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Reduction of Cloud Obscuration in the MODIS Snow Data Product

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ABSTRACT

A challenging problem in snow mapping is the discrimination of snow from clouds. Snow and clouds often have similar spectral reflectance features across the spectrum and may have similar temperatures making discrimination difficult. Data from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the NASA Earth Observing System (EOS) Terra spacecraft, is used to generate many geophysical products including snow extent and cloud properties. MODIS snow and cloud mask data products have been generated in a consistent series from 1 November 2000 to the present. The MODIS snow algorithm uses the cloud mask data product to identify clouds. The MODIS cloud mask algorithm employs many cloud spectral tests to determine if a pixel is cloud or clear; a cloud mask summary flag as well as all the cloud spectral tests applied are stored in the product. The production version of the MODIS snow algorithmuses the cloud mask summary flag to discriminate snow from cloud. The cloud conservative nature of the cloud mask algorithm generally results in more cloud obscuration than necessary, relevant to snow identification, which has impacted the ability to map snow extent. Analysis of the cloud mask algorithm techniques, processing paths and cloud tests, has led to improved usage of cloud spectral test data for masking clouds in the snow algorithm. Described are refinements in the use of cloud tests from the cloud mask product that minimize cloud obscuration of snow cover, maximize snow identification and constrain confusion between snow and clouds, leading to an improved mapping of snow cover extent.

Keywords: remote sensing, snow cover, MODIS.

INTRODUCTION

The MODIS snow algorithm produces maps of snow extent using reflective and thermal data from the MODIS instrument at the swath level. Snow extent products are generated at several levels from a swath, about 2030 x 2330 km coverage, at 500 m resolution to daily composited global Climate Modeling Grid (CMG) products at 0.05 degree resolution. Algorithm techniques vary with level but all are produced in sequence beginning with the swath product in which snow and cloud are discerned. Algorithms at subsequent levels composite the preceding level to different temporal or spatial scales. Discussed here is the discrimination of snow and cloud in the swath level snow algorithm.

Snow has rather unique spectral characteristics compared to most other terrestrial surface features. Snow has high reflectance in the visible and strong absorption in the infrared spectral regions. Those characteristics are key to detection of snow by use of reflectance ratios. However, some types of clouds exhibit very similar spectral characteristics, which makes discrimination

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between snow and clouds very difficult in some situations. Discrimination of snow from cloud is a major challenge in both snow mapping and cloud mapping (Ackerman *et al*., 1998).

Cloud obscuration is a limitation to snow extent mapping using visible and thermal infra-red (IR) data. It is necessary to identify clouds for two reasons: to show where clouds obscure the view of surface and to avoid errors by misidentifying clouds as snow. In the first case clouds prevent knowing with certainty the state of the surface. In the second case the goal is to alleviate erroneous identification of clouds as snow, thus improving the accuracy of the resulting snow map.

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. MODIS is onboard the first NASA EOS satellite, called Terra, launched on December 18, 1999 and on the Aqua satellite, launched on May 3, 2002. Terra has a sun-synchronous, near polar, circular, 705 km orbit with a 10:30 a.m. local time descending mode. Aqua has a similar orbit but with a 1:30 p.m. local time ascending mode.

Snow Algorithm

The automated MODIS snow-mapping algorithm uses at-satellite reflectances in MODIS bands 1 (0.659 µm), 2 (0.865 µm), 4 (0.555 µm) and 6 (1.64 µm). Also used are the thermal bands 31 (11.03 µm) and 32 (12.02 µm). Several tests for snow in a grouped criteria technique are used to identify snow, and the MODIS cloud mask product is used to create a cloud mask. The principal test for snow is the normalized difference snow index (NDSI) (Hall *et al*., in press). The NDSI is calculated as (band 4 - band 6) / (band 4 + band 6). Other tests for snow characteristics or non-characteristics 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) allowed for improved snow mapping in forested areas. The normalized difference vegetation index (NDVI), using MODIS bands 1 and 2 is calculated and used along with the NDSI to improve snow mapping in dense forests, as snow will tend to lower the NDVI and NDSI in forests (Klein, *et al*., 1998). A surface temperature screen was included in a recent revision to alleviate mapping warm surfaces with spectral features similar to snow as snow. The summary cloud flag from the cloud mask product has been used in the MODIS snow algorithm.

