**Reviewer 1: J Garvelmann**

*First we want to thank J. Garvelmann for his constructive review and his good suggestions. We are answering his comments in the following, for clarity we repeat the original comment (C) and answer (A) afterwards:*

*Major comments:*

*C: The authors nicely describe the background and the motivation for snow farming. However, there is missing the clear formulation of the motivation for the study and the most important research questions that the study will address at the end of the introduction section.*

*A: Thank you for this hint we add the following sentence at the end of the Introduction section: "A rising number of expertise on snow farming has been requested at SLF in recent years. This motivated us to (i) provide a review on current snow farming praxis (i) to perform a detailed field study on snow farming and (iii) to describe and evaluate the model used for snow farming expertise by the SLF. "*

*C: The methods are described clear and understandable. On page 7 (lines 24+25) the authors mention that they used the model SNOWPACK for the simulation of both snow heaps. However, there are only shown results from the Flüela snow heap in the results section later. I recommend showing also results from the Martell site for completeness of the study.*

*A: This is principally right, we focus on the Flüela data and only provide the most important information for Martell. The reason is that the principal findings from both sites do not differ much: Adding more Martell details would not provide new findings and the added value would be very small. For readability we therefore decided to focus on the Flüela results and to only show the most important values for Martell (in brackets). This is also described in the text.*

*C: There are sentences that should be moved to the introduction section. The sentence on page 7, lines 25-27, for example, describes the motivation for the modeling of the snow heaps. Or the sentence on page 8, lines 22-25 describes the motivation for the sensitivity analysis.*

*A: It is right that these sentences would also fit to Introduction content-wise. However, Introduction already contains this information. We deliberately repeat this information in section 2.4 for readability and clarity.*

*C: The simulation of the stored snow was carried out using the one-dimensional snow cover model SNOWPACK. However, the authors mention twice that the use of a spatial distributed snow model such as Alpine3D for example would have been more appropriate to model the snow piles. The first thought while reading the manuscript is, why such a model was consequently not used in this study? Please provide an explanation for this.*

*A: We see the point of the reviewer. It is right that using a distributed model such as Alpine3D could account for spatial heterogeneity (most important: insolation depending slope and aspect) but spatial distributed input information (e.g. information on the local wind field, spatial variability of the cover material) required for such more sophisticated analysis was not available. This uncertainty of the input data would probably be larger than the resulting spatial variability of the results. Moreover, as insinuated in the new sentences in Introduction, SNOWPACK is the model that has been used for snow farming engineering projects by the SLF so far. Such projects aim to provide rough estimations on expected mass losses for specific sites and covering methods. Such requests can well be answered with a 1D model (SNOWPACK). Setting up and running SNOWPACK and analysing the results is easier and more straight forward and therefore more cost effective. Our paper shows well, that*

*SNOWAPACK is well capable for this purpose. For detailed analysis of processes and their spatial variability, we definitively aim to apply Alpine3D in future (projects to come). This will be interesting from a scientific perspective.*

*C: The simulation was carried out just for one point of the snow heaps, the point with maximal HS. Please indicate those points in figure 5 and 6. Why was the simulation not carried out for multiple points at the snow heap?*

*A: The points are now indicated in Fig 5 and 6. As explained before, the added value of multiple point simulations would be rather small.*

*C: Another concern is related to the used parameters shown in the results section. Why are the results shown for snow height? You have height/volume and density. Why are the simulations not carried out for SWE? Another possibility would be to calculate (and simulate) total snow mass and mass loss in kg. For the TLS measurements providing snow volume and the measured snow density it would be simple to present some quantities of total snow mass loss ect. This would also be possible for the simulations since the calculation was carried out for a quadratic area of 1 m2 as described on page 13. Please provide the results for actual snow mass or provide at least a detailed discussion why the results are only shown in snow depth.*

*A: Generally it is true, that snow mass or SWE is the quantity that would be most interesting in snow farming. However, snow height is the quantity that is measured by laser scanning. Snow height and volume can be measured very accurate. Contrary, only few density measurements required to calculate SWE or mass from HS were available, adding some uncertainty for the related quantities. Moreover, snow depth is a more concrete quantity for practitioners and laymen (who are also addressed by this paper). We therefore decided to stick with snow height/volume in Sec 3.3. Furthermore, the influence of densification is already discussed in detail, most important findings (relative losses) are also provided for SWE and simulation results are also shown (e.g. Fig 10) in SWE.*

*Minor comments:*
*A: we adapt most suggestions of the reviewer in the text and only answer to non-technical comments:*

*C: Figure 1 and 2: The authors could think about providing a map for each study site showing the surrounding terrain.*

*A: We have considered showing such a map. However, considering the already large number of Figures (11) and also that the character of the surrounding area can already be seen in Figs. 1 and 2 we decided against showing additional figures.*

*C: Table 2: Needs a better explanation in the table caption*

*A: The table and the caption have been changed such that the initialization should be clearer now.*

*C: Page 8, Line 5ff: Is this assumption really realistic that the properties of sawdust and the mixture of sawdust and wood chips are similar? I would expect that the porosity is different ect.*

*A: This is a reasonable doubt. From our investigations we think that the difference between the materials is much smaller than the uncertainty in the estimations of these properties and the spatial variability of the cover material (which is especially large for the mixture of chipped wood and saw dust). To test the effect of porosity (and therefore water storing capacity) we performed some model runs with varying grain sizes of the covering layer. Increasing the grain radius (from 0.1 mm to 1 mm) by a factor of 10 did not reveal any difference in the final mass loss. Only much larger grain sizes (3 mm) increased mass loss slightly. Wood chips of that size (or even bigger) exist in the Martell covering*

*Material, but the finer particles clearly dominated. Moreover, from laboratory measurements of small samples from both heaps we found nearly identical dry densities. We therefore believe that the assumption of same properties of the covering material is appropriate. We include a corresponding sentence in the text.*

*C: Figure 3: You are showing net longwave, right? Please add this info. It would also be very helpful to indicate the exact dates when the snow heaps were covered with the isolating material and when it was removed. Please provide the same figure for the Martell site as well*

*A: Yes it is net longwave. We will clarify this in the new draft. The figure for Martell is already in the paper (Fig 4).*
*The heaps were covered from mid of April till 19 October in Flüela and from 19 May till 28 October in Martell. Snow was then immediately distributed to the tracks. We add this information in the Study site section.*

*C: Figure 5+6: The authors could also provide a figure with the fraction (in percent) of snow loss at the two snow heaps.*

*A: This is a good suggestion, but the added value is only small and we are therefore not showing an additional figure.*

*C: Page 14, line 9: You describe earlier that the model was initiated with 8,6 m. Please clarify*

*A: 8.6 m is the height of snow without saw dust and 9 m is the height of the entire heap with saw dust cover. We think it is already clearly stated.*

*C: Page 15, line 2: Earlier in the manuscript you mention that snow density was 555 kg/m3. Please check.*

*A: 555 is the mean of the density measurements. 553 is the density used in the model. This density is calculated from the volume fractions of water, ice and void. The difference to 555 is attributed to rounding of these fractions to two digits.*

*C: Page 17: An explanation of figure 10b, 10c, and 10d is missing.*

*A: The explanation is later in the text (Page 18). A reference to Fig 10d will be added.*

*C: Page 18, Line 21: Please quantify this high correlation here.*

*A: We are not talking about a statistical correlation in that context. To clarify we change the sentence to: "This underlines the high impact of sawdust thickness on energy available for snow melt."*

*C: Page 18, Lines 7-9: This is hardly visible in figure 11. I recommend to recolor the sum of the individual energy balance components and change the color of heat of precip to black.*

*A: Figure has been recolored.*

*C: Page 22, Line 2: Please provide more information here.*

*A: We added the range of losses (12-50%) (based on an survey of several snow farming sites)*

*C: Page 22, Line 27: Please provide more information about operation costs. I think this is very important information here for interested readers*

*A: Right, so we added the following information which is based on the personal communication of the responsible persons (Norbert Gruber & Werner Putzi) of community of Davos:*
*"Operational costs have to be evaluated for each snow farming project specifically considering the applied technical and logistical solutions. For example in Davos 15 CHF per m3 snow were estimated for the first snow farming project in 2008. Till 2016 these costs could be strongly reduced to about 9 CHF per m3 thanks to larger snow volumes stored and improved infrastructure and work flow. Investments for structural measures at the storage location are not considered in this calculation. Two thirds of the expenses were caused by the distribution of the snow along the cross-country track followed by the removal of the saw dust (14%) and material costs for saw dust (10%) , assuming a five year operational live-time (Norbert Gruber and Werner Putzi personal communication). Generally, it can be stated that snow production costs are minor compared to covering and especially distribution costs. "*

**Review 2: B. Nordell**

*C: This is paper is scientifically good but a bit dry to read. It could be improved by moving details of the measurement equipment to an appendix. I suggest that the paper is accepted for publishing in TC after some minor editorial changes in the tex.*

A: Thank you for this brief feedback. We believe that the methods section is mandatory for the paper and not very exhaustive anyway. We therefore think that is should remain in the main text.

