SPATIAL AND TEMPORAL SNOW DYNAMICS AT THE SOUTHERN MARGIN OF NORTH AMERICAN CONTINENTAL SNOW DISTIBUION

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ABSTRACT

Snow is crucial for stream flow and water use needs of large populations throughout the western United States, especially in the arid southwest. Accurate estimates of spatial distribution and temporal dynamics of snow cover are important for forecasting as well as understanding sensitivity to future climate change. We examined regional-scale temporal trends in snow distribution across central and northern Arizona using MODIS MOD10 snow products, consisting of two tiles of 2,928 daily images between October 1, 2003 and June 1, 2014. The area studies covered a 245,041 km^2 area of 51 HUC8 watersheds. We employed a Mann-Kendall test to examine the temporal trends during this time period, and compared these trends at SNOTEL point locations for temporal context. We found 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 covered days (SCD) over the 12-year period 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. These results are important in understanding the role forest restoration might play in snow accumulation and retention. (KEYWORDS: northern Arizona, MOD10, ephemeral snow cover, snow trend, sensitive snow, accumulation and retention)

INTRODUCTION

Accurate estimates of seasonal snow cover distribution and temporal dynamics are crucial at local and global scales, as snow provides a key water source for stream flow (Cayan, 1996; Cayan et al., 1999) and drinking water for much of the world's population (Barnett et al., 2005; Dietz et al., 2012). Snow cover in the Northern Hemisphere is very sensitive to climate oscillations and a key indicator of climate change (Brown, 2000; IPCC, 2013). In both spatial extent and temporal duration, snow cover has generally decreased in the Northern Hemisphere due to warming temperatures and increased climatic variability (Brown, 2000; Dye, 2002; Brown and Mote, 2009; Peng et al., 2013, Lute and Abatzoglou, 2011), and are projected to decrease through the 21st century (Adam et al., 2009; Mastin et al., 2011; Ashfaq et al., 2013; Brutel-Vuilmet et al., 2013). 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), 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; IPCC, 2013).

In the desert southwest, increased temperatures and a shift in rain-delivered precipitation will likely reduce mountain snowpack and have significant impacts on stream flow and water resources. This will greatly affect the Colorado River Reservoir system and the Salt-Verde Watersheds of Arizona, with large implications for water supply and hydroelectric power for southwestern metropolitan areas (Barnett et al., 2005), including large cities of Los Angeles and Phoenix. 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 (ADWR, 2010). This study serves as a baseline for existing snow cover in the high elevations of northern Arizona and southwestern Colorado watersheds, and provide context for future studies of local scale differences in managed forests.

Satellite remote sensing provides a cost effective, consistent data source which can be used to estimate and monitor the spatial and temporal distribution of snow at local to global scales (Hancock et al., 2013; Rittger et al., 2013). Snow has unique reflective and absorption properties in the visible and near infrared wavelengths of the

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electromagnetic spectrum, and can be effectively observed from space (Dozier, 1984). Satellite-derived global snow products, however, have varying degrees of accuracies and errors. MODIS snow products have been widelyemployed at a regional scale, with overall accuracies up to 95% (Hall et al., 2001a; Stroeve et al., 2005; Hall and Riggs, 2007; Pu et al., 2007; Wang et al., 2008; Huang et al., 2011; Besic et al., 2014). There are several factors effecting the classification of snow by MODIS data, including cloud cover, snow cover of less than 10 cm depth, and complex topography, which can vary substantially within a 500 meter pixel (Hall and Riggs, 2007; Gafurov and Bárdossy, 2009; 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 periods of transition, such as accumulation or melt (Rittger et al., 2013) and continued testing of remote sensing 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).

For this study, we examine the MOD10 snow product in estimating Arizona's highly variable snow distribution. 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 due to high solar radiation (Ffolliott et al., 1989; Molotch et al., 2005; Harpold et al., 2012). Detection of ephemeral, thin, and discontinuous snow cover is particularly challenging with coarse-resolution global products such as MODIS (Rittger et al., 2013; Marchane et al., 2015). The large spatial and temporal variability in snow cover across this 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 is 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 (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" (USDA, 2013). This study is meant to provide a regional scale baseline for snow cover dynamics and trends, which might be used to compare post-thinning forest snow cover to recent historical snow cover.

