Tracking Changes in Buried Melt Freeze Crusts

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ABSTRACT: Melt freeze crusts are a frequent occurrence in the mid-latitudes, often forming in the snowcover due to rain or wet snow in the fall and insolation in the spring. Such crusts are frequently found at the bed surface of deep slab avalanches. Although faceting and weakening at the boundaries and in the interior of crusts under low temperature gradients has been documented, few long term systematic observations exist. This omission is potentially important, as an understanding of these processes may improve forecasting the strength of deep crusts. For the past two winter seasons, the University of Calgary Applied Snow and Avalanche Research group (ASARC) has monitored naturally occurring crusts in the Columbia Mountains of Western Canada. Properties such as grain form and size, density, temperature and hardness were observed on a weekly basis. Starting in the 2008-09 field season, the specific surface area (SSA) of three crusts was measured weekly using near infrared digital photography, resulting in 23 observations over two months including the transition to near-isothermal snow, where substantial structural changes were observed. This paper details these and other results.

KEYWORDS: specific surface area, crust evolution, near-infrared photography, snowpack stratigraphy

1 INTRODUCTION

The importance of the layered character of the seasonal snowpack with respect to the formation of weak layers and triggering of avalanches has long been understood (e.g. Colbeck, 1991). Furthermore, the persistent nature of some of these layers renders many traditional methods of testing, such as stability tests and shear-based indices, time-consuming and perhaps impractical once layers are deeply buried.

The advent of models such as SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002a,b) promises to mitigate some of these challenges; however many processes at the microstructural level are not well-understood and consequently not always well-modeled. One such process is the equi-temperature metamorphism of buried melt-freeze crusts (Smith et al., 2008). Although several studies have examined the the formation of weak layers at crust or buried wet layer boundaries under relatively high temperature gradients (e.g. Greene, 2007; Jamieson and Fierz, 2004), a number of experienced practitioners have reported the development of facets and laminations in buried crusts even when the depth-averaged temperature gradient would imply such such weakening should not take place (John Hetherington, *pers. comm. 2009*). Colbeck and Jamieson (2001) presented theoretical explanations for such behaviour that were verified by Jamieson and Fierz (2004) for wetted snow overlain by dry snow.

Monitoring changes in microstructure over time presents significant difficulties: Spatial variability reduces the size of the ideal study area and by extension reduces the practicality of destructive snowpack tests. Additionally, many manual observations are subjective and require the definition of discrete layers potentially masking information about variability or localized abrupt changes in temperature or vertical temperature gradient. Lab-based experiments are limited to a relatively small sample which may reduce the number of tests that can be performed if the crust is being tracked over a long period of time.

Optical properties of snow change significantly past the upper end of the visible spectrum at 700 nm. In this region the reflectivity is a function of both grain size and shape making it impractical for use in characterizing microstructure on the small scale. The specific surface area (SSA), defined here as the area per unit volume (e.g. Matzl and Schneebeli, 2006, hereafter MS06) is a stronger function of grain shape only and is of interest in a number of disciplines including remote sensing (e.g. Toure et al., 2008; Nolin and Dozier, 2000) and atmospheric chemistry (e.g. Legagneux et al., 2002). Generally the SSA decreases over time as new snow transitions from dendritic to rounded forms (Legagneux et al., 2003), though Dominé et al. (2008) record three instances where it increased. Dominé et al. (2007) proposed parameterizations for a number of grain types based on snow density.

A number of techniques have been used to measure the SSA of natural snow: The use of CH_4 absorption (Legagneux et al., 2002), although accurate, requires supplies of methane and liquid nitrogen. Gallet et al. (2009) used laser diodes and an integrating sphere to measure reflectance at 1310 nm and 1550 nm, while MS06 modified a digital camera to record reflected light in a broad spectrum from 830 nm to 940 nm. This last technique is relatively simple and inexpensive to employ in the field.

