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# Optimization of over-summer snow storage at mid-latitude and low elevation

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**Abstract.** Climate change, including warmer winter temperatures, a shortened snowfall season, and more rain-on-snow events, threatens nordic skiing as a sport. In response, over-summer snow storage, attempted primarily using wood chip insulation, has been successfully employed as a climate change adaptation strategy by high elevation and/or high latitude ski centers in Europe and Canada. Such storage has never been attempted at low elevation, low latitude sites nor have studies quantified snowmelt rate through the summer or correlated snow melt rate with environmental characteristics including ground and air temperature, humidity, wind, and solar radiation. Such data, along with tests of different insulation strategies, are needed to optimize snow storage strategies.

Here, we assess the melt rates of two snow piles (each ~200 $m^3$) emplaced during spring 2018 in Craftsbury, Vermont (45° N and 360 m asl). We monitored volume change over the melt season using terrestrial laser scanning. We continually logged air-to-snow temperature gradients under different insulating layers including rigid foam, open cell foam, and wood chips both with and without an underlying insulating blanket and an overlying reflective cover. We also measured ground temperatures to a meter depth both under and adjacent to the snow piles and used a snow tube to measure snow density.

Snow volume of the two piles changed similarly over the summer, with minimum rates of change (-0.29 $m^3$ $day^{-1}$ and -0.88 $m^3$ $day^{-1}$) in September and maximum snow loss rates in July of -1.98 $m^3$ $day^{-1}$ and -2.81 $m^3$ $day^{-1}$ . Snow density changed little over time indicating that most volume reduction was the result of melting.

Wet wood chips underlain by an insulating blanket and covered with a reflective sheet was the most effective combination for minimizing melt, likely because the surface reflected incoming shortwave radiation while the wet wood chips provided significant thermal mass, allowing much of the energy absorbed during the day to be lost as blackbody radiation at night. Together, the data we collected demonstrate the feasibility of over-summer snow storage even at low latitudes and altitudes and suggest efficient insulation strategies.

## 1 Introduction

Earth's climate is warming in response to the addition of $CO_2$ and other greenhouse gasses to the atmosphere (Steffen et. al., 2018). This warming is expressed not only in warmer nights and days but also in the number of winter rain events and thaws which degrade snow packs. The duration, extent, and thickness of lake ice and snow have both decreased over the past several decades in response to increasing temperatures, especially at high latitudes (Hewitt et. al., 2018; Sanders-DeMott et. al., 2018). Winter recreation is particularly vulnerable to such warming. The ski industry has responded by increasing snowmaking as well as attempting to reduce melt by covering snow (Scott and McBoyle, 2007; Pickering and Buckley, 2010). Over the past several decades, research has optimized snow-making strategies and facility operations both to maintain the industry financially and to decrease their output of greenhouse gases (Koenig and Abegg, 1997; Moen and Fredman, 2007; Tervo, 2008; Kaján and Saarinen, 2013).

Many sites organizing major winter sports events, such as cross-country or alpine world cup races, have adopted over-summer snow storage in response to the unpredictability of snowmaking weather conditions. In areas of high humidity and warm average fall temperatures, summer snow storage is safer than relying on weather conditions sufficiently cold and dry for making snow at the start of a regular winter ski season. For example, the 2014 Olympic games at Sochi relied on 750,000 $m^3$ of snow storage (Pestereva, 2014). Such snow storage is analogous to refrigeration techniques used commonly before the advent of mechanical cooling (Nagnengast, 1999) such as ice houses used to store large blocks of lake ice beneath sawdust over the summer (Rees, 2013). Such over-summer snow storage (sometimes referred to as "snow-farming") begins with the creation of snow piles during winter months. The pile is insulated (often with sawdust or wood chips) and sometimes covered with geotextiles before the snow is stored over the summer (Skogsberg and Lundberg, 2005). In the fall, the pile is uncovered and snow is spread onto trails. Nordic ski centers require less snow-covered area to open than downhill ski centers and so snow storage on the scale of thousands of cubic meters is practical and cost-effective.

Snow storage has been employed predominately at high elevation and/or high latitude ski centers (Fig. 1) many of which benefit from cool, dry summers that minimize energy transfer to the snow, increase evaporative cooling, and thus slow snowmelt. Here, we examine the feasibility of snow storage in the northern United States at a low latitude and low altitude ($45^o$ N and 360 m asl) site with a humid, temperate climate including warm summer temperatures (>$30^o$ C) and high relative humidity (Fig. 1). We report data on the melt rate of snow stored over the summer and consider those data in the context of both ground temperature and meteorological data that together help define the energy flux into the snow piles responsible for melt. The goals of this research are to: 1) determine the melt rate of experimental snow piles, 2) infer the environmental factors which most influence snowmelt, and 3) suggest an optimized snow insulation strategy based on these data.

## 2 Background

Although the physics of snowmelt has been considered extensively (Dunne and Leopold, 1978; Horne and Kavaas, 1997; Jin et. al., 1999), there has been limited application of physical and energy transfer knowledge to the problem of over-summer snow storage (Grünewald et. al., 2018). Snowmelt occurs when a snowpack absorbs energy sufficient to raise snow temperature to the melting point ($0^o$ C) and then absorbs additional energy to enable the phase change from solid to liquid water (80 cal $g^{-1}$). The snowpack gains energy from incoming short and long wave radiation, sensible and latent heat transfer from condensation of atmospheric water vapor and cooling and refreezing of rain water, conduction from the underlying ground, and advective heat transfer from wind (Dunne and Leopold, 1978). Loss of energy from the snow pack occurs through convective and conductive heat transfer to the air and ground as well as blackbody radiation to the atmosphere.

Both regional and local climatic factors influence the energy balance of snow. Shortwave radiational gain is related to latitude (highest near equator and least near the poles), time of year (greatest in summer and least in winter), snow pile surface albedo, slope and aspect, as well as cloud and tree canopy cover. Long wave radiation depends on atmospheric emissivity, cloudiness, and vegetation cover. Rain may fall on the snowpack transferring heat. Conductive heat transfer from the ground depends on soil thermal conductivity and temperature (Kane et. al., 2000; Abu-Hamdeh, 2003). Snowpack melt typically varies on a diurnal cycle with melt increasing after sunrise, peaking in the afternoon and decreasing after sunset (Granger and Male, 1978).

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Once surface melt occurs, water either refreezes if it percolates into a sub-freezing snowpack, flows through an isothermal (0º C) snowpack, infiltrates into the ground below, or flows along the ground surface below the pile depending on soil infiltration rate (Schneebeli, 1995; Ashcraft and Long, 2005).

