Validation of Satellite Snow-Cover Maps in North America and Norway

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ABSTRACT

Satellite-derived snow maps from NASA's Earth Observing System Moderate Resolution Imaging Spectroradiometer (MODIS) have been produced since February of 2000. The global maps are available daily at 500-m resolution, and at a climate-modeling grid (CMG) resolution of 1/20º (~5.6 km). We compared the 8-day composite CMG MODIS-derived global maps from November 1, 2001, through March 21, 2002, and daily CMG maps from February 26 – March 5, 2002, with National Oceanic and Atmospheric Administration (NOAA) Interactive Multisensor Snow and Ice Mapping System (IMS) 25-km resolution maps for North America. For the Norwegian study area, national snow maps, based on synoptic measurements as well as visual interpretation of AVHRR images, published by the Det Norske Meteorologiske Institutt (Norwegian Meteorological Institute) (MI) maps, as well as Landsat ETM+ images were compared with the MODIS maps. The MODIS-derived maps agreed over most areas with the IMS or MI maps, however, there are important areas of disagreement between the maps, especially when the 8-day composite maps were used. It is concluded that MODIS daily CMG maps should be studied for validation purposes rather than the 8-day composite maps, despite the limitations imposed by cloud obscuration when using the daily maps.

INTRODUCTION

Daily and 8-day composite global snow-cover maps derived from automated algorithms have been available following the 1999 launch of the Earth Observing System (EOS) Terra spacecraft with the Moderate Resolution Imaging Spectroradiometer (MODIS) on board (Hall et al., in press A). The products are archived and distributed by the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, via the EOS Data Gateway (EDG) (Scharfen et al., 2000) http://nsidc.org/~imswww/pub/imswelcome/index.html.

The MODIS snow-cover maps represent potential improvement relative to hemispheric-scale snow maps that are available today mainly because of the improved spatial resolution and snow/cloud discrimination capabilities of MODIS, and the frequent global coverage. Their absolute accuracy, however, has not yet been established, nor has the accuracy of existing operational maps. In this paper the MODIS snow maps are compared with NOAA's Interactive Multi-Sensor Snow and Ice Mapping System (IMS) operational maps to assess the relative accuracy of the 8-day composite and the daily MODIS maps. For Norway, snow cover and depth maps from the Meteorologisk Institutt (MI) (The Norwegian Meteorological Institute), as well as

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NOAA AVHRR images and Landsat 7 ETM+ quick-look images were used. A series of 14 CMG maps from the period 1–14 April was studied. The snow cover and depth maps from MI are based on synoptic measurements as well as visual interpretation of AVHRR images.

BACKGROUND

MODIS instrument

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.

NOAA operational snow maps

The Satellite Analysis Branch of the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS) began to generate Northern Hemisphere Weekly Snow and Ice Cover analysis charts derived from NOAA visible satellite imagers 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) has been used by analysts to produce operational products daily at a spatial resolution of about 25 km (Ramsay, 1998). The IMS incorporates a wide variety of satellite imagery (AVHRR, GOES, SSMI, etc.) as well as derived mapped products (USAF Snow/Ice Analysis, AMSU, etc.) and surface observations http://www.ssd.noaa.gov/PS/SNOW/index.html. The product is input into several National Weather Service (NWS) computer weather prediction models and is used by several other governmental agencies.

NOAA's National Hydrologic Remote Sensing Center (NOHRSC) also produces operational snow maps http://www.nohrsc.nws.gov/, on a near-daily basis for the United States and parts of Canada at 1-km resolution during the snow season.

MODIS snow-mapping products and algorithms

The MODIS snow products are provided as a sequence of products beginning with a swath product (at 500-m resolution), and progressing, through spatial and temporal transformations, to an 8-day global-gridded product known as the climate-modeling grid (CMG) (at 1/20°th resolution resolution, ~5.6-km resolution at the equator) (Figure 1). For a more complete description, see Riggs et al. (2000). Quality-assessment (QA) information is included in the products. Fractional snow cover (from 40 to 100%), for each pixel is available in the CMG products. The daily products used in this paper show all snow cover (from 40 to 100%) and cloud cover from 80 to 100%. Because cloudcover often precludes the detection of snow cover from visible and near-infrared sensors, the daily maps are composited, and 8-day composite products are also available.

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., in press A). The NDSI is the basis for snow detection in the algorithm. A grouped-criteria technique utilizing many additional tests are also used in the algorithm.

