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A physiographic approach to downscaling fractional snow cover data in mountainous regions

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ABSTRACT

Accurate characterization of snow-covered area (SCA) and snow water equivalent (SWE) in complex terrain is needed to improve estimation of streamflow timing and volume, and is important for land surface modeling. Direct field observations of SWE, SCA and atmospheric forcing inputs for models of snow accumulation and ablation are typically sparsely sampled in space. Satellite imagery is, therefore, a critical tool for verification and confirmation of snow model estimates of SCA. The Landsat system provides snow-covered area estimates at a spatial resolution of 30 m with a 16-day return interval, while daily estimates of SCA and fractional SCA (f_{SCA}) are available at 500 m from the Moderate Resolution Imaging Spectroradiometer (MODIS). This study describes and tests a linear model to downscale MODIS MOD10A1 f_{SCA} (500 m) data to higher-resolution (30 m) spatially explicit binary SCA estimates. The algorithm operates on the assumption that two variables, potential insolation and elevation, control differential ablation of snow cover throughout spring melt at 30 m to 500 m scales. The model downscales daily 500 m f_{SCA} estimates from MODIS to provide daily SCA estimates at a spatial resolution of 30 m, using limited Landsat SCA for calibration and independent Landsat SCA estimates for validation. Downscaled SCA estimates demonstrate statistically significant improvement from randomly generated model ensembles, indicating that insolation and elevation are dominant factors controlling the snow cover distribution in the semi-arid, mountainous region in southwestern Idaho, USA where this study is performed. Validation is performed with Landsat data not used for calibration, and is also performed using Landsat 500 m aggregate f_{SCA} instead of MODIS f_{SCA} as an ideal case. Downscaled estimates show reasonable accuracy (test metric outperforms random ensembles at $p = 0.01$ significance level for multiple ranges of snow cover) with only one calibrated parameter.

1. Introduction

In complex terrain, the characterization of snow-covered area (SCA) and snow water equivalent (SWE) at a resolution less than 500 m could substantially improve estimation of streamflow timing and volume, as SCA can vary over length scales much less than the resolution of data from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Anderson, McNamara, Marshall, & Flores, 2014). Since more than one-sixth of the world's population depends on seasonal snowmelt for water resource supply (Barnett, Adam, & Lettenmaier, 2005), predicting the spatiotemporal evolution of snow processes is of great importance for conveying reliable hydrologic information. Accumulation and melting of snow occur variably, producing heterogeneity in snowpack disappearance that must be modeled with accuracy in order to estimate melt runoff for a catchment (Clark et al., 2011). However, the ability to predict these variable snow processes is limited in part because variability occurs at length scales of less than 100 m, while in situ observation networks have a resolution several orders of magnitude larger and are confined to a relatively narrow elevation range in flat terrain (Bales et al., 2006; Martinec & Rango, 1981). In addition, while field sampling can be performed at the necessary spatial resolution, it is time consuming and costly and therefore is typically limited to small spatial extents and coarse temporal resolution (Elder, Dozier, & Michaelsen, 1991). Thus, satellite remote sensing observations are often employed in conjunction with simulation models to improve the estimation of snowpack states and resultant hydrologic fluxes. For example, studies assimilating satellite-derived areal snow cover information into hydrologic models have demonstrated improvements to simulated streamflow and SWE (Clark et al., 2005; Rodell & Houser, 2004; Thirel, Salamon, Burek, & Kalas, 2011). In other studies, snowmelt depletion curves have been accurately constructed using similar SCA information in combination with energy balance melt modeling (Homan, Luce, McNamara, & Glenn, 2011). Retrospective analysis of SCA data combined with distributed temperature-index and energy balance snowmelt modeling

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has been used to reconstruct basin-wide SWE at the time of maximum accumulation, comparing favorably with results of intensive field campaigns (Cline, Bales, & Dozier, 1998; Durand, Molotch, & Margulis, 2008; Martinec & Rango, 1981; Molotch, 2009). This approach depends on distinct accumulation and ablation periods, however, and therefore may provide accurate peak SWE distribution only under certain conditions. Mid-winter rain and melt, as well as late spring snowfall can cause problems with this approach, as the technique assumes ablation dominates and albedo is constant between SCA estimates.

The space-borne Landsat remote sensing system is capable of retrieving snow-covered area and albedo data for hydrologic studies at the catchment scale (Dozier, 1989; Dozier & Marks, 1987; Rosenthal & Dozier, 1996). Similarly, the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument, aboard NASA Aqua and Terra satellites, can be used to map SCA at a much higher temporal but lower spatial resolution (Hall & Riggs, 2007; Hall, Riggs, & Salomonson, 1995; Justice et al., 1998; Painter et al., 2009; Riggs, Hall, & Salomonson, 1995; Salomonson & Appel, 2004, 2006). These products are highly valuable for their utility in updating and constraining distributed snow models (e.g., Clark et al., 2005; Luce, Tarboton, & Cooley, 1998, 1999; Thirel et al., 2011). However, each of these snow cover products has spatial or temporal limitations. For instance, Landsat has a relatively high spatial resolution of 30 m with a 16-day return interval under ideal, cloud-free conditions. Conversely, estimates from MODIS can be derived at a 500 m spatial resolution on a daily basis. The fractional snow-covered area (f_{SCA}) product derived from MODIS (Hall & Riggs, 2007; Riggs et al., 1995; Salomonson & Appel, 2004, 2006) provides a sub-grid approximation by estimating the percentage of each pixel that is snow-covered, but does not explicitly resolve SCA at sub-pixel scales. The MODIS f_{SCA} product has led to significant improvements in ablation modeling at coarse resolutions (e.g. Yatheendradas et al., 2012). Many model applications, however, require snow cover information at finer resolutions. For example, hydrologic models in mountainous complex terrain commonly adopt the 30 m resolution of readily available digital elevation models. At this scale, knowledge of the percentage of a 500 m pixel that is snow-covered is of value only in understanding basin-scale trends in snow cover. Whereas Landsat offers a spatially finer resolution product, the temporal resolution is not sufficient. Since snow cover often varies extensively within 500 m and over 2 weeks, it is desirable in many applications to have snow cover information at the spatial resolution of Landsat and the temporal resolution of MODIS.

