

## Mapping Snow Cover During the BOREAS Winter Experiment

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### ABSTRACT

An algorithm is being developed to map snow cover using Moderate Resolution Imaging Spectroradiometer (MODIS) data from the Earth Observing System which is expected to be launched in 1998. A prototype algorithm is currently being tested using Landsat Thematic Mapper (TM) and MODIS Airborne Simulator (MAS) data. A significant limitation in mapping snow cover by satellite is caused by forest cover. In the Boreal Ecosystem Atmosphere Study (BOREAS) study area in Saskatchewan, forests are shown to mask the snow signal and preclude the mapping of some snow cover. Using the 6 February 1994 TM image of the BOREAS site, more snow cover was mapped in coniferous forests than in the deciduous forests (72 and 14 percent, respectively). This is probably due to the high density of trees in the deciduous forests which effectively blocks the view of the ground, and to the fact that snow was present on the coniferous canopy.

Key words: Remote sensing, snow, MODIS, EOS

### INTRODUCTION

The winter component of the BOREAL Ecosystem-Atmosphere Study (BOREAS) was held in February 1994 in and near Prince Albert National Park, Saskatchewan (approximately 54° N, 106.5° W). As part of a project to determine the optimum algorithm for mapping global snow cover using future Earth Observing System (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS) data (Hall et al., in press), MODIS Airborne Simulator (MAS) data

were acquired over the BOREAS test site. An algorithm called SNOMAP has been developed to map snow using TM and MAS data as surrogates for MODIS data. Flight lines were flown from the NASA ER-2 aircraft over the southern BOREAS site on 8 February. Landsat Thematic Mapper (TM) data were acquired on 6 February. Simultaneous ground-truth observations indicated that the entire area was snow covered. In this paper, we discuss the effectiveness of mapping snow cover using SNOMAP on the MAS and TM scenes of the BOREAS site.

### BACKGROUND

#### Description of MODIS

MODIS is an imaging radiometer which will use a cross-track scan mirror and collecting optics, and a set of individual detector elements to provide imagery of the Earth's surface and clouds in 36 discrete spectral bands. MODIS is scheduled for launch as an EOS facility instrument. EOS is a polar-orbiting platform to be launched in 1998. Key land surface objectives are to study global vegetation and ground cover, global land-surface change, vegetation properties, surface albedo, surface temperature and snow and ice cover on a daily or near-daily basis (Salomonson et al., 1992; Running et al., 1994).

The spatial resolution of the MODIS sensor at nadir will vary with spectral band. The spectral bands will cover parts of the electromagnetic spectrum from about 0.4 - 14.0  $\mu\text{m}$ . There will be two bands with 250-m resolution (in the visible/near-infrared parts of the spectrum), 5 bands with 500-m resolution (in the visible through middle-infrared parts of the spectrum), and 29 bands with 1-km resolution (in the

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visible through thermal-infrared parts of the spectrum).

Because of the high reflectivity of snow compared to most other land-surface features, snow cover is amenable to mapping by satellite. The National Oceanic and Atmospheric Administration (NOAA) has mapped snow cover in the Northern Hemisphere since 1966 (Matson, 1991). Additionally, the NOAA National Operational Hydrologic Remote Sensing Center (NOHRSC) produces weekly snow-cover maps for portions of the United States and Canada on a weekly basis during the snow season (Carroll, 1990). Landsat-derived maps, while not suitable for global snow mapping, are useful for detailed snow mapping and provide good snow/cloud discrimination because of a spectral band located at about 1.6  $\mu\text{m}$ . Future snow-mapping efforts will permit global snow mapping with good snow/cloud discrimination as discussed later.

**The MODIS Airborne Simulator (MAS) and the Landsat Thematic Mapper (TM)**

The MODIS Airborne Simulator (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 cloud and terrestrial surface targets (King et al., 1995).

