MEASURING SNOW SURFACE TEMPERATURE: WHY, WHY NOT, AND HOW?

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ABSTRACT: Avalanche forecasting operations measure snow surface temperature, Tss, for up to three objectives: 1) to infer near surface faceting (NSF) from Tss and the snow temperature 10 cm below the surface; 2) to measure change in the snow surface temperature over time (e.g. days) usually at study plots; 3) to determine the point-in-time surface temperature. We review the surface properties of snow and the energy exchange at the snow surface and identify the low albedo of contact thermometers as problematic for measuring snow surface temperature. Using field studies with contact thermometers, hand-held IR thermometers and an IR camera, we show that a contact thermometer on a shaded part of the snow surface can be up to 6 °C above the surface temperature. While hand-held IR thermometers are promising for measuring Tss, some units are more accurate than others and some units are slow to adjust to the ambient temperature. Since the true snow surface temperature varies widely within hours and the near surface temperature gradient usually reverses twice per day, a point-in-time measurement of the surface temperature – even with an accurate handheld IR thermometer - is less indicative of NSF than observations of the sky cover. We suggest observations or measurement methods for each of the three objectives of avalanche forecasting operations.

KEYWORDS: surface temperature measurement, snow surface, infrared thermometers, contact thermometers, temperature gradient, near surface faceting

1. INTRODUCTION

1.1 Why avalanche forecasting operations measure the snow surface temperature

Avalanche forecasting operations measure the snow surface temperature for at least three different objectives:

1. To estimate the temperature gradient (TG) in the top 10 or 20 centimeters and hence infer whether current faceting (weakening) of near surface layers is likely. The temperature gradient is calculated from the surface temperature and a snow temperature usually 10 cm below the surface, T10, respectively.

2. To determine the change in the snow surface temperature over time in a study plot from readings taken once or twice per day. This is used to infer the change in temperature of near surface snow layers over time, e.g. days. When warmed, creep increases in near surface layers, which weakly contributes to instability (Schweizer et al., 2013)

3. To determine the point-in-time surface temperature for (a) estimating the amount of warming required to bring the surface of similar slopes to the melting point, and (b) validating the reading from a downward facing infrared (IR) sensor on a tower at a nearby weather station, or from a snowpack evolution model.

Surface temperature measurements for objectives 2 and 3b are made only at fixed sites, usually study plots (Greene et al., 2010; CAA, 2016). Traditionally, shaded contact thermometers (alcohol, bi-metal or electronic thermometers) have been used to measure snow surface temperature.

1.2 The energy exchange at the snow surface

To understand the advantages and limitations of contact and infrared (handheld or tower-mounted) thermometers, we briefly review the energy exchange at the snow surface, emphasizing the radiation exchange (Figure 1).

Short-wave (SW) radiation from the sun enters the upper atmosphere. The fraction that is not absorbed by particles, water droplets in clouds, etc., or blocked by terrain or vegetation reaches the surface as direct SW. Indirect SW radiation is the fraction of incoming SW radiation that is scattered by the atmosphere, especially clouds, or reflected by surrounding terrain.

Snow reflects most SW radiation. The fraction of reflected radiation is known as the albedo, which can range from less than 50 % for dirty old wet snow to over 90 % for fresh dry snow (Male and Gray, 1980). Since as recreationists and avalanche practitioners, we often move around on top of fresh dry snow — which reflects most SW radiation — we sometimes get sunburns on the underside of our chins (if we didn't apply sun cream) and wear sun glasses (or squint). The fraction of SW that enters the snow is called absorbed SW. It partly reflects off snow grains, bouncing around within the upper snowpack, and is increasingly absorbed with depth. Little SW radiation reaches more than 30 cm into the snowpack, which is why you know if you cut the roof of your snow cave thinner than about 30 cm. The absorption results in fast warming, which decreases strongly with depth.

