DUST ON SNOW, ICE COLUMN FORMATION, AND MELTWATER FLOW PATHS AT NIWOT RIDGE, COLORADO

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ABSTRACT

The presence of dust on the snow's surface has been shown to decrease albedo by as much as 40% compared to a clean snow cover. Thus dust on snow affects snow surface radiative fluxes, generally resulting in earlier snowmelt compared to "clean" snowpacks. Less understood is how dust on snow events may affect infiltrating meltwater movement in the snowpack. An aeolian dust event with a distinctive red color that was deposited in February of 2006 at Niwot Ridge in the Colorado Front Range provides opportunity to investigate how dust on snow may change the surface characteristics of snow and meltwater movement through the snowpack. Ice columns found in clean snow had a mean depth of 60 cm, which was significantly longer ($p=0.0001$) compared to the mean depth of 16.7 cm in red snow. The shape also varied, with ice columns in clean snow having a uniform width along the entire length, whereas those found in red snow were widest at the snow surface and decreased in width with depth. The movement of liquid water through the snowpack in "red" snow appears to be more uniform, decreasing the size of preferential flowpaths that give rise to ice columns when compared to "clean" snow. Thus the variation in ice column morphology between red and clean snow gives insight into how dust deposition events may affect the energy balance, subsequent melt, and meltwater flowpaths in snow covered areas. (KEYWORDS: meltwater, ice columns, dust on snow, flowpaths, surface roughness)

INTRODUCTION

Dust deposition in the western United States has increased since the 1800's as a result of westward expansion and land-use changes to grazing and agriculture (Neff et al., 2008). The presence of dust on the snow's surface has been shown to decrease albedo by as much as 40% compared to a clean snow cover (Painter et al., 2007). Thus dust on snow affects snow surface radiative fluxes resulting in earlier and faster rates of snowmelt compared to "clean" snowpacks.

It has been well established that dust on snow increases melt rates (Conway et al., 1996; Warren and Wiscombe, 1980; Painter et al., 2007). Less understood is how dust on snow events may affect infiltrating meltwater movement in the snowpack. Many studies have attempted to understand meltwater flow through snow (Wankiewicz, 1978; Colbeck, 1979; Colbeck, 1991; Marsh and Woo, 1984a, b, 1985; Kattelmann, 1985, 1989; McGurk and Marsh, 1995; Williams et al., 2010). However, success has been limited due to the ephemeral nature of snow and problems caused by destructive sampling techniques.

Studies of ice columns in late season snowpacks may provide some insight into meltwater flow through snow. Ice columns, described previously by Ahlmann and Tveten (1923), Ahlmann (1935), Seligman (1936), and Gerdel (1948) were recognized to be the residual flow network in cold snow by Sharp (1951). At the surface, zones of preferential flow may form depressions as snow grains coalesce and settle (Seligman, 1936; Gerdel, 1948). This is supported by a multi-lysimeter study by Kattelmann (1989) that found that a lysimeter located under a depression in the surface collected a greater volume of water than the other lysimeters. Williams et al.'s (2000) results suggest that there is a positive feedback system whereby the ice columns continue to grow in diameter as liquid water freezes on the outside of the existing ice columns. Thus, ice columns provide a schematic of the remnants of flowpaths at the initiation of melt, allowing the ability to use ice columns to learn something about meltwater flowpaths.

The overall objective of this study is to gain insight into the influence of dust deposition on meltwater flow through snow by observation of ice columns in a late season continental snowpack. An eolian dust event with a distinctive red color that was deposited adjacent to areas of clean snow in February of 2006 at Niwot Ridge in the Colorado Front Range provides the opportunity to investigate how meltwater flowpaths may vary between dust on snow versus clean snow.

