LABORATORY SIMULATIONS OF RADIATION-RECRYSTALLIZATION EVENTS IN SOUTHWEST MONTANA

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ABSTRACT: During the winter seasons of 2006/2007 and 2007/2008, Montana State University researchers collaborated with the Yellowstone Club Ski Patrol to investigate near-surface metamorphism. Detailed weather information as well as daily observations and grain-scale images were collected. Several radiation-recrystallization events were observed throughout this period. Near-surface facets were successfully developed using laboratory simulations of recorded field data. The observed facets formed in a manner consistent with observations made in the field. A Comparison of measured data with a thermal model indicated that low-density snow may be conducive, but is not obligatory, to form near-surface facets. Using samples from laboratory experiments, time-lapse movies of facet growth were captured using a microscope equipped with a cryo-stage capable of inducing a temperature gradient. Preliminary data indicates the penetration resistance of the surface layer, measured using a Snow MicroPen, varied as the near-surface facets developed. This ongoing collaborative effort improved and will continue to improve the understanding of the processes surrounding near-surface faceting.

KEYWORDS: Near-surface Facets, Radiation Recrystallization, Heat-Transfer Model, Snow MicroPen

1. INTRODUCTION

Near-surface faceted snow is well documented as a weak-layer that significantly contributes to avalanche activity. However, the processes that form these crystals are not well understood. Previous research primarily included field investigations (Fukuzawa and Akitaya, 1993; Höller, 2004) and analytical techniques (Colbeck, 1989). Research in southwest Montana has generally focused on examining facet formation due to diurnal temperature fluctuations (Birkeland et al., 1998). The process of radiation-recrystallization, which is the focus of this paper, was first reported by LaChapelle (1970).

The precursor to this research was conducted by Morstad et al. (2007). Using constant environmental conditions in a laboratory, it was shown that near-surface faceted crystals form in a matter of hours in a cold, dry, and dense snowpack. In an attempt to further understand the conditions surrounding the radiation-recrystallization process, two field weather stations were established on Pioneer Mountain at the Yellowstone Club (YC) near Big Sky, MT. Cooperstein et al. (2004) originally established these sites while examining the relationship between slope aspect and the development of surface hoar and near-surface facets. Staples et al. (2006) also used these weather stations as the basis for calculating snow surface temperature using a model.

The following research is part of a collaborative effort with the YC Ski Patrol, who in a companion paper discuss six significant radiation-recrystallization events at a south aspect weather station (McCabe et al., 2008). Of these six events, three were selected for examination using laboratory simulations. Additional experiments were performed using the Snow MicroPen and a microscope with cryo-stage. The intent of this research was to further understand the environmental conditions that influence near-surface facet formation through the comparison of field and laboratory grown crystals.

2. PROCEDURE

Recorded air temperature and shortwave radiation data from a south-facing weather station at the YC was used to conduct laboratory simulations in an environmental chamber. Three days were examined: February 14th (Feb14), March 6th (Mar6), and April 3rd (Apr3).

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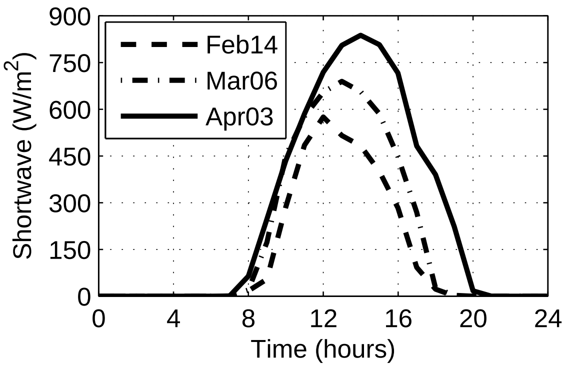
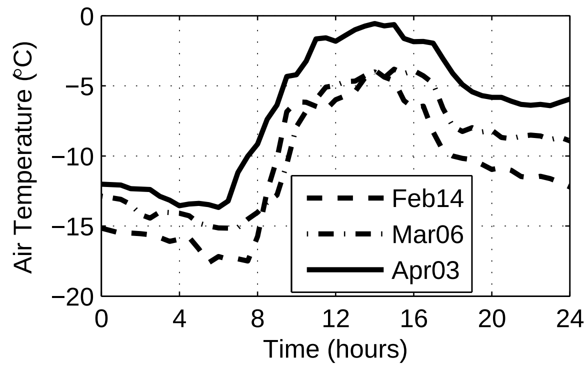


(a)



(b)

Figure 1: (a) Incoming shortwave radiation measured at the American Spirit Station, and (b) air temperature measured at the south-facing location for February 14th, March 6th, and April 3rd.