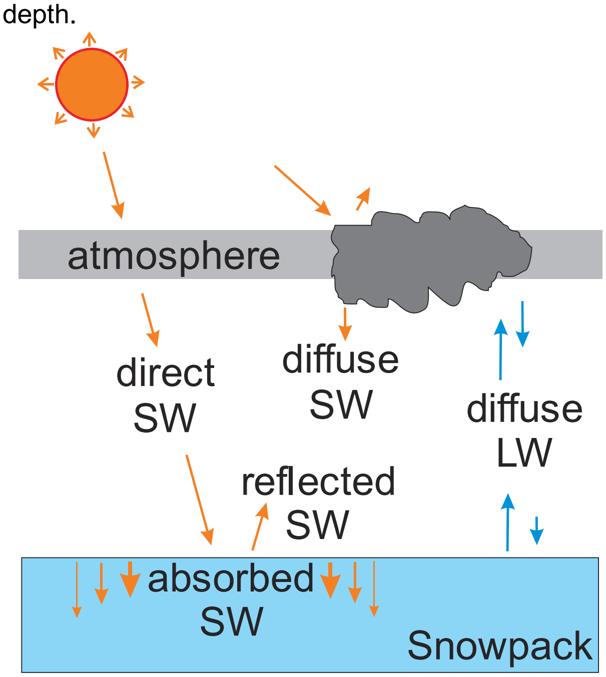

Figure 1. Radiation exchange at the snow surface. The heat transferred by wind, precipitation, evaporation, sublimation and deposition of surface hoar or rime is not shown.

Everything, including the snow surface, emits radiation according to its temperature and emissivity. Emissivity is a measure of how efficiently a surface radiates, and ranges between 0 and 1. Snow is a very efficient radiator; many snow surfaces have an emissivity between 0.98 and 1.0 (Dozier and Warren, 1982). Given the range of snow surface temperature, the snow surface emits long wave radiation. This upward radiation is partly absorbed by atmospheric particles, water droplets in clouds, as well as greenhouse gasses such as water vapor, carbon dioxide and methane. These particles and molecules are warmed and re-emit diffuse LW radiation in all directions. The downward portion of this LW radiation warms the earth's surface, including the snow surface. (This greenhouse effect favors life in the lower atmosphere at most places on Earth.) Vegetation, as well exposed rock and earth, also emit LW radiation, some of which reaches and adds energy to the snow surface.

While the radiation exchange often dominates the heat exchange at the snow surface, there are other mechanisms. Although diffusion from still air has little effect on the energy exchange, warm wind can supply heat to the snow surface, or a cool wind can draw heat from the surface. Deposition of surface hoar or rime will release heat at or near the snow surface. Sublimation and evaporation will absorb heat from at or near the snow surface. Rain can add heat to the upper snowpack and contribute to melting. Snowfall can also be warmer or cooler than the previous snow surface and thus contribute to the heat exchange.

Adding heat can warm the snow at and near the surface, OR it can contribute to melting (provide latent heat with no temperature change). Also, a loss of heat from the snow surface can result in cooling OR freezing of liquid water in the snow at and near the snow surface with no temperature change.

Ok, now let's talk about thermometers. Like snow, contact thermometers emit LW radiation efficiently but they have lower albedo, that is, they absorb more incoming SW radiation than the snow surface. For example, the stainless steel shaft of a dial stem thermometer likely has an albedo around 70 %. So, when placed on the snow surface or in the top 30 cm of the snowpack, contact thermometers give temperatures higher than the snow they are supposed to be measuring (e.g. Morstad et al., 2007). Shading of contact thermometers is discussed in Section 3.2.

IR thermometers are passive sensors of the IR radiation emitted by the surface they are measuring. They can measure the temperature of a surface whether it is in the sun or shade. The emissivity of the surface, often 0.98 to 1.0 for snow, must be entered into the sensor to get an accurate reading.

1.3 Effect of terrain on snow surface temperature

Slope angle and aspect can have strong effects on the radiation exchange when the sky is clear. On a sunny day, a steep south-facing slope, inclined at, say, 30 to 40°, with clear view of the sky absorbs more SW than it emits LW. In contrast, a steep north-facing slope with a clear view of the sky emits more LW than it absorbs SW. Under a clear sky with little wind the surface temperature on the steep north-facing slope will be cooler than the steep south-facing slope (which might be at its melting temperature). This difference in the radiation exchange will be reduced on less steep slopes, say,10 to 20°. Under common conditions, near surface warming of dry snow can be predicted for the coming day with the SWarm model (Bakermans and Jamieson, 2009)

1.4 Diurnal surface temperature and the near surface temperature gradient

Figure 2 shows a common fluctuation in the near surface temperature gradient. Four profiles of the upper snowpack were taken with 15 hours (Fierz, 2011) during which the sky was initially clear. As is common, the near surface temperature gradient reversed in the morning and afternoon. In the four profiles, the strongest temperature gradients (favorable to faceting) were in the top 2 to 6 centimeters. Temperature gradients based on the difference in temperature between Tss and T10 often miss or underestimate the strongest gradients. The profile at 00:30 is the clearest example since the temperature difference across the top 10 cm is near 0 °C (suggesting no faceting) whereas the magnitude of the temperature gradient in the top 3 cm is greater than 150 °C/m (suggesting rapid faceting).