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SITE DESCRIPTION

Research was conducted in 2006 on Niwot Ridge, located in the Colorado Front Range of the Rocky Mountains about 5km east of the Continental Divide (40^{o}03'N, 105^{o}35'W). This site is an UNESCO Biosphere Reserve and a Long-Term Ecological Research (LTER) network site. Ice columns measurements were taken at the Saddle area at an elevation of approximately 3,500 m. Slope angles range from 0-15^{o} with a median of about 4^{o}; azimuth ranges from 0 to 365^{o} with slopes predominately flat to east facing (Williams et al., 1999). A meteorological station, subnivean laboratory, snow lysimeter array, and index snowpit is located at the Saddle site.

The climate is continental consisting of long, cool winters and a short growing season of one to three months. Mean annual temperature is -3.7°C and annual precipitation is about 1000 mm (Williams et al., 1996). Approximately 80% of the annual precipitation falls as snow (Caine, 1996). Strong westerly winds in this area commonly redistribute snow (Erickson et al., 2005).

On the night of February 15-16, 2006, 6.4 cm of snow fell at Niwot Ridge, Colorado. The bottom half of the snowfall was red with dust, while the upper half was white, with a sharp distinction between the layers. This dust layer covered most of the state of Colorado from the San Juan Mountains to the Front Range (Rhoades et al., 2010). It is believed that strong southwest winds picked up loose dust from the Four Corners area, which had been experiencing a long drought, leaving the ground bare and susceptible to eolian transport. Due to the wind patterns associated with the dust event, dust was redistributed non-uniformly providing areas covered with red dust adjacent to control "clean" areas with no dust (Figure 1).

Figure 1. Photograph of research area illustrating the distinct patches of clean snow adjacent to red snow.

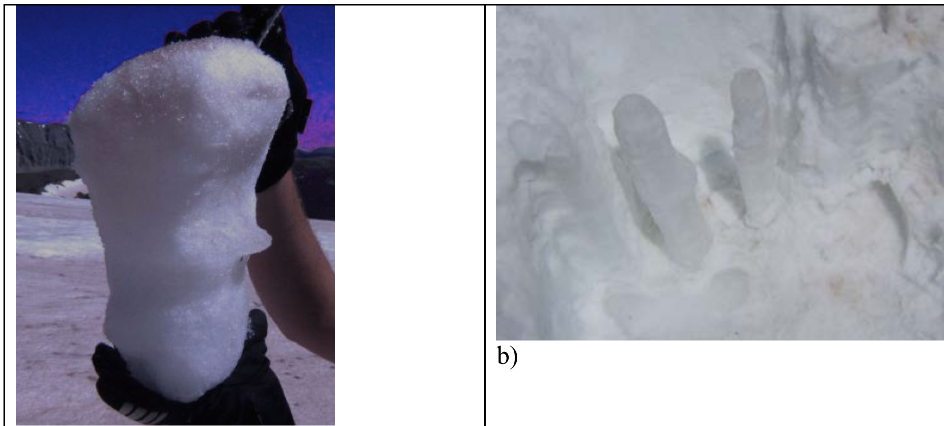
METHODS

Ice columns were identified following similar criteria as Williams et al. (2000): 1) Unusual hardness relative to the surrounding snow; 2) enlarged grain size; and 3) notable depression relative to surrounding snow. Five ice columns were randomly selected from "clean" and "red" snow areas.

The morphology of individual ice columns was investigated through excavation and measurement. Before excavation, columns were measured for surface diameter using a metric tape measure. Using shovels, lower density snow carefully was removed from the denser and harder ice columns to its lower terminus. Excess snow was removed by hand. Dimensions of height and upper, lower, and maximum diameter were made with a metric tape measure. Layer thickness was measured at the lower terminus of the ice column. Photographs of the freestanding column were taken to document location and relative size.

RESULTS

Analyses of ice column morphology showed large differences between "red" snow and "clean" snow (Figure 2). Ice columns found in clean snow had a mean depth of 60 cm, which was significantly longer ($p=0.0001$) compared to the mean depth of 16.7 cm in red snow (Table 1). The length of red ice columns ranged from 10-21 cm, whereas ice columns in clean snow had a larger range of 55-76 cm.



a) b)

Figure 2. (a) Ice column excavated from red snow, and (b) ice columns excavated from clean snow.

