Limitations of using an infrared camera to measure snow pit-wall temperatures

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ABSTRACT: Driven by temperature gradients, kinetic snow metamorphism is important for avalanche formation. Recent studies that visualized small scale (< 10 cm) thermal structures in a profile of snow layers with an infrared (IR) camera. The studies found melt-freeze crusts to be warmer or cooler than the surrounding snow depending on the large scale gradient direction. However, an important assumption within the studies was that a thermal photo of a freshly exposed snow pit was similar enough to the internal temperature of the snow. In this study, we tested this assumption by recording thermal videos during the exposure of the snow pit wall. In the first minute, the results showed increasing gradients with time, both at melt-freeze crusts and at artificial surface structures such as shovel scours. Cutting through a crust with a cutting blade or a shovel produced small concavities even when the objective was to cut a planar surface. Results of cold lab experiments suggest there is a surface structure dependency of the thermal image, which is only observed at times with large temperature differences between air and snow. The immediate adjustment of snow pit temperature as it reacts with the atmosphere complicates the capture of the internal thermal structure of a snowpack even with thermal videos. Instead, the shown structural dependency of the IR signal may be used to detect structural changes of snow caused by kinetic metamorphism. The IR signal can also be used to measure near surface temperatures in a homogenous new snow layer.

KEYWORDS: Measurement techniques, snow metamorphism, artifacts.

1 INTRODUCTION

Faceting as part of the kinetic snow metamorphism is strongly related to avalanche formation. Faceted crystals close to melt-freeze crusts were observed even in the absence of gradients needed for kinetic metamorphism when measured with thermometers 10 cm apart (Jamieson, 2006; Smith et al. 2008). One explanation for the development of facets during the absence of gradients may be found in the coarse measuring resolution. Thus, recent studies were promising (Shea and Jamieson, 2011; Shea et al., 2012; Shea et al., 2012a) where a thermal camera was used to image the wall in snow pits, which delivers a resolution of less than 2 mm. Shea et al. (2012) found melt-freeze crusts to be warmer than the surrounding snow. In an hourly measurement setup they presented a warm crust during cooling of the atmosphere. The authors proposed that the warm crust resulted from increased snow internal temperature gradients and water vapor fluxes. They assumed a relatively smaller ice conduction at the crust which resulted in remnants of undissipated latent heat at the crust. This would indicate that the latent heat transfer is larger than what the conductive ice lattice can handle and thus, warm the grains. In Shea et al. (2012b) they found also relatively cold crusts and related this observation to a reverse large scale snow internal gradient (warmer on top). They assumed that at those times, the crust may have good conduction through the ice matrix (better than adjacent layers), which would cool the grains relative to adjacent layers. However, the ice matrix was shown to be very conductive, likely to be conductive enough to transport additional latent heat immediately away (Pinzer et al., 2012). The assumption that conductivity characteristics of a crust relative to adjacent layers will reverse with time, dependent on the direction of a large scale snow internal gradient, seems to be improbable.

Other explanations for the hot-crust/cold-crust phenomenon can be found in the delicate interpretation of the thermal signal and the immediate interaction between the exposed pit wall with the surrounding air. Even when the aim was to produce a planar surface, vertically cutting through a snow pit with a cutting blade or a shovel produced heterogeneities, especially at crusts. Given the rough porous surface of a snow pit and a pixel size of 1 mm of a thermal image, a wide range of viewing angles may be possible. Angular dependencies were found to be important in literature. Snow may not be a perfect diffuse emitter, which may result in more radiation measured by the camera for the nadir angle compared to off-nadir angles. Dozier and Warren (1982) theoretically achieved angle dependencies for emissivity values of snow. With field measurements Hori et al. (2006) found var-
yng emissivity values for different snow types. Shea et al. (2012) discussed an additional error source. During the assimilation of the exposed snow pit to air temperature, heat may be conducted unevenly from behind, depending on different heat conductivity properties in certain layers. Furthermore, they did not find a relevant sharpening of temperature differences (gradients) between pixels with exposure time.

Our goal with this study was to show systematically, if a thermal camera could be applied to measure snow pit-wall temperatures. We wanted to assess whether the issues described above substantially affected the results. Since most of the issues cannot be applied directly in a quantitative manner, especially given the small spatial resolution of approximately 1 mm per pixel, we chose to perform additional field experiments. In Shea et al. (2012, 2012a) thermal pictures were taken within 90 s of pit wall exposure. We performed thermal videos while digging and exposing the pit wall, in an attempt to reflect the true internal temperature profile and to gain further insight into how the thermal signal changes after exposure. We made observations in the field, and took systematic measurements in a temperature-controlled laboratory.

2 METHODS

Thermal cameras were used both for snow pits in the field and for snow specimen in the cold lab.