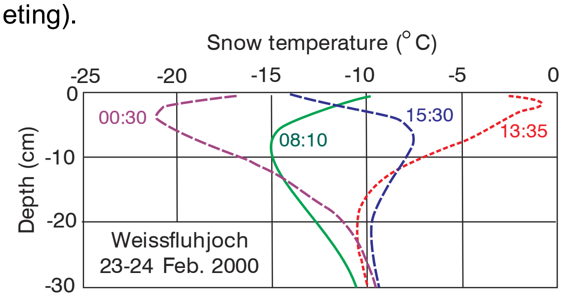

Figure 2. Temperature profile in top 30 cm of snowpack at four times during 15 h under initially clear sky. After Fierz (2011).

1.5 Objectives of this study

The objectives of this paper are:

- to identify advantages and limitations of contact and handheld IR thermometers, and
- to stimulate discussion regarding which type of thermometer or observation is preferable for each of the operational objectives stated at the start of this paper.

Recommending specific models of IR thermometers is not an objective of this study.

2. INSTRUMENTS

We used two contact thermometers: a Bios dial stem thermometer (~US$30) and a Oakton Series 5 Acorn (accuracy 0.1 °C, ~US$250), as well as five IR thermometers, which ranged in price from approximately US$30 to US$250 (Figure 3).

As a reference temperature for some of the experiments we used a IR camera (FLIR B300, about US$9000, accuracy of ±2 %)

Figure 3. Contact thermometers (Bios in bottom left, Oakton Acorn in bottom right) and five IR thermometers (above), four of which are pistol-shaped.

The stated accuracy of the hand-held IR thermometers varied between ± 1.5 to 2 °C, or 1 to 2 % (whichever is greater) typically over the approximate range of -50 to +400 °C. The range of interest to avalanche practitioners is a small part of the range of most IR thermometers as shown in Figure 4. According to the manufacturers, each of the tested thermometers was temperature compensated, meaning the reading should not be affected by the ambient air temperature. However, temperature compensation takes time. The instructions for one IR thermometer stated compensation could require at least 30 minutes.

The emissivity of each IR thermometers was set to 0.98, although values up to 1.0 are reasonable. Fortunately, for IR thermometers held within a metre of the snow surface, emissivity values within between 0.98 and 1.0 are unlikely to shift the temperature measurement by more than 0.2 °C (Shea and Jamieson, 2011).

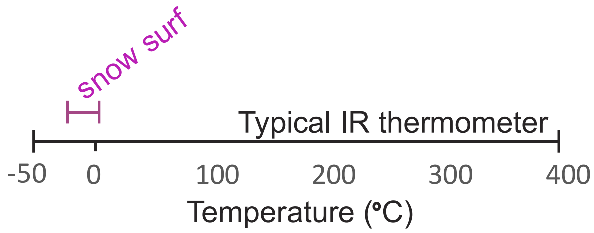

Figure 4. The range snow surface temperature of interest for avalanche forecasting along with the wider range of many hand-held IR thermometers.

3. METHODS

3.1 Accuracy of various IR thermometers for wet snow

The accuracy of the IR thermometers for a wet snow surface was tested on 2016-04-04 at a shaded valley bottom site where the snowpack was isothermal. Several centimeters of dirty wet snow were scraped away to expose an apparently clean wet snow surface. One at a time, each of the IR thermometers was pointed at 90° to the cleaned snow surface, held within 50 cm of the surface, at least 40 cm away from the operator's pant legs, and moved in small circles. To reduce heating of the snow surface by the operator, insulated clothing including gloves should be worn, and the operator should not have been with a few metres of the measurement site for more than a minute or so (Shea and Jamieson, 2011).

