INTER- AND INTRA-ANNUAL VARIABILITY IN SNOW ALBEDO, GRAIN SIZE, AND SNOW COVERED AREA FROM THE AIRBORNE SNOW OBSERVATORY DURING LOW SNOW YEARS (2013-2015), TUOLUMNE RIVER BASIN, CA

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ABSTRACT

The Sierra Nevada snowpack is critical to the state of California, and the consistently lower than average snowfall during the dry winters of 2012-2015 contributed to statewide water stress. These 'snow drought' years could become more frequent in a warmer future; therefore it is of interest to understand spatial and temporal trends in snow properties during low snow years. Here we assess inter- and intra-annual variability in snow-covered area, snow albedo, grain size, and impurity radiative forcing across three low snow years in the Tuolumne River Basin above Hetch Hetchy Reservoir. Snow properties retrievals are made by the Airborne Snow Observatory (ASO), a coupled imaging spectrometer and lidar platform, which has been measuring spatial and temporal distribution of both snow water equivalent and snow albedo across key basins in the Western US since 2013. It is generally understood that net solar radiation (as controlled by variations in snow albedo and irradiance) provides the energy available for melt in almost all snow-covered environments, yet there are no spaceborne sensors that can adequately capture trends in this critical snow property at relevant spectral, spatial, and temporal scales in mountainous terrain. This data set offers the unprecedented opportunity to improve our understanding of what controls snow albedo in mountain basins, and its relationship with spatial and temporal snowmelt patterns. (KEYWORDS: remote sensing, snow hydrology, snow albedo, snow grain size, Airborne Snow Observatory)

INTRODUCTION

Mountain snow cover is a critical water resource, accumulating and storing water through the winter and then releasing it in the spring and summer. In the western US over 70% of water resources come from snowmelt, yet measurements of mountain snow water equivalent are sparse, and automatic measurement stations are located only in mid to low elevations. Additionally, there are no spaceborne remote sensing platforms that can provide information about snow water equivalent or snow albedo at the scale of mountain watersheds. To address the mountain snow observation gap, NASA's Jet Propulsion Laboratory developed the Airborne Snow Observatory (ASO), a coupled lidar and imaging spectrometer platform. ASO measures snow depth and snow reflectivity, the two most critical components for determining how much water is held in the form of snow and when it will melt. ASO began its demonstration mission in 2013 regularly observing two basins, approximately weekly in the Tuolumne River Basin, Sierra Nevada, CA and monthly in the Uncompahgre Watershed, San Juan Mountains, CO. These retrievals are the first high-resolution spatially extensive measurements of snow water equivalent and snow albedo over entire mountain basins.

The Tuolumne River Basin (TRB) in the Sierra Nevada Mountains, CA is a critical watershed that provides water to city of San Francisco. ASO monitors the upper TRB, surveying in entirety the area above Hetch Hetchy Reservoir. The beginning of measurements in 2013 coincided largely with the start of the recent California drought, which was exacerbated by low snowfall and limited snow accumulation in the Sierra Nevada Mountains. The first three years of ASO observations (2013-2015) over the Tuolumne River Basin were considered low snow years relative to the average, with 2015 being one of the worst years on record. As of April 1st, the snowpack was less than 40 percent of normal at many snow courses, with many areas that would typically be snow covered remaining snow free for the course of the season. With warming climate, low snow years may become more frequent, and therefore these observations allow us to understand the behavior of a reduced mountain snowpack.

The two core products from ASO are snow water equivalent and snow albedo. Snow water equivalent is determined from ASO acquisitions by fusing measured snow depth, from the lidar, with modeled snow density (Figure 1). This product is delivered in near real time, within 24 hours, to water managers to support reservoir

