

Intercomparison of Satellite-Derived Snow-Cover Maps

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Abstract

In anticipation of the launch of the Earth Observing System (EOS) Terra, and the PM-1 spacecraft in 1999 and 2000, respectively, efforts are ongoing to determine errors of satellite-derived snow-cover maps. EOS Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Microwave Scanning Radiometer-E (AMSR-E) snow-cover products will be produced. For this study we compare snow maps covering the same study area acquired from different sensors using different snow-mapping algorithms. Four locations are studied: 1) southern Saskatchewan; 2) a part of New England (New Hampshire, Vermont and Massachusetts) and eastern New York; 3) central Idaho and western Montana; and 4) parts of North and South Dakota. Snow maps were produced using a prototype MODIS snow-mapping algorithm used on Landsat Thematic Mapper (TM) scenes of each study area at 30-m and when the TM data were degraded to 1-km resolution. National Operational Hydrologic Remote Sensing Center (NOHRSC) 1-km resolution snow maps were also used, as were snow maps derived from $\frac{1}{2}^\circ \times \frac{1}{2}^\circ$ resolution Special Sensor Microwave Imager (SSM/I) data. A land-cover map

derived from the International Geosphere-Biosphere Program (IGBP) land-cover map of North America was also registered to the scenes. The TM, NOHRSC and SSM/I snow maps, and land-cover maps were compared digitally. In most cases, TM-derived maps show less snow cover than the NOHRSC and SSM/I maps because areas of incomplete snow cover in forests (e.g., tree canopies, branches and trunks) are seen in the TM data, but not in the coarser-resolution maps. The snow maps generally agree with respect to the spatial variability of the snow cover. The 30-m resolution TM data provide the most accurate snow maps, and are thus used as the baseline for comparison with the other maps. Comparisons show that the percent change in amount of snow cover relative to the 30-m resolution TM maps is lowest using the TM 1-km resolution maps, ranging from 0 to 40%. The highest percent change (>100%) is found in the New England study area, probably due to the presence of patchy snow cover. A scene with patchy snow cover is more difficult to map accurately than is a scene with a well-defined snowline such as is found on the North and South Dakota scene where the percent change ranged from 0 to 40%. There are also some important differences in the amount of snow mapped using the two different SSM/I algorithms because they utilize different channels.

Introduction

The launch of the Earth Observing System (EOS) Terra, and the PM-1 spacecraft in 1999 and 2000, respectively, will allow us to produce global snow maps, that are superior to those available today, from the EOS Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Microwave Scanning Radiometer-E (AMSR-E). Efforts are ongoing to determine errors of satellite-derived snow-cover maps, and these efforts will continue in the EOS era.

In previous work, we have estimated theoretical errors in snow maps in eight different land covers under conditions of continuous snow cover, using Landsat thematic mapper (TM) data and land-cover maps, and extrapolated those errors globally (Hall and others, 1998). For the present study, we compare snow maps derived from TM data, degraded to 1-km resolution, with National Operational Hydrologic Remote Sensing Center (NOHRSC) and Defense Meteorological Satellite Program (DMSP)/Special Sensor Microwave Imager (SSM/I) snow maps over four study areas located in North America (Table 1) to determine relative errors as compared to 30-m resolution TM-derived snow maps. The TM snow maps were derived using the MODIS prototype algorithm, SNOWMAP (Hall and others, 1995; Klein and others, 1998a). These maps are considered to be the most accurate because of the good spatial resolution, and because some of the errors with this method of snow mapping have recently been evaluated under conditions of continuous snow cover (Hall and others, 1998). Two different algorithms were applied to the SSM/I data, and the results of a comparison of the resulting snow maps are also discussed. Results demonstrate some of the problems in quantitative

comparison of snow maps derived from different sensors at different spatial resolutions. These problems will continue to plague researchers in the EOS era.

Background

EOS snow-cover products. The EOS Terra spacecraft will fly in a sun-synchronous, near-polar orbit with a 10:30 a.m. equatorial-crossing time and will include the MODIS instrument as part of its payload (Kaufman and others, 1998). The MODIS and AMSR-E instruments will be placed on the EOS first afternoon (EOS PM-1) spacecraft which is scheduled to be launched in 2000.

