USE OF THERMAL PHOTOGRAPHY TO MEASURE SNOWPACK PROPERTIES

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ABSTRACT: Many snow processes are linked to snow temperature. A thermal photograph captures tens of thousands of surface temperature measurements in a single, powerfully visual image. Surface temperature directly drives surface hoar growth and near surface faceting, and it indirectly affects albedo and crust formation. We introduce this new application of thermography by presenting images (thermographs) and thermographic videos from winter 2010. Three different aspects are presented: (1) the link between surface temperature and surface hoar formation, (2) the spatial variation of temperatures on a pit wall, and (3) the effect of crystal type on conduction. Currently, due to cost and technical demands, thermography may remain primarily a research tool. However, thermography is a promising new technique that produces both quantitative and intuitively visual results.

KEYWORDS: Heat conduction, Surface hoar, Thermal photography, Thermal profile

1. INTRODUCTION

Many snow weak layers form at least partly due to heat, in the form of input, output, or gradients. Such layers include: surface hoar, facets, crusts, depth hoar, slush – the list goes on. And yet the main and usually only way that heat in the snowpack gets measured in the field is by taking a temperature profile in a snow pit. In this paper, we present and demonstrate a simple new application of thermal photography, also known as thermography: measurement of the temperature of snow.

Visual light photography no longer surprises us as a technology. We take a sort of visual light photograph with our eyes everywhere we look. We, however, cannot *see* heat, except with our skin, and even then only in general categories of warm or cold. Despite our inability to see it, emitted heat is actually the same thing as light, except it has a different wavelength. So the *idea* of a thermal camera is not so far-fetched.

Indeed, thermal wavelength sensors (of at least one pixel) have existed since 1899, and thermal cameras of many pixels have even been in space since 1978, via the Landsat satellite program (Lillesand et al., 2008). In the last ten years, handheld thermal cameras which are relatively small, simple to use, and durable have decreased in price by an order of magnitude.

In the winter of 2009-2010, we acquired a thermal camera with the intent to study thermal processes related to surface hoar growth. However, instead of just studying surface hoar, we found that whenever we pointed the camera at snow or a process related to snow, we learned something new.

And, after taking hundreds of thermal images – also known as thermographs – and hours of thermal video during the season, we have compiled some of the more interesting results in this paper. It is our hope as authors that these images and concepts inspire the same curiosity and fresh ideas in you as our reader as they have inspired in us.

2. METHODS

Everything with a temperature above absolute zero emits heat. And that means everything on Earth emits heat. People emit heat. This paper you are holding in your hands (or this computer monitor you are reading the paper on, even when it is off) emits heat. Snow, even though it is cold, emits heat. These emissions occur in the form of *thermal infrared radiation* for most things on Earth, and, in the various wavelengths they emit, there is usually a peak between approximately 7 and 14 μm.

Snow is no different than any other material in this regard. By (a) making a sensor that can sense thermal infrared, (b) pointing it at snow, (c) scaling by the tendency for snow to emit a lot of infrared at a given temperature compared to other materials (the measure of this tendency is called *emissivity*), and (d) correcting for distance and any heat from air or humidity or pollution or reflections, one can obtain

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the temperature of the snow.

Modern thermal imagers measure thermal infrared by using an array of heat-sensitive pixels called a microbolometer. This array allows a thermal camera to sense heat through voltage changes. The voltages are then translated into visual color – usually brighter colors for warmer temperatures and darker colors for cooler temperatures, but often selectable by the user. The studies in this paper were performed using a FLIR B300, which has a 240 x 320 pixel resolution, a 2 °C or better absolute temperature accuracy, and a 0.5 mC between-pixel accuracy, also known as the sensitivity.

The corrections which need to be performed on the images all fall neatly out of how the world physically works, but since the world is rather complex, the image corrections can often be complex as well. This, combined with the cost of the equipment, means that we are not now suggesting that everyone go purchase a thermal imager.