Table 1. Ice Column Height

Sample	**Total Height (cm)**
Red Snow #1	21
Red Snow #2	17
Red Snow #3	17
Red Snow #4	10
Red Snow #5	17
Mean	**16.4**
White Snow #1	76
White Snow #2	57
White Snow #3	55
White Snow #4	57
White Snow #5	60
White Snow #6	55
Mean	**60**

The shape also varied between red and clean snow, with ice columns in clean snow having a uniform width along the entire length, whereas those found in red snow were widest at the snow surface and decreased in width with depth by as much as 6 cm (Table 2). The mean upper diameter of ice columns in clean snow was 11.5 cm and in red snow was 13.6 cm. The mean lower diameter was similar between clean and red snow at widths of 11.5 and 11.7 cm, respectively.

Table 2. Ice Column Width

Sample	Measured Upper Diameter (cm)	Lower Diameter (cm)
Red Snow #1	17	11
Red Snow #2	8	10
Red Snow #3	14	10
Red Snow #4	14	12
Red Snow #5	15	12
Mean	**13.6**	**11**
White Snow #1	16	14
White Snow #2	14	13
White Snow #3	9	9
White Snow #4	10	9
White Snow #5	12	15
White Snow #6 (extra)	8	10
Mean	**11.5**	**11.7**

Ice columns in both snow types had a lower terminus that was an ice layer. Ice layers are features commonly observed in melting snowpacks and are often found connecting areas of vertical flow (Colbeck, 1991; McGurk and Marsh, 1995; Schneebeli, 1995; Williams et al., 2010). Ice layers/lenses are impermeable and thus transport meltwater laterally to other parts of the snowpack (Colbeck, 1973; Higuchi and Tanaka, 1982; Colbeck, 1991). In clean snow, ice layer thickness at the terminal end of the ice column was consistently 6 cm. In red snow, ice layer thickness ranged from 3-7 cm with a mean thickness of 4.6 cm (Table 3). Similarly, in a study on Niwot Ridge in 1996 and 1997, Williams et al. (2000) found ice lens 6 cm in thickness beneath ice columns. The differences observed between the ice layer thickness in red versus clean snow may be related to the same processes that are responsible for differences observed in column morphology.

Table 3. Ice Layer Thickness

Sample	Lower Ice Layer Thickness (cm)
Red Snow #1	3
Red Snow #2	3
Red Snow #3	5
Red Snow #4	5
Red Snow #5	7
Mean	**4.6**
White Snow #1	6
White Snow #2	6
White Snow #3	6
White Snow #4	6
White Snow #5	6
Mean	**6**

DISCUSSION

Analysis of ice column morphology showed significant variations between those found in clean snow areas versus those in dust-covered areas. The length of ice columns found in clean snow fit within the range of ice columns previously studied in the Colorado Front Range (Williams et al., 2000). These lengths are consistent with those found in a cold snow cover in the Canadian arctic by Woo et al. (1982). In contrast, the red snow ice columns were much shorter with a mean length of only 16.4 cm.

The widths of both clean and red snow ice columns were similar, ranging from 8 to 17 cm. Much smaller widths of 1.5 to 3.6 cm have been observed in the Sierra Nevada (Marsh and Woo, 1984a; McGurk and Marsh, 1995). However, Kattelmann (1985) found flowpath openings ranging 3 cm to 18 cm, and McGurk and Kattelmann (1988) found openings of 5-15 cm also in a Sierra Nevada snowpack. Thus, the widths observed in red and clean snow in this study fit within those found by previous studies. The small flow fingers are likely due to a smaller amount of liquid water content at the surface (McGurk and Marsh, 1988). The consistency and size of column widths observed in our study may be related to the timing of observation and associated temperature regime of the snowpack. In the Sierra Nevada's the snowpack remains near isothermal most of the winter (Kattelmann, 1985), unlike the continental snowpack on Niwot Ridge, which may become briefly isothermal at various times throughout the winter, but does not become isothermal until April or May.