METHODS

Regional Study Area Description

Our regional-scale analysis was performed across all of central and northern Arizona, USA (see poster). 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 3,850 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. Average temperature across the study region ranges from 22°C at low elevations to 2°C at high elevations. Average annual temperature in this region is believed to have increased 1.5-2.3C over the last ~80 years (Jardine et al., 2013; Murphy and Ellis, 2014). Average annual precipitation is ~440 mm across the region with bi-modal peaks in winter and summer. A total of 51 US Geological Survey Hydrologic Unit Code (HUC8) watersheds were included in this study mostly representing the Upper and Lower Colorado hydrological regions. Watersheds that are largely in AZ, but are partially in the neighboring states of southern Utah, southern Nevada, southwestern Colorado and western New Mexico were also included. The watersheds in Arizona covered 243,913 km^2 of northern and central Arizona comprising 73.3% of the study region, while the remaining watershed components covered 65,050 km^2 or 26.6% of the entire study region. The study region also included a total of 21 microclimate Snow Measurement Telemetry (SNOTEL) Stations established by the Natural Resources Conservation Service (NRCS), USDA. Of the 21 SNOTEL sites, 16 are standard sensors and 5 are enhanced sensors. The standard sensors record daily SWE, snow depth, daily precipitation, and daily minimum, maximum, and average temperature, whereas the enhanced sensors also record soil moisture and temperature at belowground depths of 10, 20, and 50 cm. This information is freely available and reported multiple times a day in near real time (http://www.wcc.nrcs.usda.gov/snow/snotel-wedata.html). The daily SNOTEL records can be compared to daily remote sensing data products such as the MODIS snow cover map. A total of 16 SNOTEL site records in the study region date back as far as the initial date, 2001, of the MODIS time-series used in this study.

MODIS and SNOTEL data analysis

MODIS/Terra Snow Cover Daily L3 Global 500m Grid, Version 5 dataset MOD10A1 was primarily used for this study. Temporal gaps in the winter season time series were filled with imagery from MODIS/Aqua Snow Cover Daily L3 Global 500m Grid, Version 5 dataset MYD10A1. Snow cover data is processed in the same way for both satellites and they are here collectively referred to as the MOD10 data product (Hall et al., 2006). MOD10, derived from the MODIS sensor aboard both the Terra and Aqua satellites (Hall et al., 1995; Hall et al., 2006), includes daily snow cover, snow albedo, and fractional snow cover at 500 m resolution. Only the MOD10 daily, binary snow cover product was used in this study. The MOD10 snow cover is determined through several criteria: 1) Normalized Difference Snow Index (NDSI) $((\lambda_{0.6} - \lambda_{1.6}) / (\lambda_{0.6} + \lambda_{1.6}))$ greater than 0.4, 2) MODIS band 2 reflectance greater than 0.11, and 3) MODIS band 4 reflectance greater than 0.10 (Hall et al., 2001b). NDSI values less than 0.4 are further tested against NDVI values to determine snow cover in forested areas (Riggs et al., 2006). The MOD10 data product overall accuracy is assessed at 93% and can be acquired in 1,200 x 1,200 tiles (http://nsidc.org/data/mod10a1).

We acquired two tiles (8,5 and 9,5) of daily MOD10 data (http://nsidc.org/index.html) for a total of 2,928 days between October 1, 2003 to June 1, 2014. The images were: 1) re-projected from sinusoidal to NAD83 UTM zone 12N projection and datum, 2) mosaicked to combine the two tiles, 3) spatially subset to the study region boundary, and 4) temporally subset to annual snow seasons from October 1 to June 1. This resulted in 12 complete annual snow season image stacks with 244 daily images per year. Within each annual image stack, we summed the number of snow cover days (SCD) for each pixel to create a single snow season "image". We then correlated the MODIS-derived SCD to the ground-based SNOTEL measurements of annual SCD (days with SWE>0) across the study region. We also stacked together the 12 snow season images to create the final time-series.

