DESERT DUST AND SNOW STABILITY

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ABSTRACT: Deposition of Colorado Plateau desert dust onto the Colorado mountain snowcover has increased over recent decades. Consequent reductions in snow cover albedo are routinely influencing snowmelt runoff behaviors but dust-on-snow has also affected avalanche processes, often in predictable ways. Observations of dust-enhanced mid-winter and spring avalanche processes are presented and associated with familiar snow stability and metamorphism theory. Ski areas, back country operators and recreationists, mountain guides, highway operations, natural resource development operations, avalanche warning agencies, and snow and ice researchers are all potentially subject to the effects of desert dust on snow stability.

KEYWORDS: snow albedo, snow stability, desert dust, snow avalanches

1. INTRODUCTION

In the Colorado Rocky Mountains, deposition of desert dust from the Colorado Plateau is rapidly increasing (Brahney et al. 2013) and the consequent radiative forcing caused by reductions in snow cover albedo have become a routine factor influencing spring snowmelt runoff behaviors (Painter et al. 2012; Skiles et al. 2012). Between 2005 and 2014 the Center for Snow and Avalanche Studies, in Silverton, Colorado, has documented and monitored 91 dust-on-snow events at its Senator Beck Basin Study Area, at Red Mountain Pass in the San Juan Mountains, and at ten other locations in the Colorado mountains. Collaboration with soil scientists has verified the Colorado Plateau as the principal source of these events, and informed our understanding of the high capacity for absorption of solar energy by that dust (Neff et al. 2008, Lawrence et al. 2010, Goldstein et al. 2013). CSAS's Colorado Dust-on-Snow Program advises Colorado and Federal water management agencies and other snow agencies about the likely hydrologic impacts of that dust-on-snow (Center for Snow and Avalanche Studies 2014).

Desert dust deposited onto the Colorado mountain snow cover (i.e., dust-on-snow) has also been observed to affect avalanche processes, often in predictable ways. Late winter and spring snow stability is subject to dramatic increases in the snow surface energy budget when dark, mineral dust is at *or near* the snowpack surface, reducing snow albedo and absorbing direct solar radiation. Unusually rapid development of wet snow instability can be anticipated. In mid-winter, dust-induced weak layer formation in dry snow is perhaps less common, but episodes of very rapid kinetic metamorphism have been observed in new snow when dust is present. Snow cornices containing dust also appear vulnerable to loss of strength.

Examples of these dust effects on snow stability are presented and associated with familiar 'clean' snow avalanche formation processes. Although this article focuses on observations of desert dust impacts on snow stability in Colorado, dust, soot, and other aerosols capable of reducing snow albedo are observed in mountain systems throughout the western United States and in other snow and ice landscapes worldwide. Ski areas, wintertime back country operators and recreationists, mountain guides, highway operations, natural resource development operations, avalanche warning agencies, and snow and ice researchers are all potentially subject to the effects of desert dust and other snow impurities on snow stability.

2. DUST-ON-SNOW DEPOSITION

Deposition of Colorado Plateau dust onto the Colorado mountain snowpack is typically associated with a strong wind field from the S-W quarter (180°-270°) in advance of a significant, synoptic scale, wet or dry weather system. Occasionally, strong NW winds have also produced dust-on-snow events. Because of travel distance from the Colorado Plateau to the Colorado mountains, most

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dust-on-snow events are not apparent to snow observers, as reduced visibility or as actual dust deposition, until later afternoon or evening, or the following day. A total of 91 dust-on-snow events were logged from winter 2004/2005 (Water Year 2005) through Water Year 2014, the majority of which fell during the months of March, April, and May (Fig. 1). A dust-on-snow event is defined, here, as a visually discernible layer within the snowpack or as visually detectable new dust on the snow surface. Mass measurements of single dust-on-snow events have ranged from 0.15 gm/m^2 to 47.5 gm/m^2.

