Responses to Reviewers

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Interactive comment on "Optimization of over-summer snow storage at mid-latitude and low elevation" by Hannah S. Weiss et al.
Anonymous Referee #2
Received and published: 6 May 2019

Author Response below.

The paper, which summarizes a small field test of snow storage in Vermont, US, is concisely and nicely written. Different types of thermal insulation were tested and evaluated by careful measurements of temperature and melting at two test plants, which both contained 200 m3 snow. Similar tests have previously been carried out in e.g. Sweden, Austria and Japan. Still I think it is a good paper since it suggests the most appropriate thermal insulation for a climate where such snow storage technology would be applicable. This paper has valuable information for future snow storage projects and should be accepted for publication in The Cryosphere.

Minor comments:

SI units are generally used. There are some examples where it is not (80 cal g-1) (g m-3) and these could be changed.
Author Response: Thank you for catching this inconsistency and non-SI units will be changed in the revised manuscript.

Page 1, Line 31 says: Earth's climate is warming in response to the addition of CO2 and other greenhouse gasses to the atmosphere (Steffen et. al.,2018). Suggested revision: Earth's climate is warming (Steffen et. al.,2018).
Author Response: Thank you for this concision suggestion and the suggested change will be made.

Page 5, section 1; The maximum rate of precipitation is given. I miss the mean annual precipitation, which should be added.
Author Response: Thank you for this suggestion. We will include mean to provide additional context.

The paper refers to research done in Sweden, Austria and Japan but there is no reference to Ed Morofsky, who was involved in ice and snow storage research in Canada?

Author Response: Thank you for the researcher suggestion – we will cite Morofsky in the revised manuscript.

I also miss that they did not do any calculations of the heat transfer through the thermal insulation.

Author Response: Thank you for this note – we did not include heat transfer calculations as the models were not ready at the time of publication, and the inhomogeneous wood chip layer and melt pattern rendered calculations less valuable. We hope to include heat transfer calculations in future publications when we have more consistent

Interactive comment on "Optimization of over-summer snow storage at mid-latitude and low elevation" by Hannah S. Weiss et al.
Nina Lintzen (Referee)
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Received and published: 5 May 2019

Author Response in green.

General comments:

1) The paper presents over-summer snow storage at mid-latitude and low elevation. The tests were performed in Vermont, USA. The goals of the research (according to the statements in the introduction) was to: 1) Determine the melt rate. 2) Infer the environmental factors that most influence snow melt. 3) Suggest an optimized insulation strategy based on the data. I would have liked to see clear responses to all these questions in the conclusions section.
Author Response: Thank you for this comment – we realized we've focused on 1 and 3 (though not explicitly) but did not address goal 2 in our conclusion. We will make this change in our revision. The data collected allows us to address goals 1 and 3, yet not goal 2 which we will remove from the introduction. We will then more clearly address 1 and 3 in the conclusion.

2) The climate in Europe is warmer than in North America at a similar latitude. A comparison between actual weather data from other over-summer snow storages with warm summer climate (for example in Europe, Russia and South Korea) would have been desirable.
Author Response: Great suggestion – we discussed this comparison yet it did not end up in the final paper. We will incorporate this into revision.

Specific comments:

3) The results should be discussed and explained more in detail. For example, what do we see in Figure 4?
Author Response: We appreciate this comment – initially, we had extensive narration and decided to simplify the section but perhaps removed too much. We will add more narration in revision.

4) How much did the temperature change between the different test methods? The scaling in the figures is not so clear so this is obvious just by looking at the figures. I think the results are very interesting but a detailed comparison of foam with and without reflective cover, how much the temperature changed in the "between- foam-spot" etc. would have given more depth to the study. Similar for figures a and b as well as e and f. How much lower was the temperature above the concrete curing blanket if you compare e and f?
Author Response: Thank you for this analysis of Figure 4. Power-Density Spectrum Analysis (PDS in Figure 5) is more useful for analyzing effectiveness of different insulation test methods than temperature change alone. However, within Fig. 4 we will include ranges for the sensors at the snow-insulation interface to demonstrate temperature differences between insulation types.

Our goal in using PSD is to determine which temperature signals still displayed the diurnal oscillations – if certain insulation combinations damp the temperature signals more thoroughly than others, these insulations were more effective at preventing heat from radiating into the pile. The individual temperatures were not as important as their signals throughout the week. It's clear that we did not explain PSD in an accessible way and will revise this.

5) In figures 4 c and d, the temperature on the snow seems to be much higher than 0◦C in the end of the experiments. Is this due to some measurement error? Or how do you explain this temperature increase?
Author Response: Thanks for this note. Due to the rigidity of the foam boards and the non-uniform melting of the pile, the foam shifted and exposed snow to direct solar radiation, as well as allowed warm air to be trapped between the snow and the foam. In panels c and d, we see this reflected in the temperature sensors at the snow interface reading significantly higher values than 0◦C. We will make this clearer as it could help the reader understand the ineffectiveness of the rigid foam panels.

6) The PSD and the results in Figure 8 needs to be explained more in detail. What is the PSD? How do you calculate the PSD? What do we actually see in the figures?
Author Response: We thank you for identifying the lack of clarity about PSD. We realize in retrospect that we did not explain the concept in an accessible way and will in further revisions.

7) I would suggest to enlarge and develop the discussion section. Discuss the three goals with this research and compare them to other studies. Are there for example other studies where the melt rate has been studied and how do your results relate to these? Which were the environmental factors that most influenced the snow melt and how did you reach this conclusion?
Author Response: This restructuring suggestion is very helpful for streamlining our discussion section. There are few studies thus far that address melt rate of snow within the context of snow storage, however none measured at the weekly time intervals at which we measured snow melt. We can infer most influential environmental factors through looking at which insulation combination was best. We'll restructure to address the three goals.

Comments from the text:

8) Page 6, # 15: How do you conclude that larger piles using an optimized insulation strategy allow for efficient over-summer snow storage from these experiments? For sure this is possible, it has been done at places with warm climate (for example in Sochi, Russia and Pyeongchang, South Korea).
Author Response: Thanks for the comment. Larger piles have lower surface area/volume ratio of large piles in comparison to smaller piles. We will do a better job of incorporating the SA/V ratio into this section.

9) Page 6, # 30: The planned snow storage for the summer 2019 is interesting, but not relevant for this presented study and experiment.
Author Response: Thank you for this observation – if we are short on space, we will remove it. If we do not remove it, we will be sure to more accurately label as "Future Work" to clearly identify it is not part of the current study.

10) Page 7, # 20: Conclude answers to your three research questions. Also, conclude and point out that based on your experiments and from the different experimental setups you tested, the three layer insulation was the best. Scaling up from 200 m3 to 7000 m3 will increase the remaining amount of snow, but this is not a conclusion from the performed tests in this study. Scaling up to any larger volume will render a larger remaining volume of snow, but this is not a relevant conclusion from the tests performed in this presented study. However, in the discussion section I would suggest that you mention the fact that larger volumes of snow will increase the efficiency of snow storage, as have been seen in previous studies, and as you have mentioned in #25 and 30 on page 6.
Author Response: Thank you for the clarifying and structuring suggestions – you're correct that we did not test the effects of snow melt for different size piles and we will be sure to more clearly define our conclusions based on the insulation

experiments alone. Great suggestion to include the larger volume, more snow scenario in the discussion section and could reference this in the conclusion while still staying true to the limitations of our experiments.

Technical comments:

11) Page 4, # 5: "man-made" snow should be changed to "machine-made snow".
Author Response: Thank you - we will change this phrase to remove the outdated gender bias.

12) Page 4, # 35: Were the sheets of plastic and wood chips removed from the whole pile or just from the 1 m2 test area?
Author Response: The sheets of plastic and wood chips were removed from just the test areas – we will clarify this in the revision.

13) Page 5, # 5: It says that the humidity remained high, but how high is a high humidity? A number would have been interesting.
Author Response: Agreed – we will make this comparison in the next revision.

Interactive comment on "Optimization of over-summer snow storage at mid-latitude and low elevation" by Hannah S. Weiss et al.
Thomas Grünewald (Referee)
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Received and published: 7 May 2019

Author response in green.

Weiss et al present a case study on over-summer snow storage (snow farming) at two sites in Vermont, US. Melt rates of two small snow piles were calculated from repeated high resolution snow volumes measured with terrestrial laser scanning (TLS). Meteorological parameters and temperatures in the covering layer were continuously measured. Moreover and they investigate the performance of different settings of covering materials (combination of wood chips, open-cell foam, rigid foam, blanket); It is shown that snow storage seems possible, even at such a low-elevation site. The novelty of the study is the high temporal resolution of the snow volume surveys (14 surveys over summer-season) and the detailed assessment of temperature gradients within the covering-material. Such data have not been presented before. Data and results are generally presented nicely and are definitively worth publication in TC after a careful revision; some sections are unclear and need to be reformulated or enlarged (see below). Most important, I think that the large potential of the data set is not fully exploited: The high spatial (10cm) and temporal (about 2 weeks) resolution of the TLS data would allow a more detailed analysis (see specific comments). Considering the effort of the suggested additional analysis and the many smaller things to be changed I suggest major revision (could also be major minor revision);

Author response: Thank you for your detailed, constructive comments; they strengthen the manuscript significantly.

Specific comments:

1) TLS section requires more detailed information (settings of device, accuracy, references)
Author response: We will revise the manuscript to provide further description of hardware and software settings, registration workflow, and add additional necessary references.

2) Section 5.1 should be enlarged with an analysis on spatial and temporal variability of snow melt (TLS data). Interesting questions to be answered are: How do melt rates principally vary spatially (e.g. depending on slope and aspect of the piles)? How does the type of covering material combination affect melt rates? (Compare the different areas) How does the spatially varying depth of the wood chips (known from first survey) affect melt? Addressing these questions would be very interesting and would substantially improve the impact of the paper.
Author response: We appreciate the suggestion for further spatial and temporal analysis of melt from the TLS scans. We will analyze spatial and temporal variability of the melt of the piles and identify if that analysis can help to address the suggested questions. Likely, a spatial/temporal analysis of melt rates will be inconclusive in addressing some of the questions given the small size of our snow piles and we observed shifting (sliding) of the wood chip insulation over the study period.

