Impacts of dust on snowmelt and streamflow in the Colorado River Basin

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Abstract

The Colorado River is the lifeblood of the southwestern U.S., providing water for irrigation, hydroelectric power, and daily use for 40 million residents, among a litany of ecosystem services. The timing and volume of runoff from the Rocky Mountains, which feeds the river, are significantly impacted by the deposition of dust on mountain snowpack. By decreasing snow albedo, dust increases radiative forcing, accelerating snowmelt and peak runoff by approximately three weeks each spring. Climate change is predicted to amplify these effects, particularly on the timing of peak snowmelt. Incorporating dust fluxes into river management tools and adopting practices to mitigate dust production, such as reducing intensive grazing, are essential to safeguarding the river's resources for years to come.

1. Introduction

The Colorado River has been essential to life in the desert southwest since the first indigenous peoples arrived on the Colorado Plateau. Today, forty million people in seven western states of the U.S., plus Mexico, depend on the waters of the Colorado River (Deems et al., 2013). Humans have divvied the water to meet diverse stakeholder needs from agriculture and household use to hydroelectric power, recreation, and conservation (Garrick et al., 2008), overallocating the river beyond mean annual flow (Painter et al., 2010). Though the river's annual runoff is approximately 15 million acre feet (maf), yearly allocation exceeds this by about 1.5 maf, for distribution is based on an anomalously wet period in the early twentieth century (Garrick et al., 2008).

Most of the runoff into the Colorado River comes from snowmelt in the Rocky Mountains, part of the Upper Colorado River Basin (Deems et al., 2013). Reservoir storage capacity in this area is limited relative to the drier Lower Basin, meaning water managers rely more on timing of snowmelt to ensure sufficient supply (Deems et al., 2013). The reliance on snowpack in the Rockies makes the entire basin, but principally the upper portion, sensitive to perturbations. Climate change in particular is projected to reduce runoff by 10% or more by the middle of this century, further straining the region (Christensen et al., 2004; Seager et al., 2013).

The timing and rate of peak runoff are crucial to annual water allocations for the Colorado River because delivery is often restricted by timing of peak flow or specific date ranges (Kenney et al., 2008). Dust, because of its effects on reducing snow albedo, plays a significant role in controlling the timing of both snowmelt and runoff. The Colorado Rockies are adjacent to the largest sources of dust in North America – the Mojave Desert, the Great Basin, the Colorado Plateau, and the Sonoran Desert (Tanaka and Chiba, 2006). One range in particular, the San Juan Mountains, is an important source of runoff to the river (**Fig. 1)**; its geographical position and water contributions make this range ground zero for understanding the dust-snowmelt relationship (Painter et al., 2007, 2012b; Skiles et al., 2012). The proximity of this range to these southwestern dust sources leads to high volumes of eolian deposition, making it ideal for investigating snow surface energy budgets, particularly the effects on snowmelt timing and total runoff (Neff et al., 2008).

Despite its essential role, dust has only recently been included in climate and hydrological models for the Colorado River because of a paucity of data. Understanding the dynamics of dust's impacts is essential to making future projections under climate change and to developing robust river management plans (Painter et al., 2010; Deems et al., 2013).

2. Dust Sources and Radiative Forcing

2.1 Sources of Dust

Most dust comes from wind erosion of soil (Tanaka and Chiba, 2006). While global dust generation and transport may be modeled, local proxies, specifically alpine lake sediments, provide insights into shifts in historical accumulation rates at a regional scale. In the San Juan Mountains, dating of radiogenic lead (^{210}Pb) and carbon (^{14}C) from lake sediments in alpine areas with little soil or human disturbances offers a robust record of regional deposition for approximately the last 5000 years (Neff et al., 2008). Results from these approaches suggest dust loads in the Western U.S. have increased by 500% in the last 200 years compared to late Holocene averages (Neff et al., 2008). Analysis of samarium-neodymium isotopic ratios (^{147}Sm/^{144}Nd), strontium isotopes (^{87}Sr/^{86}Sr), and particle size distributions in the same lake sediments suggests dust contributions to the Colorado River Basin are dominantly derived from regional sediments of the southwestern U.S. (**Fig. 2**) (Neff et al., 2008). In particular, the size of the lake sediment is too coarse (mostly >10 μm) to suggest more than minor contributions from the deserts of Asia (Neff et al., 2008). For policymakers, this points to the potential for regional management of dust loads in the desert southwest.