**Reviewer 3: S.R. Fassnacht**

*We are grateful to S.R. Fassnacht for his very positive and constructive review. We are answering his comments in the following, for clarity we repeat the original comment (C) and answer (A) afterwards:*

**General Comments**

*C: This is a somewhat novel idea and I applaud the authors for using a modeling approach with field data to assess the utility of snow farming. There are no major problems with this paper and with some clarification, it will make a good contribution.*

*A: Thank you for this positive feedback.*

*C: The differences in ablation between the two sites is attributed to the "potential warming effect of the black paved road at Martell resulting in lateral advection of heat (page 21 line 1)." Can this be quantified at all? This is an important point.*

*A: Together with the good suggestion to do full three-dimensional (Alpine3D) simulations also for the snow heap, it will be interesting to see (probably in a future study), in how far the road may contribute to stronger melt. However, it will not be adequate to present a calculation of the effect in the current paper, which presents a simplified analysis based on one-point simulations at the top of the pile. A "back of the envelope calculation", which could be done based on an assumed road temperature could be done but is considered not to be very useful as we don't have time-resolved estimates of surface temperatures for both the side of the pile and the road. Thus, at least* *rudimentary radiative transfer modelling in combination with local energy balance modelling would be required to quantitatively estimate the effect. For this, we do not have sufficient input data and it is beyond the scope of the analysis as presented in this paper.*

*C: The writing is good, with a few instances of paragraphs that seem to short. There are a few words uses that are somewhat subjective, such as "huge" on page 20 line 31. These can be distracting. The figures are good, but could be slightly improved, such as adding section letters (e.g., Figure 11, use a. depth of covering layer) and increase the font size on axes.*

*A: We are carefully revising these points and implementing changes where required (see detailed comments)*

**Specific Comments**

*- page 1, line 11: "a factor of 12" instead off "or"*
*A: changed*

*- page 1, line 15: this sentence is confusing "switching of precipitation of completely would strongly increase melt"*
*A: Sentence was changed to "No significant effect of additional precipitation could be found as the sawdust remained wet during the entire summer, already with the measured quantity of rain. Setting precipitation amounts to zero, however, strongly increased melt."*

*- page 1, lines 17-21: another citation could be the pozo de nieve (snow wells) that were extensively used in Spain well into the 19th century*
*A: Thank you for this hint, we have added a citation (Morley 1942)*

*- p2, l 2-5: While it is an old citation, it is an interesting approach to reduce mass loss of small glaciers/snowfield due to sublimation - Slaughter (1970 US Army CRREL Special Report 130)*

*A: It is indeed an interesting paper. As it is, however, not directly linked to snowfarming we believe that it is not meaningful to discuss in the context of our study.*

*- p3, l 27: it may be intuitive to you, but add direction to the location, i.e., lat: 46.808°N, long: 9.868°E (I assume).*
*A: We have added directions for both study sites.*

*- p3, l 29-30: could you simulate how different natural snow in piles would be? "A large snow pile is formed by machine made snow produced during the winter months."*
*A: This would be possible by changing the initial properties of the snow heap in the input file. However, differences between well settled, aged natural and technical snow are marginal and simulation results with old natural snow would therefore not reveal significant differences.*

*- p4, l 3-5 and 12-13: did you compare the met station on top of the building to the met station on top of the snow heap?*
*A: Yes we did for TA and VW and developed a correction for VW. This is described in Sect. 3.1*

*- p4, l 4-7: you use new symbols that do not seem common – air temperature (TA), relative humidity (RH), wind speed (VW), direction (DW), incoming shortwave radiation (ISWR), incoming longwave radiation (ILWR). Are this necessary, or can you use more common*

*symbols?*
*A: We changed symbols for wind speed (WS) and wind direction (WD).*

*p5, l 14: you "calculate snow volumes." What about mass?*
*Snow mass or SWE cannot be directly calculated from TLS measurements. It also requires snow density. Only few density measurements were available, it would therefor add uncertainty to results to use SWE instead of HS (which was measured highly accurate). We therefore focus on volume for the measurement but also address SWE when analysing model results (also see reply to review by J. Garvelmann).*

*p5, l 17: state the wavelength of the TLS "near-infrared spectral range"*
*A: the wavelength is 1064 we added it in brackets.*

*p7, l 10: is the word "extremely" necessary?*
*A: removed*

*p7, l 19: do you mean "crown" instead of "crone?"*
*A: yes that's right.*

*p7, l 19: be specific about the type of "linear interpolation"*
*A: We changed to "…by triangulation with the nearest points".*

*p7, l 31: the "grain size of 1mm" seems quite small*
*A: This should be "grain radius" instead of grain size. 2mm is a typical grain size for well settled technical snow.*

*Table 2: is a spectral albedo of sawdust of 0.5% correct? This seems low, or explain what this is.*
*A: yes, this is a mistake. It should be 50%¨*

*p8, l 13-14: data were "resampled to 30 min time steps" but the "modeling time step was set to 15 min." Please rectify or discuss this discrepancy*
*A: We changed to "All input data were filtered, quality checked and resampled to the modeling time step of 15 min using the meteorological input-output library MeteoIO"*

*p8, l 18 and 21: should this read "Table 3-5", instead of Table 3.5?*
*A: it should be Table 3.*

*p9, l 15: change "Lower temperatures and irradiation is mainly*
*A: changed*

*Figure 3c: maybe use two axes the same as Figure 3a and b, with net SWR in red on the left and net LWR in blue on the right.*
*A: I think that the figure is quite clear as it is. I see no reason for adding a second axes with the same units and dimensions.*

*Figures 3 and 4: use Oct rather than Okt. Think about putting these two sets of figure beside one Another*
*A: labelling has been changed.*

*p11, l 3-4: delete the first two sentences: "This section presents results obtained from the TLS surveys. The focus of the analysis is on the Flüela data set. Values for Martell are provided in brackets."*
*A: Sentences have been removed.*

*p11, l 5 and beyond: use a period as the decimal place "8.99m" rather than a comma "8,99m"*
*A: changed*

*Figure 5: consider changing the color ramp so that white is no change, blue is an addition and red is a less. At present it is confusing as blue can be a small gain or loss.*
*A: We changed the colour map according to the suggestion.*

*Figure 5: there is a scale bar. Think about adding dimensions (in x and y) to one of the figures instead so we know how big it is.*
*A: We removed the scalebar and indicate scale in the x-axes now*

*p13, l 12: perhaps show this "respective coordinate" on Figure 5a and 6a*
*A: We are showing the coordinate in Fig 5c, 5d, 6c and 6d now*

*Figure 7: do you mean "aspect" for "exposition?" The x-axis for Figures 7b and 7d are unclear*
*A: yes it should be aspect. We changed it and reworked the axis.*

*p16, l 4: what is meant by "*in dependence of the different settings?"*?" Also, add a number to "(Table )"*
*A: Deleted. See below.*

*p16, l 4-6: I would delete these sentences. They are not necessary. What is meant by "The difference pictures densification?"*
*A: Deleted. It was meant to explain the difference in relative losses in SWE and HS; this is attributed to an additional effect of densification on HS (losses in HS are larger than in SWE).*

*Figure 10d. I am surprised that precipitation does not appear to change the results at al.*
*A: The reason is that the cover remains wet even for the case of no additional rain. Additional wetness seems to have not much additional cooling effect. This is described in the text.*

*Table 5: how is the albedo of the snow heap modelled over time, as this influence net SWR.*

*A: Albedo of saw dust albedo is modelled with a constant value of 0.5; We cannot quantify temporal change of saw dust albedo but is probably limited over a single summer. Albedo of snow (only relevant for simulation without sawdust cover) chages in time dependent of snow properties as described in Schmucki et al. 2014*

*Figure 11: would this be clearer is there were log scales (both positive and negative), as some of the bars are difficult to see.*
*A: We have tested this suggestion. As expected, log scale improves readability of the small fluxes. However, the large difference in contribution of the single fluxes to melt is then less pronounced. We think that emphasising this relative difference is more important than readability of the smaller, relatively unimportant fluxes and therefore remain with a linear scale.*

*p20, l 9-10: can you quantify "total mass balance can be rated as marginal?"*
*A: yes of course; let's assume a total size of the gaps of 10m2 (which is large) and a mean error introduced by interpolation of 0.5 m (which is also large). This results in a volume uncertainty of 5m3; relating this to snow volume of the entire heap (5000-7000 m3) is below 0.1%*

*p20, l 31: is the word "huge' necessary?*
*A: removed*

*p20, l 31-31: "Possible explanations are different properties of the covering materials." I assume that you did not model Martell? Can you do some simple calculations to describe the differences between saw dust and wood chips. While you subsequently say that it is likely not important, we don't know this.*

*A: We also modelled Martell, but with the same properties of the covering layer. We believe that the general properties of saw dust and the mixture of saw dust and wood chips in Martell are similar. To test this we did some modelling (see our reply to J. Garvelmanns review below). However, the large heterogeneity of the surface, especially in Martell, with very dark areas consisting of older cover material and with areas of fresh, brighter material might well have effects, e.g. on albedo.*