The MAS, with 50 spectral bands in the wavelength range from 0.55 to 14.2  $\mu\text{m}$ , is flown aboard a NASA ER-2 research aircraft at an altitude of about 20 km. It is mounted in the Q-bay behind the pilot where it operates continuously during flights of up to six hours duration, and records data on 8-mm data tape. Its 45° angle scan mirror rotating at constant speed through nadir in a plane perpendicular to the flight line of the aircraft, views 43° on either side of nadir with an Earth swath footprint of 75 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 instrument consists of the optical bench-mounted sensor within an aluminum housing, the digitizer/controller, and tape drives.

At the time the BOREAS data were acquired, only 7 bands were operating properly, including 2 visible bands, 4 near-infrared bands and 1

short-wave-infrared band as shown in Table 1. The MAS has since been modified, and now has a 16-bit digitization, thereby allowing 12 bits of noise-free data to be recorded with a dynamic gain adjustment of 16. Additional MAS data of snow cover in Alaska were acquired in April 1995. Those data, with the full 50 channels of the MAS in operation, will be a better simulation of MODIS data than are the data from the February 1994 mission that is discussed herein.

Table 1. MODIS Airborne Simulator (MAS) bands in operation during the 8 February 1994 aircraft overflight of the BOREAS site in Saskatchewan.

MAS band	Wavelength range ( $\mu\text{m}$ )
2	0.529 - 0.572
3	0.635 - 0.688
4	0.770 - 0.810
5	0.810 - 0.852
6	0.852 - 0.893
7	0.926 - 0.969
8	1.595 - 1.652

The Thematic Mapper (TM) sensor was first launched in July 1982 on the Landsat-4 satellite. Another TM was launched in March 1984 on the Landsat-5 satellite. The Landsat-5 TM is still operating. The Landsat-6 satellite was lost during launch in 1994. The TM sensor has 7 spectral bands in the visible through thermal-infrared regions of the electromagnetic spectrum (Table 2). The spatial resolution of TM bands 1 - 5 and band 7 is approximately 30 m, and the spatial resolution of the thermal band, band 6, is approximately 120 m. Landsat-7 with an enhanced TM (ETM) sensor will be launched in 1998 as part of EOS. The ETM will have the same bands that are available on the TM, but with an additional 15-m resolution panchromatic band. Also, the resolution of the

thermal-infrared band will be improved from 120 m (for the TM), to 60 m for the ETM.

Table 2. Spectral bands of the Thematic Mapper.

TM Band	Spectral range (in $\mu\text{m}$ )
1	0.45- 0.52
2	0.52 - 0.60
3	0.63 - 0.69
4	0.76 - 0.90
5	1.55 - 1.75
6	10.40 - 12.50
7	2.08 - 2.35

## STUDY AREA AND METHODOLOGY

One TM scene and two MAS scenes were acquired over Prince Albert National Park and the surrounding study area on 6 and 8 February 1994, respectively. Figure 1 is a TM band 2 image covering the study area acquired on 6 February 1994. The MAS scenes were registered to the full TM scene using numerous "tie points," which are targets that are common to the MAS and TM images (Figure 2).

The SNOMAP algorithm was applied to the TM and MAS scenes (see description of SNOMAP below). This allowed us to calculate the snow-covered area on the TM and MAS scenes, and to compare the results.

Field measurements show that the entire area was snow covered. At the time of the Landsat overpass and the aircraft overflight, the temperatures were very low. In the mornings, temperatures were about  $-40^{\circ}\text{C}$ , warming up to about  $-25^{\circ}\text{C}$  by afternoon. The snow depth, as measured at one site, in Prince Albert National Park, south of Waskesiu Lake, was approximately 43 cm in deciduous-forest stands, 23 cm in coniferous-forest stands, and 40 cm in mixed deciduous-coniferous stands.