Recent research at nordic ski centers in Davos, Switzerland and Martell, Italy (Grünewald et al., 2018) has applied snowmelt physics to optimize over-summer snow storage at high elevation (~1600 m) and mid latitude (~46º N). Each nordic center built piles of artificial snow and covered them with 40 cm of wet sawdust and wood chips; researchers then used utilized terrestrial laser scanning to measure the initial (spring) and final (fall) volumes of the two piles. These snow piles retained 74% and 63% of their volume over the summer. Using thermal models, Grünewald et al. suggested that the most effective insulation was a 40 cm thick layer of mixed wet sawdust and wood chips, which reduced energy input into the pile by a factor of 12 (1504 MJ $m^{-2}$ without wood chips as opposed to 128 MJ $m^{-2}$ with wood chips). During the day, solar radiation caused evaporation from surface wood chips while capillary action continually supplied moisture from the melting snow to the surface. The wet wood chips/sawdust also provided a thermal mass slowing the transfer of energy from the surface to the snow beneath. The Davos location has an average summer relative humidity of 79%.

Lintzén and Knutsson (2018) reviewed current knowledge of snow storage and experience from areas in Scandinavia and reported new results from an experiment in northern Sweden, analyzing melt loss of stored snow. They report that the most common snow storage insulation method employees a breathable surface layer over an insulating material. From field observations at multiple nordic ski centers, they have found that the choice and age of insulation affects melt rate; older wood chips were less effective insulators than fresh chips. Lintzén and Knutsson also determined that wood chips were a more effective insulator than bark. They measured snow volumes three times over the summer and found that higher relative humidity increased melt rate. They also investigated the geometry of snow piles and determined that shaping piles in a way that maximized volume to surface area minimized melt loss; however, steeper snow pile sides caused sliding and failure of insulation materials (Lintzén and Knutsson, 2018).

Data related to snow storage for the purpose of summer cooling to improve energy efficiency and comfort supplements those gathered from ski centers. In central Sweden, the Sundsvall Hospital conserves snow over the summer for air conditioning with a 140 m x 60 m storage area (holding 60,000 $m^3$ snow) and underlain by watertight asphalt (Nordell and Skogsberg, 2000). After covering with 20 cm of wood chips, the majority of natural snowmelt resulted from heat transfer from air (83%), while heat transfer from groundwater drove 13% of melt and heat from rain accounted for 4% of melt. Similar work was done by Kumar et. al., (2016) in Canada, and by Hamada et. al. (2010) in Japan.

## 3 Setting

We conducted our experiment at the Craftsbury Outdoor Center (COC), a sustainability-focused year-long recreation venue that is located in northeastern Vermont (Fig. 1) an area with warm, humid summers and cold dry winters. Average maximum monthly air temperature at St. Johnsbury, VT (closest National Oceanic and Atmospheric Administration (noaa.gov, 2018) station to the COC about 30 km south east) between 1895 and 2018 ranges between 3.6° C (January) and 29° C (July), while minimum air temperature ranges between -34° C (December) and 15° C (July). Soils in the area (USDA), are very rocky, silty loam, sandy loam, and loam developed on glacial till. Average annual summer precipitation is ~107 mm (NOAA). The most common landcover types are forest and woodlands (USGS). The COC maintains 105 km of groomed nordic ski trails and hosts national and international races several times each winter.

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## 4 Methods

On March 30, 2018, two snow piles were emplaced at the COC using Piston Bully snow groomers in two separate sites (Fig. 2). At the time of emplacement, the snow was transformed and had a density of > 0.5 g cm$^{-3}$. At site 1, 225 m$^3$ of man-made snow was banked against a slope facing north. At site 2, about 1 km away, 210 m$^3$ of natural snow was shaped into symmetrical, rounded pile. The two piles were draped with sheets of plastic and covered with an irregular layer of wood chips averaging 20 ±10 cm (1 SD) on April 21, 2018.; chip thickness ranged from a minimum of 6 cm to a maximum of 40 cm, Fig. 3. In early July, about 30 m$^3$ of snow was removed from the pile at site 1 by COC personnel for a 4th of July holiday sledding party, the plastic was removed, and the remaining snow was covered again with wood chips and left for continued monitoring.

Weather stations adjacent to each pile (Davis Vantage Pro 2) collected air temperature, humidity, precipitation, solar radiation, wind speed/direction, and barometric pressure data. The weather stations record data at 15-minute intervals and transfer them to the web where they are publicly accessible (wunderground.com/personal-weather-station/dashboard?ID=KVTCRAFT2#history). Soil temperatures both below and adjacent to both snow piles were measured at 20-minute intervals using HOBO Onset dataloggers with thermistors installed at four different depths (5 cm, 20 cm, 50 cm and 1 or 1.05 m below the surface).

During spring and summer of 2018, the shape and volume of the piles were measured every 10-14 days using terrestrial laser scanning (REIGL VZ-1000)). Six to ten permanent tie-points around each pile were established during the initial survey by fastening reflective 5 cm disks to stable surfaces such as large trees and buildings. This first survey was done prior to snow pile placement in order to establish ground surface topography. Tie-point locations were determined and fixed relative to the scanner GPS position during the initial scan. Each survey consisted of three or four scans per site (depending on available vantage points), which were combined in the RiSCAN Pro software (v 2.6.2). Scans were collected at a horizontal angular resolution of 0.08° and a vertical resolution of 0.04°. Scans were collected from distances less than 100 m resulting in average point spacing over the pile <1 cm. Scans from multiple positions were registered together in RiSCAN Pro through fine scanning tiepoints.

To calculate snow pile volumes and volumetric change over time (between scans), point clouds of each pile were processed into digital elevation models (DEMs). Processing workflow involved cropping the point-cloud to the area of interest and converting to a 10 cm resolution DEM using a min-Z filter and QT Modeler software (v. 8.0.7.2). Volume calculations and differences in volume between sequential surveys were calculated in QT Modeler using these DEMs.

Snow density was measured using a Rickly Federal Snow Sample Tube. The snow tube was weighed, pushed into the snow, removed and weighed again. The weight of the tube was subtracted from the combined weight of the snow and tube, and density calculated by dividing the mass of snow by the volume (length of snow within the tube multiplied by the area of the opening, ~13 cm$^2$ ).