*Reply to J. Garvelmann: From our investigations we think that the difference between the materials is much smaller than the uncertainty in the estimations of these properties and the very small-scale spatial variability of the cover material (which is especially large for the mixture of chipped wood and saw dust). To test the effect of porosity (and therefore water storing capacity) we performed some model runs with varying grain sizes of the covering layer. Increasing the grain radius (from 0.1 mm to 1 mm) by a factor of 10 did not reveal any significant differences in the final mass loss. Only much larger grain sizes (3 mm) increased mass loss slightly. Wood chips of that size (or even bigger) exist in the Martell covering Material, but the finer particles clearly dominated. Moreover, from laboratory measurements of small samples from both heaps we found nearly identical dry densities. We therefore believe that the assumption of same properties of the covering material is appropriate. We include a corresponding sentence in the text.*

*p21, l 1: can you try to quantify the "potential warming effect of the black paved road at Martell resulting in lateral advection of heat?"*
*A: See detailed explanation above*

*p21, l 14: delete "such"*
*A: done*

*p22, l 28: I think you mean "proved" rather than "proofed." I think that this word is too strong as you only modeled one point at the top of the pile.*
*A: we changed to "proved"*

# Snow farming: Conserving snow over the summer season

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**Abstract.** Summer storage of snow for winter touristic purpose tourism has seen an increasing interest in the last years. Covering large snow piles with materials such as sawdust enables to conserve more than two thirds of the initial snow volume. We present detailed mass balance measurements of two sawdust covered sawdust-covered snow piles obtained by terrestrial laser scanning during summer 2015. Results indicate that 74% and 63% of the snow volume remained over the summer for a pile in Davos, Switzerland and Martell, Italy. If snow mass is considered instead of volume, the values increase to 8583% and 72%which . The difference is attributed to settling and densification of the snow. Additionally, we adapted the one-dimensional, physically based snow cover model SNOWPACK to perform simulations of the sawdust covered snow piles. Model results and measurements agreed extremely well at the point scale. Moreover, we analyzed the contribution of the different terms of the surface energy balance to snow ablation for a pile covered with a 40 cm thick sawdust layer and a pile without insulation. Shortwave radiation was the dominant source of energy for both scenarios but the moist sawdust caused strong cooling by long-wave emission and negative sensible and latent heat fluxes. This cooling effect reduces the surface energy balance by a factor of energy available for melt by up to a factor 12. As a result only 9% of the net shortwave energy remained available for melt. Finally, sensitivity studies of the parameters "thickness of the sawdust layer, air temperature, precipitation and wind speed ", "air temperature", "precipitation" and "wind speed" were performed. We show that sawdust thickness has a tremendous effect on snow loss. Higher air temperatures and wind speeds increase snow ablation but are less important. No significant effect of additional precipitation could be found as the sawdust remained wet during the entire summer. However, switching of precipitation of completely would strongly increase melt. , already with the measured quantity of rain. Setting precipitation amounts to zero, however, strongly increased melt. Overall, the 40 cm sawdust provides sufficient protection for mid-elevation (approx. 1500 m a.s.l.) Alpine climates and can be managed with reasonable effort.

## 1 Introduction

Snow storage or snow farming is the conservation of snow during the warm season of the year. Purposes of summering snow or ice are diverse. Already in ancient timetimes, ice and snow were stored for cooling of food and houses (Taylor, 1985; Skogsberg and Nordell Another example for a traditional application of snow storage is the collection of snow in deep underground wells e.g. in Afghanistan (Bhattacharyya et al., 2004). The water stored in the snow could be used for irrigation or as drinking water during summer. Rising energy costs have increased interest in snow or ice as cooling source (Nordell, 2014). In several regions of the world, such as Scandinavia, Northern America, China or Japan snow storage has seen a revival for air conditioning of buildings (Skogsberg and Nordell, 2001; Nordell and Skogsberg, 2007; Morofsky, 2007; Hamada et al., 2010, 2012) or food cooling (Kobiyama et al., 1997; Nordell, 2014): During winter, large amounts of natural or machine-made snow are collected and stored. During summer the melting snow provides cooling energy for air conditioning.

Another application of snow conservation is the protection of glaciers from melt. At some ski resorts, thin textile covers, called geotextiles have been used to blanket critical areas of the glacier surface at the end of the winter season (Olefs and Lehning, 2010). The properties of the covering material, such as albedo, thermal conductivity, emissivity or permeability influence the energy balance of the snow and the glacier resulting in reduced ablation (Olefs and Obleitner, 2007; Olefs and Lehning, 2010). Olefs and Fischer (2008) performed field tests at two Austrian glaciers where they analyzed different types of geotextiles and plastic fabrics as covering material. They found that ablation could be reduced by up to 60% in comparison to a natural snow surface. Finally, Olefs and Lehning (2010) used the snow cover model SNOWPACK to simulate the effect of geotextiles on energy balance and snow ablation on glaciers. They showed that most of the performance of geotextiles is attributed to increased short wave reflectance compared to the dirty firn surface. Thermal insulation and cooling by latent heat transfer contribute, but are less important. Olefs and Lehning (2010) summarize that geotextiles are very effective covering materials for glaciers but were not suitable at lower elevations where turbulent fluxes typically dominate the energy balance.

The idea to conserve snow for touristic purposes, also at lower elevations, came up in Scandinavia more than a decade ago. Similar to the previously mentioned snow storage applications, large amounts of snow are collected at the end of the winter or produced by snow machines and conserved over the summer months. In the following autumn, the remaining snow is used as basis for the preparation of winter sport facilities such as cross-country tracks, ski-runs or ski-jumps. A frequent motivation of winter sport destinations to store snow is the hosting of large sports events, such as cross-country races in autumn or early winter. The conserved snow provides a ~~guaranty~~ guarantee for a basic amount of snow for track preparation, independent of the current weather conditions which may be unfavorable for artificial snow production. Examples for such events are the Cross-country Skiing World Cup in Davos, Switzerland, the Biathlon World Cup in Östersund, Sweden or the Ski-jumping World Cup in Titisee-Neustadt, Germany. The largest application of snow storage was performed for the winter Olympics held in Sotschi, Russia in 2014. About 800.000 $m^3$ of snow were preserved as reserve for the preparation of alpine ski-racing tracks in case of lack of snow (Lintzen, 2016). Other motivations are the early preparation of training facilities for athletes or an early opening of ski slopes for the public. Some ski resorts collect snow at the end of the winter and conserve it at neuralgic spots, such as terrain breaks or depressions. In the succeeding winter the remaining snow is used for leveling of these depressions.

Different organic materials, such as sawdust, chipped wood, cutter shaving, bark mulch or straw have been used for the coverage of the snow piles (Skogsberg and Lundberg, 2005). Moreover, non-organic fabrics such as styrofoam plates, polymeric foam, geotextiles and combinations of different materials have been applied. All these materials act as insulating layers that reduce heat transfer from the atmosphere to the snow. Depth, thermal conductivity and heat capacity are the key characteristics for their insulation performance. In addition, most organic materials are able to store significant amounts of moisture. Evaporation of the water cools the surface and reduces snow ablation (Skogsberg and Lundberg, 2005). Moreover, the high shortwave reflectivity (albedo) of some cover materials reduces solar energy input. Obviously, meteorological conditions, such as air temperature, solar radiation, humidity, precipitation and wind strongly affect snow melt. First investigations (Rinderer, 2009), basic calculations (Skogsberg and Nordell, 2001) and reports from practitioners indicate that the amount of snow that is lost during summer is in the range of 20 to 50%. However, mass balances based on accurate measurements have not yet been published.

In recent years the number of snow-conservation projects and sites has strongly increased, especially in Scandinavia but also in the Alps. Snow farming can be seen as an adaption strategy to climate warming but is also required to satisfy customers demands of an early winter season start. However, ~~direct economic effects, such as increasing numbers of~~ the number of additional tourists in the early winter season ~~are~~ due to snow farming is probably limited (Dreier, 2010). The main benefit for the destinations will rather be related to higher media presence and positive image in relation to general snow security of the destination and for hosting professional winter-sports events such as word-cup races independent of the weather conditions.

Detailed mass balances ~~on this application of snow storage~~ for snow storage applications are currently not available. The only study known to the authors is a field test by Rinderer (2009) who observed two snow heaps at a location near Davos, CH (1620 m a.s.l.). One was covered with geotextile (4 mm) and the other with a 40 cm layer of sawdust. Based on a simple analysis of time lapse photography, Rinderer (2009) concluded that the first pile nearly melted completely while the latter lost about 30% of its volume. Additionally, the different cover layers were implemented into the physically based snow cover model SNOWPACK (Lehning et al., 2002a). Simulations of the field experiments showed plausible results. But due to the limited quantification of the volume losses a precise validation of the model results were lacking.