However, we have started documenting what corrections other research fields use when taking thermal photographs, how well the corrections work for snow, and what new corrections or precautions snow requires. This is in the hopes that when thermal imagers fall in price again that we as a field are ready to take full advantage of them.

If you are interested in these corrections and the technical use of thermal imagery specifically for studying snow, you may be interested in a free and open access technical discussions paper (Shea and Jamieson, 2010a) which goes into further detail. Other resources also offer non-snow-specific thermography information, including Wolfe and Zissis (1978), or snow specific information from a satellite remote-sensing perspective, including Dozier and Warren (1982). For the purposes of this paper, it will be useful to note that the following conditions can add error to a thermographic measurement and should be corrected for or minimized:

- Air temperature between subject and camera
- Humidity between subject and camera
- Reflected heat
- Distance between subject and camera
- Angle of camera relative to subject

All images in this paper have been corrected using the best available information. Air temperatures were taken manually using a calibrated thermometer, humidity was obtained either using a hand-held digital hygrometer or read from the output of a nearby remote weather station. Reflected heat was obtained by using a diffuse reflector of crumpled and flattened aluminum foil, which is similar in emissivity to the diffusely reflecting gold used in Salisbury et al. (1994b).

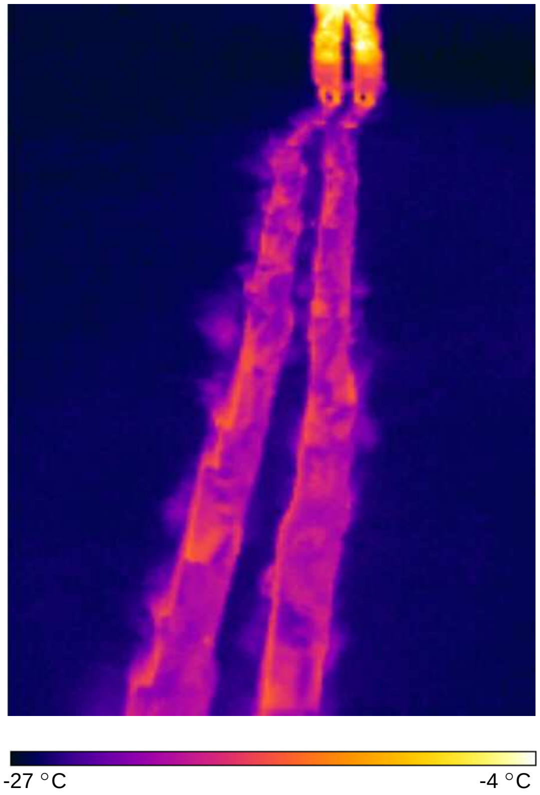

Figure 1: An example of thermal layering of snow during a night of near-surface facet and small surface hoar growth. The undisturbed snow surface is quite cold, and the parallel lines are ski tracks which have cut down into the warmer snow underlayer.

The angle of the camera can be used to measure different layers of temperature near the surface in porous materials (Salisbury et al., 1994b), and so a different angle does not necessarily generate error. However, for flat and relatively dense surfaces (like the surface of most snow pits), a surface will appear slightly hotter when photographed directly than if the thermograph is taken at an oblique angle. The difference appears to be only around 0.5 °C over 70° of obliqueness for small distances around a metre (Shea and Jamieson, 2010a), and up to 2 °C for longer distances (Dozier and Warren, 1982).

Snow lends itself to thermal photography because it has a high emissivity and thus does not reflect very much heat from other sources. In addition, most types of snow morphology emit similarly in the thermal wavelengths, that is, one does not often need to correct for crystal type. A few exceptions exist, including ice lenses which can reflect more external heat at certain angles, and wet snow which has an emissivity similar to water (Salisbury et al., 1994a).

The most powerful aspects of using a thermal camera to measure snow temperature are: (1) An entire image with many, many temperature measurements can be captured instantaneously. (2) The results can be displayed visually. And, (3) The measurements can often be corrected by giving values for humidity, distance, etc. to the camera itself, or the measurements can be stored to be corrected later for atmospheric, operator, and other effects.