2.2 Recent Peaks in Dust Production

In the eastern Colorado Plateau, high dust fluxes likely result from intense wind gusts and sediment displaced by powerful runoff associated with summer monsoons (Reheis and Urban, 2011); however, the skyrocketing dust loads of the last two centuries point to significant changes in local sources. While increasing dust could have resulted from severe drought, the dry periods during this time have been less severe than in the last several thousand years (Cook et al., 2004; Neff et al., 2008). The clearest explanation is the significant settlement and colonization of lands in the west since the mid-1800s, which led to broad human perturbations, including mining, agriculture, and chiefly livestock grazing (Abruzzi, 1995; Neff et al., 2008). With increased disturbance of protective biological soil crusts, wind erosion of soil accelerates (Belnap and Gillette, 1998). This intensive grazing was extremely destabilizing for these ecosystems (Abruzzi, 1995), leading to a peak in dust inputs about a century ago, around the time of the Dust Bowl in the U.S. (Neff et al., 2008). Not until the Taylor Act of 1934 that regulated grazing in the west did a moderate decline in dust inputs begin to occur (Neff et al., 2008).

2.3 Dust Radiative Forcing

Dust deposition's role in radiative forcing depends on the albedo of the dust compared to the albedo of the surface it covers. Here, albedo refers to the proportion of incoming solar radiation reflected by a surface (Coakley, 2003), and radiative forcing is defined as shifts in the balance of incoming solar radiation and reflected infrared radiation, where positive or negative forcing equates to warming or cooling, respectively (Pulselli & Marchi 2015). Globally, dust has a net negative effect of approximately -0.4 W/m^2 (Takemura et al., 2009), compared to the positive forcing of roughly 2 W/m^2 from greenhouse gas emissions (Painter et al., 2010). Local effects of dust are highly variable; at the surface, it can increase or decrease radiative forcing, while in the atmosphere it has a cooling effect (Liao and Seinfeld, 1998). Conversely, over high albedo regions, such as fresh snow or ice, dust decreases land surface reflectance and increases radiative forcing (Painter et al., 2012a).

For snow, albedo can be reduced from approximately 0.9 in fresh clean snow or 0.7 in old clean snow to as low as 0.3 when dust-covered (**Fig. 3**) (Painter et al., 2012b; Skiles et al., 2018).

This change causes positive radiative forcing, where more incoming solar radiation is retained in the snow, rather than reflected as infrared radiation (Pulselli and Marchi, 2015). This dust effect can cause local radiative forcing to reach more than 400 W/m^2 (Painter et al., 2007).

The dust-on-snow albedo effects extend beyond direct changes to energy absorption, for the dust initiates a feedback loop, where increased energy in the snow causes ice grains to grow. This increases ice grain absorption of radiation and furthers melting (Skiles, 2014). Moreover, the timing of heavy dust deposition in the spring takes place after most snowfall, and as melting proceeds, most dust particles are not lost with runoff but remain on the snow surface, accelerating radiative forcing (Conway et al., 1996; Skiles, 2014). Together, surface darkening and snow grain-size changes increase the rate of snowmelt, shift runoff earlier, and decrease the total magnitude of runoff (Painter et al., 2010; Deems et al., 2013).

Dust is not unique in its effects on snow albedo. Other light absorbing impurities, namely black carbon, are produced from forest fires and anthropogenic activities such as fossil fuel burning (Skiles et al., 2018). Like dust, black carbon absorbs light, increasing the albedo of snow, and its production has increased since the industrial revolution (Skiles et al., 2018). However, black carbon generally accounts for a much smaller proportion of total light-absorbing impurities in snow (Skiles and Painter, 2017).

3. Effects on Snowmelt and Streamflow

3.1 Impacts across the Basin

Our paradigm for normal dust-snowmelt-climate interactions in the Upper Basin of the Colorado River is severely limited by our myopic consideration of only the last century or so of conditions. Estimates indicate that under present dust loading in the Upper Colorado River Basin, the end of snow melt is shifted by three to four weeks and as much as seven (Skiles et al., 2015). Peak runoff is similarly shifted by approximately three weeks (Painter et al., 2010).