Cloud Algorithm

The MODIS cloud mask algorithm takes a cloud conservative approach to cloud detection. The cloud algorithm uses fourteen of the 36 MODIS bands in 18 cloud spectral tests following processing paths that vary with surface type, geographic location and ancillary data input. Results of all tests and processing flags are stored in the cloud mask data product. The summary result of whether a pixel is cloudy, clear or probably clear is reported in a single summary flag of the cloud algorithm for a pixel. A complete description of the cloud mask algorithm is presented in Ackerman *et al*., (1997, 1998) or at the MODIS Atmospheres website, modis-atmos.gsfc.nasa.gov/MOD35_L2/index.html.

Within the cloud mask algorithm an initial guess of whether snow or cloud is being viewed must be made so that the appropriate processing path and cloud spectral tests can be applied. A first guess at snow is made using the NDSI that is modified based on spectral tests so that clouds over snow can be identified and to eliminate those cloud types or situations that the NDSI falsely indicates as snow. The first guess is made with the NDSI and supplemented with ancillary data sources to refine the guess to determine the appropriate processing path. That guess is reported as the snow/ice background flag in the data product to indicate what processing path was taken for a pixel.

RESULTS & DISCUSION

The cloud mask algorithm produces a very cloud conservative mask. Analysis of many swaths of MODIS data over time has revealed that the summary cloud mask results in cloud obscuration of snow surfaces by clouds under which the snow can be observed (using natural and false color MODIS images) and that the snow signal through the clouds is strong enough to be detected by the snow algorithm, for the purpose of mapping snow extent. Also, situations have been found where the cloud mask algorithm incorrectly identifies snow cover as cloud. This may happen over snow cover in northern forests and margins of snow-covered regions in mid-latitudes. Some scenes containing these conditions were selected as case studies to determine if selective use of certain cloud mask tests would result in a more liberal cloud masking that would decrease cloud obscuration and allow for maximum snow detection.

Snow detection is primarily dependent on the NDSI in the MODIS snow algorithm. The NDSI is insensitive to most clouds except for some clouds containing ice and in some indistinct cloud situations where the cloud signature is similar to snow. The objective was to select certain cloud tests that identified clouds over snow without excessive cloud obscuration and to select tests that identify clouds that obscure the surface, snow covered or otherwise, so that an accurate snow extent map that included cloud cover could be generated. Of the many tests available in the cloud algorithm it was found that three could be used in the snow algorithm to minimize cloud obscuration over snow and to mask clouds where the clouds completely obscured the surface.

Some of the tests were implemented to detect certain types of clouds and others were generalized for all types of clouds (Ackerman *et al*., 1997). Initially all the cloud test results were included in analysis. Five cloud tests are applied where the snow/ice background flag is set for the presence of snow/ice. Nine cloud tests are applied to land surfaces those include the five applied in the presence of snow/ice. Criteria of the tests were different depending on the background, ecosystem type or elevation. Of those tests it was found that the test for high cloud (result stored at bit 14), the 3.9-11µm thermal difference test for low-level water clouds (result stored at bit 19) and the visible reflectance test for clouds over dark surfaces (result stored at bit 20) can be combined to create a cloud mask that minimizes cloud obscuration and false cloud detection of snow-covered surfaces. That combination of cloud tests was found to be very effective, however, some cloud was missed and resulted in erroneous snow mapping. An additional test to screen those cloud situations was included. The additional test marks as cloud pixels that have an NDSI value >= 0.4 and MODIS band 6 reflectance greater than 0.20 as cloud. This new cloud mask is dubbed the liberal cloud mask and is applied as follows:

Cloud if:
High cloud test (bit 14) is set to cloud
Thermal difference test (bit 19) is set to cloud
Visible reflectance test (bit 20) is set to cloud and band 6 reflectance > 0.20
NDSI >= 0.4 and band 6 reflectance > 0.20

Discussion and results for three case studies with the new liberal cloud mask are presented in the following subsections.

Central Plains of the U.S.

A swath imaging the central USA, southern and northern Great Plains, acquired on 29 November 2001 at 1750 UTC shows regions of snow cover, bare land and several cloud types (Fig. 1 a and b). The large area of snow in the upper middle of the swath shows clouds through which the underlying snow cover can be seen (compare 1a and 1b). The Missouri River and the reservoirs on it can be seen. Clouds on the upper right side of the swath obscure snow cover that continues from the middle of the swath to that edge near Lake Superior. Snow cover from a storm that swept across central Texas and Oklahoma appears in the lower right center of the swath.

