DUST ON SNOW IN THE WESTERN US: PROCESSES, PATTERNS, AND IMPLICATIONS FOR SNOW DURATION, WATER RESOURCES, AND SAFETY

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ABSTRACT: Dust deposition on snow darkens the naturally bright surface, increasing absorption of solar radiation, and providing more energy for melt. Dust is effective at shortening snow duration because it is persistent; individual layers combine at the snow surface as snow melts, compounding surface darkening as days lengthen and solar radiation increases in the spring. To date, dust-on-snow (DOS) has been most well studied at Senator Beck Basin Study Area (SBBSA), in the San Juan Mountains of southwestern Colorado, the first high elevation point of contact for dust emitted from the southern Colorado Plateau. Episodic DOS events are observed every spring at SBBSA, although the number of dust events and dust loading varies significantly from year to year. Twenty years of research at SBBSA has shown that following modern settlement of the West dust deposition rates increased five-fold, that snow darkening due to dust accelerates snowmelt by 3-5 weeks, is a stronger control on melt rates then warming temperatures, and that dust accelerated melt reduces total water yield and is correlated with errors in runoff forecasting. At the regional scale, satellite remote sensing of snow darkening indicates that dust impacts are most severe in the southern Colorado Rockies, but are still relevant across the mountains of the Western US. Here, we will summarize the detailed dust on snow record at SBBSA, and use newer study sites and the remote sensing record to put it in a regional context.

KEYWORDS: dust-on-snow, snow hydrology, energy balance, snowmelt

1. INTRODUCTION

Remote sensing records show a clear trend toward earlier snowmelt across high mountain areas in the northern hemisphere (Hock et al., 2019). Reductions in mountain snowpack have mainly been attributed to anthropogenic climate warming; specifically changes in precipitation phase (more rain than snow), and more frequent and earlier melt events. Although climate warming is having important impacts on snow patterns there are other processes shortening snow duration, including snow darkening from light absorbing particles (LAPs). When at or near the snow surface LAPs, such as deposited dust or black carbon aerosols, increase absorbed sunlight by darkening the surface. The amount of absorbed sunlight, referred to as net solar radiation, is the dominant driver of snowmelt in most snow environments (Dewalle and Rango, 2008; Marks and Dozier, 1992; Skiles et al., 2012).

Deposition of LAPs provides additional energy for melt in two ways; it lowers snow albedo, a measure of snow reflectivity, directly in the visible wavelengths, where clean snow reflects nearly all (>90%) incoming sunlight. The additional energy from the direct impact accelerates snow grain growth, indirectly lowering albedo in the near infrared wavelengths, where ice is absorptive (Warren, 1984; Painter et al., 2007). The impacts of snow darkening are quantified as a radiative forcing, which is the additional amount of sunlight absorbed due to LAPs.

In the Western United States the dominant LAP is dust, and darkening of snow cover following episodic dust deposition events is a well-documented process (Skiles et al., 2018a). Although dust can be a natural aerosol, modern levels are elevated due to human activity; surface disturbance and desertification related to land use change, in addition to drought intensified by climate change.

Dust is especially effective at accelerating melt because it is not entrained in melt water; as snow begins to melt separate dust layers, previously deposited and then buried, combine at the surface to compound surface darkening (Doherty et al., 2013; Skiles and Painter, 2017). In the spring this darkening coincides with increasing day length and higher sun angles, which leads to higher radiative forcing and earlier exposure of darker surfaces beneath the snow. Despite this well-established understanding of controls on snow albedo and snowmelt, studies have largely neglected the impact of snow darkening and dust deposition when investigating changing snow cover patterns in the Western US.

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Figure 1: Dust on snow in the San Juan Mountains, CO in May, 2009.

2. TWO DECADES OF DOS RESEARCH AT SENATOR BECK BASIN, CO

Dust-on-snow (DOS) processes and impacts have been most well studied at Senator Beck Basin Study Area (SBBSA) in the San Juan Mountains of southwestern Colorado (Painter et al., 2007; Painter et al., 2012b; Skiles et al., 2012; Skiles and Painter, 2017; Skiles and Painter, 2018, 2019). The study basin includes two snow energy balance instrumentation sites, one subalpine and one alpine, and a stream gauge at the basin pour point (Landry et al., 2014). Regular observations are collected of dust event timing, DOS concentrations, and full profile snow properties. This area was selected to study the hydrologic impacts of DOS as it is the part of the headwaters of the Colorado River, which is primarily snowmelt fed, and the first high elevation point of contact for dust emitted from the southern Colorado Plateau (Figure 1).

