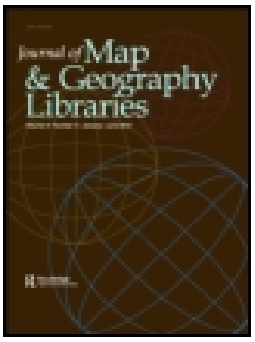

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Extending the Utility of Modis Daily Snow-Cover Products through Snow-Cover Prediction of Cloud-Obscured Areas in Idaho's Big Lost River Basin (USA)

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ABSTRACT. Increasing demand for water resources in the Western United States has given rise to many conflicts and has increased the need for more accurate and timely water management decisions. Snow-Covered Area (SCA) is an important hydrologic variable for both volumetric and daily stream flow forecasting. Satellite data provide the ideal way to map snow cover in mountain regions; however, the utility of these datasets have been limited due to the large number of scenes that are contaminated with cloud cover. To improve the utility of these datasets for the snowmelt season, in particular the Moderate Resolution Imaging Spectroradiometer (MODIS) Daily Snow-Cover Product dataset, a new procedure was developed to predict snow-cover in cloud-obscured areas using a snow-occurrence map technique. Results show that this method effectively increases the usefulness of

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the MODIS Snow-Cover product in mapping the daily evolution of snow cover extent in the Big Lost River Basin located in southeastern Idaho.

KEYWORDS. Water Resources, Snow-Cover, Stream Flow, Satellite Data, Cloud-Obscured, Mapping

INTRODUCTION

Snow is a key component of the hydrologic cycle in the western United States, where it is estimated that in the high mountain basins as much as 75% of total annual precipitation falls as snow and accounts for approximately 90% of the annual runoff (Schmugge et al., 2002). Thus, variations in snow cover are of significant importance to reservoir operators, power production utilities, and the agriculture industry (Haefner et al., 1997). In addition, human population growth and annual variations in snow accumulation require more accurate and timely water management decisions to satisfy diverse needs. Thus, there has been growing interest in utilizing satellite derived snow cover area (SCA) as input for run-off models such as the USDA-Agriculture Research Services's Snowmelt Runoff Model (SRM) (Martinec and Rango, 1986) or for validation of models such as the U.S. Geological Survey's Precipitation Runoff Model System (PRMS) (Leavesley et al., 1983). However, the utility of SCA datasets have been limited due to the large number of scenes that are contaminated with cloud cover, the long lag times between satellite overpasses, and the poor spatial resolution of the datasets.

The Moderate Resolution Imaging Spectroradiometer (MODIS) was launched aboard two of NASA's Earth Observing Satellites, Aqua and Terra, for collecting imagery of the earth's surface. Both satellites have sun-synchronous, near-polar, circular orbits at an altitude of 705 km (438 miles). However, Terra is a descending node, passing across the equator from north to south during the morning hours (approx. 10:30 AM). Aqua is an ascending node, passing south to north across the equator in the afternoon (approx. 1:30 PM) (Caldwell, 2006). The MODIS sensor collects data in 36 spectral bands, ranging from 0.4 to 14.39 μm, at resolutions of 250, 500, and 1000 meters (Barnes et al., 1998). This provides NASA with the capability to produce two independent global snow-cover extent map series on a daily basis, which are based on the Normalized Snow Index at nominal pixel resolution of 500m. This provides a superior SCA dataset when comparing its moderate spatial and high temporal resolution to other satellite derived datasets. However, cloud cover still limits the utility of either dataset for daily stream flow forecasting.

In this paper, we present a method for deriving daily, cloud-free snow cover maps from cloud contaminated MODIS daily snow-cover products. The method is based on the empirical association of snow-cover area with topography and landcover, but does not attempt to model this relationship; instead, spatially distributed snow occurrence is used as a surrogate, which is based on the idea that snow recession occurs in fairly predictable patterns from year to year. The above process is performed on two separate snow-cover products, MOD10A1 and MYD10A1 (Snow Cover Daily L3 Global 500m Grid), which provide the single best observation from MODIS/Terra and MODIS/Aqua, respectively. The two products are combined with a logic algorithm presented below, which minimizes cloud cover and maximizes snow cover. The resulting combined product is further processed using the snow cover prediction method presented below.

