CONSTRAINING PHYSICAL CONTROLS ON SNOW HYDROLOGY ALONG THE WASATCH FRONT, UT

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ABSTRACT

Like much of the Western US, the million plus people that live in the Salt Lake City metropolitan area, located along the Wasatch Front, UT, depend on snowmelt to meet water demands. A persistent reduction in the mountain snowpack would introduce stress into the current water delivery system. Impacts to snow water storage during accumulation are mainly due to increasing temperatures; more precipitation falls as rain instead of snow. Impacts to storage during ablation are mainly due to increasing net solar radiation, controlled by albedo, which drives snowmelt in almost all snow covered environments. Combined, a shallower, warmer snowpack has a lower albedo, which shifts snowmelt timing and magnitude, and further reduces water yields via increased evapotranspiration. Deposition of light absorbing aerosols, which accumulate in the snowpack through the winter and concentrate at the surface as snow melts, further compounds albedo decay. The Wasatch snowpack is at risk for deposition of both black carbon, particularly in the winter during persistent cold air pools (inversions), and dust, particularly in the spring when regional wind speeds and dust emission peak. Current snowmelt forecasting methods are not capable of accounting for the physical processes that control snow accumulation and melt, which limits their ability to adapt to changing snowmelt regimes. This is mainly due to the lack of observations to document processes, establish relationships based on first principles, and validate physically based snow energy balance models. During Water Year 2017 fieldwork efforts in the four main watersheds that dominate water deliveries to Salt Lake City, UT were aimed at addressing this paucity of data to better constrain physical controls on snow hydrology along the Wasatch Front. Here, initial results from fieldwork efforts completed between Jan-Jun 2017 are presented, as well as a remote sensing analysis to assess historical variation in snow line elevation. (KEYWORDS: snow hydrology, snow melt, snow energy balance, light absorbing impurities in snow, remote sensing)

INTRODUCTION

The mountain snowpack is a critical component of the water budget in the Western US, where allocation of annual snowmelt meets over 70% of regional water resource demand. This natural reservoir is at risk; the remote sensing record and long-term datasets from observation networks show that annual and persistent snow cover is declining (*Mote et al.,* 2005, 2006; *Hamlet et al.,* 2005; *Stocker et al., 2013*; *Selkowitz et al.,* 2016). Additionally, deposition of light absorbing impurities at the snow surface, a relatively new phenomenon in the region, is accelerating melt, shifting runoff timing and intensity, and reducing total water yield (*Painter et al.,* 2007; 2010, *Skiles et al.* 2012; 2015).

Like many other major cities in the Western US the Salt Lake City, UT metropolitan area, which is home to over 1 million people, is heavily dependent on the mountain snowpack to meet water demands. The contribution of snowmelt from the Wasatch Mountains to surface water supplies for the Salt Lake City Department of Public Utilities is up to 80% or more (*Bardsley et al.,* 2013). The majority of this comes from four streams (Figure 1), along which there is limited storage to buffer Salt Lake City water supplies in low snow years (*Bardsley et al.,* 2013). Given Salt Lake City's dependence on snowmelt, its proximity to sources of light absorbing aerosols, and the general trend in declining mid-latitude snow cover, it is of interest to better constrain the physical controls on snow hydrology along the Wasatch Front. We address this in two ways; 1) by using remote sensing to assess interannual variability and trends in the snow line elevation and snow-covered area, and 2) by using field measurements, laboratory analysis, and numerical modeling to determine spatial and temporal controls on snow albedo.