Furthermore, there is inconsistency in the shape of ice columns between red and clean snow in our study, as well as between previous studies of ice columns. In clean snow, ice columns are consistent in shape top to bottom, whereas ice columns in red snow are fatter at the top than the bottom. Williams et al. (2000) found ice columns in clean snow to have an upper diameter of 10-25cm increasing in width towards the bottom to a maximum width of 30cm. Ice columns grow in diameter as liquid water freezes on the outside of the existing column (Williams et al., 2000). While not very well understood, it seems some process was occurring whereby more liquid water was freezing at the base of the ice column perhaps due to a deeper, colder snowpack or recent cold weather that prevented liquid water formation at the surface. Kattelmann (1985) found that once open channels became larger than 3 cm, the shape evolved from circular to more oval with the width exceeding the height. He explains this to be a reflection of the layered nature of snow. The theories previously discussed do not appear to explain the difference in ice column morphology found in this study because both the red and clean areas were exposed to similar meteorological conditions and likely had similar snowpack structure, atleast initially.

We suggest the differences in ice column morphology observed in our study are due to differences snow surface roughness between the "red" and "clean" snow areas. Dust on snow has been shown to affect snow surface roughness characteristics (Rhodes et al., 1987; Betterton, 2000; Fassnacht et al., 2009). These variations in surface roughness are important in understanding surface-atmosphere interactions, in particular the response of radiation at the snow surface, which subsequently affects melt rates (Rhodes et al., 1987).

In clean snow during melt season the formation of ablation hollows or "suncups" often occur. These features form due to differential ablation resulting in a pattern of hollows bounded by ridges. Various studies have described ablation in these hollows (Matthes, 1934; Richardson and Harper, 1957; Takahashi et al., 1973).

In clean, old snow, approximately 50% of sunlight is reflected (Warren and Wiscombe, 1980). In concavities (hollows), the chance a photon will escape decreases. Additionally, as concavity increases, scattering within the hollow increases. Thus, hollows trap radiation more efficiently than peaks causing differential melting across the snow surface (Tiedje et al., 2006) and a rougher surface is observed.

The role of dust on snow surface roughness characteristics depends on the thickness of the dust layer (Betterton, 2000). As explained by the normal trajectory theory of Ball (1954), small particles of dirt adhere to the snow surface and subsequently move perpendicular to the snow surface, rather than falling straight down as the snow ablates. This is due to the adhesive forces between the snow and the particles and only applies to smaller particles where the adhesive forces are greater than gravitational forces (Jahn and Klapa, 1968). On snow containing thin layers of dust, particles migrate to the ridges, resulting in accelerated ablation on ridges versus hollows. This process degrades the ablation hollows resulting in a smoother snow surface. However, a sufficiently thick layer of dust can accelerate formation of ablation hollows by creating an insulating effect at the ridges (Wilson, 1953). Driedger (1981) found the threshold thickness of a dust layer to be approximately 3 mm. A layer of dust thinner than 3 mm promotes ablation while a layer thicker than 3 mm creates insulation.

Thus, the presence of dust on the snow surface appears to change the spatial distribution of the energy balance at the mm to cm scale. In red snow the dust particles may migrate to the ridges. The thickness of the dust layer in this study is not thick enough to insulate the ridges as explained by Wilson (1953) and Drieger (1981). Instead, the presence of dust decomposes ablation hollows. The lower albedo associated with red dust at the ridges increases melt and thus liquid water content resulting in larger snow grains as water causes snow grains to coalesce.

Larger snow grains decrease scattering and increase absorption of radiation (Warren and Wiscombe, 1980). As ridges degrade, a smoother surface forms leading to a more uniform distribution of solar radiation and melt.