The objective of this work is to develop and describe an efficient approach to downscaling melt-season fractional snow-covered area (f_{SCA}) data from MODIS (spatial resolution 500 m) to a higher-resolution (spatial resolution 30 m), yielding a spatially explicit SCA estimate at 30 m resolution. The derived high-resolution snow cover product is meant to be used to constrain future snow cover simulations. The proposed model is based on the hypothesis that the distribution of snow-covered area in a partially snow-covered region is non-random and can be predicted using terrain physiographic features (elevation, slope, and aspect). Further, since these terrain features are relatively constant year to year, snow distribution patterns are assumed to occur in similar patterns from year to year in agreement with observations (Sturm & Wagner, 2010). The algorithm we develop is based on physiographic characteristics that can be derived from ancillary data products, principally digital elevation models (DEMs). The algorithm assigns binary snow cover to a grid co-registered with a 30 m DEM that is used to derive normalized potential incoming solar radiation (insolation) and normalized relief within each 500 m MODIS pixel. The method preserves the predicted snow cover fraction at the 500 m scale. We calibrate and test the model using 13 Landsat images for a region in southwestern Idaho. The proposed approach assumes that potential insolation and elevation control the spatial distribution of snow cover at the sub 500 m scale. A similar approach could be developed for other factors controlling the distribution of snow cover in regions in which SCA is controlled by other processes.

In Section 2 we describe the satellite and terrain datasets used in this study. Section 3 outlines algorithm design, development, and procedures used for calibration and validation. Model results are presented in Section 4 and we provide a brief synopsis of the results, implications, and model limitations in Section 5.

2. Datasets

2.1. Remotely sensed snow cover: hillslope scale

The Landsat Program has provided multispectral, high-resolution data observations across the entire globe for over 40 years, offering a unique retrospective and near real-time data record for many applications. Multispectral band information from the Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) instruments is often used for automated mapping of snow cover. The Normalized Difference Snow Index (NDSI) has been used in efforts to distinguish snow-covered pixels from other land surfaces, leveraging the large difference in reflectance of snow in the visible and shortwave infrared portions of the electromagnetic spectrum (Dozier, 1989). This ratio is described as

$$NDSI = \frac{R_{vis} - R_{swir}}{R_{vis} + R_{swir}} \tag{1}$$

where R_{vis} represents reflectance in a visible band and R_{swir} is reflectance in a short-wave infrared band. These correspond to Landsat TM bands 2 and 5, respectively. The NDSI is an analog to the ubiquitously used Normalized Difference Vegetation Index (NDVI) (Tucker, 1979) which utilizes similar principles to estimate vegetation properties. Other studies have exploited spectral mixture analyses to classify snow-covered and snow-free pixels, utilizing spectral libraries for pure end-member reflectance values and solving a set of linear combinations of their relative fractions for the observed reflectance in each pixel (e.g., Nolin, Dozier, & Mertes, 1993; Painter, Dozier, Roberts, Davis, & Green, 2003; Rosenthal & Dozier, 1996).

In this study, a series of 13 Landsat scenes over a mid-latitude, semi-arid region in southwestern Idaho (path/row 41/30) are compiled over a range of snowmelt season dates (January to May) between 2000 and 2011. We employ the NDSI to estimate binary snow coverage. These scenes serve as high-resolution calibration and validation data for the development of the downscaling routine. A combination of Landsat TM and ETM+ scenes are chosen in which cloud cover is minimal (i.e. <20% for whole scene) and qualitatively inspected such that any perceived cloud cover does not occur over the mountainous regions of interest (Table 1). Within the Landsat scenes, we chose subsets known to retain seasonal snow cover for calibration and validation regions and that are of interest for modeling exercises (Fig. 1). Subset (*a*) in Fig. 1 contains the Dry Creek Experimental Watershed (DCEW), a 27 km^2 watershed north of Boise

Table 1
Image calibration dates and sensors utilized with corresponding cloud coverage for the Landsat scenes used in this study. All scenes are path 41, row 30.

Scene #	Date	TM 5	ETM+7	Cloud cover %
1	02/03/2000	x		0
2	02/19/2000		x	0
3	03/01/2001		x	0
4	04/18/2001		x	4
5	05/04/2001		x	0
6	02/16/2002		x	2
7	03/04/2002		x	2
8	04/08/2003		x	6
9	05/10/2006	x		0
10	04/27/2007	x		0
11	03/12/2008	x		20
12	05/15/2008	x		13
13	02/01/2011	x		6