The importance of being able to visualize a phenomenon as our eyes would see it cannot be overstated. We all know – theoretically – that the snow surface gets cold at night during clear and calm conditions, but it is another thing to actually *see* ski tracks light up with warmth relative to the surface as in Figure 1.

3. RESULTS

This section contains a sampling of results from the 2009-2010 winter, including the effect of different snow types on heat absorption, using a thermal camera to see spatial thermal profiles on pit walls, and the effect of tree shading on surface hoar preservation.

3.1 Heat absorption and conductivity

Generally, one might expect denser snow to conduct heat more quickly as it has more ice (and thus, presumably, more bonds) per unit volume (Armstrong and Brun, 2008, pg 36). Although generally this may be true, multiple cold lab experiments showed that exceptions exist. Layers of rounds up to 0.5 mm (dense, 300 to 390 kg m^{-3}) and polycrystals up to 6 mm (less dense, up to 290 kg m^{-3}) were tested by heating them from front and back.

Figure 2 shows frames from one informal yet easily visualized experiment. With rounds on the right and polycrystals on the left, a hand was put right in front of the snow surface without contact for 30 seconds, then removed. The polycrystals heated faster and cooled faster than the rounds, which gives the right side of the frames a delayed and persistent heat signature. The other hand was used to show that it was not just that one side of a palm happens to be hotter than the other.

Other, much more formal heat conduction studies were also captured using thermal video (Shea and Jamieson, 2010a), and these confirm that polycrystals can heat and cool quite quickly and in more complex patterns than can be seen in the hand video. Rounds, on the other hand, resembled a slow-absorbing, slow-drying heat sponge in these experiments.

3.2 Surface hoar metamorphism

Previous work has shown that, all other things being equal, larger surface hoar grows where the snow surface can get cooler during the night (Shea and Jamieson, 2010b). Likewise, we expect surface hoar to be preserved during the day in areas which receive minimal heat input. To examine this, we performed a semi-random spatial sampling across a tree shadow after a night of surface hoar growth.

We measured surface hoar size at 48 points within a square area 6 m on a side. Minimum and maximum surface hoar crystal size were measured using a crystal screen and loupe at each point to obtain a mean crystal size at each point. The sample was taken in March on a clear day on an east-facing but nearly flat area. The area experiences very little wind. The tree was to the east of the sample area, that is, it cast a shadow across the sample area.

The change in tree shadow position from the beginning to end of the sampling time may be seen in Figure 3a and 3b. We used thermal imaging rather than visual photography to capture the shadow, which shows that (a) the protection from the sun follows the shadow itself, and (b) the snow surface cools and heats relatively quickly once the shadow or sun is over an area.

The sample locations were generally visited starting farthest from the tree, and moving closer. The location of the surface hoar crystals outline where the shadow of the tree was when the sun came up in the east, which is also where the shadow was when we began sampling the area. This implies that the crystals were preserved in the coolness of the tree shadow and were destroyed where solar heat reached the snow surface.

3.3 Thermal profiles of a pit wall

Another application of thermal photography is to expand what happens with a thermometer in a snow pit. Compared to taking a thermal profile point-by-point with a thermometer, however, taking a thermal profile with a thermal camera may not be as simple as it seems. First, a thermal camera image records only those temperatures *at the surface of the snow*. If an operator exposes a pit wall and waits around for only a few minutes while the snow surface equalizes with the atmosphere temperature, the wall can become quite a different temperature than when it was buried in the snowpack.