The average temperature over 5 seconds was recorded for each IR thermometer. To test the temperature compensation these measurements were made:

- promptly after the units were removed from the operator's jacket, and
- at several times while the units were exposed to the ambient air temperature for approximately 20 minutes in the shade

3.2 Shading of the snow surface

As is common in avalanche forecasting operations, an area of the snow surface was shaded with the blade of an inverted snow shovel (Figure 5). The dark shovel blade was 30 to 50 cm from the snow surface to allow for unimpeded convective heat exchange at the snow surface and reduce LW radiation from the shovel reaching the snow surface.

On sunny days as shown in Figure 5a, the shovel blade – especially the back - will absorb SW radiation, and all surfaces will radiate LW radiation. The snow surface and thermometers in shade of the blade can be warmed by LW radiation from the lifting surface of the blade. Increasing the distance of the blade from the snow surface will decrease this effect but reduce the effect of shading on cloudy days when most SW radiation is diffuse, i.e. when the boundary of the blade's shadow is not sharp. We did not experiment with varying distance between the shovel blade and the snow surface, nor with different colors of shovel blades.

Figure 5a. Shading of the snow surface by a shovel blade on a clear day. The temperature in the shade is being measured with the two contact thermometers.

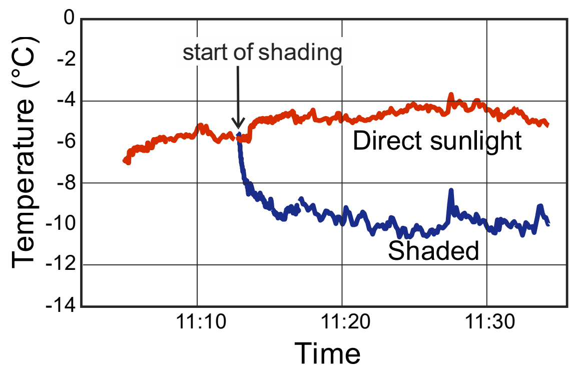

Figure 5b. Snow surface temperature from the IR camera in a pixel shaded by the shovel and an unshaded pixel.

3.3 <u>*Comparison of contact and IR thermometers under clear and cloudy skies*</u>

To compare the readings from two contact thermometers (Oakton Acorn and Bios) and three IR pistol thermometers, measurements were taken in the shade of a shovel on a sunny day (Figure 6) and a day with broken sky. On both days, the IR camera recorded the surface temperature in the shade of the shovel and outside the shaded area. The readings from the various thermometers were taken prior to shading (when the contact thermometers are expected to be warmer than the snow surface) and at various times after the shading shovel was placed.

Figure 6. Experiment in 2014 to compare the readings from two contact thermometers in the shade of the shovel and an IR thermometer (not shown).

4. RESULTS AND DISCUSSION

4.1 <u>*Accuracy of three handheld IR thermometers*</u>

As described in Section 3.1, on 2016-04-04 under cloudy skies in the shade of a tree, four readings were taken over 17 minutes (about 4 minutes apart) of a cleaned wet snow surface with three IR pistol thermometers, labelled IR 1, IR 2 and IR 3. Figure 7 shows the distribution of the four readings as box plots for each thermometer. Readings from IR 1 ranged from -2.6 to -3.4 °C. The readings from IR 2 and IR 3 each averaged -0.9 °C and had a narrower range.

The readings from IR 2 and IR 3 were within the stated accuracy of ±1.5 to 2 °C of the melting point. The averages from these two IR thermometers were below 0 °C. Readings from IR 1 averaged -2.9 °C, which is outside its stated accuracy.

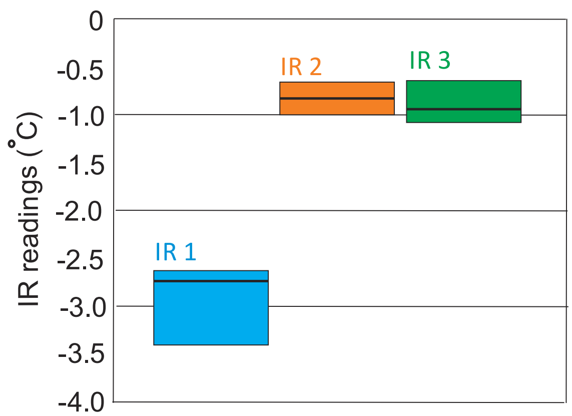

Figure 7. Box plots showing the range and median (thick line) of four readings of a wet snow surface by three IR thermometers shortly after removal from the operator's jacket.

