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Multi-scale analysis of snow dynamics at the southern margin of the North American continental snow distribution

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ABSTRACT

Snow provides a key water source for stream flow and agricultural production across western North America and drinking water for large populations in the Southwest. Accurate estimates of snow cover spatial distribution and temporal dynamics are important at regional and local scales as snow cover is projected to decrease due to global climate change. We examined regional-scale temporal trends in snow distribution across central and northern Arizona using two tiles of 2928 daily images of MOD10 snow product. The analysis included the entire MODIS archive time period, October 1, 2003–June 1, 2014, and a 245,041 km^2 area of 51 HUC8 watersheds. We also examined the effects of a regional forest restoration effort, known as the Four Forest Restoration Initiative (4FRI), aimed at enhancing snow accumulation and retention for increased groundwater recharge through forest thinning and burning treatments. We analyzed 66 Landsat TM/ETM + images spanning 26 years between 1988 and 2014 at five sites and one hyperspectral image from 2014 at two sites. The MOD10 snow product performs well in estimating Arizona's thin and discontinuous snow distribution. Mann-Kendall time-series analysis indicate significantly increasing trends in the annual number of snow cover days (SCD) over the 12-year period in 1.6% of the region at elevation transitions such as the Mogollon Rim in central Arizona, while significantly decreasing trends are observed at a few locations of lower elevations leading to the desert margins in eastern Arizona. The observed temporal trends are mostly consistent with ground-based SNOTEL snow measurements. An Arizona specific, Landsat sensor-derived binary classification model, similar to the MOD10 product, was developed at a local scale. It performs better than commonly-used simple threshold-based approaches, but demonstrates the continued challenges associated with Landsat sensor-derived snow classification in Arizona likely due to its coarse temporal resolution. Landsat-derived multi-temporal Normalized Difference Snow Index (NDSI) analysis indicate that treated (thinned and thinned-and-burned) forest sites had significantly greater NDSI values than untreated control sites. Snowpack at treated sites also appeared to persist longer into the spring season with potentially greater contributions to groundwater recharge in this semi-arid region. The high-resolution hyperspectral data analysis indicate that sites treated to approximately 24% forest canopy cover appear to have an optimum threshold for accumulating and maintaining snowpack. It balances canopy cover versus canopy gap, which reduces snow interception and sublimation by canopy, while providing enough shade. These results are encouraging for the 4FRI, the first and largest forest restoration effort in the US history, aimed at improving watershed health and function in the face of changing climate.

1. Introduction

Accurate estimates of seasonal snow cover distribution and temporal dynamics are crucial as snow provides a key water source for stream flow (Cayan, 1996; Cayan et al., 1999), agricultural production, and drinking water for much of the global population (Barnett et al., 2005; Dietz et al., 2012). Snow cover in the Northern Hemisphere is one of the key indicators of climate change (Brown, 2000; Intergovernmental Panel on Climate Change (IPCC), 2013). Both the spatial extent and temporal duration of snow cover have been shown to have decreased in the Northern Hemisphere due to warming temperatures and increased climatic variability (Brown, 2000; Brown & Mote, 2009; Dye, 2002; Peng et al., 2013), and are projected to decrease through the 21st century (Adam, et al., 2009; Ashfaq et al., 2013; Brutel-Vuilmet et al., 2013; Mastin et al., 2011). In snow-dominated watersheds of western North America, regional-scale studies have similarly demonstrated decreases in snow accumulation (Barnett et al., 2005; Hidalgo et al., 2009), shorter duration of snow cover (Harpold et al., 2012), decreases in precipitation falling as snow (Knowles et al., 2006), decreases in annual April 1 snow-water equivalent (SWE) in snowpack (Brown, 2000; Mote, 2006),

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earlier snowmelt (Barnett et al., 2005; Clow, 2010), decreases in runoff (Stahl et al., 2010), and decreased summer low flows (Stewart, 2009). These effects will likely have an even greater impact on water supply and ecosystem services in the coming decades (Adam et al., 2009; Ashfaq et al., 2013; Intergovernmental Panel on Climate Change (IPCC), 2013).

Winter and spring temperatures in the western US have increased 1 °C over the last 50 years and further 1–2 °C increase is projected by the middle of the century (Intergovernmental Panel on Climate Change (IPCC), 2013). Increasing temperatures are expected to further accelerate the onset of spring and early snowmelt (Harpold et al., 2012; Kapnick & Delworth, 2013; Mote et al., 2005) and decreases in the percent of precipitation falling as snow, which has generated much concern regarding future water supplies (Abatzoglou, 2011; Knowles et al., 2006). In the desert Southwest, these impacts will be coupled with an expected decrease in precipitation due to a northward shift in the mid-latitude storm track (Christensen et al., 2004; Dettinger et al., 1998). Consequently, reduced mountain snowpack will have significant impacts on the Colorado River Reservoir system and the Salt-Verde Watersheds with large implications for water supply and hydroelectric power for southern California and central Arizona metropolitan areas (Barnett et al., 2005) including large cities of Los Angeles and Phoenix with populations of several millions of people. Spring snowmelt, for example, provides approximately 85% of the annual water supply to the Phoenix metropolitan area in central Arizona with a population of 4 million growing at 2.7% per year and expected to reach over 9 million by 2040 (Arizona Department of Water Resources (ADWR), 2010). We examine the effects of regional forest restoration efforts aimed at improved watershed function, which are expected to have significant implications for these large urban populations.