~~This~~ A rising number of technical feasibility studies on snow farming has been requested at SLF in recent years. This motivated us to (i) provide a review on current snow farming techniques (ii) to perform a detailed field study on snow farming and (iii) to describe and evaluate the model used for snow farming applications by the SLF. This paper presents the first scientific publication on snow farming for touristic purposes as described above. Contrary to Rinderer's relatively rough estimation, we present detailed measurements of the volume loss based on high-resolution terrestrial laser scanning surveys. In 2015, measurement campaigns have been performed at two sites, at the same site as Rinderer's study (Davos) and in the Martell valley of South Tyrol. ~~These measurements for the first time allow for a detailed analysis of the volume loss of such snow farming applications.~~ We present an analysis of the small-scale spatial characteristics of snow ablation at the two snow heaps. The study is completed by simulations using the SNOWPACK model. Model runs of for the two sites are performed to evaluate the ability of SNOWPACK to reproduce the evolution of the snow piles and to analyze the impact of the different terms of the surface energy balance. Finally, a sensitivity study, assessing effects of different settings and changed atmospheric conditions is performed. The respective results are discussed and summarized in the end of the paper.

## 2 Methods and data

### 2.1 Study sites and snow deposits

Observations of snow-farming projects at two study sites in the Alps are presented. The first is in the Flüela valley near the city of Davos in the Eastern part of Switzerland (Fig. 1). The storage site is a forest clearing at the valley bottom located at

**Figure 1.** Flüela snow heap after coverage with sawdust in autumn 2015

**Table 1.** Measured meteorological parameters.

| Parameter | Abbreviation | Unit |
|---|---|---|
| Air temperature | TA | °C |
| Relative humidity | RH | % |
| Wind speed | WS | m/s |
| Wind direction | WD | ° |
| Incoming shortwave radiation | ISWR | $W/m^2$ |
| Incoming longwave radiation | ILWR | $W/m^2$ |
| Precipitation | P | mm |

1620 m a.s.l. near to the mouth of the Flüela valley (lat: 46.808°N, long: 9.868°E). The direction of the valley is west to east and the site is shadowed by mountains, in particular by a 2500 m high mountain in the South.

Snow farming has been operated at the Flüela site since 2008. A large snow pile is formed by machine made snow produced during the winter months. The snow pile also contains relatively small amounts of natural snow resulting from precipitation events during winter. In spring this pile is smoothed and covered by a 40 cm layer of sawdust. In 2015 the snow heap was covered between 13 and 18 April and the sawdust was removed on 19 October. The purpose of snow farming in Davos is to provide a short track for cross-country skiing that is usually opened by the beginning of November. The track serves as training facility for professional athletes and also provides the snow basis for the cross-country skiing world cup in early winter.

~~Meteorological data~~

Meteorological data (Table 1) from two different automatic stations were analyzed for the Flüela site. The station "Wind-tunnel" measuring air temperature (TA), relative humidity (RH), wind speed (~~VW~~WS) and direction (~~DW~~WD) is installed at

**Figure 2.** Martell snow heap covered with sawdust and wood chips in spring 2015. The Riegl VZ6000 laser scanner can be seen in the foreground.

the roof of a concrete building next to the snow heap. The height of the sensors is about seven meters above ground which is similar to the height of the snow pile. The remaining meteorological parameters required as input for the simulations (incoming shortwave radiation (ISWR), incoming longwave radiation (ILWR) and precipitation (P)) were taken from weather station DAV that is located at a similar elevation (1596 m a.s.l.) in the town of Davos about 2 km away and has high quality meteorological observations. The local effect of terrain shadowing to incoming shortwave radiation was corrected by applying a shade-filter available in the pre-processing library for meteorological data, MeteoIO (Bavay and Egger, 2014). This filter transfers measured radiation of a measurement station to another site taking into account local shading.

No automatic station had been set up directly on top of the snow pile in 2015. However, a simple weather station had been placed from 27 May to 17 July 2016 at the top of the snow heap. These observations could be applied to assess the representativeness of the sensors and to correct the input data used for the simulation. Moreover, the long record of meteorological data at DAV (since 1998) enables to characterize the summer 2015 in comparison to the climatic mean.

The second snow pile was in the Martell valley of South ~~Tirol~~ Tyrol (Fig. 2). The ~~storing~~ site is a forest clearing at 1710 m a.s.l. at the bottom of the valley (lat: 46.517°N, long: 10.720°E). Up to 3700 m high mountains surround the valley that opens to the Northeast. The snow dumping site is a concave, northerly exposed slope with steepness rising from 0 and 50°. Work flow and purpose of the pile are similar to Flüela: Snow is produced with snow machines during the cold season and covered in spring. In contrast to Flüela, the covering material at Martell also contained a portion of larger wood chips. In 2015 the snow heap was covered from 6 May to 13 November. 3.5 km of cross-country tracks could be prepared with the stored snow ~~. Same as in~~ in that year. Similar to Davos, the aims of snow farming are the provision of early training possibilities for athletes and a guarantee of basic snow amounts, independent of weather conditions during autumn and early winter.

We used meteorological observations of the automatic weather station Hintermartell (Autonome Provinz Bozen, 2016b) to assess meteorological forcing. This station is only 250 m away and is equipped with sensors for TA, RH, P, ISWR, ~~VW and DW~~WS and WD. Measured ILWR is not available in the region and was therefore parametrized (see Sect. 2.4).

As the station was only established in 2009, we employed data from the slightly higher (1851 m a.s.l.) and 1.2 km distant station "Stausee Zufritt" (SZ) (Autonome Provinz Bozen, 2016a) to evaluate the climate conditions of summer 2015 in a climatological context.

## 2.2 Field measurements

### 2.2.1 Terrestrial laser scanning

Measurements of the snow volume stored at the end of the winter season and of the volume that remained in autumn were performed by terrestrial laser scanning (TLS). TLS proved as a highly accurate method to obtain digital surface models. Changes of surface volumes can easily be obtained by subtracting of two succeeding surveys. Repeated TLS was successfully applied to calculate snow volumes in high spatial resolution and with a vertical accuracy of less than 10 cm (e.g. Prokop et al., 2008; Grünewald et al., 2010; Revuelto et al., 2014).

We used a Riegl VZ6000 terrestrial laser scanner (Riegl Laser Measurement Systems GmbH, 2015) shown in Figure 2. The VZ6000 (1064 nm) operates in the near-infrared spectral range and is characterized by high accuracy (15 mm), precision (10 mm) and a beam divergence of only 0.12 mrad. Measurement frequencies of 300 kHz were used. For this study, the maximum measurement distance of the target area was less than 150 m. The respective beam width for this distance would be 33 mm. Because of this rather small measurement range the maximum angular step width (0.002°) could be reduced to 0.03°. To overcome scan shadows and to capture the complete snow piles TLS measurements from six (five) positions were taken at each survey day at the Flüela (Martell) snow pile. TLS surveys were performed at the Flüela site ~~at~~ on 29 April and 8 October 2015. These two data sets allow for the calculation of the volume change of the snow heap during summer. In order to determine the absolute volume and by this the relative loss of the snow pile a bare ground (without snow pile) elevation model would be required. Such a model was not available and could not be surveyed as the site was always covered, either by the snow heap (during summer) or by the stored sawdust (after snow removal). However, the site is a quite homogeneous, only slightly sloped flat area that could well be approximated by a plane that was interpolated from the edges of the snow pile. Note that at the time of both surveys the snow pile was covered by a layer of sawdust. In autumn 23 manual measurements of the sawdust depth were performed in two cross transects with an avalanche probe perpendicular to the slope. The mean depth was 32 cm (standard deviation 11 cm) corresponding to a depth of about 38 cm when calculated in vertical (gravitational) direction.

At the Martell field site TLS measurements were performed ~~at~~ on 19 May and 28 October 2015. Similar to Flüela these dates indicate the beginning (few days after the pile was covered) and the end of the melt season (briefly before the snow was turned out to the cross country track). Identical to the Flüela data set the period between the two surveys corresponds to 163 days but both surveys were obtained three weeks later. In contrast to Flüela, the covering material was not ~~sawdust but~~ only sawdust but saw dust with wood chips. Particle size of these wood chips varied from 0.1 mm (like sawdust) to pieces with

**Table 2.** Estimated volumes of snow remaining in the Martell dump.

| Zone | Snow depth [cm] | Area [$m^2$] | Volume [$m^3$] |
|---|---|---|---|
| 1 | 10-20 | 1290 | 129-258 |
| 2 | 50-100 | 407 | 204-408 |
| 3 | 150-200 | 170 | 255-340 |
| Sum | | 1867 | 588-1006 |

a size of several ~~centimetres~~centimeters. It needs to be considered that additionally the surface of the pile was covered by a thin layer of snow during the second survey that resulted from an early snow fall. We calculated a mean snow height (HS) of 6 cm (standard deviation 1.5 cm) from 27 manual HS measurements. During data processing, this mean value was applied to remove the additional volume caused by the snow cover. As the wood chips layer was hard frozen, its thickness could not be measured with a penetrating probe but, based on the roughly known total volume of wood chips (800-1000 $m^3$) deployed it was estimated to be about 35 to 45 cm (Martin Stricker personal communication). As mentioned before, the ground surface of the dump is not flat at Martell but characterized by ~~variable~~ sloped topography. Therefore, a third TLS survey was performed at 19 November. Even though most snow had been turned out at that time, some snow still remained in the dump. Unfortunately, HS could not be measured with a probe as the snow was extremely hard frozen. We therefore had to estimate the remaining snow amount based on our visual impression: The surface was visually classified to three zones that were then mapped with a differential GPS. The respective values are listed in Table 2. Based on these estimations we used a mean value of 800 $m^3$ for the corrections of the heap volumes.