3) Section 5.2 must be revised; Temperature alone cannot be used as criterion to judge covering material performance; TLS data could be used to analyze effects of different cover on snow melt;
Author response: Our experimental design used temperature as a means of determining insulation efficiency. This makes sense because a change in temperature is directly related to heat flux and melt rate. We only ran insulation experiments on 1m X 1m plots instead of the full pile which means that we cannot spatially nor temporally compare the temperature data from the experiments (collected over 1 week) to the full-pile melt data which was usually acquired every 10-14 days. The Power Density Spectrum (PDS) analysis was included to determine the effectiveness of insulation combinations based on temperature; we will revise these sections to be clearer about both the scope of the insulation experiments and the results from the PDS analysis.

4) Results should be related to earlier studies and other snow farming projects;
Author response: We will more explicitly compare this project to other projects within the results and discussion section as it will strengthen the conclusions.

5) Many statements need to be rephrased for correctness and more clarity. More details can be found in the technical comments below.
Author response: Thank you for the technical comments; we will address all of them.

Technical comments:

6) Abstract: should be a single paragraph. Remove line-breaks
Author response: The change will be made.

7) p1 l 13: this statement "has never been attempted at low elevations..." is too rigid. There are some low-elevated places (e.g. Ruhpolding Germany, elevation 700m) that successfully operated snow farming for many years. Please formulate more carefully.
Author response: Thanks for pointing this generalization out – we meant to indicate the uniqueness of our study site in terms of its combined elevation (300 m asl) and latitude (44°) and will edit this sentence to better reflect our intentions.

8) L 22-24: It is unclear how the two piles were covered and to which pile the mentioned rates of change refer; what is meant with "minimum rates of change"? I suggest to provide ranges and mean for the rates of change.
Author response: We will edit to clarify. We will include ranges of snow melt rates.

9) L25: replace "blackbody radiation" with "long-wave emission"
Author response: Thanks for the clarification. We will change the phrase.

10) L32-33: "This warming... snow packs." This statement requires a reference
Author response: Reference will be added.

11) L36 in that context it is unclear what is meant with "... by covering snow". Please reformulate; moreover the current review paper of Steiger et al 2017 could be cited in that context;
Author response: We will add "…by covering snow *in various insulative materials to impede snowmelt* ". Thank you for the addition of the relevant and recent Steiger paper we will included it in our revision.

12) P2 L1-3: there was only little research on snow making (from the science side) in the last decades; most of the innovation came directly from industry; This changed a bit in the last years when the public sector and science began to realize the importance of snow making and snow management and the challenges of climate change for the skiing industry; Examples for recent publications are Hanzer et al. 2014, Grünewald and Wolfsperger 2019 or Spandre et al. 2016;
Author response: We will amend to put more emphasis on industry's role in the innovation of snow making. Thank you for the paper suggestions.

13) L 6: why is snow storage safer than relying on weather conditions? Please be more concrete here
Author response: Snow storage is safer than relying on weather conditions because optimal snow making conditions are becoming increasingly rare as climate change affects winters. We will revise to more explicitly state this important piece.

14) L8-14: For cooling people mainly used lake or river-ice; the cited reference (Nanegast 1990) also seems to refer to ice; snow was (and is still used) in some areas of Asia and Scandinavia. As formulated now, the paragraph is bit confusing; Please reformulate and be careful not to mix ice storage with snow-farming for winter sports as described in the end of the paragraph;
Author response: We will change the statement to be clearer that we're referencing ice storage to demonstrate that organic materials (sawdust/wood chips) have been used in the past to keep vestiges of winter cold – not that we are attempting to compare snow-farming for winter sports to ice houses as these have very different intentions.

15) L14: snow storage is quite expensive (see Grünewald et al. 2018)
Author response: We agree that the insulation process is expensive and we will be clearer that we mean inexpensive compared to a center not being able to open their season on time (and thus, loosing significant business). However, the Cost-Benefit Analysis has not yet been completed so we will be careful with how we discuss this idea.

16) L16 Besides solar radiation, air temperature is most important for snow melt (see Fig 11 in Grünewald et al. 2018); precipitation is less relevant; why should evaporative cooling be higher in cold and dry climates? Evaporation is depending on the temperature gradient between surface and air, wind and wetness of the covering-layer.

Author response: Thanks for pointing this out – high summer relative humidity limits evaporation in Vermont. We will clarify.

17) L22 I suggest to point out the research gap and the novelty of the study here
Author response: Thank you for the suggestion – we will include the research gap and novelty when discussing the goals of the research to put it into context.

18) L27 use J/kg as unit for energy instead of cal/g
Author response: We will make this edit.

19) L31 use long wave emission or long wave radiation instead of blackbody radiation
Author response: We will make this edit.

20) L34 Long wave radiation especially depends on surface temperature (Stefan Blozmann law: power of 4!)
Author response: We will include surface temperature when discussing what affects longwave radiation.

21) L36 snow melt instead of snowpack melt
Author response: We will make this edit.

22) P3 L5 I am not happy about the formulation “high elevation”; if 1600 is high, what is 3000m? And: the latitude of Vermont (45◦) was called “low” (P2 L17);” here a very similar latitude of 46◦ is called “mid”; this is not consistent;
Author response: We will revise the manuscript for consistency.

23) L6 I suggest to write machine-made or technical snow instead of artificial snow
Author response: We will change “artificial” to “machine.

24) L6 remove “wet”
Author response: We included the fact that the wood chips contained moisture because moisture plays a key role in reducing snowmelt; dry wood chips would not have been as effective at preserving snow.

25) L8 write “Using a physically based model” instead of “thermal models”
Author response: We will make this change.

26) L8/9 please clarify context: most effective means in relation to work/cost effort; deeper layers can safe more snow but the effort is higher
Author response: It is important to define “effective” in this context and we will make this change.

27) L11 write “capillary flow” instead of ”capillary action”
Author response: We will make this edit.

28) Section 3: The section is very short. I suggest to merge section 3 and 4 to “Methods and settings” and then to introduce subsections; (e.g. study site, Weather stations, terrestrial laser scanning, snow density, insulation experiments...)
Author response: We will make this edit.

29) L30 what is the elevation of the site?
Author response: We will include the elevation (~360 m asl).

30) L33 What is the elevation of the station?
Author response: We will include the elevation of the weather station (~215 m asl).

31) L 31-33: please also indicate mean temperatures not only minimum and maximum
Author response: We included only min and max because these represented both best and worst case scenarios for summer weather. We will include mean.

32) L 34-36 USAD, NOAA, USGS > citation style is wrong; year is missing
Author response: We will fix the citation style.

33) P4 L1 please describe differences between the two sites (pile 1 and 2), e.g. shadow, slope
Author response: We will include differences between the piles within the Settings section.

34) L5 provide a reference to snow density section
Author response: We will provide average snow density ranges for comparison.

35) L5 provide more information on the properties of the plastic sheets (e.g. thickness, size, water permeability, thermal conductivity . . .) and for what reason they were used (I guess to reduce snow pollution as stated later); such information should also be given for the foam used in for the insulation experiments
Author response: Thank you for the suggestion. We will provide the properties we are aware of – you are correct that they were used to reduce snow contamination by woodchips. We will include a similar rationale and properties for the foam.

36) L6 brackets are missing (Fig. 3)
Author response: We will include brackets.

37) L9 at which height above ground were the meteorological measurements performed?
Author response: The measurements were preformed at a ~3m above ground. We will include this information.

38) L12 be more clear about soil temperatures: how many sensors? Where were the sensors? Where the sensors in the ground or in the covering layer?
Author response: We will be more specific about the ground temperature sensor details in revisions.

39) L15 this section requires more details: the dates of the scans should be provided, e.g. in a table; Also add a table with the technical specifications of the laser scanner; Was multi-station adjustment used for registration; why not? It is an easy approach to improve registration of the data; What is the accuracy of the data? Were data gaps (scan shadows) existing? How were they handled? If a direct accuracy evaluation of the data is not possible, at least references to earlier studies that assessed TLS accuracy in similar settings should be added, e.g. Prokop et al. 2008, Grünewald et al. 2010, Grünewald and Wolfsperger 2019;
Author response: Thanks for these suggestions and additional references on TLS accuracy. We will update the manuscript to provide further details on the workflow of scanning. We did run MSA in RiScan and will specify that detail. We did not conduct an analysis of data gaps, but given the relatively small size of the piles, it was feasible to get very good coverage with few scan positions – and thus had minimal data gaps. We will revise manuscript to clarify DEM generation settings about filling of any potential data gaps.

40) L32 please add for how long the insulation experiments lasted; until end of summer?
Author response: These experiments lasted a week. It is possible to find this information in the accompanying figures; we will include it in the text as well.

41) L32 please state what kind of R (e.g. Pearson's correlation coefficient) is used
Author response: We will be clear about what kind of "R" value we use.

42) P5 Sect 5.1 Sum of precipitation should also be given; How were condition of the recorded summer season in relation to long term climate? Data from station COC described in Sect. 3 could be used to rate this summer;
Author response: Great suggestion to place the conditions of summer 2018 into context – we will include this information.

43) L10-17: It is not clear which measurements are described here: the sensor below the piles or the ones next to the piles? Is there an explanation for the much larger T – variability for the 5 cm sensor at site 1 in relation to site 2? To which of the two sites does Fig 5 refer to?
Author response: The measurements refer to the sensors next to the pile. The ground temperature data in Site 2 was disrupted halfway through the winter due to a faulty sensor and because of the frozen ground, we were unable to replace until warmer weather. Figure 5's panel a) is data from Site 1 – we will be sure to specify in the following draft. Data in panels b) - d) are from the weather station located closer to Site 1.

44) L17-19 unclear: only measurements of one site (below pile or next to pile) are shown in Fig 5;
Author response: Yes – the only measurement displayed in Fig. 5 is the GT next to the pile in Site 2. We will specify.

45) L24: add a reference to Fig 3 (after . . ."for pile 2.")
Author response: We will add this reference.

46) L25 use kg/m3 instead of g/m-3
Author response: Thank you for the suggestion – we will switch from g to kg.

47) L25-26 Where were densities measured (in which depth) obtained? Densification should be related and discussed in relation to the results of Grünewald et al. 2018 who showed an increase in density, both in time and in depth;
Author response: Density was collected at the top of one pile three times. We will be provide these details.

48) L26-27 “Relative to . . . (0.9g/cm-3).” Relating density to fresh snow is not meaningful in that context and could be removed;
Author response: We believe this context is useful to demonstrate to diverse audiences the high level of snow compaction that occurred over the summer. We will leave the context.

49) L27: I do not think that this is an adequate explanation. Snow with a density of 500 kg/m3 should already be fully decomposed and rounded; Was the snow dry during density measurements? Or was there some liquid water content? Or did you identify ice aggregations resulting from refrozen water? What was the grain size in March?
Author response: Quantitatively analyzing snow morphology was not within the scope of this study, though we will include qualitative observations (wet as opposed to dry snow, high liquid water content).