The effects of melt timing have important implications for total runoff. Models suggest that runoff decreases by about 5% due to increased evapotranspiration during the extended snow-free season, reducing soil moisture and lengthening the growing season (Deems et al., 2013). Recent work suggests the effects of dust radiative forcing are sufficient to explain much of the variability in the rising limb of the Colorado River hydrograph at Lee's Ferry (**Fig. 4)** (Painter et al., 2018). Although temperature is commonly believed to drive snowmelt, "dust radiative forcing so dominates the surface energy flux that snowmelt rates are insensitive to air temperatures over the rising limb of the hydrograph" (Painter et al., 2018). This is particularly true early in the season when air temperatures remain cool and snow cover is high (Painter et al., 2018).

3.2 Case Study: Grand Mesa and Swamp Angel

A case study in the Colorado Plateau is instructive for exploring how these changes to snowmelt and peak runoff are controlled by dust deposition (Skiles et al., 2015) Two sites, Swamp Angel and Grand Mesa were used for the study – both sites are located in western Colorado and have similar elevations and environmental conditions, but Swamp Angel, in the San Juan Mountains, receives much higher dust inputs than Grand Mesa. Changes in albedo over the snow melt season was measured for four years (**Fig. 5**). Overall, the site with higher dust inputs, Swamp Angel, had a lower albedo at nearly all time points. This was most striking after big dust events; in particular, in 2010 there were a number of severe dust events that directly correlated with plummeting snow albedo.

After studying annual albedo variability, dust-driven snowmelt compared to idealized dust-free snowmelt was modeled using the data from these two sites (Skiles et al., 2015). Changes in snow water equivalents over the melt season were modeled for the four years of albedo data and compared to field measurements of snowmelt, which correlated well with the model (**Fig. 6**). The results demonstrated that dust triggered complete snowmelt two to four weeks earlier for the less dusty Grand Mesa and four to seven weeks earlier for Swamp Angel compared to idealized clean snow. Although direct measurements of past snowmelt are impossible, this study provides insight into the possible historical timing of runoff in the Upper Basin, prior to the spike in dust inputs beginning in the nineteenth century. These specific findings are consistent with modeled estimates for the entire basin (Painter et al., 2010).

4. Shifts under Climate Change

Across the Colorado Plateau, climate change, coupled with shifts in land use, is projected to have intersecting impacts across ecosystem services, including on water availability, soil and cropland productivity, recreational tourism, wildlife and vegetation, and spiritual and cultural resources (Copeland et al., 2017). Models suggest that increasing aridity with climate change will result in a decrease in vegetation cover and biological soil crusts that are crucial for preventing soil erosion and dust production (Munson et al., 2011). Furthermore, changes to precipitation patterns may intensify the summer monsoon season, which could raise dust fluxes in the eastern part of the plateau (Reheis and Urban, 2011). Black carbon deposition from forest fires may also increase with climate change (Skiles et al., 2018).

These changing dust inputs will shift runoff patterns for the Colorado River Basin. For the Lee's Ferry hydrograph under 2050 climate scenarios with a range of dust loads, climate impacts shift peak flow earlier in the year and reduce total flow (**Fig. 4**) (Deems et al., 2013). Under future scenarios, dust especially controls initial runoff and peaks; extreme dust deposition shifts peak snowmelt three additional weeks earlier by 2050 and causes a 1% reduction in annual flow (Deems et al., 2013). With climate change, flow timing is highly sensitive to dust; however, flow volume becomes proportionally less affected by dust because future runoff is controlled more by changes in total precipitation (Deems et al., 2013). Climate-driven shifts in runoff initiation and flow volume from increased dust deposition in an already over-allocated system like the Colorado River have high potential for cascading ecological and human use effects.

5. Management Implications

5.1 Water Allocation and Management

Given the current impacts of regionally high dust fluxes and potential effects with climate change, the implications of including dust inputs in water management decisions are tremendous. Snowmelt runoff projections for hydrographs in the Western U.S. often include errors of up to 40%, especially early in the season when dust radiative forcing truly dictates melting (Painter et al., 2018). Extreme dust deposition in Colorado in 2009 and 2013 severely strained water infrastructure; ongoing erraticism in the rising limb of the hydrograph complicates management decisions (Painter et al., 2018). For reservoir managers, future changes in runoff timing will create added uncertainty when planning for "reservoir release, large reservoir fluctuations, and regular shortages" (Painter et al., 2010). Impacts will likely extend to other Colorado River projects such as wetland restoration, high flow experiments, or water flow below the Morelos Dam with Mexico. This points to an urgent need to incorporate dust fluxes in climate and hydrologic models used by land managers (Bryant et al., 2013).