Since SBBSA was established in 2003 dust events have been observed every year, with the majority of events occurring in the spring (March, April, May) (Painter et al., 2012b). Daily mean radiative forcing in the spring, on the scale of 50-65 W m^{-2}, have been shown to accelerate snowmelt by 3-5 weeks (Skiles et al., 2012; Skiles et al., 2015). The acceleration of melt significantly shifts the timing and magnitude of peak runoff (Skiles et al., 2012), which may reduce total water yield (Painter et al., 2010). The rates of snowmelt runoff in the region are directly related to the magnitude of dust radiative forcing, and do not exhibit a relationship with air temperature (Painter et al., 2018). Correspondingly, the acceleration of melt correlates with errors in operational temperature-based snowmelt runoff forecasting (Bryant et al., 2013).

Dust events coincide with high wind speeds, which tend to be pre- or post-frontal, and duration of deposition is typically on the scale of hours. Dust can be dry deposited, or entrained in precipitation and wet deposited. Dry deposited events tend to be thin, well defined, layers in the snowpack, whereas wet deposited events tend to be thicker, more diffuse, layers (Skiles and Painter, 2017). The amount of dust deposited by each event is variable and the total amount of dust deposited each snow season, ranging from 1 mg g^{-1} in average years to 4 mg g^{-1} ppm in extreme dust years, does not correlate with the number of dust events (Skiles et al., 2015; Painter et al., 2012b).

At SBBSA the physical and chemical properties of deposited dust correspond to the chemical signatures found across arid regions of the Colorado Plateau (Lawrence et al., 2010). Back-trajectory modeling also indicates that events transporting the most dust mass are associated with southwesterly winds that transport dust from source regions in the southern Colorado Plateau (Skiles et al., 2015). In this region, deposition rates have increased significantly (5-fold) following modern settlement of the Western US, directly linking dust emission and loading to land use change and surface disturbance (Neff et al., 2008; Brahney et al., 2013).

3. SPATIAL VARIABILITY

3.1 In Situ Observations

To understand how dust deposition timing and magnitude varied across headwaters of the Colorado River a partner site to SBBSA was established on the northern rim of the Grand Mesa in west central Colorado in 2010. Multiple years of coincident observations at Grand Mesa Study Plot (GMSP) established that regionally, dust processes and impacts were similar. Dust was deposited by the same events at both locations (Figure 2), and back-trajectory modeling showed that all major events at both sites originated in the southern Colorado Plateau (Skiles et al., 2015).

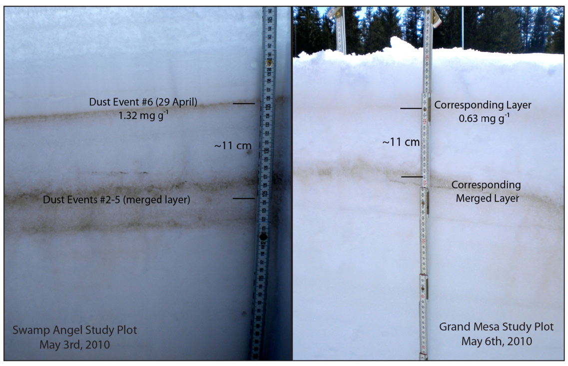

Figure 2: Photographs of the upper ~50 cm of two snow pits at Swamp Angel Study Plot (SASP) and Grand Mesa Study Plot (GMSP) in early May 2010. *From Skiles et al., 2015 with permission.*

The more northern site does have lower dust concentrations, daily mean radiative forcing in spring (32 – 50 W m^{-2}), and accelerated snowmelt (15 – 30 days), attributed to being farther away from the source region. Snowmelt response to dust is similar at both sites, with degree of accelerated melt exhibiting a linear relationship with dust concentrations (Skiles et al., 2015).

Dust event timing and DOS concentrations have also been recorded in the Wasatch Mountains since 2009, where dust originates from sources in the Great Basin (Hahnenberger and Nicoll, 2012; Steenburgh et al., 2012; Lang et al., 2023). In 2017 instrumentation, similar to that at SBBSA and GMSP, was installed at Atwater Study Plot (ASP) in Little Cottonwood Canyon to quantify impacts of dust on snow albedo and melt rates (Skiles et al., 2022). Over this still relatively short record, dust has been shown to accelerate melt on the scale of 1-3 weeks (Skiles et al., 2018b; Lang et al., 2023). Dust impacts are not as dramatic because dust loading, and dust color, is lighter relative to the southern Rockies (Skiles et al., 2018b). Although, dust deposition may be intensifying in part due to exposure of dry lake bed as the Great Salt Lake declines (Lang et al., 2023).

Although less extensively studied, DOS has been documented in other parts of the Western US. For example, in the eastern Sierra Nevada dust has been shown to dominate snow darkening and radiative forcing. Concentrations, though, are lower than those sampled in the Colorado Rockies and Wasatch (Sterle et al., 2013).

3.2 <u>Satellite Observations</u>

Spring time dust radiative forcing, mapped near daily with the NASA Moderate Resolution Imaging Spectrometer (MODIS), shows that dust impacts in the Rocky Mountains generally decline along a northwestern gradient (Painter et al., 2012a). The dust radiative forcing is consistently highest in the southern Rockies, where SBBSA is located. This pattern corroborates that the southern Colorado Plateau is the primary dust source region impacting the headwaters of the Colorado River Basin (see Figure 2 in Painter et al., 2012a), and that distance from the source region is a primary control on the magnitude of dust radiative forcing.