MODIS is a 36-channel spectroradiometer covering visible, near-, shortwave-infrared and infrared bands from 0.4-14 μm (Barnes and others, 1998). The AMSR-E is a twelve channel, six-frequency passive-microwave radiometer system. It measures brightness temperatures at 6.925, 10.65, 18.7, 23.8, 36.5, and 89.0 GHz in both vertical and horizontal polarizations.

MODIS-derived daily, global snow-cover maps are planned to be produced using data from the Terra and EOS PM-1 satellites, and both MODIS- and AMSR-E-derived snow maps will be produced from sensors on the PM-1 platform. Algorithms are being developed that will use both AMSR-E and MODIS data, together, to map global snow cover (Tait and others, 1999 and in press).

A fully-automated algorithm, SNOWMAP, has been developed that will map global snow cover, cloud-cover permitting, on a daily basis at 500-m spatial resolution using MODIS data (Hall and others, 1995; Riggs and others, 1996; Klein and others, 1998a). Shortly after launch, there will be daily and 8-day composite global snow-cover

products at 500-m resolution, and daily and 8-day and monthly-composite climate-modeling grid (CMG) products at $1/4^\circ \times 1/4^\circ$ spatial resolution. MODIS snow and ice data products will be archived at and distributed by the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado (Scharfen and others, 1997).

Detailed studies of the SNOWMAP algorithm have been conducted in many different land covers, resulting in estimates of snow-mapping errors in at least eight individual land-cover classes under conditions of continuous snow cover (Hall and others, 1998). Preliminary results, under cloud-free conditions, show the highest average errors in forested areas (15%) and the lowest average errors in non-forested areas (5%). Errors are expected to be greater when snow cover is not continuous, and are expected to be greatest in alpine areas containing patchy snow cover (J. C. Shi, written communication, 1999).

Currently, a global, daily snow-cover data set at 500-m resolution (or better) does not exist, therefore, a direct comparison of the MODIS and AMSR-E-derived products with “actual” global snow cover will not be possible following the launch of Terra and PM-1. Instead, the EOS snow maps will be compared with other hemispheric-scale maps such as the Northern Hemisphere weekly snow-cover maps produced by the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data and Information Service (NESDIS), and maps prepared by NOHRSC. Precise errors of these snow maps have not been established. The EOS snow maps will also be compared with maps derived from passive-microwave data (e.g., Chang and others, 1987 and 1997; Grody and Basist, 1996; Tait and others, in press) from the SSM/I. At regional and local scales, MODIS snow-cover maps will be validated using snow-cover maps

derived from the Landsat-7 Enhanced Thematic Mapper Plus (ETM+), launched on 15 April 1999, and Terra's Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER).

NOHRSC snow maps. The Geostationary Operational Environmental Satellite (GOES) imager scans portions of the Earth every fifteen minutes. The visible images are navigated and registered using 169 landmarks in the Northern and Southern Hemispheres. The navigation specifications require the visible data to be within 4 km and infrared data to be within 6 km. Using 15 minute visible imagery during the past 52 weeks, 90 percent or greater of landmarks met specifications for the north-south direction (except for three weeks) and 95 percent or greater of landmarks met specifications for the East-West direction (except for two weeks).

Once daily, from Saturday through Thursday GOES East and GOES West infrared (IR bands 2, 4, and 5) and water vapor (band 3) images are resampled to match the 1-km resolution of the visible data using an inverse distance function. Each pixel in the visible band is normalized to solar noon using a simple cosine correction. The normalized visible raster and the reprojected and resampled infrared bands are used as input to an algorithm that produces 32-bit rasters of cloud and snow/cloud. Each image is given an 80-byte header, which contains the ancillary information required to read and utilize the images. The three rasters are divided into smaller, more manageable rasters for analysis. Each subdivided raster is analyzed to produce a cloud mask image and a snow/cloud image. A coastline vector file is layered on one of the visible images to derive the north-south and east-west shift required to align or register the final snow-

cover image. The cloud and snow/cloud images are merged to produce an image of snow, cloud, and no-snow/no-cloud for each subdivided image; the smaller images are mosaicked to produce an unregistered east or west snow-cover map. Alphanumeric tabulations of percent of snow cover by hydrologic basin and elevation zone are produced and are made available on the NOHRSC web site (<http://www.nohrsc.nws.gov/>), and are sent to the National Weather Service (NWS) offices over the NWS communications lines and sent by ftp over the Internet to interested agencies.