Within the scientific community, remote sensing and modeling tools are being employed to better understand variability and aid in these management decisions. Models such as those used by Skiles and collaborators (2015) are providing insights into present effects of dust, but these are currently constrained by the limited availability of detailed site-specific measurements outside of select areas in the San Juan Mountains (Painter et al., 2018). The MODIS Dust Radiative Forcing in Snow model is the first remote sensing tool to allow estimates for radiative forcing to be extended to areas where direct measurements are not feasible while capturing a high level of variability (Painter et al., 2012a). While researchers work to reduce bias and uncertainty in these models through additional data collection and validation, they may still be employed to inform decision making.

5.2 Dust Management

In addition to incorporating dust-snow effects into decision making, there is a broader need to reevaluate dust control measures in the Western U.S. Bare soil exposure is significantly related to seasonal dust deposition on the plateau (Li et al., 2013); in the coming decades, population growth and intensification of land use are likely to reduce vegetation cover in these regions, increasing bare soil and subsequent dust production (Field et al., 2010). Land managers and policy makers therefore need to explicitly account for land use effects on ground cover and dust production (Field et al., 2010).

Despite probable increases in dust production, local dust emissions can be mitigated at a relatively small scale, unlike the global solutions required to combat climate change. Moreover, specific regions have very different dust dynamics and therefore require more targeted regulation. For example, the Colorado Plateau has much greater seasonal variation in dust fluxes due to its windiness than does the Mojave Desert (Reheis and Urban, 2011). However, bringing dust production in line with pre-industrial levels through efforts could completely counteract shifts in runoff timing associated with global warming (Deems et al., 2013). This could be achieved by managing controls on emissions, especially from grazing, plowing, mining and other industrial activities (Neff et al., 2008). Furthermore, increased regulations on activities affecting dust have potential co-benefits for desert ecosystems, soil preservation and human health.

Additional research will lend clarity to remaining uncertainly surrounding dust sources, dust-snow interactions and variability, and ecosystem recovery and resilience to disturbances. Meanwhile, enhanced cooperation between scientists and decision makers is required to ensure these findings translate to water allocation, land management, and future planning.

6. Conclusion

Radiative forcing from regional dust deposition plays an important regulatory role in the timing and magnitude of snowmelt and therefore runoff in the Upper Colorado River Basin. Intensive grazing and plowing by settlers increased dust fluxes across the region during the nineteenth century, pushing snowmelt approximately a month earlier. With climate change, snowmelt is projected to shift several additional weeks earlier and may result in decreases to total runoff. Coupled with declines in total precipitation and increased aridity in the west, this has potential to disrupt economic sectors and ecosystem services that rely on the Colorado River. To minimize these disruptions, predictive models that include dust loads must be employed to inform new management approaches to limit preventable dust production (e.g. by limiting grazing to restore biological soil crusts) and allocate water based on the most robust estimates of flow timing and volume.