In addition, when an operator in ski clothing

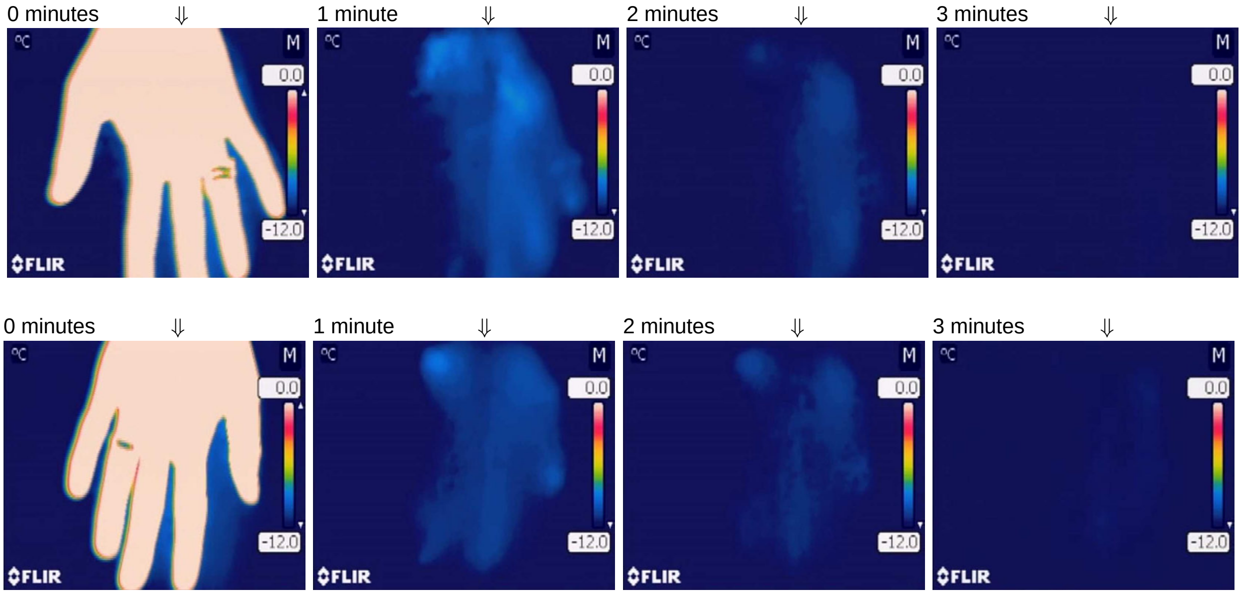

Figure 2: An informal demonstration of how polycrystals and rounds react to heat differently. Two thick layers were extracted from the snowpack and turned sideways so that rounds appear on viewer's right, polycrystals appear on viewer's left. A hand was held as a heat source a few millimetres from the snow for 30 s and then removed. A downward arrow at the top of each image indicates the location of the boundary between the crystal types. Each image shows a frame from a time-lapse thermal video. The scale on the right of each photo ranges from 0 °C down to -12 °C.

stands close to the wall – within about a meter – he or she will warm the snow surface by about 0.1 °C per minute, or about 1 °C every ten minutes. This has been confirmed with a multi-condition experiment involving hundreds of thermographs (Shea and Jamieson, 2010a) and the trend has a significance of $p < 10^{-3}$. After thirty or so minutes, the heat from an operator can penetrate to depths greater than 15 cm, the length of most thermometer shafts. So, the camera operator has to move quickly and aim to take thermographs of the pit wall within about a minute.

Despite these complications, thermal profiles are not only possible, but give us much more information than ten or so points from a thermometer. Figure 4 shows two such thermal profiles obtained using a thermal camera: one of a snowpack containing a complex crust, and a second containing multiple layers of surface hoar. We also confirmed a photographic thermal profile using the traditional method of inserting a calibrated thermometer into the snowpack every 10 cm (Canadian Avalanche Association, 2007). Although a thermometer measures snow temperatures slightly *behind* the snow surface, the correlation between the camera-measured and thermometer temperatures was r = 0.96, with a significance of $p < 10^{-4}$ (Shea and Jamieson, 2010a).

The thermal profiles in Figure 4 show a spatially complex heat signature. For the pit containing a crust (Figure 4a), the crust itself remains cooler than the surrounding snow both above and below it. Further, the boundaries of the thermal differences around the crust are relatively sharp and well-defined, rather than a gradual change from one point to the next. This may help explain why dynamic change occurs within crusts despite having only small temperature gradients across them when measured with a point thermometer – the real temperature gradients in the profiles in Figure 4 seem to occur on a much smaller spatial scale.

