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RESEARCH REPORT

Continuous Snowpack Temperature Monitoring for the Idaho State Highway 21 Avalanche Program

RP 276

By

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16. Abstract

Predicting metamorphism within seasonal snowpacks is critical for avalanche forecasting and runoff timing as it relates to water supply management. Snowpack temperature gradients play a key role in snow metamorphism, and their magnitude controls how snow strength changes; therefore, they are of interest to avalanche forecasters. Before major melt, the snowpack must warm to isothermal conditions at 0^{o} C. Measuring this transition from warming to the ripening phase could help improve our current models for runoff timing. Measuring snowpack temperature gradients is currently a non-automated process that requires disturbance of the snow profile, and only gives a snapshot in time of the temperature conditions. Here we demonstrate an automated method to monitor in situ snowpack temperature using a thermocouple array, co-located with the Banner Summit SNOTEL site in central Idaho. Showing the location and duration of critical temperature gradients helps avalanche forecasters detect warning signs related to possible facet formation. During the 2019 winter, we observed large temperature gradients in the bottom 20cm of the snowpack, with the gradient falling below critical ($< 0.1^{o}$ C/cm) by early January. Critical gradients were observed near the surface throughout the winter, and temperatures were within $\pm 0.06^{o}$ C of the melting point when the snowpack became isothermal in the spring. We anticipate this dataset will inform snowpack energy balance models and aid in the prediction of avalanche hazards and runoff timing.

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Technical Advisory Committee

Each research project is overseen by a Technical Advisory Committee (TAC), which is led by an ITD project sponsor and project manager. The TAC is responsible for monitoring project progress, reviewing deliverables, ensuring that study objectives are met, and facilitating implementation of research recommendations, as appropriate. ITD's Research Program Manager appreciates the work of the following TAC members in guiding this research study.

- Project Sponsor: Michael Garz, P.E.
- Project Manager: Bill Nicholson
- TAC Members: Chantel Astorga
  Eric Nelson
- FHWA-Idaho Advisor: Brent Inghram, P.E.

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List of Abbreviations and Acronyms

BSTA	Banner Summit Temperature Array
CryoGARS	Cryosphere Geophysics and Remote Sensing
ITD	Idaho Transportation Department
BSU	Boise State University
SP&R	State Planning & Research (FHWA)
TAC	Technical Advisory Committee

Executive Summary

Avalanche forecasters monitor snowpack temperature throughout the winter, because the vertical snowpack temperature profile is one of the major controls on whether snow is strengthening or weakening and is an indicator of liquid water movement. Manual snow temperature observations are very time consuming, and cause disturbance to the site, and therefore time series observations even at intensive snow research areas are made, at best, monthly. Boise State's Cryosphere Geophysics and Remote Sensing (CryoGARS) group began discussing with the Idaho Transportation Department's Avalanche Team (District 3) about possibilities for continuous snow temperature observations at Banner Summit in 2018. This developed into a proposal for a feasibility study for continuous temperature observations, with two objectives to support avalanche forecasting: 1) track temperature gradients at the base of the snowpack and in the near surface, to estimate if strengthening or weakening is taking place, and 2) track the temperature profile in the spring, and determine when the snowpack reaches the melting point throughout, leading to liquid water movement.

The stability of a snow slope from an avalanche perspective is a function of the strength of the snowpack as a function of depth, and the overburden load. The load can be estimated from measurements of precipitation at weather stations and snow study plots and knowledge of slope angles but tracking snow strength is much more complex. Snowfall creates snow grains that are highly unstable, and continuously undergo rapid change throughout their lifespan, from the time they are formed in the atmosphere, until they melt and enter the soil as liquid water. The way in which snow grains change and develop bonds, termed snow metamorphism, is controlled by overburden load, and the temperature conditions present.

Predicting metamorphism within seasonal snowpacks is critical for avalanche forecasting, as the type of metamorphism controls whether a given layer is strengthening or weakening. There are two different types of snow metamorphism: 1) *equilibrium metamorphism*, in which snow grains round and form bonds between each other, and 2) *kinetic metamorphism*, where grains grow sharp corners and become poorly bonded. The dominant form of metamorphism depends on the temperature gradient, and therefore continuously monitoring snow temperature could provide a valuable tool for avalanche forecasting.

The *absolute temperature* controls the speed of metamorphism, and the magnitude of the *temperature gradient* (the change in temperature with depth) controls how snow strength changes; therefore, temperature profiles are of interest to avalanche forecasters. Before major melt, the snowpack must warm to isothermal conditions at 0 degrees Celcius (^{o} C). Measuring this transition from dry to wet snow will help improve our current models for runoff timing, which impacts wet snow avalanches. Measuring snowpack temperature gradients is currently a non-automated process that requires disturbance of the snow profile, and only gives a snapshot in time of the temperature conditions. Here we demonstrate an automated method to monitor in situ snowpack temperature using a thermocouple array, co-located with the Banner Summit SNOTEL site in central Idaho. Showing the location and duration of critical temperature gradients can help avalanche forecasters detect warning signs related to possible facet formation. During the 2019 winter, we observed large temperature gradients in the bottom 20 centimeters (cm) of the snowpack, with the gradient falling below critical ($< 10^{o}$ C/m) by early January.

Critical gradients were observed near the surface throughout the winter, and measured temperatures were within ±0.06° C of the melting point when the snowpack became isothermal in the spring. We anticipate this dataset will inform snowpack energy balance models and aid in the prediction of avalanche hazards and runoff timing.

This research project has shown that monitoring snow temperature in a 3-meter snowpack is viable and can provide accurate temperature profiles at 5cm resolution throughout the snow season. We demonstrated that temperature gradients can be monitored, to track strengthening/weakening conditions, as well as the onset of spring snowmelt. A temperature array design, based on a similar study for snow hydrology in a 1.5-meter snowpack, was slightly modified. This design includes a welded steel frame with thin horizontal cables that support thermocouples and reference thermistors. Using a data logger, two multiplexers, and a satellite modem, we developed a package that transmitted the snow and near surface air temperature profile every hour. We worked with the District 3 Avalanche Team and Snowbound Solutions to import this data into their system and visualize the continuous snow temperature observations. The objective of continuously observing snow temperature, logging hourly and transmitting to the District 3 Avalanche Team's database, and visualizing the data, has been achieved.

To move this method into practice, some work is required to link the snow temperature observations at Banner Summit, directly to snow conditions in the starting zones that affect Idaho HW21. This is the age-old issue of relating point observations to regional conditions and requires a longer time series to develop statistical or experience-based relationships between point index sites, and larger regions. The highest priority next step is to keep the temperature time series going. We might need 5 years of data to develop statistically significant relationships. Snow modeling could really help improve the accuracy and amount of data required but would need field campaigns to calibrate the models. As part of the NASA SnowEx Mission, we flew high resolution airborne LiDAR over the HW21 corridor in February 2020 and February 2021 and performed weekly snowpit observations. These 0.5m resolution snow depth maps, and weekly snowpit time series, will greatly improve our ability to spatially model snow conditions throughout the winter, which in turn will help build relationships between the Banner Summit snow study site and the HW21 avalanche starting zones.

1. Introduction

Avalanche forecasters monitor snowpack temperature throughout the winter, because the vertical snowpack temperature profile is one of the major controls on whether snow is strengthening or weakening and is an indicator of liquid water movement. Manual snow temperature observations are very time consuming, and cause disturbance to the site, and therefore time series observations even at intensive snow research areas are made, at best, monthly. Boise State's Cryosphere Geophysics and Remote Sensing (CryoGARS) group began discussing with the Idaho Transportation Department's Avalanche Team (District 3) about possibilities for continuous snow temperature observations at Banner Summit in 2018. This developed into a proposal for a feasibility study for continuous temperature observations to support avalanche forecasting, with two objectives: 1) track temperature gradients at the base of the snowpack and in the near surface, to estimate if strengthening or weakening is taking place, and 2) track the temperature profile in the spring, and determine when the snowpack reaches the melting point throughout, leading to liquid water movement.

Snow in Idaho serves a critical role not only for recreationists but for the state economy. A majority of irrigated agriculture in Idaho relies on surface water managed by a series of canals and reservoir systems. A majority of this water comes as snow during the winter months and is then stored in reservoirs for use during the growing season. Because of this, water managers in Idaho are actively looking for ways to better predict snowmelt runoff. Also, snow and snowmelt can have significant impacts on infrastructure and transportation throughout the state. Avalanches in central Idaho cause closures on Idaho State Highway 21 and there is a strong push by local avalanche forecasters to better measure temperature conditions of the snowpack leading up to elevated avalanche hazards. By looking at specific snowpack characteristics, it is possible to gain insight into conditions leading to avalanche hazards, floods caused by rain on snow events, and significant runoff.