Several key refinements to the original snow-mapping algorithm have been instituted. A refinement developed by Klein et al. (1998) allows snow to be mapped in densely forested areas. The normalized difference vegetation index (NDVI), utilizing MODIS bands 1 (0.620–0.670 µm) and 2 (0.841–0.876 µm) is calculated and used along with the NDSI to improve snow mapping in dense forests, as snow will tend to lower the NDVI (Klein et al., 1998). Riggs and Hall (in press) have identified key cloud-spectral tests from the MODIS cloud mask (Ackerman et al., 1998) that result in less cloud obscuration that had previously been the case. The introduction of a "thermal mask," (e.g., see Romanov et al., 2000 for an example of a thermal mask) on October 3, 2001, improved the algorithm by eliminating much of the spurious snow cover that was found in many parts of the globe in the earlier MODIS snow maps. These pixels of "false snow" were generally caused by bright surface features or boundaries between water bodies and land. If the temperature of a pixel is >277 K, then the pixel will not be mapped as snow. Results in snow-covered areas did not change much, but results in warm areas improved dramatically. Additionally, much work has been undertaken to measure fractional snow cover using automated algorithms that employ MODIS data (Barton et al., 2000; Appel and Salomonson, 2002; Kaufman et al., in press). The algorithm developed by Appel and Salomonson (2002) is based on the original snow-mapping algorithm, and is currently undergoing testing to determine if it will be suitable to replace the current binary algorithm.

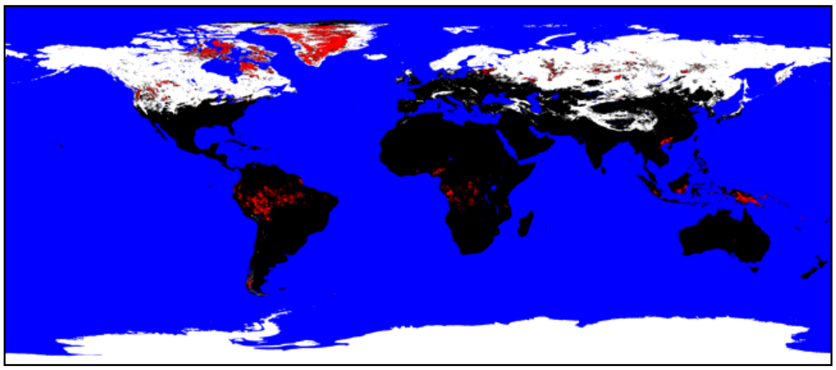

Figure 1. MODIS eight-day composite CMG snow map for March 6–13, 2002.

The eight-day composite climate-modeling grid (CMG) products are available to download from the MODIS snow site http://snowmelt.gsfc.nasa.gov/MODIS_Snow/modis.html, and from the National Snow and Ice Data Center (NSIDC) through the EOS Data Gateway (EDG) data-ordering system http://nsidc.org/~imswww/pub/imswelcome/index.html . The daily global snow-cover CMG product has been in production since February 3, 2002, and may be ordered through the EDG.

The 8-day composite map shown in Figure 1 is produced at 1/20° x 1/20° resolution, from the daily products from March 6 – 13, 2002, showing maximum snow extent and minimum cloud obscuration during the period. All eight days of observations for a cell are examined. Persistent clouds are reported for cells in which 80 – 100% cloud cover was present in a given CMG grid cell, for all days of the period. Errors of commission in the 8-day composite global maps have been very low. For example, errors of commission in Australia on three separate 8-day composite snow maps ranged from 0.02 to 0.10%.

Work by Hall et al. (in press B) discussed the relative accuracy of the MODIS and NOHRSC data. Results showed that overall the data sets were comparable for the winter of 2000–01, but the MODIS maps tended to map more snow than did the NOHRSC maps. Generally this is because MODIS is a daily product and MODIS maps maximum snow cover. The NOHRSC product is not a daily product, and tends to miss some snow cover, especially ephemeral snow cover, that the MODIS maps show. Both maps are limited by the presence of cloudcover.

DATA AND METHODOLOGY

Eight-day composite CMG map products of North America were studied from November 2, 2001, through March 21, 2002, and daily CMG maps were studied from February 26 – March 5, 2002. The daily IMS maps were used to make 8-day composite maximum snow cover maps to match the time periods of the MODIS 8-day composite CMGs. Then the IMS maps were registered to the MODIS CMG maps. Image-processing software was used to register the IMS image onto the MODIS maps. About 50 ground-control points (GCP) were determined from both images and saved as a gcp file. Then a "registration" routine was used to place the IMS snow map (uncorrected) onto the MODIS map (georeferenced) using the gcp file and a curve-fitting technique. With third order polynomial transformation, the RMS error of the registration process is 0.75.