### Description of SNOMAP

SNOMAP is the snow-mapping algorithm that we employ to map snow using TM and MAS data as surrogates for MODIS data. Snow is identified by its unique reflectance characteristics. The decision process is made with criteria tests for snow as described in Riggs

et al. (1994). The heritage for this algorithm comes from earlier work of Kyle et al. (1978) and Dozier (1984) where the normalized difference of a visible and a short-wave-infrared band are used to map snow cover. SNOMAP is designed to detect snow, if present, in each pixel (Riggs et al., 1994; Hall et al., in press). Optimum detection of snow cover by reflectance properties requires that data be expressed in physical units, i.e., reflectance. Thus, the MAS and TM digital number (DN) data are first converted to reflectances. DNs for the TM may be converted to at-satellite reflectances using formulation by Markham and Barker (1986). MAS reflectances have also been calculated from the DNs using formulation designed specifically for the MAS data. Then the normalized difference snow index (NDSI) is calculated. For the TM data,

$$\text{NDSI} = (\text{TM } 2 - \text{TM } 5) / (\text{TM } 2 + \text{TM } 5) \quad [1]$$

where TM 2 is TM band 2 and TM 5 is TM band 5.

For the MAS data,

$$\text{NDSI} = (\text{MAS } 2 - \text{MAS } 8) / (\text{MAS } 2 + \text{MAS } 8) \quad [2]$$

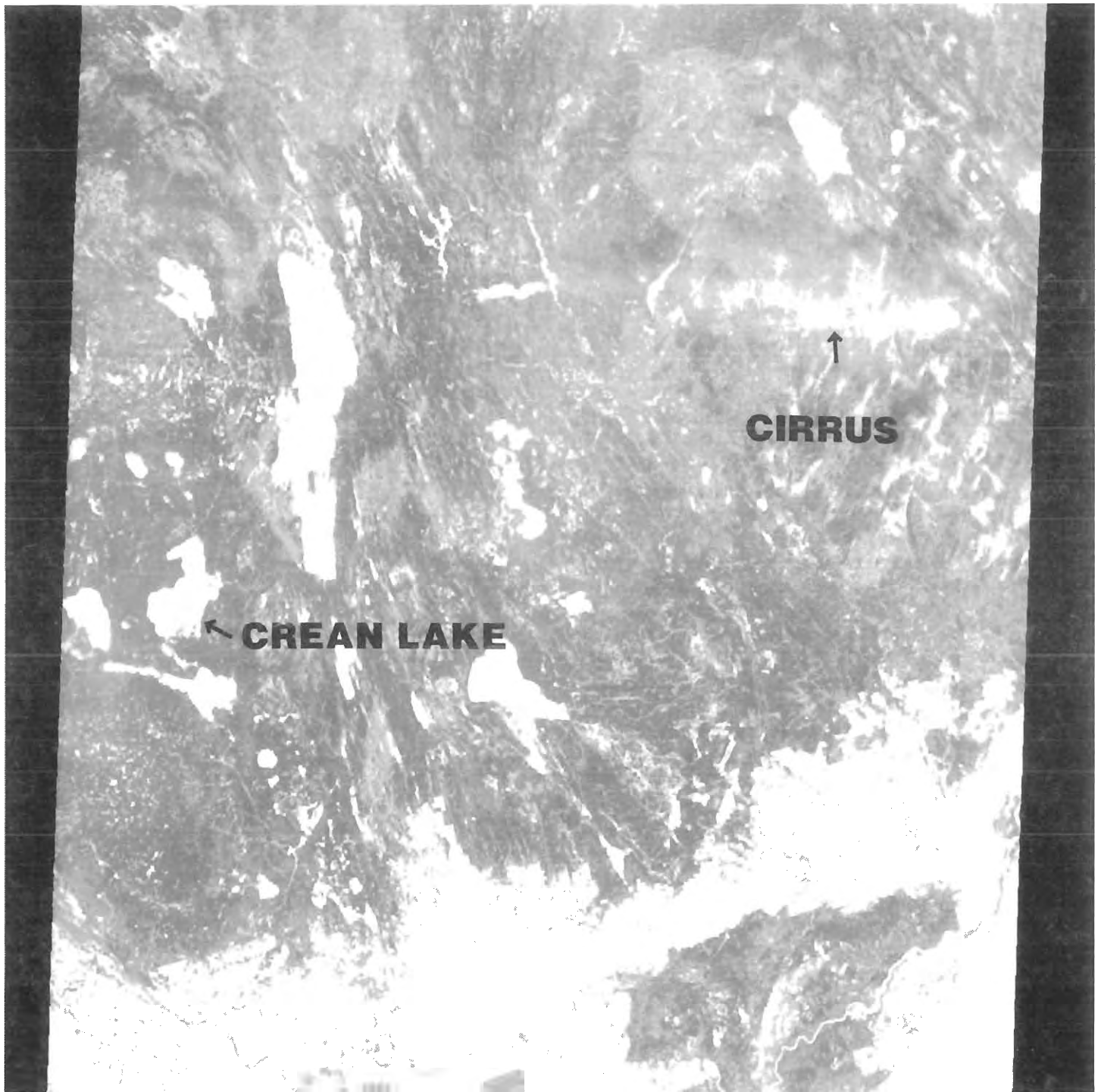
where MAS 2 is MAS band 2 and MAS 8 is MAS band 8.