7. Figures

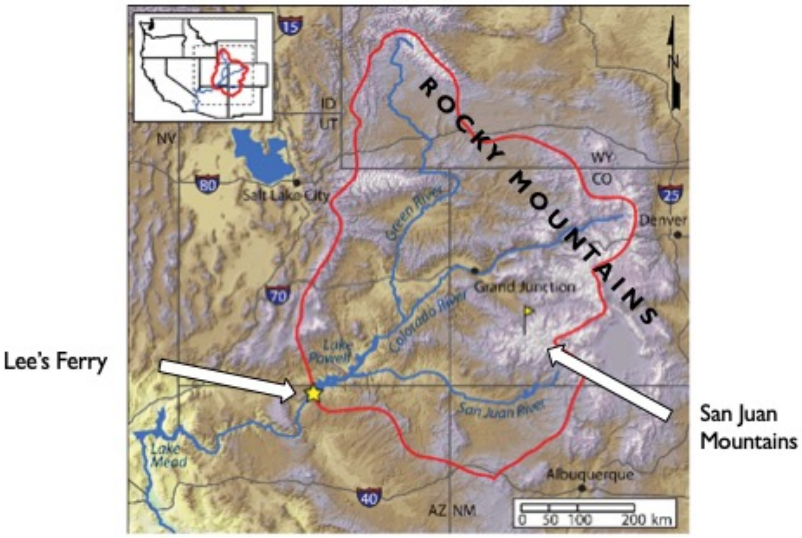

Figure 1: Map of the Upper Colorado River Basin above Lee's Ferry, showing the location of the San Juan Mountains, a range of the Rocky Mountains in southwestern Colorado with high dust deposition and significant runoff to the Colorado River. Modified from Deems et al., 2013.

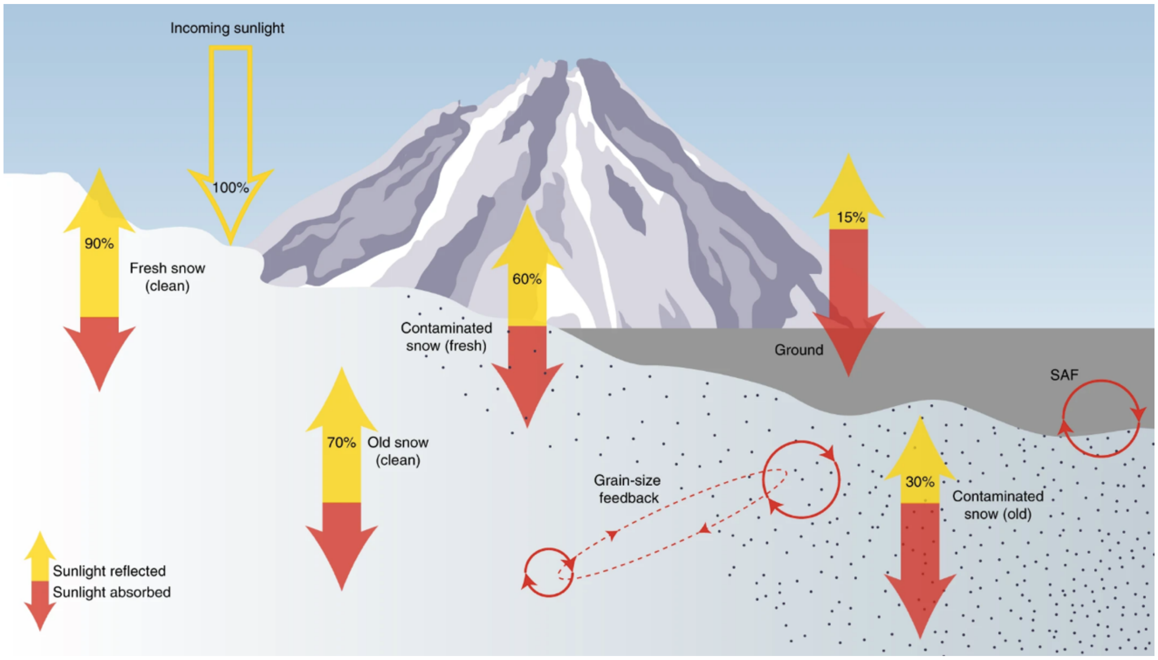

Figure 2: Conceptual diagram showing the balance of reflected and absorbed sunlight for clean and dirty snow (yellow and red arrows, respectively); percentages indicate surface albedo. From Skiles et al., 2018.