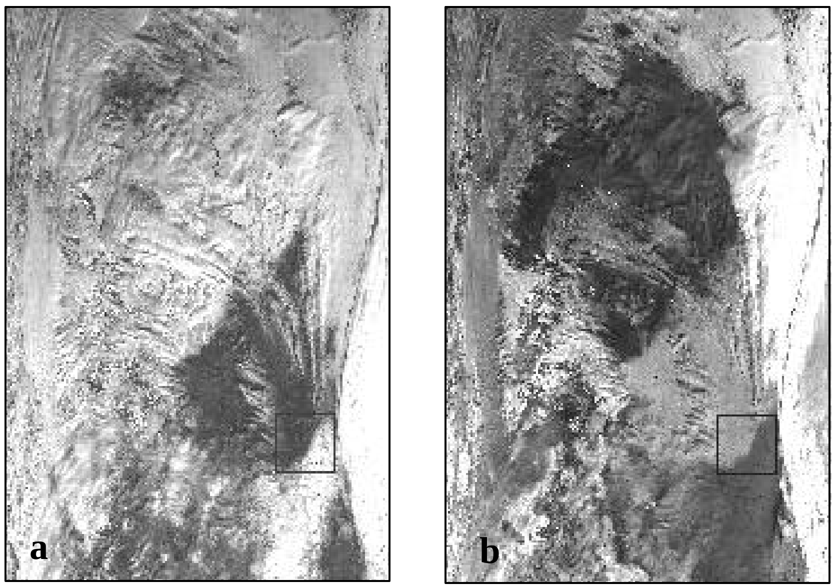

Figure 1. a) MODIS band 2, b) MODIS band 6. In the band 2 image, the clouds and snow are visually difficult to discriminate because both have high reflectance. In band 6 snow has very low reflectance but cloud has high reflectance. Snow cover is bright in band 2 and dark in band 6, which helps discriminate snow from cloud. Cloud reflectance in band 6 depends in part on cloud type and may be bright, e.g. on right edge of swath, or less bright e.g. gray clouds on left side of image.

The extent of snow and cloud estimated by the snow algorithm using the conservative (summary) cloud mask is shown in Figure 2a. The cloud conservative nature of the cloud mask is evident by the fairly extensive cloud found in the swath and especially over the Northern Plains snow covers. Visual comparison with the visible image (Fig. 1 a and b) reveals that the snow cover is evident under parts of that cloud cover. Extent of observable snow increases when the liberal cloud mask is used (Fig. 2b) because the semi-transparent clouds do not block the detection of snow cover as occurred with the conservative cloud mask. Opaque clouds are mapped with the liberal cloud mask. Another improvement is that the false cloud that appeared on the perimeter of snow-covered areas, e.g. central Oklahoma in the rectangle in Figs 1 and 2, was eliminated with the liberal cloud mask (Fig. 3). Some of the visible cloud tests in the cloud mask algorithm often identify transition regions between snow cover and snow free land (e.g. the oval in Fig. 3c), where snow cover is thin or fractional, as clouds. The visible cloud test over dark surfaces, stored in bit 20, often is the cause those false clouds because of the mixed signal for the surface. That test often fails over bright surfaces Ackerman *et al*. (1997). However it is a test that detects clouds that are not found by other cloud tests. That is the reason it is used in the liberal cloud mask but with the restriction that the band 6 reflectance be greater that 0.20 for the test result to be valid for snow mapping. If band 6 reflectance is greater than 0.20 it is assumed that the feature is not snow.

