a threshold in the near-infrared wavelengths (MODIS band 2, TM band 4 (0.76–0.90 μm)) of 11% or greater was used to separate snow from water. This criteria test is used because the near-infrared reflectance of water is very low.

However, as can be seen in **Figure 1**, many forested pixels containing snow have NDSI values considerably lower than 0.40. To correctly classify these forests lower NDSI values must be considered snow-covered. The ideal approach would be to use land cover information to separate forested from non-forested areas and have separate classification criteria for the two classes. However, this approach is precluded at the current time because global land cover maps at sufficient resolution simply do not exist.

Instead, lowering the allowable NDSI value for forested cases, while limiting potential impacts in non-forested areas, is accomplished by using the pixel's NDVI in combination with the its NDSI. This combination enables snow-free from snow-covered forests to be distinguished. Improvement in snow-mapping accuracy has been seen for both coniferous

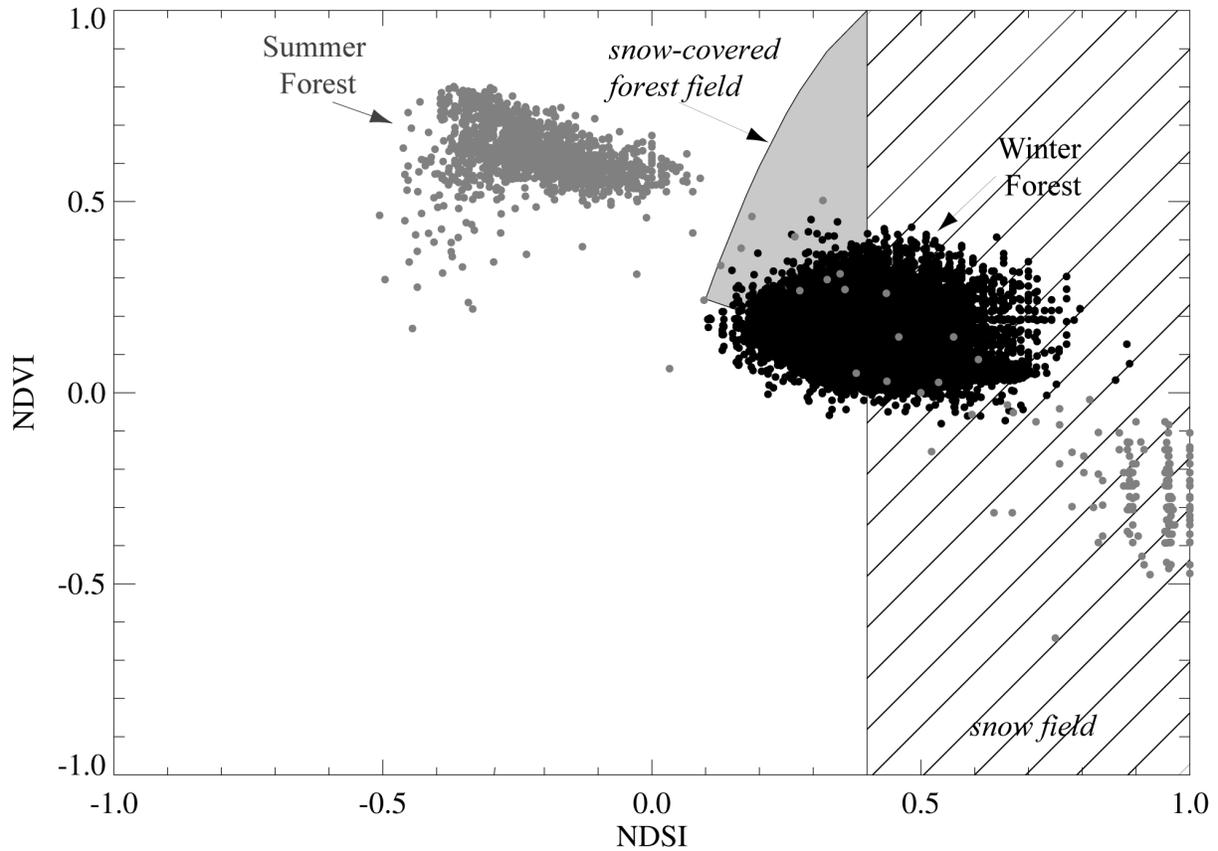


Figure 1. Major classification criteria for the enhanced MODIS snow-mapping algorithm.