Paper presented Western Snow Conference 2017

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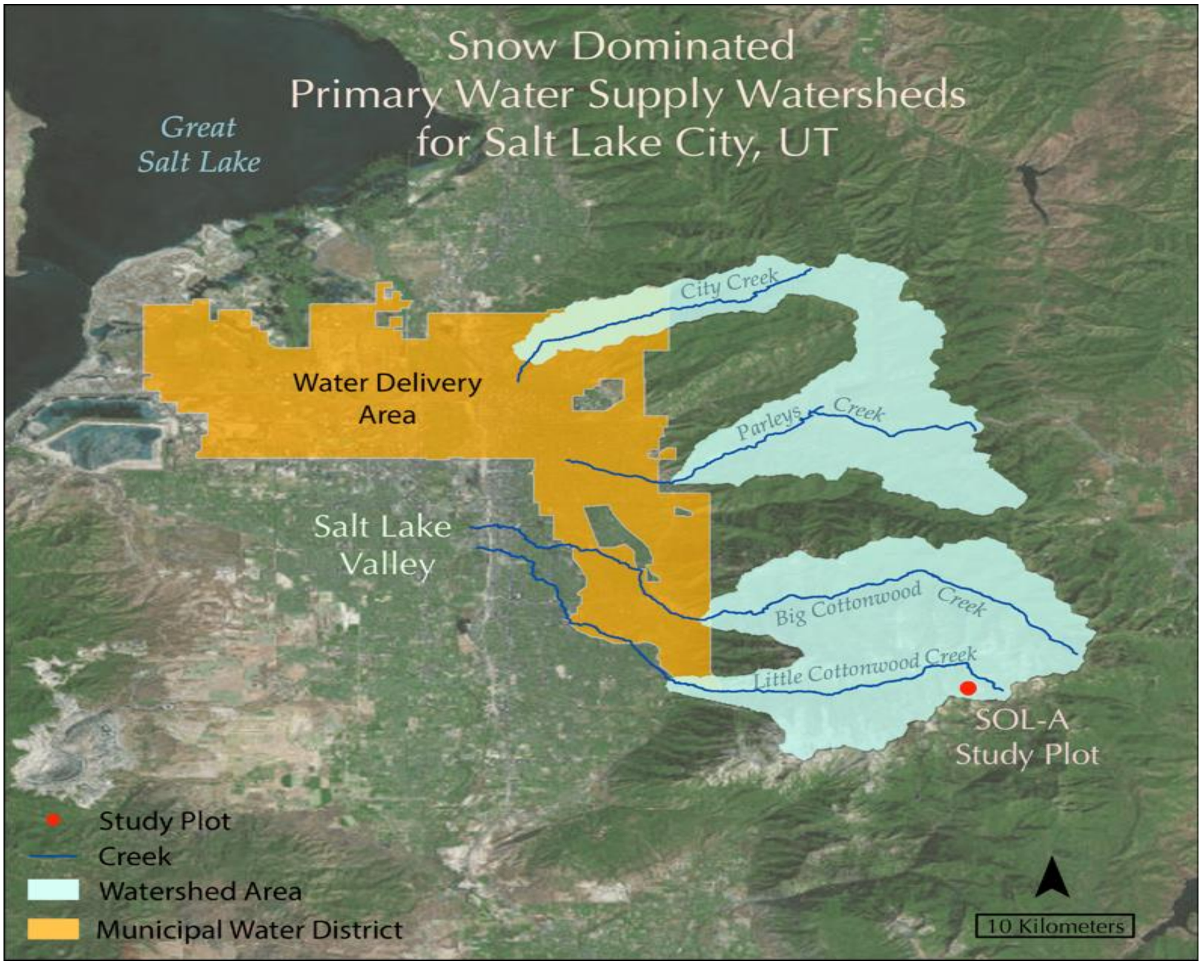

Figure 1. Overview of the Wasatch Mountains near Salt Lake City, UT showing key watersheds and water delivery area. Measurements were focused on these four watersheds for Water Year 2017.

BACKGROUND

Shifting climate and energy balance regimes impact snow covered area (SCA) and snow water equivalent (SWE) during both accumulation and ablation/melt. Warmer temperatures shift precipitation phase from snow to rain, which results in a higher snow line and less total accumulation/storage. Shallow snowpacks are more susceptible to energy balance inputs, and accelerated snowmelt shifts runoff timing and intensity, uncovers darker substrate earlier (the snow albedo feedback), and increases evapotranspiration rates. Springtime snow cover has been declining across the Northern Hemisphere by 11.7% per decade since 1967 (*Stocker et al.,* 2013), which is attributed to warming temperatures (less snow accumulation) amplified by snow albedo feedbacks (faster melt).