4.2 <u>*Effect of exposing the sensors to ambient spring air temperature*</u>

Figure 8 shows the wet snow readings of three IR thermometers shortly after removal from the operator's jacket and 4 to 5 more times over 23 minutes. Between readings the thermometers were placed in the shade where the air temperature was 5.5 °C. The first readings for each IR thermometer are comparable to the readings in Figure 7. Readings from thermometers IR 1 and IR 2 decreased in the first 5 minutes. After 5 minutes, all thermometers showed an increasing trend. IR 3 showed the most stable readings, increasing from -1 °C to +0.1 °C. For all six readings, IR 1 was outside its stated accuracy during the exposure to ambient air temperature. For three of four readings after more than a minute of exposure to ambient air, IR 2 was also outside its stated accuracy. For IR 2 and IR 3, the most consistent readings were obtained promptly after removal from the operator's jacket.

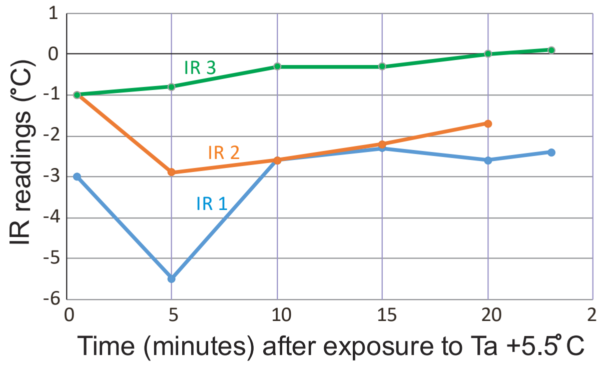

Figure 8. Time series of readings of a wet snow surface from three IR thermometers over 23 minutes after removal from the operator's jacket.

4.3 Comparing contact and IR thermometers

On a sunny day with the IR camera providing the reference snow surface temperature in the shade of a shovel and adjacent to the shaded area, readings were taken with two contact thermometers in the shade (Figure 9). Prior to the start of shovel shading at 11:13, both contact thermometers displayed temperatures near the melting point, which was approximately 6 °C above the surface temperature recorded by the IR camera. After the start of shovel shading, the IR camera shows that the snow surface took about 8 minutes to cool. The contact thermometers required a similar time to cool but the Acorn and Bios thermometers were approximately 4 and 5 °C, respectively, above the surface temperature as recorded by the IR camera. The contact thermometers in the shade were reading close to the surface temperature in the sun, but this was a coincidence.

Figure 10 shows the readings from the IR camera, a handheld IR thermometer (pistol) and the same two contact thermometers when the sky was broken. Prior to shovel shading, the contact thermometers were reading about 6.5 °C too high. After shovel shading, which started at 10:13, the contact thermometers were reading about 6 °C above the reference temperature. These errors are primarily due to the lower albedo of the contact thermometers compared to the snow surface.

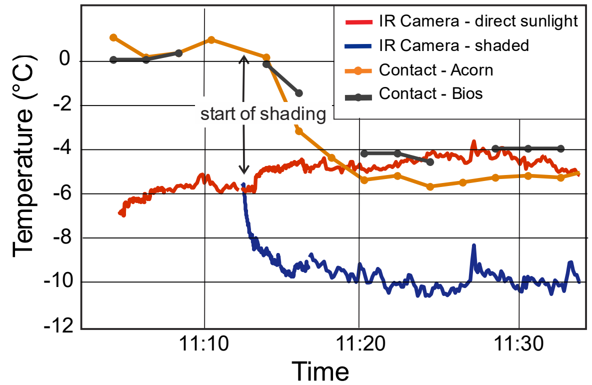

Figure 9. Surface temperature measured with two contact thermometers before and after shovel shading at 11:13 under clear sky compared to reference temperature from an IR camera.

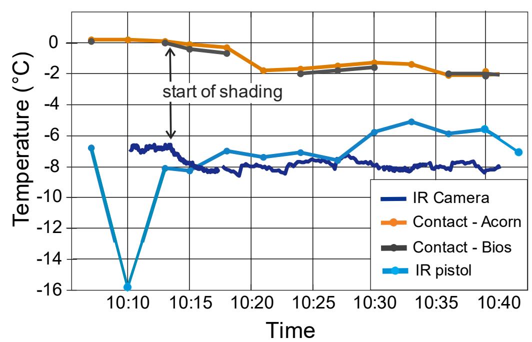

Figure 10. Surface temperature measured with two contact thermometers before and after shovel shading started at 10:13 compared to a reference temperature from an IR camera. The sky was broken.