These days were characterized by recent snowfall followed by a cool morning and a clear, relatively warm day with intense solar radiation, as shown in Figure 1. Each of these days resulted in significant near-surface facet growth (McCabe et al., 2008) with a melt-layer underlying a frozen layer at the surface. In all simulations, the tested snow was more dense than in the field. Through the use of a thermal model, a comparison between the simulation and field data was conducted. Once the model was shown to reasonably mimic the snow surface temperature of the simulations, the model was re-run changing only the snow parameters to match those observed in the field. This provided results for the simulations as if each had been conducted with snow matching the conditions observed in the field. Snow MicroPen data was recorded before and after exposure to shortwave radiation; due to instrumentation difficulties, only data for two experiments is reported. Additionally, using a microscope with cryo-stage, an experiment was conducted to observe real-time faceted growth. Details of each component are included in the following sections.

2.1. Field Stations

Field data was recorded on north- and south-facing slopes on Pioneer Mountain near Big Sky, MT. For details regarding the weather station locations see Cooperstein et al. (2004) and McCabe et al. (2008). Each site was similarly instrumented to measure air temperature and humidity (Campbell Scientific, Inc. CS215), snow depth (NovaLynx Corp.), snow surface temperature (Everest Interscience, Inc. 4000.4ZL), incoming longwave radiation (Eppley Lab., Inc. PIR), incoming and reflected shortwave radiation (LI-COR, Inc. Li200), wind speed and direction (Met One Instruments, Inc. 034B-L), and subsurface snow temperature taken at 2 cm intervals (Omega Eng., Inc. type T thermocouples). Data was recorded with Campbell Scientific, Inc. (CSI) CR10(x) dataloggers. A third location at the top of a ridge (American Spirit Station) measured unobstructed incoming shortwave and longwave radiation (Eppley Lab., Inc. PSP and PIR). The YC Ski Patrol also maintained a daily record of images and notes describing the top 5 cm of the snow.

2.2. Laboratory Simulations

Laboratory studies were conducted in an environmental chamber with a solar simulator (K.H. Steuernagel Lichttechnik GmbH). Snow was placed in an insulated container measuring 70 cm square by 50 cm deep. The snow used for the experiments was collected throughout the winter at various locations. Instrumentation included shortwave radiation (Kipp & Zonen CMP6 or Eppley Lab., Inc. PSP), longwave radiation (Kipp & Zonen CGR3), and snow surface temperature (Everest Interscience, Inc. 4000.4ZL). Type T thermocouples were used to measure air, snow base, and subsurface (1 cm intervals) temperature. The relative humidity was measured using built-in laboratory hardware. Each simulation was run for approximately 24 hrs beginning at midnight. Figure 2 is a comparison between lab and field shortwave radiation and air temperature for Feb14. A similar relationship was observed for each of the simulations. Feb14 was replicated three times, Apr3 twice, and Mar6 once; replicates are denoted as a number following the name (e.g. Feb14 #1).