## RESULTS AND DISCUSSION

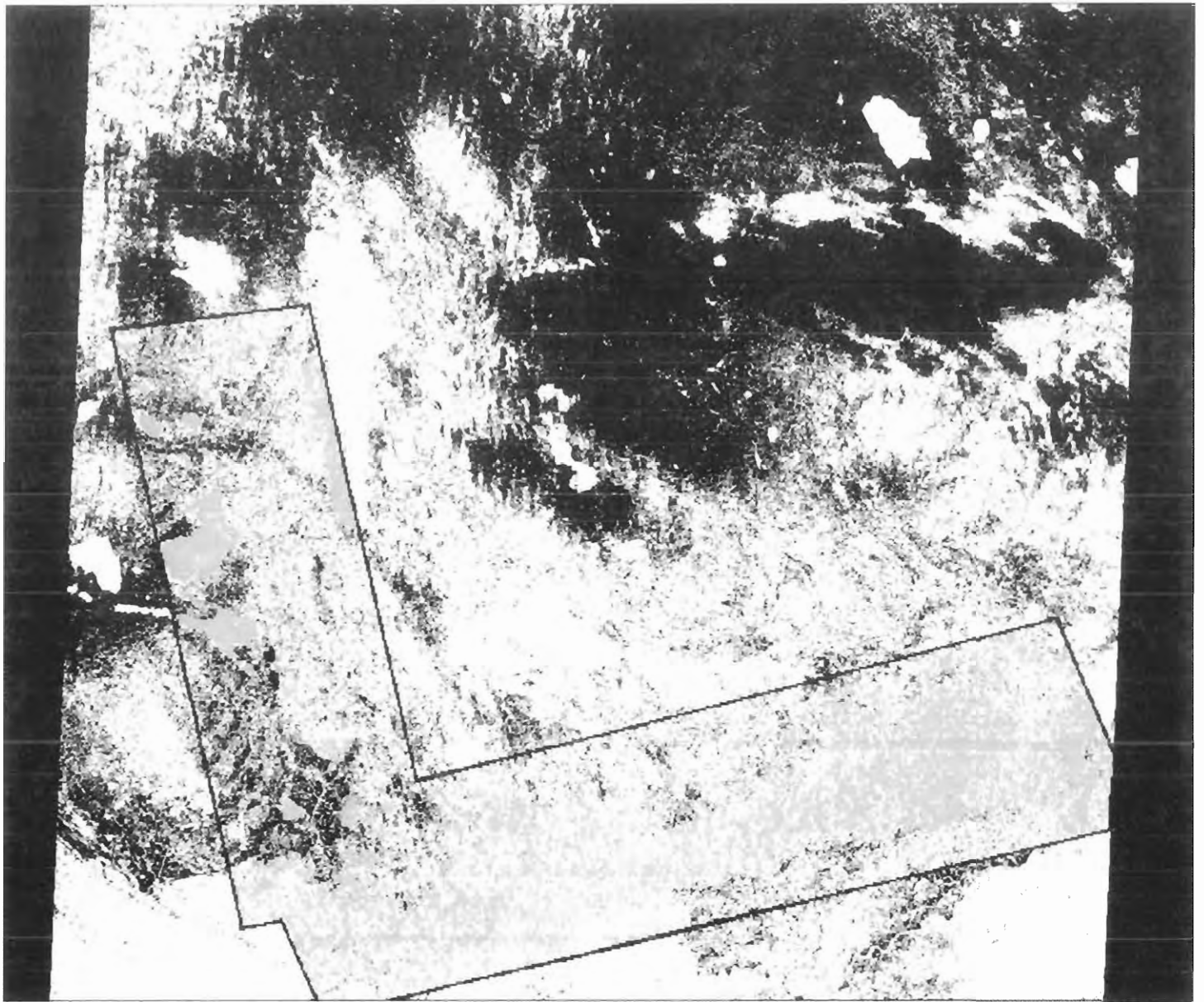
### SNOMAP results

In the 6 February 1994 TM scene (Figure 1), 48 percent of the scene is mapped as snow covered using SNOMAP (Figure 3). A well-defined cirrus cloud in the northeastern part of the image precludes the mapping of the underlying snow cover. Thinner cirrus clouds elsewhere on the image also obliterate the underlying snow cover. Additionally, coniferous and especially deciduous forest cover obstruct some snow from being mapped as discussed in the next section.




SNOMAP was also applied to the two MAS scenes. For the area covered by MAS scene "A," in Figure 2, 1924  $\text{km}^2$  of snow were mapped using TM data, while only 1524  $\text{km}^2$  were mapped using MAS data. This represents 58.5 and 48.1 percent of the total area of the TM



*Figure 1. Thematic Mapper (TM) band 2 scene (id.#53629-171919) of southern Saskatchewan, Canada, acquired on 6 February 1994.*