50) L29: Please check the numbers: Considering the very similar melt rates of the two sites (Fig 7) the difference between 1.24 and 1.5 m3/d seems very high; is the removal of the 30m3 snow possible part of the melt rate?
Author response: We will review our calculations to determine melt rate. The removal of snow halfway through the summer was not included in the calculations.

51) L29-32 Discussing melt rates is the main focus of the paper; Please discuss them in more detail; Your data set should allow a much more detailed analysis! e.g. how do melt rates change in time and how does this related to meteorology? Do melt rates vary spatially? What is the difference between the two piles? What is the difference between sections with different cover material?
Author response: As described in comment 2, we will do further analysis of the spatial/temporal patterns of melt rate on the piles. While there are limitation to this analysis given the insulation depth was not constant (due to shifting/sliding) and the insulation experiments were preformed over a 1 m X 1 m section of the 200 m³ piles, we believe it will still add further insight to melt processes.

52) L32-37 possibly even the effect of the crevasses could be seen in the TLS data (e.g. local changes in melt rates?
Author response: Yes, crevasses are visible in the TLS data. However, there were so many factors influencing melt rate that we could not draw direct relationships between the forming of the crevasses and melt rate.

53) P6 Sect 5.2. This section is pretty poor. It should be enhanced: a discussion and reasoning on the effects of the different covering types (properties of materials and how do they interact with snow and atmosphere is missing; Currently only temperatures are analyzed but this is not enough to judge performance of the different materials; The TLS data could be used to quantify and discuss if and how volume losses differ under different covering materials.
Author response: Thanks for the general suggestions for improving this section. There is some discussion of the material properties and interactions with atmosphere within the manuscript, but we can enhance the section.

54) add references to the specific panels for Fig 4
Author response: We will revise the manuscript to specifically reference individual panels of Figure 4.

55) L2 insulation efficiency is not only a function of T, e.g longwave emission or turbulent fluxes are not only depending to T but very relevant for the energy balance;
Author response: Thank you for this note. We will incorporate this language into the paper, though we do not have longwave emission data.

56) L12 the presented experiments used wood chips and a plastic planked not only wood chips;
Author response: You’re correct – thanks for the clarification. We will make this change.

57) L13-14 climate is not only a function of latitude and elevation; please rephrase
Author response: We will rephrase to be sure we’re acknowledging that there are more factors that influence climate apart from latitude and elevation.

58) L 15 (fairbanksmuseum, 2019)) > remove bracket
Author response: We will remove the bracket.

59) L36 Provide more details on the PSD method; how does it work and what is its benefit? How is it interpreted? Add references;
Author response: The PSD section will be reworked to be clearer.

60) P7 L6-9 This explanation is too simple: heat transfer is not simply depending on air temperature; surface temperature, cloudiness (longwave radiation) and wind (turbulent fluxes) are also crucial; See discussion of simulation results in Grünewald et al. 2018 and the sections about energy balance, and snow melt of the recent review paper of Mott et al. 2018; these references and possible also other earlier work should be cited in context of the discussion;

Author response: Thanks for providing suggestions to strengthen this section – we will revise to acknowledge the different factors that influence heat transfer.

61) L11 what is the "R-value"?
Author response: "R-value" is an accepted term in the United States refers to the insulating abilities of a material. We will fully explain "R-value" in the next revision.

62) Section 7: Conclusions should be prolonged; Here all three research questions form the introduction should be shortly answered; an outlook on future research that might be useful to enhance our understanding on snow storage might also be added;
Author response: We agree that the conclusion should be restructured to include our three research questions and provide a clearer path for future research.

Figures
63) Figure 1 b) it would be nice if the list would be ordered geographically; Several sites are missing (see attached pdf; Reference: Wolfsperger et al 2018)
Author response: Thanks for the geographic organization suggestion – we will reorganize in a more intuitive way. We appreciate the addition of the new sites.

64) Figure 4: T fluctuation of the blue line is hardly visible; possibly change axis or figure dimension
Author response: The blue line actually does not fluctuate as it records temperature at the snow-insulation interface – which is likely why it is difficult to see it.

65) Figure 5: Figure a should be enlarged vertically to improve readability; grids or vertical lines should be added; For humidity and radiation adding daily mean values as line could also help to improve readability; Legend: To which snow pile does the figure refer to? Ground temperatures below or next to pile?
Author response: We will enlarge the figure to the specifications allowed and we will improve readability. We will be clearer about the origins of the GT values.

66) Figure 6: Please add a legend relating colors to dates.
Author response: Thanks for the suggestion – we will include a legend.

67) Figure 7: Why is the increase in volume from April 1 to May 1 for site 2 so much larger than for site 1? Was there such a big difference in volume of chips added? Are colors between the two panels possibly mixed? The huge melt rate drop on July 1 might be correct for Site 1 (blue) but not for site 2; Add a grid or horizontal lines for readability;
Author response: The difference in wood chips is partially the result of the shape of the pile – pile 1, which received less wood chips, was banked against the side of a hill while pile 2, which received slightly less than twice the amount of wood chips, was a domed pile. Because these piles had difference geometry and thus different surface areas, different amounts of wood chips were needed to cover them. The melt rate calculations will be checked and the graph will be improved for readability.

68) P9 L15 doi seems to be wrong
L22 and L 24 The papers are not cited in the text;
Having only checked few selected references I found three mistakes; I guess that there are more. Please check your citations and references carefully!
Author response: Thanks for checking references. We will more carefully check and revise them.

Summary list of edits to the manuscript by section

- General edits were made to improve flow and provide data to increase specificity as requested by reviewers.
- We added methods, results and discussion of data obtained in 2019 from a snow pile created to validate the approach we optimized in 2018.
- The abstract was edited to include 2019 data.
- The introduction (1) was edited to include more citations and acknowledge the novelty of studying snow storage. Data were added and research goals were refined to include the 2019 test of over-summer storage at scale.
- The background (2) was edited to discuss Grünewald et. al.'s research more completely, and more citations were added.
- Methods (3) Were split into individual sections.
- (3.1) was edited to include more data and reformat some citations.
- (3.2) was edited to include more specificity about location differences for test sites and the plastic covering.
- (3.3) was edited to include specifications about the soil temperature measurements.
- (3.4) was edited to include more specifics related to the terrestrial laser scanning unit.
- (3.5) was edited to include the times of year snow density data were collected.
- (3.6) was edited to clarify the experimental setup and define R-value.
- (3.7) was created to better explain the Power Spectral Density function.
- (3.8) was created to include methods for the 2019 test of over-summer storage at scale.
- (4.1) was edited to include more inclusive weather data.
- (4.2) was edited for unit preferences.
- (4.3) was edited to acknowledge multiple factors that influence heat transfer, increase specificity of the cover experiment, and include ranges for temperatures.
- (4.6) was created to specifically discuss the results of PSD function
- (4.7) was created to discuss results from the summer 2019 test of over-summer storage at scale.
- The discussion (5) was edited to reflect initial goals and all three goals were described in more depth
- The conclusion (6) was edited to show how the 2019 summer data validated the 2018 summer data.
- The citations were reviewed and checked for proper formatting.
- Figure 1 was edited to group ski centers by geographic region
- Figure 2 was edited to include two photos from summer 2019
- Figure 4 was edited to increase readability of the figure
- Figure 5 was edited to increase readability
- Figure 6 was edited to include a legend and improve clarity of the images
- Figure 7 was edited to include summer 2019 data

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 chips as a covering material, 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 a site with both a low altitude and latitude, and few studies have quantified snowmelt repeatedly through the summer. Such data, along with tests of different cover strategies, are prerequisites to optimizing snow storage strategies. Here, we assess the melt rates of two wood-chip covered snow piles (each ~200 m^3) emplaced during spring 2018 in Craftsbury, Vermont (45° N and 360 m asl) to develop an optimized snow storage strategy. In 2019, we tested that strategy on a much larger, 9300 m^3 pile. In 2018, we continually logged air-to-snow temperature gradients under different cover 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. During both years, we monitored volume change over the melt season using terrestrial laser scanning. In 2018, snow volume loss ranged from -0.29 to -2.81 m^3 day^{-1} with highest rates in mid-summer and lowest rates in the fall; mean melt rates were 1.24 and 1.50 m^3 day^{-1}, 0.6 to 0.7 % of initial pile volume per day. Snow density did increase over time but most volume loss was the result of melting. Wet wood chips underlain by an insulating blanket and covered with a reflective sheet was the most effective cover 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 by long-wave emission at night. The importance of pile surface area to volume ratio is demonstrated by the melt rates of the 9300 m^3 pile emplaced in 2019 which lost only <0.16% of its initial volume per day between April and September, retaining 75% of the initial snow volume over summer. Together, these data demonstrate the feasibility of over-summer snow storage at mid-latitudes and low altitudes and suggest efficient cover strategies.

1 Introduction

Earth's climate is warming (Steffen et. al., 2018). This warming is expressed not only in warmer nights and days but also in the number of winter rain and thaw events that degrade snow packs (Climate Central, 2016). 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 using various materials to slow snow melt (Scott and McBoyle, 2007; Pickering and Buckley, 2010; Steiger et. al., 2017). Over the past several decades, the ski industry has improved snow-making strategies and facility operations both to maintain financial stability and to decrease their output of greenhouse gases (Koenig and Abegg, 1997; Moen and Fredman, 2007; Tervo, 2008;

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Kaján and Saarinen, 2013). Recent research focuses on analyzing and optimizing stages in the snow production cycle to assist industry efforts (Hanzer et. al., 2014; Spandre et. al., 2016; Grünewald and Wolfsperger, 2019).

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 more reliable than expecting weather conditions to be sufficiently cold and dry for making snow at the start of the winter ski season. For example, the 2014 Olympic games at Sochi relied on 750,000 m^3 of stored snow (Pestereva, 2014).

Historically, stored ice provided summer refrigeration. For example, ice houses stored large blocks of lake ice beneath sawdust over the summer (Nagnengast, 1999; Rees, 2013). Today, the ski industry today uses stored snow to support the early winter ski season. Modern over-summer snow storage (sometimes referred to as "snow-farming") begins with the creation of snow piles during winter months. Piles are covered (often with sawdust or wood chips) and sometimes geotextiles before the snow is stored over the summer (Skogsberg and Lundberg, 2005). In the fall, the pile is uncovered and snow 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, allowing the center to open on time, instead of losing business if unable to make snow and thus opening later.