The physical properties of snow play an essential role in avalanche prediction. Under the right conditions, temperature gradients within a snowpack drive vapor migration. As vapor migrates through the snowpack, it changes the snow's microstructure and can lead to a substantial water loss of 15-20 percent (Hood et al., 1999; Marks and Dozier, 1992; Kattelmann and Elder, 1991). Continuous monitoring of snowpack temperature gradients is valuable for avalanche forecasting because the development of weak, faceted layers, such as depth hoar, depends on a temperature gradient. Depth hoar is a snow crystal type that grows under strong temperature gradients at the base of snowpacks and provides a weak layer for slab avalanches. The rate at which this process (called kinetic metamorphism) occurs depends on several different factors, including the initial snow characteristics, magnitude and duration of temperature gradients, vapor barriers caused by ice layers, and the snowpack's cold content (Sommerfeld and LaChapelle, 1970; Colbeck, 1983). Although this is a continuous process that occurs over a wide range of temperature gradients, the critical gradient to produce faceted forms in alpine snow is about 0.1^{o} C/cm (e.g., Mcclung and Schaerer, 2009). When temperature gradients are less than critical, the snow undergoes primarily equilibrium metamorphism and water molecules move mainly by vapor diffusion to new positions that decrease the surface free energy (Sommerfeld and LaChapelle, 1970). Thus, equillibrium metamorphism is controlled by surface curvature effects, and leads to rounding and bonds forming between individual snow grains. Both time and temperature are significant factors in determining the stage of metamorphism. If the snow is very cold, it will change slowly; and if it's close to the freezing point, it can change rapidly. In the case of depth hoar, if the critical temperature gradient no longer persists, the snow will undergo equillibrium metamorphism, which breaks down many of its facets (Sommerfeld and LaChapelle, 1970).

It is important to consider the thermal conductivity of snow, which plays an important role in the transfer of energy within the snowpack. The thermal properties of snow vary with density, microstructure, and temperature (Arenson et al., 2015). The thermal conductivity of snow ranges from 0.04 to 1 Watts per meter per degree (W/m/K) over the density range of 100 - 550 kilograms per cubic meter (kg/m^3). Although thermal conductivity varies primarily with density, variations in microstructure and crystal anisotropic orientation can affect it by a factor of two. Figure 1.1 shows how effective thermal conductivity increases with snow density. Thermal conductivity variations near ice layers can induce large temperature gradients that lead to faceted, weak layer formation, and can be a significant cause of avalanches (Arenson et al., 2015). Banner Summit's snowpack rarely forms ice layers during the dry snow season, because air temperatures remain below 0 °C for the majority of the winter, which prohibits the initial melt required to form an ice layer.

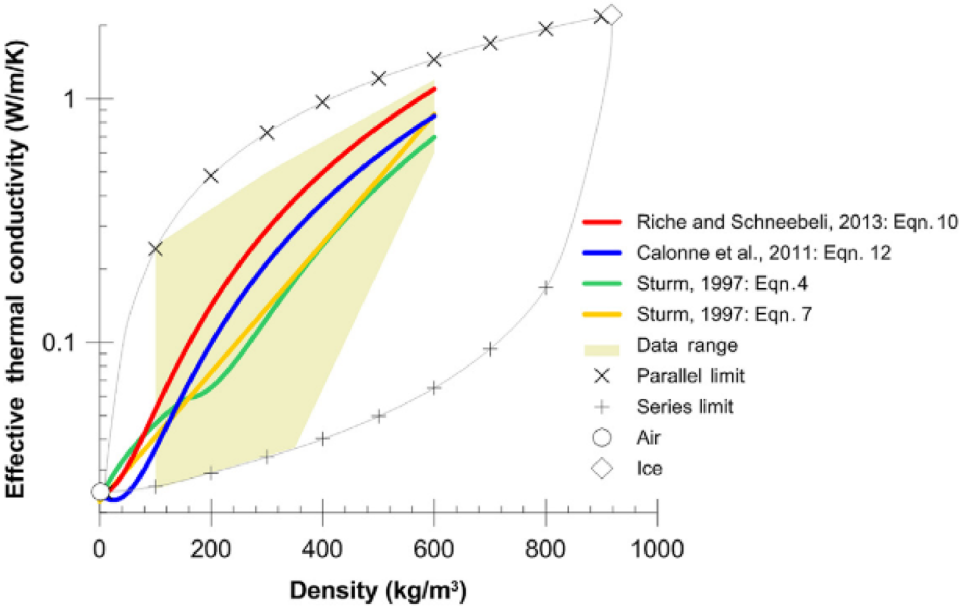

Figure 1.1: Variation of thermal conductivity with density, the range of data in the literature summarized by Sturm et al. (1997), and several proposed models (from Arenson et al., 2015).

Near Banner Summit in Idaho, a significant concern for avalanche forecasters is in the development of depth hoar. Depth hoar is large-grained, faceted, cup-shaped crystals near the ground and forms because of large temperature gradients within the snowpack (Akitaya, 1974). Depth hoar most commonly forms in the early season because the snowpack is shallow, and there is not much snow insulating the lowest layers from the cold atmosphere. The geothermal heat flux keeps the snow-ground interface temperature very close to 0° C (Figure 1.2). This condition, combined with a shallow snowpack and cold air temperatures, leads to large sustained temperature gradients in the early season. The duration and magnitude of critical temperature gradients in the lower snowpack is not frequently measured, as typically it is measured during manual snowpit observations; for example, the ITD avalanche forecasters measure this gradient once per month.

Dry-snow avalanches are primarily a concern in fall and winter. As spring approaches, a snowpack temperature profile provides insight into the snowmelt process and can indicate when wet snow avalanches are possible. There are three primary phases a snowpack must go through to have considerable melt and runoff: *warming, ripening, and output* (Dingman, 2015); these terms relate to the melting stage of the snowpack, as it progresses from dry to saturated, and are described in more detail below. Any energy absorbed by the sub-freezing snowpack during the *warming phase* raises its average temperature until it reaches isothermal conditions at 0° C. This energy required to warm a snowpack to isothermal conditions is known as the cold content (Q_{cc}), and can be calculated directly from the temperature profile (Dingman, 2015):

$$Q_{cc} = -c_i * p_w * h_m * (T_s - T_m)$$

Where c_i is the heat capacity of ice, T_s is the average temperature of the snowpack, T_m is the melting point of ice, ρ_w is the density of water, and h_m is the snow water equivalent (SWE).

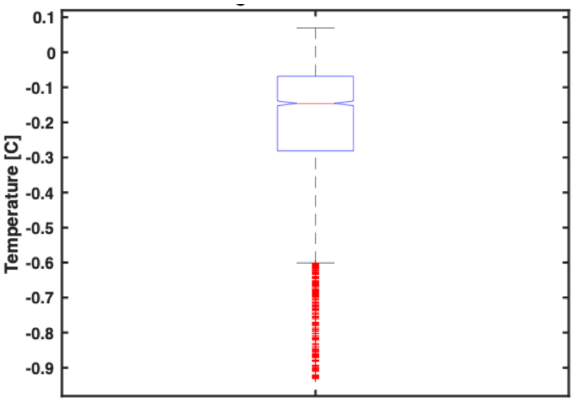

Figure 1.2: Temperature of the snow-ground interface measured with the BSTA during Winter 2019.

Once the snowpack is isothermal, it enters the *ripening phase* where absorbed energy melts snow, but the meltwater is retained in the snowpack by surface tension forces. After the snowpack reaches its water holding capacity and it is "ripe," it enters the *output phase* where further absorption of energy produces water output (Dingman, 2015). Because isothermal conditions mark the beginning of the ripening phase, it may be possible to predict snowmelt runoff timing more accurately by measuring the snowpack's temperature profile continuously.

Snow is a prime example of the observer effect; the mere observation of a phenomenon within the snowpack inevitably changes the phenomenon. The current method for measuring the temperature profile of a snowpack is a time consuming, destructive process that is not automated. It requires someone to dig a snow pit and manually measure the snow temperature by inserting probes at equal depth intervals. Not only does this disturb the snow profile and change its characteristics, but it is a snapshot in time, while snow temperature conditions change on an hourly time scale in the upper part of the snowpack, and on a weekly time scale at depth. Until this project, there has been no continuous record of the snowpack temperature profile at Banner Summit, and avalanche forecasters with the Idaho Transportation Department are interested in measuring the magnitude and duration of critical temperature gradients in the upper 25cm and lowest 20cm of the snowpack. They perform monthly in-situ snowpits and measure the gradient manually.

It is important to note that current technology can only measure a snowpack temperature profile at a single point in space, rather than the basin scale. Although snowpack conditions can vary widely at the basin scale, the Banner Summit Thermocouple Array (BSTA) serves as a valuable tool because it may be possible to build statistical relationships between this site and a nearby basin, or avalanche starting zones. The purpose of this study was to develop a mechanism for collecting a continuous record of snow temperature at various depths, to provide the ability to track snow temperature conditions that lead to avalanches.