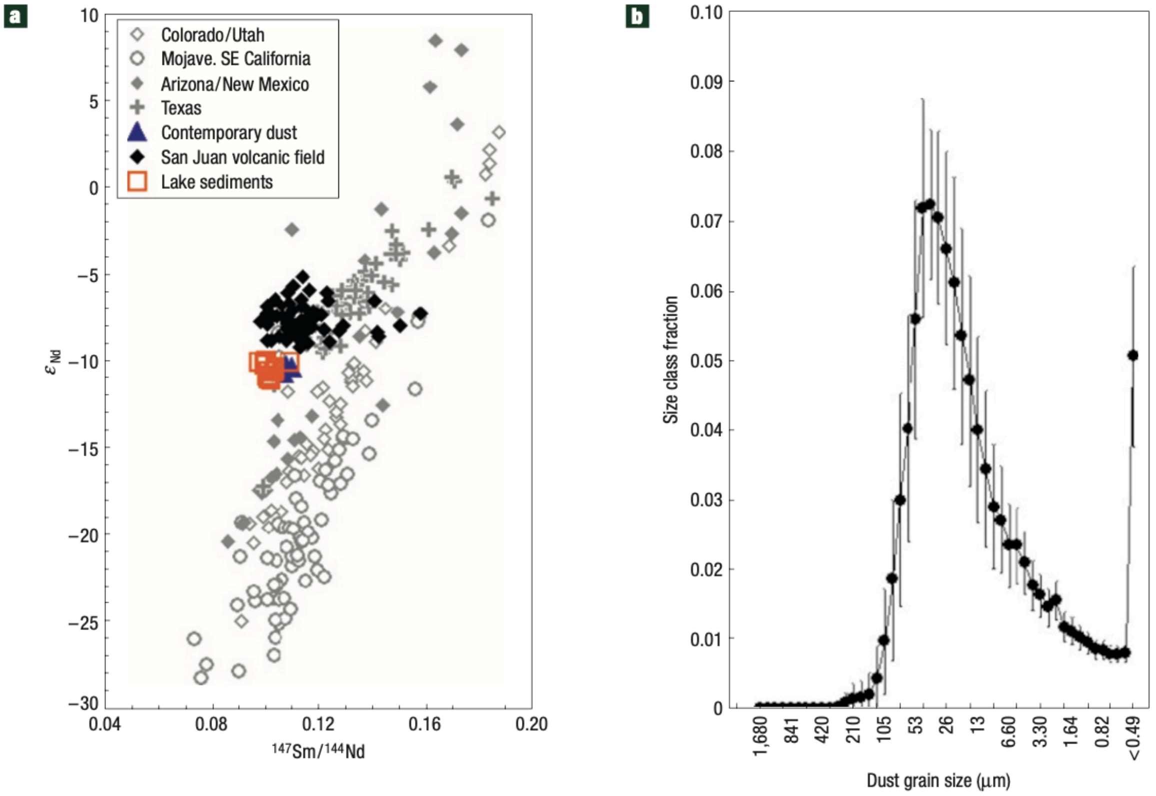

Figure 3: **(a)** Plot of stable isotopic measurements (ε_{Nd} versus ^{147}Sm/^{144}Nd) of San Juan lake sediments (orange squares), a dust proxy, compared to potential regional dust sources (basement rock), showing strong correlation. **(b)** Particle size distribution showing most San Juan lake sediments are >10μm and therefore likely locally derived. From Neff et al., 2008.

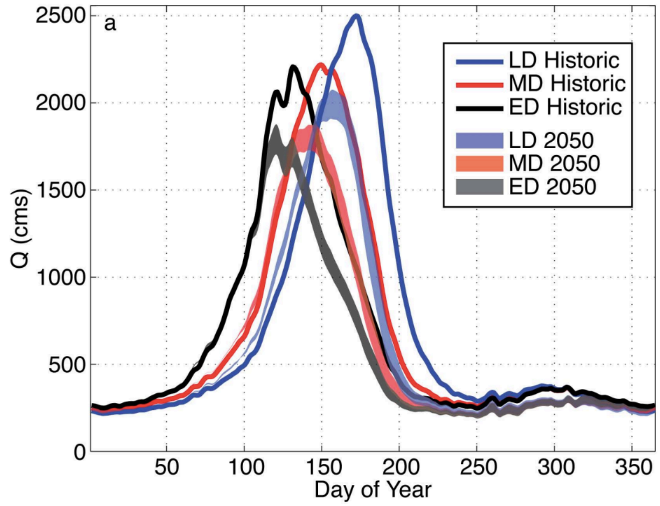

Figure 4: Plot of the Lee's Ferry hydrograph under historic conditions and 2050 climate scenarios (lighter shades), with low dust deposition in blue, medium dust in red, and extreme dust in black. Discharge (Q) in cubic meters per second (cms) is plotted by day of the year. Under every scenario, climate impacts shift peak flow earlier in the year and reduce total flow, while dust controls initial and peak runoff. From Deems et al., 2013.

