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Limitations of using a thermal imager for snow pit temperatures

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Abstract

Driven by temperature gradients, kinetic snow metamorphism is important for avalanche formation. Even when gradients appear to be insufficient for kinetic metamorphism, based on temperatures measured 10 cm apart, faceting close to a crust can still be observed. Recent studies that visualized small scale (< 10 cm) thermal structures in a profile of snow layers with an infrared (IR) camera produced interesting results. 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 (holes) even when the objective was to cut a planar surface. Our findings 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. We were able to reproduce the hot-crust/cold-crust phenomenon and relate it entirely to surface structure in a temperature-controlled cold laboratory. Concave areas cooled or warmed slower compared with convex areas (bumps) when applying temperature differences between snow and air. This can be explained by increased radiative transfer or convection by air at convex areas. Thermal videos suggest that such processes influence the snow temperature within seconds. Our findings show the limitations of the use of a thermal camera for measuring pit-wall temperatures, particularly in scenarios where large gradients exist between air and snow and the interaction of snow pit and atmospheric temperatures are enhanced. At crusts or other heterogeneities, we were unable to create a sufficiently homogenous snow pit surface and non-internal gradients appeared at the exposed surface. 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.

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 and Jamieson, 2009). 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., 2012c, b) 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. (2012c) 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 vapour 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., 2012a) 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

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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. Angular dependencies were found to be important in literature. Dozier and Warren (1982) theoretically achieved angle dependencies for emissivity values of snow under the assumption of Kirchhoff's law. They concluded that temperature determination errors of up to 3 °C are expected when the effect of viewing angle is neglected. Viewing angles in a snow pit depend on the layering and the porosity. Cutting through a snow pit with a cutting blade or a shovel will produce 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.

Emissivity values are not constant for different snow characteristics. For certain grain sizes and wavelengths (12 µm), the emissivity of snow varies between 0.963 and 0.995 (Dozier and Warren, 1982, Fig. 1). No significant dependencies on density, grain size and size were found. Applying these results to small pixel sizes of 1 mm is highly questionable. At this scale, averaging over non-isotropic grains cannot be assumed.

Salisbury et al. (1994a) measured emissivity values and compared their results to those theoretically derived by Dozier and Warren (1982), also under the assumption of Kirchhoff's law. Oppositely, they found dependencies on grain size and density: larger particles and denser snow were found to have larger emissivity values. Furthermore, Salisbury et al. (1994a) concluded with laboratory measurements that the assumption of Kirchhoff's law is questionable for extremely low density samples, especially when a thermal gradient is present in the sample. This makes sense, since Kirchhoff's law was derived for isothermal samples at the same temperature as the background to which it radiates (Salisbury et al., 1994a). They used low density quartz powder and applied a thermal gradient to simulate the heating effect of the sun. A highly decreasing density close to the sample's surface was observed (fairy castle structure, see Salisbury et al., 1994a), which resulted in a very low thermal conductivity. They concluded that the heat transfer in the uppermost layer (i.e. the radiating layer) is dominated by atmospheric conduction and convection. This layer was radiating to the cooler laboratory environment and was greatly influenced by air temperature, which was not the case for the interior of the sample. Thus, a steep gradient developed in the radiating layer. Salisbury et al. (1994b) assumed similar behaviour for snow and the results were later confirmed by Korb et al. (1999) with field experiments. As a result of this steep gradient in the radiating layer, the camera may be able to see either warmer lower or colder upper sample layers depending on the viewing angle. This was also observed by Shea and Jamieson (2011) on snow surfaces. The thermal camera used in our study calculates temperature using Kirchhoff's law, although a freshly exposed snow pit obviously does not fulfil the strict assumptions, i.e. the sample is not isothermal and in some time periods, a large temperature difference between sample and surrounding air exists.