These sharp thermal differences can also be seen in a surface hoar profile (Figure 4b), where multiple layers of surface hoar are clearly and sharply delineated by their relatively cooler temperature. Surface hoar is a different crystal type and can sometimes – on a small scale – be close to flat ice which has a lower emissivity than seasonal snow (Dozier and Warren, 1982). Because of this, and all other things being equal, surface hoar might *appear* cooler than seasonal snow at the same temperature. So, the question arises as to whether the apparent surface hoar temperature difference may be due to this difference in emissivity.

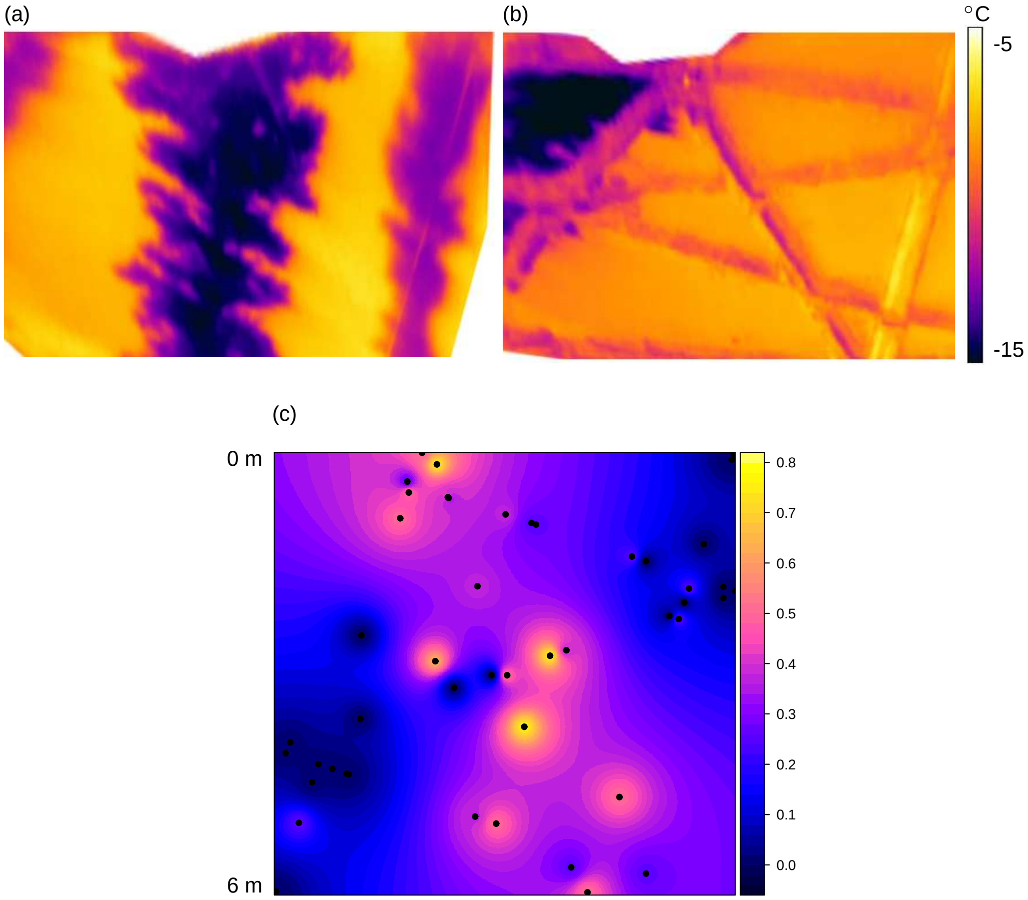

Figure 3: Time lapse thermographs of a tree shadow over the surface hoar sample area in (a) and (b). The times were (a) 1030, pre-sampling, and (b) 1130, post-sampling, both local time. The sampling transects may be seen in (b) due to photographic angle differences on the edges of the ski tracks. The surface hoar crystal sizes found in the area can be seen in (c), with black dots indicating sample locations and the scale showing mean crystal size in mm. All three images show a birds-eye view of the same 6 m x 6 m area in the same orientation. East is at the top of the images, and the tree is located nearly in the middle of the top.