In this study, we have continuously measured the snowpack temperature profile at Banner Summit, since fall 2018. This data further develops our understanding of temperature gradient metamorphism in snow, it provides insight into snowpack processes that lead to significant snowmelt, and helps address the following questions:

1. What is the duration and magnitude of temperature gradients in the upper and lower portions of the snowpack?
2. How long do critical temperature gradients persist?
3. Can the onset of liquid water movement in the snowpack be detected from the temperature profile?

We present a continuous snowpack temperature monitoring system, the BSTA, along with methods for analyzing temperature gradient metamorphism and melt. Results suggest this instrument is successful at measuring the temperature profile of a snowpack with an accuracy of ±0.06° C and an uncertainty in temperature gradient estimates of ±0.003° C/cm. These temperature uncertainty estimates are based on temperatures measured in wet snow, and temperature gradient uncertainy is based on Monte Carlo simulations using estimates of temperature uncertainty, combined with uncertainty in temperature probe positions.

2. Literature Review

Few studies have proposed methods for continuous monitoring of the snowpack temperature profile. One commercial instrument that measures snow temperature is the SM4 temperature and snow depth sensor. The NIVEXC is another instrument that has been used to record temperature profile measurements. Both of these systems are installed at avalanche starting zones and they measure temperature gradients using thermistors. In addition to these sensors designed for avalanche starting areas, Conway and Benedict (1994) created a thermistor array designed to study the infiltration of water during rain-on-snow events.

The main objective of the SM4 (Ingolfsson and Grimsdottir, 2008) is to accurately measure snow depth in avalanche starting areas. The SM4 is series of digital thermistors mounted at 20cm intervals on a pole that extends through the snowpack (Figure 2.1). The SM4 measures snow depth by identifying thermistors buried in the snow, based on damping of temperature fluctuations that is caused by the snowpack's insulating properties. Ingolfsson and Grimsdottir (2008) have developed an algorithm that calculates the snow depth as a function of the temperature profile. This snow depth algorithm can be more reliable than acoustic snow depth sensors during storms and ice buildup. However, the algorithm is challenged when the temperature of the atmosphere approaches the temperature of the snowpack. It is typically installed in avalanche starting areas where it is coupled with ultrasonic snow depth sensors for verification. Measurements are logged with a 1-5 minute interval and are regularly transferred to a central computer through wireless GSM telephone connection. In addition to snow depth, the SM4 is being used to detect and visualize high temperature gradients within the snowpack.

Figure 2.1: An ultrasonic sensor and a SM4 snow depth sensor covered with icing.

Like the SM4, the NIVEXC (Barbolini et al., 2013) is designed to accurately measure snow depth in avalanche starting areas. The NIVEXC is an electronic snow-pole with a vertical array of sensors. It is able to record and transmit important snow cover properties, such as total snow height, snow precipitation amounts and rates, and temperature profiles. Although the SM4 and the NIVEXC both measure the temperature profile of a snowpack, their primary objective is to indirectly measure snow depth through the temperature dampening effect caused by the snowpack. One limitation of both these products is the vertical resolution, which is only 20cm. In addition, melt water tends to run down the sensor, causing incorrect temperature readings as soon as any surface melt occurs.

Conway and Benedict (1994) used a rectangular grid of thermistors to study the infiltration of water during two midwinter rain-on-snow events, to better understand avalanches occurring during these rain events. The progress of wetting is tracked in real time by monitoring changes in the position of the zero-degree isotherm. Conway and Benedict (1994) used these methods to calculate the infiltration rate and found that infiltration was not uniform. Water penetrated through localized channels that often occupied less than 50 percent of the total volume of the snowpack. Their sensor array was installed at 915m elevation in the Cascade Mountains near Snoqualmie Pass, Washington during 1991-1992. Measurements were made at 15-minute intervals using up to 110 thermistors (Thermometrics p100DA202M) multiplexed to a data logger. The thermistors were wrapped in white heat-shrink tubing and white epoxy to make them waterproof and minimize heating from solar radiation. Each thermistor was field calibrated at the melting point for seasonal snow. Calibration was achieved at a time when the snow surrounding the thermistor was ripe and the electrical resistance of the thermistor had stabilized to a constant temperature. The temperature of ripe snow is 0^{o} C. The temperature resolution was better than $\pm 0.01^{o}$ C.

The thermistors were arranged in a vertical, rectangular grid 1.5 m wide and up to 2 m deep. Each string consisted of 11 thermistors spaced 15 cm apart. A parallel horizontal string set at the same height 1 m away supported the leads from the thermistor beads to the multiplexer. The vertical spacing between thermistors was about 15 cm, but the thermistors were free to settle with the snowpack and the spacing decreased with time.

Charlie Luce and Tom Black with the USFS (Luce and Black, 2018) in Boise, ID constructed a thermocouple array that was installed at Bogus Basin, ID for snow hydrology studies. The design for the Banner Summit Thermocouple Array (BSTA) is based on the thermocouple array at Bogus Basin. Charlie and Tom shared their designs and information during a meeting in October of 2018.

In summary, few studies have monitored snow temperature continuously. Two instruments in development were designed to measure snow depth in avalanche starting zones, but depth resolution (20cm) is too low for this application, and the accuracy of the temperature measurements is not known. These two instruments were developed as part of several research studies, but do not appear to be commercially available. One study showed that liquid water movement could be detected using high accuracy temperature sensors. We collaborated with a group from the USFS Rocky Mountain Research Station in Boise, who shared their design for a snow temperature array they built for snow hydrology studies, which we modified slightly in the BSTA.

3. Methods

This section covers the approach to measuring snow temperature continuously with a thermocouple array, and the analysis approach for calculating temperature gradients.

3.1 Thermocouple Array

Our temperature sensor is located at Banner Creek Summit in central Idaho. This location has an elevation of about 7,040 feet above sea level and is proximal to Idaho State Highway 21. The area around Banner Summit receives an average of 1.9 meters of snow each year and frequently experiences extreme low temperatures, as low as -40^o C. The 2018-2019 winter season experienced an above-average snowfall, with a peak snow water equivalent (SWE) measured at Banner Summit of 120 percent of average. Site visits occurred on a biweekly basis unless weather or road closures prevented access. During each visit, we downloaded data from the instrument and snow samples were collected for stable water isotope analysis. Figure 3.1 shows a picture of the array at Banner Summit SNOTEL in late spring.

Figure 3.1: BSTA at the Banner Summit SNOTEL site.

The structure of our sensor is comprised of a steel, rectangular frame with thin, metal cables running horizontally in 5cm increments (Figure 3.2). A single Omega Type T thermocouple is attached to each wire, a quarter distance between the two support posts, which forms a vertical array of temperature sensors spaced 5cm apart, up to 2.5m above the ground. Two thermocouples are buried in the soil at 10cm and 5cm below ground. The buried 10cm thermocouple was installed directly adjacent to a thermistor (Campbell Scientific T107) for absolute calibration, as the thermocouples measure temperature differences very accurately. The 53 thermocouples were multiplexed using a Campbell Scientific AM32 to a Campbell Scientific CR1000 data logger. Temperature measurements were recorded every 5 minutes. The design for this sensor came from Charlie Luce and Tom Black at the USFS and it was based off an existing sensor installed at Bogus Basin, near Boise, ID, with some improvements.

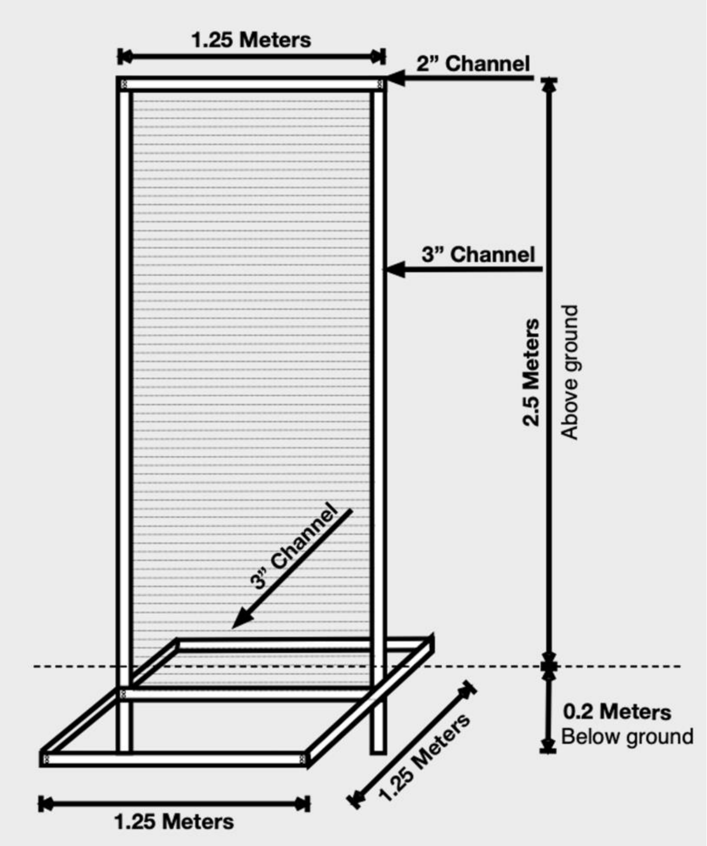

Figure 3.2: Diagram of the Banner Summit Thermocouple Array Structure

A Micro-Specialties satellite telemetry system was installed during the 2020 water year so that data were accessible in near-real time. Data was transmitted every six hours using an hourly average from the measurements taken the hour before each transmit. In Winter 2020, the output was increased to hourly at the request of the avalanche forecasters and is currently functioning and transmitting in real time. A visualization of the temperature profile is now available within the District 3 Avalanche Team’s database and visualization system, in collaboration with Snowbound Solutions, which is updated hourly.