and deciduous canopies. However, sufficient data do not yet exist to determine in which forest type improvement will be the greatest. An additional NDSI-NDVI field (the gray field in **Figure 1**) was added to the existing snow classification criteria to improve the mapping of snow-covered forests. The NDSI-NDVI field was constructed through analysis of Landsat TM images and canopy modeling. The selected area attempts to enclose the maximum possible range of NDSI-NDVI values observed for snow-covered forests. However, pixels containing a mix of snow and soil overlap with the snow-covered forest values below the lower (straight) boundary of NDSI-NDVI field. The position of the lower boundary represents a compromise between mapping too little forest and mapping too much non-forested areas as snow. Had additional NDSI-NDVI values been included, non-forested pixels containing only a small fraction of snow would have been mapped as snow

One other classification criterion was added. A reflectance in MODIS band 4 of greater than or equal to 10% is required for a pixel to be classified as

snow. This prevents dark targets, such as very dense coniferous forest stands, from being classified as snow despite high NDSI values. As MODIS data become available after launch, the MODIS snow-mapping algorithm will continue to be refined and improved.

ALGORITHM VALIDATION ACTIVITIES

In the time prior to the launch of MODIS, the performance of the original and enhanced snow-mapping algorithms is being evaluated using images collected by both satellite and airborne sensors. These 'pre-launch' validation activities serve several purposes. The first is to determine which version of the MODIS snow-mapping algorithm, the original or enhanced, to implement as the 'at-launch' version of algorithm. Secondly, the validation activities are used to provide a preliminary estimate of how well the MODIS snow-mapping algorithm can be expected to perform. Thirdly, these validation activities serve to help develop improved validation strategies for use after MODIS is launched – the so called 'post-launch' period.

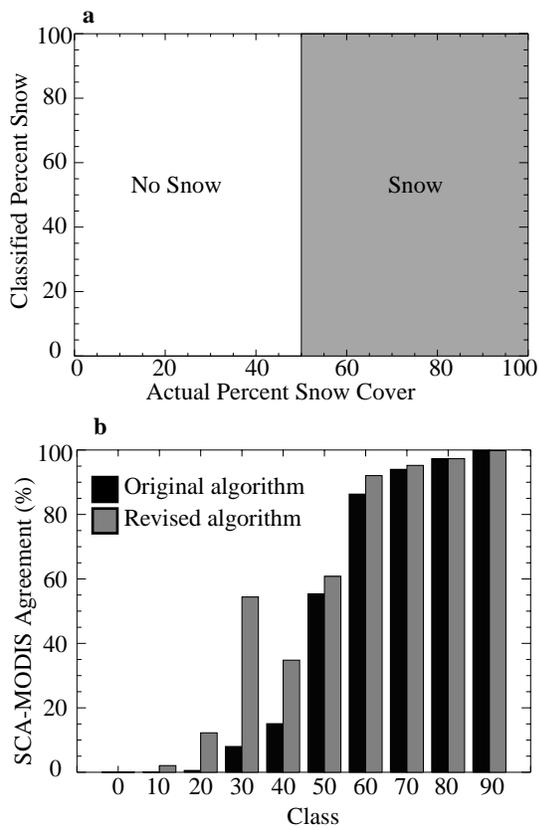


Figure 2. (a) A perfect binary classifier, (b) performance of the original and enhanced MODIS snow-mapping algorithms

Sierra Nevada, California

One question that has been raised concerning the MODIS algorithm is how closely does it approximate the behavior of a perfect binary snow classifier (e.g. **Figure 2a**). Ideally, the MODIS snow-mapping algorithm would classify pixels with 50% or greater snow cover as snow and those with less than this amount as snow free. In reality, the behavior of the MODIS snow-mapping algorithm could deviate considerably from this ideal behavior. Assessing the actual behavior of the MODIS snow-mapping algorithm is limited by the lack of suitable independent estimates of snow-covered area for comparison.

Currently, the best algorithm to compare the MODIS results to is the snow-covered area (SCA) algorithm developed by Rosenthal and Dozier (1996). This algorithm uses a combination of spectral mixture analysis and a decision tree approach to make quantitative determinations of SCA at a sub-pixel level. The algorithm was developed for the Sierra Nevada, California and has undergone validation using high-resolution aerial photography.