Land-cover maps. To determine land-cover type, International Geosphere-Biosphere Project (IGBP) land-cover maps of North America developed from 1-km Advanced Very High Resolution Radiometer (AVHRR) data are used (Loveland and Belward, 1997). These maps are based on monthly normalized difference vegetation index (NDVI) composites from 1992 and 1993. Using these maps, Hall and others (1998) classified the Northern Hemisphere into the following eight land-cover classes: forest, mixed agriculture and forest, barren/sparsely vegetated, tundra, grasslands/shrublands, wetlands, permanent snow and ice, and water, and estimated snow-cover mapping errors in each land-cover class for continuous snow-cover conditions based largely on field studies.

Study Areas and Satellite Data

TM, NOHRSC and SSM/I data were acquired for four study areas located in: 1) southern Saskatchewan, Canada, 2) New England (Massachusetts, New Hampshire and Vermont) and eastern New York, 3) central Idaho and western Montana, and, 4) parts of

North and South Dakota in the United States (Table 1). The site in Saskatchewan is characterized by gentle relief and rolling hills (interior lowlands) and is composed predominately of boreal forest (aspen and spruce), and some mixed agriculture and forest. It is located in an area of prairie snow cover according to Sturm and others (1995). Land cover in the New England study area is predominately composed of northern hardwood forests, and the snow cover is maritime snow cover (Sturm and others, 1995). In the Idaho study area, terrain is mountainous (northern Rocky Mountains) and forested (mainly fir trees), and the snow cover is prairie, alpine or maritime (Sturm and others, 1995). In the study area in North and South Dakota, the terrain is mainly flat (the Great Plains), and land cover is composed of grassland/shrubland in the west and mixed agriculture and forest in the east, and the snow cover is classified by Sturm and others (1995) as prairie snow.

The SNOWMAP algorithm was applied to the 30-m and 1-km resolution TM data (Klein and others, 1998a) to map snow. Using the SSM/I data, two different algorithms were used to map snow. The Grody and Basist (1996) method uses the difference between the microwave brightness temperature (T_B) at 37 and 19 GHz, and at 85 and 22 GHz vertical polarizations, and a decision tree whereby filters are used to isolate the snow-cover signature. The Chang and others (1997) method (without forest-cover corrections) was also used. This is based on the difference between the 19 and 37 GHz channels,

$$SD = 1.6 * (19H - 37H) - 8.0 \quad [1]$$

where SD is snow depth (in cm).

One of the main problems with SSM/I-derived snow-cover maps is the presence of melting snow. Liquid water coating snow grains absorbs microwave radiation producing an increase in T_B . To minimize this problem, only the early-morning satellite observations were used because this is when the surface temperature is generally the coldest.

The SSM/I maps may not cover the exact same areas on the ground as do the TM and NOHRSC maps, although efforts were made to register the data. It is possible that the SSM/I maps are as much as 25 km offset from the other maps. The lack of ground-control points observable on the SSM/I data meant that the registration could only be done using latitude and longitude lines.

The spatial resolutions of the various snow maps discussed herein are different. TM maps have 30 m and are also degraded to 1-km resolution, and the NOHRSC maps have 30 arc-second resolution (approximately 1-km resolution at the equator). The resolution of the SSM/I snow maps is $1/2^\circ \times 1/2^\circ$; at a latitude of 50° , this is approximately 35 X 55 km.

Results and Discussion

The NOHRSC and SSM/I maps were registered digitally to the Landsat TM-derived maps using EASI-PACE software. Then the percentage of snow cover was determined from the TM, NOHRSC and each of the SSM/I maps for the area covered by TM data (Table 2).

The 30-m resolution TM data were degraded to 1-km resolution in the following way. Each band of the TM data that is used in the SNOWMAP algorithm was reprojected from 30- to 25-m spatial resolution separately using EASI-PACE software. Then 40 X 40 pixels were averaged to equal the spatial area ($1600 \text{ pixels} \times 625 \text{ m}^2$) of a 1-km pixel ($100,000 \text{ m}^2$). The data from individual bands, at 1-km resolution, were then used in the MODIS prototype algorithm to create a snow-cover map. The SNOWMAP algorithm was applied to the data *after* the degradation in spatial resolution.