3.2 Temperature Gradient Analysis

In this analysis, we calculated the hourly average temperature gradients in the upper 25cm and the lowest 20cm of the snowpack using a first-order polynomial regression between depth and temperature (Figure 3.3). The slope of each polynomial, i.e., the temperature gradients in the upper 25cm and lowest 20cm, were automatically calculated every hour and stored in a database. This was done in MATLAB using the built-in function *polyfit.m*.

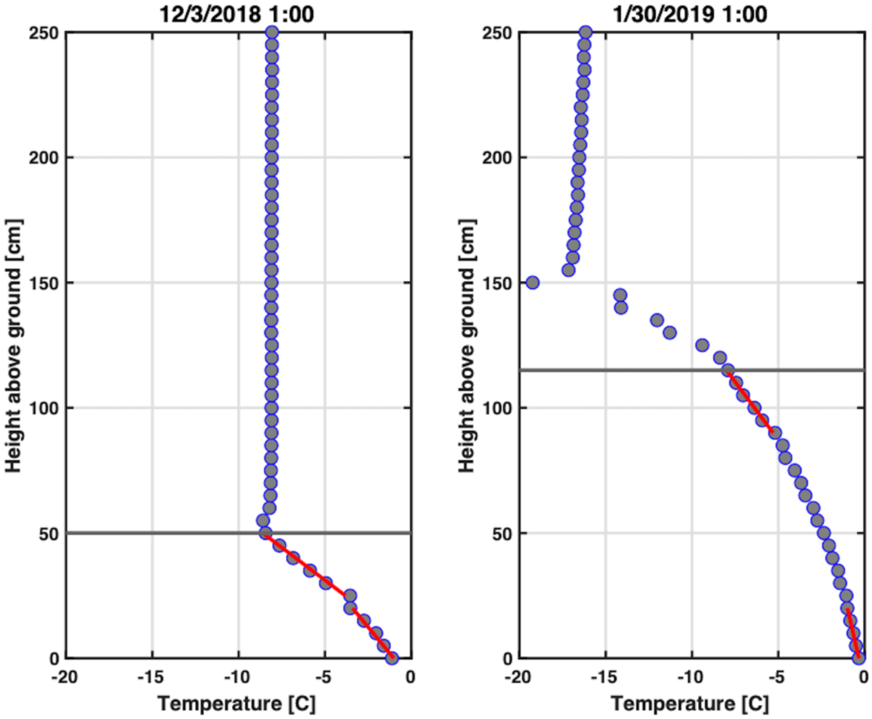

Figure 3.3: Snow temperature profile examples. Black line is snow surface, red lines are locations where upper and lower snowpack temperature gradients are calculated.

There are three significant features observed from this dataset: 1) a gradient in the lower 20cm, which is the location of observed depth hoar and the depth over which avalanche forecasters are most often interested in tracking the temperature gradient, 2) a near surface temperature gradient that changes diurnally and is often the location of the largest gradient, and 3) a snow surface temperature that is below the air temperature much of the time, due to longwave emission and sublimation.

Data in the upper 25cm are selected because solar radiation penetrates between ~15 - 25cm depth, and the upper 25cm experiences significant diurnal variations. Additionally, the ITD avalanche forecasters are primarily interested in temperature gradients in the upper 25cm, and at the base of the snowpack. The snow surface for the upper 25cm calculation is measured by the nearby SNOTEL site. Snow bridging increases the uncertainty of the temperature gradient measurements in the upper 25cm but has a minimal impact on measurements deeper in the snowpack. The lowest 20cm are selected because there was an observed change in snow structure in this layer during December, and this is the location that has experienced a significant temperature gradient for the longest period. It is of interest to know when this location's temperature gradient drops below the critical threshold and starts to strengthen.

The temperature gradient analysis focuses on three subsets from the 2018-2019 winter season. These three subsets are selected because they illustrate critical elements of how temperature gradients evolve throughout the season. An early-season subset between November 31 to December 28 shows large temperature gradients throughout the shallow snowpack; observations made in snowpits on these two dates show depth hoar existed at the base of the snowpack. A mid-season subset during February shows extreme cold events and significant snowfall; the lowest portion of the snowpack is well insulated and no longer experiences critical temperature gradients. The late-season subset during March shows the snowpack as it reaches isothermal conditions.

Temperature gradients at the top of the snowpack change diurnally because it is not completely insulated from the air. In cold, alpine environments such as Banner Summit, there was often extreme temperature gradients in the top 25cm that can lead to the formation of faceted snow.

4. Results

4.1 Thermocouple Array

The instrument was installed and fully operational on November 16, 2018 and has collected continuous temperature measurements for three complete seasons. Some challenges have included: (i) sagging of the support cables, (ii) snow bridging between vertical steel supports causing a deeper snow profile, (iii) snow depths exceeded the height of our uppermost sensor, (iv) some thermocouples functioning intermittently, and (iv) channelized/irregular melt patterns around the structure of the sensor in the spring. Despite the above challenges, this dataset suggests that it is possible to use this instrument as a tool for continuously measuring the temperature profile of a snowpack.

Throughout the season, as snow accumulates, the settling snowpack applies an increasing downward force on the sensor. As a result, some of the support cables sag a few centimeters. In 2020, springs were added to each cable to reduce the amount of sag; this was successful and greatly reduced error in the height of each measurement. The cables also act as a support for the snowpack, so as the snow settles, there is often an elevated snow surface at the temperature array (Figure 4.1, 4.2). Figure 4.1 shows the temperature profile as a function of depth and time, with the colorbar on the right in degrees Celcius. The white line shows the SNOTEL measured snow depth, however the temperature profile indicates the total depth is likely at the location indicated in pink in Figure 4.1. This larger snow depth at the array was confirmed during site visits, due to the wires preventing settlement and drifting snow (Figure 4.2). This promotes the growth of a snow bridge between the two vertical supports. This bridging effect is observable in this data when comparing the snow depth to the temperature profile. The past 2 seasons we visited the site weekly and removed the accumulated snow sticking to the cables, reducing this problem.

Thermocouples buried in the soil and at the ground surface consistently read about 0^{o} C (as previously illustrated in Figure 1.2, page 13). Moving up through the snowpack during cold conditions, there is a consistent temperature decrease from the 0^{o} C ground measurement to the air temperature. The array of thermocouples above the snowpack typically measures the same temperature at this wind protected site and have much larger diurnal fluctuation than buried sensors. The snowpack has a large damping effect on temperature fluctuations which makes it possible to estimate snow depth using the temperature profile. However, the snow bridging is evident (Figure 4.1, 4.2).

An alternative approach to visualizing snow and air temperatures from the BSTA is shown in Figure 4.3. In this example, temperature measurements deep in the snowpack (0-55cm, top) show large variations with depth, and change at a weekly time scale. Temperature probes above the snow surface (bottom) all show very similar temperatures, until they are buried. The same time period (December 2018) is also shown in Figure 4.4 as a heatmap, with temperature shown as colors (colorbar in degrees Celcius on right in Figure 4.4), as a function of depth (y-axis) and time (x-axis).