DATA SET

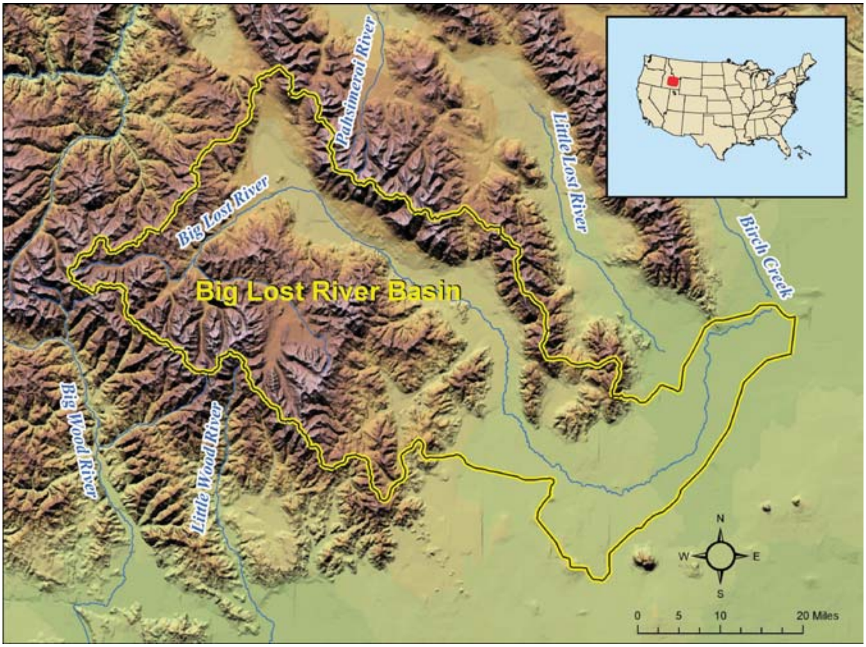
Study Area

The Big Lost River study area is located in Northern Basin and Range Province along the northeastern edge of the Snake River Plain in Idaho, covering an area of 15,225 km^2. This region has a high desert climate dominated by seasonal precipitation which typically falls as snow during the winter months (November – March). Precipitation ranges from about 9" in the valley floors to 24" in the higher mountain ranges. The topography is characterized by abrupt changes in elevation ranging from 1450 m to 3950 m. Most of the non-cultivated land is sagebrush/grass range with open forest and scrubland on northern exposures in the mountainous regions.

MODIS Daily Snow-Cover Products (MOD10A1 & MYD10A1)

The MODIS MOD10A1 and MYD10A1 Daily Snow Cover products were acquired from National Snow and Ice Data Center (NSIDC) NASA Distributed Active Archive Center (DAAC) for the entire periods of record. This ranged from February 24th, 2000 to July 24th, 2004 for the Terra/MOD10A1 product and from July 4th, 2002 to July 24th, 2004 for the Aqua/MYD10A1 product. In addition, an automated subscription

FIGURE 1. Study area map.



was established with NSIDC to continue to receive new daily tiles as they become available for near real-time processing of cloud free snow-cover maps.

The daily snow-cover products (level 3 snow product) are just one of the multiple snow-cover products automatically generated from MODIS instrument measurements. Each cell is generated by selecting the "best" pixel from multiple observations where the observation was acquired nearest nadir and has the greatest coverage of the grid cell (Riggs et al., 2003). Tiles are approximately 1200×1200 km^2, have a spatial resolution of 500 m. The daily snow-cover tile from Terra is MOD10A1 and is validated to stage 2. The MYD10A1 tile is generated from Aqua and the validation is provisional (Hall, 2005).