The shortwave radiation data, as reported by McCabe et al. (2008) and shown in Figure 1, was recorded at the American Spirit Station. The data

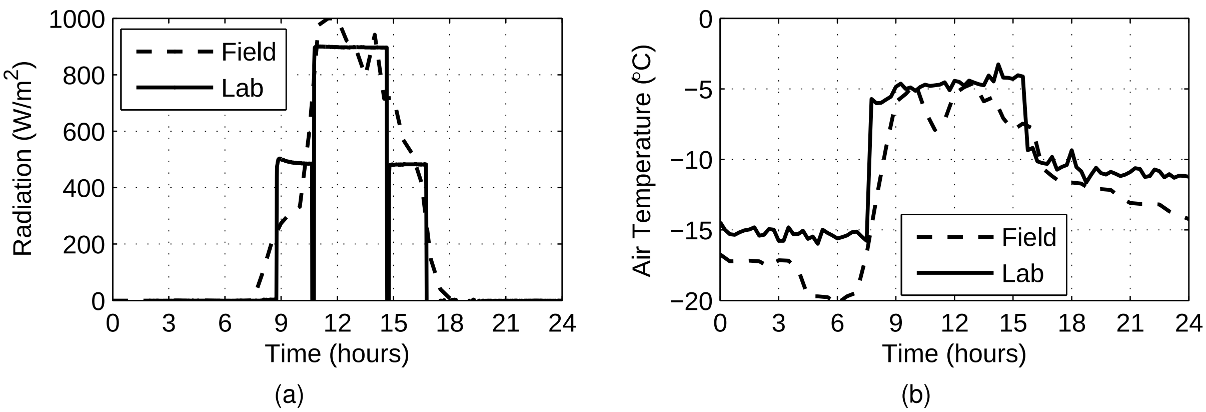


Figure 2: Comparison between February 14th recorded field data from the south weather station and associated laboratory simulation data for (a) shortwave radiation and (b) air temperature.

from this sensor is considered the most reliable due to location and sensor quality. The shortwave data shown in Figure 2 was recorded at the south location and used for the simulations. Radiation readings were higher at this location, but are reasonable estimates and comparable in magnitude to calculated values using estimates of solar zenith angle, slope angle, aspect, and atmospheric transmissivity.

2.3. Temperature Measurements

Temperature profiles were measured with thermocouple arrays buried in the snow. Unfortunately, the accuracy of these measurements was influenced by heating of the thermocouple wires from exposure to solar radiation. In the field studies, this solar contamination was unavoidable and this data is not included in this discussion. In the laboratory this issue was mitigated by periodically turning the solar source off. Figure 3 illustrates that the thermocouples near the snow surface increased 3 °C within two minutes of the solar lamp turning on. A similar behavior was observed when the lamp was powered off.

For the Feb14 #2 and #3, and both Apr3 experiments, melting of the snow occurred at or just below the surface, with the snow surrounding the thermocouples melting first. Due to this melting, a direct comparison between experiments is problematic. Thus, a heat-transfer-based thermal model was utilized for calculating temperature gradients in all cases; see the following section for a discussion of this model.

2.4. Thermal Model

The thermal model used in this research is detailed in Morstad et al. (2007) and was shown to reasonably predict snow temperatures in similar laboratory studies.

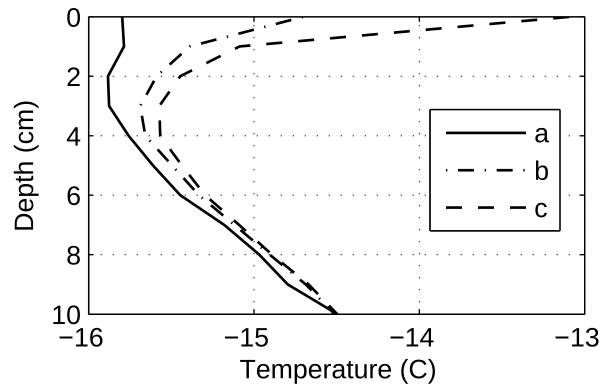


Figure 3: Measured thermocouple data (a) one minute prior to, and (b) one and (c) two minutes after the solar lamp was powered on.

The model was initialized with a temperature profile equivalent to midnight before the simulated day. Input for the model included measured values for longwave and shortwave radiation, air and snow base temperature, and relative humidity. The snow was assumed to have constant properties with depth with the following parameters assumed constant: wind velocity (1.7 m/s), emissivity (0.988), layer thickness (0.5 cm), time step (60 s), and atmospheric pressure (84 kPa).