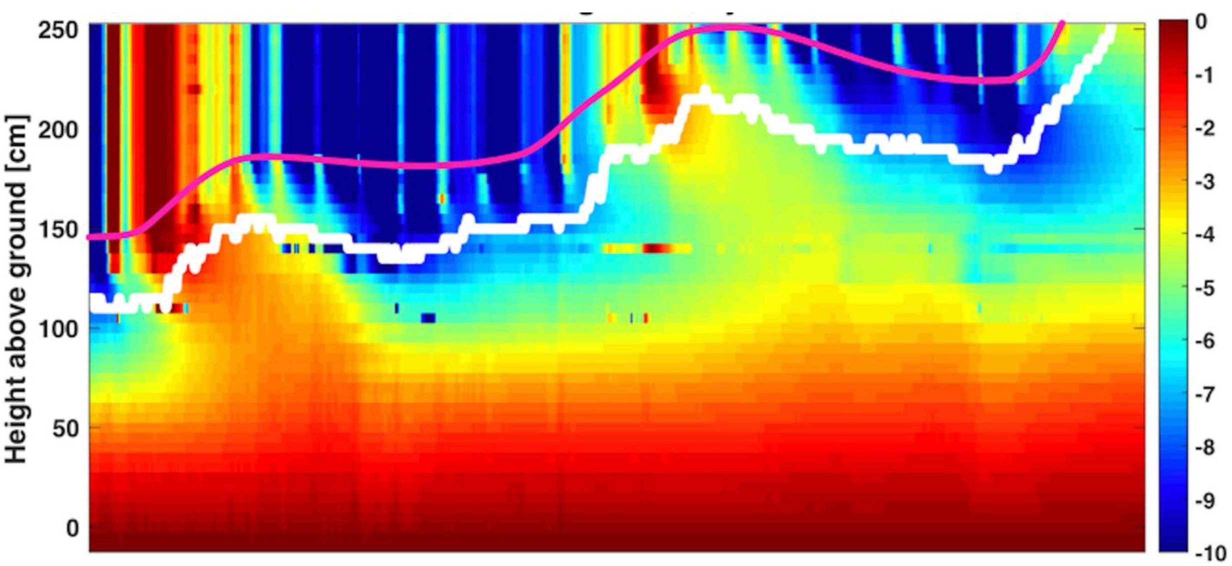

Figure 4.1: Temperature profile of snowpack vs. time, Banner Summit, Feb 2020.

Figure 4.2: Photograph of instrument array on 01/18/19 showing major snow accumulation.

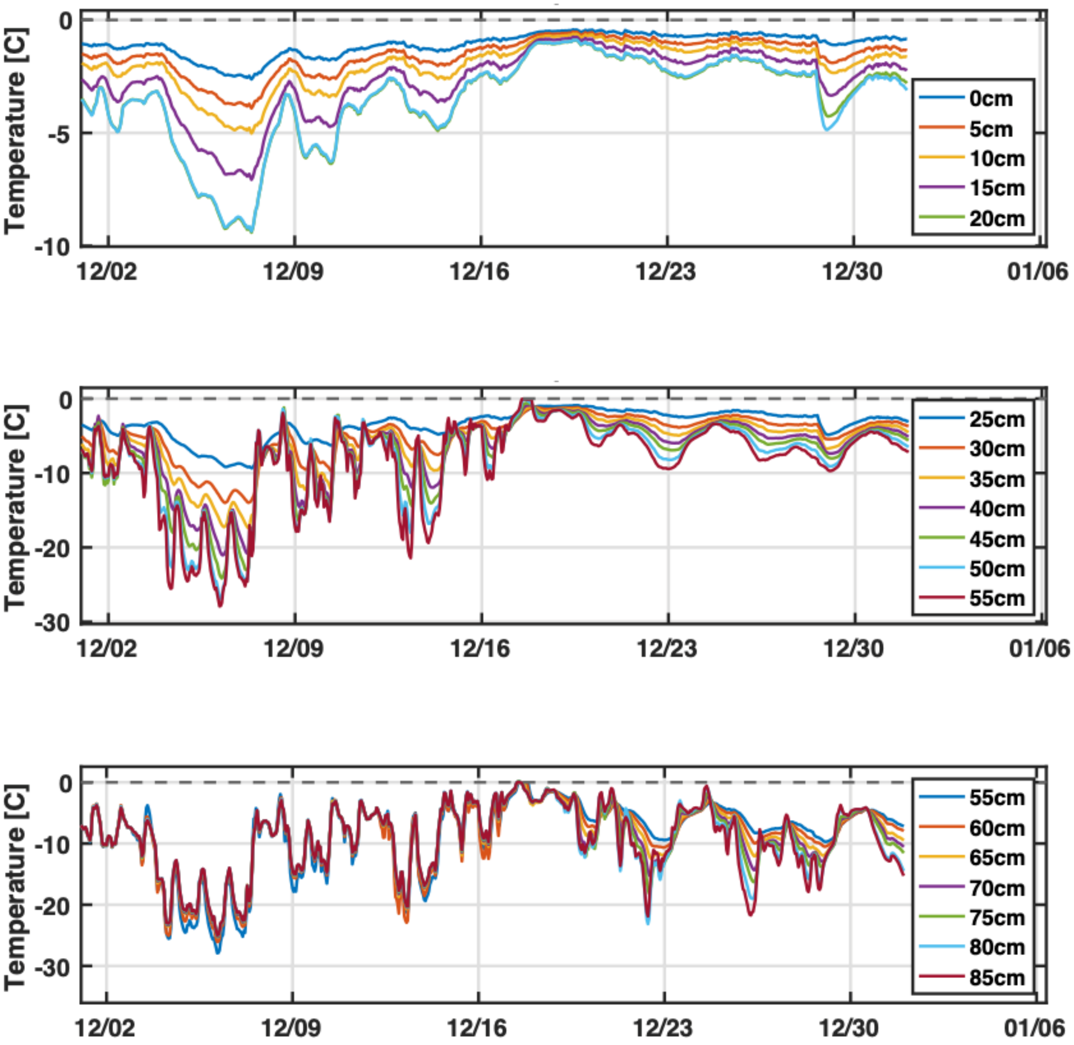

Figure 4.3: Temperature as a function of time, at different heights above the ground.

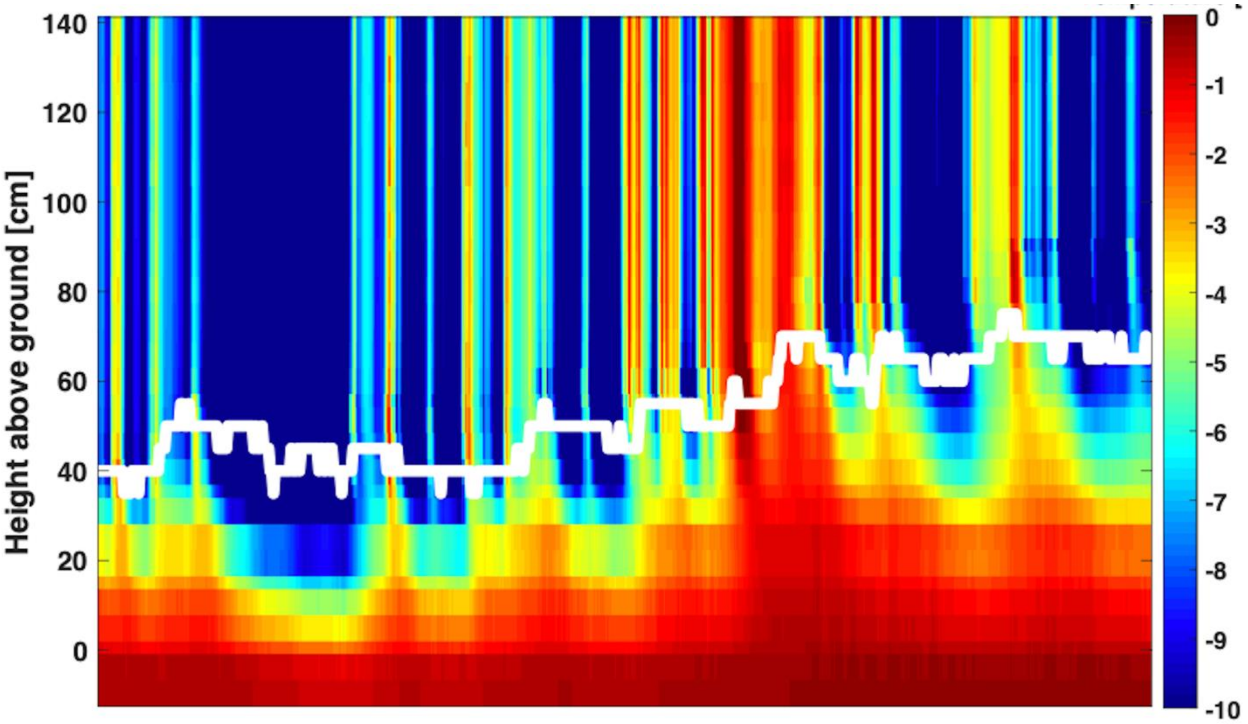

Figure 4.4: BSTA temperature measurements between December 1 – 30, shown with color scale (right) in degrees C. Snow depth is indicated by the white line.