Using the registered data, difference maps were created for the 8-day composite CMG products. These maps show areas where the MODIS and IMS maps agree, and where either MODIS maps show snow or the IMS maps show snow. Additionally, clouds that were present on the MODIS maps are also shown. (No clouds are shown on the IMS maps.) Difference maps were also created for the daily maps from February 26 to March 5, 2000.

For Norway, we used snow cover and depth maps from Meteorologisk Institutt (MI) (The Norwegian Meteorological Institute), as well as NOAA AVHRR images and Landsat 7 ETM+ quick-look images. A series of 14 CMG maps from the period 1–14 April was studied. The snow cover and depth maps from MI are based on synoptic measurements as well as visual interpretation of AVHRR images.

RESULTS AND DISCUSSION

In the early part of the 2001–02 winter, there are large areas where the MODIS 8-day composite maps show snow cover and the IMS maps do not. These tend to be on the edges of the snow-covered areas. Because the MODIS snow-mapping algorithm maps maximum snow cover in a day (based on one or more swath snow maps) and thus maximum snow cover during the 8-day CMG period, the MODIS maps will tend to map ephemeral snow cover including snow cover that may only last on the ground for a few hours. As long as it was on the ground when the image was acquired, the snow will be mapped. Generally this explains the large areas of disagreement when the MODIS maps are showing more snow than is shown on the IMS maps. The same was found when the MODIS–NOHRSC difference maps were studied (Hall et al., in press B).

There are also large areas on many of the maps where the IMS maps show snow cover and the MODIS maps do not (see Table 1). For example, on the December 27, 2001–January 3, 2002 CMG map, there is a large area in Virginia, the Carolinas, Georgia and into eastern Alabama in the United States, where snow is mapped correctly on the IMS map but it is not shown on the MODIS map. A storm occurred on January 2 and 3, 2002, and the clouds persisted until January 4, snow up to ~30 cm in depth accumulated in North Carolina, with lesser amounts surrounding it. Therefore the MODIS sensor did not detect the result of the storm until after the 8-day period ended when the clouds cleared. In the next 8-day period, the MODIS map correctly shows the snow cover that resulted from the storm. The fact that the snow is not shown on the December 27 – January 3 composite image is not an error, however it does represent a limitation of the 8-day composite product. When snow falls near the end of an 8-day period, clouds will frequently persist beyond the end of the 8-day period. Since the IMS maps rely on other information, including ground reports, to map snow cover, storms such as the early January 2002 storm in the southern states of the U.S. will be mapped accurately as being snow covered. Table 1 shows that the disagreement between the MODIS and IMS 8-day composite maps is variable. While the overwhelming majority of snow is mapped by both maps, there can also be large areas of disagreement because of the reasons mentioned above.

Beginning on February 3, 2002, the MODIS daily, global CMGs became available through the NSIDC in Boulder, CO. Comparison of the daily maps with the IMS maps has some advantages, for example, they enable a more direct comparison of snow cover. However, the cloudcover on any given day is normally quite high thus precluding comparisons beneath the clouds. We compared a time series of MODIS and IMS maps and produced difference maps for each day, February 26 – March 5, 2002, inclusive. The maps are produced by gridding the 500-m resolution daily snow data (40% or greater snow in the 500-m pixel) into a 1/20º X 1/20º degree grid cell such that each 500-m cell is classified as snow, cloud or other. Thus a CMG grid cell will be composed of 100 500-m cells and we can determine snow cover and cloudcover percentages accordingly (Riggs et al., 2000). For the maps used herein, cloudcover from 80 – 100%, derived from the input data, is shown. Results show that there is significant cloudcover and there are large areas of agreement between the MODIS and IMS maps. Statistics for the daily comparison maps are shown in Table 2. Note again, as in Table 1, that the majority of the snow-covered area is in agreement between the maps.

Table 1. The percentage of snow mapped by both the MODIS and IMS 8-day composite maps as determined from a series of MODIS/IMS difference maps. Percentage of clouds (from the MODIS maps) is also given. The cloud percentage represents only those clouds that persisted for the entire 8-day period.

