MODIS Snow Cover Algorithms and Products – Improvements for Collection 6

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ABSTRACT

Over the past decade scores of journal papers and workshop proceedings have presented research using the Moderate-Resolution Imaging Spectroradiometer (MODIS) snow cover products. Review of those works reveals how the MODIS snow-cover products have been used including details regarding accuracy of snow mapping and issues encountered. In response to that body of feedback the MODIS snow-cover algorithms are being revised to reduce and alleviate, when possible, errors in the snow-covered area and fractional snow-cover products. Though the MODIS snow-cover maps have accuracies reported of ~90% (or higher) in good observing conditions, users have reported some problems with snow/cloud discrimination, errors of commission and omission, and with detection of summer snow cover in mountains. The daily snow-cover gridded tile product, MOD10A1, is the product most used by the community. The next revision of the MODIS snow-cover algorithms and products, which will constitute Collection 6, is ongoing with the goal to minimize snow errors identified since the last revision for Collection 5. One major change is that the snow-cover and snow fraction algorithms will use the MODIS surface reflectance product MOD09GA, as input. In addition, screens for snow detection in certain situations have been modified or added, and a new Quality Assessment (QA) scheme will be applied. Testing shows increased accuracy in the revised snow maps relative to the Collection 5 snow-cover maps. It is expected that the overall accuracy of the Collection 6 snow-cover maps will be higher than the Collection 5 maps, thus making the snow-cover maps even more valuable for the user community.

Keywords: MODIS, snow cover, fractional snow cover, cryosphere.

INTRODUCTION

Snow may cover up to about 50 million km^2 of the Northern Hemisphere land surface (http://climate.rutgers.edu/snowcover/) and thus has a major impact on the Earth's energy balance because of its high albedo and low thermal conductivity. Albedo, the ratio of reflected to incident solar energy, governs how much solar energy is absorbed by land and ocean surfaces can change dramatically, for example from 0.2 to 0.8 or greater, when snow first accumulates. Snow cover also has a major influence on atmospheric circulation by modifying overlying air masses.

Because so much of the water supply used by humans comes from snow cover, especially in mountainous areas throughout the world, snow water equivalent (SWE) is a critical snowpack parameter. However SWE cannot yet be measured remotely with the accuracy required by hydrologic models. To obtain accurate SWE estimates from space, other sources of information,

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including station data and satellite derived snow-covered area, should be used together to increase the usability of snow-covered area and SWE in land-surface models.

NASA's Earth Observing System Data and Information System (EOSDIS) processes the data collected by the Moderate-Resolution Imaging Spectroradiometer (MODIS) instruments on board the Terra and Aqua spacecraft into data products that are stored and distributed to the community. Over the history of EOSDIS scientists developing and studying the algorithms and data products have developed improved or new algorithms and products so that occasionally the EOSDIS will reprocess an entire collection of MODIS data from first day of mission to present day to make a new collection of the improved data products. The EOSDIS is preparing to make a new collection, which will be Collection 6 (C6) of the MODIS data, including the snow data products, to eventually replace the current Collection 5 (C5).

Over the past decade scores of journal papers and workshop proceedings have presented research using the MODIS snow cover products *(see listing of papers that use MODIS cryosphere products at* http://modis-snow-ice.gsfc.nasa.gov/?c=publications). Review of those works reveals how the MODIS snow-cover products have been used including details regarding accuracy of snow mapping and issues encountered. In response to that body of feedback the MODIS snow-cover algorithms are being revised to reduce and alleviate, when possible, errors in the snow-covered area and fractional snow-cover products. Described here are the major changes planned for the MODIS snow cover algorithms and products in C6.