A Mann-Kendall rank correlation trend test (MK) was used to determine the existence and magnitude of monotonic trend in each pixel of the final MODIS time-series dataset as well as the winter season-summed SNOTEL station SCD. The MK test is often used to understand the direction and magnitude of trend, as well as the significance of that trend in environmental data (Helsel and Hirsch, 2002; Neeti and Eastman, 2011). The MK tau (τ) coefficient (Eastman et al., 2009; Mann, 1945; Kendall, 1948) is a non-parametric hypothesis test for statistical dependence of observations from two random variables X and Y. Applied to a time series, Y is the temporal component of the time-series data. MK τ ranges from −1 to 1, where positive coefficients indicate an increasing trend, while negative coefficients indicate a decreasing trend. A τ coefficient near zero indicate absence of a trend. Significance is tested through a a two-tailed p-value. MODIS cells in which there was no snow for at least half of the time series (6 years) were excluded from the analysis, so as to identify trends in locations with consistent seasonal snow cover. MK has been used frequently in recent years (de Jong et al., 2011; Li and Guo, 2012; Gao et al., 2012; Czerwinski et al., 2014). It is well suited for environmental data: it is resistant to outliers (Neeti and Eastman, 2011; Neeti et al., 2012), performs well with small sample sizes (Yue and Wang, 2004), and does not assume a normal distribution of data (Neeti and Eastman, 2011).

RESULTS and DISCUSSION

Approximately a 168,892 km^2 area (675,567pixels; 69.2% of the study region) was analyzed for temporal trends in MOD10 snow covered days (SCD) (see poster). Within this area, a total of 2,650 km^2 (10,600 pixels; 1.6% of the study region) had significant trends ($p<0.05$). Of these, 2,544 km^2 (10,176 pixels; 96% of the significant trend) showed significantly increasing trends, while 106 km^2 (424 pixels; 4% of the significant trend) had significantly decreasing trends in the number of SCD over the 12-year study period. The significantly increasing number of SCD areas overlapped with several SNOTEL stations, which also indicated an increasing trend over the 12-year study period (see poster). The MODIS-derived number of SCD correlation coefficient (R) with SNOTEL SCD was 0.80 with a significant p-value of 0.001 (adjusted R^2 = 0.62) (see poster), when all SNOTEL sites were combined. The degree of correlation varied across the SNOTEL sites, when 16 SNOTEL sites with matching 12-year records were individually examined (Table 1). The MODIS-estimated number of SCD was significantly correlated at all SNOTEL sites except at Workman Creek and Snowslide Canyon sites (p-values of 0.146 and 0.939, respectively) (Table 1).

MODIS global snow product, MOD10, appears to perform well in Arizona, where snow is thin and patchy with a large spatial variability. Other MOD10 studies in similarly challenging discontinuous snow environments have had to introduce complex correction factors and snow detection thresholds of 10 cm (Marchane et al., 2015). However, MOD10 generally correlated well with most SNOTEL measurements in our study region. In general, the MOD10-derived number of snow cover days (SCD) under-predicted the SNOTEL-measured SCD by only 1.6 days in our study region, contrary to other MODIS studies that documented large omission errors (60%) (Metsämäki et al., 2002; Rittger et al., 2013). The SNOTEL stations with the poorest correlation coefficients in our study were located in complex terrain where elevation, slope, and aspect were highly variable within a MODIS pixel (500 m), consistent with previous conclusions (Marchane et al., 2015). Taken as a whole, our results extend to the Southwest previous observations of high accuracy of MODIS-derived snow maps over large areas of non-forested, uniform terrain (Salomonson and Appel, 2004; Hall and Riggs, 2007; Pu et al., 2007; Wang and Xie, 2009; Huang et al., 2011), but demonstrated that complex terrain remains to be a challenge (Hall et al., 2001a; Romanov and Tarpley, 2007; Shreve et al., 2009; Czyzowska-Wisniewski et al., 2015). Future studies in the Southwest can test MODIS fractional snow cover estimates in complex terrain to enhance MOD10-derived snow maps.