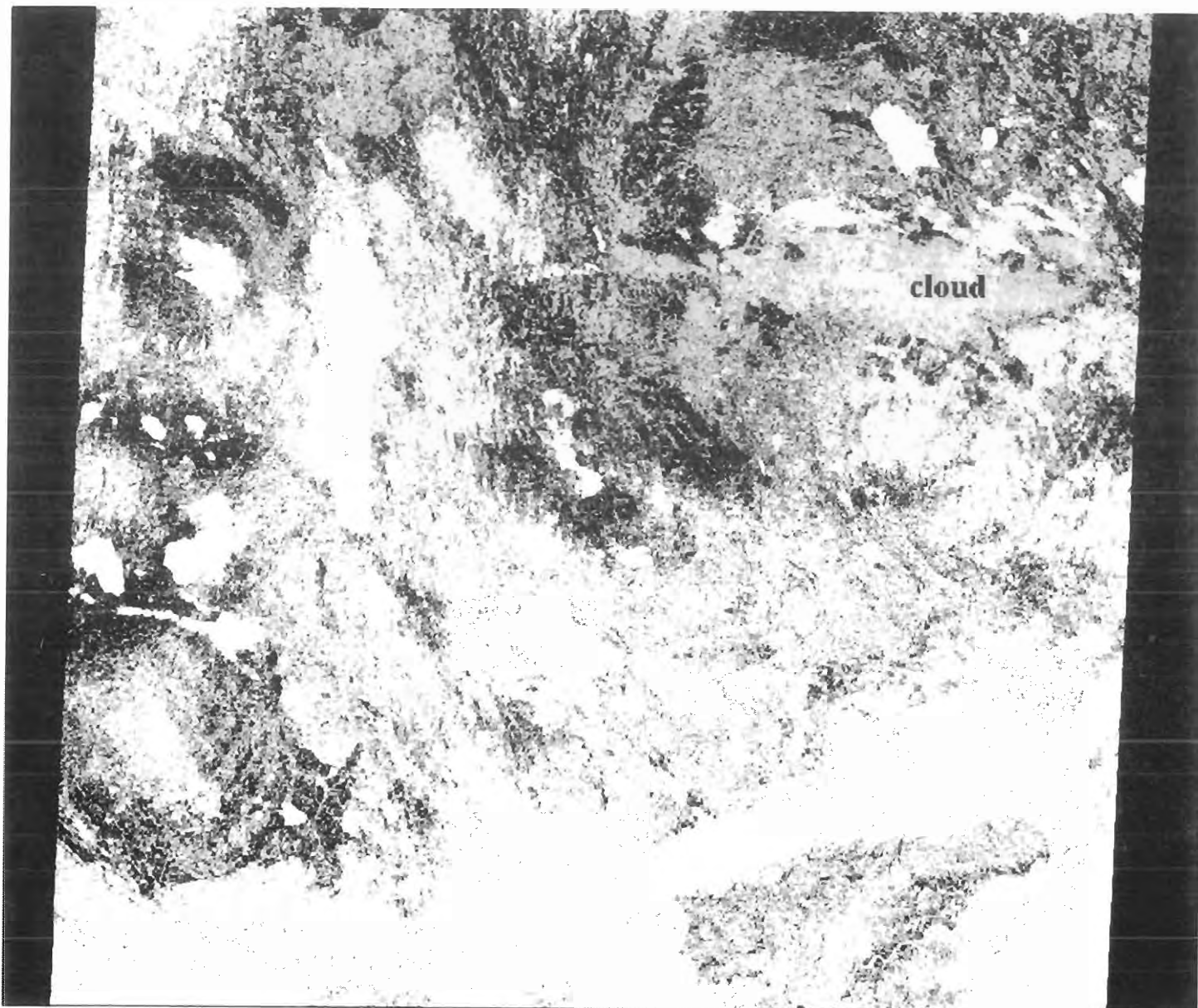


**TM (06 Feb 94) and MAS (08 Feb 94)**

- |   |                           |   |                          |
|---|---------------------------|---|--------------------------|
|  | SNOW MAPPED ON TM AND MAS |  | SNOW MAPPED ON TM OR MAS |
|  | OTHER                     |   |                          |

*Figure 2. Results of SNOMAP as applied to the 6 February 1994 TM full scene (id.#53629-171919) and the two MODIS Airborne Simulator (MAS) scenes (A (left rectangle) and B (right rectangle)). Snow is shown in white and non-snow-covered areas are shown in black.*





**Date: 06 February 1994**

**Scene ID: 53629-171919**



**SNOW**



**CLOUDS**



**OTHER**

*Figure 3. TM-derived SNOMAP result of the 6 February 1994 TM scene (i.d.#53629-171919). The clouds (grey) were classified by a supervised-classification technique to simulate a cloud mask which will be provided by another EOS investigator.*

and the MAS scenes, respectively, that was mapped as being snow covered. In the area of the MAS scene "B," in Figure 2, 3982 km<sup>2</sup> of snow were mapped using TM data, while only 3415 km<sup>2</sup> using MAS data, representing 84 and 77 percent of the scene, respectively, again with more snow cover being mapped in the TM image than in the MAS. The better resolution (about 30 m) of the TM data as compared to the MAS data (about 50 m), helps to explain why more snow is mapped using the TM versus the MAS.

Theoretically, the MAS should not map any additional snow as compared to the TM. However, since the scenes are separated by 2 days, cirrus clouds at the time of the TM data acquisition, 06 February, precluded mapping some snow that was detected by the MAS sensor on 08 February when sky conditions were clearer.

Prototyping efforts will be enhanced when data from the 50-channel MAS become available following a series of flights over snow-covered surfaces in Alaska in April 1995. These flights should permit selection of optimum bands for snow mapping.