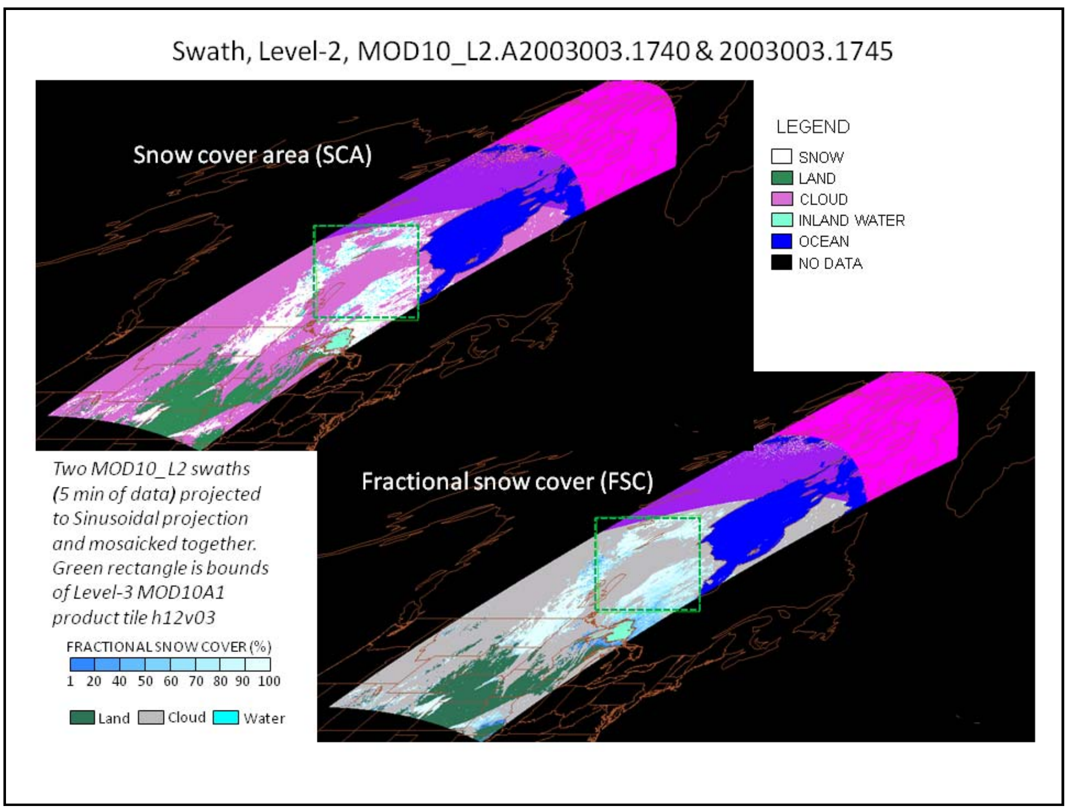

Figure 1. Projected SCA and FSC maps from two swaths of the MOD10_L2 product covering from Hudson Bay, Canada to the Great Plains of the USA. The swaths butt together at midpoint of this image. The green rectangle is tile outline of the next product, MOD10A1 the daily composited, projected and tiled snow maps (Fig. 2).

MODIS SNOW PRODUCTS

The MODIS snow cover products are produced as a sequence of products beginning with the Level-2 swath product, MOD10_L2 (Fig. 1) to a daily Level-3 gridded and projected product at 500 m resolution, MOD10A1 (Fig. 2). Snow covered area (SCA), a thematic map of snow cover and surface features, and a fractional snow cover (FSC) map are contained in those data products. The subject of this paper is the revisions planned for these two snow algorithms and products. The sequence of MODIS snow products continues with a daily global snow product, MOD10C1, at 5 km resolution (Fig. 3) and to 8-day composite products at the tile and global scales. Complete description of the MODIS products is found in the snow products user guide (Riggs *et al*., 2006) and at the National Snow and Ice Data Center (NSIDC) EOSDIS Distributed Active Archive Center (DAAC) (NSIDC 2011). MODIS snow products can be searched for and ordered from the NSIDC EOSDIS-DAAC.

Complete description of the MODIS SCA and FSC algorithms is given in the MODIS Snow Products User Guide (Riggs *et al*., 2006). The core of both algorithms is the normalized snow difference index (NDSI) which is based on the characteristic of snow being highly reflective in the visible and very absorptive in the near infra-red wavelengths. The NDSI is calculated as: NDSI = (band4 – band6)/(band4 + band6) in the Level-2 snow algorithms using the MODIS top-of-atmospheric reflectance. The basic SCA algorithm detects snow if the NDSI $\geq$ 0.4 and if other screens for false snow detections are passed; there is also a subroutine that uses a combination of