Insulation experiments were performed at both sites in June and July, 2018. At site 1, 10 cm of rigid foam (R=3.9) was compared to a 20 cm cover of wood chips both with and without a reflective cover (aluminized space-blanket). At site 2, we covered snow with a double layered, 2.5 cm thick insulating concrete curing blanket (R=3.3) and overlaid the blanket with either open-cell foam (R=3.5) or a layer of wood chips (20 cm) both with a reflective sheet. Insulation experiments were conducted in areas of 1 m$^2$ each, with thermosensors placed in the center of each quadrat at varying depths between layers (Fig. 4).

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## 5 Results

### 5. 1 Meteorological Data/Ground Temperature Data

Climate at our study site is strongly seasonal – such seasonality is clear in the meteorological data collected between June, 2017 and October, 2018 (Fig. 5). Between June 2017 and October 2018, air temperature varied between -28.2 and 33ºC (mean annual temperature = 6 ºC). Precipitation fell at a maximum rate of 22 mm day$^{-1}$ and humidity ranged between 14%-93% (mean 78 ± 15%,). Solar radiation had a 24-hour average of 109 W m $^{-2}$ and maximum of 1144 W m $^{-2}$ . Air temperature and solar radiation followed similar trends over the sixteen months, decreasing during winter months and increasing during summer months. Precipitation did not follow any significant pattern and humidity remained high, varying more during summer than winter months.

Ground temperature from all four depths at both locations followed similar trends. The shallowest sensor (5 cm below the surface) recorded the greatest variance over time (SD=7.4º C for site 1, and for site 2, SD = 4.6º C). Ground temperature variations decreased in amplitude as soil depth increased; at 1 m in depth, the atmospheric temperature signal was damped (SD = 3.9º C for site 1 and 4.3º C for site 2). Ground temperatures for all depths showed consistent warming from installation (June 11th, 2017) through late August 2017 and then decreased through February 2018. The shallowest sensor revealed slight warming after February while the deeper sensors remained stable until May 2018. During May, warming increased more noticeably for all four sensors. Ground temperature depth trends inverted during both May and November. During the winter, the coldest temperatures were at the surface; during summer, the coldest temperatures were at depth. Ground temperatures below both snow piles remained near or at freezing throughout the summer in contrast to the ground temperatures in areas not covered by snow which rose substantially.

### 5.2 Snow Volume/Density

Snow in both piles lasted until mid-September; however, snow volume decreased consistently throughout the summer (Fig. 6, Fig. 7). Comparing the laser scan survey completed just after wood chip emplacement, with the initial bare snow survey, showed that the layer of chips ranged in depth from 6-40 cm, with an average of 19 cm±11 for pile 1 and 21cm±11 (1 SD) for pile 2. After adding wood chips, snow volume in both piles decreased following similar trends (Fig. 6); initial decreases in volume were partly related to compaction and increases in snow density as snow density was ~ 0.5 g cm$^{-3}$ at emplacement, 0.6 g cm$^{-3}$ in May, and 0.7 g cm$^{-3}$ in July. Relative to newly fallen snow (0.1-0.2 g cm $^{-3}$), the snow in these piles were closer to ice (0.9 g cm$^{-3}$). These measurements are supported by visual changes in snow crystal morphology over the summer (increased rounding), size (up to 5 mm by July), and clarity (from white to clear by summer's end). Continued volume loss over the summer was predominately the result of melt. Average rates of change for both piles were similar (1.24 m$^3$ day$^{-1}$ and 1.50 m$^3$ day$^{-1}$). Maximum melt rates, recorded in July, reached -1.98 m$^3$ day$^{-1}$ and -2.81 m$^3$ day$^{-1}$ (Fig. 7.) Minimum rates of change for both piles occurred in September and were -0.29 m$^3$ day$^{-1}$ and -0.88 m$^3$ day$^{-1}$. As summer shifted into fall, melt rate decreased (Fig. 7).

As the piles decreased in volume over the summer, large crevasses formed along the edge of the plastic sheeting, which exposed the snow to direct sunlight and increased melt rates. We did not observe meltwater around either of the piles suggesting melt occurred at a rate which allowed for infiltration into the rocky sandy loam soil below. The woodchips deeper in the layer remained cold and wet throughout the summer while the woodchips on the surface were consistently dry in the absence of rainfall.

### 5.3 Insulation Experiments

Experiments revealed that different combinations of cover materials resulted in a variety of insulation efficiencies (Fig. 4). We assessed insulation efficiency by determining which material combination maintained the lowest and steadiest temperature at the snow-insulation interface. On the rigid foam, open-celled foam, and wood chip plots, the highest temperature was measured in air above the surface (max = 41.2° C) and lowest temperatures (min = ~0° C) at the snow surface (Fig. 4). During this first experiment, air temperatures above the reflective blanket were higher than above the non-reflective surface. When all plots were covered with a reflective blanket, all air temperatures above the pile were similar; yet, temperatures at lower depths, under different insulators (wood chips and open cell foam) varied significantly. The lowest and most stable temperatures at the snow/insulation interface resulted when the stored snow was covered directly with an insulating concrete curing blanket, then 20 cm of wet wood chips, and finally by a reflective sheet.

## 6. Discussion

The survival of snow through the summer in small piles and with simple, wood chip only insulation, suggests that larger piles, using an optimized insulation strategy, will allow for efficient over-summer snow storage summer at mid latitude (<45° N) and low altitude (< 350 m asl). Our results are particularly encouraging given the relative warmth of the 2018 summer season (2018 was Vermont's third-warmest summer since 1895 (fairbanksmuseum.org, 2019)), the simple and spatially inconsistent nature of our insulation (20±10 cm of woodchips), and the small size of the test piles (~200 m$^3$).

Our insulation strategy starting the experiment was not optimal. The thickness of wood chips, the insulation we used for these two test piles, was not uniform and became less uniform over time as melt changed pile shape (Fig. 3). Wood chip depth changed over the summer as crevices, which grew over time, exposed bare snow to direct sunlight and led to non-uniform melting of the piles. These crevices appeared to form along boundaries of large plastic sheets, which had been emplaced to prevent woodchips from dirtying the snow. Openings in the wood chip cover also appeared to result from snow slumping within the pile – both piles had steep sides and the pile DEMs reveal snow moving downslope (Fig. 6). Lintzén and Knutsson (2018) reference similar snow pile/insulation failure due to steep pile-side geometry.

