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Merging complementary remote sensing datasets in the context of snow water equivalent reconstruction

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Abstract

Time series of snow covered area (SCA) estimates from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat Enhanced Thematic Mapper (ETM+) were merged with a spatially explicit snowmelt model to reconstruct snow water equivalent (SWE) in the Rio Grande headwaters (3419 km^2). A linear optimization scheme was used to derive SCA estimates that preserve the statistical moments of the higher spatial resolution (i.e. 30 m) ETM+ data and resolve the superior temporal signal (i.e. ~daily) of the MODIS data. It was found that merging the two SCA products led to an 8% decrease and an 18% increase in the basinwide SWE in 2001 and 2002, respectively, compared to the SWE estimated from ETM+ only. Relative to SWE simulations using only ETM+ data, the hybrid SCA estimates reduced the mean absolute SWE error by 17 and 84% in 2001 and 2002, respectively; errors were determined using intensive snow survey data and two separate methods of scaling snow survey field measurements of SWE to the 1-km model pixel resolution. SWE bias for both years was reduced by 49% and skewness was reduced from −0.78 to 0.49. These results indicate that the hybrid SWE was closer to being an unbiased estimate of the measured SWE and errors were distributed more normally. The accuracy of the SCA estimates is likely dependent on the vegetation fraction.
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Keywords: Remote sensing; Snow water equivalent; Snow covered area

1. Introduction

Accurate characterization of hydrologic states is becoming increasingly important due to the uncertainty of future climate on one hand, and due to increasing demands on limited water resources on the other. Remote sensing measurements show great potential for use in deriving improved estimates of hydrologic states (Beven & Fisher, 1996). Available remote sensing products exist at a wide variety of spatial, spectral and temporal resolutions. Historically, hydrologists have attempted to choose one remote sensing product that is tailored to the needs of a specific estimation problem. However, it is often the case that a perfect remote sensing product does not exist for a given hydrological application. An attractive alternative to this approach is to merge multiple remote sensing products with complementary characteristics.

An example of an application in which no perfect remote sensing product exists is snow water equivalent (SWE) reconstruction, in which visible time series of snow covered terrain are analyzed to estimate snow accumulation patterns based on the timing of snow covered area (SCA) depletion. Landsat Enhanced Thematic Mapper (ETM+) SCA estimates are attractive for their 30-m spatial resolution, but are available only every sixteen days (in the absence of clouds) and furthermore are very expensive. Moderate Resolution Imaging Spectroradiometer (MODIS) SCA estimates, on the other hand, have 500-m spatial resolution but are available daily. Characterization of snow cover properties is a field in which the hydrologic state variables of interest vary dramatically at the length scale of several meters, have months of autocorrelation time, but can change dramatically within the period of a few weeks during the ablation season. Thus, an SCA estimate at high spatial resolution and temporal resolution would be ideal.

The objective of this paper is to demonstrate an example of a methodology for merging two remote sensing products with complementary spatiotemporal resolution characteristics. Our

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hypothesis is that the "hybrid" remote sensing estimate will carry the beneficial characteristics of both the ETM+ and MODIS measurements. The following section presents our rationale for this study by examining previous work done in remote sensing of snow cover, SWE reconstruction, and merging remote sensing measurements. The third section describes the study area and data, and gives the details of the methodology employed for merging the datasets and the details of the SWE reconstruction algorithm. Results obtained from driving the SWE reconstruction algorithm with the hybrid snow depletion timeseries are presented and discussed in the fourth section.

2. Background

2.1. Remote sensing of snow cover

Obtaining high spatial and temporal resolution estimates of SWE has been the focus of many hydrologic studies. Early attempts to characterize snowpack using remote sensing observations such as Barnes and Bowley (1968) were primarily designed to obtain estimates of SCA, though snow depth was inferred at least as early as the study of McGinnis et al. (1975). Solar radiation reflected by the earth surface at visible and near-infrared (Vis/NIR) wavelengths is sensitive to the presence of snow, while terrestrial-emitted radiation at longer (e.g., passive microwave, PM) wavelengths is sensitive to the quantity of snow (Chang et al., 1987; Goodison & Walker, 1995; Hallikainen & Jolma, 1992). However, the use of PM measurements is problematic due to the coarse spatial resolution at these longer (centimeter) wavelengths which derives from the fact that the radiance intensity of emitted terrestrial radiation is far less than that of reflected shortwave radiation.