Satellite remote sensing provides the most effective approach to consistently estimating and monitoring spatial and temporal distribution of snow at regional and global scales (Hancock et al., 2013; Rittger et al., 2013). The unique reflective and absorption properties of snow in the visible, near infrared, and shortwave infrared wavelengths make detection by satellite sensors feasible (Dozier, 1984). Satellite-derived global snow products, however, have varying degrees of accuracies and errors (Hancock et al., 2013). Among them, MODIS snow products have been widely employed at a regional scale, with overall accuracies between 90% and 95% (Besic et al., 2014; Hall & Riggs, 2007; Hall et al., 2001a; Huang et al., 2011; Pu et al., 2007; Stroeve et al., 2005; Wang et al., 2008). MODIS (MOD10 Version 5), however, suffers from several sources of snow classification error, including cloud cover, snow cover of less than 10 cm depth, and complex topography that vary substantially within a pixel (Gafurov & Bárdossy, 2009; Hall & Riggs, 2007; Marchane et al., 2015). While the agreement between MODIS binary snow product and ground data is high, previous research indicates it is not sufficient for monitoring snow cover during transition periods (Rittger et al., 2013). More recently, MODIS fractional snow cover products have been developed including MODSCAG (Painter et al., 2009; Arsenault et al., 2012). Continued testing of both the binary and fractional estimates of snow spatial and temporal dynamics are necessary for understanding snow during a time of climatic transition and at spatial transitional zones for snow (Nolin, 2010; Dietz et al., 2012). Of the two MODIS products, we examine here the MOD10 binary snow product in estimating Arizona's highly variable snow distribution. We intend to examine the MODIS fractional snow product in our future studies in Arizona.

Snow cover in Arizona represents the southernmost extent of snow distribution in western North America, where projected decreases in seasonal snow extent are largest (Brutel-Vuilmet et al., 2013). Arizona snow distribution is found at a transition from nearly continuous to ephemeral-mountainous snow cover type with several distinct peaks of accumulation followed by rapid snowmelt within each winter season due to high solar radiation (Ffolliott et al., 1989; Harpold et al., 2012; Molotch et al., 2005). Detection of ephemeral, thin, and discontinuous snow cover is particularly challenging with coarse-resolution global products such as MODIS (Marchane et al., 2015; Rittger et al., 2013). The large spatial and temporal variability in snow cover across this spatial transition area is further enhanced with a range of topographic, climatic, and hydrological characteristics across central and northern Arizona (Ffolliott et al., 1989). Taken together, the spatial and temporal distribution of snow cover in Arizona provide a unique opportunity to apply, test, and expand upon currently available global snow products and methods.

The spatial and temporal snow dynamics at this transition zone in Arizona are expected to be substantially altered over the coming decades due to a regional-scale forest restoration initiative, known as the Four Forest Restoration Initiative (4FRI), the first and largest restoration effort in the US history to improve forest health (United States Department of Agriculture (USDA), 2013). Through the 4FRI, the U.S. Forest Service plans to conduct forest restoration treatments over a million hectares of Ponderosa pine forest in northern Arizona over the next 20 years to reduce wildfire hazard and improve forest health. One of the 4FRI's key objectives is to thin and burn the forests to create within-stand openings that "promote snowpack accumulation and retention which benefit groundwater recharge and watershed processes at the fine (0.5–5 ha) scale" (United States Department of Agriculture (USDA), 2013). Accurate estimates and monitoring of these expected effects on snow cover are crucial in providing timely information for regional water management and adaptive restoration objectives. Currently lacking is a multi-scale and multi-temporal remote sensing assessment to determine if snow accumulation indeed is greater in treated forests compared to untreated sites and as a result snow persists longer into the spring season in restored forests (Ffolliott et al., 1989; Harpold & Molotch, 2013).

Forest canopy cover substantially impacts snow accumulation by intercepting up to 60% of annual snowfall and sublimating up to 40% of the snowfall in the canopies (Andreadis et al., 2009). As forest canopies are mechanically thinned or burned, much of this effect is expected to be reduced (Varhola et al., 2010 and references therein) leading to increased snow accumulation on the ground and changes in the timing of snowmelt (Gottfried & Ffolliott, 1980). However, these effects are not often quantified at watershed scales (Ffolliott et al., 1989) and integrated into land surface process models (Andreadis et al., 2009). Leveraging three different image sources, we present here regional-scale analysis of spatial and temporal variability of snow cover across central and northern Arizona as well as local-scale, finer-resolution analysis of snowpack and retention following forest restoration treatments. Our objectives were to: 1) assess MODIS data product MOD10 Version 5 (500 m resolution) in daily estimates of Arizona snow spatial variability at a regional scale and evaluate the temporal trend in seasonal snow cover days over the entire MODIS archive time period of 2003–2014, 2) assess multi-temporal Landsat-derived (30 m resolution) snow indices at a local scale to determine snow accumulation changes due to forest treatment and develop an Arizona-specific snow classification model, and 3) determine the optimum ponderosa pine forest canopy cover for snow accumulation and persistence into the spring season using a high-resolution (25 cm resolution) hyperspectral data at forest stand scale in northern Arizona.

2. Methods

2.1. Regional study area description

Our regional-scale analysis was performed across all of central and northern Arizona, USA (Fig. 1). The study region encompasses an approximate area of 245,041 km^2 of the Colorado Plateau and central highlands of AZ spanning an elevation gradient from 450 m in central AZ to 3850 m in northern AZ. The vegetation types along this elevation gradient are chaparral shrublands, high desert grasslands, pinyon–juniper woodlands, ponderosa pine forests, and mixed conifer forests.