This serves as an example of (a) how really knowing what one is thermally measuring can be quite important, and (b) how contextual evidence can help one analyze thermographs. Without additional information, there would be no way to know if the surface hoar only appears cooler (without being so) due to its different physical properties, or whether it was actually physically cooler. Here, we take additional information: lower emissivity means that a material reflects more of the temperature of its surroundings (Salisbury et al., 1994b). Since the surroundings that day were hotter than most of the snow, and a warm operator was standing in front of the pit taking pictures, increased reflectance would have made the surface hoar appear hotter, not cooler. Yet cooler it appears, and with clarification as to it being a physical rather than apparent temperature difference.

Capturing a temperature profile in a snow pit with thermography can be performed more quickly than a traditional temperature profile, and a thermography profile provides much more information. Taking snow temperature profiles with a thermal imager represents perhaps the greatest immediate interest for general field use; for more information, please also refer to Brusseau and Latosuo (2010) in these proceedings.

Speaking of thermal profiles, the thermal camera helped answer another question. When taking the temperatures nearest the surface in a thermal profile, the operator will often shade the snow surface over the profile with a shovel blade. The question from this is: *Does it matter how close the shovel blade is to the snow?* In a cold lab environment, a metal shovel blade was held above a snow sample at varying distances. The blade was heated from be-