2.1 Thermal cameras

The FLIR B300 and FLIR P660 were used in this study. These cameras are identical to those used in Shea et al. (2012) and Shea et al. (2012a), respectively. These cameras measure in a spectral range of 7.5 μm to 13 μm. The main differences are the spatial resolution (320 x 240 compared to 640 x 480 pixels) and the measurement frequency (1 Hz compared to up to 30 Hz). The P660 is able to store thermal videos whereas the B300 requires an external laptop. Different frame rates were chosen (1 Hz, 10 Hz) to address the anticipated fast temperature assimilation and to possible short time fluctuations due to wind gusts. To be consistent with earlier work, the emissivity was chosen to be 0.98 for the whole picture.

2.2 Snow pits

Thermal videos were made while digging snow pits. Regular digital videos in the visual spectrum were overlayed with the thermal videos. These videos were helpful to detect crusts, surface structures like shovel scours, as well as to see if dirt or debris was placed at the pit wall due to cutting. The cameras were placed 1 m away from an already dug snow pit. While recording, the snow pit was dug back another 20 cm. The emphasis was to be fast as possible while creating a smooth snow pit surface with a shovel, a cutting blade or a rear side of a snow saw.

2.2 Cold lab

In separate experiments, natural snow columns including a natural crust, laterally isolated boxes with sieved snow and artificial crusts, and artificial snow surfaces of sieved snow were used. All specimens were prepared with artificial concavities and convexities (Figure 1a and b). The scale of the artificial roughness varied from the 1 cm to 10 cm. The snow columns were placed outside until isothermal conditions were achieved when the air temperature was approximately -3 °C. To simulate the sudden exposure of a snow pit, the specimens were placed in the cold lab at approximately -16 °C. Thermal videos of the snow columns during the first 10 min were recorded. Similarly, after isothermal conditions in the cold lab, the columns were placed outside or in a cooled room of approximately +3 °C. To achieve a larger control of the conditions, the cold lab temperature was adjusted. Furthermore, the effect of air flow was tested with fans.

3 RESULTS

In the next two paragraphs the results achieved in the snow pits and in the cold lab are presented separately.

3.1 Snow pits

Cutting through the natural crust produced small concavities even when the aim was to make a smooth surface. This can be explained with the strong bonding between grains forming aggregates, which broke out in total during the cutting process. Figure 2 shows the first frame after pit wall exposure. This first frame was delayed by a few seconds while the operator smoothed the wall and removed debris which lay on the ground and obstructed the pit wall. A melt-freeze-crust in the lower part of the image appeared to be relatively warmer than adjacent snow layers. Also visible are shovel scours. In Figure 4, a mean vertical temperature profile is plotted for different time steps after pit wall exposure. In the first frame (0 s), the crust is approximately 0.4 °C warmer than the layers above. The cooling process after exposure was caused by the large difference between snow and air temperature (-17 °C). After 1 and 4 min, the pit wall cooled approximately 1 and 2 °C,
respectively. The cooling was less pronounced at the crust, which caused the gradient to increase to 0.9 °C between the crust and the layers above after 4 min. Similar effects were observed at the shovel scours.

Figure 1. a) Snow column with artificial concavities and a natural crust, b) with artificial convexities and concavities.

Shovel scours and sharp edges at the side of a pit wall were not visible in the thermal signal during situations with nearly equal temperatures of snow and air. These findings point to structure dependencies only relevant during temperature assimilation of the pit wall, which was more systematically studied in the cold lab.

Figure 2. Thermal image of a snow pit including a natural crust. Colorbar in °C.

3.2 Cold lab

Specimens were stored outside overnight during calm wind and overcast conditions (-3 °C) after which the specimens were assumed roughly in equilibrium with the surrounding atmosphere. In this condition, both the artificial roughness and the roughness of the crust were hardly visible in the thermal signal (not shown). Differences between convex and concave areas were smaller than 0.2 °C. This roughness became visible when relatively warm specimens were placed in the cold lab (air temperature -16 °C). Concave areas appeared relatively warm, oppositely to convex areas as can be seen in Figure 4.

Figure 3. Mean vertical temperature profile depending on the time after pit wall exposure. The black line represents the situation in Figure 2.

Figure 4. Thermal image of the specimen shown in Figure 1b) after approximately 4 min in the cold lab. Artificial concavities are relatively warm, convexities relatively cold. Colorbar in °C.

The time development of the two marked concave and convex area is shown in Figure 5. Convex areas cooled faster compared to concave areas, which is consistent with the snow pit observation in the field. After 30 s, the differences between convex and concave were larger than one degree. This resulted in an increase of gradients between these areas or between pixels.
4 DISCUSSION

The experiments in the cold lab showed differences in the temperatures of a crust or artificial roughness. They cannot be related to the internal process of the snow, since no snow internal gradient was applied. Thus, it can be concluded that the thermal image is highly influenced by an energy balance process between snow and air. The larger exposure of convex areas compared to flat surfaces and concave areas resulted in a faster assimilation of the snow temperatures to air temperatures. This is probably due to either a larger radiative transfer or a larger convective transfer by air at convex areas. The explanation of a convective structure dependent heat exchange is furthermore supported by the observation that leeward areas were cooling slower compared to windward areas when a directional wind flow was present in the cold lab.