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 mid-latitude, low altitude (45° N and 360 m asl) site with a humid, temperate climate including warm summer temperatures and high relative humidity which limits evaporative cooling (Fig. 1). Out of the 26 known snow storage locations, our study location has the highest average June-July-August temperature (24 ° C) and highest solar radiation (Worldclim.org, 2019). 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, responsible for melt, into and out of the snow piles. The goals of this research are to: 1) determine the melt rate of small experimental snow piles, 2) suggest an optimized snow storage strategy based on those data, and 3) test the optimize strategy on a larger snow pile sufficient for ski area opening. Our data fill a research gap in measurements of stored snow melt rates provide a novel case study for snow storage at low elevation and mid latitude.

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 the snowpack absorbs energy sufficient to raise snow temperature to the melting point (0° C) and then absorbs additional energy to enable the phase change from solid to liquid water (0.334 MJ kg^{-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, evaporative cooling, and long-wave emission to the atmosphere.

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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. Longwave radiation balance depends on atmospheric emissivity, cloudiness, and vegetation cover and temperature of the snow pile surface. Rain falling on the snowpack transfers heat. Conductive heat transfer from the ground depends on soil thermal conductivity and temperature (Kane et. al., 2000; Abu-Hamdeh, 2003). Snow melt typically varies on a diurnal cycle with melt increasing after sunrise, peaking in the afternoon, and decreasing after sunset (Granger and Male, 1978). Once surface melt occurs, water either refreezes if it percolates into a sub-freezing snowpack, flows through an isothermal (0° C) snowpack and then 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 (~46° N). Each nordic center built piles of machine-made 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 a physically based model, Grünewald et al. suggested that the most effective cover, in relation to work and cost, 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). Deeper cover layers can save more snow but costs are higher. During the day, solar radiation caused evaporation from surface wood chips while capillary flow 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 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 covering affects melt rate; older wood chips were less effective at reducing melt than fresh chips. Lintzén and Knutsson also determined that wood chips were a more effective cover 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 cover 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) and Morofsky (1982) in Canada, and by Hamada et. al. (2010) in Japan.

3 Methods and Setting

3.1 Study Location

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We conducted our experiment at the Craftsbury Outdoor Center (COC), a sustainability-focused, full year recreation venue that is located in northeastern Vermont at 360 m asl (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 southeast, at 215 m asl) between 1895 and 2018 ranges between 3.6° C (January) and 29° C (July), mean temperatures range from -8.3° C (January) to 20.7° C (July), and minimum air temperature ranges between -34° C (December) and 15° C (July). Soils in the area are very rocky, silty loam, sandy loam, and loam developed on glacial till (USDA, 2019). Average annual summer precipitation is ~300 mm (NOAA, 2019). The most common landcover types are forest and woodlands (USGS, 2019). The COC maintains 105 km of groomed nordic ski trails and hosts national and international races several times each winter.

3.2 Snow Pile Experiment

On March 30, 2018, two snow piles were emplaced at the COC using Piston Bully snow groomers at two separate sites (Fig. 2). Site 1 is adjacent to the COC's main campus buildings in direct sunlight, with minimal wind protection. Site 2 is 1 km north of Site 1, within a cleared depression in the forest also inn direct sunlight, but more protected from wind than Site 1. At the time of emplacement, the snow was transformed and had a density of >500 kg m^{-3} (see section 3.5 for snow density measurement methods). At site 1, 225 m^3 of machine-made snow was banked against a slope facing north. At site 2, 210 m^3 of natural snow was shaped into symmetrical, rounded pile. The two piles were draped with this sheets of clear plastic. The plastic sheets, about 0.15 mm thick, were impermeable, and emplaced to prevent wood chips from mixing with the snow. The piles were then 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, the plastic was removed, and the remaining snow was covered again with wood chips and left for continued monitoring.

3.3 Weather Stations

Weather stations adjacent to each pile and 3-4 m above the ground surface, (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). Local soil temperature was measured with temperature sensors installed at four depths within the soil (5 cm, 20 cm, 50 cm and 100 or 105 cm below the surface) adjacent to each snow pile. Two HOBO Onset dataloggers recorded temperatures at four depths at 20-minute intervals between June, 2017 and October, 2018.

3.4 Terrestrial Scanning Field Methods and Processing

During spring and summer, the shape and volume of the piles were measured every 10-14 days using a terrestrial laser scanner (Reigl VZ-1000)). Terrestrial laser scanning (TLS) is a highly accurate method for obtaining digital elevation models (DEMs) of various terrain types, including snow surfaces (Prokop et al., 2008; Molina et al., 2014). 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. The 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

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software (v 2.6.2). Scan registration was done in RiSCAN using a combination of tie-point registration (finding corresponding points), and the multi-station adjustment routine using plane patches and tie-objects. Similar studies of monitoring bare and covered snow surfaces with TLS have applied this technique (Prokop et al., 2008, Grünewald et al., 2018, Grünewald and Wolfsperger, 2019. Scans were collected at a horizontal and vertical angular resolution of 0.08°. Scans were collected from distances less than 100 m resulting in average point spacing over the pile <1 cm.

To calculate snow pile volumes and volumetric change over time (between scans), point clouds of each pile were processed into DEMs. Processing workflow involved cropping the point-cloud to the area of interest in RiSCAN Pro and exporting cropped point clouds into .las format, projected into Vermont State Plane NAD83 coordinates. Point clouds were converted to a 10 cm resolution DEM using the min-Z filter and QT Modeler software (v. 8.0.7.2) and adaptive triangulation to fill in small data gaps. Volume calculations and differences in volume between sequential surveys were calculated in QT Modeler using these DEMs.

3.5 Density

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). Density was collected three times throughout the summer in March, May, and July at the top surface of pile 1.

3.6 Cover Experiments

Cover experiments were performed at both sites in June and July, 2018. At site 1, two 5-cm-thick, impermeable, rigid foam boards (R=3.9 per 2.5 cm, value expressing resistance to conductive heat flow) were stacked and compared to a 20 cm, uniform, porous layer 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 per 2.5 cm) and overlaid the blanket with either open-cell, permeable foam (R=3.5 per 2.5 cm) or a uniform, porous layer of wood chips (20 cm height) both with a reflective cover. For both foam experiments, wood chips and plastic sheeting were removed from the test area. For wood chip experiments, plastic sheeting was removed from the test area. Individual cover 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).

3.7 Power Spectral Density Function

We compute the Power Spectral Density function (PSD) to determine relative effectiveness of the different covers. The temperature signal is first decomposed in a series of waves of well-defined frequencies:

$$\mathrm{T}(\mathrm{t})=\frac{1}{\mathrm{N}}\sum_{k=0}^{N-1}\tilde{T}_k\exp(i2\pi f_k t) \tag{1}$$

where $\tilde{T}_k$ is the Fourier mode at frequency $f_k = k/2\Delta T$, $1/\Delta T$ is the sampling frequency of temperature acquisition, and N is the number of samples in the time series. The Fourier mode contains both amplitude and phase information for each wave. The PSD is the power of the signal,

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$$\mathrm{PSD}(T)=\frac{\Delta t}{N}\sum_{k=0}^{N-1}\left|\hat{T}_k\right|^2$$

which is the sum of the contributions of each wave to the power (or variance) of the signal. Typically plotted on a log-log plit, the norm of the Fourier modes as a function of frequencies is a powerful tool to detect dominant frequencies (Welch, 1967). In the summer, the dominant oscillation in temperature is diurnal; thus, using PSD we can judge the effectiveness of over materials by their ability to damp the diurnal signal and relevant harmonics. We computed the PSD (Fig. 8) for all temperature records in selected cover experiments (Fig. 4, panels b, e, f).

3.8 Validating Cover Method, Summer 2019

Based on data collected during summer 2018, the COC chose site 2 (Fig. 2) as their snow storage site. Based on cost and ease of installation, they chose a two layer cover system, a uniform layer of wood chips with a reflective covering. The pile filled an former, oblong pond basin and was gently sloped. During February, machine-made snow was blown into the pile using fan-less snow making wands. Snow density at and just after emplacement was high, ranging between 500 and 600 kg m^{-3}. In March, the snow pile was shaped and further compacted with Piston Bully groomers and excavators; at that time, LiDAR showed the pile had a volume of about 9300 m^3, without wood chips. During the next 6 weeks, the snow pile was allowed to compact and grow denser. In later April, the pile was partially covered in woodchips. By the end of May, the snow pile was completely covered in wood chips (total ~ 650 m^3). Using the surface area of the pile without wood chips (2300 m^2) and the volume of woodchips, we calculate the average woodchip thickness to be 28 cm. By the end of June, the snow pile was covered in a white, 75% reflective and breathable Beltech 2911 geofabric, secured by ropes and rocks to prevent wind disruption. Between March and September, the pile was scanned using LiDAR every two weeks and processed using methods described in section 3.4.

4 Results

4.1 Meteorological Data/Ground Temperature Data

Climate at the COC 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 33°C (mean annual temperature = 6 °C). Precipitation fell at a maximum rate of 22 mm day^{-1} (mean 0.06 mm day^{-1}) and relative 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, relative humidity remained high (NOAA classifies above 65% as high and relative humidity remained above this level for the summer), varying more during summer than winter months. Average summer temperature in 2018 (June, July, and August 22.4 °C) was ranked by NOAA as "Much above average the average of 20.7 °C"; while in 2019, average summer temperature ranked "Above Average" (21 °C). Both years had near average precipitation (NOAA, 2019; wunderground.com, 2019).

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 = 7.4° C for site 1). Ground temperature variations decreased in amplitude as soil depth increased; at 1 m in depth, the atmospheric temperature signal was damped (SD = 3.9° C for site 1). Ground temperatures for all depths showed consistent warming from installation (June 11, 2017) through late August 2017 and then decreased through February 2018. The shallowest sensor revealed slight warming after February while the deeper

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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. Figure 5 displays data from sensors adjacent to pile 1 – data were collected at both sites but are missing from Site 2 between December 12, 2017 and April 21, 2018.