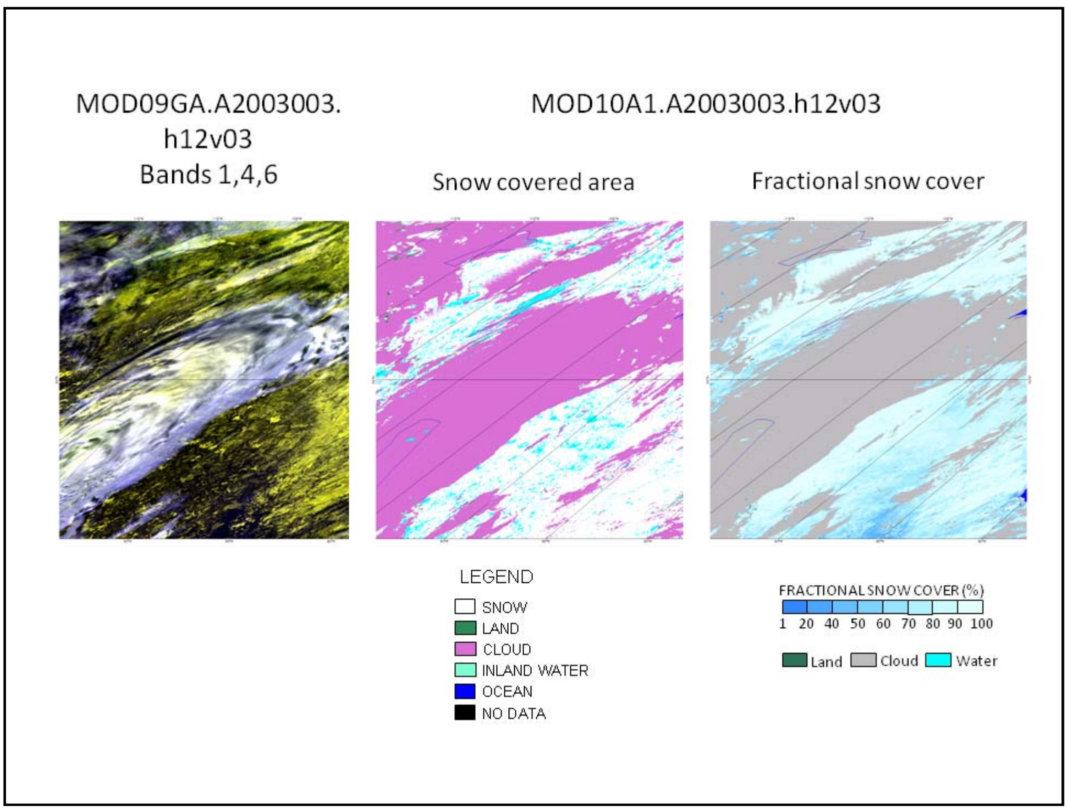

Figure 2. Projected SCA and FSC maps from MOD10A1, the daily composited snow maps product. False color image of MODIS bands 1, 4, and 6 from the daily surface reflectance product, MOD09GA, shown on left for visual interpretation. This tile, h12v03, of MOD10A1 covers approximately 50° to 60° latitude and -77° to -121° longitude; the outline of Lake Winnipeg is in left lower quadrant and a bay of Hudson Bay is in upper right quadrant.

the NDSI and normalized difference vegetation index (NDSI) to extend snow detection in some vegetation conditions with lower NDSI values. An example of MODIS SCA map is shown in Fig. 1, upper left image.

The FSC algorithm uses the NDSI, full range of 0.0 – 1.0, to calculate FSC using a regression equation that was developed by Salomonson and Appel (2004). Fractional snow cover is estimated based on the strength of snow reflectance features in reflectance from the surface; it is not an estimate of the physical spatial extent of snow in a pixel on the surface. Because the FSC is calculated over the entire range of NDSI, 0.0 – 1.0, that snow may theoretically have, it usually maps more snow cover, especially at edges of snow cover and in sparse snow cover or in vegetation compared to the SCA. The same screens for false snow detections are applied as for SCA. An example of MODIS FSC map is shown in Fig. 1, lower right image.