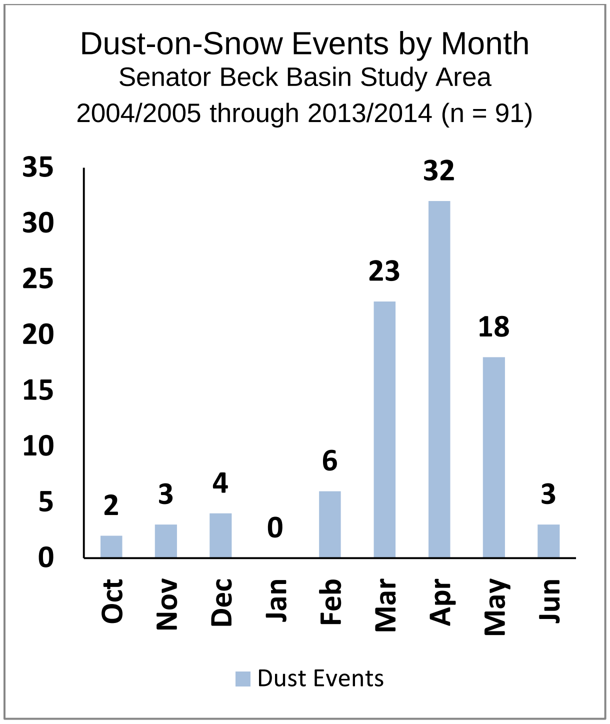

Fig. 1: Dust-on-snow log by month, Senator Beck Basin Study Area, San Juan Mountains, Colorado.

Over those ten years of observation, dust-on-snow events were either deposited dry, without any accompanying snow precipitation, or wet, with associated snowfall (Fig. 2). Dust delivered during wet events is most commonly entrained in the early snowfall of a given winter storm and subsequently buried by cleaner snow during the remainder of the storm. Wet dust deposition is subject to the same wind redistribution effects as the accompanying snow. Some wet dust-on-snow events at Senator Beck Basin occur entirely at night. No dust is apparent the next day until digging a snow profile and revealing a dust layer buried at some depth beneath the new snow surface.

Dust deposited dry is not typically redistributed by wind, once on the snowcover. If deposited during daylight hours, even faint daylight, dry dust-on-snow events immediately reduce snow surface albedo and increase the absorption rate of direct solar radiation at the snow surface.

The timing, during the day or night, and the wet/dry character of a particular dust-on-snow event are partially determinative of the impact of a given dust event on snow stability. Subsequent weather (sunny vs. cloudy, dry vs. stormy) and the condition of the underlying snowpack (still cold vs. isothermal) also influence whether a given dust layer's impact on snow stability is immediate or delayed.

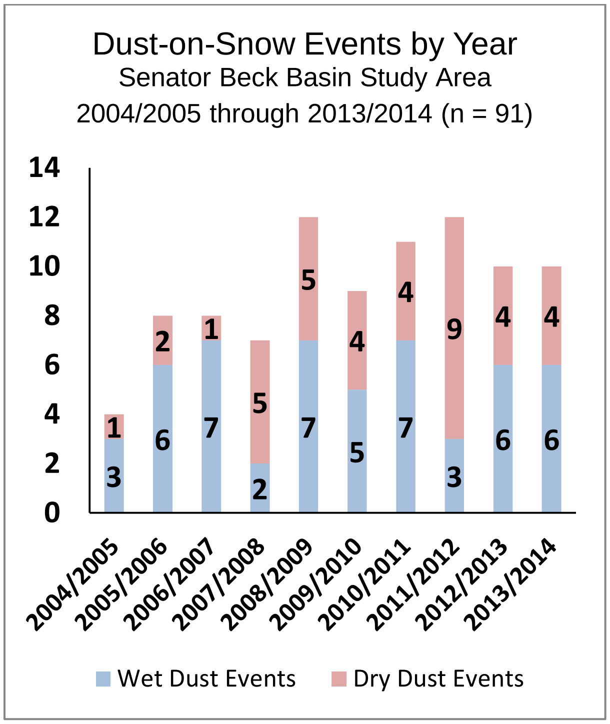

Fig. 2: Dust-on-snow log by season, and wet/dry type, Senator Beck Basin Study Area, San Juan Mountains, Colorado.

3. DUST IMPACTS ON SNOW STABILITY

The impacts of dust-on-snow can be broadly separated into mid-winter, dry snow, slab avalanche formation processes and springtime, wet snow avalanche processes. In both cases, these effects are driven by reductions in snow albedo, resulting in increased absorption of solar (short wave) radiation. In many cases, dust-on-snow produces effects similar to near-surface faceting processes described by Birkeland (1998), although the results are often quite exotic given what seem to be unusually strong vapor pressure gradients within complex snow structures.