#### 2.2.2 Snow density

Snow densities are on the one hand required for the initialization of the SNOWPACK model and on the other hand for the transformation from snow volume to snow mass or snow water equivalent (SWE).

Snow densities were measured at the beginning (Apr 2016) and at the end of the storage periods (Oct 2015) at different locations and depths of the Flüela snow heap. Five snow volumes were extracted with a core driller providing cylindric snow samples (~~$d = 72\ ,mm$~~$d = 72\,mm$) of different length. Ten volume samples were taken with a 100 $dm^3$ cubic density cutter. Additionally, three cubic snow samples were taken to determine densities by X-ray micro-computer tomography (micro CT) (Heggli et al., 2011). No densities could be measured at Martell.

### 2.3 Data processing

TLS requires substantial efforts of data post-processing which was done with the commercial software RiSCAN Pro provided by the manufacturer (Riegl Laser Measurement Systems GmbH, 2011). In a first step the ~~extremely~~ large amount of data needs to be reduced. This was done by removing all data outside of the area of interest and by aggregating the remaining data points to a 5 cm 3D grid (octree filter). Then the data points from the multiple scan positions need to be combined. For this registration a set of eight (seven) reflector tiepoints that were installed at fixed locations such as walls of buildings in the surrounding were used. Global coordinates of the reflectors were recorded with differential GPS and total station. In a second step an optimization function called Multi Station Adjustment was applied to further improve the registration of the scan positions (Riegl Laser Measurement Systems GmbH, 2011). Finally, the data of each survey were transformed to the global coordinate system (CH1903 and UTM respectively) by applying the global coordinates of the reflectors and the merged and filtered point clouds were exported. ESRI ArcMap 10.2 was used to rasterize the data. Data were triangulated and data gaps that were partly existing, especially at the ~~crone~~ crown of the pile, were closed by ~~linear interpolation~~triangulation with the nearest points. Finally, raster data with a resolution of 10 cm were composed and used for volume calculations and further analysis.

### 2.4 Snowpack model

SNOWPACK is a one-dimensional physically based snow model which has been developed to simulate state and evolution of the snow cover. The multi-layer model rests upon a detailed description of the energy and mass fluxes within the snow and between snow, atmosphere and soil (e.g. Lehning et al., 2002a, b; Wever et al., 2015). For this publication SNOWPACK was applied to simulate the evolution of the two snow heaps during a complete summer season. Aims were to identify the dominant processes related to mass conservation during snow farming and to evaluate the models applicability to improve and plan existing and upcoming snow farming projects.

SNOWPACK is initialized with a snow profile, describing the state of the snow at the beginning of the simulation. With the one-dimensional SNOWPACK model, we chose to simulate ablation at the top of the respective piles. Corresponding to the maximal HS measured at the two heaps, HS were set to 8.60 m for Flüela and 7.20 m for Martell. The snow was subdivided to ten homogeneous layers of fully rounded grains with a grain ~~size~~ radius of 1 mm and a density of 553 $kg/m^3$. These values are typical for settled ~~machine made~~ machine-made snow and are based on the measurements described earlier. Moreover, the snow was assumed isothermal (snow temperature 0°C) holding a portion of 3% liquid water. Temperature and water content were not measured directly but are based on our impressions during density sampling. Two ~~layers of soil~~ extra layers were added to the snow profile. One at the bottom (ground) and one at the surface representing the covering material. A 40 cm thick covering layer representing the amount of sawdust obtained from measurements at the two snow heaps is ~~entitled~~ used as reference simulation in the following. Characteristics of the sawdust layer are listed in Table 3. SNOWPACK allows the representation of soil (Lütschg et al., 2008) and other materials (e.g. Olefs and Lehning, 2010) by specifying mechanical and thermal layer properties. As we assume similar properties of sawdust and the mixture of sawdust and wood chips used in Martell, the same model settings were used for all simulations.

SNOWPACK is driven by the meteorological measurements TA, RH, ~~VW, DW~~WS, WD, ISWR, ILWR and P (Table 1). These parameters were obtained from nearby automatic weather stations as described earlier. As no measurements for ILWR were available for the Martell region, it was approximated using a combination of a clear-sky parametrization (Dilley and O'Brien, 1998) ~~)~~ and an all-sky algorithm (Unsworth and Monteith, 1975) as described in Schmucki et al. (2014). This parametrization was also applied to account for changes in long wave radiation that go along with increasing temperatures (Schmucki et al., 2014) as simulated in the sensitivity runs with higher air temperatures (Sect. 3.5).

**Table 3.** Initial properties of the sawdust cover layer~~as applied in~~. Note that SNOWPACK characterizes soil and other layers with the volume fractions of the dry material, the void and the water fractions. The ~~values~~ properties of the dry material are partly based on ~~investigations of Rinderer (2009)~~measurements and partly on experience (e.g. Rinderer, 2009).

| | |
|---|---|
| Volume fraction of soil [%] | 50 |
| Volume fraction of water [%] | 20 |
| Volume fraction of void [%] | 30 |
| Density of ~~soil~~ saw dust [$kg/m^3$] | 245 |
| ~~Bulk density~~ Thermal conductivity of saw dust [~~$kg/m^3$323 Thermal conductivity~~ W/mK] | 0.07 |
| specific heat capacity [J/kgK] | 990 |
| Spectral albedo [%] | ~~0.5~~ 50 |

**Table 4.** Parameters and settings (offset or factor) applied for the sensitivity study.

| Parameter | Offset | Factor |
|---|---|---|
| Depth of covering layer [cm] | -40,-30,-20,-10, +10,+20 | |
| Air temperature [°C] | -1, +1,+2,+5 | |
| Wind speed [m/s] | | 0*, 2, 5 |
| Precipitation [mm] | | 0, 2, 5 |

* Constant minimum wind speed of 0.3 m/s as hard-coded in SNOWPACK to avoid model instability due to zero surface fluxes of sensible and latent heat

All input data were filtered, quality checked and resampled to ~~30~~the modeling time step of 15 min ~~time steps~~ using the meteorological input-output library MeteoIO (Bavay and Egger, 2014). ~~The modeling time step was set to 15 min.~~ Model outputs are time series of snow profiles and fluxes reflecting the state of the snow pack at different points of time. In context of this study, snow height, snow mass, density, water content and the respective energy and mass fluxes are the parameters of interest. In addition to the reference simulation with measured meteorological data and a 40 cm sawdust cover, sensitivity studies were performed by varying the meteorological input parameters and the depth of the covering surface layer (Table 4). For each run, only one of the parameters was changed while the measured input was used for the others (as described above). We performed seven sensitivity runs for different depths of the covering material by increasing it from 0 to 60 cm. In addition to the reference simulation, we performed two model runs for wind speed, three runs for precipitation and four runs for temperature as shown in Table 4. Note that also ILWR was adapted for the temperature simulations as described above, which increases the consistency of the temperature sensitivity runs (Schmucki et al., 2014). Sensitivity runs are on the one hand valuable to identify the most relevant impact factors that can help to improve settings for snow farming projects and on the other hand to test the operability of snow farming as presented to other sites or to future climatic conditions.

# 3 Results

## 3.1 Meteorological data

Half-hourly meteorological measurements of ~~VW~~ WS and TA obtained by the stations at the top of the Flüela snow pile and the station Windtunnel (WT) were ~~analysed~~ analyzed for the period 27 May to 17 July 2016. Air temperature at Windtunnel was highly correlated ($R^2 = 0.9$) and showed a low bias of 0.4°C with measurements at the pile. Contrary to TA, ~~VW~~ WS showed stronger deviations. A mean ~~VW~~ WS of 0.3 m/s measured at Windtunnel indicates a clear underestimation of the wind at the pile (mean = 0.9 m/s). This might be attributed to wind sheltering effects of local topography and surrounding trees. Based on the measured data we calculated a linear regression function (~~$VW = 2.1 * VW_{WT} + 0.3$~~ $WS = 2.1 * WS_{WT} + 0.3$, $R^2 = 0.6$) that was then applied to correct ~~VW~~ WS for the simulations.

Meteorological input data as applied for the simulations are presented in ~~Figure~~Figures 3 and 4. Note that the data were aggregated to daily values for the plot while half-hourly values were used as input for the simulations. Mean temperatures of the survey period (29 Apr to 8 Oct) were 11.3°C at Windtunnel and 10.6°C at Hintermartell (19 Mai to 27 Oct). The mean of corrected ~~VW~~ WS at Windtunnel was 0.86 m/s and the measured ~~VW~~ WS at Hintermartell (HM) was 1.3 m/s. Precipitation cumulated to 543 mm (HM: 534 mm). Net shortwave radiation summed to ~~4101~~1476 ~~$kJ/m^2$~~ $MJ/m^2$ (HM: ~~3371~~1213 ~~$kJ/m^2$) and~~ $MJ/m^2$) and net longwave radiation was calculated ~~-276~~-992 ~~$kJ/m^2$~~ $MJ/m^2$ (HM:~~-166~~-596 ~~$kJ/m^2$)~~ $MJ/m^2$) for a heap covered with 40 cm of sawdust. Lower temperatures and irradiation is mainly attributed to the survey period at Martell that was three weeks later. This is confirmed by a comparison of data for an identical period (1 April to 30 September 2015) that demonstrated very similar climatic conditions at the two sites (WT: 10.1°C /, 514 mm; HM: 10.2°C, 514 mm).