Varying emissivity values for different snow types were found with field measurements by Hori et al. (2006). The emissivity for coarse grain snow was found to be 0.927 at 12.5 µm for an off-nadir angle of 75 °C, while for fine dendrite snow for a nadir angle the emissivity was found to be 0.984. When integrating over the used camera's spectrum, the grain type differences may be diminished.

Shea et al. (2012c) 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 thermal 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. (2012c, b) 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 Method

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. (2012c) and Shea et al. (2012b), respectively. These cameras measure in a spectral range of 7.5 µm to 13 µm. The main differences are the spatial resolution (320 × 240 compared to 640 × 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.

2.1.1 Snow pits

Thermal videos were made while digging snow pits. Regular digital videos in the visual spectrum were overlaid 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 specimens 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 (holes) and convexities (bumps). Two examples of snow specimen can be seen in Fig. 1. The scale of the artificial roughness varied from the 1 cm to 10 cm. The snow specimens 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 specimens during the first 10 min were recorded. Similarly, after isothermal conditions in the cold lab, the specimens were placed outside or in a cooled room of approximately +3 °C. To achieve a larger control of the conditions, experiments were performed inside the cold lab with changing temperatures. Furthermore, the effect of air flow was tested with fans.

3 Results

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 laying on the ground which 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 Fig. 3, mean vertical temperature profiles are 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 (~ −4 °C) 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 4 represents a horizontal temperature profile through the shovel scours. Similarly, the initial warm regions did not cool as fast during the general cooling process, resulting in an increased gradient adjacent to these initially warm areas. Overlay photos of crusts in the IR and visual range (not shown) suggest that at sheltered concave areas, the temperature is either warmer or colder compared with flat surfaces, depending on if the air is colder or warmer than the snow.

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.

3.2 Cold lab

Specimens were stored outside overnight during calm wind and overcast conditions (air temperature −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 Fig. 5. The time development of the marked flat, concave and convex area is shown in Fig. 6. 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 areas were larger than one degree. This resulted in an increase of gradients between these areas or between pixels. Another specimen with artificial concave areas and a natural crust is shown in Fig. 7a. Both areas appear to be warmer when placed in the cold lab. After a night in the cold lab, these differences were hardly visible in the thermal signal again. When the cold specimens were placed outside of the cold lab with warmer air temperatures, the opposite was observed. The concave areas and the crust were relatively colder (Fig. 7b) caused by a slower warming process.

This process of different assimilating speed of snow to air temperatures could be observed in the cold lab itself. The cold lab temperature was set to change every 105 s from warming to cooling. In Fig. 8 it can be seen that convex areas reacted much faster to changing temperatures than concave areas. As a result, gradients between areas and pixels were appearing and disappearing (not shown). The effect of air flow (i.e. wind) can be seen in Fig. 9. Large fans in the cold lab produced an air flow from left to right. On the sheltered leeward side of a several centimetre thick convex area, the snow was cooling slower and thus resulted in a relatively warm area. This effect is also visible in Fig. 7a, which shows a general gradient from top left to bottom right.

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 or 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 Figs. 2 and 3 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. (2012c) were typically performed 90 s after pit wall exposure. In the cold lab, we observed snow temperature gradients to change substantially within these first 90 s.

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. Our explanation with a surface energy process does not need to assume that a crust is a gap in ice conduction as done in Shea et al. (2012a), 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 cold 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.

In the Introduction, other explanations were mentioned for a warm crust, i.e. emissivity differences between crusts and adjacent layers or angle differences which will briefly be discussed in the following. During equilibrium of snow and air, only small temperature differences could be observed. This shows that both effects are relatively small in comparison to the surface energy exchange process. Moreover, the measurement function used with our thermal camera (e.g. Eq. (2) in Shea et al., 2012c) implies that different emissivity values would cause an opposite effect since crusts likely have lower emissivity (Hori et al., 2006). A relatively warm pixel in a crust during a cooling process would be even warmer after an individual emissivity correction of this pixel. This is true as long as the reflected apparent temperature is colder than that of the sample, which should be the case during a cooling process. Similarly, an adjustment of a relatively cold pixel in a crust during a warming process would result in an even colder pixel. Thus, a warm or hot crust cannot be easily explained with different emissivity values.