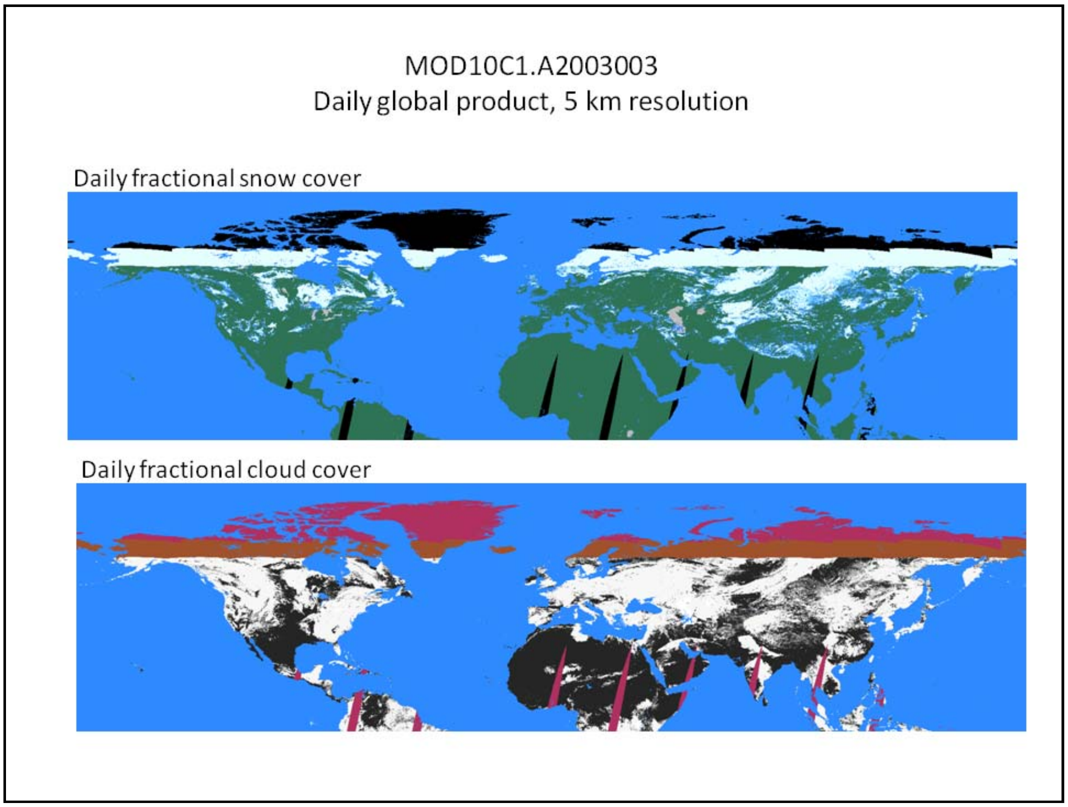

Figure 3. MODIS daily global snow cover product, MOD10C1. The daily fractional snow cover is made by binning of the MOD10A1 SCA to 5 km resolution and mapping the amount of snow cover in each 5 km cell of the global projection. The daily fractional snow cover and the daily fractional cloud cover data layers need to be used together to give a complete image of snow cover for a day.

The cloud mask for the SCA and FSC is taken from the MODIS Level-2 Cloud Mask Product, MOD35_L2. The cloud mask algorithm has a cloud conservative approach so it tends to detect clouds in situations where there is doubt between cloud and other features, like snow cover. If the cloud mask product flags a pixel as certain cloud then that pixel is cloud in the snow cover product.

The MODIS Level-3 snow products are the result of mapping, gridding and compositing the Level-2 SCA and FSC into a single daily product that is a tile of the projection then selecting the best observation from several that may have been acquired for a cell on the grid to make the daily snow cover SCA and FSC in the MOD10A1 product (Riggs *et al.*, 2006). An example of the MOD10A1 product is shown in Fig. 2. The daily global snow product, MOD10C1 (Fig. 3) is made by binning the MOD10A1 maps to 5 km to report the proportions of snow cover, cloud cover or snow free observations in a gridded cell.