A number of studies have attempted to obtain higher resolution SWE derived from measurements at visible wavelengths (Cline et al., 1998; Liston, 1999; Martinec & Rango, 1981; Molotch & Bales, 2005). Although measurements at these wavelengths are not directly sensitive to snow mass, SWE can be reconstructed by integrating modeled snowmelt flux over the period of satellite-observed snow cover. An important limitation of this methodology is that it assumes that no precipitation falls during the melt season. It is thus inapplicable in locations where spring precipitation constitutes a significant portion of the water budget. In locations where this is not the case, these SWE reconstruction methods allow for the inference of high spatial resolution patterns of snow accumulation from readily available data. There are many uncertainties associated with application of the SWE reconstruction method, including the meteorological data and the snow melt parameterizations (Molotch and Bales, 2006).

Perhaps the greatest limitation of the reconstruction method derives from the accuracy and availability of the SCA estimates. One dimension of this limitation derives from the fact that remote sensing measurements are available only at discrete times during the snowmelt season, but the SWE reconstruction methodology requires temporally continuous SCA estimates in order to scale the modeled potential melt flux (Molotch et al., 2004). Hence, an interpolation method is used to infer the SCA depletion curve from some other variable, either time (e.g., Baumgartner et al., 1987) or predicted cumulative melt flux (e.g., Molotch & Bales, 2005). The shape of the depletion curve can have a profound influence on the final estimates of the reconstructed SWE as the estimate of the maximum SWE is equivalent to the integration of the depletion curve. In this paper we attempt to use the timing of MODIS measurements to infer the shape of the ETM+ depletion curve, resulting in a hybrid SCA estimate.

2.2. SCA measurement characteristics

In this paper, we use the standard MODIS binary 500-m SCA product (MOD10A V.4, Hall et al., 2003) and a product derived from 30-m ETM+ measurements and the Multiple Endmember Snow Covered Area and Grain size algorithm (MEMSCAG) of (Painter et al., 2003a). The MEMSCAG algorithm is a direct spectral unmixing approach (Painter et al., 2003a), developed from radiative transfer theory and utilizing extensive libraries of the spectral response of the endmembers encountered in partially snow-covered terrain. The MEMSCAG algorithm was developed for monitoring snow at the basin scale and at high resolution. MEMSCAG was originally developed and validated using data from the airborne visible/infrared imaging spectrometer (AVIRIS) for a site at Mammoth Mountain, California; the validated accuracy was approximately 4% (Painter et al., 2003b).

In this paper, we utilize the MEMSCAG algorithm applied to ETM+ data. Cloud cover can be identified based on ETM+ measurements in bands 3 and 4.Thus, a fractional SCA estimate can be obtained at 30 m every sixteen days, except when a pixel is covered with clouds. Although the use of the MEMSCAG algorithm with ETM+ measurements has not been demonstrated explicitly in the literature, we hypothesize that the MEMSCAG algorithm with ETM+ measurements will yield accurate SCA estimates for several reasons. First, spectral unmixing analysis very similar to MEMSCAG and Landsat TM (the predecessor of ETM+) data were used to train the regression tree algorithm of Rosenthal and Dozier (1996) with good results when validated against aerial photographs. Since the regression tree output was accurate, we assume that the spectral unmixing results in that study were also accurate. Second, the use of a similar spectral unmixing algorithm with MODIS satellite data (MODSCAG) has yielded accurate SCA estimates (Dozier et al., 2006; Rice et al., 2006). Thus, we hypothesize that MEMSCAG SCA measurements are still accurate even when applied with discrete spectral bands instead of the hyperspectral AVIRIS measurements. Finally, SWE modeled from an SCA product derived from the use of the MEMSCAG algorithm with ETM+ measurements was found to be relatively accurate (Molotch & Margulis, 2007).

While the MEMSCAG algorithm was developed for monitoring snow at the basin scale at high resolution, the MODIS algorithm was developed for mapping global SCA at 500 m. The algorithm is based on the Normalized Difference Snow Index (NDSI), calculated as the quotient of the difference and sum of MODIS bands 4 and 5 (Hall et al., 2003). The MODIS algorithm also accounts for the presence of vegetation through the use of the normalized difference vegetation index from bands 1 and 2, and areas too warm to contain snow using MODIS bands 31 and 32. The MODIS SCA product has been