The extinction coefficient was independently estimated for each simulation using thermocouple data. The critical depth was estimated as the depth at which the thermocouples were not affected by the incoming solar radiation. Referring to Figure 3, this critical depth would be approximately 8 cm, resulting in an extinction coefficient of approximately 60 1/m. The initial albedo was estimated using a hyperspectral imaging system (Resonon, Inc., Pika I). Table 1 summarizes the measured albedo and density, as well as the estimated extinction coefficient and critical depth.

As previously mentioned, a comparison between the simulations and field data was completed using the density, albedo, and extinction coefficients given in Table 2. These values were estimated using density information from McCabe et al. (2008) and tabulated data in Marshall (1989), assuming an effective grain radius of 1 mm. Little variation existed in the environmental conditions between simulation replicates; for simplicity only one replicate per day (Feb14 #3 and Apr3 #2) was used for the field/simulation comparisons.

Table 1: Summary of measured density (ρ) and albedo (α), and estimated critical depth (d_{cr}) and extinction coefficient (κ) for each laboratory simulation.

Experiment	$\rho(kg/m^3)$	$\alpha(\%)$	$d_{cr}(cm)$	$\kappa(1/m)$
Feb14 #1	177	93	8	60
Feb14 #2	213	90	7	70
Feb14 #3	284	92	9	50
Mar6	350	87	6	80
Apr3 #1	284	91	8	60
Apr3 #2	320	89	6	80

Table 2: Summary of estimated albedo (α) and extinction coefficient (κ) based on density (ρ) recorded in the field.

Experiment	$\rho(kg/m^3)$	$\alpha(\%)$	$\kappa(1/m)$
Feb14	50	93	50
Mar6	82.5	93	80
Apr3	75	93	80

2.5. Snow MicroPen and Grain-Scale Experiments

A grain-scale experiment was conducted using a Nikon Eclipse 80i microscope with a Qimaging Retiga-2000R camera equipped with a temperature gradient stage (Linkam GS120). This experiment was performed concurrently with Feb14 #3 using a sample taken from the simulation just prior to shortwave exposure. The snow was contained in a 16 mm diameter, 2 mm tall crucible and exposed to a temperature gradient of 200 °C/m; one-side of the sample was set to -5 °C and the other to -5.4 °C. This gradient was evoked across the diameter, allowing the microscope to view the sample perpendicular to the gradient. The snow was observed over a period of five hours with images taken every two minutes.

Snow MicroPen (Schneebelli et al., 1999) data was collected during the Feb14 #3 and Mar6 simulations, and was recorded at a rate of 20 mm/s. Three profiles were taken immediately before and after the snow was exposed to a full day of shortwave radiation.

3. RESULTS AND ANALYSIS

3.1. February 14th Simulations

Each of the three replicates resulted in the growth of faceted crystals within the snow surface. The first experiment (Feb14 #1) resulted in the most significant faceting when compared to the second and third experiments (Feb14 #2 and Feb14 #3). The major difference between these experiments was the initial snow density (Table 1).

Field notes recorded by the YC Ski Patrol on February 14th explain that the snowpack was comprised of decomposing new snow and small surface hoar particles, and that due to radiation-recrystallization, "crystal growth had occurred throughout the day." These conditions were similar to the snow as tested in the Feb14 #1 simulation, with the exception of the density. Images of the crystals before and after to exposure shortwave radiation are included in Figure 4.

Comparing the measured and modeled snow surface temperature confirmed that the thermal model reasonably predicted the behavior of the snow in the laboratory simulations (Figure 5). McCabe et al. (2008) reported that the upper 1 cm of the snow remained frozen while the underlying snow was wet. The temperature gradient across this layer was approximately -400 °C/m. Using the field snow parameters and re-running the thermal model showed that the temperature gradient increased in the top 1 cm during peak solar radiation to more closely match this value, as shown in Figure 6. Additionally, the snow surface temperature decreased to match more closely with data recorded at the south weather station (Figure 7). The differences observed in this graph are likely due to the difference between the simulated and actual solar radiance, as shown in Figure 2. As such, it is expected that if the Feb14 simulations were conducted with the snow from the field, larger faceted crystals would develop, as was observed by the YC Ski Patrol.