NSIDC statistics (Fowler, 2011) show that the daily tiled, projected MODIS snow product, MOD10A1 (Fig. 2), has been the most frequently ordered product of the available MODIS snow products. The literature reflects that fact in that a large majority of research uses the MOD10A1 product. Researchers using global scale models that use snow cover as input use the daily global gridded, 5 km MOD10CMG snow product, e.g. Sujay (2011). A frequent usage of the MOD10A1 has been to monitor snow cover during the ablation season and use it to develop snow cover depletion curves (e.g. Dery *et al*., 2005). It has also been compared to other snow maps or station data to assess the accuracy of snow cover mapping. Nearly all studies have used the SCA instead of the FSC. The SCA algorithm is restricted to NDSI range of 0.4 – 1.0 but the FSC algorithm uses the NDSI range of 0.0 – 1.0, making it the more sensitive algorithm for snow cover detection, thus the FSC is the better choice for study of snow cover in some studies because the edges of snow covered areas are more accurately mapped *cf.* Fig. 4. However, the caveat with FSC is that a slightly higher number of snow commission errors may occur compared to the more conservative SCA. Note that the FSC was available beginning in C5 of MODIS snow data products, so prior to about January 2007 when C5 processing began, the FSC was not available. A comprehensive listing of publications that used MODIS snow products is provided at the project home page, http://modis-snow-ice.gsfc.nasa.gov/ under the “Publications” link.

REVISIONS FOR SNOW COVER DETECTION

Reduce snow/cloud confusion

Investigation and evaluation of the snow products by the development team and gleaning of the scores of research papers has revealed hindrances to accurate snow cover detection in the MODIS snow cover algorithms. Cloud cover prevents detection of snow cover and that cannot be resolved, but in some situations where confusion or uncertainty exists between cloud and snow, resolution may be possible with use of more input information.

Snow/cloud confusion on the edges of a snow covered region in which there is no visually apparent cloud is a frequently observed problem. This confusion is attributable to the MODIS cloud mask algorithm reporting certain cloud based on a single visible reflectance test for cloud according to Riggs and Hall (2003). An example of this situation is shown in Figure 4 where cloud is mapped over the transition from snow-covered plains to snow-free plains despite no visual evidence to indicate clouds.

There is a previous version of the snow algorithm in which an alternative use of the cloud mask was employed to alleviate this snow/cloud confusion situation (Riggs and Hall, 2003). Though the technique was effective at alleviating the problem, it also resulted in some types of cloud cover not being flagged with a result of snow free ground which had a greater detrimental impact on the quality of the snow maps compared to the snow/cloud confusion at the edges of snow cover. That technique was abandoned before the start of the C5 processing, without further investigation to refine the technique to accurately detect clouds when clouds were present.

A new approach using the cloud flags from both MOD35_L2 and the MODIS daily surface reflectance product, MOD09GA, to alleviate snow/cloud confusion at the edges of snow cover has been developed. The MOD09GA carries the MOD35_L2 cloud flag and its own internal cloud flag. For a cloud to be detected the MOD35_L2 cloud flag state must be certain cloud and the MOD09GA internal cloud flag must also be set to ‘cloud’. If the MOD35_L2 cloud flag state is ‘certain cloud’ and the MOD09GA cloud flag is set to ‘clear’, then the pixel is considered clear for purpose of snow detection in the algorithm. This interpretation of both cloud flags has alleviated