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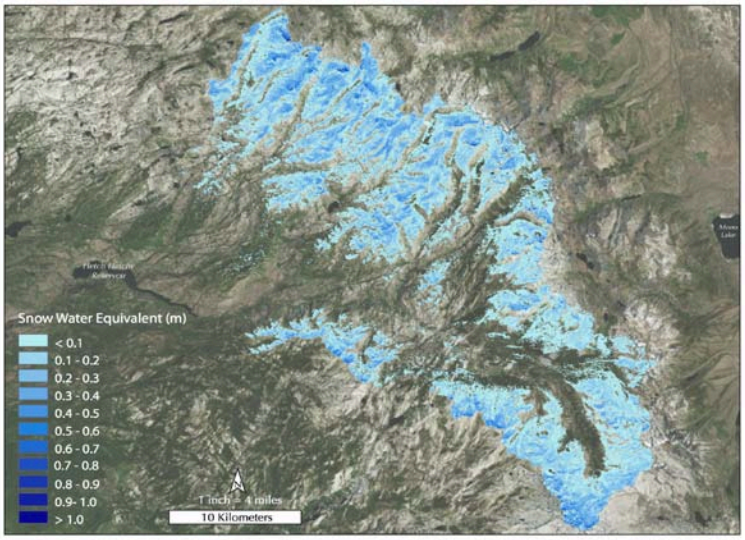

Figure 1. ASO snow water equivalent map in TRB from April 3, 2015.

operations and planning. Snow albedo is determined by combining atmospherically and topographically corrected surface reflectance, from the imaging spectrometer, with modeled solar irradiance. This is relevant for snow hydrology because net solar radiation, itself determined mainly by variation in snow albedo, is the main driver of snowmelt in almost all snow-covered environments. An imaging spectrometer is required because snow albedo varies spectrally; in the visible wavelengths albedo is controlled by the presence of light absorbing impurities, which darken the snow surface, and in the near infrared wavelengths by snow grain size, with larger grains have a longer absorbing path length. By leveraging the unique spectral signature of snow ASO is able to map not only snow albedo, but also snow covered area, snow grain size, and radiative forcing by light absorbing impurities in snow. Here, we assess inter- and intra- annual trends in imaging spectrometer retrievals and snow water equivalent between 2013 and 2015 in the TRB. Additionally, we compare April 1 acquisitions from these years to the April 1, 2016 acquisition, the first average snow year over the ASO observation record.

ASO PLATFORM, INSTRUMENTATION, and PRODUCTS

The Airborne Snow Observatory currently flies on a King Air A90 aircraft, which allows ASO to fly relatively high (~23,000 ft msl) and fast (~200 knots). ASO can cover the TRB in a single flight, lasting approximately 4 hours, using a 'lawn mower' pattern along 26 north/south-oriented lines and 1 east/west oriented crossing line. Upon landing the ASO flight crew transfers data disks from the plane, based at the Mammoth-Yosemite airport, to the mobile compute system that is deployed at the Sierra Nevada Aquatic Research Laboratory (SNARL), where the ASO compute team at JPL remotely kicks off automated data processing.

The lidar, a Riegl LMS-Q1560 laser scanner, maps surface elevations via a unique dual-laser system with fore- / aft-looking capabilities, high pulse rates, and a 60° field of view. Full-waveform recording sensor improves ground detection in forested areas and distinguishes numerous targets per pulse. Snow depth, calculated by subtracting snow-off and snow-on elevations, is integrated with observed and modeled snow densities from the physically based distributed snow model iSNOBAL (Marks et al., 1999) to map snow water equivalent (SWE). The imaging spectrometer, an ITRES CASI 1500, measures surface reflectance across 72 bands between 365 and 1050 nm, and has a 40° field of view. Imagery is used to classify the land surface as snow, vegetation, rock, or water based on unique spectral signatures. Snow properties (albedo, grain size, and impurity radiative forcing) are then retrieved over the snow covered area using the ISnARF algorithm (Painter et al., 2013). The core products for water manager delivery include maps of snow water equivalent (SWE), broadband snow albedo, and basin-integrated statistics such as snow covered area, total SWE, and SWE per elevation band. For a full description of the ASO platform and data processing stream please see Painter et al., 2016.