3.1 Dry Snow

As seen in Figure 1, dust-on-snow events can occur here in Colorado throughout early and mid-winter months (October through February), falling onto generally cold snowpacks. These represent a small percentage of our total observed dust-on-snow events at Senator Beck Basin. Of those, most had no impact on snow stability until late spring, as the snowcover ablated to their level low in the snowcover and they contributed additional dust mass to many already merged dust layers.

However, in some cases, early- and mid-winter dust-on-snow can result in persistent features within the snowcover that sooner or later result in dry slab avalanching, under natural or artificial triggering. Several effects have been observed.

On a few occasions in mid-winter, dry dust-on-snow depositions, of varying intensity, remained exposed to direct solar radiation for some period of hours or days before becoming buried by subsequent snowfall. Even a very minor dry dust deposition does reduce albedo quickly enough to cause surface melting during daylight, despite relatively weak solar radiation (compared to spring). A thin layer of dirty ice can 'glaze' the snow surface after these weak, dry dust events, leaving a slick surface for subsequent snowfall to adhere to, particularly if that next snowfall occurs at night (Fig. 3).

Fig. 3: Dry deposited dust 'glaze' on cold snowpack in mid-winter, showing wind erosion of recent snow.

If the dry dust event is 'heavy', and a thicker mass of melting snow develops during daylight and is then covered by a shallow (i.e., <15 cm), low density snowfall in the afternoon or evening before skies clear overnight, very large temperature gradients will quickly develop between the wet, dirty snow and the new snow surface. Very rapid kinetic, melt-layer recrystallization (Birkeland 1998) can develop throughout the shallow new snow layer. Whether that layer of faceted grains will persist above the dirty snow depends on subsequent weather.

A prolonged period of surface melting can also result in shallow infiltration of free water. During mid-winter that wetting front quickly encounters much colder snow and refreezes as a thin ice layer. Multiple such ice layers have been observed. Given sufficient pore space around the resulting ice layer, some faceting may occur as a result of the vapor pressure gradient between the 'warm' ice and surrounding cold snow, or the ice layer may act as a barrier to vapor migrating toward the snow surface from deeper within the snowcover.

Early season dust-on- snow events, at the very beginning of snowpack formation, have been observed to result in total early season snowpack ablation back to bare ground, on sunny aspects, and/or thick layers of melt-freeze forms, often comprised of depth hoar grains. The latter crusts have been observed as the dirty bed surface of subsequent dry, deep-slab avalanches failing in the overlying depth hoar.

Finally, under very particular conditions, wet deposition of dust during early and mid-winter storms has resulted in rapid development of faceted grains, without associated melt, within the new snow layer. In most of these cases, strong winds during the onset of precipitation contain dust which is then entrained in the new snow, in more-or-less diffuse concentrations.

Fig. 4: Dry, hard slab avalanche showing multiple shear failures above and below dust layers. Photo courtesy of Chris George and Don Bachman.

In this scenario, which resembles radiation recrystallization (Birkeland 1998), just enough solar radiation is absorbed by the dark mineral dust to emit thermal energy and establish a strong vapor pressure gradient between precipitation particles containing the mineral material and the surrounding matrix of 'clean' precipitation particles, but without actually melting any particles.

Observations suggest that this scenario is comparatively rare and can occur when a dust deposition event begins in very late afternoon, under low and declining solar fluxes (particularly on shady aspects). The process is enhanced by low precipitation intensity during the dust-fall phase of the precipitation event. Faceting can be very rapid within, below, and above the portion of the new snow layer containing the dust. The resulting weak layer may yield direct action avalanches, given sufficient additional new snow loading by the dust-delivering storm, or may remain as a persistent weak layer vulnerable to future natural or artificial triggering.

It should be noted that deposition of dust onto an early or mid-winter snowpack does not always play a role in subsequent dry slab avalanching. The processes described above are very often not observed following an early or mid-winter dust-on-snow event. Dry slab avalanches may include embedded dust layers that played no role in the avalanche release (Fig. 5).

Fig. 5: Dry, hard slab avalanche debris containing an intact dust layer. Photo courtesy of Chris George and Don Bachman.

3.2 Wet Snow

Late winter and spring (March, April, and May) produce the vast majority of dust-on-snow events in the Colorado mountains (Fig. 1). During those months, multiple dust-on-snow events are typically deposited as discrete layers within the upper snowpack, separated by clean snow (Fig. 6). Occasionally, dry dust events fall onto exposed dust layers, as dust-on-dust-on-snow.