It is well understood that net solar radiation provides the energy for snowmelt in nearly all snow-covered environments. Net solar radiation itself is determined by variation in snow albedo, which is inherently controlled by impurity content across the visible wavelengths, where they darken the surface, and snow grain size across near infrared, where ice is absorptive. The larger impact is from aerosols because the impact is in the wavelength range where snow is most reflective and where solar radiation peaks. The two main aerosol constituents that impact snow albedo are dust, from arid and disturbed regions, and black carbon (BC), from incomplete combustion of fossil and bio fuels. The impact of aerosols deposition on snow is well established in the Western US, a suite of studies in the Colorado Rockies have shown that spring dust deposition advances melt by 1-2 months, shifts timing and intensity of peak runoff, and reduces total water yield (*Deems et al.*, 2013; *Painter et al.*, 2010; *Painter et al.*, 2007b; *Skiles et al.*, 2012; *Skiles et al.*, 2015a). The presence of dust on snow has also been documented in the Wasatch Mountain Range (*Carling et al.,* 2012; *Reynolds et al.,* 2013) but these studies have not estimated the impact to snow albedo, radiative transfer, and snow melt rates.

Additionally there is no study, of which we are aware, that has measured BC in snow in the Wasatch, despite proximity to an urban center. Although the presence of BC can be inferred from the analysis of chemical and optical data of dust in snow samples from this region (*Reynolds et al.*, 2013), BC concentrations in snow and their contribution to radiative forcing are unknown. *Hall et al.* (2014) found a relationship between ion concentrations and persistent cold air pools (inversions), leading us to hypothesize BC concentrations might exhibit similar elevation gradient patterns, which would have important implications for low-elevation snow cover albedo and energy balance. It is also worth noting that the Great Salt Lake reached a new record low in fall 2016, with >50% of the lakebed exposed to potential erosion. Downwind precipitation stations have recorded increases in ion concentrations, suggesting an increase is salt deposition, which has the potential to lower the melting point of snow.

Snow modeling approaches have been empirically dependent on temperature due to the relative abundance of temperature measurements, the lack of measurements of other energy fluxes, and the loose positive relationship between melt and temperature. The assumption that the melt phase is controlled by temperature is increasingly invalid, and calibrated temperature/snowmelt relationships will lose utility under altered energy balance regimes, be it due to climate warming and/or to other forcings, such as snow darkening from deposition of light absorbing aerosols. Understanding the physical controls on variation in snowmelt runoff timing and magnitude, and returning to first principles in physically based models, is key to improved simulation and forecasting, and for more accurate projection of the changes in water resources under a changing climate.

METHODS

Snow Observation and Sampling

Snow sampling locations were identified in each of the four main watersheds for Salt Lake City (Figure 1), Little and Big Cottonwood Canyons, Parleys Canyon, and City Creek Canyon, and were designed to capture gradients in aspect and elevation. Total there were ten full snow profile sampling and observation sites, five of which had repeat observations, and numerous additional snow surface sampling sites. The timing of snow observations and sampling was intended to capture during and after persistent cold air pools, after episodic dust events, and during snow melt. At the full profile sites snow observation and sampling was completed in the following order, weather permitting, 1) measure spectral snow reflectance, 2) excavate a snowpit to the ground, 3) measure temperature profile and note stratigraphy, 4) measure snow density across the full profile for snow water equivalent, 5) bag the top 10 density cuts to analyze for impurity content in the top 1m of snow, and 6) collect three co-located 50ml samples at the snow surface and if present, at individual dust layers. At surface sample sites, three co-located 50 mL samples were collected by scraping vials across the top ~2 cm of snow until the vial was filled. Snow reflectance was measured with an Analytical Spectral Devices (ASD) handheld2 VIS/NIR field spectrometer. Snow density was measured with a 1-L triangle density cutter, continuously across the full profile (Figure 2), and electronic field scale. Snow sample bags and 50 mL sample vials were scientific grade and certified ultra clean, and all snow samples were kept frozen between time of collection and time of analysis.