4.2 Snow Volume/Density

Snow in both 2018 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 ±11 cm for pile 1 and 21±11 cm (1 SD) for pile 2 (Fig. 3). 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 ~ 500 kg m^{-3} at emplacement, 600 kg m^{-3} in May, and 700 kg m^{-3} in July. Relative to newly fallen snow (100-200 kg m $^{-3}$), the snow in these piles was closer in density to ice (900 kg m^{-3}). These measurements are supported by qualitative observations of changes in snow crystal morphology over the summer (increased rounding), size (up to 5 mm by July), increasing wetness (higher liquid water content) 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 volume change for both piles were relatively similar (1.24 m^3 day^{-1} and 1.50 m^3 day^{-1}) representing 0.6 to 0.7 % of initial pile volume per day. Maximum loss rates, recorded in July, reached 1.98 m^3 day^{-1} and 2.81 m^3 day^{-1} (Fig. 7.) As summer shifted into fall, loss rate decreased (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 the piles decreased in volume over the summer, 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 cover remained cold and wet throughout the summer while the woodchips on the surface were consistently dry in the absence of rainfall.

4.3 Cover Experiments

Thermal buffering is a function of air temperature, longwave emissions, and turbulent fluxes. We chose temperature at the snow/cover interface to indicate cover efficiency because all experiments were subjected to similar external conditions and because we have continuous data series of temperature at depths in, above, and below, the cover during each of the experiments. Two experiments preformed on 1 m^2 plots on each snow pile revealed that different combinations of cover materials resulted in a variety of cover efficiencies (Fig. 4). Each experiment lasted about a week and took place in June and July, respectively. We assessed cover efficiency by determining which material combination maintained the lowest and steadiest temperature at the snow-cover interface and which most effectively damped the diurnal temperature signal (detected using PSD analysis). For all panels (Fig.4), temperature ranges at the snow-cover interface (blue line) are (a) 0.21– 4.33◦C, (b) -0.04 – 3.69◦C, (c) -0.22 – 44.57◦C, (d) -0.09 – 9.86◦C, (e) 0.47 – 23.89◦C, (f) 0.04 –2.44◦C. 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, Fig. 4 panel f). 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 cover materials (wood chips and open cell foam) varied significantly. The lowest and most stable temperatures

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at the snow/cover 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.

4.6 Power Spectral Density

The dominant frequency in all our records is diurnal as expected (Fig. 8). The air sensors at 46 cm (yellow lines) also measure significant contributions of harmonics at periods of 12 h, 6 h and 3 h (peaks at 10^{0}, $10^{0.1}$, $10^{0.2}$, Fig. 8). These harmonics can also be detected in temperature records collected at different depths in the cover materials with various relative strengths. In the foam cover experiment (b), the diurnal frequency and its harmonics are detectable in all layers; however, the three-layer system (insulating blanket, wet wood chips, and reflective cover, panel &c) fully damps all oscillations, as shown by the flatness of the PSD below the cover. In the absence of an insulating blanket, the two material cover system (reflective blanket and wood chips) is slightly less efficient at damping the diurnal oscillation (Fig. 8 a).

4.7 Summer 2019

The 9300 m^3 snow pile emplaced in 2019 lost volume at an average rate of 15 m^3 day^{-1} (min= 5 m^3 day^{-1} in early July, max = 25 m^3 day^{-1} in between April and May, when the snow pile was compacting and being covered by wood chips. Between the initial LiDAR survey in March and the last survey in September, the pile shrank 2,460 m^3, a 27% volume loss. The average percentage loss per day was 0.16% of the initial volume.

5 Discussion

Data collected during this research all us to: 1) determine the melt rate of small snow piles stored over summer with different coverings, 2) suggest an optimal snow preservation strategy for low elevation, mid latitude sites based on these data, and 3) test this an optimized snow storage strategy at scale.

5.1 Experimental snow pile melt rate

The survival of small (200 m^3) snow piles through the warmer than average summer of 2018 and the results of both repeated LiDAR surveys and continuous in situ thermal data collected during a variety of different snow cover experiment suggest ways to optimize snow over summer snow storage at low elevations and mid latitudes. The snow piles experienced non-uniform cover, non-ideal geometry, and developed crevices that exposed snow to direct sunlight; all of which increase melt rate. Field observations and LiDAR surveys demonstrated that the thickness of wood chips covering the snow 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 which led to rapid and non-uniform pile melting. Crevices formed along boundaries of the large plastic sheets, which had been emplaced to prevent woodchips from mixing with the snow. Openings in the wood chip cover also resulted from snow slumping within the pile – both piles had steep sides and the LiDAR DEMs revealed snow moving downslope (Fig. 6). Lintzén and Knutsson (2018) reference similar snow pile/cover failure due to steep pile-side geometry.

Snow pile size likely impacts melt rate significantly. 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)

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which allows more effective heat transfer through radiation, conduction, and latent heat transfer. 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 larger pile. As larger piles have a lower SA/V ratio in comparison to smaller piles, there is comparatively less snow near the surface thermal boundry, which decreases melt rate.

5.2 Optimal approach for over-summer snow preservation at mid-latitude and low elevation

The survival of snow through the summer in small piles and with simple, wood chip, foam and reflective coverings, suggests that larger piles, using an optimized cover strategy, will allow for practical over-summer snow storage at mid-latitude (< 45° N) and low-altitude (< 350 m asl) locations. Previous snow storage studies found success with woody covers as well. Grünewald et. al., (2018) suggested that a 40 cm layer of sawdust sufficiently optimized snow retention in Davos, Switzerland and Martell, Italy. Skogsberg and Nordell (2001) reported that wood chips reduced snowmelt by 20-30% at the Sundsvall Hospital in Sweden. Lintzén and Knutsson (2018) built snowmelt models and ran field tests in northern Scandanavia, revealing that thick layers of woody materials successfully minimized snowmelt. Our results are encouraging given the relative warmth of the 2018 summer season, the simple and spatially inconsistent nature of our cover material (20±10 cm of woodchips), and the small size of the test piles (~200 m^3).

The experimental data (Fig. 4), show that the magnitude of daily temperature oscillations at the snow surface below the covering (blue line in all panels) is highly dependent upon the cover strategy. For example, in Figure 4c), the temperature within the rigid foam board increases above air temperature (purple line increasing above the yellow line). Due to the rigidity of the foam boards and the non-uniform melting of the pile, the foam shifted and exposed snow to direct solar radiation, as well as allowed warm air to move between the snow and the foam. Such failure of the cover system, allowed temperatures at the snow interface to rise significantly above 0 ◦C. The three-layer cover (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 4e). The comparison between foam and saturated wood chips PSDs (Fig. 8) show the dramatic effect on the heat transfer from the atmosphere to the snow caused by the high heat capacity and thus thermal inertia of wet wood chip. The damping of diurnal temperature peaks by the three layer cover system suggest it will be the most effective for preserving snow over the summer.

Although the relevant heat transfer mechanisms remain uncertain, Figure 8 demonstrates the effectiveness of the three layer cover approach to buffering heat transfer from the environment to the snow. Deducing specific heat transfer mechanisms will require different and more complex measurements, as heat transfer is dependent upon not only air temperature, but also surface temperature, long-wave radiation, and turbulent fluxes. 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, which influence long-wave radiation through cloudiness and turbulent fluxes through wind, 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 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 cover material in damping daily temperature fluctuations at the snow surface.

5.3 Summer 2019, Testing the Optimized Snow Storage Strategy at Scale

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Field, LiDAR, and thermal observations from the 2018 experiments allowed for a full scale test of our optimized snow storage strategy. Optimization began by further excavating the storage area so the resulting pile would sit within a pit and have gently sloping sides. Snowmaking was done so that the density of the snow emplaced was already high to minimize settling after covering and then the snow was then compacted by repeated passes of large excavators and Piston Bully groomers. Letting the snow settle and transform before covering, we reduced the chance of mass movements compromising the pile and cover integrity. Rather than use metallized cover material, which was expensive, fragile and impermeable, we used a high albedo (0.75) white, permeable geofabric that allowed rain to infiltrate, thus mitigating regulatory concerns related to a large, potential impermeable area.

The 2019 data validate the optimization approach suggested by the 2018 experiments. The most rapid volume loss in 2019 was early in the melt season as the snow in the pile transformed and compacted; later summer rates of volume loss later in the summer, while higher in absolute terms than those in 2018 because the pile was 45 times larger, were more than 3X lower in percentage terms. Compared with the average percentage loss per day of the 2018 summer's piles (0.55% per day), the 2019 snow pile average percentage loss per day was 0.16%. We suspect that the difference in volume loss reflects primarily the surface area to volume ratio of the 2019 snow pile which is 3 times greater than the small piles tested in 2018. Other factors may also be important. The complete covering of the 2019 pile with a reflective geofabric likely slowed melt by rejecting shortwave radiation as well as protecting the snow even if the wood chips shifted. LIDaR imagery from 2019 demonstrates that gentle side slopes of the pile prevented any large mass movements of snow indicating that pile shape and pre-consolidation are important.

LIDaR data show that from April until September more than 65% of the snow initially placed in the 2019 pile remained. Using the snow density from 2018, which increased from 500 to 700 kg m^{-3} over the summer, much of this volume loss could be accounted from by compaction rather than melting. As suggestion supported by the lack of surface water draining from the pile, which is underlain by relatively impermeable rock and clay-rich glacial till. With September temperatures and sun angle dropping, incident solar radiation as well as convective and conductive heat transfer are diminished greatly from mid-summer values. This means that the COC will have > 5000 m^3 of snow to spread in November for early season skiing. Covering 5 meter wide trials 50 cm deep will allow at least 2 km of skiing at opening as well as providing a base so that any natural snow that does fall will be retained.

6 Conclusions

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. Using 14 terrestrial laser scans between March and September, 2018, we determined melt rates of two, 200 m^3 snow piles covered in wood chips. Average volume loss rates were 1.24 m^3 day^{-1} and 1.50 m^3 day^{-1}, with highest melt rates in July and lowest melt rates in September. A three-layer cover approach was most effective: concrete curing blanket, a 20 cm layer of woodchips, a reflective covering. This cover approach reduces solar gain and buffers the effect of >30° C summer daytime temperatures and high (>78%) relative humidity on stored snow. Using data collected during summer 2018, we tested our experimental results in summer of 2019 by creating a 9300 m^3 snow pile. Due to cost and logistical issues, we covered the pile using a two layer approach - 650 m^3 of woodchips and white, permeable geofabric. The volume loss rate between March and September was 15 m^3 day^{-1} (or 0.16% of the initial volume per day) which provided 6100 m^3 of snow at the end of the summer. This quantity of snow is sufficient

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for the COC to open their 2019 season and represents >65% retention of snow by volume, comparable to storage losses at other storage sites (at higher altitude and latitude).