4. TEMPORAL VARIABILITY

Initial analysis of MODIS spring time dust radiative over the headwaters of the Colorado River Basin for the satellite period of record, which now extends over twenty 20 years, confirms the significant interannual variability in dust impacts observed at SBBSA (Figure 3). Although extreme dust years observed at SBBSA are not always as dramatic when dust radiative forcing is integrated across the full upper Colorado River Basin. For example, 2009 was an extreme dust year at SBBSA and across the full basin, whereas 2013 was one of the highest dust years recorded at SBBSA (Skiles and Painter, 2017) but for the full basin, it was only slightly above average (Figure 3). The satellite record indicates that dust impacts were generally more intense in the first decade of the record (2001 – 2010) with less intense dust impacts in the more recent decade (2011 – 2021). Widespread dust and high radiative forcing values did return in spring 2022. A longer record will be needed to determine if these are truly decadal scale patterns, or simply a coincidence. These early results are currently being analyzed in more detail, but do indicate that dust radiative forcing is not directly related to the duration of the ongoing drought in the Western US.

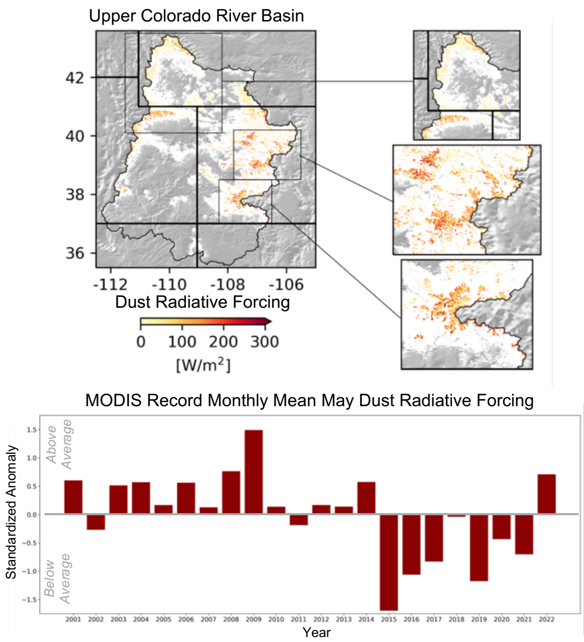

Figure 3: (Above) Example of dust radiative forcing over the Upper Colorado River Basin for May 2009. (Below) Standardized anomalies, the difference from record mean, of MODIS monthly mean dust radiative forcing in May over the upper Colorado River Basin.

5. KNOWLEDGE GAPS

The focused study of DOS at the study plot scale has led to limited understanding of spatiotemporal variability at the watershed to regional scale. Satellite remote sensing show dust impacts the Upper Colorado River Basin, but that accelerated melt may be on the scale with what has been quantified at GMSP and ASP, as opposed to SBBSA, which is located where dust impacts are most dramatic in the Western US. There are important limitations to remote sensing retrievals, though, due to current satellite capabilities, including coarse spatial resolution and limited reflectance sampling from which retrievals can be based on (Painter et al., 2012a; Warren, 2013). There are efforts to supplement satellite retrievals with higher resolution airborne retrievals, from crewed and uncrewed aircraft (Painter et al., 2013; Skiles et al., 2023), and advancing satellite technology will like fill this gap in the future.

The high interannual variability in dust event timing and loading is well documented (Skiles et al., 2015; Skiles et al., 2012; Lang et al., 2023) yet there is an incomplete understanding of what drives the variability. To fill this knowledge gap, additional interdisciplinary research is needed to relate controls on emission and transport to DOS processes and impacts. Taking a systems level approach would support better representation of source-to-sink processes in earth system models, which currently have limited capabilities with respect to simulating DOS (Oaida et al., 2015). Such an approach could aid in targeting areas for restoration to mitigate the hydrologic impacts of dust-on-snow.

Finally, the impact of episodic dust deposition on snow stability and snow safety has been noted anecdotally but has not yet received systematic study in the Western US, where the focus has been on hydrologic impacts. It is possible that dust events during the accumulation season, if exposed at or near the surface for an extended period of time, could lead to the formation of weak layers. For example, depending on length of exposure and atmospheric conditions, dust could lead to 1) near surface faceting or 2) the development of a melt/refreeze or ice crust, creating a localized temperature and vapor pressure gradients. These could lead to weak layer formation and failure above or below the dust layer, respectively, although this could depend on other factors such as duration of exposure and depth below surface. Dust events are more likely to be deposited, though, during spring when snow is already melting and slab avalanches are less of a concern. Given this, it is most likely that dust enhances the likelihood of rapid melt and wet slides.

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