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Interactive comment

Interactive comment on "Optimization of over-summer snow storage at mid-latitude and low elevation" *by* Hannah S. Weiss et al.

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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. Thomas GruÌĹnewald (Referee) t.gruenewald@gmx.ch Received and published: 7 May 2019

Author responses are below referee comments.

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 cov-

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ering 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

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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, GruÌĹnewald 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 GruÌĹnewald 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 GruÌĹnewald 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 (45âŮę) was called "low" (P2 L17);" here a very similar latitude of 46âŮę 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 ($\sim$360 m asl).

30) L33 What is the elevation of the station? Author response: We will include the elevation of the weather station ($\sim$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 $\sim$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, GruÌĹnewald et al. 2010, GruÌĹnewald 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 GruÌĹnewald 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 m^3 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 GruÌĹnewald 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.

Please also note the supplement to this comment:
https://www.the-cryosphere-discuss.net/tc-2019-56/tc-2019-56-AC3-supplement.pdf

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2019-56, 2019.