Temperature and precipitation data of the nearby weather stations DAV and Stausee Zufritt (SZ) with long-term records were analyzed to rate the summer 2015 in relation to climatic mean values. At DAV the mean temperature of the summer half year (1 Apr to 30 Sep) 2015 was 10.1°C (SZ: 9.3°C) and therefore 0.8°C (SZ: 0.4°C) warmer than the mean of the same period of the last 15 years. Precipitation cumulated to 571 mm (SZ: 409 mm) in comparison to a 15-year mean of 645 mm (SZ: 434 mm). It can therefore be concluded that the summer half year 2015 was warmer and drier at both sites, while the difference was more pronounced at Flüela. This is in agreement with the findings of climate reports for Switzerland (MeteoSchweiz, 2016) and South Tirol (Munarni et al., 2015) that rated the year 2015 as the warmest and the summer as the second warmest since start of the measurements.

## 3.2 Snow density

Four of the five density samples collected at the snow pile in spring could be used for micro CT analysis. One sample had been destroyed during preparation. Mean density calculated from the samples with a volume of about 5 $cm^3$ was 555 $kg/m^3$ (standard deviation: 18 $kg/m^3$).

Measurements obtained in autumn showed a mean density of 556 $kg/m^3$ (n=6, standard deviation: 15 $kg/m^3$) at the position nearest to the snow surface (about 3.7 m above ground and 1 m below the snow surface) increasing to 578 $kg/m^3$ (n=6, standard deviation: 8 $kg/m^3$) about 2.1 m above ground and to 681 $kg/m^3$ at the lowest sample position (n=1). The resulting bulk

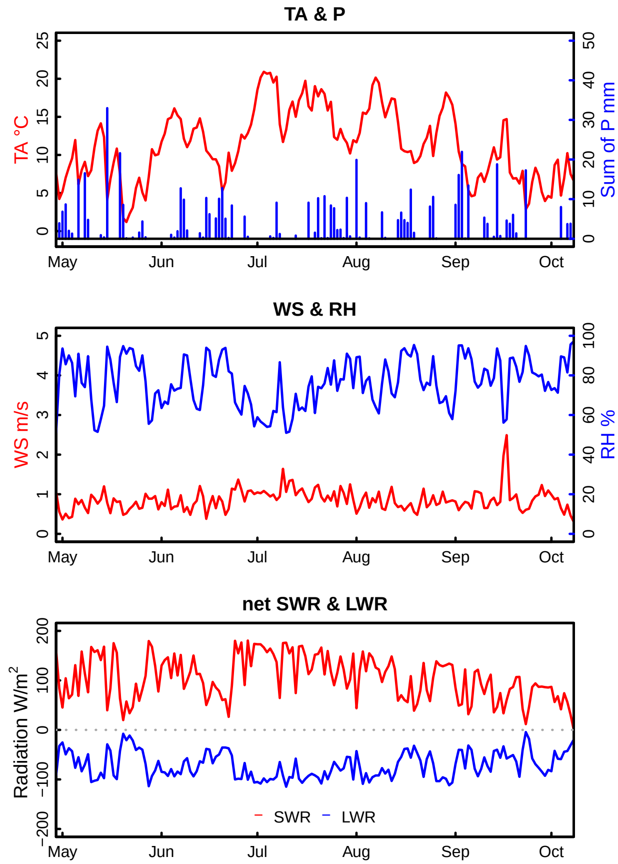


**Figure 3.** Meteorological input data aggregated to daily values for the Flüela site. Air temperature (TA) and precipitation are shown in the upper panel, wind speed and relative humidity (RH) in the middle and net shortwave (SWR) and net longwave (LWR) radiation in the lowest panel. Measurements were obtained from the stations WT (TA, ~~VW~~WS, RH) and DAV (SWR, LWR, P).

density (mean of all three levels) was 606 $kg/m^3$. This is in accordance to a densification of about 0 to 23% (9% for the mean values) in relation to the initial values.

### 3.3 Measured snow volume and mass balance

~~This section presents results obtained from the TLS surveys. The focus of the analysis is on the Flüela data set. Values for Martell are provided in brackets.~~

Snow-height maps calculated from the TLS data of the two snow heaps are presented in ~~Fig.~~Figures 5c,d ~~, Fig.~~and Figures 6c,d ~~and the respective~~ for Davos and Martell, respectively. The respective average values are shown in Table 5. The maximal height of the Flüela heap was ~~8,99~~8.99 m (Martell: ~~7,61~~7.61 m) in spring and decreased to ~~7,86~~7.86 m (Martell: ~~6,37~~6.37 m) in au-

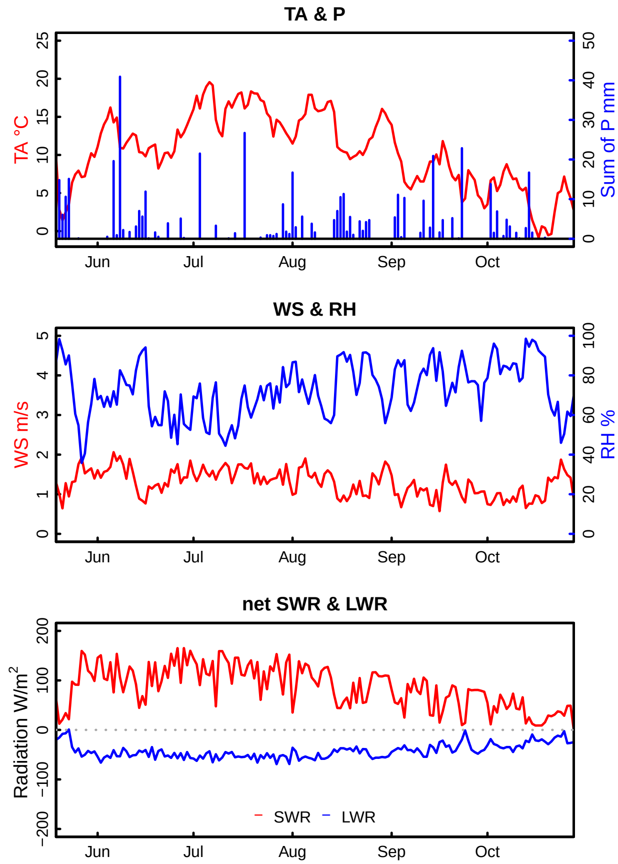


**Figure 4.** Meteorological input data aggregated to daily values for the Martell site. Air temperature (TA) and precipitation are shown in the upper panel, wind speed and relative humidity (RH) in the middle and net shortwave (SWR) and net longwave (LWR) radiation in the lowest panel. Measurements were obtained from the stations HM and LWR was parameterized as described above.

tumn. Mean HS (including sawdust layer) reduced from 4.07 m (Martell: 3.33 m) to 3.15 m (Martell: 2.18 m) and the mean change in snow height (dHS) was 2.70 m (Martell: 2.32 m).

Red colours in ~~Fig.~~Figure 5e ~~and~~ indicate that dHS was highest at the crown of the snow pile. The rather steep crest that was present in spring clearly leveled during summer resulting in the formation of a small, few meters wide plateau ~~, starred~~ with several small depressions. In contrast, the ~~dark~~ blue sections visible at the edges of the pile in ~~Fig.~~Figures 5c and 6c represent areas where height increased. This is, however, an artefact that can be explained by relocation of sawdust, caused by gravitational and man-made relocation and by the fresh snow at Martell. Low dHS values at the edges can also partly be explained by smaller snow heights, naturally limiting dHS to this initial value. ~~Moreover, red colours near to~~ Red colors near the edge of the Martell pile point at higher snow ablation in these locations (~~Fig.~~Figure 6e). These higher dHS might be attributed to increased melt caused by the proximity to the paved road (Fig. 2): It can be expected that the road heated much