The two test piles were small, only a few percent of the volume of snow typically stored over summer by Nordic ski areas. For example, in Davos, Switzerland and Martell, Italy, test piles were about 6000 m$^3$ and 6300 m$^3$ (Grünewald et. al., 2018). The Nordkette nordic ski operation in Innsbruck, Austria stores ~13,000 m$^3$ of snow and Ostersund, Sweden stores 20,000 to 50,000 m$^3$ piles, Small piles have a larger surface area to volume ratio (SA/V) which, allows more effective heat transfer through both radiation and conduction. A simple comparison of two hemispheres, one containing 200 m$^3$ of snow and the other containing 20,000 m$^3$ of snow indicates that SA/V changes from 0.43 to 0.04 between the smaller and large pile. For the summer of 2019, the COC will store and we will monitor about 7000 m$^3$ of snow with a SA/V of 0.07; the lower SA/V should significantly reduce melt loss and thus increase the percentage of snow surviving the summer season and thus be available for early winter skiing.

The magnitude of daily temperature oscillations at the snow surface (blue line in all panels, Fig. 4) is highly dependent upon the insulation strategy. The three-layer (insulating blanket, wet wood chips, and reflective cover) minimizes heat transfer into the stored snow as evidenced by the lack of diurnal temperature oscillations at the snow surface during this and only this experiment (Fig 4, panel e). To quantify this observation, Figure 8 displays the Power Spectral Density function (PSD) of selected insulation experiments (Fig. 4, panels b, e, f). PSD decomposes the temperature signal into component frequencies.

Only the three-layer (insulating blanket, wet wood chips, and reflective cover, Fig. 8 c) results in a flat PSD signal at the snow surface, a signal which does not reflect a diurnal (24 hour) oscillation nor any relevant harmonics (6 or 12 hours). Thermal records from all other insulation strategies clearly display a diurnal signal at the snow/insulation interface.

Although Figure 8 demonstrates the effectiveness of the three layer insulation approach to buffering heat transfer from the environment to the snow, the relevant heat transfer mechanisms remain uncertain. Deducing them will require different and more complex measurements. Perhaps, evaporation of water from the wet wood chips absorbs thermal energy during the day which is released as the latent heat of condensation at night when the reflective blanket cools – effectively increasing the thermal mass of the wood chip layer. Depending on weather conditions, the heat transfer may be directed toward the snow pile (warm nights) or radiated to the atmosphere (cold nights). In any case, the large thermal mass of wet wood chips, in concert with an underlying insulation layer (the concrete curing blanket), and rejection of shortwave incident radiation from sunlight by the reflective cover, appears more important than the R-value of the insulating material in damping daily temperature fluctuations at the snow surface.

## 7 Conclusions and Implications

Using the repeated terrestrial laser scan surveys and temperature data collected from the two small (200 $m^3$) snow piles, we have designed an over-summer snow storage system that optimizes snow preservation at mid-latitudes and low altitudes. Our three layer insulation approach reduces solar gain and buffers the effect of >30° C summer daytime temperatures and high (>75%) relative humidity on stored snow. Scaling up from 200 $m^3$ test piles to a 7,000 $m^3$ operational pile size will increase the efficiency of snow storage because the surface area to volume ratio will decrease, reducing energy per unit volume of snow available for melting. Data presented here show that snow storage at mid latitudes and low altitudes is a practical climate change adaptation that can extend the nordic ski season and the sport's viability as climate continues to warm.

### *Data Availability*

Data is available at https://doi.pangaea.de/10.1594/PANGAEA.899744

### *Author Contribution*

P. Bierman and Y. Dubief co-conceptualized the experiment. H. Weiss and Y. Dubief curated the data. H. Weiss, Y. Dubief, S. Hamshaw conducted the formal analysis. H. Weiss and P. Bierman acquired funding, developed the methodology (assisted by S. Hamshaw), conducted the investigation, and validated data. H. Weiss, P. Bierman, and Y. Dubief prepared data visualizations. H. Weiss and P. Bierman wrote the original manuscript draft. All authors contributed to the review and editing process.

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## Tables

**Table 1: Weather parameters measured between June 2017 and October 2019 at the Craftsbury Outdoor Center, Craftsbury VT.**

| | Air temperature (° C) | Humidity (%) | Precipitation (mm day$^{-1}$) | Solar radiation (W m $^{-2}$) |
|---|---|---|---|---|
| Minimum | -28 | 14 | 0 | 0 |
| Maximum | 33 | 93 | 22 | 1144 |
| Mean | 9 | 79 | 0.1 | 109 |
| Standard Deviation | 12 | 15 | 0.4 | 205 |