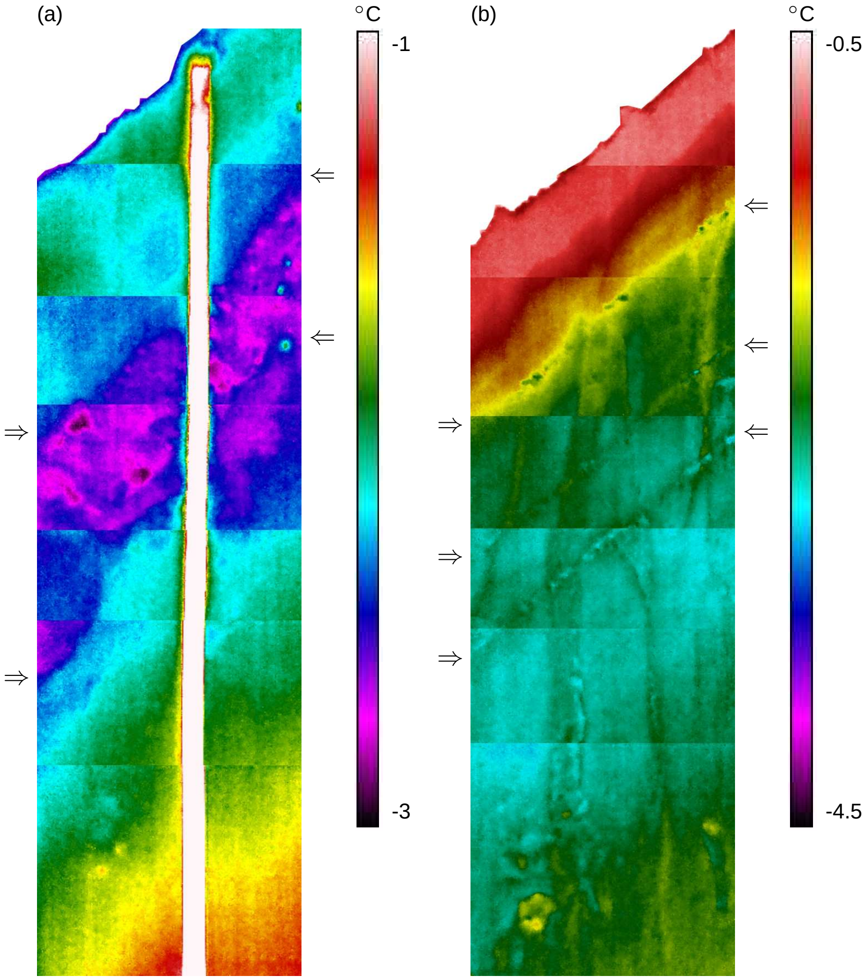

Figure 4: Two example thermal profiles taken with a thermal camera. Multiple overlapping images compose one profile to obtain maximum detail. Images are shown with older images tiled under newer images. (a) A snowpack containing a complex crust. A ruler is present in the center (warm compared to the snow) for image alignment. Arrows show where the top and bottom of the crust touch the left and right boundaries of the image. An ice mass – which appears thermally similar to the crust – can be seen on the right side, under the crust. (b) A snowpack containing multiple surface hoar layers. Arrows mark three layers of surface hoar where they touch the left and right boundaries of the image.

hind by an infrared bulb much stronger in infrared wattage than what a typical snow surface sees from the sun, but which gives an idea of change over a shorter time. At 50 cm above the snow, the warmed shovel blade heated the snow surface by 0.05 °C per minute, 25 cm above the snow caused 0.4 °C per minute, and 10 cm above the snow caused 0.9 °C heating per minute.

The thermal profiles and surface heating from a shovel together show that although thermography may primarily be a research tool at present, it can not only be applied directly to current field methods, but the results are accessibly visual and fast to obtain.

4. DISCUSSION AND CONCLUSIONS

Now that we have discussed everything from conductivity to surface hoar preservation, it might be time for some general thoughts and take home messages. First and foremost, heat in the snowpack is complex. Other work has shown this as well (Schneebeli and Sokratov, 2004; Kaempfer et al., 2007), but it deserves saying again: *heat in the snowpack is really complex*.

The heat conduction experiments in Section 3.1 show that the time to absorb and emit heat depends on crystal type, and there are often many different crystal types in one snowpack. The surface hoar experiments presented in Section 3.2 show that even small-scale thermal differences – as small and simple as a tree shadow – can preserve or destroy surface hoar.

The thermal snow pit profiles presented in Section 3.3 show that as heat trickles up from the ground or down from the sun-warmed surface it stops and starts and clusters in a very complex fashion. Taking a temperature above and below one of the bottom two surface hoar layers in Figure 4b, for example, would show no temperature gradient, but a thermal photographic profile reveals very small gradients right next to the surface hoar layers. When we can see, photographically, more of what heat does, we see its corresponding complexity.

Imagine this analogy. Everyone in North America gets in their car over on the East Coast and starts driving west across the continent at the same time. Sure, they would use the whole spread of roads from north to south available, but this would still be crazy. Heat is not so different than a whole mess of cars, in that cars tend to seek out the uncrowded places with less traffic and heat tends to seek out the cooler places, i.e. the places with less heat.

Now imagine you wanted to characterize the resulting traffic madness and mayhem that comes of this experiment by looking at *only* ten intersections evenly spaced across the country. Would that capture it? It would show parts of it, of course, but not all of it. Well, this is what we do when we stick our thermometers in at ten points in the snowpack. Except that instead of heat (cars) starting at the ground (the East Coast) and leaving only *once*, heat gets generated *all winter long* from the ground and creates microscopic complexity all the way to the surface. And this is still a simplified picture of what is happening, heat-wise, in the snow.

But that is not the take home message. If you work in the field every day (and even if you will not be using thermal photography), here is the take home message: *Be careful with heat*. Keep your shovel well away from the surface when you are using it to provide shade. Take temperature profiles as soon as the pit wall is exposed. Stay away from the area you are measuring with the thermometer because your body heat can penetrate deeper than your thermometer shaft. Doing these things will help your data show you what is really happening in the snow, rather than what you may be doing to the snow by virtue of simply being a hot human near cold snow.

On the other hand, if you are looking to research and develop new field techniques and knowledge about snow, hopefully the results in this paper have introduced a new way of measuring and visualizing temperature. Thermography is a spatial, intuitive, and instantaneous way to measure the surface heat of snow.

5. ACKNOWLEDGEMENTS

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