The effect of different thermal conductivity between layers could not be studied, but will add – if existent – uncertainty in the interpretation of the thermal signal. Shea et al. (2012c) found no relevant sharpening of gradients with exposure time in 35 pairs of overlapping IR photos captured at different times after exposing the pit wall. They found seven cases in which the median gradient of the overlapping zone decreased with time (larger than pixel sensitivity) and only one significant increase. This finding is opposite to what is presented in this study. During pit wall observations, we occasionally found gradients decreased with time. More regularly, an increase of gradients as shown in Fig. 3 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. One explanation for the different findings could be that the overlapping areas used in Shea et al. (2012c) were too large for such a comparison. Large in-between pixel differences regularly occurred only at thin areas (at the edge of roughness elements) in our study. Typically an increase of a gradient was observed in these thin areas (compare Fig. 4). For the majority of the pixels, at the homogenous parts of the picture, no increase was observed. The small amount of pixels in an overlapping area with an increase of gradients might not have an influence on the median calculation done by Shea et al. (2012c).

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. (2012c). 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. (2012c) 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.

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. (2012c). 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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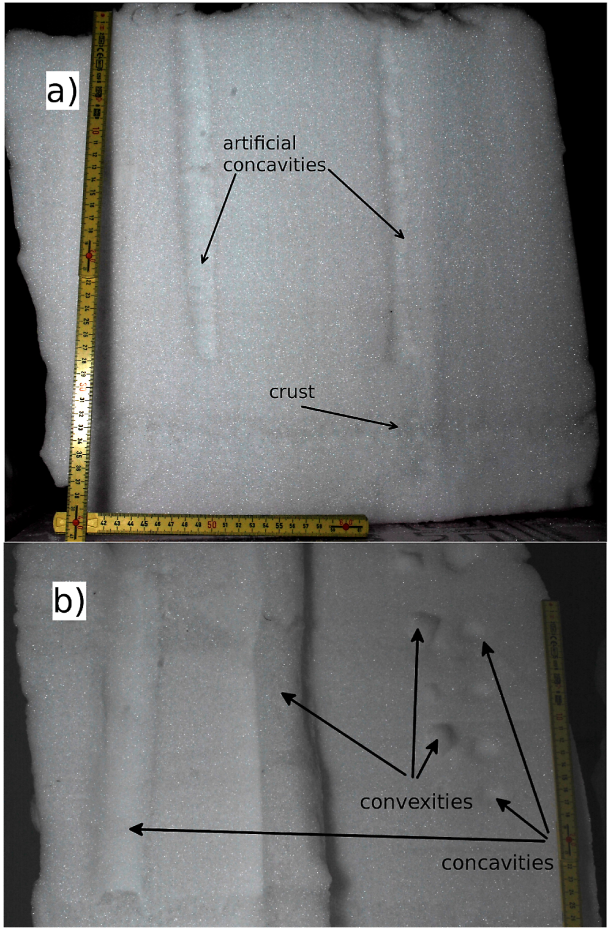

Fig. 1. Specimen with **(a)** artificial concavities (holes) and a natural crust, and **(b)** with artificial convexities (bumps) and concavities. Due to the angle of the flash light convexities are dark.