Snow-cover classification was performed using both the SCA and MODIS algorithms using Landsat TM data at spatial resolutions ranging from the original 28.5 m TM resolution to 1 km (**Figure 3**). The original MODIS snow-cover algorithm correctly classifies the majority of pixels containing at least

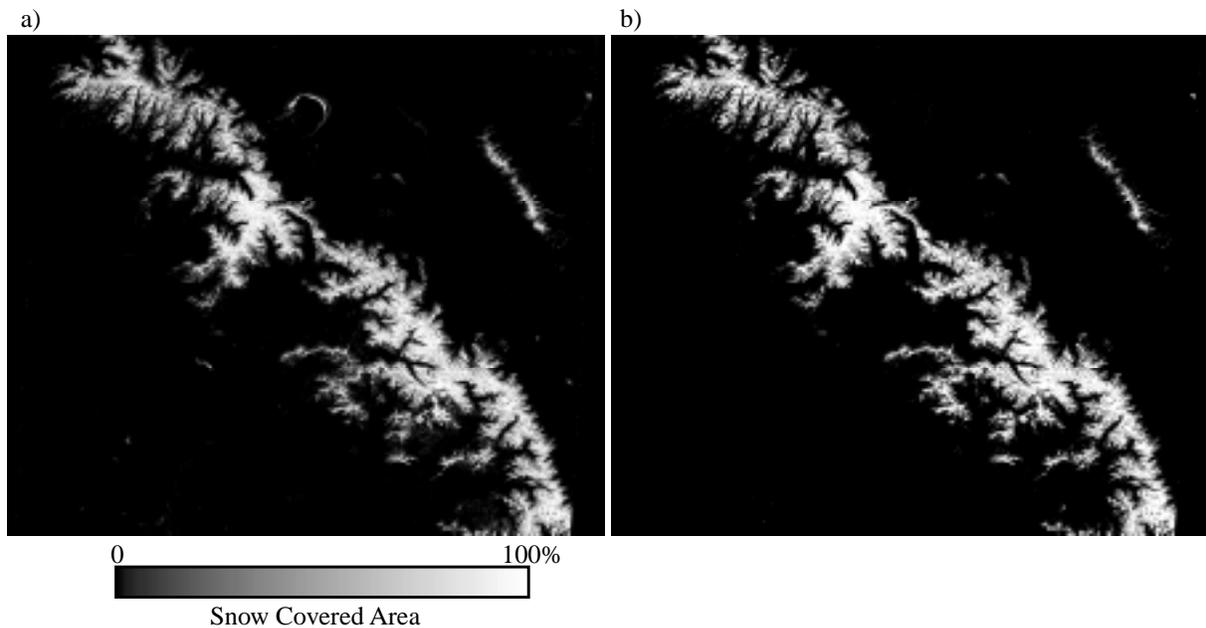


Figure 3. Comparison (a) the SCA algorithm and (b) the enhanced MODIS snow-mapping algorithms for the Sierra Nevada, California.

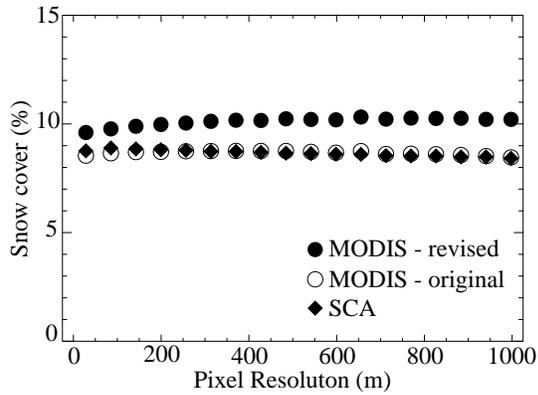


Figure 4. Comparison of the total snow-covered area calculated by the SCA algorithm and the original and enhanced MODIS snow-mapping algorithms

50% snow-cover as estimated by the Rosenthal and Dozier (1996) algorithm as snow. In addition, a low percentage of pixels with less than 50% snow cover

are classified as snow. Thus, the original and enhanced MODIS snow-mapping algorithms approximate the behavior of an ideal binary snow classifier for this alpine region (Figure 2b). The enhanced MODIS algorithm classifies a greater proportion of pixels with less than 50% snow cover as snow and thus, in this single case, deviates more from the behavior of ideal binary classifier than the original algorithm.