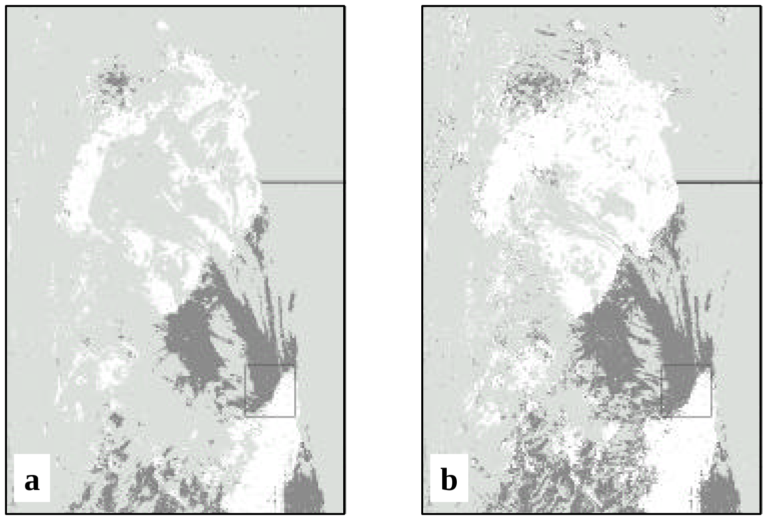

Figure 2. Snow map with conservative (a) and with liberal (b) cloud mask. Snow—white, land—dark gray, cloud—medium gray.

Clouds detected by the liberal cloud mask tests (listed above) are shown in Figure 4 a-d. In each figure the clouds detected by each of the liberal cloud mask tests are shown. Cloud is mapped in a pixel if any one of the four liberal cloud mask criteria is met. The liberal cloud mask results in approximately 19% reduction in cloud cover and a 43% increase in snow cover.

Lake Winnipeg

A swath imaging the northern plains and central Canada acquired 4 June 2001 at 1805 UTC was used as a test. Snow was not present in this swath. Major features in the swath were boreal forest, Lake Winnipeg, and clouds. Several types of clouds obscured about 50% of the image. The snow algorithm was applied using the conservative cloud mask and liberal cloud mask in separate runs. The snow map from the run with the conservative cloud mask resulted in zero percent snow cover which agreed with visual interpretation and with NOAA Interactive Multisensor Snow and Ice Mapping System (IMS) snow map. The snow map from the run with the liberal cloud mask mapped snow on a few cloud types for a false snow error amount of about 3%. All the error occurred on clouds that had spectral features similar to snow and that were not detected as clouds by the liberal cloud mask. This result demonstrates the need for further refinement of the liberal cloud mask to alleviate this type of error.

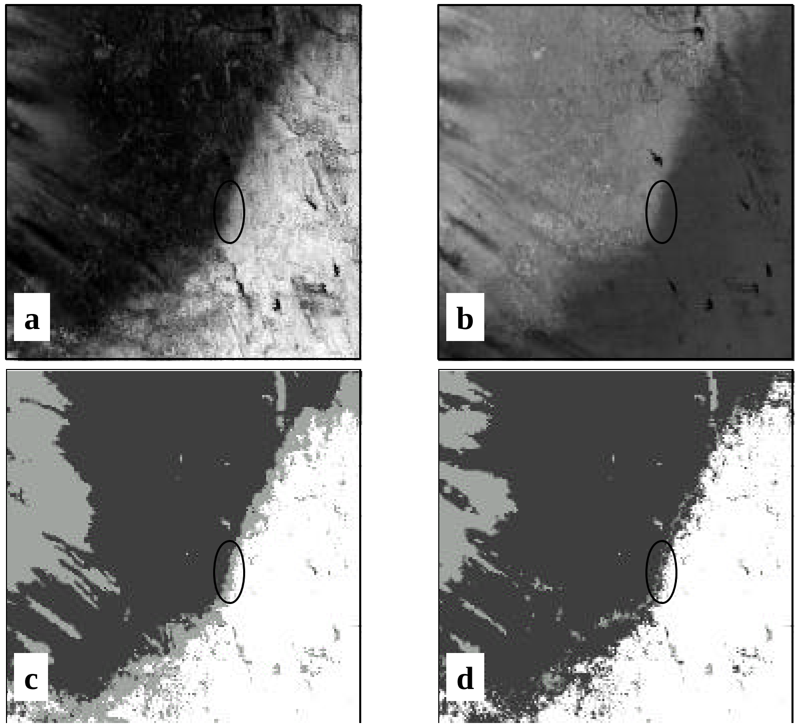

Figure 3. Reductions in misidentified clouds in transition area between snow-covered and snow-free land. Area shown is that of the rectangle in Figs 1 and 2, Snow—white, land—dark gray, cloud—medium gray. Snow is bright and land is relatively dark in MODIS band 2 (a). That contrasts with the low reflectance of snow in band 6 and higher reflectance of land (b). The conservative cloud mask (c) gives false clouds in the transition area e.g. area within the black oval. The liberal cloud mask eliminates most of those clouds (d) allowing for unobstructed mapping of the snow cover.