#### **Mapping snow through forest cover**

Satellite-based snow mapping is limited due to the difficulty of mapping snow cover through forests. In the BOREAS test site there are coniferous and deciduous stands as well as mixed-forest stands. A forest-cover map of the BOREAS study area, classified from an 6 August 1990 TM scene, was produced by Forrest Hall, NASA/GSFC. The forest-cover-classification map was digitally registered to the 6 February 1994 SNOMAP result derived from TM data. An interesting finding is that more snow was mapped using SNOMAP on the 6 February 1994 TM scene, in coniferous forests than in deciduous forests. In the coniferous forests, about 72 percent snow cover was mapped, while only about 14 percent snow cover was mapped in the deciduous forests. Preliminary results indicate that the snow that is intercepted in the coniferous canopy is mapped by SNOMAP. Whereas in the deciduous forests, there is very little, if any, canopy interception of snow. As noted earlier, the snow depth in coniferous stands is only about half of that as measured on the ground in deciduous stands. Furthermore, the deciduous stands in this study (Figure 4) are more dense than the coniferous

stands and therefore the surface snow is effectively obscured.

In locations where the forest cover is sparse, the NDSI appears to map snow adequately. The NDSI threshold can be altered to allow more snow to be mapped in densely-forested areas, but would also cause non snow-covered pixels to be mapped as snow in other areas on other scenes. We may implement a strategy that allows us to change the threshold of the NDSI over dense forests to allow the mapping of more realistic snow-cover amounts. Global 1-km forest-cover maps will be required to fully implement a global algorithm that will use different NDSI values over dense forests. Such maps, available now, will be refined when MODIS is launched.

#### **Snow-cloud discrimination**

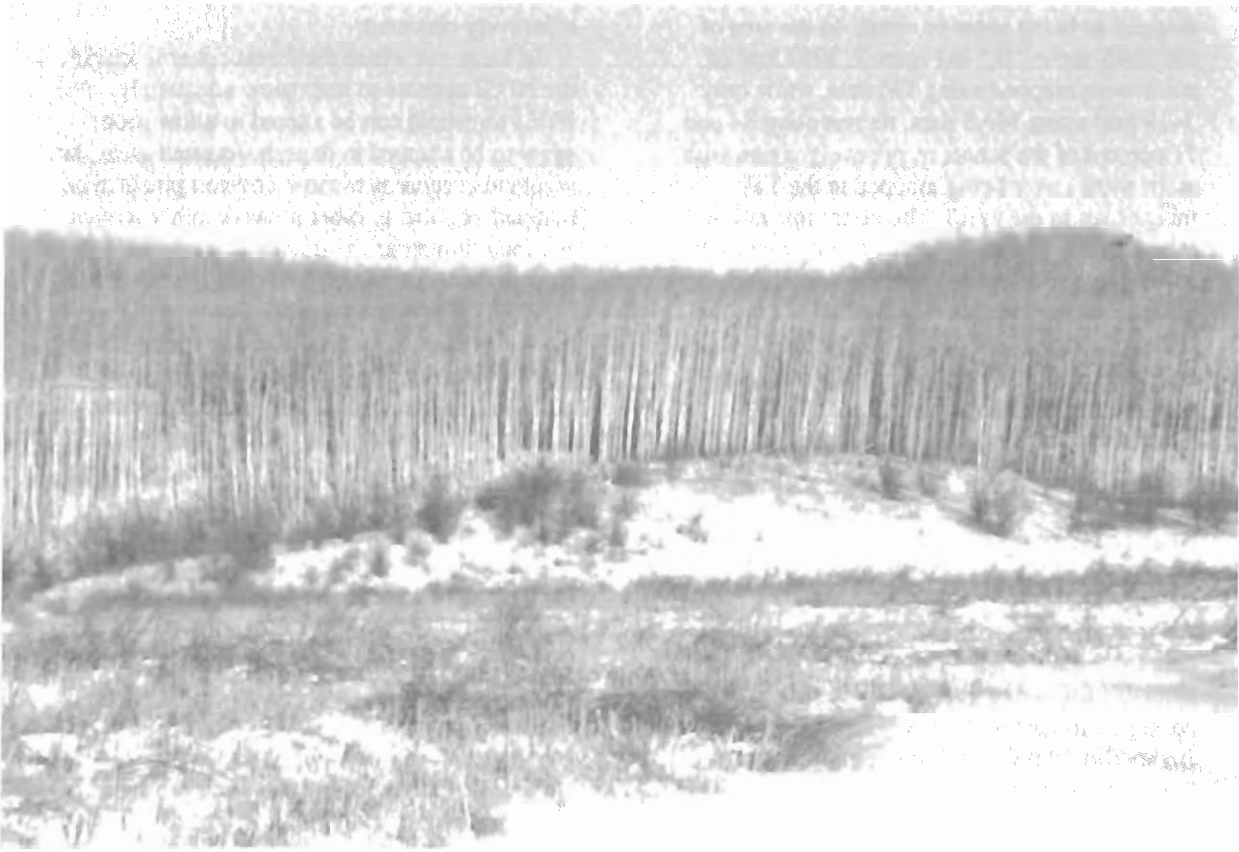
Currently our algorithm distinguishes snow from clouds and other features, but does not specifically identify clouds. In the MODIS era, we are planning to use a cloud mask produced by another MODIS investigator. The product will then be able to show the location of snow and clouds (Figure 3). In Figure 3, SNOMAP was applied to map snow and "other features," then a supervised classification was done to map the clouds.