An area of concern for hydrologic modeling is the accuracy of MODIS derived estimates of total snow-covered area for a region. A comparison of the snow-covered area determined by the SCA and the MODIS algorithms for the May 10 Landsat scene is shown in Figure 4. For this scene, the original MODIS algorithm and the SCA algorithm are quite comparable. However, the enhanced MODIS algorithm maps a higher total area of snow (~2%) greater.

The reason for this discrepancy is the larger percentage of pixels with low SCA mapped as snow in the enhanced versus the original MODIS algorithm

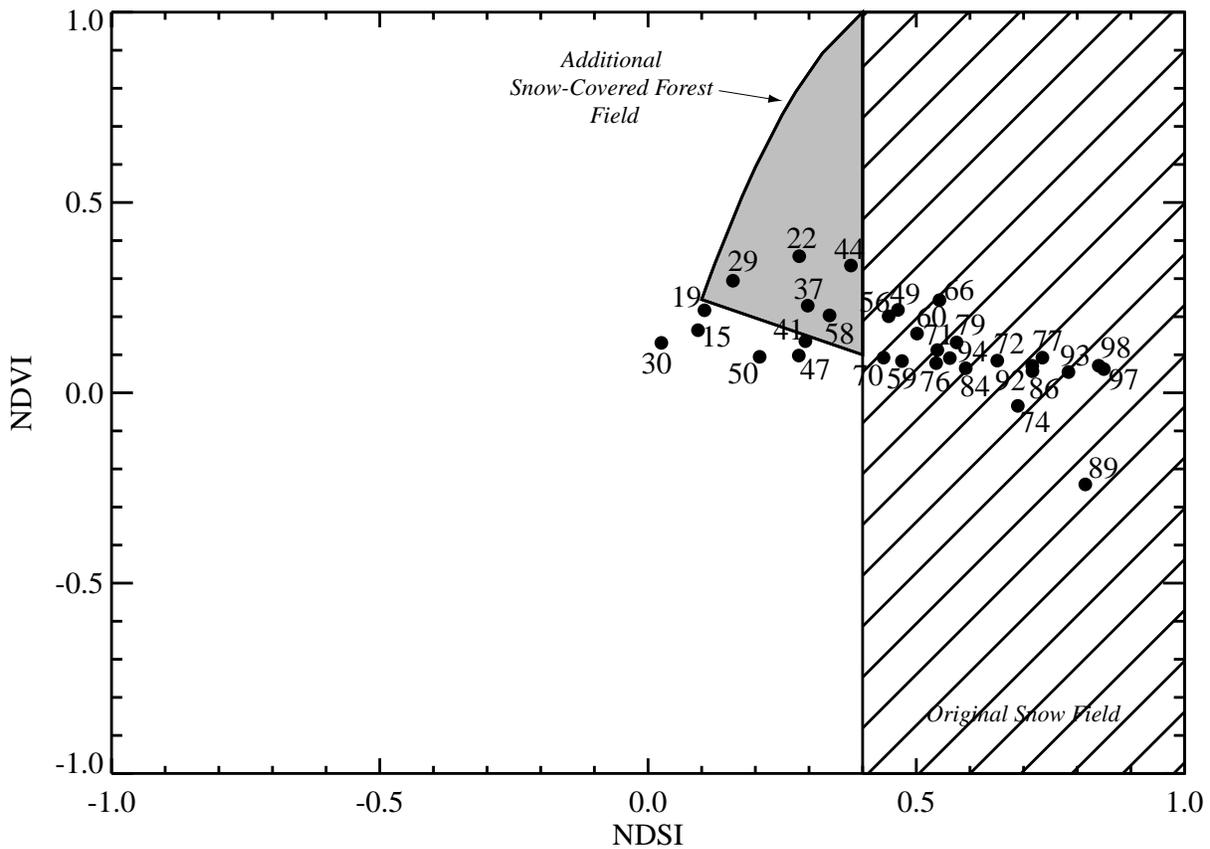


Figure 5. Mean NDSI-NDVI values for individual SCA classes determined from a MODIS image spatially degraded to 500 meter resolution of MODIS. The major classification criteria for the enhanced MODIS snow-mapping algorithm are also shown.