3.2. Mar 6th Simulation

The March 6th simulation resulted in faceted growth, despite the much higher density snow than observed in the field. The YC Ski Patrol stated in the field notes that in the late morning no evidence of facets

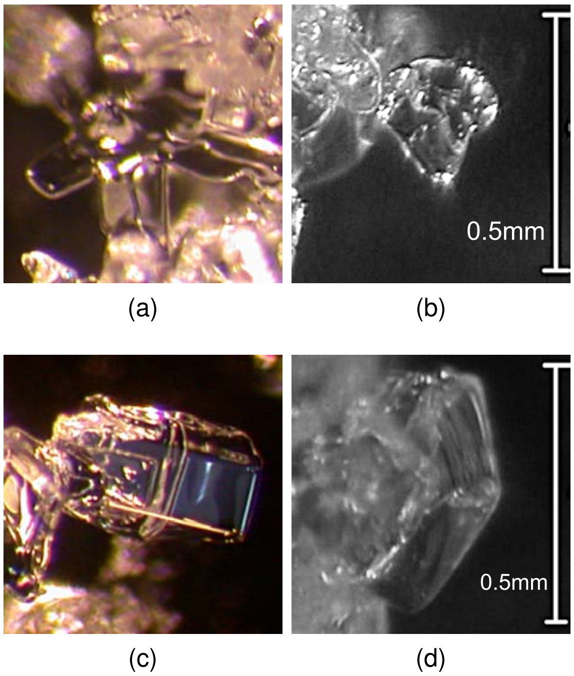


Figure 4: Images before (a, b) and after (c, d) exposure to shortwave radiation from February 14th simulation #1. The images on the left-side are similar in size to those on the right.

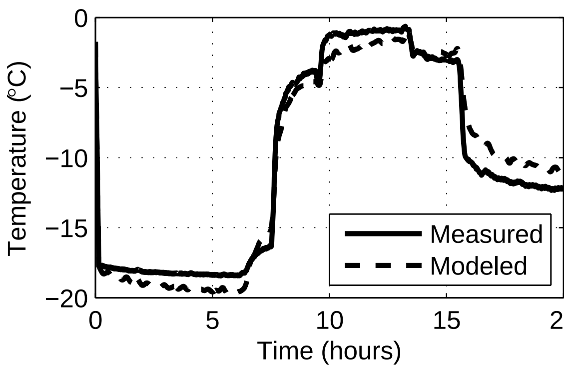


Figure 5: Comparison between the measured and modeled snow surface temperature for the Feb14 #3 simulation.

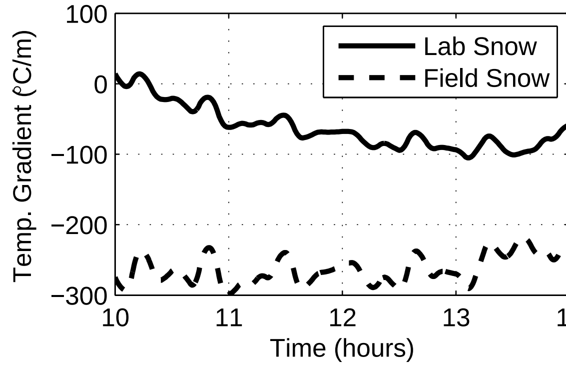


Figure 6: Temperature gradient in the top 1 cm during peak solar radiation comparing Feb14 simulated environmental conditions modeled with the snow as tested and snow as observed in the field.