Both products are based the normalized difference snow index (NDSI), which leverages the fact that snow is highly reflective in the visible region of the spectrum, and compared to the low reflectivity in the shortwave region of the spectrum (Dozier, 1989). A pixel is characterized as having snow if it meets three criteria:

$$\text{NDSI} \geq 0.4 \text{ and band } 2\,(\text{NIR}) > 0.11 \text{ and band4} > 0.10$$

Areas that are characterized with dense forest and have snow-cover may yield values less than 0.4. For determining snow in these areas further tests are conducted using NDVI ((band 2 – band 1)/(band 2 + band 1)) and other selection criteria. If a pixel has NDSI and NDVI values that fall within a defined polygon of a scatter plot of the two indices and band 2 reflectance greater than 0.11 and band 1 reflectance greater than 0.1, it is determined to have snow and is added to the results from the previous test (Riggs et al., 2003). For a detailed description of the snow-mapping algorithm refer to the *Algorithm Theoretical Basis Document (ATBD) for the MODIS Snow and Sea Ice-Mapping Algorithms* by Hall et al. (2001). Each of the individual raw snow-cover tiles is subset to the study area and projected from the native sinusoidal map projection to the Universal Transverse Mercator Zone 12.

METHODOLOGY

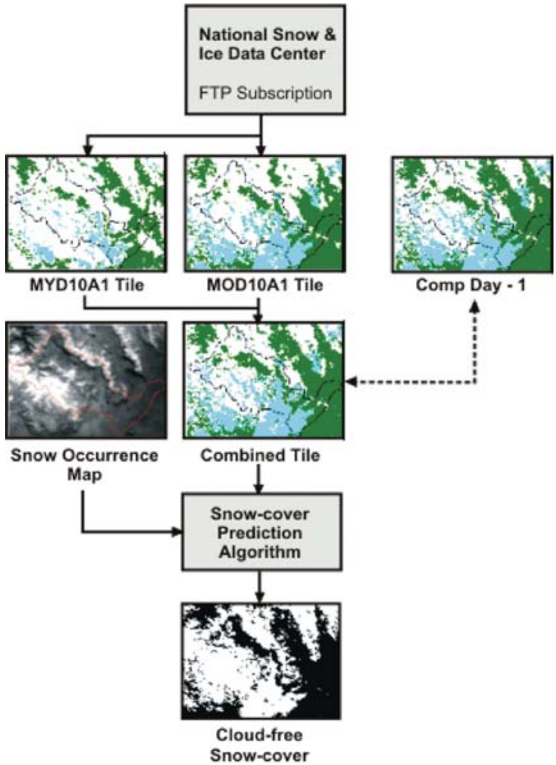
Production of Daily MODIS Derived Snow-Cover Extent Map

The development of cloud-free snow-cover products is based on the combination of the MYD10A1 and MOD10A1 products to leverage look-angles and changing cloud patterns, which maximizes visible snow-cover and minimizes cloud cover for derived daily SCA.

This method assumes that snow- and cloud-cover are accurately mapped by NASA's snow-cover mapping algorithm. The combination grid consists of discrete values for visible snow-cover, cloud-cover, and bare ground. In addition, integration of the previous day's visible snow-cover was also evaluated to further reduce cloud cover, results of the separate workflows are presented below.

Once the individual data products have been combined, the result is processed to predict snow-cover for the remaining cloud obscured areas using a zoned snow occurrence map. For this study, the snow occurrence map was derived by summing up the number of times snow was mapped to every individual pixel for the entire period of record of the MODIS/Terra MOD10A1 dataset. The individual occurrences values were classified into 25 discrete zones to optimize snow-cover prediction for the snow-melt season. This was performed using an iterative validation process which is

FIGURE 2. Processing Flow.