Figure 2. Picture of snow pit in upper Parleys showing 1-L density cuts for SWE and snow sampling. A combined dust layer (D1-3) can be seen as a distinct darker layer below ~20 cm of new snow.

In addition to observing and sampling snow at single observations points, spatial variation in snow depth at the plot scale (Atwater Snow Study Plot, Little Cottonwood Canyon) was also regularly mapped as a part of this project. This was done using the photogrammetric technique known as structure-from-motion (SfM), which uses a series of overlapping 2d images to reconstruct a 3d surface. There are different SfM platforms, for this project a camera

(Sony A5100), automated to take a picture in RAW format every 1-second, was mounted on an unmanned aerial vehicle (UAV; DJI Phantom 2), which was flown in an overlapping grid pattern over the study plot. Pictures were then processed to point clouds using commercially available proprietary SfM software (Agisoft PhotoScan). Digital surface models were then modeled from the point clouds in ArcMap. Snow depth was mapped by taking the difference between the snow free surface, flown fall 2016, and the snow on surfaces, flown winter 2017. Multiple flights took place between Feb and April, and automated snow depth was recorded at the site during snow depletion.

Sample Analysis

Snow sample analysis for different impurity constituents is ongoing to characterize physical, chemical, and optical properties. This will help constrain source region, microphysical interaction with snow, and radiative impacts. One early set of snow samples was sent to NASA's Jet Propulsion Laboratory, where they have been analyzed for dust concentration and BC carbon content following the protocol described in *Skiles and Painter* (2016). Lead author Skiles is in the process of setting up a new lab at University of Utah, where the remaining 1-L snow samples will be analyzed for total dust mass, BC content, particle size distribution, and impurity mixture reflectance. One of the 3 co-located 50 mL samples will also be analyzed for BC content in her lab. The second 50 mL sample will be analyzed for turbidity, conductivity, alkalinity, and salt content at Utah State University (USU). Larger surface samples collected at chosen sites when dust was at the surface (bulk samples) will also be analyzed at USU, they will evaporated and precipitated salts will be separated and weighed. The remaining dust material will be analyzed for organic content (TOC analyzer). The third 50 mL sample will be analyzed for trace and major element concentrations by ICP-MS at the University of Utah following *Carling et al.* (2012). Comparison of the chemistry of each fraction will allow for determination of particle-bound and dissolved element fractions, with implications for snowmelt behavior of snowpack. To evaluate the mineral composition of dust in snowpack, additional samples containing dust will be sent to Brigham Young University (BYU), where they will be melted and dust seperated by centrifugation, the dust will then be analyzed by X-ray diffraction. This will allow for quantifying relative abundances of silicate, carbonate, and Fe/Mn oxide mineral content in individual dust layers. This compositional data can be used to further evaluate radiative property of specific dust layers.

Aerosol Radiative Forcing and Contribution to Melt

Spectral reflectance measurements were used to retrieve snow grain size, and in combination with lab analysis, will be used to quantify impurity radiative forcing (RF) with the SNow, Ice, and Aerosol Radiation (SNICAR) model (*Skiles,* 2014; *Skiles and Painter,* 2016a; *Skiles et al.,* 2016). To most accurately capture overall impact on albedo reduction, the regionally specific optical properties of deposited impurities will be retrieved and updated in SNICAR, following *Skiles et al*., 2016. To determine the unique and combined impacts of dust and BC, relative and total concentrations will be used as inputs for individual runs SNICAR following *Skiles*, 2014. The radiative forcing melt contribution of *Painter et al.* (2013) will also be applied to inform contribution to snowmelt. Furthermore, trends in grain size and RF will be related to the snow covered area analysis discussed further below. In the future snow albedo will both force and validate a spatially distributed snow energy balance model to demonstrate the skillfulness of physically based hydrologic models in snow dominated watersheds, building on previous work by lead author Skiles (*Skiles*, 2014; *Skiles et al.,* 2015a).