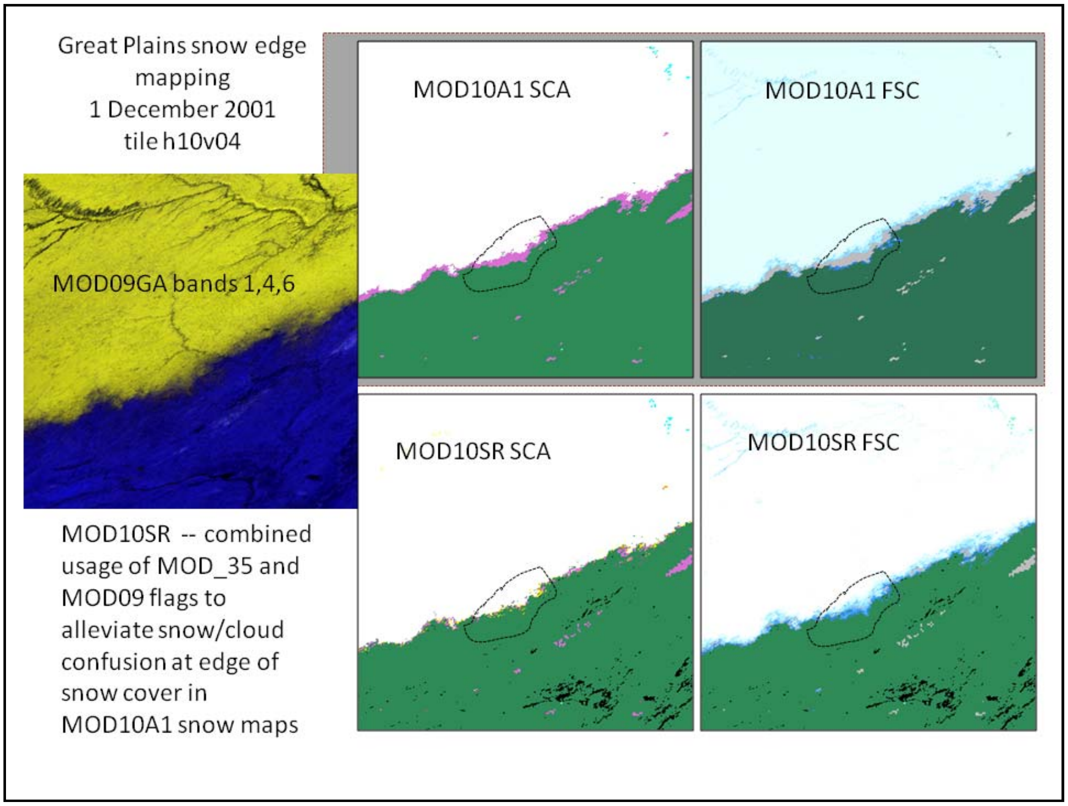

Figure 4. Snow/cloud confusion at edge of snow cover. A false color image, MODIS bands, 1, 4, 6 of MOD09GA, far left image, where snow appears yellow, shows no visually apparent cloud cover over the edge of the snow cover on the Great Plains. In the current snow algorithm snow/cloud confusion can occur at the edges of a snow-cover area where the cloud mask erroneously flags cloud, colored in pink and gray in the top right two images of MOD10A1. In this situation the snow/cloud confusion is alleviated by using the MOD35_L2 and MOD09GA cloud flags together, bottom right two images.

much snow/cloud confusion at the edges of snow cover as exhibited in Fig 4 (lower pair of images). In order to demonstrate usage of the two cloud flags the new implementation of the snow algorithm and product labeled as MOD10SR in Fig. 4 was used. The MOD10SR product is further described in the Discussion & Conclusions section. Investigation to date has not found this technique to cause snow errors of omission or commission in other situations. Visual interpretation has found that when a cloud is definitely apparent in visible bands, that typically both the MOD35_L2 and MOD09GA flag a cloud but, in scattered cloud cover or a closely spaced pattern of clouds the two cloud mask frequently disagree, especially on fringes of clouds in the cloud cover. We continue to investigate ways to alleviate snow/cloud confusion in situations where the two cloud flags disagree.

Remove low visible reflectance screen

The snow algorithm has a low visible reflectance screening test for the purpose of screening out snow commission errors caused by small water bodies not included in the MODIS land/water mask. This screen prevented pixels that were identified as snow but that had top-of-atmosphere (TOA) reflectance values below 10% in MODIS bands 2 (0.86 µm) and 4 (0.55 µm) from being detected as snow. Water bodies can have very high NDSI values despite having very low visible reflectance because the relative difference between visible and NIR reflectance can be large resulting in a large ratio that causes them to appear as snow in the algorithm, if not otherwise screened from the algorithm. The MODIS land/water mask did not mask numerous small water bodies, lakes or rivers, thus numerous erroneous snow pixels could be detected if the water bodies were not masked. The low visible reflectance screen is effective at preventing erroneous snow detection on water bodies. However, recently it was discovered that summer snow cover in some mountain ranges, e.g. Sierra Nevada (Painter, 2010) would disappear (Fig. 5). We found the cause of the “disappearing” snow to be that snow reflectance either in TOA reflectance or MOD09GA surface reflectance decreases below 10% in the summer which was then screened by the low visible reflectance screen and set to snow-free land. In other mountain ranges, e.g. in Afghanistan with summer snow cover the snow reflectance remains above the 10% level during the summer, the snow decision is not affected by the low visible reflectance screen.