TUOLUMNE RIVER BASIN

The Tuolumne River Basin above Hetch Hetchy is 1,181 km^2 (456 square miles) and ranges in elevation from 1081 m to 3935 m with a mean elevation of 2688 m (3546 ft – 12911 ft; 8819 ft). It is located on the western slope of Sierra Nevada, and the basin aspect is 31% west facing, 27% south facing, 20% easting facing, and 21% north facing. The slope ranges from 0 to 85 degrees with a mean slope of 19 degrees. The National Land Cover Dataset (NLCD 2011; http://www.mrlc.gov/) classifies the basin as 1% open water, 25% barren land, 35% evergreen forest, 32% shrub scrub, and 5% herbaceous. The portion of the basin that is classified as forested has an elevation range of 1127 m to 3799 m, with an average elevation of 2598 m. The mean elevation of the snow pillows in the basin is approximately 2600m, with 60% of the basin at elevations above these sensors. From ASO vegetation heights, the average tree height in the forested area is 4.9 m. ASO has flown over the TRB three times during snow-off conditions, once each in summer 2012, 2014, and 2015. There are now nearly 50 snow-on acquisitions, 38 of which occurred during the low snow years of 2013, 2014, and 2015. Generally flights occur weekly March-June to capture peak snow water equivalent and snow cover evolution during ablation.

RESULTS

Snow Covered Area

As might be expected the area of the basin covered by snow was generally highest across the first few acquisitions in March/April, which is typically when the snowpack begins the transition from accumulation to ablation, with a declining trend as the season and snow melt progressed (Figure 2). Increases in SCA always followed snowfall. Spatially, snow cover retreated from the east to west; with snow cover being retained the longest in the highest elevations around the basin boundary (corresponding to lower grain sizes/higher albedo, discussed below). Both 2013 and 2014 exhibited similar trends in snow covered area (SCA) decline, with SCA ranging from 84-33% and 89%-30%, respectively. Although 2015 had consistently lower SCA, it had the widest variability, widest range, and fastest rate of decline, with acquisitions capturing between 95% and 19% of the basin covered by snow. On April 1, 2016 the SCA was 89%, similar to the SCA in 2013 (84%) and 2014 (89%), but nearly a quarter more of the SCA in 2015 (54%) (Figure 3).

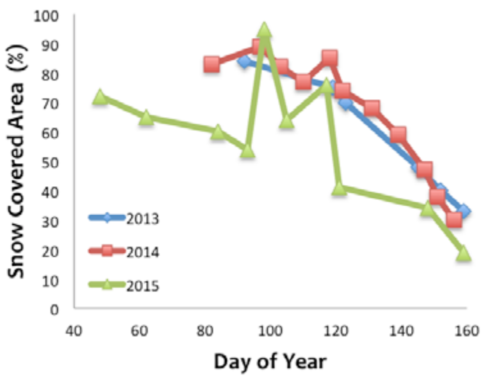

Figure 2. Snow covered area, as percent of total basin area, time series.

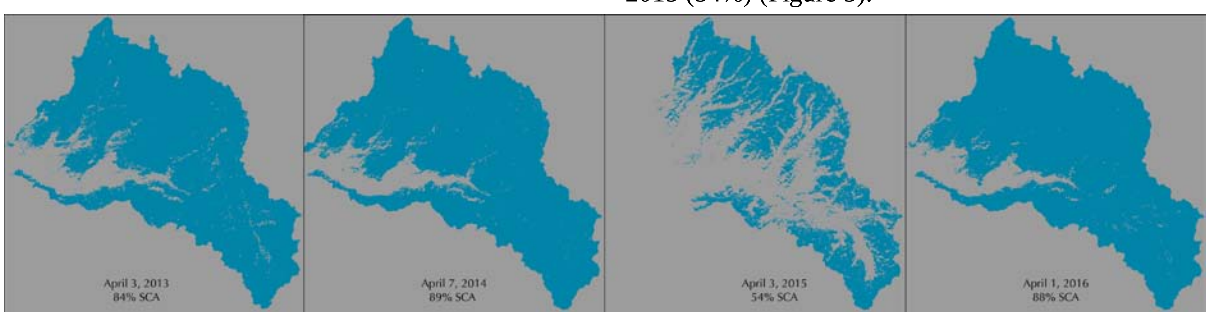

Figure 3 Snow covered area maps for the acquisition closest to April 1. Date of acquisition and percent SCA labeled indicated on maps.