(Figure 2b). By examining the mean NDSI-NDVI values for each individual SCA class (**Figure 5**), it can be seen that with the exceptions of the SCA classes 50% and 58%, the mean NDSI values for classes < 50% fall outside the snow classification field of the original MODIS algorithm. The only SCA class < 50% that has a mean NDSI value in excess of 0.4 is the SCA 49% class. The additional classification field in the enhanced algorithm (**Figure 5**) encompasses the mean NDSI-NDVI values of several additional SCA classes causing a significantly higher proportion of pixels have snow-covered area of < 50% to be classified as snow by the enhanced MODIS algorithm.

Comparing the SCA algorithm with the MODIS algorithms suggests that for this single scene the proposed revisions to the MODIS algorithm do not offer improved snow detection. However, it is also known that the performance of the SCA and original MODIS algorithm differs depending on the Landsat scene used in the analysis (J. Shi personal communication). Also as will be demonstrated by the two other comparisons, any single area or algorithm is inadequate for assessing the accuracy or relative performance of the original and enhanced MODIS snow-mapping algorithms that will be used to map snow on a global basis.

Upper Rhein-Felsburg Basin, Swiss Alps

While the Sierra Nevada serves as a useful comparison between the MODIS snow-mapping algorithm and a well-validated regional algorithm, it does not indicate how well the MODIS snow-mapping algorithm will perform in other alpine environments. The upper Rhein-Felsberg basin in the eastern Swiss Alps serves as a good additional study

area as both the requisite satellite images and independent estimates of snow-cover extent are available.

As part of a study examining the impact of climate change scenarios on seasonal runoff modeling by researchers at the Swiss Federal Institute of Technology (ETHZ), the areal extent of snow in the basin has been periodically mapped using Landsat TM, MSS and SPOT-XS images (Seidel *et al.* 1997). The snow-mapping technique employed is more sophisticated than the MODIS snow-mapping algorithm. A Digital Elevation Model (DEM) is utilized to segment the satellite images into different illumination classes prior to classifying bare ice, snow and snow-free and transition zones using multivariate statistics (Ehrler and Seidel, 1995).

A comparison of the ETHZ and MODIS algorithms was performed for a portion of two Landsat TM scenes (May 25 and July 12, 1994) covering the basin. As can be seen in **Table 2**, the enhanced MODIS algorithm maps more of both the ETHZ snow-covered and transitional classes (50% snow covered) as snow than does the original. However, both MODIS algorithms have large errors of omission, particularly in the 12-July 1994 scene, when only one-half of the snow-covered pixels are mapped as snow by either MODIS algorithm.

In the July 12 image, a significant proportion of the all the pixels classified as snow by the enhanced and original MODIS algorithms (28.8% and 26.4% respectively) were not classified as either snow or transitional by the ETHZ algorithm. Visual examination show some of these areas to be bare glacier ice or influenced by cloud or topographic shadowing, but in many instances it is unclear why they failed to be classified as snow by the ETHZ

Table 2. Percentage of pixels within different classes as determined by the ETHZ algorithm classified as snow by the MODIS algorithms

For <i>All</i> Areas	25 May 94		12 July 94	
	Original	Enhanced	Original	Enhanced
Snow Areas	69.65%	84.65%	45.00%	54.12%
Transitional Areas	32.14%	47.93%	14.69%	21.30%
Non-Snow Areas	02.35%	04.41%	01.02%	01.45%

For <i>Forested</i> Areas	25 May 94		12 July 94*	
	Original	Enhanced	Original	Enhanced
Snow Areas	61.04%	76.26%	—	—
Transitional Areas	22.91%	37.32%	—	—
Non-Snow Areas	0.28%	0.75%	—	—

*Forested areas on 12 July 1994 contain too few snow-covered pixels for reliable statistics

algorithm.

This comparison demonstrates several things. The first is that the MODIS snow-mapping algorithms appear to perform adequately, if imperfectly, in other mountain areas besides the Sierra Nevada. Secondly, the enhanced MODIS algorithm appears to outperform the original compared to the ETHZ algorithm. Lastly, in MODIS validation activities, care must be taken when assuming that the comparison data sets are themselves providing accurate maps of snow cover extent.