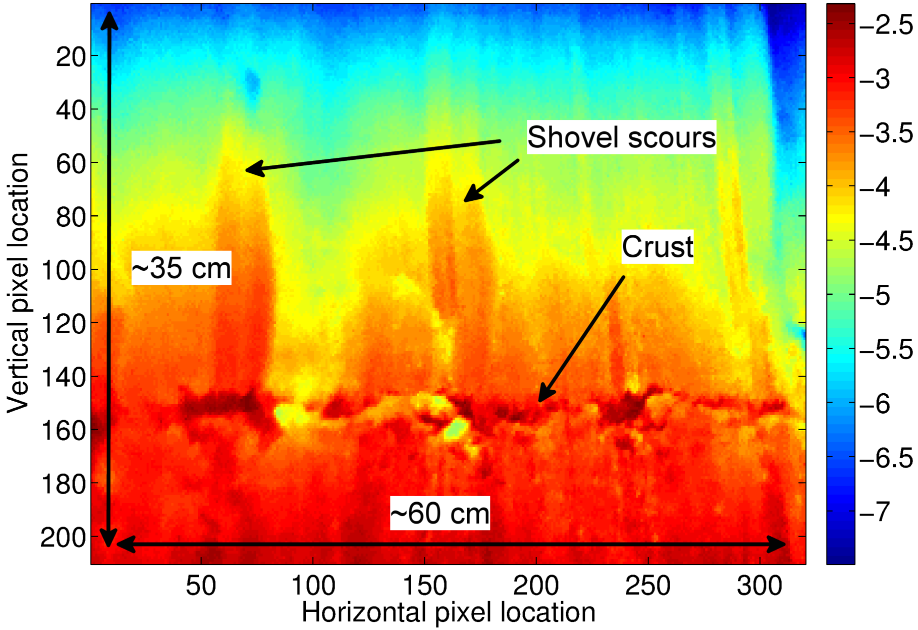

Fig. 2. Thermal picture of a snow pit including a natural crust. Colorbar in °C.

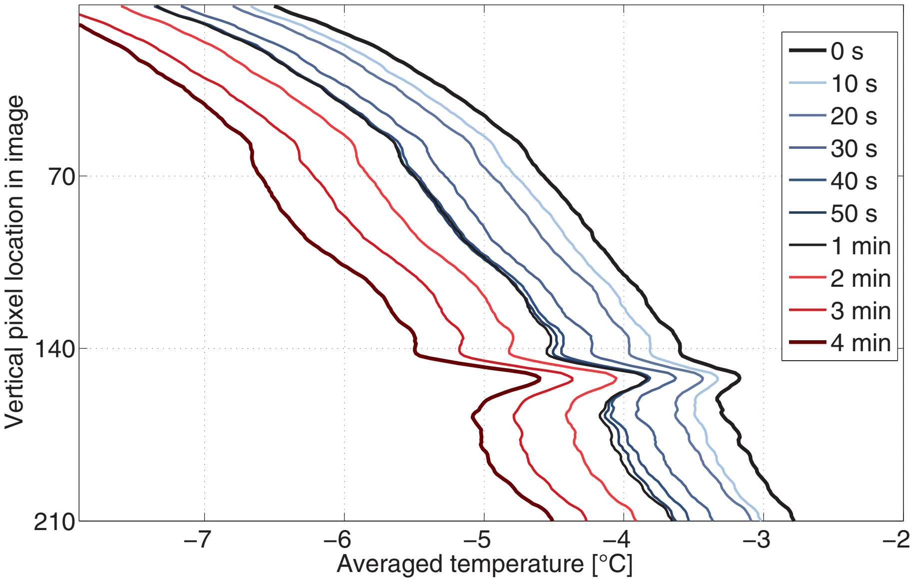

Fig. 3. Mean vertical temperature profiles depending on the time after pit wall exposure. The thick black line represents the situation of Fig. 2.