Snow Albedo and Snow Grainsize

Snow albedo is generally highest immediately following snowfall, and decays over time as snow ages and darkens (Figure 4). Although impurity radiative forcing is consistently non-zero in the TRB, indicating the presence of light absorbing impurities, snow albedo decline is more strongly related to effective grain size growth (Figure 4). Snow grain sizes are always lowest right after a snowfall and grow over time (Figure 4). In the TRB the rates of growth are slowest at the highest elevations and exhibit an inverse relationship with elevation, exhibiting the fast grain growth rates below 8,000 ft where metamorphisms are more active with higher temperature gradients and more liquid water is present (snow melt initiates first at the lower elevations). Snow grain sizes typically range between 100 μm – 200 μm for fresh snow, and between 500 and 1500 μm for aged snow. The range is in part controlled by the length of time elapsed between the last snow fall and ASO overflight, with the smallest average basin grainsize retrieved the day following new snowfall, and the largest when weeks had elapsed since last snowfall.

Patterns in snow albedo follow patterns in grain size. At the highest elevations around the basin boundary, albedo ranged from > 0.8 to ~0.4. Basin averaged broadband albedos range from 0.65 to 0.4; in 2013 and 2014 the trend was generally decline between the first (March) and last (June) acquisition. In 2015, the shallow snowpack already had a fairly low albedo when measurements began in February, and the highest albedos were then retrieved after snowfall events in April, after which albedo remained fairly steady through May, declining quickly in June just prior to melt out. All near April 1 acquisitions had basin mean albedos between ~0.5 and ~0.6 (Figure 5).

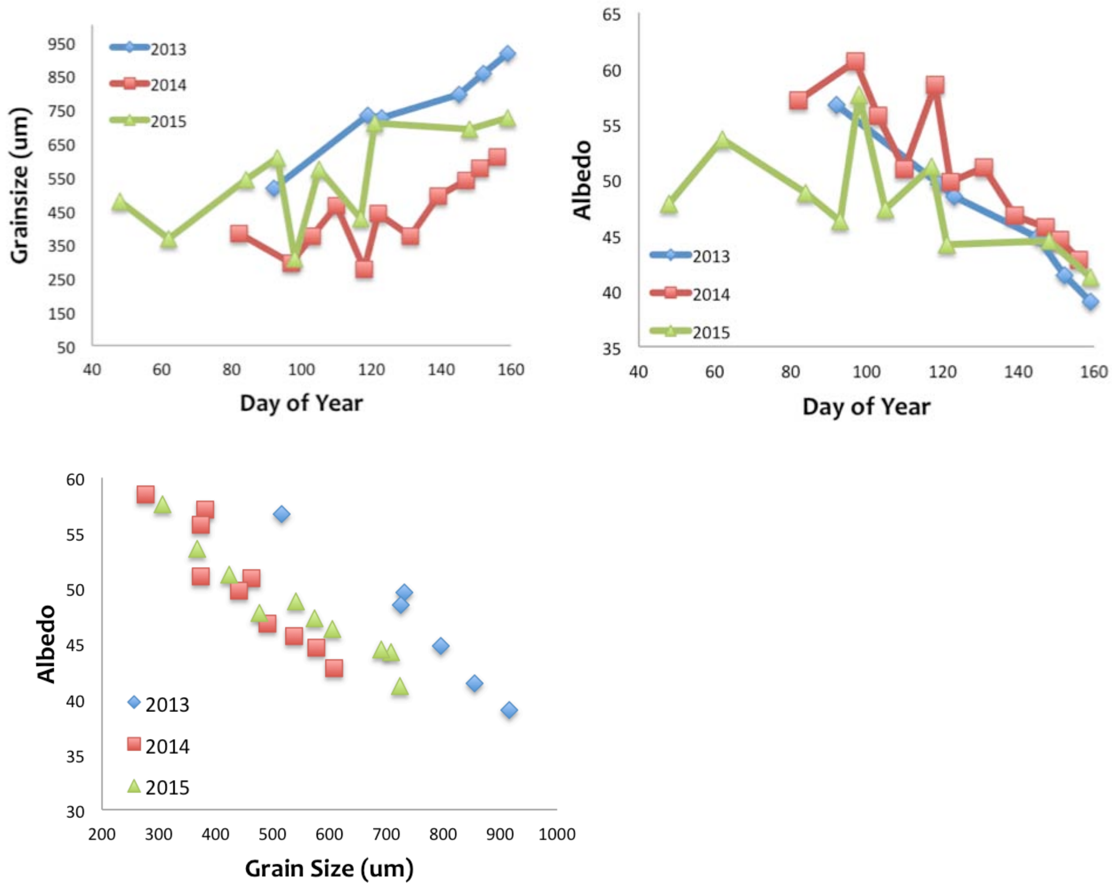

Figure 4. Basin means snow grainsize time series (top left), albedo time series (top right), and the relationship between the two (bottom left).