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 Lidar and PSD 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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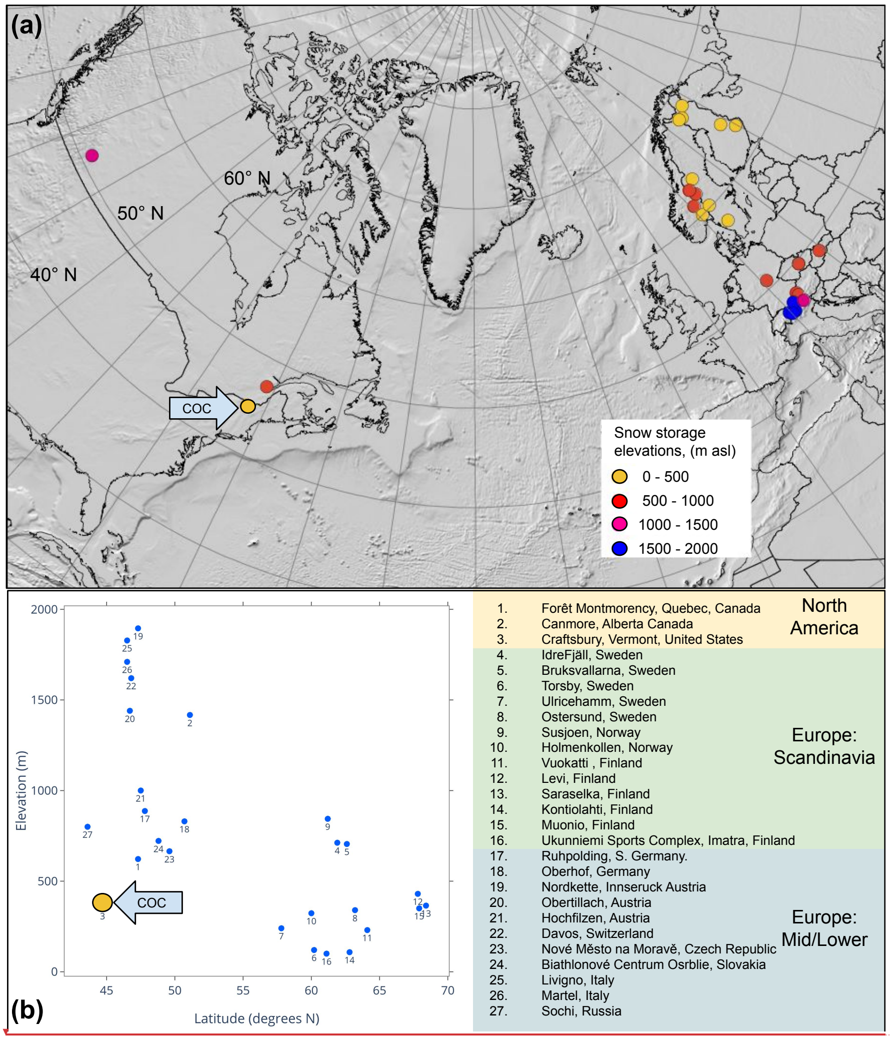
Tables

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



1.	Forêt Montmorency, Quebec, Canada	North America
2.	Canmore, Alberta Canada	
3.	Craftsbury, Vermont, United States	
4.	IdreFjäll, Sweden	Europe: Scandinavia
5.	Bruksvallarna, Sweden	
6.	Torsby, Sweden	
7.	Ulricehamm, Sweden	
8.	Ostersund, Sweden	
9.	Susjoen, Norway	
10.	Holmenkollen, Norway	
11.	Vuokatti , Finland	
12.	Levi, Finland	
13.	Saraselka, Finland	
14.	Kontiolahti, Finland	
15.	Muonio, Finland	
16.	Ukunniemi Sports Complex, Imatra, Finland	
17.	Ruhpolding, S. Germany.	Europe: Mid/Lower
18.	Oberhof, Germany	
19.	Nordkette, Innseruck Austria	
20.	Obertillach, Austria	
21.	Hochfilzen, Austria	
22.	Davos, Switzerland	
23.	Nové Město na Moravě, Czech Republic	
24.	Biathlonové Centrum Osrblie, Slovakia	
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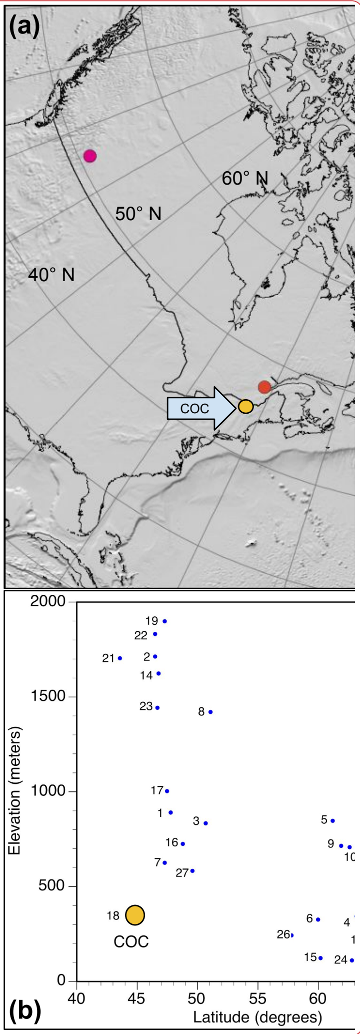

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Figure 1: Locations of over summer snow storage. (a) Conical projection shows known locations of over-summer snow storage at nordic ski centers. The Craftsbury Outdoor Center is highlighted with a blue arrow labeled COC. The relative elevations of 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.

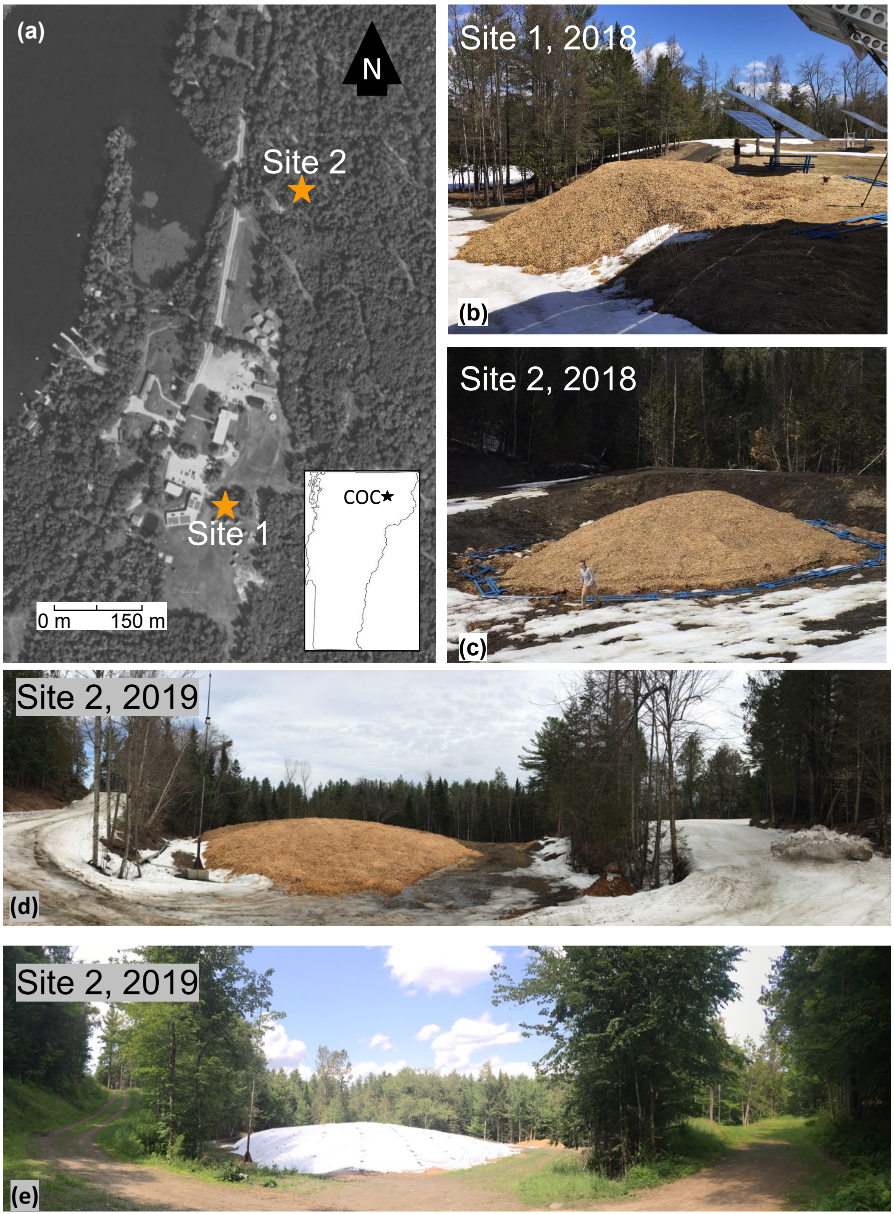

Figure 2: Snow storage at Craftsbury Outdoor Center. (a). Areal view of the Craftsbury Outdoor Center (COC) in Vermont, from http://maps.vcgi.vermont.gov. Both study site locations shown by number. (b). Site 1 (225 m^3), covered in woodchips on April 21st, 2018, with trees and solar panels for scale. (c). Site 2 (209 m^3) when installed. Site 1 received 24 m^3 of woodchips and Site 2 received 42 m^3 of woodchips. Person for scale. (d) Site 2 in April, 2019; 9271 m^3 of snow covered in 650 m^3 of woodchips, (e) Site 2 in July, 2019, the snow pile overlain by a reflective geofabric. Trees for scale.

