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# Assessment of the relative accuracy of hemispheric-scale snow-cover maps

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ABSTRACT. There are several hemispheric-scale satellite-derived snow-cover maps available, but none has been fully validated. For the period 23 October–25 December 2000, we compare snow maps of North America derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) and operational snow maps from the U.S. National Oceanic and Atmospheric Administration (NOAA) National Operational Hydrologic Remote Sensing Center (NOHRSC), both of which rely on satellite data from the visible and near-infrared parts of the spectrum; we also compare MODIS maps with Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) passive-microwave snow maps for the same period. The maps derived from visible and near-infrared data are more accurate for mapping snow cover than are the passive-microwave-derived maps, but discrepancies exist as to the location and extent of the snow cover even between operational snow maps. The MODIS snow-cover maps show more snow in each of the 8 day periods than do the NOHRSC maps, in part because MODIS maps the effects of fleeting snowstorms due to its frequent coverage. The large ($\sim$30 km) footprint of the SSM/I pixel, and the difficulty in distinguishing wet and shallow snow from wet or snow-free ground, reveal differences up to $5.33 \times 10^6$ km$^2$ in the amount of snow mapped using MODIS vs SSM/I data. Algorithms that utilize both visible and passive-microwave data, which would take advantage of the all-weather mapping capability of the passive-microwave data, will be refined following the launch of the Advanced Microwave Scanning Radiometer (AMSR) in the fall of 2001.

## INTRODUCTION

The areal extent of snow cover has been monitored continuously from satellite observations by the U.S. National Oceanic and Atmospheric Administration (NOAA) since 1966 (Matson and others, 1986). Although several weaknesses have been identified (Robinson 1993) in the long-term operational snow product, it is nevertheless the longest climatological time series of snow cover available. Passive-microwave maps of snow cover have been produced since 1978, providing information on snow extent as well as some information on snow-water equivalent. In order to improve the snow-cover record to optimize future long-term climate studies, and as input to general circulation models, it is important to develop an objective way of mapping snow globally, if trends in snow cover, such as those discussed in Brown (1997), are to be validated. In addition, the accuracy of the snow-cover input data needs to be verified in order to establish the accuracy of the model output (Derksen and LeDrew, 2000).

In December 1999, the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor was launched by the National Aeronautics and Space Administration (NASA), and some daily, global maps of snow cover at a spatial resolution of 500 m began to be available in February 2000. Snow maps have been orderable through the U.S. National Snow and Ice Data Center, Boulder, CO, since 13 September 2000. In this paper, we compare 8 day composite MODIS snow maps, NOAA/National Operational Hydrologic Remote Sensing Center (NOHRSC) operational maps, and passive-microwave-derived maps from the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/ Imager (SSM/I). Each map is known to have a unique set of problems or limitations. The 30 m resolution Landsat Enhanced Thematic Mapper Plus (ETM+) and the NOAA operational product, the Interactive Multisensor Snow and Ice Mapping System (IMS), are used as ancillary data and are considered "ground truth" for this work.

## BACKGROUND

### MODIS-derived snow maps

The MODIS snow-mapping algorithm is fully automated, which makes the results consistent from scene to scene. The algorithm uses reflectances in MODIS bands 4 (0.545–0.565 $\mu$m) and 6 (1.628–1.652 $\mu$m), uncorrected for atmospheric effects, to calculate the normalized-difference snow index (NDSI) (Hall and others, in press). Snow cover is mapped using a grouped-criteria technique algorithm. A pixel will be mapped as snow if the NDSI is $\geq$0.4 and reflectance in MODIS band 2 (0.841–0.876 $\mu$m) is $\geq$11%. However, if the MODIS band 4 reflectance is $<10\%$, then the pixel will not be mapped as snow even if the other criteria are met. This prevents pixels containing very dark targets from being mapped erroneously as snow. MODIS bands 1 (0.620–0.670 $\mu$m) and 2 (0.841–0.876 $\mu$m) are used to calculate the normalized-difference vegetation index (NDVI). An additional test using the NDSI and NDVI is used to improve the detection of snow in dense forests (Klein and others, 1998). A cloud mask (Ackerman and others, 1998) and a land/water mask are inputs to the MODIS snow-cover maps.