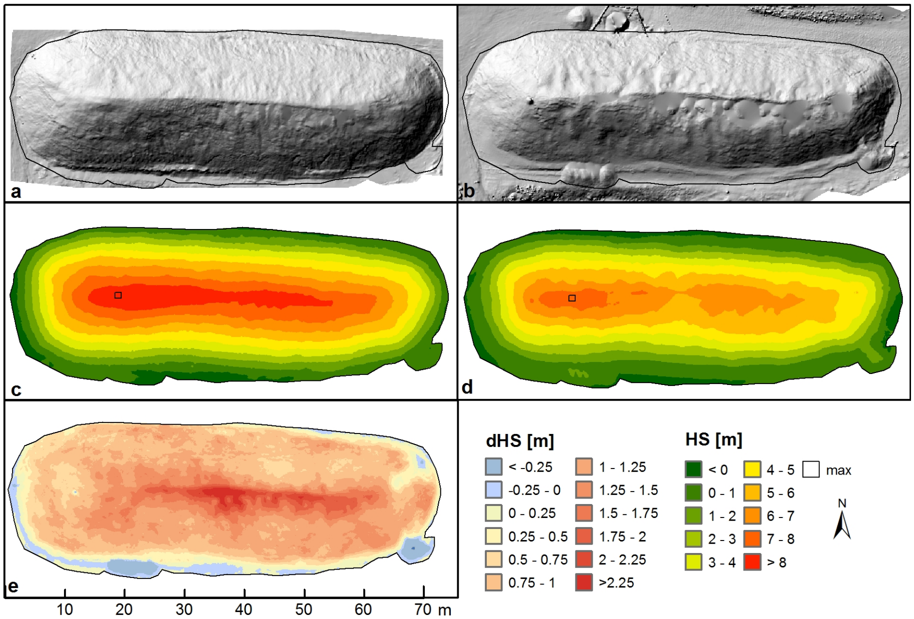


**Figure 5.** Flüela snow heap: Hillshade images (a: 29 Apr, b: 8 Oct), snow heights HS (c, d) and snow height change dHS (e). The area of the maximum HS at 29 Apr is indicated in c and d.

stronger due to low albedo and thermal properties and thus contributed additional energy by lateral advection of heat towards the snow heap ~~(Mott et al., 2013, 2015). Besides~~ (Mott et al., 2013, 2015, 2017) or by longwave radiation. Apart from this no eye catching patterns such as a possible influence of exposition are visible. This impression is confirmed by ~~Fig.~~Figure 7a that shows boxplots relating dHS to aspect. ~~Fig.~~Figure 7b, however, indicates a negative relationship of dHS and slope. Higher ablation seems to happen in flatter places. Lower wind speeds over steep slopes might be a possible explanation. The ablation pattern is in general consistent with a significant contribution of longwave radiation and turbulent fluxes to the cooling of the heap as discussed below.

Hillshade images and maps of HS and dHS are displayed in Fig. 6 for the Martell snow pile. Note that HS and dHS shown in ~~Fig.~~Figures 6c,d,e were not corrected for remaining snow in the depot and for fresh snow covering the surface during the survey in autumn. The reason is that only few measurements or estimations of the correction values were available that might well be used for reasonable adjustment of mean values or total snow volumes but are inadequate for correction in high spatial resolution. Complementary to overall lower HS at the edges mentioned earlier, this fact ~~, explains many of the~~ contributes to the observation of negative HS at the edges of the heap (~~Fig.~~Figures 6c,d) and negative dHS in ~~Fig.~~Figure 6e. Contrary to Flüela, the geometry of Martell heap was much flatter and no such remarkable changes in surface characteristics, such as the formation of a plateau could be detected (~~Fig.~~Figures 6a,b). Same as for Flüela, aspect seems not to significantly influence dHS (~~Fig.~~Figure 7c). Moreover, ~~Fig.~~Figure 7d, does not suggest a clear relationship between dHS and slope.

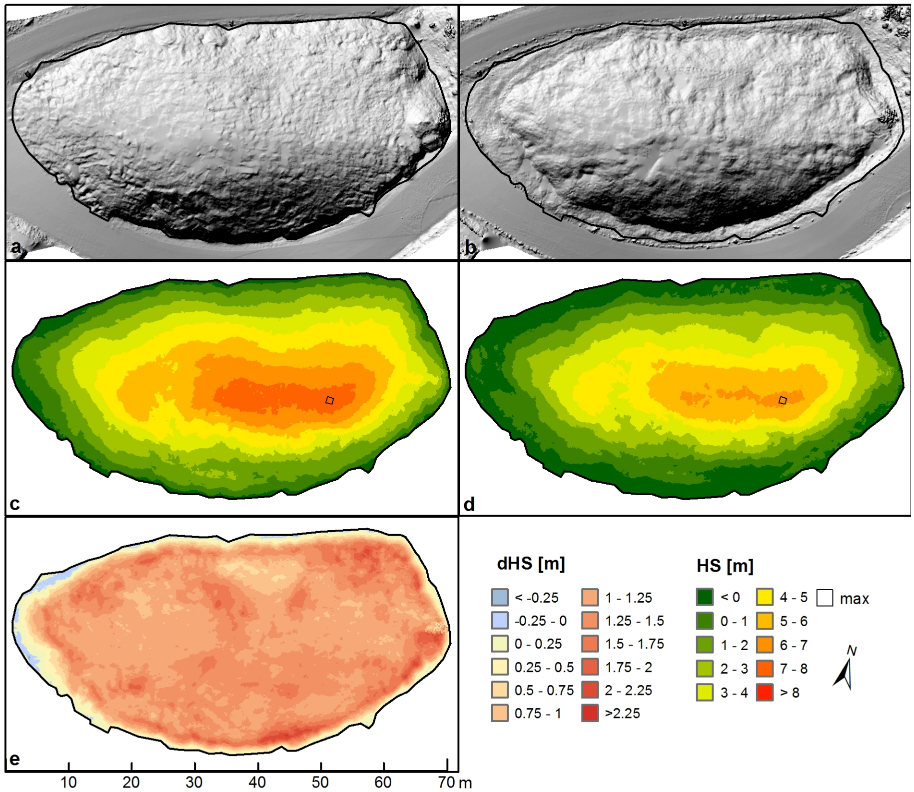


**Figure 6.** Martell snow heap: Hillshade images (a: 19 Mai, b: 28 Oct), snow depth HS (c, d) and snow height change dHS (e). Displayed are raw data that were not corrected for remaining snow in the depot (c, d) and fresh snow at the surface (d, e). The area of the maximum HS at the 19 Mai is indicated in c and d.

The calculated spring snow volume of the Flüela snow pile, including covering material was 6862 $m^3$ (Martell: 7138 $m^3$) and decreased to 5307 $m^3$ (Martell: 4820 $m^3$). This corresponds to a shrinking of 23% (Martell: 32%). If we relate volume reduction to the initial volume of snow after removing the estimated amount of covering material (Flüela: 830 $m^3$, Martell: 860 $m^3$), these values increase to 26% for Davos and 37% for Martell.

Nevertheless, it needs to be considered that volume loss and dHS are not only attributed to snow ablation but also to densification of the snow by settling. The density measurements described above point at a contribution of about 9%. This would mean that the effective snow ablation reduces to ~~15~~17% (28%) or – in other words that 72 to ~~85~~83% of the snow mass that had been covered in spring could be conserved over the summer. Note that some snow will additionally be lost during de-covering and distribution of the snow to the ski tracks.

Results obtained from measurements are compared to results of the SNOWPACK simulations in the next section. It is, however, not meaningful to relate model results calculated for a single point to volume changes for the entire snow pile. We therefore chose to relate model results to the respective coordinate (and settings of the model run) which are the locations

**Table 5.** Geometric properties and snow depth statistics of the Flüela and the Martell snow heap as calculated from the TLS surveys.

| | **Flüela** | | | **Martell** | | |
|---|---|---|---|---|---|---|
| | 29 Apr | 8 Oct | Difference | 19 May | 28 Oct | difference |
| 3D surface area [$m^2$] | 2087 | 1992 | | 2150 | 2094 | |
| Ground area [$m^2$] | 1685 | | | 1913 | | |
| Volume [~~$m^2$~~ $m^3$] | 6862 | 5307 | 1555 | 7138* | 4820** | 2318 |
| Relative loss [%] | | | 22.6 | | | 32.5 |
| $HS_{mean}$ [m] | 4.07 | 3.15 | 0.92 | 3.33 | 2.18 | 1.15 |
| $HS_{max}$ [m] | 8.99 | 7.86 | | 7.61 | 6.37 | |
| $HS_{sd}$ [m] | 2.64 | 2.25 | 0.52 | 2.14 | 2.0 | 0.39 |
| $dHS_{max}$ [m] | | | 2.70 | | | 2.32 |
| $dHS$ at $HS_{max}$ [m] | | | 1.35 | | | 1.25 |
| Relativ loss at $HS_{max}$ [%] | | | 15.1 | | | 16.6 |

*800 $m^3$ (remaining snow) added to raw data. ** 800$m^3$ (remaining snow) added and 126$m^3$ (fresh snow) removed. Details are described in Sect. 2.2.1.