The precision and accuracy of this instrument is tested during isothermal conditions in the snowpack. During water year 2019, the snowpack went isothermal around March 31. Following warm storm events in early April that deposited a few inches of snow, peak snowmelt started on April 16. This followed a couple warm storm events that deposited a few inches of snow in early April. The instrument has an uncertainty ±0.06^{o} C, which is the standard deviation of all the thermocouple measurements during the isothermal snow conditions, when the snow was saturated with liquid water. As seen in Figure 4.5, thermocouples show variations less than ±0.05, with the exception of a bad thermocouple at a height of 80cm, and the soil thermocouples. The histogram of temperatures during this period is shown in Figure 4.6. An uncertainty of ±0.06^{o} C is a very conservative estimate, with temperature accuracies closer to ±0.03^{o} C for majority of the depths. We use the conservative estimate of ±0.06^{o} C for simulating the uncertainty in temperature gradient estimates. Since the thermocouples we used measure temperature differences relative to each other, and have very linear behavior, we assume this estimate of uncertainty is valid for the entire temperature range measured.

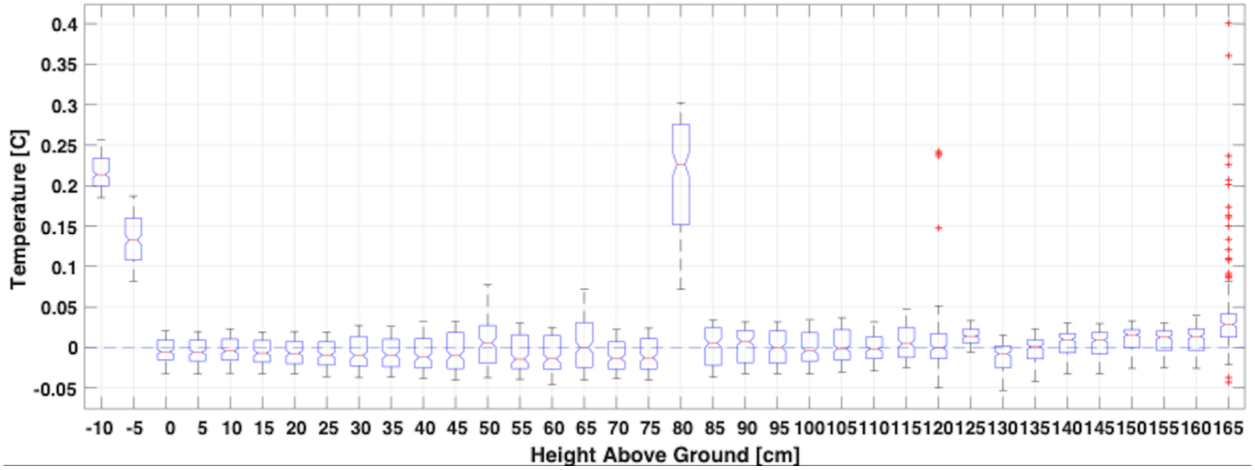

Figure 4.5: Hourly average temperature for each thermocouple during April 2019.

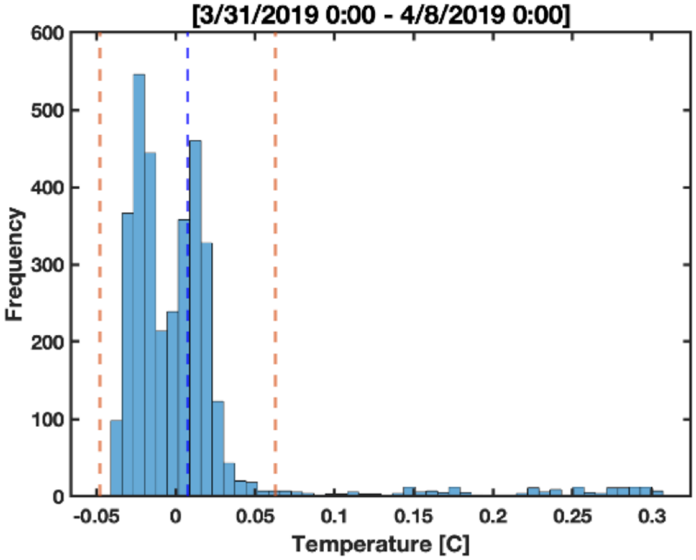

Figure 4.6: Histogram of the temperature at BSTA in April 2019 (standard deviation = ±0.06 degrees C).

In the beginning of April, each buried thermocouple showed very little daily temperature fluctuations (Figure 4.7). Directly after peak snowmelt started, the daily range for each thermocouple increased greatly and in some cases is larger than 1° C. This increase in temperature fluctuation is likely caused by preferential flow of snowmelt due to the instrument. During the melt season, a channel formed between the two vertical supports creating a depression in the snow surface where the thermocouples are placed. Because the instrument has different thermal properties (e.g. albedo and thermal conductivity), it affects melt rates and characteristics of the snow it is in contact with. It is suspected that the instrument facilitates an increased downward flow of water which creates air pockets around the sensor that affect its ability to accurately measure snow temperature in the spring; however this effect is much less than that from a vertical temperature string such as those discussed in the Literature Review.

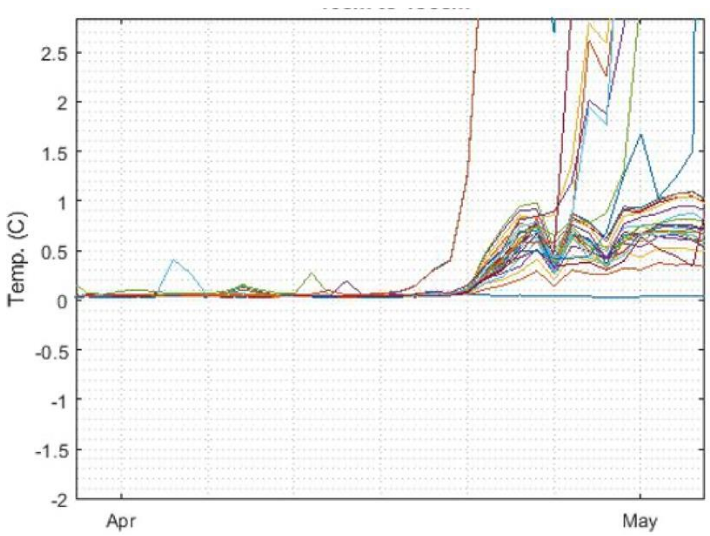

Figure 4.7: The daily temperature range for each thermocouple between -10cm to 135cm.

4.2 Temperature Gradient Analysis

Avalanche forecasters are primarily interested in the timing and duration of critical temperature gradients in the snowpack. Figure 4.8 shows temperature gradients in the upper 25cm (top) and the lowest 20cm (bottom) throughout the whole period of record. These results suggest that higher than critical temperature gradients persist in the lower 20cm throughout December 2019, but not subsequently. These results illustrate the high amount of variability in the upper layers of the snowpack. Unlike temperature gradients in the lowest 20cm, the top 25cm continually changes because it is not insulated from the atmosphere. For the whole season, the upper layers continually fluctuate between the two significant types of snow metamorphism; equilibrium and kinetic. The continuous temperature record provided by the BSTA provides insight to the duration and nature of the temperature profile in the upper 25cm as it fluctuates diurnally, and the lower 20 cm as it progresses from high gradients at the beginning of the season, to lower gradients as it becomes buried. Analysis will now be split into three specific periods: December, February, and late March, as presented in histograms.

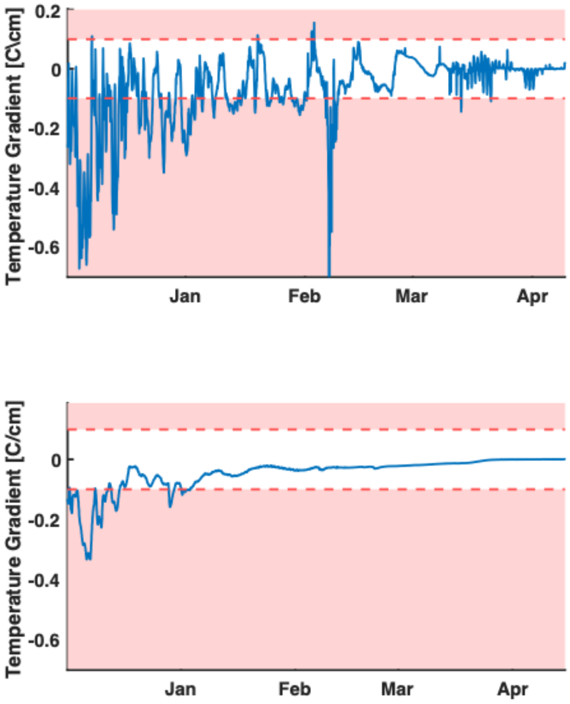

Figure 4.8: Temperature gradients during 2019 in the upper 25cm (top), and lower 20cm (bottom). Gradients in the shaded red area indicate when kinetic metamorphism (weakening) is likely to occur.

December, 2019: In both the upper 25 cm and lower 20 cm (Figure 4.9), temperature gradients show a long tail towards negative values, and 50 percent of measurements fall within the above-critical range at both depths. Cold air temperatures, coupled with a shallow snowpack during December forced above-critical temperature gradients on the snowpack for most of the month, and led to weak layer formation at the base.