Prior to shovel shading (Figure 10), the IR pistol was twice within its stated accuracy, which is about ±2 °C, and once about 7 °C below the reference temperature. After shovel shading the IR pistol was higher than the reference temperature by 1 °C or less for seven measurements and 2 to 3 °C higher than the reference temperature for four measurements. Only for two of the eleven measurements in the shade was the IR pistol error greater than the stated accuracy of 2 °C. These experiments were conducted in 2014. With different and newer IR thermometers in 2016 we found the accuracy of IR 2, IR 3 to be within specification (Figure 7).

5. CONCLUSIONS AND RECOMMENDATIONS

The snow surface temperature is difficult to measure accurately with any technology.

Since the albedo of contact thermometers is substantially lower than the albedo of snow, readings from contact thermometers can be substantially higher, e.g. up to 6 °C higher, than the snow surface temperature even in the shade. Handheld IR or tower mounted IR thermometers are preferable for measuring snow surface temperature. (Unfortunately, hand-held IR thermometers are not suited to measure the temperature profile on snow pit walls partly due to the typical exposure time of the pit wall as well as the effect of hollows, grooves, bumps and ridges in the pit wall (Schirmer and Jamieson, 2014)).

Before multiple units of the same make and model of inexpensive IR thermometers are purchased, the accuracy of a sample unit should be tested for the temperature range of interest or, at least, for slush (°C),

Our limited data suggest that temperature measurements with inexpensive IR thermometers should be done shortly after removal from a person's jacket. In the coming winter, we plan on testing IR thermometers shortly after removal from a backpack.

Some avalanche operations may choose to measure Tss in artificial shade. After shading by an object such as a shove blade, a sunny snow surface can cool for at least 8 minutes before reaching its shaded temperature. After shading begins, a contact thermometer on the surface will cool partly because it is absorbing less SW and partly because it is in contact with snow that is cooling.

Inferring the near surface faceting from a point-in-time surface temperature measurement (even with an IR thermometer) and a snow temperature measurement 10 cm below the snow surface is inferior to a few observations of the sky condition (J. Schweizer, pers. comm., 2016). When the sky is relatively clear for at least a few hours, faceting of near surface layers is more likely at night or on north quadrant slopes. Near surface faceting is best observed manually with a loupe and crystal screen. When manual field observations are impractical, snowpack evolution models such as SNOWPACK or CROCUS are useful.

Traditionally, at least in Canada (CAA, 2016, p. 4), shaded contact thermometers have been used to measure Tss once or twice a day in study plots. One reason for this measurement may be to track the change in surface temperature from day to day. However, the value of tracking Tss in a study plot is debatable, and Greene et al. (2010, p. 4) do not include this measurement in standard study plot observations.

If an operation chooses to measure Tss in a study plot, then an IR thermometer is preferable because of the large errors associated with contact thermometers.

Based on results and arguments presented above, Table 1 shows our suggestions for the type of observation or measurement for the three objectives of avalanche forecasting operations.

Table 1: Suggested type of thermometer or observation for the three typical objectives of avalanche forecasting operations related to surface temperature

	Objective		
	1.Near surface faceting	2. Tss change over days	3. Tss current
Reg. obs. in study plot	Sky	IR[a,b]	IR
Roving profile	Sky	n/a	IR

[a] same time each day
[b] in most study plots, surface exposure to sun/shade varies during the winter.

Especially in a roving snow profile in which the time required for measuring Tss takes away from other observations, we see little forecasting value in measuring Tss with a contact thermometer.

Reasons for continuing to measure snow surface temperature with contact thermometers in a study plot include: consistency with operational datasets, consistency with observation guidelines such as CAA (2016) or with training programs. For operations concerned that a switching to IR thermometers would compromise interpretation of their historical datasets for Tss, we suggest numerous, say 100, measurements with both types of thermometers under varied weather and snow surface conditions. This might facilitate a conversion for historical Tss measurements in level study plots, and might further clarify the limitations of contact and IR thermometers.

Even considering the 2 °C accuracy and limitations of inexpensive hand-held IR thermometers, they are more accurate than contact thermometers for measuring Tss. Also, IR thermometers can measure Tss when the snow surface is directly in the sun. For more on the science behind IR thermometers, see Shea and Jamieson (2011).

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