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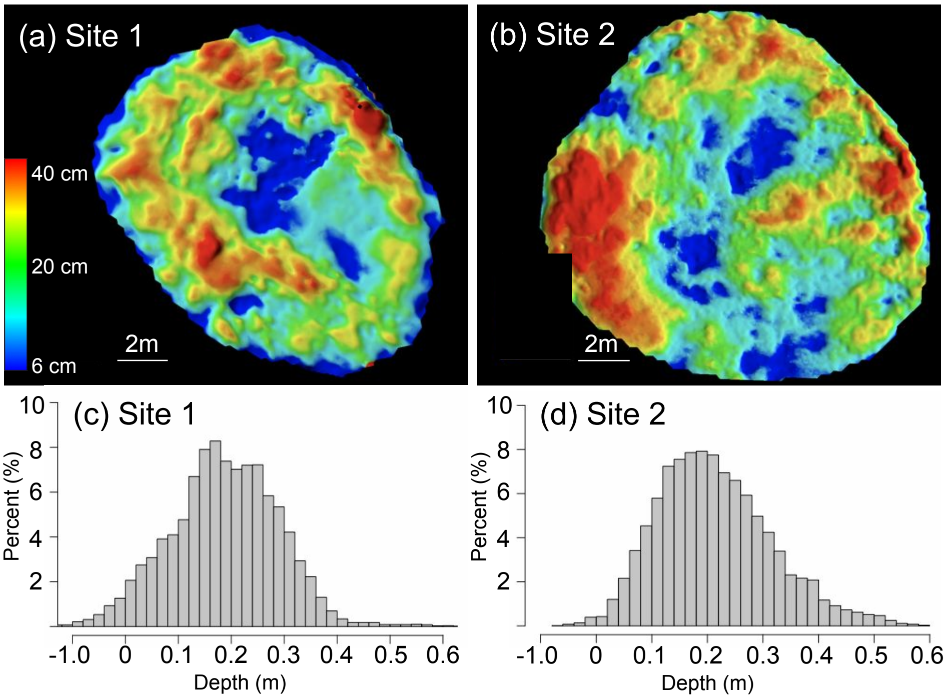


Figure 3: Wood chip thickness distribution maps of pile 1 (a) and pile 2 (b) with red indicating areas of high thickness and blue indicating areas of low thickness. Panel (c) represents the chip thickness histogram for pile 1 and (d) is chip thickness histogram for pile 2. Negative thickness values likely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

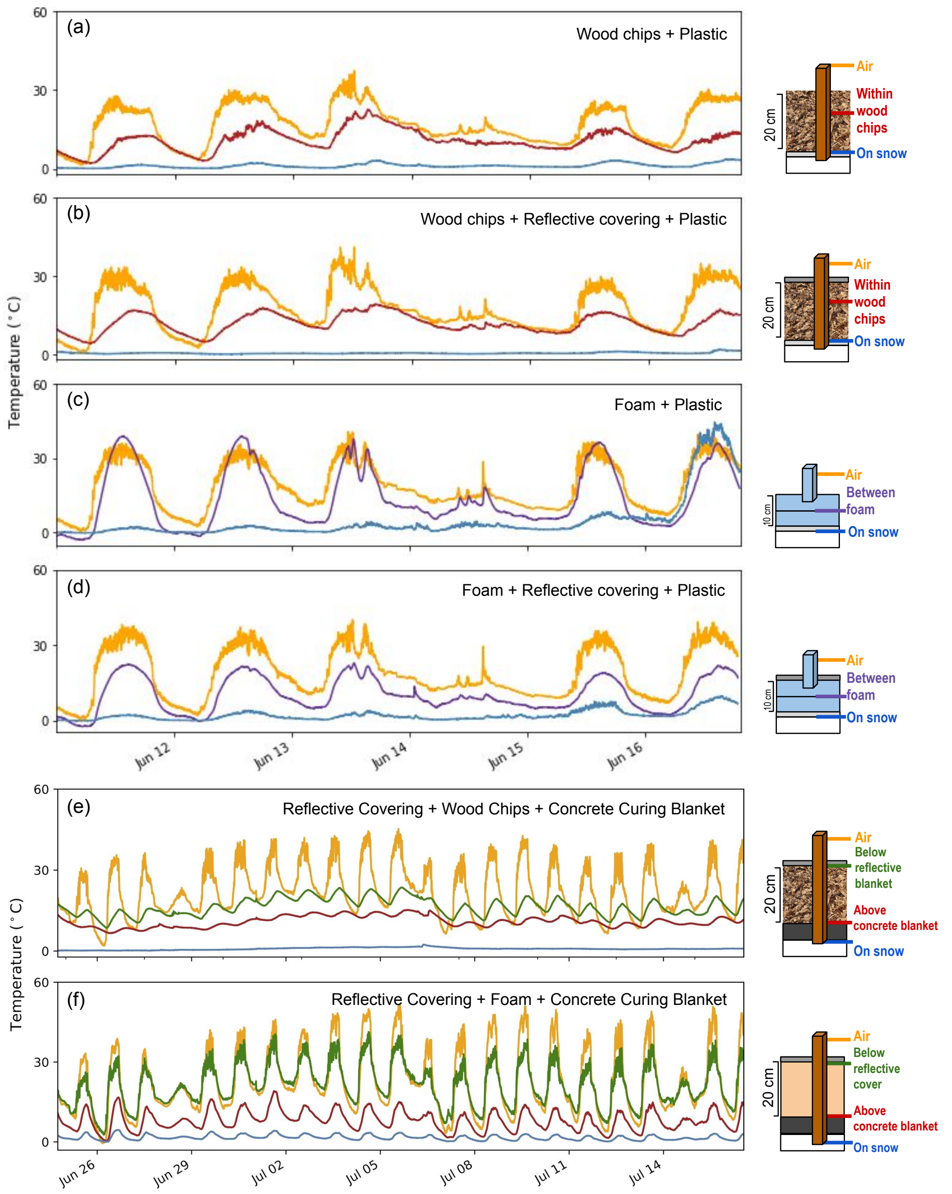
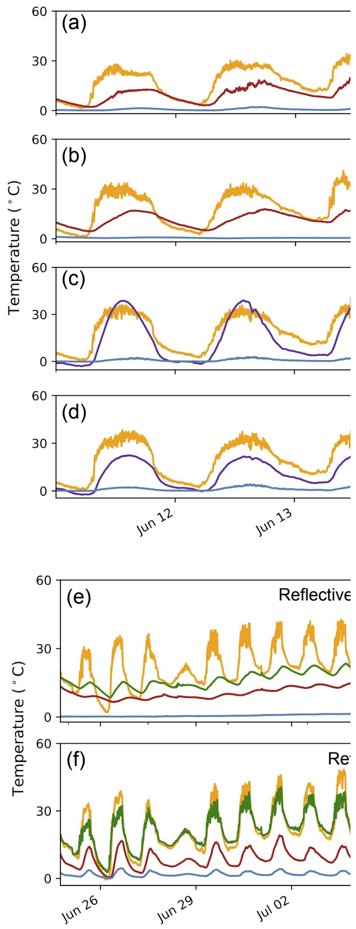


Figure 4: Cover experiments and resulting temperature records. (a) Site 1, woodchips underlain by plastic (b) Site 1, wood chips underlain by plastic and overlain by reflective cover (c) Site 1, foam underlain by plastic (d) Site 1, foam underlain by plastic and ad overlain by reflective cover (e) Site 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.



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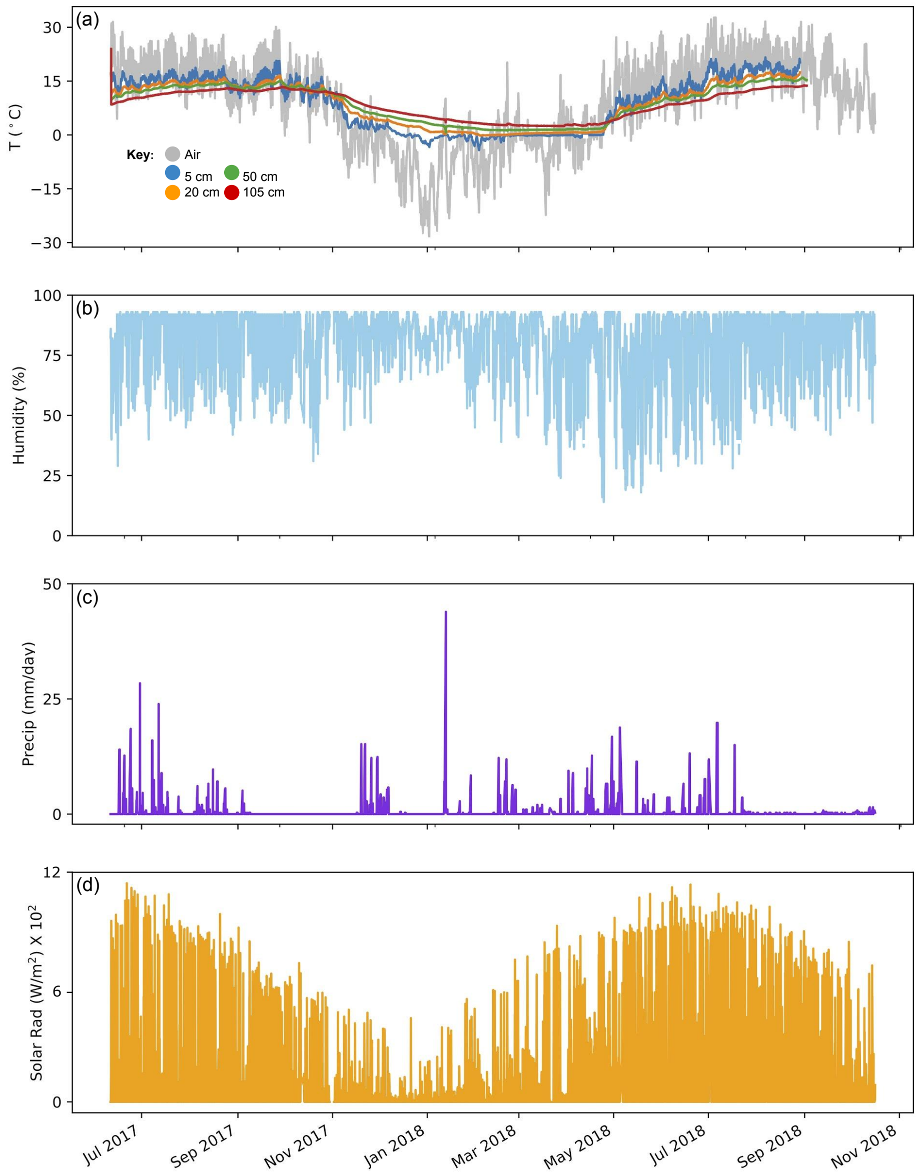
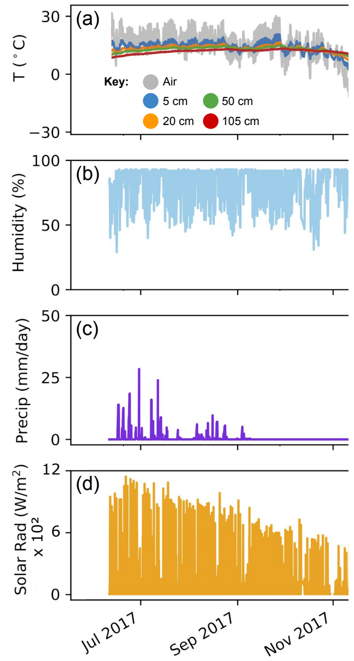


Figure 5: Meteorological conditions and soil temperature between June 11, 2017 and October 16, 2018. Weather conditions were collected by the Davis Weather station at the Craftsbury Outdoor Center near Site 2. (a) Air temperature (grey), collected at 30-minute intervals plotted with ground temperature. Ground temperature was collected at 20-minute intervals adjacent to pile 1 by four HOBO Onset dataloggers at depths below the ground surface of 5 cm (blue), 10 cm (orange), 50 cm (green), and 105 cm (red).