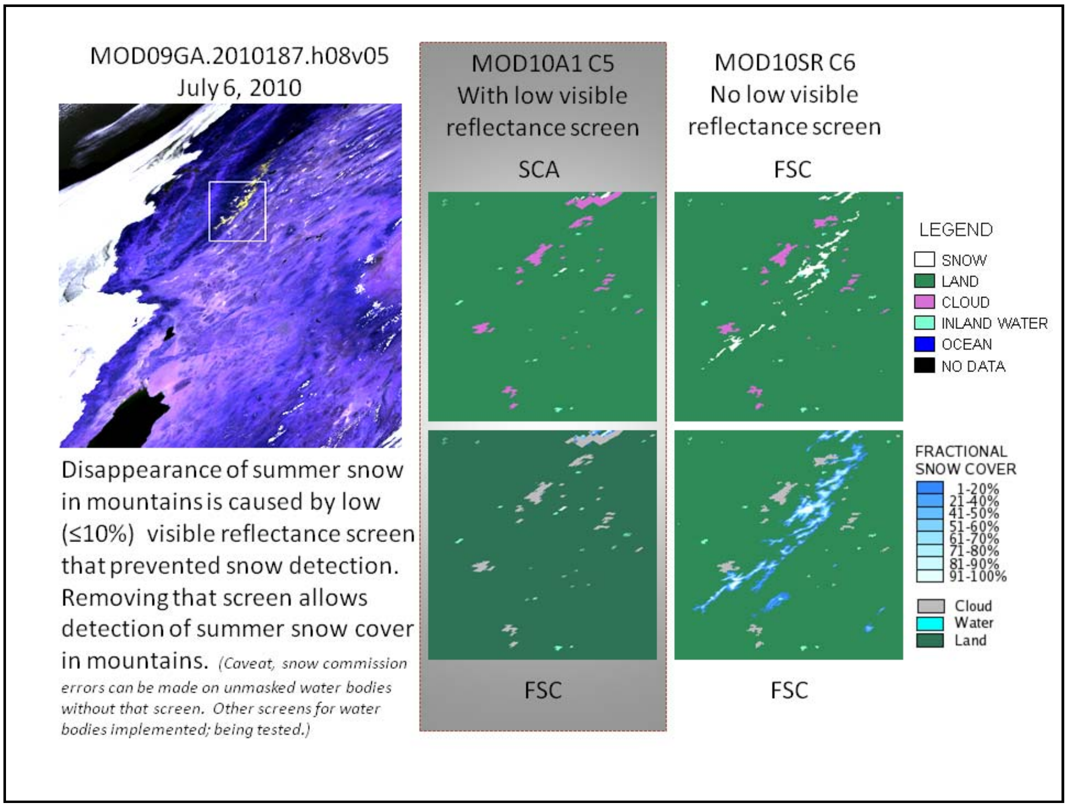

Figure 5. Summer snow in mountains. A false color image, MODIS bands, 1, 4, 6 of MOD09GA, far left image, shows summer snow cover in the Sierra Nevada, snow cover appears as yellow, clouds as white, the white rectangle is area shown in images to the right. MOD10A1 SCA and FSC in the middle column show no snow. MOD10SR SCA and FSC, right column, made without the low visible reflectance screen show snow cover in the Sierra Nevada.

Removing the low visible reflectance screen, for either TOA or surface reflectance, allows for detection of summer snow cover on mountains. The effect of removing the low visible reflectance screen is an accurate mapping of mountain snow cover in the summer as exhibited in Fig 5. In Fig 5 the MOD10SR SCA and FSC extents agree very well with the visual interpretation of snow cover in the MODIS bands 1,4,6 image. However, removing the low visible reflectance screen may have unintended consequence of increasing snow commission errors associated with unmasked water bodies, lakes and rivers. That consequence is lessened in C6 by use of a new, more accurate water mask at 250 m resolution (Carroll *et al.*, 2009) that masks more and smaller water bodies. However some small water bodies will not be masked so other screens for water are being investigated for use in the snow algorithm.

DISCUSSION AND CONCLUSION

Snow cover algorithm revisions planned for C6 are to implement changes in the MOD10_L2 algorithm and continue through the sequence of snow products so that C6 will have continuity with C5. The major revision will be abandoning the low visible reflectance screen in the MOD10_L2 algorithm with the objective of improving detection of summer snow cover on some mountain ranges, and low illumination conditions, along with adding other screen(s) to alleviate snow commission errors associated with water bodies in both the SCA and FSC algorithms/products.