Trends in Snow Covered Area and Snowline Elevation

Interannual variability in snow covered area and snow line elevation was assessed using the Moderate Resolution Imaging Spectrometer (MODIS) Snow Covered Area and Grain size (MODSCAG) fractional snow covered area product (fSCA; *Painter et al.,* 2009). The skillfulness of this product at identifying snow is well established (*Raleigh et al.,* 2013; *Rittger et al.,* 2012), and fSCA is more useful for snow analysis over mountainous terrain than binary products due to the relatively coarse spatial resolution (500 m) of MODIS. Daily products are available in near real time and historically since 2000. A robust algorithm to efficiently retrieve total snow covered area and snowline elevation over a time series has been developed by lead author Skiles, and currently the algorithm is being automated for the Wasatch Mountains using 8-day composites images, which are less likely to have cloud artifacts. Here, we present an initial analysis for the first week in April, which is typically the center of mass for snow water equivalent in the Wasatch Mountain Range. An example of MODSCAG snowline for April 15th, 2003 (2168 m snowline; a higher-than-average snow year) and 2015 (2531m snowline; a lower-than-average snow year) for the area of interest is shown in Figure 3. For more information on the remote sensing analysis please see, *'Trends in snow line elevation along the Wasatch Front, Utah from MODIS fractional snow-covered area' (Peterson and Skiles),* in these proceedings.

INITIAL RESULTS AND DISCUSSION

Black Carbon

Here, we present BC concentrations from a set of surface samples collected at multiple sites on January 15th, 2017. There was a persistent cold air pool in place during sampling (active inversion), and was preceded by another persistent cold air pool that spanned the final week of 2016 and first week of 2017. Surface samples were collected at four sites; an urban site in Salt Lake City ('urban'; 1,350 m), the Little Cottonwood Park and Ride lot ('LCC PnR'; 1,630 m), White Pine Meadow ('White Pine'; 2560 m), and Grizzly Gulch below Twin Lakes Pass ('Grizzly'; 2819 m). At White Pine and Grizzly, full snow profile observation and sampling also took place. BC concentrations were highest in the low elevation snow, 458 ppb for the urban site and 602 ppb at the LCC PnR. There was a clear elevation gradient for the three LCC samples; highest at the LCC PnR, lower but still relatively high at White Pine (238 ppb), which is in the cold air pool 'slosh' zone, and lowest at Grizzly (6 ppb), which is well above the cold air pool cap elevation. For comparison, BC concentrations in the southern Colorado Rockies range from ~1 to 20 ppb (*Skiles and Painter*, 2016a) and in the Sierra Nevada can reach over 100 ppb during periods of melt (*Sterle et al.*, 2013). There are additional days that need to be analyzed for BC, initially though; these results indicate that BC concentrations are higher along the Wasatch Front than other mountainous areas in the Western US, and that persistent cold air pools could lead to higher BC concentrations in lower elevation snow.

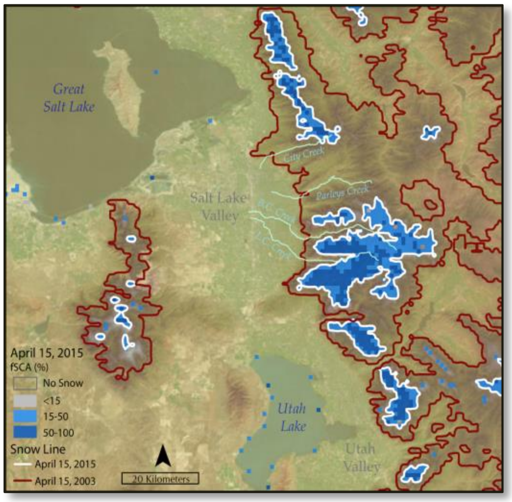

Figure 3. Example of snow line elevation analysis for April 15th, 2015 (white) and April 15th, 2003 (red) from MODIS fractional snow covered area, shown here for 4/15/2015 (blue).