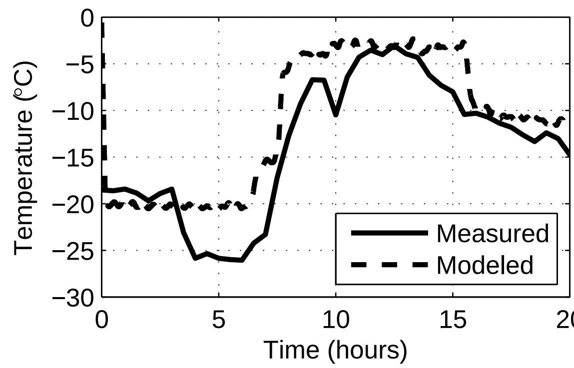


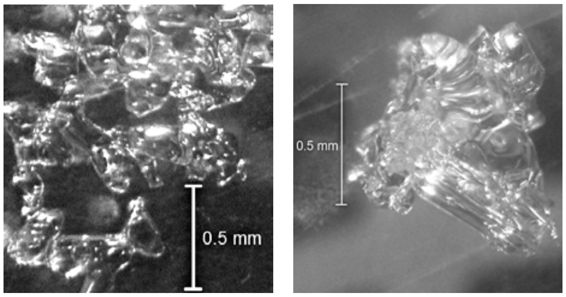
Figure 7: Comparison between the Feb14 measured snow surface temperature from the south weather station with the modeled snow surface temperature using snow parameters estimated from field data and simulation environmental conditions.

or surface hoar existed, but in the afternoon "small cups and needles were observed in the cold snow on the surface." A similar behavior was observed in the laboratory where a frozen layer existed on the surface with a melt-layer below. Figure 8 shows the before and after crystal structure within the surface layer.

As was done for the Feb14 simulation, the thermal model was run using the laboratory conditions with snow properties as tested and as reported in the field. The results were similar to that of Feb14. The model and measured snow surface temperature match well, and the temperature gradient between the surface and the melt-layer decreased to match the value of 400 °C/m as reported in McCabe et al. (2008). The temperature gradient was considered across the top 4 cm. Examining the modeled temperature profiles (Figure 9) at 13:30 indicated, as in McCabe et al. (2008), that this melt-layer would be present if the snow for the simulations was similar to that in the field.

3.3. April 3rd Simulations

The April 3rd experiments did not result in near-surface facet growth. Instead, the entire surface layer melted, as shown in Figure 10. One major difference between these simulations and the Feb14 and Mar6 tests was the air temperature. Referring to the field temperature data (Figure 1), the air temperature was higher for April



(a) (b)

Figure 8: Images prior to (a) and after (b) exposure to shortwave radiation from March 6th simulation.

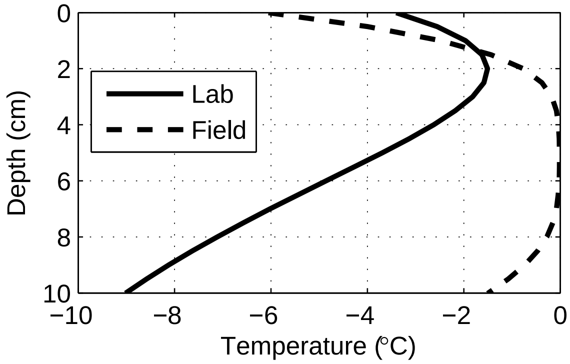


Figure 9: Snow temperature in the top 10 cm of the snow for the Mar6 simulated conditions with the snow as tested (lab) and the snow as observed in the field (field). For the field snow profile, the surface temperature, melt-layer at 4 cm, and temperature gradient above this melt-layer matched well with observed conditions at the YC.

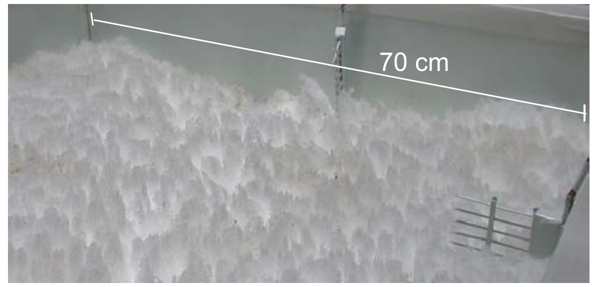
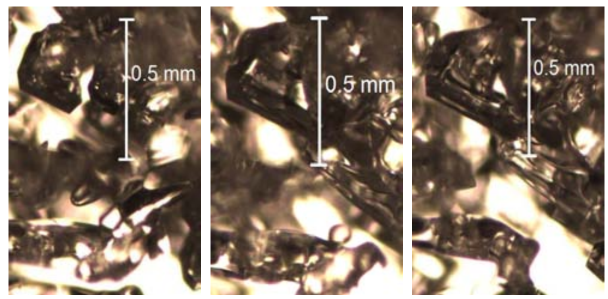


Figure 10: Both replicates of the April 3rd simulations resulted in surface layer melting and formation of snow mirco-pentients.