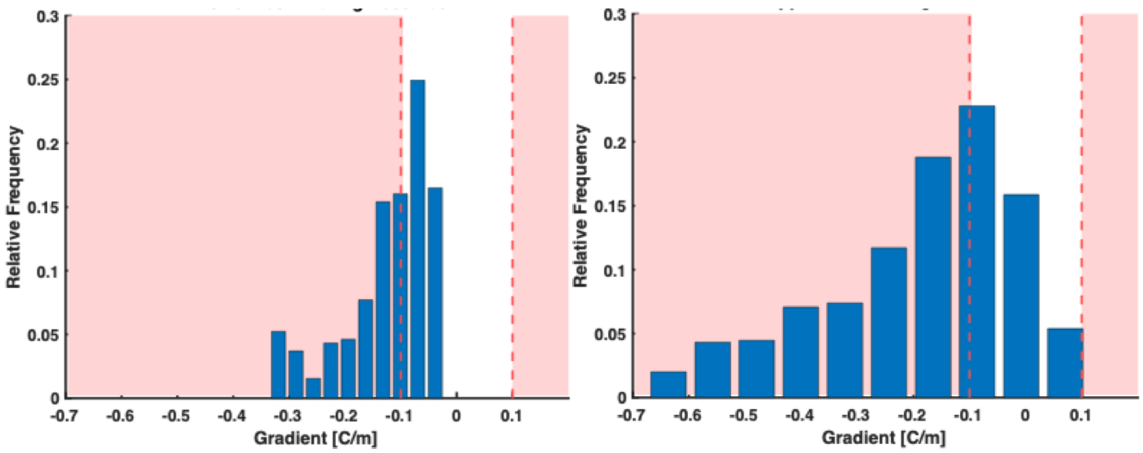

Figure 4.9: Relative density histogram of temperature gradient in lower 20cm (left) and upper 25cm (right) during December 2018.

February, 2019: The upper 25 cm shows a reduced range of temperature gradients (Figure 4.10), such that only 12% of measurements fall within the above-critical range. The lower 20cm has become nearly isothermal, so that gradients show a very narrow range that cluster slightly below 0° C/m (Figure 18). By this point in the season, the lowest 20cm of the snowpack is well insulated; thus, there is little to no temperature gradient, and we would expect this portion of the snowpack to be strengthening over time. In contrast, the upper portion of the snowpack experiences substantial temperature gradients, which can lead to mid-pack weak layers.

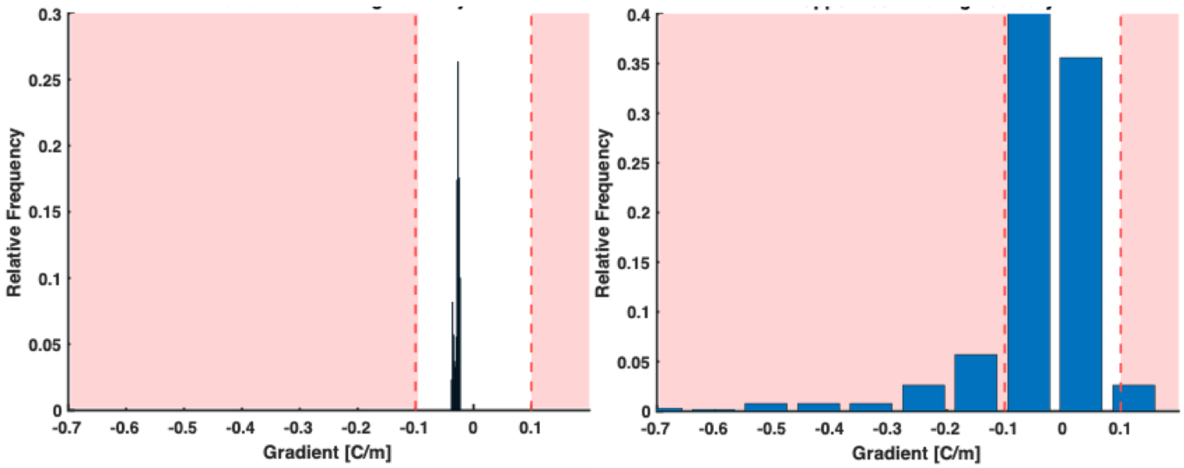

Figure 4.10: Relative density histograms of temperature gradients in the lower 20cm (left) and upper 25cm (right) during February 2019.

Late March, 2019: Warmer air temperatures during March prevented large temperature gradients in the upper 25cm (Figure 4.11, left). Much like the February subset, the lowest 20cm are very insulated and isothermal at very close to 0° C/m (Figure 4.11, right)). This subset displays the snowpack as it progresses towards isothermal conditions.

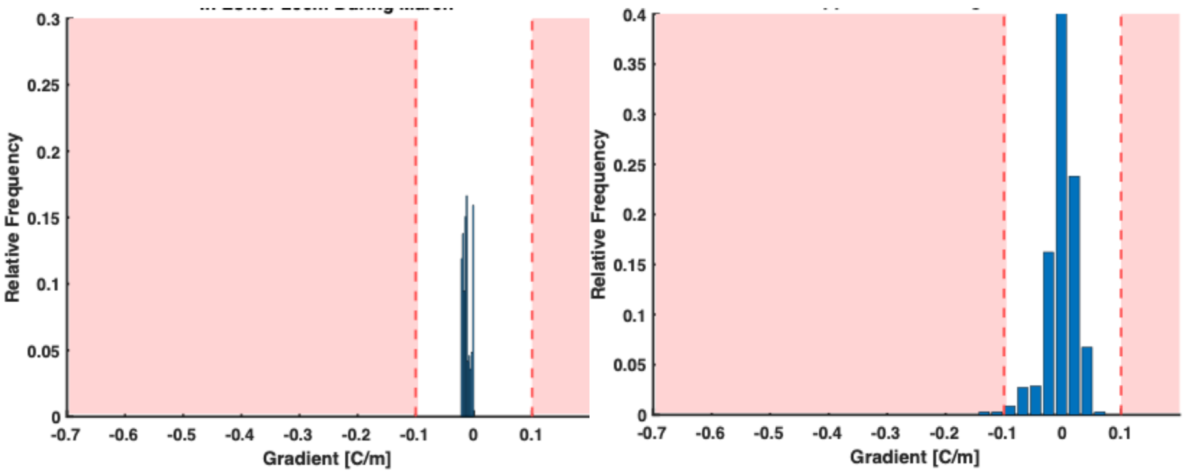

Figure 4.11: Relative density histograms of temperature gradients in the lower 20cm (left) and upper 25cm (right) in March 2019.

In addition to the figures shown here, please see: https://www.youtube.com/playlist?list=PLN7P9tpWCRZofzf19t5gqyeo645Kbmsac for time-lapse movies which are a helpful way to visualize how temperature gradients change over time. These movies highlight the depth of diurnal solar radiation input and help provide context that aids in the understanding of these processes.

The uncertainty of this temperature gradient analysis is calculated in MATLAB using a Monte-Carlo Simulation. First, the built in MATLAB function *randn.m* is used to produce normally distributed, randomly generated data with a mean of zero and a standard deviation of one. This data is then multiplied by the standard deviation of thermocouple measurements during the isothermal snowpack to create a synthetic error distribution with mean of zero and standard deviation of 0.06° C. This error is added to the first order polynomial best fit for a given temperature gradient, then this whole process is repeated 1,000 times to create normally distributed, synthetic temperature gradient measurements. Results are shown in Figure 4.12. The uncertainty in the sensor location, due to sagging of the wires, would also impact the temperature gradient estimates. Including this effect will be the subject of future work.

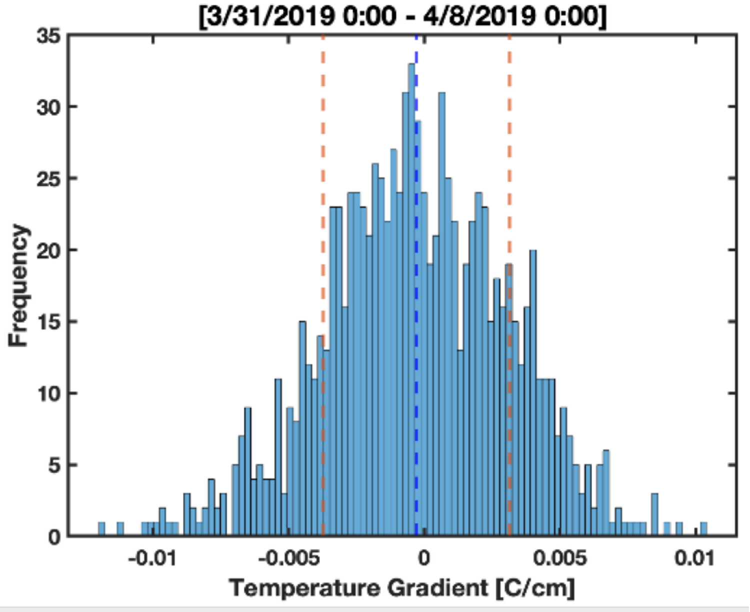

Figure 4.12: Monte Carlo uncertainty estimates of temperature gradients

5. Discussion

In December of 2019, the lowest 20cm formed depth hoar and had above critical temperature gradients for around 50 percent of the month. Critical temperature gradients were no longer present in the lower 20cm after the beginning of January. Comparatively, critical temperature gradients in the upper 25cm are present throughout the season and can have a much larger magnitude, but the duration relies primarily on the diurnal solar cycle. Snow bridging on our sensor increases the uncertainty in upper gradient calculations and more work needs to focus on preventing this snow buildup. Although this bridging effect influences data in the upper portion of the snowpack, there is a minimal effect on lower temperature measurements. Although snowpack conditions can vary widely at the basin scale, the BSTA provides the opportunity to develop statistical relationships between a single site and nearby features such as avalanche starting zones.