Saskatchewan. The 27 January 1996 30-m resolution TM snow map (TM-1) of southern Saskatchewan showed 70% snow cover (Figure 1). The boreal forest in the northern part of the scene contains both coniferous and deciduous trees. Unless there has been a recent snowfall, the tree canopies, branches, stems and trunks will likely be mapped as non-snow covered because the snow is often blown or falls from a tree canopy, or the snow sublimates over time. Previous work has shown that it is very difficult to map snow through both dense coniferous and dense deciduous forests (Hallikainen and others, 1988; Foster and others, 1994; Hall and others, 1998). While some areas in the central and western parts of the TM scene are not mapped as snow covered, the southern part of the scene which is composed of mixed agricultural and forest (but is predominately agricultural land), is nearly 100% snow covered as seen on the TM-derived maps. The snow map created from the TM data, degraded to 1-km resolution (TM-2), shows 86% snow cover. The NOHRSC and both SSM/I-derived snow maps all show 100% snow cover for the scene (Table 2).

New England. Most (96%) of the area included in the 21 January 1997 TM scene of New England (including eastern New York, parts of Vermont, New Hampshire and

Massachusetts) is composed of forest (Figure 2). While the TM 30-m resolution map shows only 37% snow cover, the TM 1-km map shows 52%, and the NOHRSC and SSM/I-1 maps, show 77% and 73% snow cover, respectively (Table 2). Across most of the scene, snow cover was intermittent as determined from field work and meteorological-station data (Bayr and others, 1997; NOAA, 1997a; Klein and others, 1998b; Tait and others, 1999). (Note that the NOAA meteorological stations tend to be in open areas where less snow may be present than in the forests.) For example, Berlin, New York had about 13 cm and Glens Falls, New York had 10 cm (NOAA, 1997a). In Keene, New Hampshire, NOAA data show 5 cm of snow on the ground on 21 January 1997, though reports from Keene indicate patchy snow cover in the surrounding areas on that date (Klaus Bayr, written communication, 1999). To the east, in Manchester, New Hampshire, there was no snow reported on the ground (NOAA, 1997b). In the southeastern part of the scene, in Massachusetts, the TM, NOHRSC (Figures 2 and 3) and the SSM/I-derived maps are shown as snow-free. This is consistent with the meteorological-station data of that area, for example, New Salem, Massachusetts, had only a trace of snow on the ground on 21 January (NOAA, 1997a).

The SSM/I-derived snow map using the Chang and others (1997) algorithm, (SSM/I-2), without forest-cover correction, shows 96% of the New England scene as being snow free. This is probably due to the fact that the snow is shallow and wet and therefore its signature is similar to the surrounding snow-free ground. Also, this is a forested area which often causes problems for snow mapping using SSM/I data since emission from trees increases the T_B (Foster and others, 1994) especially under patchy-snow conditions. The SSM/I-1 algorithm utilizes the 85-GHz channel which is more

sensitive to snow cover, and therefore maps shallower snow than does the SSM/I-2 algorithm. This may be why the SSM/I-1 algorithm maps more snow cover in this scene than does the SSM/I-2 algorithm, and why the SSM/I-1 algorithm.

The New England snow maps (with the exception of the SSM/I-2 map) generally agree with respect to the location of snow cover, but not with respect to amount of snow cover. Probably the main reason that the TM map shows less snow cover than the other maps (Table 2) is that the intermittent snow in the forests in the area is mapped as full snow cover on the NOHRSC and SSM/I-1 maps, and, more correctly, as partial snow cover on the TM map.

In the forested New England study area, there is patchy snow cover in New Hampshire, Vermont and New York, but in Massachusetts (southeastern part of the scene) the area is basically snow free according to meteorological-station data. All of the snow maps show this area to be snow free.

Idaho. In Idaho, on the 28 January 1998 TM-1 snow map, in a predominately forested site, snow is mapped over 62% of the scene while the TM-2, NOHRSC and both SSM/I maps show greater amounts of snow cover (Table 2). The TM-1 map does not show continuous snow cover in the forests, while the other snow maps do (Figures 4 and 5). Mountain shadows are present and are incorrectly mapped as being snow free using the TM-1 and -2 maps. The apparently snow-free area on the TM maps is cloudcover (see arrow on Figure 4).