In addition, a new daily MODIS snow cover product independent of the current sequence of products is planned for C6. The motivation for this product is to generate snow maps from the surface reflectance product at the daily tile level, which has an improved ability to map SCA and FSC. Using the surface reflectance as input can slightly increase the quality of SCA and FSC by reducing snow commission and omission errors in low illumination conditions, provides an atmospherically corrected reflectance input, provides additional cloud mask data that reduces snow/cloud confusion in some situations, and provides a great amount of quality assessment (QA) data that can be used to assess the quality of the SCA and FSC outputs. The MODIS algorithms for SCA and FSC currently used to make the MOD10_L2 in the Level-2 processing will be adapted to make this new product in the Level-3 processing provisionally named MOD10SR. The MOD10SR algorithm will include the improvements discussed in this paper. A MOD10SR testing data set will be made available for community evaluation and a vetting process will be used to determine whether it should become a standard product. The MOD10SR SCA and FSC maps are exhibited in Fig. 4. It is expected that MOD10SR will eventually supersede MOD10A1 in usage.

Another algorithm/product activity not discussed in this paper is the ongoing investigation/evaluation of how to develop better QA data and information in the products. Currently the QA data in the products is infrequently used, partially because it may be difficult to understand and in current form gives only an indication if the result is good or bad. The objective of improving QA is to provide it in an easily usable form and for it to give a ranking of the quality of the result. Modelers want an error estimate along with the variable they are ingesting so that they can assess the reliability of the data being ingested. We are working with modelers to include error estimate(s) relevant to needs of the models.

A new product in C6 will be the MODIS cloud-gap-filled (CGF) daily climate-modeling grid (CMG) product (Hall *et al.,* 2010). The CGF algorithm generates a cloud free daily snow cover map by retaining the last clear observation of the surface when the current day is cloudy. The last clear observation is kept as the observation if a day is cloudy but is replaced with current day observation if in clear sky condition. A companion to that CGF daily snow map is a data layer that reports the number of days since the last clear view was obtained, which is the count of consecutive cloudy days previous to the current day that a user can use as a QA measure of the snow cover map for a grid cell. In general, as a period of cloud persistence lengthens the inferred accuracy of the snow cover map decreases.

Improvements for C6 based on feedback from the user community and continuing analysis by the MODIS snow team improve accuracy and quality of the MODIS SCA and FSC products. Until production of C6 begins, probably sometime in boreal spring of 2012, community involvement in evaluation of test outputs of C6 products is welcome.

REFERENCES

Carroll M, Townshend J, DiMiceli CM, Noojipady P, and Sohlberg R. 2009. A new global raster water mask at 250 meter resolution. *International Journal of Digital Earth* **2**(4). glcf.umd.edu/data/watermask/ (Accessed 13 July 2011).

Dery SJ, Salomonson VV, Stieglitz M, and Hall DK, Appel I. 2005. An approach to using snow areal depletion curves inferred from MODIS and its application to land surface modeling in Alaska. *Hydrological Processes* DOI: 10.102/hyp5784.

Hall DK,Riggs GA,Foster JL and Kumar S. 2010.Development and validation of a cloud-gap filled MODIS daily snow-cover product. *Remote Sensing of Environment* **114**:496−503, DOI: 10.1016/j.rse.2009.10.007.

Kumar SV. 2011. Personal communication.

NSIDC, National Snow and Ice Data Center. 2011. EOSDIS-DAAC http:\nsidc.org/daac/index.html. Last accessed 30 June 2011.

Painter T. 2010. *GOES-R AWG Cryosphere Team:Snow Cover Algorithm*. 2010 GOES-R Algorithm Working Group and GOES-R Risk Reduction Review, 7-11 June, 2010, Madison, WI.

Riggs GA and Hall DK, 2003. Reduction of cloud obscuration in the MODIS snow data product. In *Proceedings of the 60th Eastern Snow Conference, 4-6 June 2003, Sherbrooke, Quebec, Canada.*

Riggs GA, Hall DK, and Salomonson VV. 2006. *MODIS Snow Products User Guide to Collection 5*, http://modis-snow-ice.gsfc.nasa.gov/?c=userguides, last accessed June 28, 2011.

Salomonson VV and Appel I. 2004. Estimating the fractional snow cover using the normalized difference snow index. *Remote Sensing of Environment* **89**(3):351−360.