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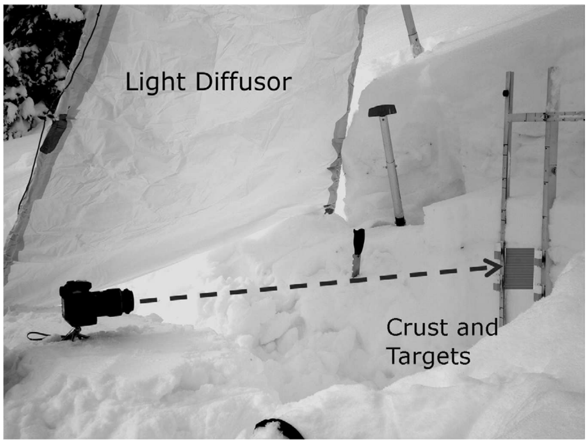

Figure 1: *Equipment and configuration used for near infrared photography.*

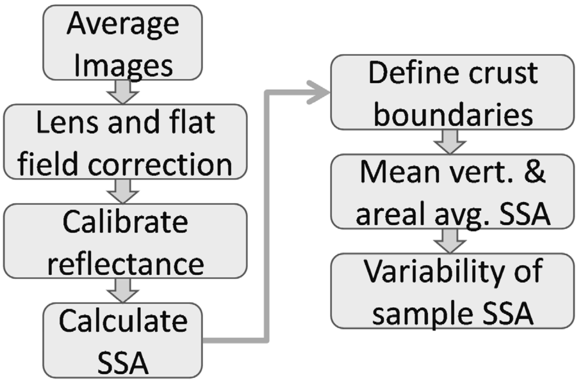

Figure 2: *Post-processing of near infrared crust images.*

This paper presents initial results from the use of near infrared digital photography to track changes in the SSA of buried melt-freeze crusts. Starting in February 2009, three crusts were photographed weekly in freshly exposed pit walls. The near-IR data were supplemented with traditional manual observations such as test profiles, compression tests (CAA, 2007), propagation saw tests and both manual and continuous measurement of the bulk vertical temperature gradient. These observations were undertaken until early April 2009, when the snowpack became isothermal.

2 METHODS

The study area was approximately 5 m by 10 m on a uniform Southeast facing slope at 1960 m in the North Columbia Mountains of British Columbia, Canada. Three melt-freeze crusts, formed due to solar insolation and named according to their date of burial as CR090127,CR090222 and CR090301, were tracked throughout the winter of 2008-09 and all were assumed to have an initially uniform structure across the study slope. CR090127 remained exposed for several days and was subject to diurnal fluctuations in temperature and vertical temperature gradient, while crusts CR090222 and CR090301 were buried quickly after formation. Thermocouples were placed above, below and within each crust to track the temperature and vertical temperature gradient.

On each visit the observation wall was cut back by a minimum of 1 m, and a standard test profile was followed by shear frame tests, push tests and near-infrared digital photography. Push tests (e.g. Seligman, 1936) were conducted using a push-pull gauge with a flat disc of known area attached to a 10 cm rod. The disc was pushed into the crust layer with a quick smooth motion, and the maximum force was recorded on the gauge. A minimum of 10 tests was conducted on each site visit for each crust.

The use of near infrared digital photography for determining the specific surface area (SSA) of snow is described more completely by MS06 but a brief overview of the method is presented here. Each crust was exposed and the pit wall was smoothed to remove scoring and pitting. The pit wall was shaded to minimize variations in illumination as well as direct solar radiation. Four targets made of a material of known reflectance (Spectralon, r=50$\%$ and 99$\%$) were placed on either side of the crust sample. Three photographs were taken with the targets and again with a flat field target in front of the crust. Figure 1 shows the exposed pit wall with Spectralon targets placed around the crust.

Processing of the images was done using the IDL language. Each set of images was averaged and corrections applied for vignetting caused by the lens. All photographs were stored in JPG format. After evaluation of exposure and contrast in each channel, the green channel was chosen for all subsequent processing. The averaged intensity was transformed into near infrared reflectance (NIR) by deriving a linear best-fit equation from measured intensity at the 50% and 99% Spectralon targets. The SSA was then calculated using the equation derived in MS06:

$$SSA = Ae^{r/t} \tag{1}$$

Where r is the reflectance, A = 0.017mm^{-1} and t=12.222. A flow chart illustrating the process is shown in Figure 2. The boundaries of the crust were manually defined in each processed image and the average vertical profile of SSA as well as the sample variability in the horizontal and vertical directions were calculated.