Start day of the 8-day period	Snow on both maps	Cloud (MODIS)	Snow MODIS only	Snow IMS only	No snow on either map
11/2/01	26.32	1.70	8.19	5.87	57.93
11/9/01	33.38	2.39	7.04	4.75	52.44
11/17/01	32.07	2.51	10.09	3.29	52.03
11/25/01	54.67	6.87	2.24	8.46	27.76
12/3/01	57.55	0.95	3.34	6.07	32.09
12/11/01	50.06	3.18	5.60	9.02	32.14
12/19/01	58.99	1.12	2.95	7.30	29.64
12/27/01	62.17	2.00	1.56	10.62	23.66
1/1/02	64.04	1.91	1.64	10.87	21.55
1/9/02	57.92	1.86	1.86	9.69	28.66
1/17/02	59.47	4.57	2.18	10.28	23.50
1/25/02	61.83	4.81	1.57	8.90	22.90
2/2/02	63.58	3.39	1.44	9.19	22.40
2/10/02	58.49	3.28	1.28	8.81	28.14
2/18/02	60.42	0.17	1.77	7.98	29.66
2/26/02	63.39	2.20	1.39	10.38	22.64
3/6/02	59.70	2.81	2.17	6.40	28.92
3/14/02	53.54	5.98	1.82	9.14	29.51

Table 2. The percentage of snow mapped by both the MODIS and IMS maps as determined from daily maps from February 26 to March 5, 2002. Percentage of clouds (from the MODIS maps) is also given.

Date	Snow on both maps	Cloud (MODIS)	Snow MODIS only	Snow IMS only	No snow on either map
2/26/02	28.07	47.77	0.93	5.45	17.77
2/27/02	19.35	55.71	0.80	6.07	18.07
2/28/02	20.93	50.25	0.85	5.95	22.03
3/1/02	25.77	51.23	0.99	6.17	15.83
3/2/02	25.13	55.37	1.10	6.01	12.38
3/3/02	16.80	61.56	0.94	5.20	15.50
3/4/02	18.70	54.53	1.32	6.07	19.37
3/5/02	22.03	48.28	1.01	7.90	20.78
2/26–3/5/02	63.39	2.20	1.39	10.38	22.64

The total snow cover for each map and the percent of snow mapped on both maps is shown in Figure 2. More snow is mapped on the IMS maps than on the MODIS maps.

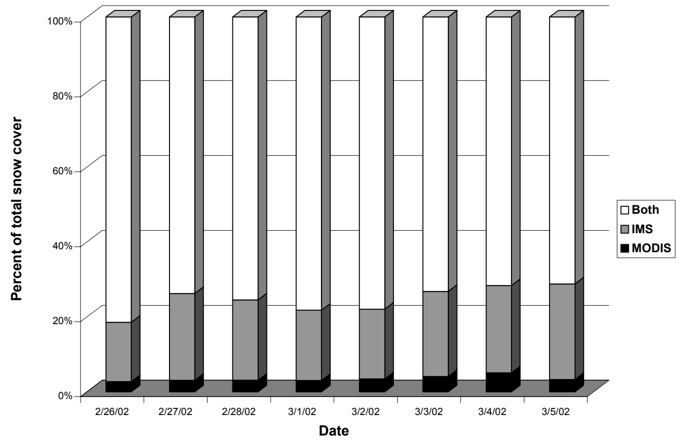

Figure 2. Total snow cover mapped on the MODIS/IMS difference maps, shown by category.

There are several areas of particular interest in the daily maps. On the February 28, 2002, MODIS/IMS

comparison map, there is an area stretching from eastern Montana to western Minnesota that the IMS map shows as snow covered and the MODIS map shows as snow free. Inspection of the MODIS Direct Broadcast data from the University of Wisconsin Space Science and Engineering Center (SSEC) http://ssec.wisc.edu/ (go to polar orbiting weather satellite images, then to Terra MODIS direct broadcast real-time and past Terra MODIS images) for that date indicates that on February 28 and March 1, there was no snow cover in that area (see Figure 3). Thus the MODIS snow map is correct in this case.

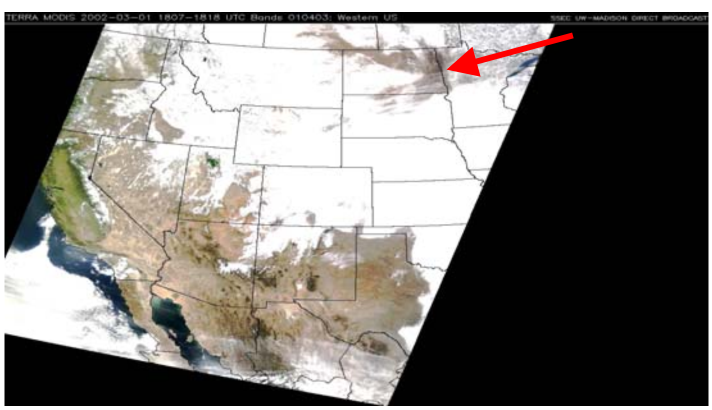

Figure 3. A black and white depiction of a true-color (bands 5, 4, 3) MODIS image from the SSEC image archive from March 1, 2002, shows that there was no snow in eastern North Dakota and western Minnesota on that date which corroborates the accuracy of the MODIS snow map in that area.