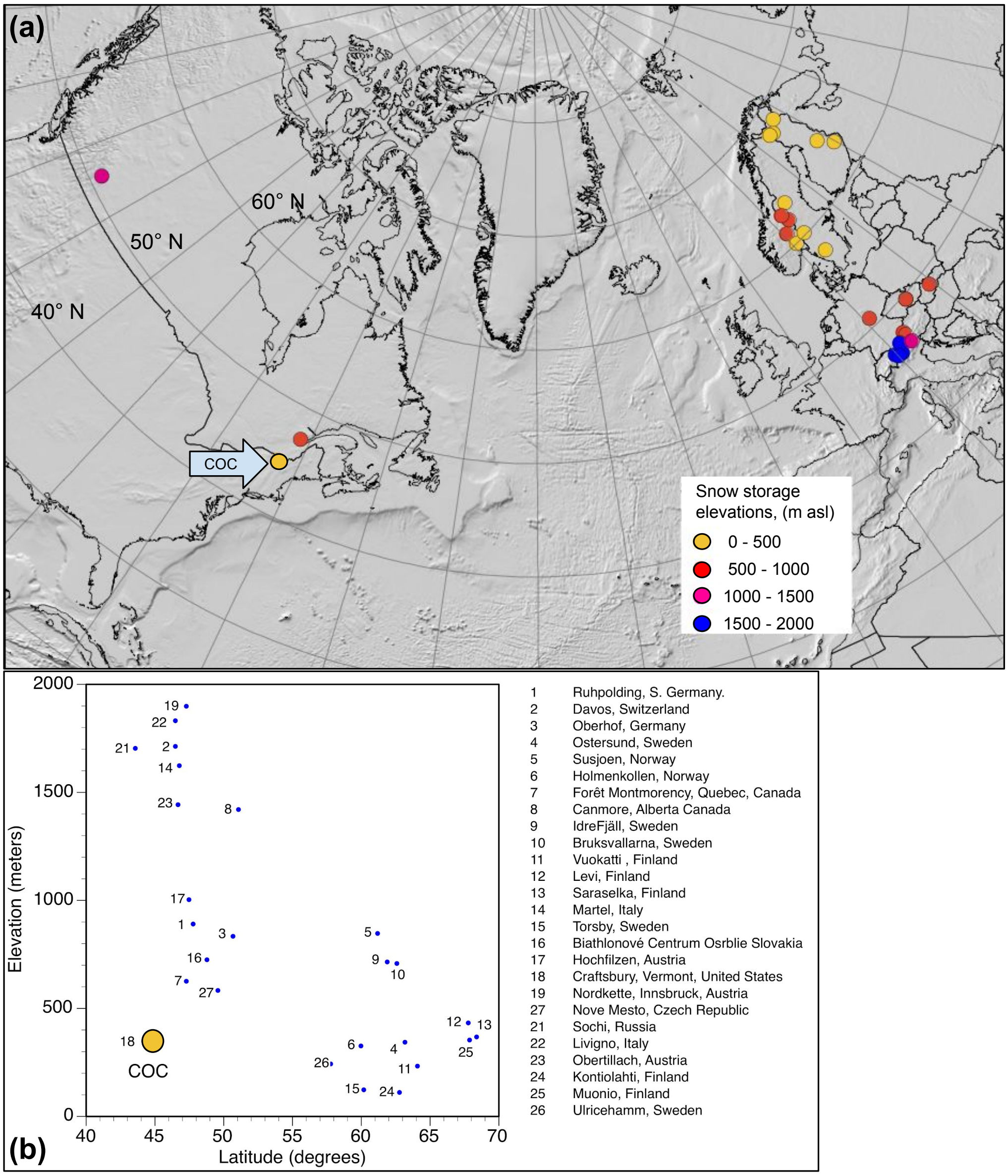

**Figure 1: Locations of over summer snow storage. (a) Conical projection shows known locations of over-summer snow storage at nordic ski centers. The Craftsbury Outdoor Center is highlighted with a blue arrow labeled COC. The relative elevations of ski centers are displayed as a color gradient, marked in the legend. (b) Scatterplot of same locations as shown in A. The Craftsbury Outdoor Center (#18) is large yellow dot (COC). It is the lowest combination of altitude and latitude of any snow storage yet attempted.**

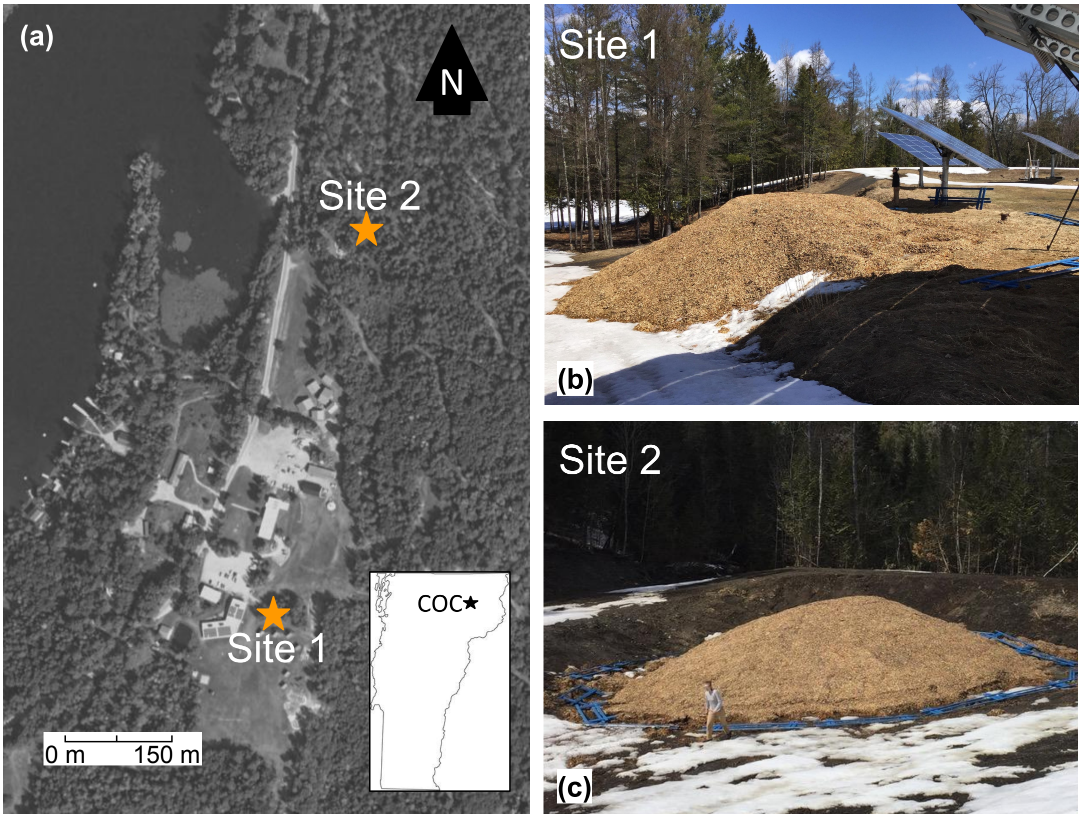

Figure 2: Snow storage at Craftsbury Outdoor Center. (a). Areal view of the Craftsbury Outdoor Center (COC) in Vermont, from http://maps.vcgi.vermont.gov. Both study site locations shown by number. (b). Site 1 (225 m$^3$), covered in woodchips on April 21st, 2018, with trees and solar panels for scale. (c). Site 2 (209 m$^3$) when installed. Site 1 received 24 m$^3$ of woodchips and 5 Site 2 received 42 m$^3$ of woodchips.