On the Idaho maps, a non-snow-covered area is shown in the southwestern part of the scene on both TM and the NOHRSC maps (Figure 4), and the SSM/I-1 map (Figure 5). The nearby station at Emmett, Idaho, just south of the scene, reported no snow cover

(NOAA, 1998a). Farther to the west the TM and both of the SSM/I maps show continuous snow cover. Meteorological-station data are sparse to the east of Emmett, but point values show 25-71 cm of snow on the ground in this area. For example, there were 51 cm in Idaho City, Idaho (NOAA, 1998a) in an area that is shown as snow free on the NOHRSC snow maps.

Other problems are evident. Both SSM/I maps show a well-delineated snowline in the western part of the scene where there is no snowline according to the TM and NOHRSC data. If the snow cover is patchy and thin, the large SSM/I pixels may not detect enough of a signal change to map the whole pixel as snow, and thus both SSM/I algorithms map the western part of the scene as snow-free.

In Idaho, a mountainous area, continuous snow cover is not mapped in mountain shadows using the TM data, but is mapped using the coarser-resolution data. In this case, it is believed that the TM-1 snow map underestimates the amount of snow cover that is present.

North and South Dakota. In North and South Dakota, a snowline is visible on all of the 7 and 8 February 1998 snow maps (Figures 6 and 7). The eastern part of all of the maps is generally snow covered, while the southern and southwestern parts are snow free. The snowline, as seen on the TM-derived maps, follows closely the boundary between the grassland/shrubland land-cover class to the west (which is snow free) and the mixed vegetation and forest class (which is snow covered) to the east (Figure 6). The snow cover remains longer in the forest than it does in the grassland/shrubland, and this is the reason that there is such an obvious snowline on the TM-derived snow maps. This

appears to be an accurate depiction of the snow-cover situation, and is corroborated by the NOAA meteorological-station data showing, for example, no snow cover in Pollock, South Dakota (NOAA, 1998b), west of the snowline, and 13 cm in Jamestown, 20 cm in Cooperstown and 10 cm of snow cover in Edgely, North Dakota on 7 February 1998 (NOAA, 1998c), east of the snowline. The NOHRSC map also shows a well-defined snowline, but in a slightly different place than shown on the TM-derived maps. In this case, it was difficult to register the TM and NOHRSC data, due to a lack of ground-control features, and therefore the positions of the snowlines may not match due to mis-registration.

Both SSM/I-derived snow maps show a well-defined snowline in the southwestern part of the scene. In addition, the SSMI-1 map shows a snow-free area in the eastern part of the scene in a location that is snow covered according to the other maps and the meteorological-station data. These snow-free pixels are the result of the algorithm's precipitation filter which indicates that it may have been raining or snowing at the time the data were acquired.

There was very little change in the amount of snow on the TM-1 and -2 maps (64%) in the North and South Dakota study area. Though the TM-2 map showed slightly more snow cover than did the TM-1 map, as a percentage of the total area of the scene, both rounded off to 64%. The NOHRSC 1-km resolution maps show less snow (57%), while the SSM/I-1 and -2 maps show 89 and 86% snow cover, respectively. In terms of spatial coverage, this area provided more consistent results among the snow maps than did the maps with patchy snow cover, probably because it is much easier to map

continuous snow cover with a well-defined snowline accurately than to map patchy snow cover accurately.

Discussion. Because of the good (30 m) spatial resolution of the TM sensor, and the fact that the SNOWMAP algorithm has been evaluated for accuracy in different land covers, the assumption is that, of the snow maps studied in this paper, the 30-m resolution Landsat TM-derived snow maps (TM-1) are the most accurate. Percent change in snow cover mapped, relative to the TM 30-m resolution data is shown in Figure 8. This, however, just addresses the accuracy in terms of the total amount of snow mapped, and not the accuracy in terms of the location of the snow cover, and may be misleading. Furthermore, it is expected that the TM-2 maps should be the most similar to the TM-1 maps because the same algorithm was used to calculate snow cover using both the 30-m and 1-km resolution TM maps. The NOHRSC maps are generally accurate depictions of the location of snow cover, but show more snow cover than is probably present because the tree canopy, branches and stems are actually not snow covered as seen on the TM data. When the TM data are degraded to 1-km spatial resolution, more snow is generally mapped.

The important role of land cover in snow-cover distribution is seen in the North and South Dakota scene where there is a distinct snowline at a clear demarcation between the grassland/shrubland and the mixed agriculture and forest land-cover classes (Figure 6). This snowline is apparent on all of the satellite-derived maps.