Northeastern United States

During the northern-hemisphere snow season, daily snow cover maps are created for the conterminous United States, Alaska, and the southern portions of Canada by NOHRSC. Images from multiple satellites including AVHRR and the Geostationary Operational Environmental Satellite (GOES) are used in the construction of the NOHRSC snow maps (Hartman *et al.* 1995). Snow detection is accomplished via a multispectral snow classification algorithm (theta) that is designed to distinguish snow from cloud, land, and water over North America. Unlike the MODIS snow-mapping algorithm, the theta algorithm is not fully automated. An analyst is required to set classification thresholds and mixed pixels must be resolved subjectively (Maxson *et al.*, 1996). Because of their extensive daily coverage, NOHRSC operational products are and will remain an important dataset for MODIS snow cover validation activities.

Snow maps derived from Landsat TM using both the original and enhanced MODIS snow-mapping algorithms were compared with daily NOHRSC products. The comparison included two Landsat TM images acquired during the 1997 WINTER Cloud Experiment (WINCE) which focused on improving cloud-snow discrimination in the MODIS cloud mask. One Landsat image (path 014 row 031) covering southern New York, and portions of Pennsylvania, New Jersey and Connecticut was acquired on February 13. A second TM image (path 13 row 30) was acquired on January 21 and covered portions of Vermont, New Hampshire, and Massachusetts. At the time of image acquisition, extensive snow-covered areas occurred in both images. In addition, large tracts of both images are forested.

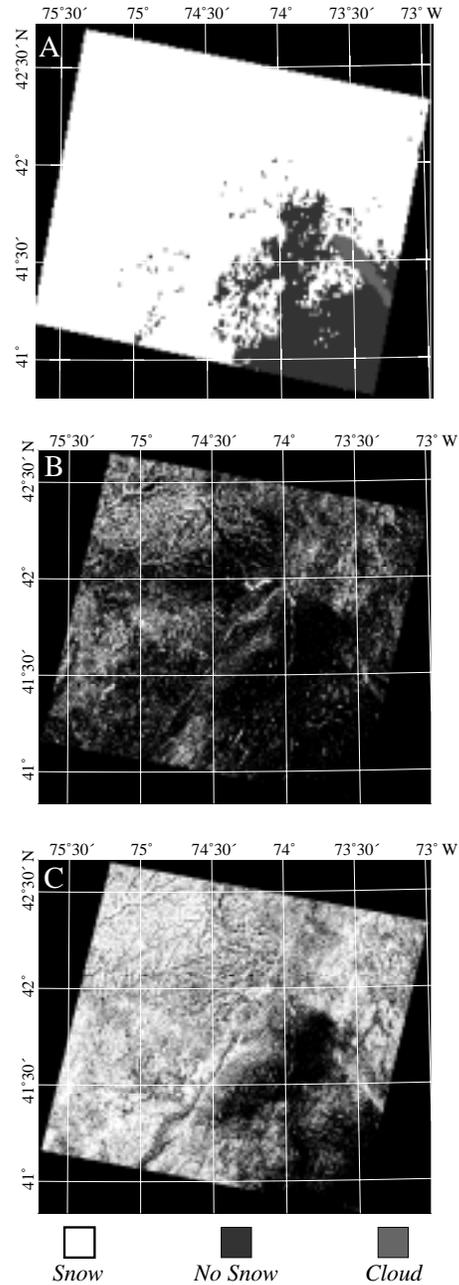


Figure 6. Snow cover maps from the (a) NOHRSC, (b) original MODIS and (c) enhanced MODIS algorithms

A comparison of the snow maps derived from the original and enhanced algorithms, reveals that for both areas, the enhanced algorithm mapped significantly more snow than did the original (**Table 3**). This comparison strongly suggests, but does not conclusively prove, that the enhanced snow-mapping algorithm outperformed the original.

However, comparison of the February 13, 1997 Landsat TM scene with the NOHRSC snow map for the same day indicates strongly that the enhanced MODIS algorithm does improve upon the original (**Figure 6a**). Given the different resolutions of the image inputs into the NOHRSC and MODIS algorithms, only qualitative comparisons are possible. However, the area mapped as snow by the original MODIS algorithm is considerably less than that mapped as snow by NOHRSC (**Figure 6b**). Land cover appears to strongly control the classification accuracy of the original MODIS algorithm in this area. Much of the snow mapped by the original algorithm lies in valleys, which in this region are more likely to be cropland or urban areas than the hillslopes that are commonly forested.