3 RESULTS AND DISCUSSION

Although vertical gradients meeting or exceeding the typical Temperature Gradient (TG) metamorphism threshold of 1°C/10cm occurred several times over the observation period for each crust, the direction of

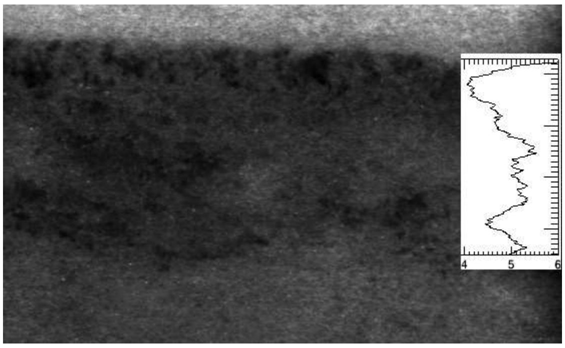

Figure 3: *CR090127 SSA image and vertical profile of cross-image averages from 10 February.*

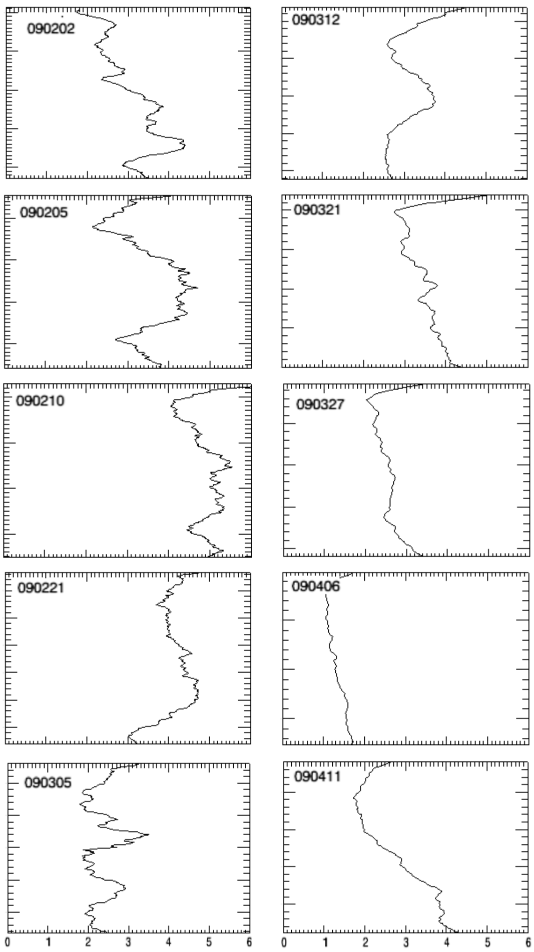

Figure 4: *Evolution of the horizontally averaged vertical SSA for crust CR090127. Order of evolution is top to bottom, left column then right at 1 week intervals.*

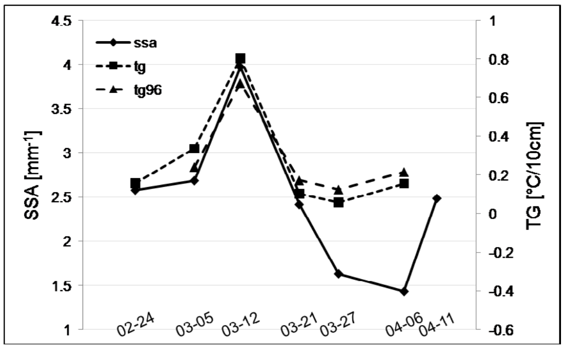

Figure 5: *Time series of SSA, TG and TG96 for CR090222.*

the gradient typically oscillated with a diurnal period. No significant development over time of facets was observed through a 8x loupe. Kaempfer et al. (2009) reported that snow samples subjected to large sinusoidal gradients formed fewer facets than if the gradient was maintained in one direction, which might explain these observations.

The ranges of SSA measured in this study may be compared with those from similar studies to ensure that they are at least reasonable. Using stereological methods, MS06 measured 6 snow samples classified as either 'crust' or 'frozen wet grains' and obtained values between 5 mm^{-1} and 20 mm^{-1} . Dominé et al. (2007) also observed crusts although the sample size was small and the classifications included ICSSG types 6mf, 9mfc and 8il (broadly equivalent to classes MF and IF in Fierz et al. (2009)). Based on their samples Dominé et al. (2007) recommended an average value of 0.86 mm^{-1} for these types. By calculating means of vertical profiles to get an areal average we obtained values ranging from 1.3 mm^{-1} to 4.9 mm^{-1}, with the lowest values recorded once the snowpack became isothermal.