The SSM/I maps are considered to be the least accurate in terms of mapping the location of snow cover accurately primarily because of the coarse resolution of the data.

There is confusion in the SSM/I-2 maps in patchy snow in forests in the New England study area. The SSM/I-1 algorithm maps precipitation as non-snow cover and maps more snow cover in the eastern part of the North and South Dakota scene than is present. In Saskatchewan, the SSM/I maps both show 100% snow cover. Due to the coarse resolution, the signature of the snow-free tree canopies and trunks is not detected because the algorithms cannot delineate sub-grid features. Even in continuous snow cover, snow-free areas exist and should be mapped as being snow free if the resolution of a satellite sensor is good enough.

Conclusions

This study demonstrates some of the difficulties involved in intercomparing satellite-derived snow-cover maps. First, we do not know which map is the most accurate though we make the assumption, in this work, that the highest-resolution map (30-m resolution) is the most accurate. In addition, since different satellite sensors are used to derive the maps, different algorithms are used. Furthermore, the maps are at different spatial resolutions, thus further complicating the comparisons. More such intercomparisons will be accomplished following the launch of the MODIS sensor on the Terra spacecraft. It will be possible to use Landsat-7 data to derive snow-cover maps and compare those with MODIS, SSM/I and AMSR-E maps. As the EOS MODIS and AMSR-E data sets become available, and such studies are repeated, we will be able to reduce the uncertainties in the accuracy assessments of various snow maps.

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Table 1. Satellite data used in this study.

Location	Snow Map	Date
Saskatchewan	TM	27 Jan 1996
	NOHRSC*	26 Jan-01 Feb 1996
	SSM/I**	26 and 28 Jan 1996
New England	TM	21 Jan 1997
	NOHRSC*	18-21 Jan 1997
	SSM/I	21 Jan 1997
Idaho	TM	28 Jan 1998
	NOHRSC	31 Jan 1998
	SSM/I	28 Jan 1998
North & South Dakota	TM	7 Feb 1998
	NOHRSC	7 Feb 1998
	SSM/I***	7 and 8 Feb 1998

* The weekly composite map was used.

** Since SSM/I data were not available on 27 January 1996, SSM/I data from 26 and 28 January 1996 were combined to develop the snow map.

*** Since complete SSM/I data were not available on 7 February 1998, SSM/I data from both 7 and 8 February 1998 were combined to develop the snow map.

Table 2. Percentage of snow cover as determined from the various snow maps. SSM/I-1 refers to the SSM/I-derived snow maps using the Grody and Basist (1996) algorithm, and SSM/I-2 refers to the SSM/I-derived snow maps using the Chang and others (1997) algorithm. TM (30-m res.) and (1-km res.) refer to the snow cover mapped by the TM, using the SNOWMAP algorithm, when the TM data were used at 30-m and degraded to 1 km resolution, respectively.

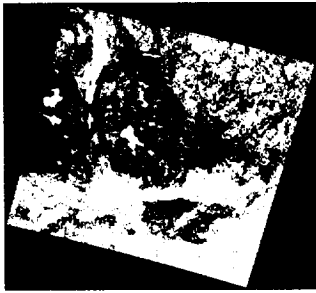
Location (and date of TM scene)	TM (30-m res.)	TM (1-km res.)	NOHRSC	SSM/I-1	SSM/I-2
Saskatchewan (27 January 1996)	70	86	100	100	100
New England (21 January 1997)	37	52	77	73	4
Idaho (28 January 1998)	62	81	87	77	67
North & South Dakota (7 February 1998)	64*	64*	57	89	86

* Though the TM (1-km resolution) data mapped slightly more snow cover than did the TM (30-m resolution) data, as a percentage of the total area of the scene, both rounded off to 64%.