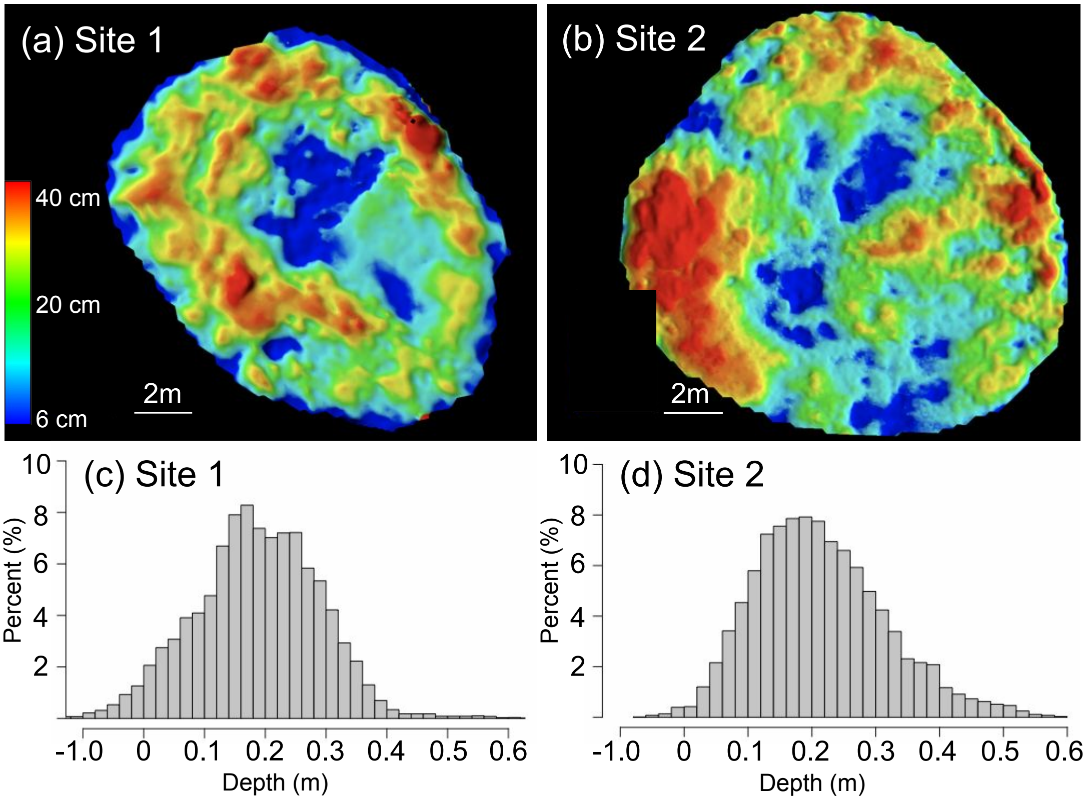

**Figure 3: Wood chip thickness distribution maps of pile 1 (a) and pile 2 (b) with red indicating areas of high thickness and blue indicating areas of low thickness. Panel (c) represents the chip thickness histogram for pile 1 and (d) is chip thickness histogram for pile 2. Negative thickness values likely represent snow settling between bare snow survey and survey after wood chip** 5 **emplacement.**

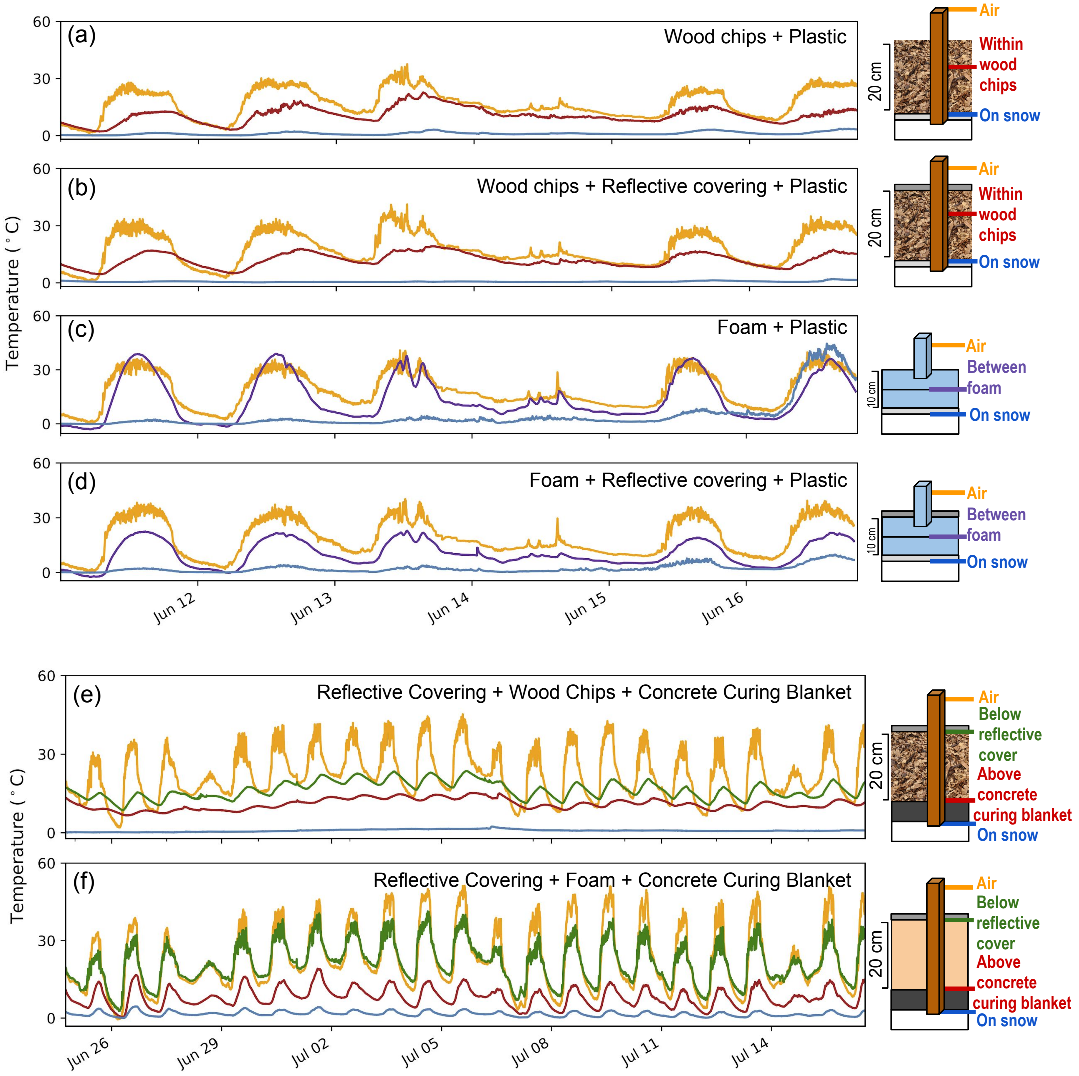

**Figure 4: Insulation experiments and resulting temperature records. (a) Site 1, woodchips underlain by plastic (b) Site 1, wood chips underlain by plastic and overlain by reflective cover (c) Site 1, foam underlain by plastic (d) Site 1, foam underlain by plastic and ad overlain by reflective cover (e) Site 2, woodchips underlain by concrete curing blanket and overlain by reflective cover (f) Site 2, open cell foam underlain by concrete curing blanket and overlain by reflective cover.**