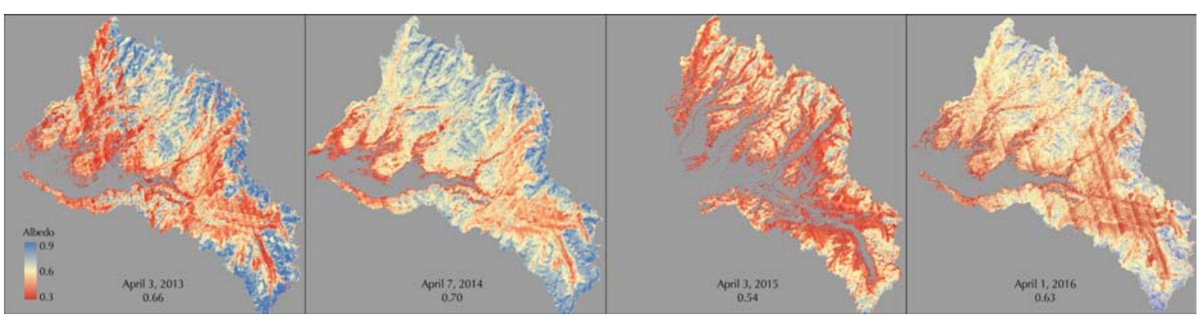

Figure 5. Snow albedo maps for the ASO acquisition closest in time to April 1, date of acquisition and basin average albedo indicated on maps.

Note that the albedo products from ASO are still undergoing calibration to and validation with ground measurements, and may be updated in the future.

Snow Water Equivalent

In all three drought years snow water equivalent (SWE) was highest in March and exhibited a declining trend until the last acquisition in June (Figure 6). Peak SWE occurred around the beginning of April in all three years, and increases in SWE corresponded to snowfall events between acquisitions. Spatially, the highest SWE values were consistently at the higher elevations around the basin boundaries (Figure 7). Of the three low snow years, 2013 had the highest observed peak SWE and widest SWE range, and conversely 2015 had the lowest peak SWE and lowest range. More time series variability in 2014 and 2015 is in part reflective of the more frequent flight timing. The time series for all three years converged on ~ 20 thousand acre-feet (TAF) around day of year 160 (July 9th). For reference, the storage capacity of Hetch Hetchy Reservoir is 360 TAF. As of June 10th, 2016 ASO was still flying with over 100 TAF in the basin remaining. This corresponds to the consistently higher SWE all season, as of April 1 there was 519 TAF in the basin, approximately double the SWE on the acquisition close to April 1 in 2013 and 2014, and 9 times that in 2015 (Figure 7).

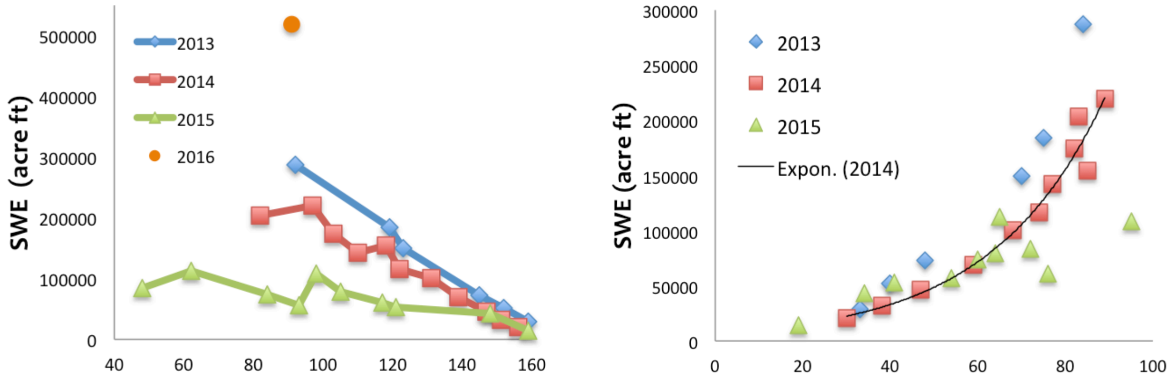

Figure 6. Basin mean snow water equivalent (SWE) time series (left), and relationship between SWE and SCA (right).