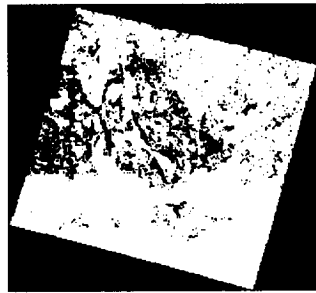
List of Figures

1. Southern Saskatchewan. Left - thematic mapper (TM)-derived 30-m resolution snow map (from TM image i.d.# 5434917022300, path/row 37/23) of southern Saskatchewan, Canada acquired on 27 January 1996. Center – TM-derived 1-km resolution snow map; right – International Geosphere-Biosphere Project (IGBP) land-cover map of the same area shown in the TM image.
2. New England. Left - thematic mapper (TM)-derived 30-m resolution snow map (from image i.d.#LT5013030009702110, path/row 013/030) of parts of New England (New Hampshire, Vermont and Massachusetts) and eastern New York, acquired on 21 January 1997. Center – TM-derived 1-km resolution snow map; right – International Geosphere-Biosphere Project (IGBP) land-cover map of the same area shown in the TM image. Approximate locations of selected meteorological stations are shown.
3. New England. Left – National Operational Hydrologic Remote Sensing Center (NOHRSC) snow map acquired on 18-21 January 1997. Center - snow map derived from Special Sensor Microwave Imager (SSM/I) data acquired on 21 January 1997 SSM/I-derived map using the Grody and Basist (1996) algorithm (SSM/I-1); right – SSM/I-derived map using the Chang and others (1997) algorithm (SSM/I-2).
4. Idaho. Left - thematic mapper (TM)-derived snow map (from image i.d.#LT5041028009802810, path/row 41/28, and LT5041029009802810, path/row 41/29) of central Idaho and western Montana, 28 January 1998; arrow points to cloudcover. Center – TM-derived 1-km resolution snow map; right – International Geosphere-Biosphere Project (IGBP) land-cover map of the same area shown in the TM image. Approximate locations of selected meteorological stations are shown.
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6. North and South Dakota. Left - thematic mapper (TM)-derived snow map (from images i.d.#50310270098038TO, path/row 31/27; 50310280098038TO, path/row 31/28; 50310290098038TO, path/row 31/29) acquired on 7 February 1998. Center – 1-km resolution TM-derived snow map; right – International Geosphere-Biosphere Project (IGBP) land-cover map of the same area shown in the TM image. Approximate locations of selected meteorological stations are shown.
7. North and South Dakota. Left - snow map derived from Special Sensor Microwave Imager (SSM/I) data acquired on 7 and 8 February 1998; left – SSM/I-derived map using the Grody and Basist (1996) algorithm (SSM/I-1); right – SSM/I-derived map using the Chang and others (1997) algorithm (SSM/I-2).
8. Percent change of the snow maps relative to the TM 30-m resolution maps.

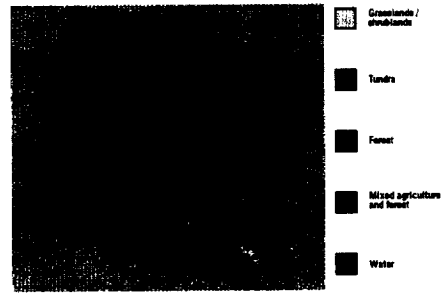
TM (30 m)



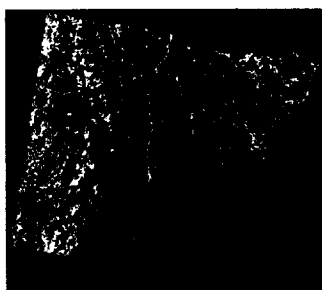
TM (1 km)



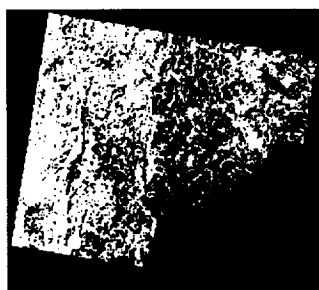
Land Cover



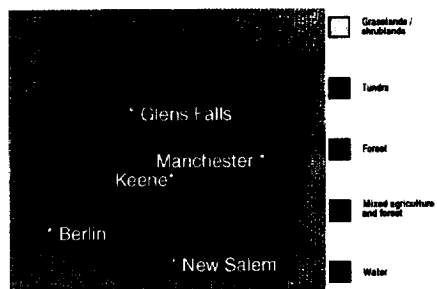
TM (30 m)



TM (1 km)