The snow map from the enhanced algorithm (**Figure 6c**) shows a much better correspondence to the NOHRSC product. This is due primarily to the higher proportion of forested areas mapped as snow by the enhanced algorithm. Fieldwork conducted in the region on February 9th indicates that snow cover was extensive in both forested and non-forested areas at the time of image acquisition. There is also good correspondence between mapped snow-free areas occupying lower elevation areas in all snow maps. This suggests that errors of commission (e.g. snow-free areas incorrectly identified as snow covered) will pose much less of a problem in the MODIS algorithm than errors of omission. In the post-launch time frame, operationally-produced NOHRSC snow maps will continue to serve as an important comparison for developing assessments of MODIS snow-cover products.

CONCLUSIONS

Based on three algorithm intercomparisons, both

Table 3. Percentage of each Landsat TM Scene classified as snow by the original and enhanced snow-mapping algorithms

	Original	Enhanced
January 21, 1997	16%	34.5%
February 13, 1997	19%	55%

the original and enhanced MODIS snow-mapping algorithms appear to map snow in a variety of settings. While the original algorithm performs slightly better compared to a snow covered area algorithm developed specifically for the Sierra Nevada, it maps significantly less snow in areas of the eastern United States containing forests than the enhanced MODIS snow-mapping algorithm. Forests still remain a problem in the enhanced MODIS algorithm, which for southern New York maps less snow than the NOHRSC algorithm. The enhanced algorithm appears to perform better than the original algorithm compared to an algorithm developed by ETHZ for the Upper Rhein-Felsburg Basin in the Swiss Alps.

ACKNOWLEDGEMENTS

Milan Allen of the National Hydrological Remote Sensing Center kindly provided the NOHRSC snow products used in this comparison. Walter Rosenthal of the University of California – Santa Barbara provided access to the Sierra Nevada Landsat Thematic Mapper scene and the SCA software used in this study. Janet Chien (General Sciences Corporation) provided valuable computer support.

BIBLIOGRAPHY

Ackerman, S., Strabala, L., Menzel, P., Frey, R., Moeller, C., Gumley, L., Baum, B. Schaff, C., Riggs, G., Welch, R. 1996. 'Discriminating Clear-Sky from cloud with MODIS', *Algorithm Theoretical Basis Document (MOD35)*, Version 3.0, pp. 109.

Hall, D. K., Riggs, G., A., and Salomonson, V. V. (1995). Development of methods for mapping global snow cover using moderate resolution imaging spectroradiometer data. *Remote Sensing of Environment* **54**, 127-140.

Ehrler, C. and Seidel, K. 1995. Mutual effects of the climate change the alpine snow cover and their influence on the runoff regime evaluated with the aid of satellite remote sensing. In "1995 International Geoscience and Remote Sensing Symposium (IGARSS'95)," Florence, Italy, pp. 1973-1975.

Hartman, R.K., Rost, A.A., and Anderson, D.M. 1996. Operational processing of multi-source snow data. In "Third International Conference/Workshop on Integrating Geographic Information Systems and Environmental Modeling". Santa Fe, New Mexico.

Klein, A.G., Hall, D.K., and Riggs, G.A.. in press. Improving snow-cover mapping in forests through the use of a canopy reflectance model. *Hydrological Processes*.

Maxson, R.W., Allen, M.W., and Szeliga, T.L. 1996. Theta – image classification by comparison of angles created between multi-channel vectors and an empirically selected reference vector. *1996 North American Airborne and Satellite Snow Data CD-ROM*, Chanhessen, Minnesota: National Weather Service.

Riggs, G. A., Hall, D. K., Feind, R. E., and Welch, R. (1996). A comparative look at two algorithms for mapping snow cover from Earth Observing System Instruments. In “Proceedings of the 53rd Eastern Snow Conference”, May 2-3, 1996, Williamsburg, VA. pp. 1-11.

Rosenthal, W., and Dozier, J. (1996). Automated mapping of montane snow cover at subpixel resolution from the Landsat Thematic Mapper. *Water Resources Research* **32**, 115-130.

Salomonson, V. V., Toll, D. L., and Lawrence, W. T. (1992). Moderate resolution imaging spectroradiometer [MODIS] and observations of the land surface. In “1992 International Geoscience and Remote Sensing Symposium (IGARSS'92),” Houston, TX, pp. 549-551.

Siedel, K., Ehrler, C. and Martinec, J. 1997. Effects of climate change on water resources and runoff in an alpine basin. In “Proceedings of the 54th Eastern Snow Conference,” May 4-8, Banff, Alberta, pp. 221-228.