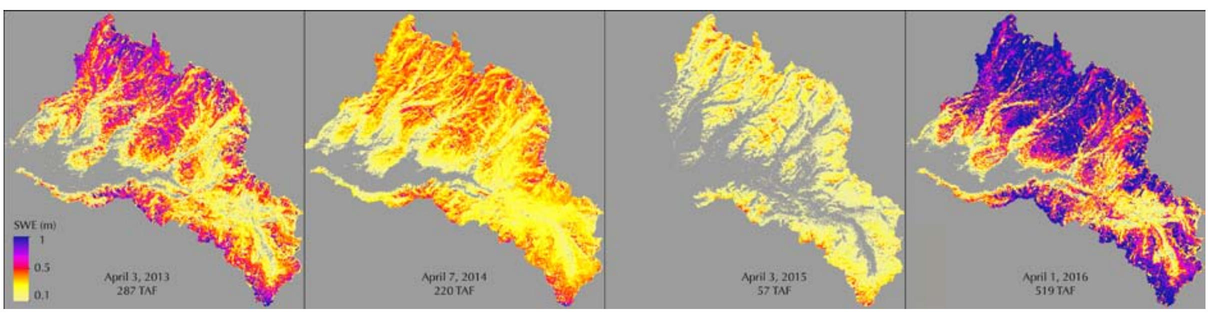

Figure 7. Snow water equivalent (SWE) maps for the ASO acquisition closest in time to April 1, date of acquisition and basin average SWE indicated on maps.

Although decreases in SWE general correspond to decreases in SCA, there is no consistent relationship exhibited between SWE and SCA in low snow years (Figure 6). The poorest relationship was exhibited in 2015, when the two highest SWE acquisitions, both ~100 TAF, had corresponding SCAs of 60% and 90% on March 5th and April 9th, respectively. In 2013 and 2014 there was an exponential relationship as SCA approached 100%, but the steepness of the curve varies between the two years depending on peak SWE, which we would expect to be even more steep in an average or high snow year. These results indicate it is difficult to infer how much water is held in the form of snow across a mountain basin from SCA alone.

CONCLUSIONS

This is the first high temporal resolution, spatially extensive, dataset of snow properties over an entire mountain basin. It has proven useful for reservoir managers to predict inflow into Hetch Hetchy, particularly after snow has melted out above the highest automated instrumentation site. ASO data products are powerful tools for understanding the relationships between precipitation, elevation, vegetation, and snow accumulation and ablation patterns. We found that although 2013, 2014, and 2015 were all low snow years, 2015 exhibited more intraanual variability. This is likely due to the low accumulation and SWE at the beginning of the season, and then snowfall events in April and May that increased SCA and SWE, freshened up albedo, and allowed the snowpack to persist through June similar to the other two years.

Albedo reductions were always fastest at the lowest elevations, and below tree line. Over the three years of observation albedo was also more strongly related to grain size growth than impurity content. Over each season albedos typically remained high at higher elevations above tree line, where grain size growth rates are slower and more snow accumulates, and more rapid declines in albedo occurred at lower elevations. There were rapid changes in SCA between acquisitions, with rapid increases associated with snowfall and rapid decreases near the end of the season. Declines in SCA followed trends in albedo decline, with snow melt out occurring first at low elevations and the longest duration of snow cover at the highest elevations. Although the highest SWE values also occurred at the highest elevations, there is no consistent intra-annual relationship between SWE and SCA. These observations confirm the general understanding of snow cover evolution, that snowmelt is driven by changes in albedo and that snow is retained for the longest at higher elevations, but this is the first time they have been observed at such high spatial and temporal resolution. After the completion of the 2016 season we will be able to assess how snow accumulation and ablation patterns in low snow years compare to a higher, more typical, snow year.

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