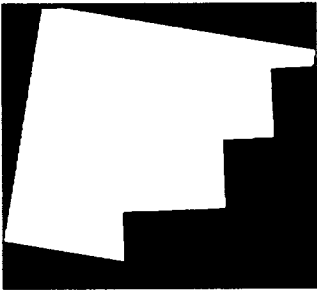
Land Cover



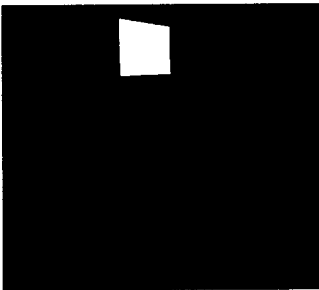
NOHRSC



SSMI-1



SSMI-2



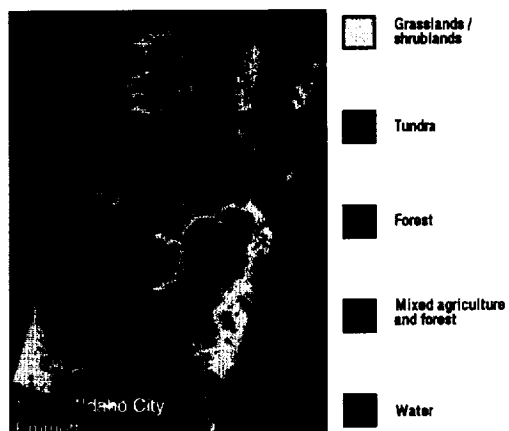
TM (30 m)



TM (1 km)



Land Cover

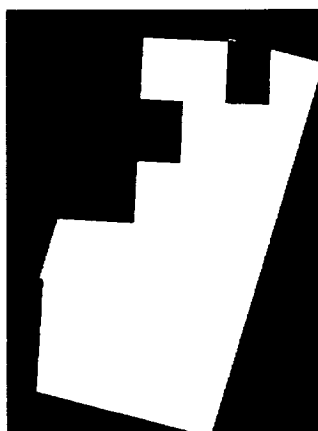


NOHRSC



- ☐ Snow
- ☐ No snow
- ☐ Cloud
- ☐ River/Stateline
- ☐ Not estimated

SSMI-1



SSMI-2



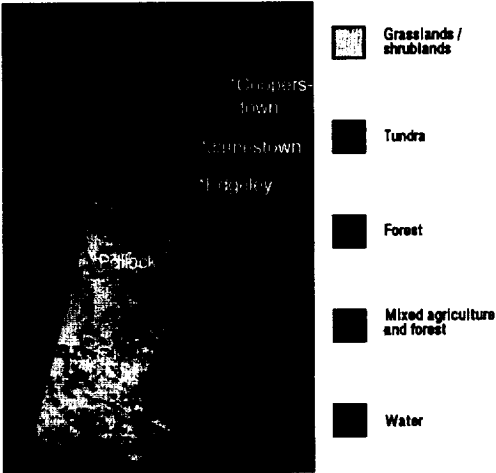
TM (30 m)



TM (1 km)



Land Cover



NOHRSC

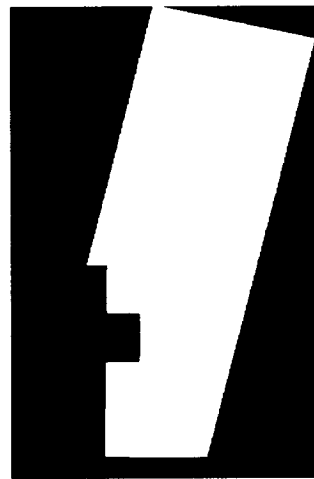


- ☐ Snow
- ☐ No snow
- ☐ Cloud
- ☐ River /stateline
- ☐ Not estimated

SSMI-1



SSMI-2



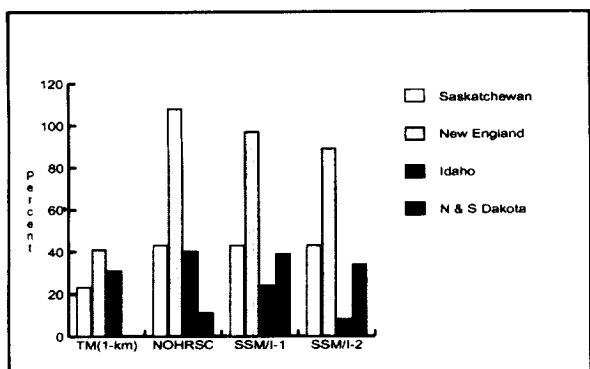


Figure 8. Percent change of snow maps relative to the TM 30-m resolution maps.