Kinetic metamorphism is the process of vapor transport along a thermal gradient (Sommerfeld and LaChapelle, 1970). As long as the gradient is maintained, as is usually the case in cold environments, the process continually acts on the snowpack. The snow characteristics during the beginning of this process have a strong effect on its progress. In new, fine grained, porous snow, there are more grains in which the diffusing vapor can freeze. Consequently, the grains do not grow very large, and hollow pyramids are not common (Sommerfeld and LaChapelle, 1970). If temperature-gradient metamorphism starts in larger-grained, equi-temperature metamorphosed snow, there are fewer crystals on which the vapor can freeze. Under a consistent thermal gradient, these crystals will grow larger, and hollow pyramids along with lattice grains may be found (Akitaya, 1967).

Many different factors affect the rate and nature of temperature-gradient metamorphism, and a continual collection of the snowpack temperature data and snow microstructure observations are critical to improving our understanding of these processes. Further work should focus on collecting more frequent snow pit observations to document the rate of change in the snow's microstructure, and these observations will be valuable to improve models of snow metamorphism. During the 2020 and 2021 winter, as part of the NASA SnowEx Mission, we performed weekly snowpit observations and measured microstructure with a SnowMicroPenetrometer monthly. These data will be used in the future with the BSTA temperature profiles, to calibrate snow metamorphism models.

6. Conclusion

The Banner Summit Thermocouple Array (BSTA) was successfully developed, fabricated, and installed at Banner Summit in the fall of 2018. It has been successfully measuring snow temperatures at 5cm intervals for the past 3 winters, every 15-minutes. We added a satellite modem and adapted the data logger software to transmit snow temperature profiles every hour. We worked with the ITD District 3 Avalanche Team, and Snowbound Solutions, to integrate these snow temperature profiles into their database, and snow temperature gradients are now visualized in their custom software in realtime. The engineering objective was successfully met, as we developed a continuous snow temperature sensor, maintained it for 3 winter seasons, transmitted the data hourly, and provided that data and its visualization to ITD avalanche forecasters. We quantified our uncertainty in temperature observations using a calibration during wet snow conditions, and found our system measures snow temperatures with an accuracy of better than $\pm 0.06^{o}$ C. We assume this temperature accuracy is constant across the temperature range, due to our technique of using thermocouples, which measure temperature differences. We use this uncertainty with Monte Carlo simulation to estimate our accuracy of our calculated temperature gradients, at $\pm 0.03^{o}$ C/m. We met our proposed accuracy requirement of 0.1 degrees Celcius.

This engineering objective allowed us to quantify temperature profiles and automatically calculate temperature gradients in the upper and lower parts of the snowpack, providing the data needed to meet our objectives of measuring temperature gradients and quantifying how long they were above the critical level for kinetic metamorphism, or weakening. Finally, our snow temperature measurements indicated liquid water was moving in the snowpack when temperatures reached near 0 degrees Celcius, confirmed with in situ observations of liquid water content, meeting our third objective.

In December of 2019, the lowest 20cm formed depth hoar and had above critical temperature gradients for around 50 percent of the month. Critical temperature gradients were no longer present in the lower 20cm after the beginning of January. Temperature gradients in the upper 25cm can have a much larger magnitude, but are subject to the strong gradients for a shorter period of time, and at a lower absolute temperature, therefore the kinetic metamorphism has less impact. These observations are valuable for improving estimates of snow metamorphism, by providing calibration and validation data for snow modeling. While the Banner Summit location doesn’t necessarily represent the starting zones that affect Highway 21, with some experience relating these measured gradients to avalanche activity, the BSTA should provide a valuable tool for forecasters.

Because this instrument precisely measures isothermal conditions in a snowpack, it may be possible to improve predictions of major snowmelt and wet snow avalanches. Although snowpack conditions can vary widely at the basin scale, the BSTA permits the construction of statistical relationships between a single site and nearby features such as stream gauges, or avalanche starting zones. A continuous snowpack temperature record, as derived via a temperature sensor array (as described here), will allow statistical analysis on avalanche hazards and snowmelt runoff. Further comparison between our results and snowpack energy balance models may provide insight into processes such as latent heat exchange and will help further our understanding of internal snowpack processes.

The method and tools developed in this study were successful at monitoring snow temperature conditions within the snowpack, which provides insight into the snow metamorphism process. This system allows avalanche forecasters to monitor temperature gradients in the upper and lower portions of the snowpack, and determine if layers are strengthening or weakening.

Our recommendations for ITD moving forward are to maintain the snow temperature array observations, as it will likely take 5 years to build a database and the experience required to relate these measurements at one location, to the starting zones that impact Idaho HW21. More work is needed to use this data to calibrate snow models, and field surveys to help link snow conditions at Banner Summit to those in the avalanche starting zones. This work is underway by the BSU CryoGARS group, and high resolution airborne lidar snow depth surveys from 2020 and 2021 will be used to help link observations from the BSTA to snow temperature conditions in the starting zones of Canyon Peak.

7. Cited Works

Akitaya, E. 1967. Some experiments on the growth of depth hoar. Physics of Snow and Ice, 1(2):713-723.

Akitaya, E. 1974. Studies on depth hoar. Contributions from the Institute of Low Temperature Science, 26:1-67.

Arenson, L. U., W. Colgan, and H.P. Marshall. 2015. Physical, thermal, and mechanical properties of snow, ice, and permafrost. In Snow and Ice-Related Hazards, Risks and Disasters, 35-75. Elsevier.

Barbolini, M., M. Baudone, F. Ferro, L. Ricchetti, and F. Stefanini. 2013. Nivexc: an electronic snow-pole for real-time monitoring of avalanche starting zones.

Colbeck, S. 1983. Theory of metamorphism of dry snow. Journal of Geophysical Research: Oceans, 88(C9):5475-5482.

Conway, H. and R. Benedict. 1994. Infiltration of water into snow. Water Resources Research, 30(3):641-649.

Dingman, S. L. 2015. Physical Hydrology. Waveland Press.

Eiriksson, D., M. Whitson, C. Luce, H.P. Marshall, J. Bradford, S. Benner, T. Black, H. Hetrick, and J. McNamara. 2013. An evaluation of the hydrologic relevance of lateral flow in snow at hillslope and catchment scales. Hydrological Processes, 27(5):640-654.

Evans, S. L., A. Flores, A. Heilig, M. Kohn, H.P. Marshall, and J. McNamara. 2016. Isotopic evidence for lateral flow and diffusive transport, but not sublimation, in a sloped seasonal snowpack, Idaho, USA. Geophysical Research Letters, 43(7):3298-3306.

Hood, E., M. Williams, and D. Cline. 1999. Sublimation from a seasonal snowpack at a continental, mid-latitude alpine site. Hydrological Processes, 13(12-13):1781-1797.

Ingolfsson, O. and H. Grimsdottir. 2008. The sm4 snowpack temperature and snow depth sensor. In Proceedings Whistler 2008 International Snow Science Workshop, September 21-27, 2008, page 808.

Kattelmann, R. and K. Elder. 1991. Hydrologic characteristics and water balance of an alpine basin in the Sierra Nevada. Water Resources Research, 27(7):1553-1562.

Luce, C. and T. Black. 2018. Personal communication on the thermocouple array at Bogus Basin. Personal Communications.

Marks, D. and J. Dozier. 1992. Climate and energy exchange at the snow surface in the alpine region of the Sierra Nevada: 2. Snow cover energy balance. Water Resources Research, 28(11):3043-3054.

McClung, D. and P.A. Schaerer. 2009. The avalanche handbook. Mountaineers Books.

Sommerfeld, R. and E. LaChapelle. 1970. The classification of snow metamorphism. Journal of Glaciology, 9(55):3-18.

Sturm, M., J. Holmgren, M. Konig, and K. Morris. 1997. The thermal conductivity of seasonal snow. Journal of Glaciology, 43(143):26-41.