In contrast, ablation hollows ("suncups") characteristic of a melting clean snowpack results in differential melting, as described by Rhodes et al. (1987), Betterton (2000), and Teidje et al. (2006). This means that the hollows melt faster than the peaks leading to greater surface roughness when compared to "red" snow. High-resolution digital imagery (spatial resolution of 0.043 mm) of the "red" and "clean" snow surfaces from Niwot Ridge in June of 2006 showed that the surface roughness of "clean" snow was about 4 times that of "red" snow, and that the range in surface roughness of "clean" snow was about 16 times that of "red" (Fassnacht et al., 2009). Thus, dust on snow events appear to have caused the snow surface during snowmelt to be smoother and more even when compared to adjacent "clean" snow surfaces.

The movement of liquid water through the snowpack in "red" snow seems to be more uniform, decreasing the size of preferential flowpaths that give rise to ice columns, as indicated by ice columns which were shorter (16.7 vs. 60 cm), fatter at the top, and more evenly spaced than those found in clean snow areas. Williams et al. (2000) found that ice columns remained warmer and had a higher heat flux that the surrounding snow due to the release of latent heat associated with greater amounts of liquid water content. Since more melt is occurring in red snow areas, greater amounts of latent heat may act to prevent further ice column develop or even degrade existing ice columns.

This process may be amplified by the preferential collection of dust in depressions noticed at the snow surface. Flow fingers represented by ice columns are associated with depressions at the snow surface due to the collapse of grain clusters, as reported by Seligman (1936) and Gerdel (1948). In areas receiving dust deposition, these depressions become preferential collectors of dust particles from the air and potentially meltwater. As melt advances, liquid water flows towards areas of preferential flow, as described by Williams et al. (2000). This liquid water may entrain dust particles as observed by Higuchi and Tanaka (1982). The dust particles may act to insulate the underlying ice column much like a thick dust layer insulates ridges of ablation hollows accelerating their formation. This would prevent interaction with potentially colder air temperatures resulting in higher melt rates. Therefore, meltwater in red snow areas appears to be routed more quickly through the snowpack than clean snow areas.

Additionally, as snowpacks ripen, meltwater flow becomes more uniform. Snow undergoes rapid changes in the presence of liquid water causing layers to degrade (Colbeck, 1979). Thus, the various layers in the dust covered area likely decomposed more quickly, especially towards the bottom of the snowpack leading to more dispersed percolation and the disappearance of distinct flowpaths as indicated by shorter ice columns in red snow.

Few studies have investigated how surface characteristics may influence meltwater flowpaths (e.g. Higuchi and Tanaka (1982)). Higuchi and Tanaka (1982) found that dendritic patterns at the snow surface resulted in a pattern of internal flowpaths that corresponded to higher flow rates than the surrounding snow. Our study also suggests that snow surface roughness characteristics are important to explaining meltwater flow through snow and should be incorporated in future snowmelt runoff models.

CONCLUSIONS AND IMPLICATIONS

Dust on snow events significantly effects the energy balance at the mm to cm scale. This study suggests that meltwater flow in dust covered areas is more uniform as a result of a smoother snow surface than that observed in clean snow areas. Thus, the variation in ice column morphology between red and clean snow gives insight into how dust deposition events may affect the energy balance, subsequent melt and meltwater flowpaths in snow covered areas.

Deserving further study is the effects meltwater flow in dust covered areas may have on ecological systems. Plant and microbial health is dependent on meltwater delivery and nutrients associated with it. Meltwater flow in dust covered areas is quicker, more evenly distributed, and may be associated with high concentration of dust particles observed at the surface depressions of ice columns.

Meltwater flow through snow has important implications for water resources, ecology, and avalanche forecasting. As dust on snow events are likely to continue to occur, a better understanding of how they will affect meltwater flow is necessary. The results from this study illustrate that incorporating the influence of snow surface roughness characteristics in snowmelt hydrological models may improve accuracy of model predictions.

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