This study, to our knowledge, is the first spatially-explicit temporal analysis of snow dynamics across Arizona. We find that the daily temporal resolution of the regional-scale MOD10 product is ideal for Arizona, where each snow season is characterized by several distinct storm events followed by rapid snowmelt (Ffolliott et al., 1989). In the Southwest, MOD10 product further complements daily SNOTEL-based temporal analysis (Molotch et al., 2005; Harpold et al., 2012) since SNOTEL stations only represent point locations distributed sparsely across large areas. The temporal trend agreement between SNOTEL and MOD10 snow product observed in this study is encouraging for consistent snow monitoring in the future at Arizona's ephemeral zone that represents the continental margins of snow distribution, which is most susceptible to global climate change (Brutel-Vuilmet et al., 2013). Trends observed at these margins can inform patterns to be expected in the future throughout the North American continent.

While the trends were spatially variable, MOD10-derived SCD Mann-Kendall trends were predominantly increasing across the study region over the 12-year study period. The increasing trends were observed at elevation transitions such as the Mogollon Rim, while decreasing trends were found at lower elevations leading to the desert margins in eastern Arizona (see poster). A similar magnitude trend of increasing SCD was observed in the SNOTEL measurements over the same 12-year period (see poster), consistent with Palmer Drought Severity Index (PDSI) trends for Northern Arizona. Twelve SNOTEL sites used in our study have records extending to the early 1980's, and exhibit trends of decreasing SCD over the multi-decadal time period (see poster), but increasing trends over the recent 12-year period at most sites (see poster). Climatic modes of Pacific origin such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) are strongly correlated with temperature and precipitation variation across western North America (Stoner, 2009; McCabe and Dettinger, 2002; Barnett et al., 2005; Svoma, 2011). The observed upward SCD trends over the 12-year time period is likely driven by the climatic variability at the sub-decadal scales, especially ENSO (Svoma, 2011). Furthermore, it is likely that the contribution of extreme events to snowfall is increasing, replacing more frequent low intensity storms with intermittent storms with greater snowfall (Lute and Abatzoglou, 2014). While such shifts cannot be explicitly examined with the MOD10 product, future temporal trend analysis could address this question using other data sources. The MOD10 time-series data can spatially demonstrate areas of AZ where extreme SCDs are observed, regardless of whether they are frequent low intensity storms or few large events, over the study period as potentially sensitive areas indicative of future trends. A map of areas of very small versus large number of SCD across AZ using the lower and upper 5 percent of the 12-year mean SCD distribution (5^{th} and 95^{th} percentiles, respectively) is shown in the poster. The very small numbers of SCD are commonly observed across central AZ along the Mogollon Rim below 1,800 m elevations including HUC8 watersheds of Big Sandy, Big Chino-Willamson Valley, Lower Verde, Tonto, Upper Salt, and San Francisco. In contrast, the very large numbers of SCD are observed mostly at high elevations above 2,800 m in the mountainous northern portions of AZ with large implications for HUC8 watersheds of Lower Colorado-Marble Canyon, Lower Little Colorado, Canyon Diablo, Middle Little Colorado, Chevelon Canyon, and Little Colorado Headwaters.

SUMMARY

Snow cover mapping in Arizona is a challenge due to the thin, ephemeral, and patchy snow distribution. We find that MOD10 product correlates well with ground-based snow measurements, and that similar trends exist between data sources, as well as correlate with climatic phenomena such as PDSI. These findings highlight the importance of temporal resolution in satellite data for mapping snow distribution in Arizona rather than spatial resolution. Furthermore, this study demonstrates the ability of MODIS satellite data products to map snow in Northern Arizona. This is important for forest management in the future, as well as determining the effects of that management in conjunction with climate change, on snow cover in an area of ephemeral snow cover at the southern edge of North American snow distribution.

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