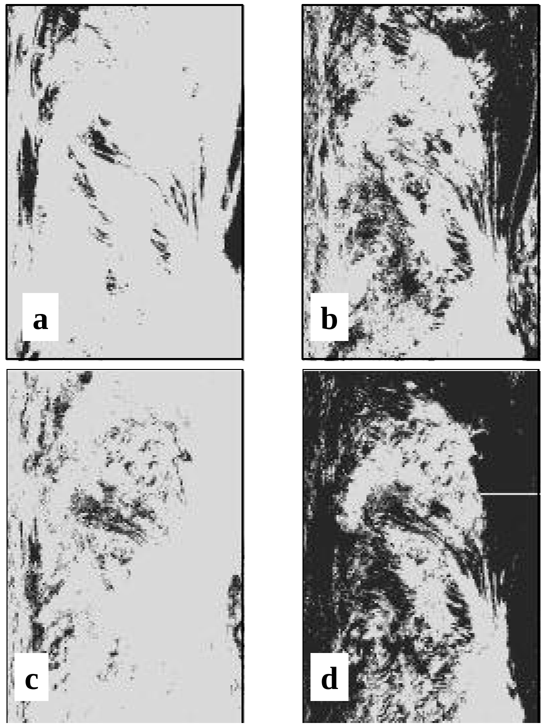

Figure 4. Clouds from each of the tests applied in the liberal cloud mask are shown in black in images a-d. Light gray indicates that cloud was not detected by the test. Image a is cloud from high cloud test (bit 14) . Image b is cloud from thermal difference test (bit 19). Image c is cloud from visible reflectance test (bit 20) and band 6 reflectance > 0.20. Image d is cloud from the NDSI >= 0.4 and band 6 reflectance > 0.20 cloud test.

Central Canada

A MODIS swath imaging Saskatchewan and Manitoba to Hudson Bay acquired 8 March 2002 was also studied. This swath was chosen because of excessive cloud obscuration shown in the cloud mask product despite comparison with MODIS radiance data that showed clear conditions. Snow cover existed in the northern third of the swath and was unobstructed by cloud from the northern edge of Lake Winnipeg north to Hudson Bay and extending eastward and westward from that location. Application of the snow algorithm using the conservative or liberal cloud masks were compared. Analysis of the conservative cloud mask revealed that one of the cloud tests for thin cirrus was causing the region of snow cover to be identified as cloud. The snow algorithm output from the liberal cloud mask correctly identified that entire region as snow covered and identified most clouds that were present. Cloud obscuration was reduced by 24% and snow cover increased by 17% with use of the liberal cloud mask. The numerous snow-covered lakes to the west of Hudson Bay that were cloud obscured in the conservative cloud mask were evident in the liberal cloud mask output. As a result, there was a 25% increase in the amount of snow-covered lakes.

CONCLUSIONS

An improved cloud mask relevant to snow mapping was developed by selective use of cloud spectral tests from the MODIS cloud mask data product along with reflectance criteria tests. The new liberal cloud mask minimized cloud obscuration and maximized the ability to map snow in clear conditions and through semi-transparent clouds. Though the liberal cloud mask exhibits improvements over the conservative cloud mask, it is not flawless. With some cloud situations, e.g. the Lake Winnipeg case study, the liberal cloud mask misses some clouds, which are then identified as snow in the snow algorithm resulting in errors in the resulting snow map. Since that error of snow/cloud confusion appears for particular cloud situations, it is probable that a specific test for these conditions can be developed to further alleviate the error in snow mapping.

Improved snow mapping from the MODIS swath products will be carried forward to the daily and eight-day composite data products, which should result in better snow maps at those levels because of reduced cloud obscuration. It is anticipated that the liberal cloud mask will be integrated into the snow algorithm, along with other revisions, in time for the Collection 4 processing of the data generation system expected to begin in October 2002. Snow data products will then be archived at the National Snow and Ice Data Center (NSIDC) (McLean, 2000) as Version 4 products.

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