RESULTS IN NORWAY

Comparison between the MODIS maps and the MI maps shows good general agreement. Figure 4 is a part of a daily CMG map showing Scandinavia for April 4, 2002. Where earlier studies showed an overestimation on the MODIS maps of snow in forested areas (spruce and pine), these areas are mostly mapped correctly now.

However, some disagreements have been identified. The snow cover is underestimated at lower elevations along the west coast. These areas are characterized by a mixture of narrow fiords, islands and coastlines with bare rock exposed. The areas are sparsely vegetated with coarse/low vegetation in general. A broad belt along the coast was mapped as snow-free even when significantly more than 50% of the area was snow covered. In addition, some clouds are misclassified as snow. At least some of these are high-altitude clouds of low temperature (probably containing ice).

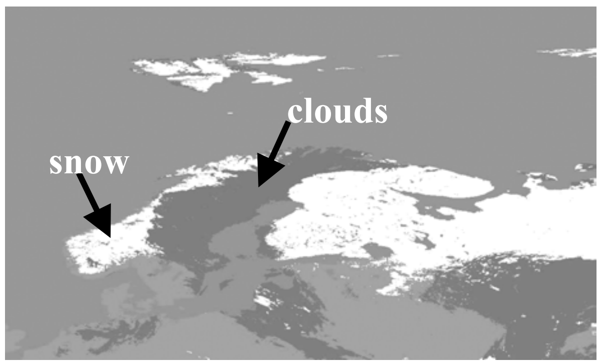

Figure 4. MODIS CMG daily snow map of Scandinavia, April 4, 2002.

DISCUSSION AND CONCLUSION

The main limitation of the MODIS daily maps is the fact that cloudcover precludes mapping much of the snow cover. And while cloudcover is dramatically reduced on the 8-day composite maps, large areas of snow cover may be not be shown on the MODIS maps if the snow fell at the end of an 8-day period when clouds remained for the rest of the compositing period. With the May 3, 2002, launch of the Aqua satellite containing a second MODIS instrument and an Advanced Microwave Scanning Radiometer (AMSR) which is a passive-microwave sensor, algorithms will be developed to use the MODIS and AMSR data, together, to map snow. This work has been ongoing for many years using existing passive-microwave sensors (e.g., see Armstrong and Brodzik, 1999). Because the AMSR will have the ability to map snow through cloudcover, snow-mapping results will be improved when both sensors are utilized together.

It is impossible to determine absolute errors in the MODIS daily and 8-day composite climate-modeling grid (CMG) 1/20° degree resolution global snow maps because a global snow map with known accuracy is not available for comparison. Comparison of the MODIS 8-day composite maps with a composite of the same eight NOAA Interactive Multi-sensor Snow and Ice Mapping System (IMS) maps demonstrates an advantage and a limitation of the MODIS maps. The advantage is that, due to its more frequent coverage, the MODIS maps show more ephemeral snow cover on the edges of snow-covered areas, than do the IMS maps, at least early in the snow season. The major limitation of the 8-day CMG maps is that they do not map snow that falls near the end of an 8-day period when the cloudcover remains until the end of the period. Thus it appears erroneously that those areas are not snowcovered. Errors of commission in Australia on three separate 8-day composite snow maps were 0.1% or less.

The relative accuracy of the daily CMG maps is good when compared to the daily IMS maps, and the MODIS maps show some ephemeral snow cover that the IMS maps sometimes miss. Some "snow cover," seen on the IMS maps, was confirmed to not be snow cover when the Direct Broadcast MODIS band data were viewed. Overall, for the time period studied, the MODIS and IMS maps studied agree well.

The comparison of Norwegian MI snow maps with MODIS snow maps shows a similar good comparison for the daily maps. However, there are some areas of disagreement and the exact reasons for the disagreement must still be determined.

MODIS, with its frequent coverage, often maps substantial areas of ephemeral snow cover which have not previously been mapped on a daily basis because it may last less than a day. This is especially evident during the early part of the snow season. The influence of large areas of ephemeral snow cover on the Earth's energy balance should be considered in long-term climate studies, and is not currently being captured by operational snow maps.

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