Figure 3 shows an example of the areal average SSA superimposed over an image of the CR090127 while Figure 4 shows its progression throughout the season. An area of decomposed surface hoar appears as an area of low SSA at the top of the profile on 2 February but disappears in subsequent observations. This crust initially had two distinct layers, with larger well-bonded grains overlying smaller grains with larger SSA. These layers became less evident as the crust aged. The profile from 6 April corresponds to observations of weakened bonding, moist snow and predominant grain types facets and rounded polycrystals. The SSA is at its lowest and least variable. By 11 April, observers noted some remaining bonds in the upper crust along with patches of wet snow. The lower part of the crust had almost no bonds and was composed once again of facets and rounded polycrystals. The doubling of the SSA in the lower portion of the crust may be interpreted as increased faceting since the previous week, or also

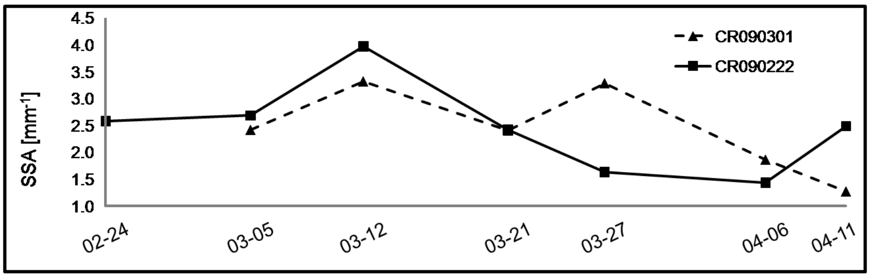

Figure 6: *Time series of SSA for CR090222 and CR090301*

Table 1: *Correlations of SSA, NIR with other crust properties. TG* denotes the omission of CR090301.*

Variable	Correlation	p	n
SSA-TG	0.69	0.001	19
SSA-TG*	0.79	0.0005	15
SSA-TG96	0.61	0.05	19
SSA-ρ	-0.46	0.04	19
SSA-Push force	0.40	0.07	21
NIR-Gsz	-0.37	0.08	23

as the influence of increased free water within the crust. Free water is almost certainly a factor and although the absortivities of snow (e.g. Dozier and Painter, 2004) and water show similar trends in the near-IR, the empirical equation of MS06 was developed using dry snow, therefore this last profile, and possibly that of 6 April, should be viewed with some skepticism. Figure 6 shows the evolution of the areal mean SSA for the other two crusts. Of note is the divergence in trends at the end of the time series; Although both crusts had been undergoing similar diurnal variations in temperature and temperature gradient and had not fallen below 0°C for several days, the SSA of CR090222 rose on 11 April while the SSA of CR090301 fell. Manual observations showed that CR090222 was composed of clusters of larger edged grains while CR090301 had clusters of much smaller rounded grains. The reason for this apparent rapid faceting in only one crust given similar conditions is not immediately obvious but should be investigated further.

Figure 5 shows a time series of SSA, TG and TG96 for CR090222. The correlation in trends between the magnitude of the temperature gradient and SSA is immediately apparent, though correlations with the other two crusts were not as strong. Correlations between the sample mean SSA, NIR and a number of other crust properties are shown in Table 1. TG* omits the measurements taken from CR090301 while TG96 is the average absolute value of the bulk vertical temperature gradient during the 96 hours preceding each observation. The relationship between SSA and the push force is weak but may suggest some correlation between measurable the grain shape and the structural strength of a crust.

The negative correlation between SSA and density was also observed by Dominé et al. (2007) for a range of crystal types, though their sample size of melt-freeze forms was too small to derive a parameterization. The weak negative correlation between NIR and grain size is expected due to the additional dependence of reflectivity on grain shape and also due to the difficulty of defining a mean grain size in a well bonded melt-freeze crust. Finally, the relatively strong and significant correlations with with temperature gradient offer promise for parameterizing the evolution of crust microstructure once the data set is expanded.

4 CONCLUSIONS AND FUTURE WORK

Three natural melt-freeze crusts have been observed from formation until the snowpack became isothermal. The specific surface area was recorded using near infrared photography and time series of sample averages and variability were determined. Based on values published in similar studies these results are reasonable. Promising correlations between SSA and vertical temperature gradient should be further studied once the data set is expanded in coming seasons.

The interpretation of these results relies on an assumption of spatial invariability. Although the periods of crust formation were marked by low wind speed and uniform insolation across the study slope there is likely an element of spatial variability that influences the results. The destructive nature of these observations and the necessity of choosing a uniform sample slope eliminates a number of spatial sampling techniques that would otherwise be useful in mitigating the effects this variability. Further experimentation under more controlled conditions in a cold lab will complement the observations of natural crusts.

Regular measurements of permeability and bulk thermal conductivity are also more easily conducted in the lab. These values may also be compared with those found in related studies by Kaempfer et al. (2005) and others, or to those assumed by models such as SNOWPACK.

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