The act of exposing a melt-freeze crust always resulted in a concavity even when using different cutting instruments with great care. Crusts showed the same surface energy exchange process as artificial concavities. However, this does not prove that internal snowpack processes are not causing similar thermal signals. The initial warm crust shown in Figure 3 and 4 may suggest such a process. We tried using cutting blades to achieve a first video frame to be closer to the initial exposure of the crust, and a relatively warm crust was always found. However, the immediate reaction observed in the cold lab suggests that this could be already a result of a surface energy exchange rather than an internal process within the snow.

Observations of Shea et al. (2012) were typically performed 90 s after pit wall exposure. In the cold lab, we observed snow temperature gradients to change substantially within this first 90 s. This can only be related to a surface energy exchange and not to snow internal processes.

Thus, the authors propose that the warm or cold crusts found in previous studies resulted mostly because of differences in roughness created by cutting through the snow pit. Snow internal processes explaining a hot crust may still be possible, but either to a small or an unknown ratio. This makes the thermal signal of a crust difficult to interpret.

In the Introduction, other explanations were mentioned for a warm crust, i.e. emissivity differences between crusts and adjacent layers or angle differences. However, during equilibrium of snow and air, only small temperature differences could be observed. This shows that these effects are relatively small in comparison to the surface energy exchange process.
During pit wall observations, we occasionally found gradients smoothed over time. More regularly, an increase of gradients as shown in Figure 4 was observed. Differences in wind intensity could have an effect on decreasing or increasing gradients, which were observed both at crusts and shovel scours. Under regulated conditions in the cold lab, no exceptions of increasing gradients due to a surface energy process were observed.

Using visual videos, some of the areas where gradients decreased could be identified as snow particles dragged with the shovel or cutting blade to another part of the snow pit (ex-situ) during the cutting process. At the beginning, large differences of this ex-situ particle resulted in large differences to surrounding pixels and thus, in large gradients. With time, these differences diminish during the general temperature assimilation with the surrounding air.

Another explanation can be found in the relatively long time before the first photo was taken by Shea et al. (2012). The largest increases in gradients were found in our study to be in the first 30 to 60 s, both in the cold lab and in the pit walls. No significant differences between single pictures may be observed after 60 s.

Shea et al. (2012) found crystal growth to be consistent with measured gradients on a millimetre scale with the IR camera. However, this could be only an apparent relation: while discontinuous layering may result in discontinuous gradients and thus to crystal growth and faceting, it also results in discontinuous cutting surfaces in a pit wall and thus, to differences in the IR signal.

5 CONCLUSIONS

This study investigated the effectiveness of using an IR camera to visualize snow temperatures and small scale gradients. We tested the camera in both field and lab experiments, focusing on the effect of a non-planar pit wall and wind on the thermal images. We found that the effect of a formerly observed cold or hot crust in the field could be related to surface energy balance processes after exposing the pit wall. Different assimilation speeds with air temperature at concave and convex areas in a pit wall were observed. Cutting through a crust with a cutting blade or a shovel produced small concavities even when the aim was to cut a planar surface. This results in the case of a cooling of a relatively warm crust, and in case of a warming of a relatively cold crust. This explanation does not need to assume that a crust is a gap in ice conduction, which contradicts the generally accepted picture of a highly conductive ice lattice. It does not assume that conductivity will be reversed at times when the internal snow gradient is reversed to explain a relatively cool crust. In our opinion, it is unlikely that another process affects internal snow gradient, since the surface energy process on the pit wall results in large and fast temperature changes.

Based on our observations and literature regarding highly conductive ice lattices, we suspect that the crust inside the snowpack is warm relative to the surrounding crystals. However, it is difficult to separate the snow internal processes from surface energy exchange processes using the IR signal, because the contribution of the warm crust to the total thermal signal is small or at least unknown.

The IR signal is unfortunately unreliable when we are most interested in using its results. For example, at times where large snow internal gradients exist, large differences between exposed snow pit and air also exist. These include cases when we are trying to explain faceting near crusts, where high gradients exist between layers. At these layers, it is more likely that the inhomogeneous pit wall structure resulting after cutting, highly influences the thermal signal.

Near surface faceting could be an interesting use for the infrared camera because it appears to be possible to create a smooth cut in these conditions. A promising picture of a subsurface warming was published in Shea et al. (2012). Regular thermocouples fail because of the influence of solar radiation. Since the thermal signal is dependent on the structure of the pit wall, it may be used for visualizing this structure, to measure the formation of columnar structure in depth hoar for example. One must keep in mind that these structures are only visible when there are differences between snow and surrounded air temperature.

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7 REFERENCES