(a) Initial (b) 60 minutes (c) 120 minutes

Figure 11: Formation of faceted crystals within cryo-stage microscope; each image is of the same crystals after the exposure to a 200 °C/m gradient, with the cooler side being the top of the image.

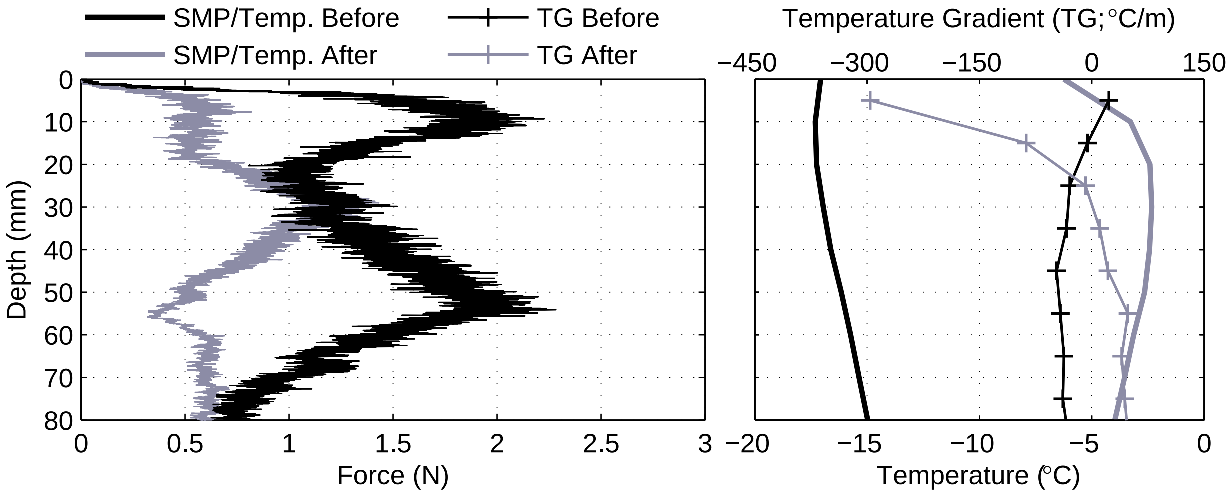
3rd than for the other simulated days. Completing the analysis as done for the previous two simulations yielded results consistent with those for the other simulations. However, the results did not correlate as well. This difference is likely due to the nature of the experimental setup. These simulations were run with the snow surface below the rim of the box, which may have prevented wind from circulating at the snow surface and aided in the melting. Interestingly, the results seen from these experiments matched closely with previous research focusing on snow micro-penitents (Slaughter et al., 2006), which had nearly identical environmental conditions.