Dust Deposition

There were four notable episodic dust on snow events in the Wasatch during Water Year 2017; March 5th, March 23rd, March 31st, and April 12th. All events were transported by prefrontal winds and were dry deposited at the snow surface. Prefrontal events are often followed by snowfall, which delays the radiative impacts of the dust until it is in the top ~10 cm of snow (*Skiles and Painter*, 2016a), but once the dust is at the surface it is persistent, is not entrained in melt water, and combines with other dust layers to compound albedo decay (*Skiles et al.*, 2012). Here, we present dust concentrations from the first three dust events, which were widespread and identified in all four watersheds. At the time of sampling in early April these dust events had combined into a single dust layer with dust concentrations, reported in parts per thousand by weight (pptw), of similar magnitude; 0.08 pptw in LCC at ~2,670 m, 0.075 pptw in Big Cottonwood at ~2,250 m, 0.068 pptw in Parleys at 2,676 m, and 0.054 pptw in upper City Creek at ~2,525 m. This indicates that dust deposition may be relatively independent of aspect/elevation, which is similar to previous results reported in the Colorado Rockies (*Painter et al.*, 2012).

Relative to the decade long dust observation and concentration record in the Colorado Rockies [*Skiles and Painter*, 2016b] all of the observed dust events would be considered 'minor', but D1 had a potentially large radiative impact because the dust emerged at the snow surface just prior to three weeks of high pressure and clear skies. Although we have not yet quantified the radiative forcing by this dust layer, mid March exhibited rapid snow melt and widespread declines in snow water equivalent (SWE). We note that the impact of dust varies by elevation, which is mainly related to the amount of snow and the timing of dust layer emergence/convergence at the surface. Water Year 2017 was an above average snow year in the Wasatch, for many mid to low elevation SNOTEL (NRCS; *https://www.wcc.nrcs.usda.gov/snow/)* sites SWE peaked prior to the March high pressure period and snow depletion was reached in mid to late April, but at higher elevation sites peak SWE occurred around May 1 and snow depletion has not yet been reached. After we have analyzed all snow samples, one focus will be on quantifying the spatial and temporally varying radiative impacts of episodic dust deposition on the Wasatch snowpack.

Snow Covered Area and Snow Line Elevation

Our initial case study of April 1 fractional snow covered and snow line elevation shows that over the last two decades, while both snow covered and snow line elevation exhibit substantial interannual variability, the overall snowline trend is positive (toward higher elevations) and the overall snow-covered area trend is negative (declining snow-covered area) (Figure 4). The two are intuitively but not linearly related, generally speaking, when there is less snow the snow line elevation is higher. The widespread Western US drought from 2012-2016 is clearly visible in both records, colloquially this been referred to as a 'snow drought' since the widespread lack of wintertime precipitation was notable for most mountain ranges in the continental Western US.

These results are preliminary and represent just a snapshot in time, although snow depth/SWE peaks around April 1 on average the center of mass distribution exhibits a wide spread, but it does indicate that the declining trend in global snow cover is also likely manifesting in the Wasatch Mountains. This has important implications for water availability, and motivates further work both with the satellite record and observation networks. Unfortunately the MODIS record is relatively short, not quite two decades since it was first launched in 1999, which means we cannot yet use it to analyze for broader decadal scale climatic patterns. Still it is the most useful spaceborne satellite in terms of monitoring mid-latitude mountain snow cover. It is worth nothing that although MODIS has already outlived its expected operating period, this record will continue by applying the SCAG algorithm to VIIRS (Visible Infrared Imaging Radiometer Suite) imagery, which was purposefully designed to be a MODIS follow-on.