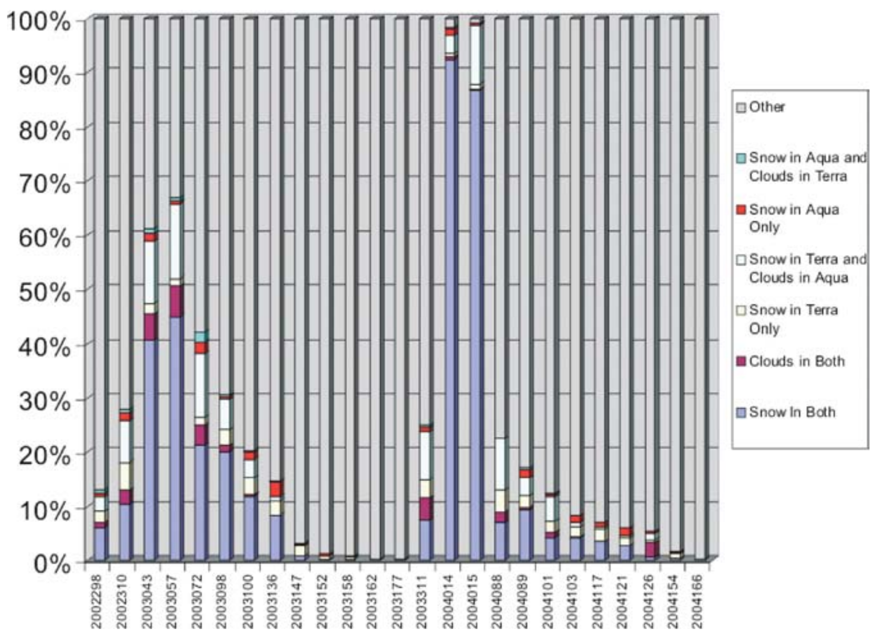
based on the assumption that there is a fairly predictable historic pattern of snow-cover recession from year-to-year across a local region. If cloud-cover exists in a zone, the percent SCA for the visible portion of the zone is calculated; if this value exceeds a predetermined threshold (50% for this study), all pixels mapped as cloud-cover were reclassified as snow-cover. If an entire zone is cloud covered, the "lower" occurrence zones are interrogated to determine if they contain snow cover, and if so, the "upper" zone is reclassified to snow-cover. The result is a best-estimate cloud-free daily snow-cover extent product.

Validation Snow Cover Prediction Process

To validate the snow-cover prediction process, a cloud-free (with snow-cover) and cloud-cover subset were selected from the original MODIS daily snow-cover dataset. The cloud-free subset consisted of 25 virtually cloud-free MODIS/Terra MOD10A1 tiles with snow-cover area ranging from 1% to 98%, along with the corresponding MODIS/Aqua MYD10A1 tile. A comparison of the Terra and Aqua validation tiles is presented in Figure 3.

The cloud-cover subset consisted of 54 total tiles, ranging 10% to 90% cloud covered. Twenty-seven images from each platform dataset were selected, which included 3 images for each 10% bin range, thus providing varying cloud patterns. To validate the snow-cover prediction method, cloud cover was extracted from each image in the cloud-cover subset and merged with each of the corresponding platform's cloud-free tiles, this resulted in a validation dataset composed of 18,225 unique combinations. The validation dataset was processed using the prediction method outlined above in section 3.1, with and without knowledge of the previous day's snow-cover extent. Predicted SCA values were compared with actual SCA value record by MODIS/Terra MOD10A1 tile for each given date.

FIGURE 3. Validation set comparison.



RESULTS AND ANALYSIS

Comparison of Cloud-Cover from Aqua and Terra Daily Snow-Cover Dataset

The difference (Aqua – Terra) between the observed cloud-cover from the two satellites has a mean of 0.06, where Aqua generally observed slightly greater cloud-cover than Terra. The confidence interval for the true mean difference is 0.045 to 0.070, indicating this difference is statistically significantly greater than 0. There are many days that are sunny or totally cloudy resulting in a concave distribution. The same pattern is seen in both the MOD10A1 and MYD10A1 products, which have a highly significant positive correlation of 0.9. There are few large differences between the observed cloud-cover from the two satellites; only 1% of dates have an absolute difference greater than 0.5. The distribution of differences is symmetric and nearly normal.

FIGURE 4. Cloud cover analysis results.