## DISCUSSION AND CONCLUSION

Analysis of the eight time periods, beginning on 23 October and ending on 25 December 2000, reveals that the MODIS maps nearly always show more snow cover than do the NOHRSC maps. MODIS, because of its frequent coverage, permits the mapping of some fleeting snowstorms that may be missed (either accidentally or intentionally) in both the NOAA operational products (NOHRSC and IMS). Since the NOHRSC and IMS products are subjective, the analysts who construct the maps may use ground data, in addition to satellite data, to refine the snow maps. Some minor snow events, located at the edges of areas mapped as snow by both maps, may not be deemed significant enough to label as snow if the snow cover is not continuous or persistent, a common occurrence especially at the beginning of the snow season. Or, the mapping techniques will miss the effects of these storms if the maps are not produced on a frequent basis. In general, there were not eight NOHRSC maps for each 8 day period, while the MODIS maps were produced from 8 days of data (except the 1–7 November period). NOAA's IMS product is produced daily. The greater temporal resolution of the MODIS maps is advantageous for mapping maximum snow cover, because several swaths of data may be obtained on the same day.

However, the MODIS maps exaggerate the amount of snow in some locations, as determined from comparisons with NOHRSC, IMS and ETM+ images. This is obvious in the Pacific Northwest (western Washington, Oregon and northern California). While there is snow in these locations — often only scattered snow cover — the MODIS maps show nearly continuous snow cover in some cases. The binning technique to map the 500 m resolution MODIS maps into 1/4° × 1/4° resolution maps may permit overestimation of snow cover in some cases. Where only a small amount of the cell is snow-covered, in these early MODIS products, the entire 1/4° × 1/4° pixel will be mapped as snow. An improved binning technique is under development. Maps will be produced at 1/20° × 1/20°, or 5.6 km resolution, beginning in the fall of 2001, and fractional snow cover will be provided as well. This should enhance the utility of the maps considerably.

A modification of the Chang and others (1987) algorithm, and the Grody and Basist (1996) SSM/I algorithm were studied, and the Grody and Basist (1996) algorithm was found to map even less snow cover in the early part of the snow season than did the Chang and others (1987) modified algorithm. It was therefore decided that the Chang and others (1987) modified algorithm was superior for the purposes of this work.

As the winter progresses, agreement between the MODIS and SSM/I maps improves. This was also noted by Armstrong and Brodzik (1999) in their comparison study using the SSM/I maps and the NESDIS weekly maps. As the snow deepens during winter, and the temperatures are consistently colder, the SSM/I mapping improves, and the agreement between the visible and passive-microwave maps improves. Areas of discrepancy are still present, however, especially in coastal areas where mixed pixels of SSM/I data erroneously map the coastal areas as snow-free when in fact there is snow. An example of this may be seen in northern Quebec on the 18–25 December 2000 MODIS/SSM/I difference map (Fig. 2).

The results herein are specific to the North American continent. There are likely to be circumstances on other continents that affect the results of snow mapping with the MODIS algorithms, and these can only be discovered by performing such studies on other continents.

With the launch of NASA's Aqua satellite in 2001, snow-mapping algorithms will be developed using the Advanced Microwave Scanning Radiometer–EOS (AMSR-E) sensor (Chang and Koike, 2000) that should utilize the superior mapping capabilities of the visible sensors, and the all-weather capabilities of the passive-microwave sensors (Tait and others, 2000). The improved spatial resolution of the AMSR-E data (up to 12.5 km), relative to the coarser resolution of the SSM/I, will facilitate comparison with visible and near-infrared snow maps.

Near-term improvements in the MODIS snow-mapping algorithm include providing the 8 day composite snow-cover maps at 5.6 km resolution, and improving the usage of the cloud mask (Ackerman and others, 1998), so that fewer clouds are mapped erroneously as snow.

While the intent of this work was not to establish which product is the most accurate, it is obvious that the passive-microwave data are less accurate in terms of mapping total snow-covered area. This is due to the relatively low (~30 km) spatial resolution of the data, and the fact that the wet snow and shallow snow may not be mapped by the existing automated passive-microwave algorithms, especially in the early part of the snow season.

Relative errors in snow-cover mapping, using both visible/near-infrared and passive-microwave maps, are easier to ascertain than absolute errors. This is because it is very often impossible, in retrospect, to determine which map is the most accurate, or precisely where the snow was located. A technique that combines ground measurements with determination of snow-mapping accuracy in different land-cover types (e.g. Hall and others, 2001) is an attempt to begin to assess the absolute accuracy of snow-cover maps.

MODIS and NOHRSC maps often agree very well, except that the MODIS nearly always maps more snow cover than does the NOHRSC (Table 1). MODIS maps show more snow than the NOHRSC maps, especially at the beginning of the snow season when the more frequent temporal coverage of MODIS permits mapping of shallow snow deposits from fleeting storms. However, we do not know which map is the more accurate since none of the hemispheric-scale snow maps has been fully validated. We can only study the relative accuracy of the maps at this time, augmented by accuracy assessments in selected locations where we have access to either ground measurements or Landsat ETM+ data.