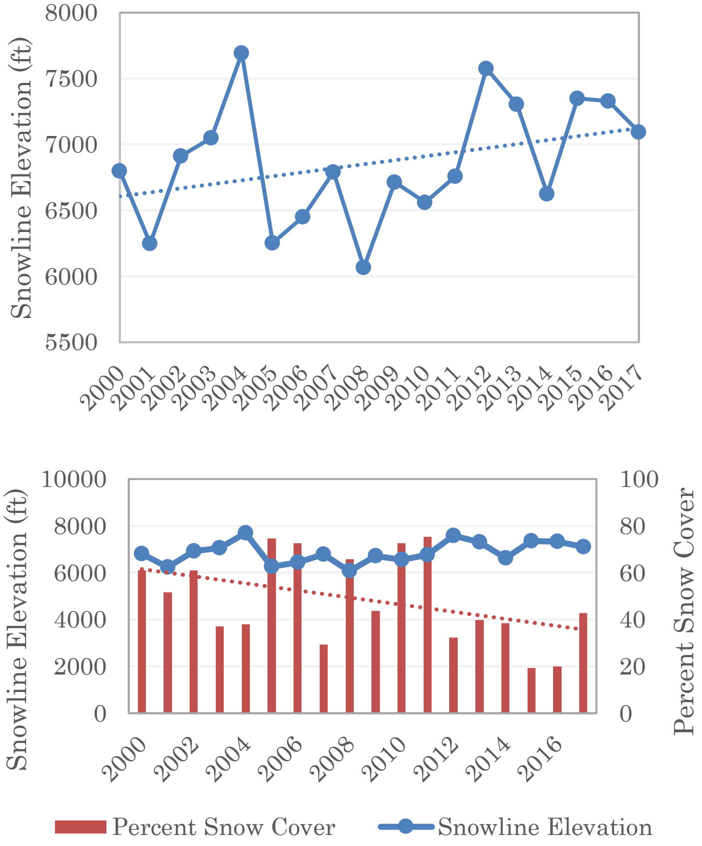

Figure 3. From this MODSCAG historical record, interannual variability and trends in April 1 snow line elevation and fractional snow-covered area, shown here as a percent of the Wasatch Mountain bounding box.

CONCLUDING THOUGHTS

The snow hydrology fieldwork effort that took place in the four main Salt Lake City watersheds in Water Year 2017 is the most comprehensive set of snow observations and samples collected to date in the Wasatch Mountains. It is also the first fieldwork based research effort that combines high-resolution snow optical and physical property observations and numerical modeling with the longer term satellite record, which will allow us to place results from a single year in a historical context. Our preliminary analysis of the remote sensing record indicates that snow cover is exhibiting a declining trend in the Wasatch. Although the bulk of sample analysis has not yet been completed initial results indicate that cold air pools do lead to higher BC concentrations at lower elevations. This is hydrologically relevant since lower elevation snow cover is consistently shallower and near the melting point, which makes it more susceptible to energy balance inputs. If the BC deposition is further depressing surface albedo it could be accelerating the depletion of low elevation snow cover and contributing to both a rise in snow line elevation and decrease in snow covered area. Early results also indicate that episodic dust on snow deposition in the spring is widespread and concentrations are relatively independent of aspect or elevation. The impact of the dust, though, is likely dependent on both aspect and elevation, factors which control amount of snow and exposure to solar radiation.

Ultimately this research effort is motivated by constraining physical controls on snow melt timing and magnitude, and understanding the regionally specific radiative impacts of light absorbing aerosols and snow albedo feedback processes, to improve the way snowmelt processes are modeled along the Wasatch Front. The Salt Lake City metropolitan area is critically dependent on the mountain snowpack to meet water demands, and will need resilient methods to adapt to variable but accelerated mountain snowmelt. The current statistically based runoff models are stochastic and depend on the future being like the past, which is no longer a safe assumption. We now have the tools and computing capability to implement spatially distributed physically based snow hydrology models, which directly account for melt processes. The models require observations for development, forcing, and validation. We plan to integrate our observations into a physically based, full distributed snow energy balance model, which we will run over the four main watersheds and then compare results to current methods, after which we will disseminate methods and results to local water managers and operational runoff forecasters.

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