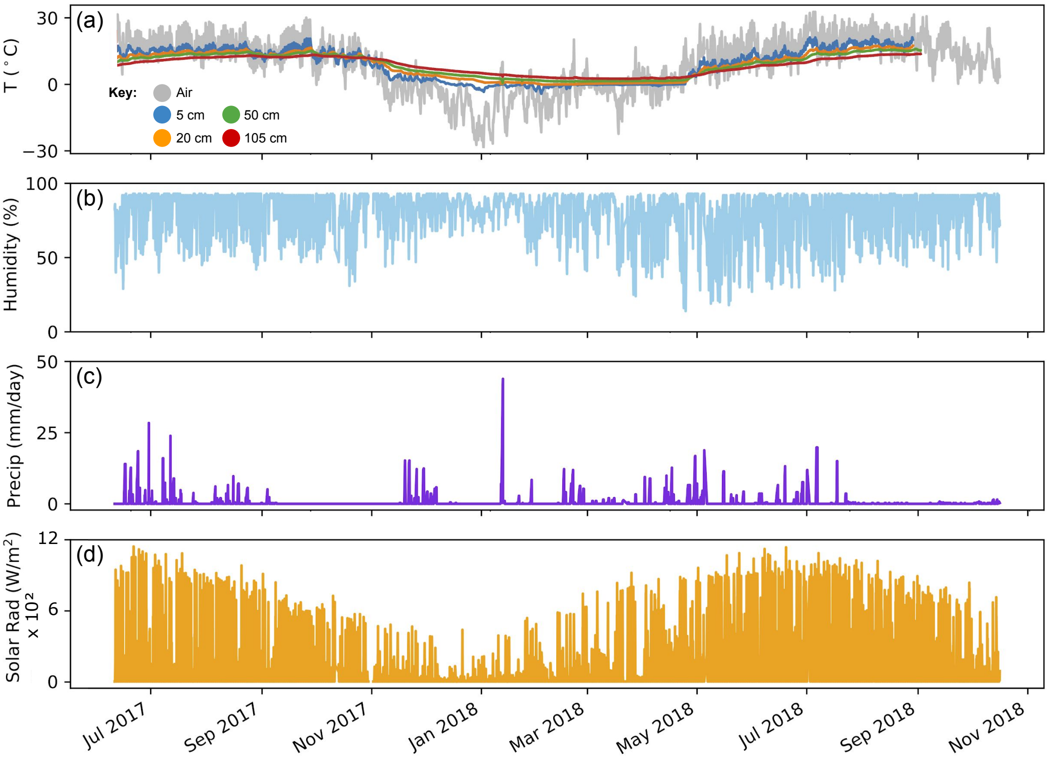

**Figure 5: Meteorological conditions and soil temperature between June 11, 2017 and October 16, 2018. Weather conditions were collected by the Davis Weather station at the Craftsbury Outdoor Center near Site 2. (a) Air temperature (grey), collected at 30-minute intervals plotted with ground temperature. Ground temperature was collected at 20-minute intervals by four HOBO Onset 5 dataloggers at depths below the ground surface of 5 cm (blue), 10 cm (orange), 50 cm (green), and 105 cm (red). Ground temperature record ends on September 2, 2018. (b) Relative humidity (%) (c) Precipitation (mm day$^{-1}$) (d) Solar radiation.**

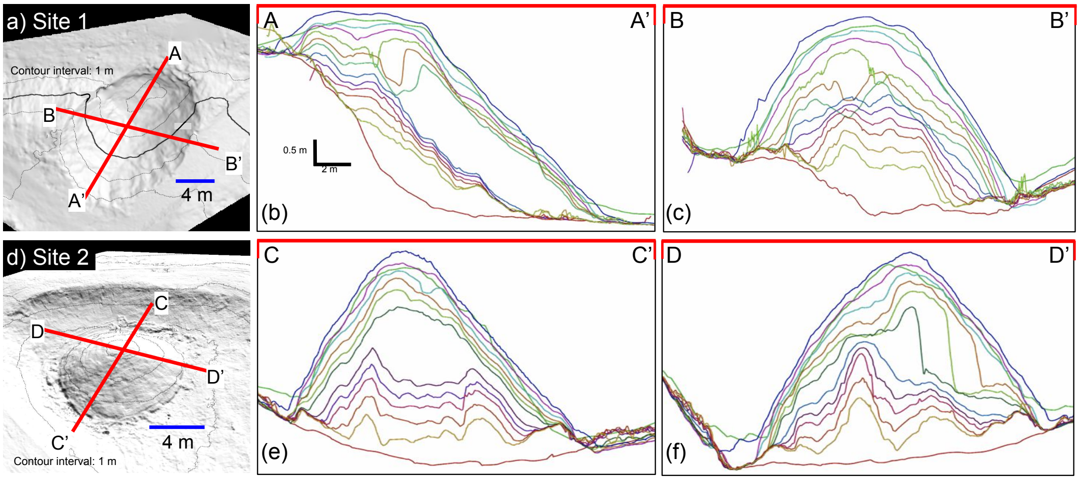

**Figure 6: Snow pile topographic change over time. (a) Oblique view of digital elevation model (1 m contours) of snow pile at site 1 with cross-sections A-A' and B-B' (April 21, 2018). (b) Profiles for each terrestrial laser scan survey (April 21, 2018 to September 9, 2018, n= 13) along section A-A'. (c) Profiles for each survey along section B-B'. On July 3rd, 2018, 30 m$^3$ of snow was removed from the pile at site 1. (d) Oblique view of digital terrain model (1 meter contours) of snow pile at site 2 with cross-sections C-C' and D-D' (April 21, 2018). (e). Profiles for each terrestrial laser scan survey (April 21, 2018 to September 9, 2018, n= 12) along section C-C'. (f) Profiles for each survey along section D-D'. Each scan represented by a line in panels b, c, e and f.**