3.4. Cryo-stage Microscope

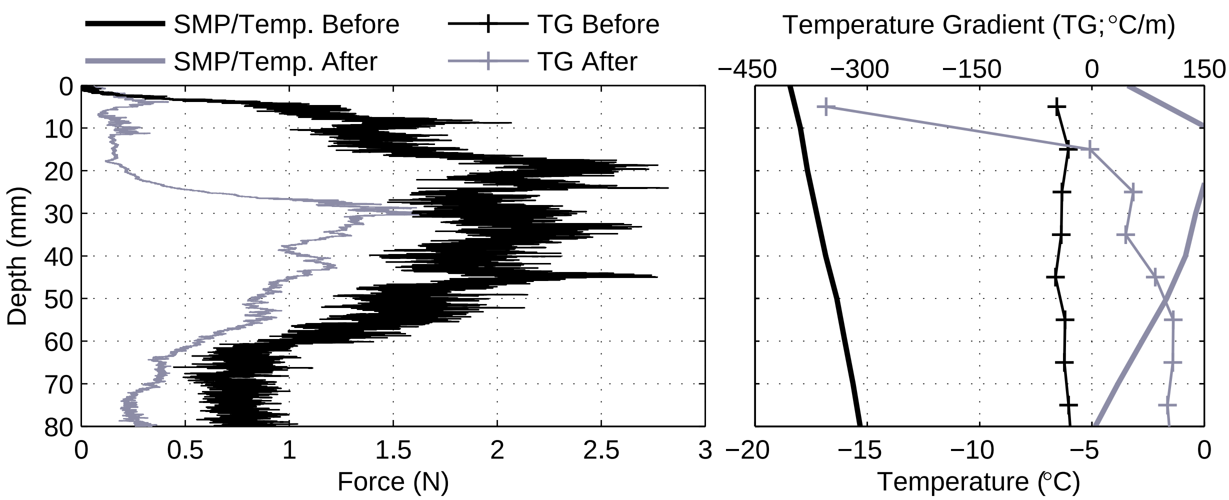
Figure 11 shows three images taken from the same location in the snow sample: initially, after 60 minutes, and after 120 minutes of exposure to a temperature gradient. A visual review of the images indicated sublimation of grains occurred on the warmer side of the sample, and recrystallization occurred on the cooler side. These results confirmed that vapor transport occurs on a small scale between adjacent grains, and facets can form in a matter of hours when exposed to high temperature gradients such as those experienced in radiation recrystallization.

3.5. Snow Strength

Based on the results of the SMP measurements for the Feb14 #3 and Mar6 simulations, an overall reduction in penetration resistance was observed for the upper 8 cm of the snowpack after approximately 8 hours of solar exposure. This was indicated by a shift to the left in the graphs shown in Figure 12. Visual grain-scale examinations of snow crystals taken from the top centimeter showed evidence of crystalline structure changes from rounded to faceted grains, as shown in Figure 8. Snow temperature profiles, shown in Figure 12, displayed gradients present from the surface down approximately 1 to 2 cm and again from approximately 3 cm to 8 cm. The graphs of resistance



(a) February 14th Simulation #3



(b) March 6th Simulation

Figure 12: Snow MicroPen data, temperature profiles, and temperature gradients (TG) before and after exposure to approximately 8 hours of solar radiation for the Feb14 #3 (a) and Mar6 (b) simulations.

taken at the end of the solar exposure displayed a low resistance for the upper 2 cm, increasing to a peak around 3 cm, followed by a reduction with depth. This peak corresponded to the point of zero gradient on the temperature profiles.

It can be speculated that the peak observed at 3 cm in the resistance graph of the radiated snow may corresponded to a point where no temperature gradient was present and thus limited metamorphism occurred. This point also corresponds to the smallest change in penetration resistance values measured before and after solar exposure.

It should be noted that this analysis was based on preliminary data with high variability. Each graph of penetration resistance represents the mean of three SMP profiles that have a coefficient of variation in excess of 50% at some locations. Hence, before drawing any definitive conclusions, additional tests should be performed to examine the variability in the data, and to determine if metamorphism is occurring at depth.

4. CLOSING REMARKS

This research has shown that weather data collected in the field can be used as input in a laboratory setting to recreate conditions favorable for radiation-recrystallization. Further quantification of the conditions affecting the near-surface facet growth was difficult due to the large number of variables that changed between experiments. However, the results show that high density, rounded snow inhibited, but did not prevent, facet growth. Through the use of a thermal model, results indicated that if these simulations were conducted with snow similar to that observed in the field, facet growth would be more prevalent, perhaps yielding more prominent faceting as observed in the field. Additionally and as expected, preliminary data indicated that the penetration resistance of snow, which is one measure of strength, may be affected by temperature gradient metamorphosis.

On a broader scale, this investigation has shown that, subject to further protocol refinements, the laboratory procedure utilized is able to simulate natural environmental conditions leading to near-surface metamorphism. As done here, when laboratory experiments are conducted in conjunction with field studies, a more coherent understanding of these conditions and associated nuances may be achieved. Despite the inherent differences in environmental conditions and the dense, highly agitated snow samples, facets developed in a similar manner to what was observed in the field.

5. ACKNOWLEDGMENTS

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