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Ground temperature record ends on September 2, 2018. (b) Relative humidity (%) (c) Precipitation (mm day^{-1}) (d) Solar radiation (W m^{-2}).

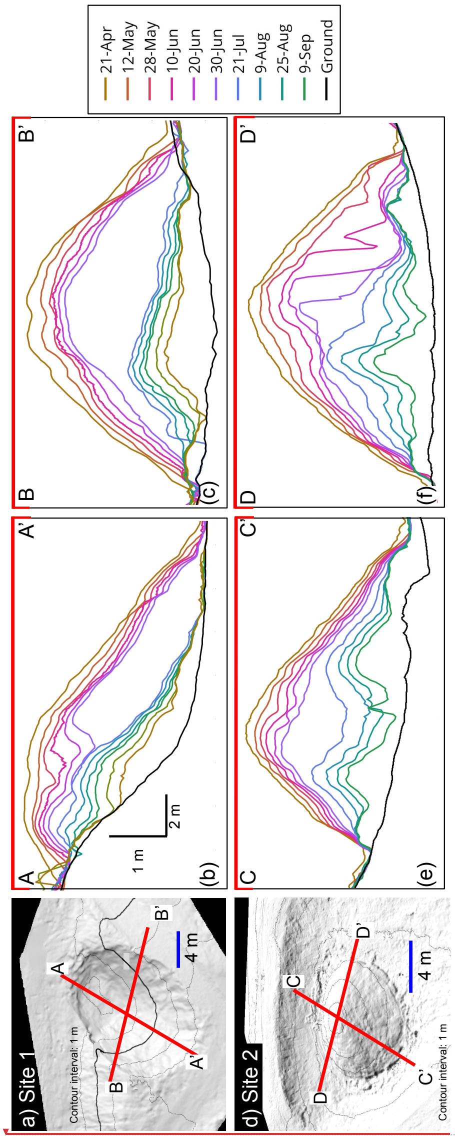

Figure 6: Snow pile topographic change over time. (a) Oblique view of digital elevation model (1 m contours) of snow pile at site 1 with cross-sections A-A' and B-B' (April 21, 2018). (b) Profiles for each terrestrial laser scan survey (April 21, 2018 to September 9, 2018, n= 13) along section A-A'. (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.

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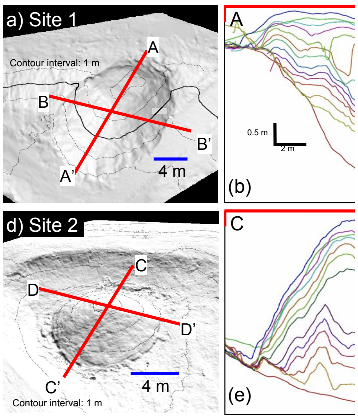

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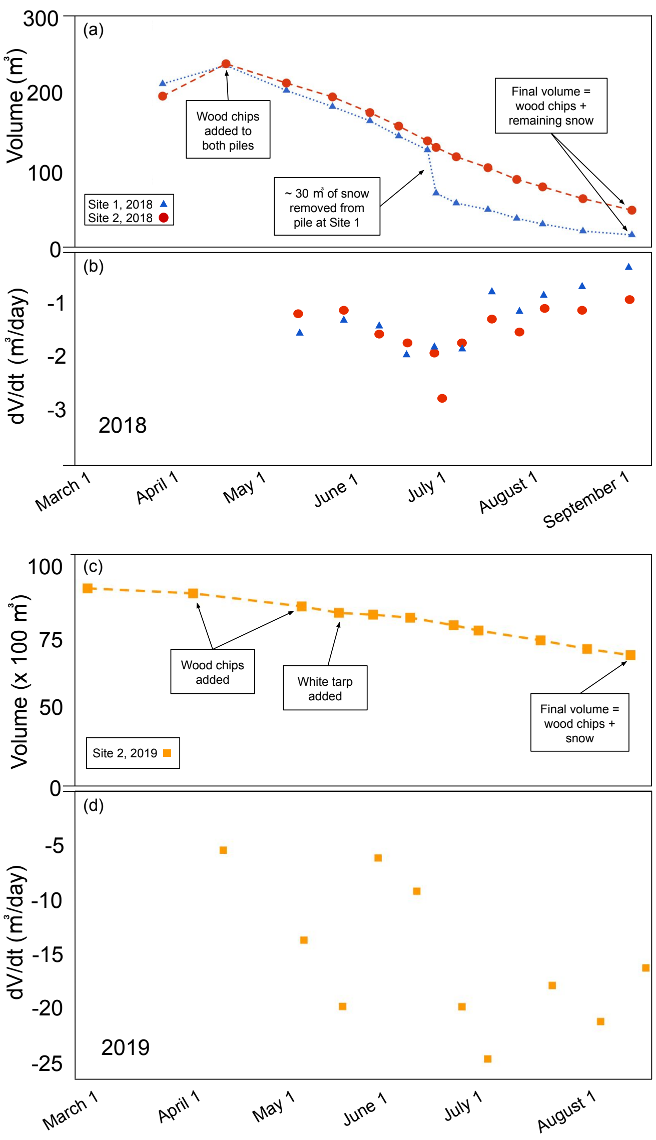
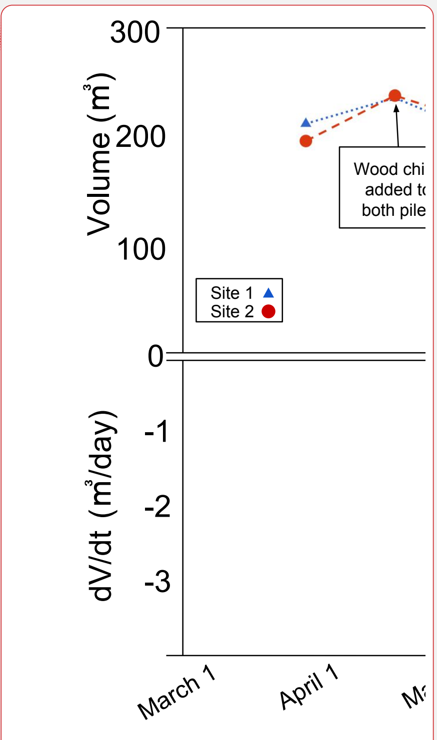


Figure 7: Volume change over time for snow piles at sites 1 and 2 measured by terrestrial laser scanning. (a) Volume of snow piles from placement in March 2018 until end of melt season in September 2018. Addition of woodchips in April and removal of snow in July at pile 1 shown by black arrows. Volumes are total including wood chips. (b) Change in volume per unit time between surveys. Rate of volume loss increases mid-summer for both piles. Site 1 received about 24 m^3 of wood chips while site 2 received about 42 m^3 of wood chips – this difference is due to pile geometry and the resulting difference in surface area. Site 1's snow pile was banked against the side of a hill while Site 2's pile was shaped like a half-sphere in the middle of an open depression. (c) Volumes of snow pile (2019) beginning March, ending September. Addition of wood chips throughout May and addition of white tarp is indicated by black arrows. Volumes include wood chip volume. (d) Change in volume per unit time between surveys. Rate of volume loss decreases towards July (after initial wood chip emplacement) and then slows into September.



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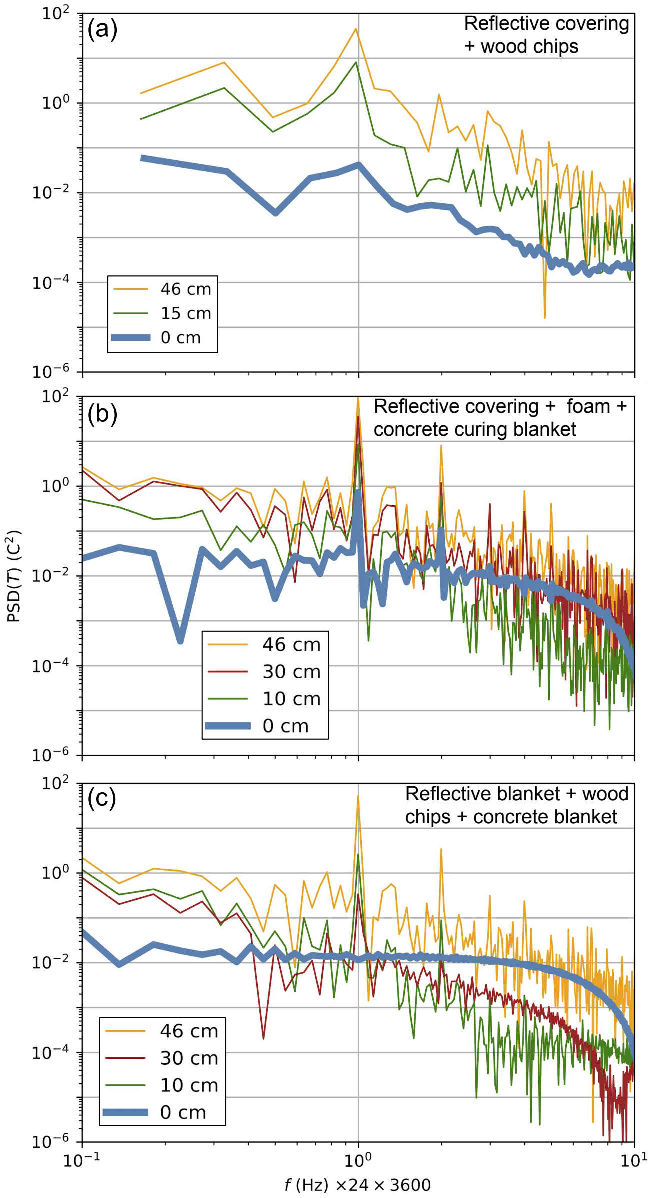

Figure 8: **Power Spectral Density of temperature records from three different cover experiments (Fig. 4 b, e, and f). PSD normalizes frequency to 24 hours = 10^0 and displays the magnitude of each temperature oscillation frequency for each of four sensors per experiment (depth in cm measured below uppermost 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.**

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