#### **Snow-cover persistence statistics**

Statistics on the persistence of snow cover will be part of the weekly snow-cover data product. The weekly snow-cover data product will be a composite of the snow-cover conditions of the previous seven days. Each pixel will contain the sum of 7 days of snow cover. Figure 5 shows snow-cover persistence in a theoretical example of 7 images of Glacier National Park, Montana, where black represents pixels that were not snow covered for the entire period and white represents pixels that were snow covered for all 7 days. The various grey tones in-between represent pixels that were snow covered from 1-6 days. A goal in developing these persistence statistics is to establish probabilities of snow cover frequency and duration. This is especially important for transition seasons.

#### **Reflectance of Snow Cover on Lakes**

There are several lakes in and near Prince Albert National Park and those lakes were ice and snow covered in early February 1994. The ice on Waskesiu Lake, in the park, was approximately 1-m thick. The snow cover was



*Figure 4. Ground photograph taken on 7 February 1994 showing the density of the deciduous-tree stand in Prince Albert National Park. Photograph by J. Foster.*



*Figure 5. This image represents a theoretical example of snow-cover-persistence statistics derived from 7 scenes of northern Montana. Black represents pixels that are snow-free (or cloudy) for the 7 scenes, and white represents pixels that are snow-covered in all 7 scenes. The intermediate grey tones represent pixels that were snow-covered in 1-6 scenes.*



continuous and was approximately 22-29-cm thick. Analysis of MAS band 8 (Figure 6) and TM band 5 (not shown), reveals a differential reflectance pattern on different parts of nearby Crean Lake. This pattern may be caused by wind-induced snow-grain-size differences. The reflectance of snow drops as grain size increases in the short-wave-infrared part of the electromagnetic spectrum. As wind blows snow crystals from the surface of the lake, it breaks apart the crystals. Smaller crystals tend to scatter more light in the short-wave infrared part of the spectrum thus causing a higher reflectance relative to larger crystals. The bright 'streaks' visible in Figure 6, and the large, bright areas, may consist of smaller crystals which were wind-blown.



*Figure 6. Reflectances on Crean Lake as derived from MAS data acquired on 8 February 1994. Higher reflectances are shown in the lighter grey tone and lower reflectances are shown in the darker grey tone.*

## CONCLUSION

When our algorithm, SNOMAP, was applied in the BOREAS test site using TM data, more snow was mapped than when SNOMAP was applied in the same areas using MAS data. This is due, at least in part, to the better resolution of the TM data relative to the MAS data. Additional MAS bands that are suitable for snow mapping will be identified when data are analyzed that were acquired in Alaska in April of 1995.

It is concluded that while SNOMAP is useful for mapping snow in a variety of surface cover types, it does not map snow very well under dense forests. The finding that more snow is mapped in coniferous-forest stands than in deciduous-forest stands was surprising, but may be explained by the presence of snow in the canopy of the coniferous stands, and the high density of the deciduous stands.

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