As described in detail by Painter (2012), detailed measurements of snow albedo are made at sub-alpine and alpine study plots in the Senator Beck Basin Study Area. Broadband albedo values routinely fall below 0.50 (50% reflectance) and have dropped as low as 0.33 (33% reflectance), with heavy dust concentrations exposed at the snowpack surface. Most of these reductions in albedo by dust occur within the visible wavelengths, making the human eye an excellent sensor for observing these albedo effects.

Fig. 6: April 22, 2009 snowcover at sub-alpine study plot, Senator Beck Basin, Colorado. Five dust-on-snow layers are contained in the upper snowpack seen here, with the most recent layer at the surface. Old, refrozen wetting fronts are also seen as ice layers and lenses below the prominent dust layers. Active, dust-enhanced melt on this day was infiltrating the upper snowcover.

These large reductions in snow albedo, when dust is at or near the snow surface, result in very large increases in the absorption of solar (short wave) radiation, overwhelming other contributors to the snow surface energy budget. Further, as day lengths increase during the spring, and sun angles increase, total potential solar radiation inputs also increase.

Under these conditions, snowmelt rates accelerate and routinely result in 40-50 mm of snow water equivalence (SWE) loss per day in late spring at Senator Beck Basin and other locales in Colorado. Such high melt rates produce considerable flux of melt water into the snowcover, accelerating the warming of the snowpack to isothermal and then generating high rates of snowmelt discharge. As the snowpack ablates, dust layers sequentially meet and merge at the snow surface, where all but the finest particles remain and aggregate and further degrade albedo over the snowmelt cycle (Fig. 7).

Fig. 7: May 13, 2009 snowcover at sub-alpine study plot, Senator Beck Basin, Colorado. All layers seen in Figure 6 have merged; mid-day broadband albedo was 0.34.

Dust-enhanced wet snow avalanche behaviors have been observed under these low-albedo, extreme snowmelt energy budget conditions. Spring avalanche involvements resulting in injury and death have occurred in Colorado in which dust very likely played an (often unrecognized) role. The most commonly observed dust effects on wet snow are described below but hybrid scenarios also occur frequently, involving both the dry snow and wet snow effects of dust.

Frequent spring snowfalls in March, April and May often result in a dust-free, clean snow layer overlying either a single recent dust layer or multiple, merged dust layers at the prior snowpack surface. Solar radiation can penetrate 30 cm or more of clean new snow before being effectively extinguished. Considerable solar radiation can be transmitted through 10-15 cm of new snow.

Depending on the thickness and other properties of the new snow layer, the underlying snow surface containing dust can very quickly resume active melt under the first available solar inputs, even under what seems to be very weak sunlight. Often, a dusty snow surface has roughened, enabling the new snow to intermesh with the complex matrix of dirty snow structure. In other cases, the underlying dirty snow surface can be quite smooth.

In either case, active melt within the dirty snow can very quickly erode the bonding between the new snow layer and underlying dirty snow, thereby enabling extensive, widely propagating, wet-loose and ‘sheeting’ avalanching in the new snow (Fig. 8). These can attain considerable volume and speed and, as always, can also act as triggers for much more dangerous wet slab avalanches downslope. Given more slab-like new snow layer characteristics, the same process can also result in wet slab behavior in new snow overlying dirty snow (Fig. 9).

Fig. 8: Skier triggered wet-loose avalanches in new snow overlying a dirty snow surface, on a north-facing slope, Red Mountain Pass, CO.

Fig. 9: A small and shallow skier triggered wet slab avalanche in new snow overlying dirty snow, May 2014, Senator Beck Basin.

Over the course of the snowmelt season, as dust-enhanced snowpack ablation proceeds, dust layers merge, progressively reducing albedo, and surface snowmelt rates accelerate. Eventually, apparently depending on the duration of sustained high melt rates (uninterrupted by new snowfalls), the snowpack structure may simply be unable to tolerate the resulting fluxes of melt water.

Fig. 10: Large wet slab avalanche on north aspect coincident with full emergence of merged dust layers, near Silverton, CO, May 2014.

Large wet slab avalanching have been observed throughout the Colorado mountains during rapid and/or prolonged increases in the snow surface energy budget, as dust layers emerge and/or merge at the snowpack surface (Figs. 10-12), often apparently failing in wetted basal facets and depth hoar.