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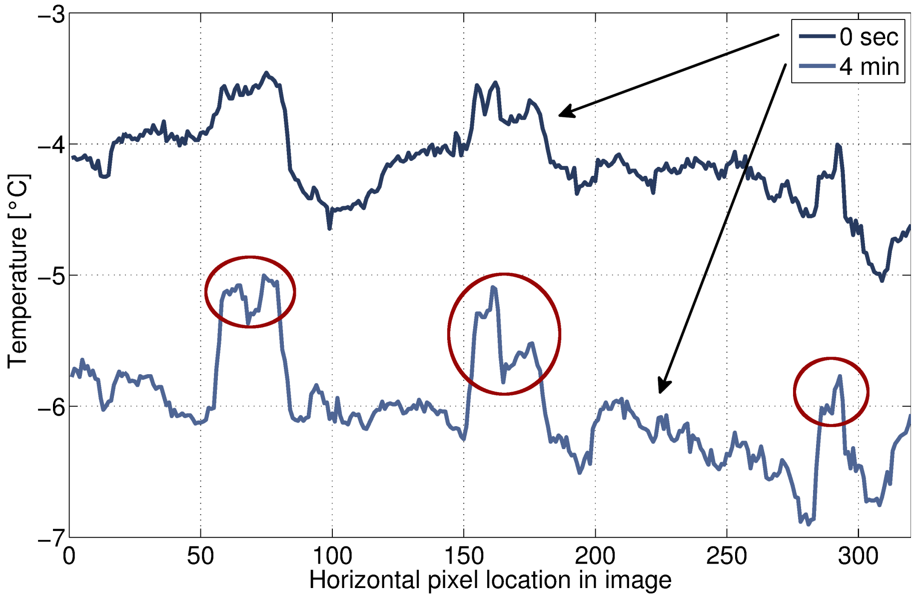

Fig. 4. Horizontal temperature profiles at the first and last time step at vertical pixel location 100 (see Fig. 2). Areas with a less fast cooling process are marked in red which correspond to the shovel scours.

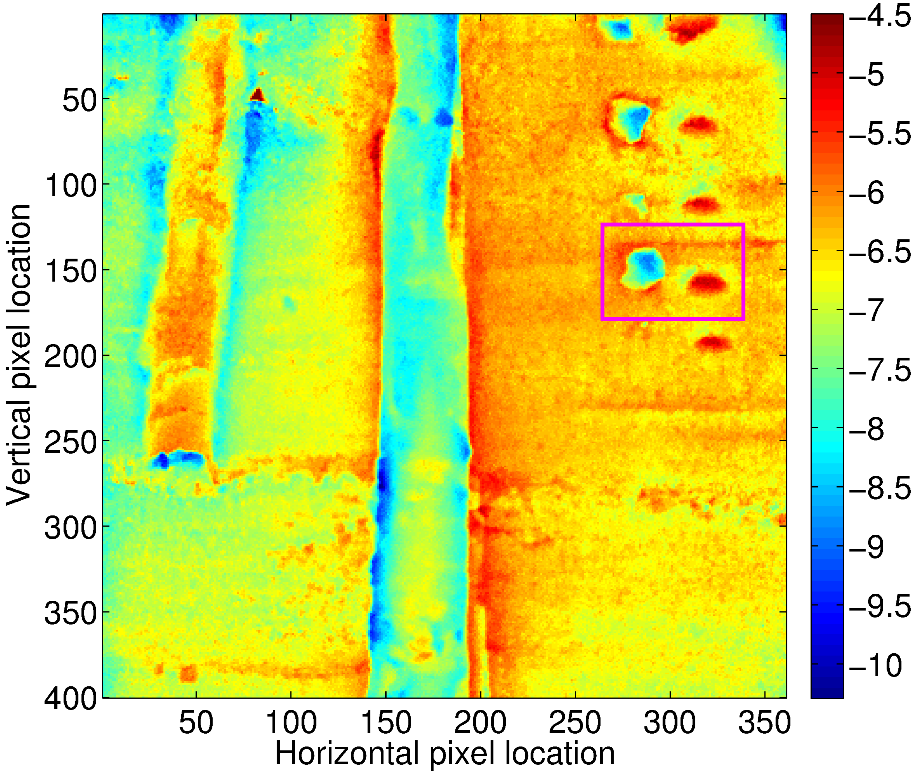

Fig. 5. Thermal image of the specimen shown in Fig. 1b after approximately 4 min in the cold lab. Artificial concavities are relatively warm, convexities relatively cold. The marked areas are further analysed in Fig. 6. Colorbar in °C.