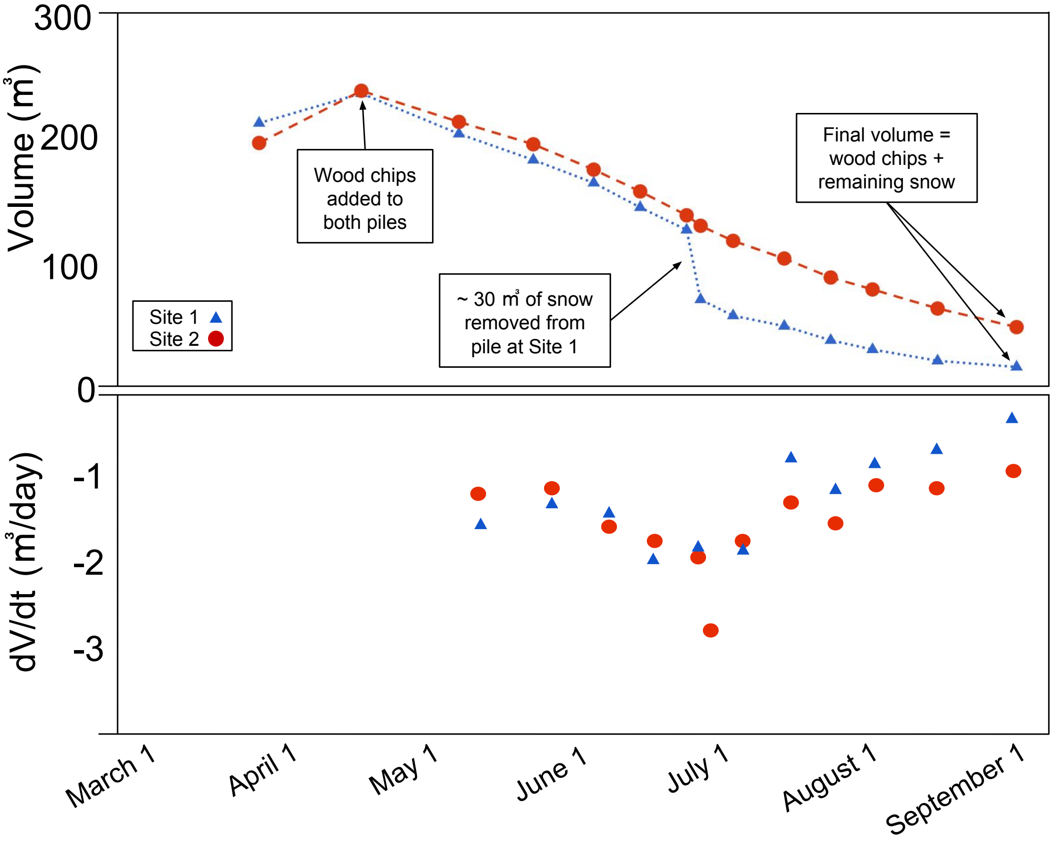

**Figure 7: Volume change over time for snow piles at sites 1 and 2 measured by terrestrial laser scanning. (a) Volume of snow piles from placement in March 2018 until end of melt season in September 2018. Addition of woodchips in April and removal of snow in July at pile 1 shown by black arrows. Volumes are total including wood chips. (b) Change in volume per unit time between** 5 **surveys. Rate of volume loss increases mid-summer for both piles.**

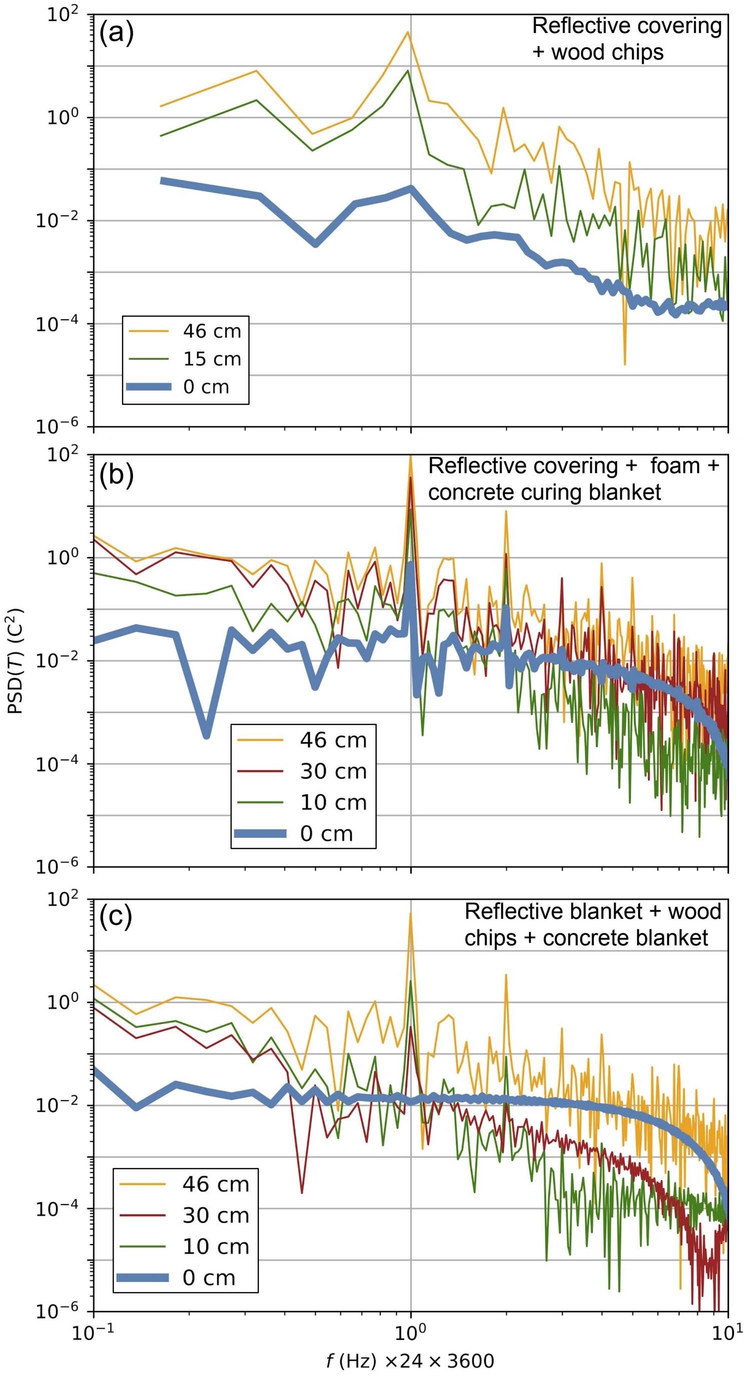

**Figure 8: Power Spectral Density of temperature records from three different insulation experiments (Fig. 4 b, e, and f). PSD normalizes frequency to 24 hours = $10^0$ and displays the magnitude of each temperature oscillation frequency for each of four sensors per experiment (depth in cm measured below uppermost sensor). (a) experiment with wood chips and reflective cover (Fig. 4b). (b) experiment with a concrete curing blanket, open cell foam, and a reflective cover (Fig. 4f). (c) experiment with concrete curing blanket, wood chips, and a reflective cover (Fig. 4e). The lack of detectable signal (flat blue line) at snow level (0 cm) in (c) demonstrates that three layer configuration with wood chips best damps the diurnal temperature signal.** 5