Fig. 11: Very large wet slab avalanche on north aspect coincident with full emergence of merged dust layers, near Silverton, CO, May 2014.

Fig. 12: Wet-loose triggered wet slab avalanche on northwest aspect, Red Mountain Pass, CO. Merged dust layers were emerging at the surface.

Finally, snow cornices containing dust-in-snow may also be vulnerable to loss of strength when the dust becomes exposed, even to indirect, reflected solar radiation. However, since beginning to carefully monitor dust-on-snow at Senator Beck Basin and elsewhere in Colorado, such cornice failures related to dust seem surprisingly rare (Figs. 13, 14).

Fig. 13: New snow containing dust routinely adheres to the leeward structure of cornices, during cornice building. Conceivably, reflected solar energy scattered from adjoining terrain could initiate rapid melt on the 'underside' of cornices like this. Photo courtesy Susan Hale.

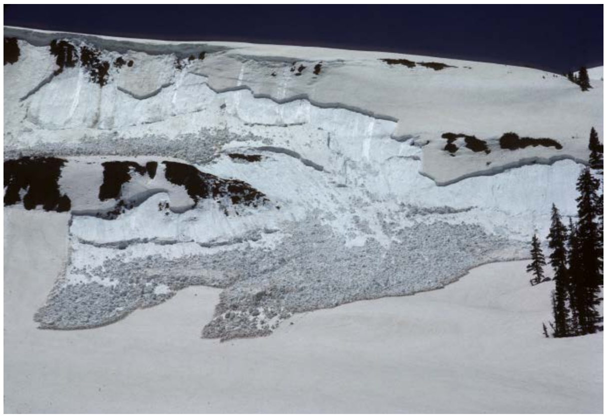

Fig 14: This wet slab avalanche appeared to have been triggered by a small cornice collapse; dust can be seen in the top surface of the remaining cornice and on the slope, directly exposed to solar radiation. Photo courtesy Chris George and Don Bachman.

4. DISCUSSION AND CONCLUSIONS

As a result of the increasing frequency and magnitude of desert dust-on-snow deposition in Colorado, the author and many others have unavoidably observed and encountered dust effects on avalanche processes. Fundamentally, dust increases the absorption of solar energy by the mountain snowcover, initiating and/or accelerating processes leading to instability. In early and mid-winter, dust can enhance kinetic metamorphism at or near the snowpack surface, creating persistent weak layers in the still-cold snowcover. Later in the season, when most dust events occur, dust-induced reductions in snow albedo can accelerate the warming of the snowpack to 0.0° C throughout, initiating the "wet" avalanche season. As dust layers are exposed, and merge at the snowpack surface, snowmelt rates increase rapidly. Wet slab avalanches may be triggered by unusually intense fluxes of melt water into the snowpack structure, eroding strength. New snow layers overlying dust layers often become rapidly unstable, as solar radiation penetrates through the new snow and generates melt at the base of the new layer, weakening bonding.

Monitoring the deposition of desert dust in the mountain snowcover can be a simple addition to routine observations in snow profiles, when done in time series at a well-sheltered study plot. Over time, increasing skill at detecting weak events is quickly attained. Forecasting the emergence of dust during spring snowmelt, across small or large tracts of terrain, is more challenging but certainly important.

This article has focused on dust-on-snow impacts on snow stability in the Colorado Rocky Mountains. Elsewhere, desert dust impacts on the cryosphere, as well as the impacts of other albedo-reducing aerosols, are gaining increased scrutiny. As is often the case, more intensive monitoring is 'finding' that dust may be more pervasive than is commonly understood within the avalanche community. The author, for one, may have often missed the impacts of desert dust earlier in his avalanche forecasting career in Colorado, when those effects were perhaps less frequent. Now, the effects of dust are a source of renewed fascination in the complex behaviors of the mountain snow system. It is hoped that this general overview and discussion stimulates new, more rigorous investigations and better understanding of the role of desert dust in snow avalanches.

ACKNOWLEDGEMENTS

The author would like to thank Hal Hartman, Jeffrey Deems, Michael Barton, and Andrew Temple for our many conversations in the field about dust-on-snow and its effects on snow stability. Thanks also to Chris George and Don Bachman for searching through their slide boxes and providing their photographs.

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