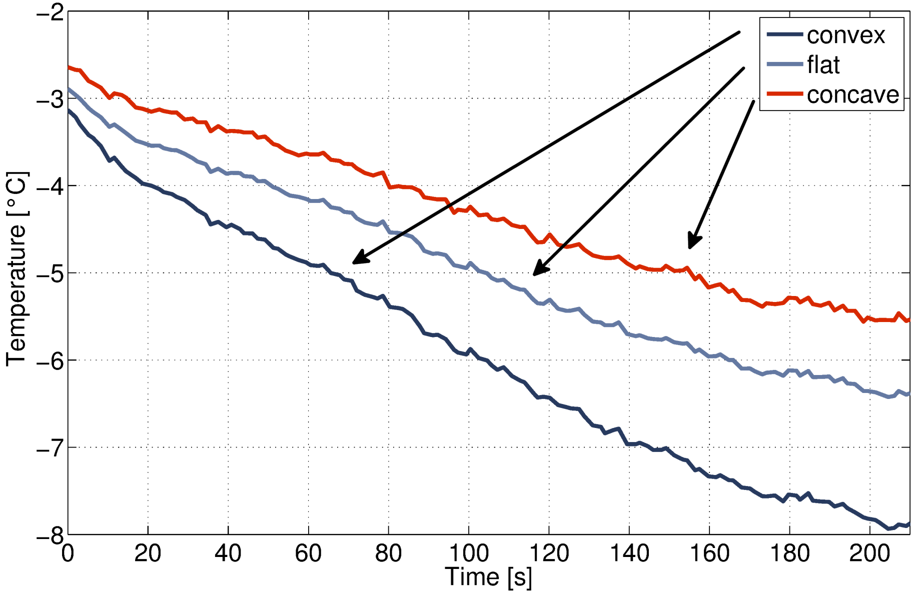

Fig. 6. Time development of the cooling process of the marked areas in Fig. 5.

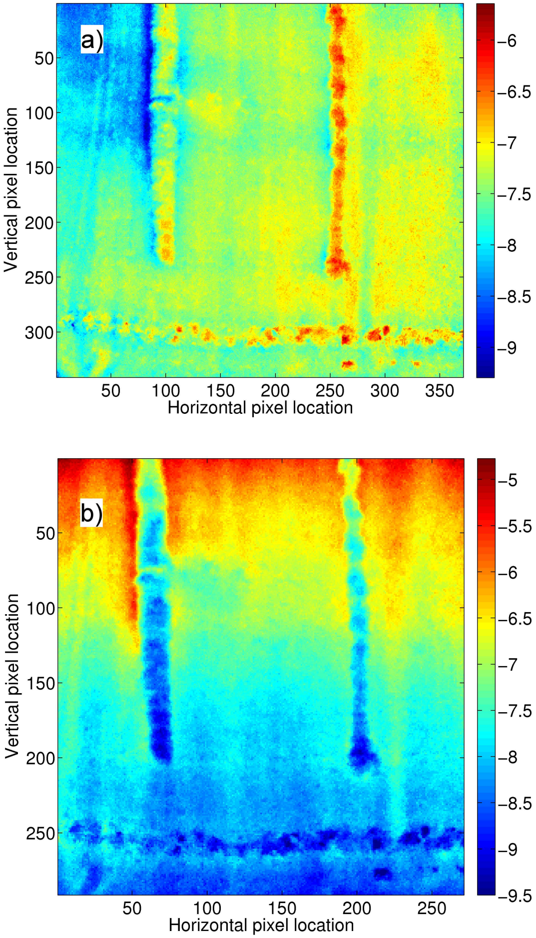

Fig. 7. Thermal images of the specimen shown in Fig. 1a after approximately 4 min, **(a)** inside and **(b)** outside the cold lab. Colorbar in °C.