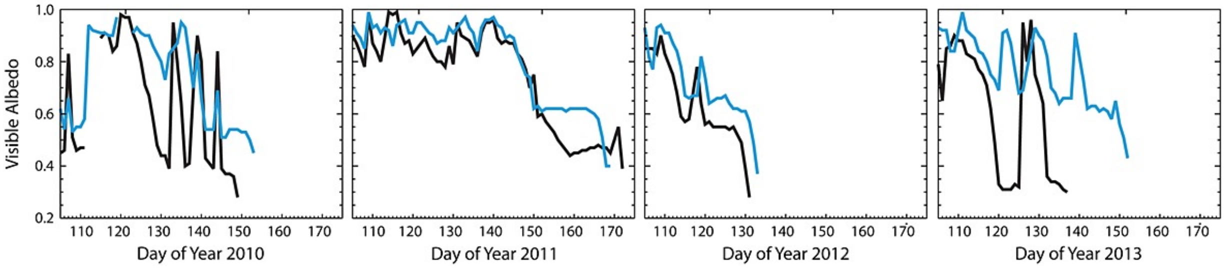

Figure 5: Plot of changes in albedo over the snow melt season across four years at two Colorado River Basin sites, Swamp Angel (black) and Grand Mesa (light blue). Overall, Swamp Angel, with higher dust inputs, has a lower albedo at nearly all time points, especially after significant dust deposition events, as in 2010. From Skiles et al., 2015.

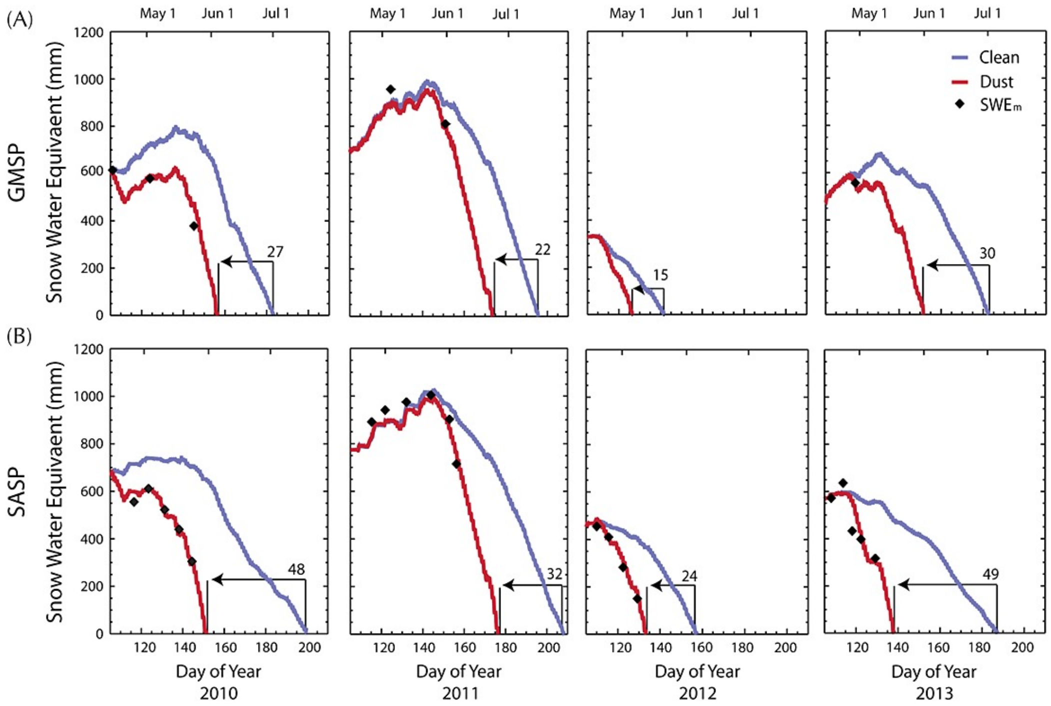

Figure 6: Plots for Grand Mesa (upper row) and Swamp Angel (lower row) showing changes in snow water equivalents over the melt season across four years. The theoretical snow melt curve for clean snow (blue line) is compared to modeled shifts in the melt curve with dust deposition (red line); field measurements (black diamonds) correlate well with the model. The number of days that total melt was shifted because of dust is indicated (black arrows). From Skiles et al., 2015.

8. References

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