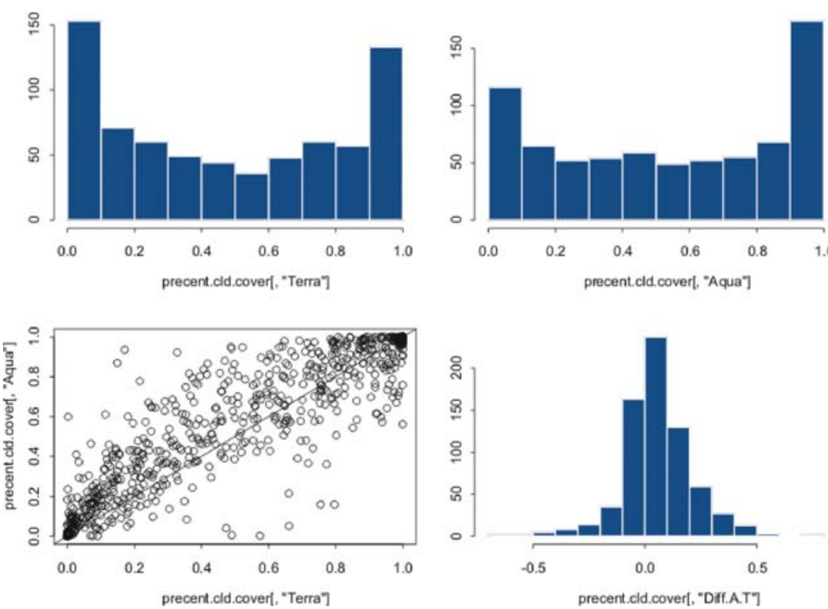


TABLE 1. Mean proportion of snow-cover correctly predicted, by categorized levels of terra and aqua cloud cover (number of records within categories) without previous day snow-cover included.

Terra / Aqua	<20%	20–40%	40–60%	60–80%	>80%	All
<20%	94% (193)	83% (339)	73% (320)	64% (301)	59% (284)	73% (1458)
20–40%	96% (554)	85% (994)	77% (956)	68% (901)	63% (868)	76% (4320)
40–60%	94% (530)	84% (962)	77% (928)	66% (890)	63% (856)	75% (4212)
60–80%	91% (535)	82% (965)	74% (933)	64% (883)	61% (851)	73% (4212)
>80%	91% (472)	82% (853)	73% (835)	62% (790)	59% (762)	72% (3753)
All	93% (2322)	83% (4180)	75% (4033)	64% (3818)	61% (3672)	74% (18225)

Snow-Cover Prediction Results

Two methods of predicting snow-cover under cloud obscured areas were presented above. The first method used only data from a single day, in addition to the zoned snow occurrence grid, where the second method incorporated the use of the previous day's actual observed snow-cover. As can be seen from tables 1 and 2, prediction results were much better when knowledge of the previous day's snow-cover was included in the prediction process. However, there is a noticeable bias toward MODIS/Terra tiles, since prediction comparison were made against the cloud-free data selected from the Terra database. The decision to use only the Terra dataset for the truth image was made because of the lack of a cloud-free tile containing snow-cover for either dataset, in addition to the provisional stage of validation of Aqua Daily Snow-Cover Tiles.

TABLE 2. Mean proportion of snow-cover correctly predicted, by categorized levels of terra and aqua cloud-cover (number of records within categories) with previous day snow-cover included.

Terra / Aqua	<20%	20–40%	40–60%	60–80%	>80%	All
<20%	97% (193)	96% (339)	92% (320)	87% (301)	84% (284)	91% (1458)
20–40%	97% (554)	96% (994)	93% (956)	89% (901)	87% (868)	92% (4320)
40–60%	96% (530)	94% (962)	91% (928)	87% (890)	85% (856)	91% (4212)
60–80%	94% (535)	93% (965)	91% (933)	86% (883)	84% (851)	90% (4212)
>80%	93% (472)	90% (853)	88% (835)	83% (790)	81% (762)	87% (3753)
All	95% (2322)	94% (4180)	91% (4033)	86% (3818)	84% (3672)	90% (18225)

CONCLUSIONS

This analysis utilizes both MODIS Snow Cover Daily L3 Global 500 m Grids in conjunction with a zoned snow occurrence map to produce a daily cloud-free snow cover extent grid for the Big Lost River Basin in Southeastern Idaho. This method overcomes most of the limitations generally associated with mapping snow-cover extent from satellite based sensor systems and provides improved input to stream flow and volumetric water supply forecasting models. This method has several advantages over using only one of the currently available MODIS Snow Cover Daily L3 Global 500m Grids: (1) visible snow is maximized by leveraging the different overpass times and viewing angles, (2) the combination of two independent datasets provides improved confidence over using a single source, and (3) cloud-free snow cover extent maps can be generated on a daily time step, significantly improving stream flow forecast accuracy by providing higher spatial and temporal resolution SCA data.

Even though there is no ideal way to evaluate the overall accuracy of this product, the validation process clearly demonstrates that prediction method present here could extend the utility of these two NASA data products, however specific assessments should be made on the improvement to runoff model outputs.

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