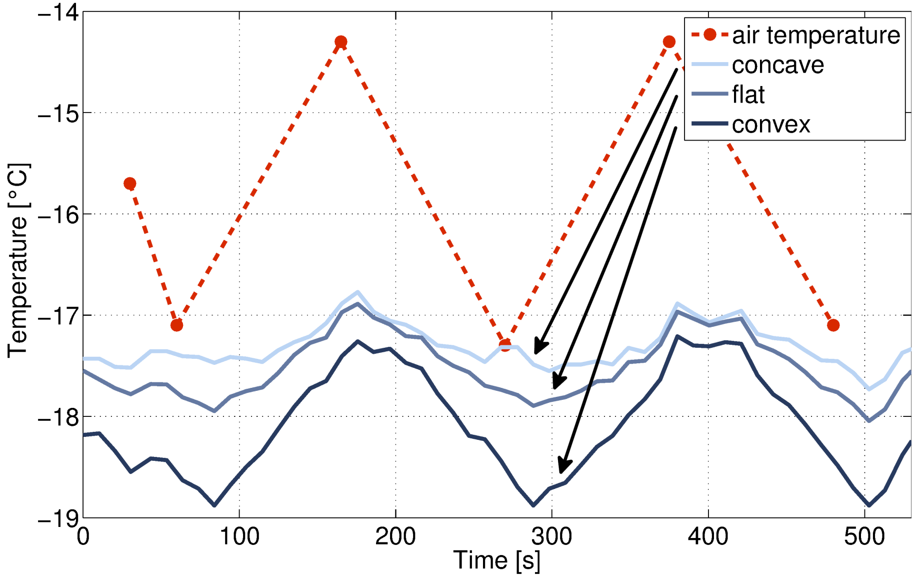

Fig. 8. Snow temperature reacting on changing air temperatures in the cold lab.

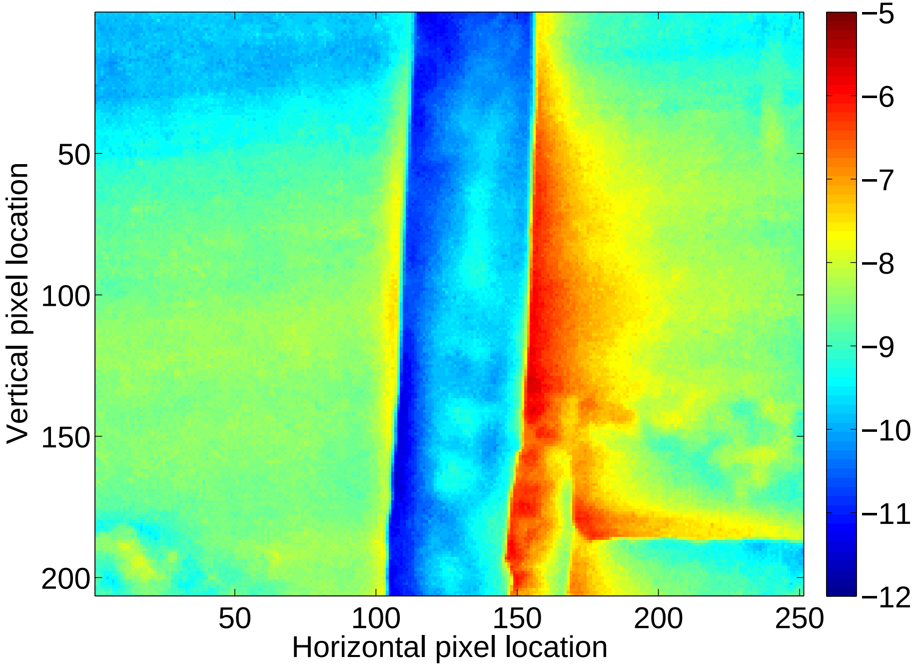

Fig. 9. Effect of cold air flow (from left). Relatively warm areas behind a convexity (some centimetres thick, similar to a specimen shown in Fig. 1b. Colorbar in °C.