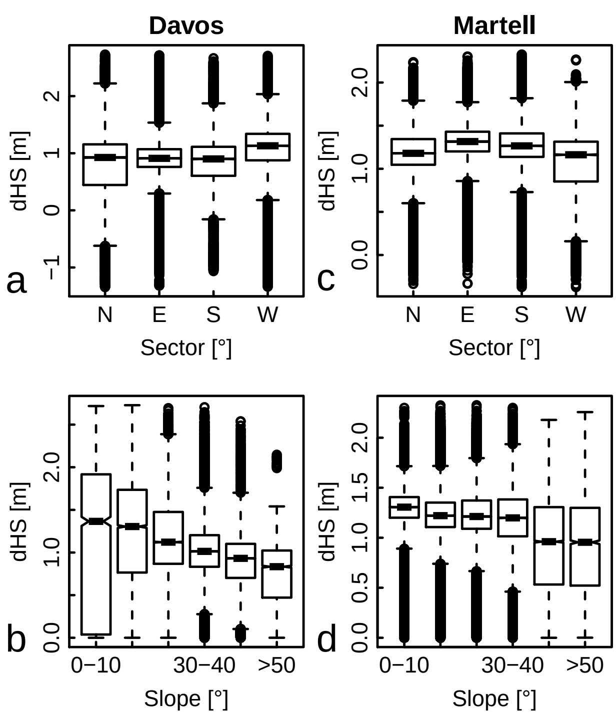


**Figure 7.** Boxplots relating dHS to ~~exposition~~ aspect (a,c) and slope (b,d) of the spring survey for Flüela (a,b) and Martell (c,d)

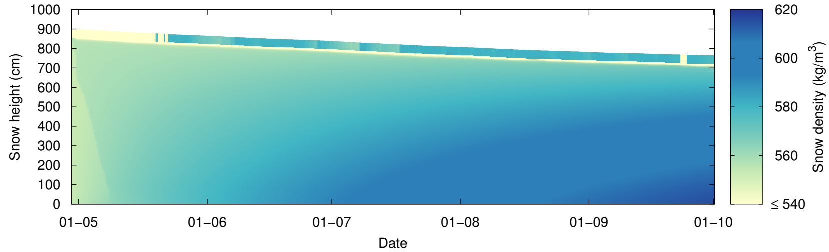


**Figure 8.** Simulated temporal evolution of snow height and snow density at the Flüela snow heap.

of maximal HS. A quadratic area of $1\,m^2$ surrounding this point was used for the calculation of measured dHS. At these areas the pile shrank by 1.35 m (standard deviation = 2.5 cm) at Flüela and by 1.25 m (standard deviation = 2 cm) at Martell corresponding to a relative reduction of $15.1 \pm 0.3\%$ (Martell: $16.6 \pm 0.2\%$).

### 3.4 Model results

Figure 8 illustrates the temporal evolution of HS and density of the 40 cm sawdust covered snow heap in the Flüela valley. The pronounced yellow line parallel to the surface reflects the lower boundary of the sawdust layer. The initial density of this layer (323 $kg/m^3$) rapidly increased in the first three weeks due to rising water content caused by rain (initial value 20%). Afterwards density and water content remained at a relatively constant level of about 580 $kg/m^3$ and 45% respectively meaning that the sawdust was always wet. Higher values cannot be reached due to a threshold in the model settings of the ~~soil~~ layer as described in Sect. 2.4. Liquid water fraction of the snow did not change considerably in relation to the initial 3%. This is attributed to the maximum water storing capacity of a snow texture which is implemented in SNOWPACK as derived from Lütschg (2005).

The height of the heap decreased steadily from 9 m to 7.60 m. This corresponds to a relative decrease in HS of 15.6% and accords extremely well with the result obtained from the measurements at the point of maximal HS. Results of the reference simulation are very similar for the Martell snow pile (not shown): Height decreases by 17.1% from 7.60 m to 6.30 m which is again an excellent match with the measurements.

Figure 8 also shows densification. It is well illustrated how snow is compacted from top to bottom and in the course of time. While simulations were initiated with a constant density of 553 $kg/m^3$, density at 8 Oct ranged from 570 $kg/m^3$ at the top to 617 $kg/m^3$ at the bottom of the profile. A comparison with the measurements presented in Section 2.2.2 denotes that the model overestimated snow density in the upper sections of the profile and underestimated it near to the bottom. The simulated bulk density of the entire profile was 600 $kg/m^3$. Hence, snow densified by 8% during the summer season. These values agree well with the mean density calculated from the measurements (606 $kg/m^3$, 9%). Surface temperature (TS) varied between 0 and 33°C for the reference scenario and showed a diurnal variation in the range of 5 to 20°C (~~Fig.~~Figure 9).

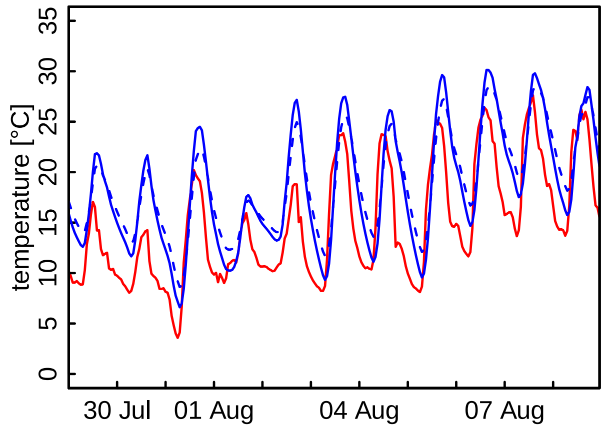


**Figure 9.** Air temperature (red) and surface temperature simulated for the Fluela snow heap with 40 cm (solid blue) and 20 cm (dashed blue) sawdust layer during four days in August.

### 3.5 Sensitivity study of depth of covering layer and meteorology

~~Figure 10 summarizes volume and mass losses of snow in dependence of the different settings (Table ) analyzed in the sensitivity runs. Black dotted lines present dHS and white triangles changes in snow water equivalent (dSWE). The difference pictures densification.~~

Figure 10a illustrates the influence of the depth of the sawdust layer. While the entire snow heap melted by mid of September when no covering layer was ~~set, dHS and dSWE respectively reduced to~~ used, dHS was reduced by 15.5% (dSWE: 7.2%) for the 40 cm deep sawdust layer (reference) and finally ~~to~~ by 11.1% (dSWE: 1.5%) for a 60 cm deep cover. The curves are characterized by an exponential decrease and are clearly flattening out at a thickness of about 40 cm. Reasons are that thicker layers decrease temperature gradients between snow surface and atmosphere. Doubling the height of sawdust, for example, reduces the gradient by a factor of two. As a result, energy input to the snow diminishes as more energy can be stored in the larger sawdust volume and thermal conduction to the snow decelerates. In addition, thicker covers add to dampening effects on TS as illustrated in Figure 9. Amplitude and extrema, especially minima are clearly enhanced for shallower covering layers resulting in higher TS during days and remarkably cooler TS during nights. Heating of the sawdust during the day and cooling during the night appears delayed by few hours. This results in regular changes of the direction of the energy fluxes at the saw-dust surface. On average, however, TS (13.8°C for 40 cm sawdust) appeared clearly warmer than TA (11.3°C) resulting in ~~a~~ net negative heat fluxes of sensible heat and longwave radiation. This mean temperature difference between surface and air clearly reduces for smaller sawdust heights (11.8°C for 20 cm), consequently diminishing cooling effects by sensible flux and longwave emission (Table 6). Once a cover layer is thick enough to prevent the surface temperature from dropping down significantly underneath the air temperature, the insulation of a snow heap works well. Having enough capacity (mass, specific heat) to store the energy during the day while not conducting much to the snow and releasing energy efficiently during night

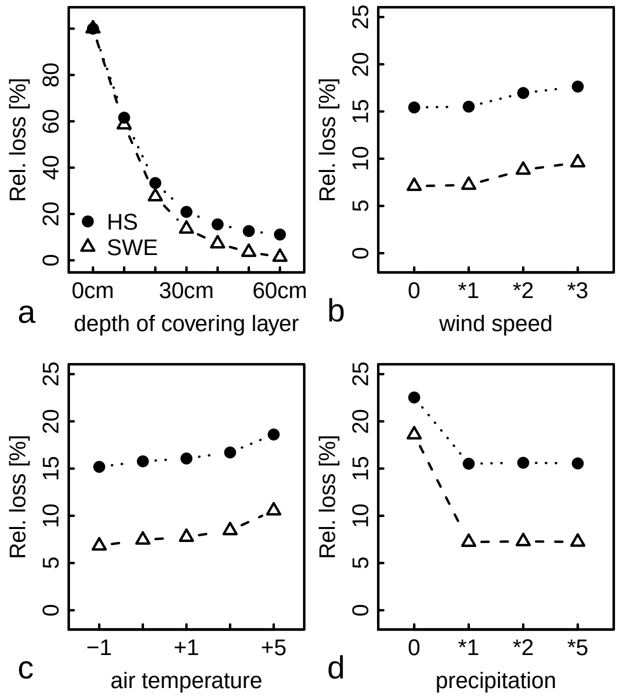


**Figure 10.** Relative loss of snow height (HS) and Snow water equivalent (SWE) calculated by SNOWPACK simulations with different thickness of the sawdust layer (a), different wind speeds (b), air temperatures (c) and precipitation (d).

can then be assured. Increasing layer thickness ~~upon~~ exceeding a certain limit shows only a minor improvements of insulation (~~Fig.~~Figure 10a). We assume that temperature gradients in the deeper parts of the cover are then no more affected by daily changes. Moreover, the relative increase of the layer decreases with thicker covers. ~~Finally~~In summary, Figure 10a indicates that a depth of about 30 to 40 cm is required to reach volume savings of 20 to 30% while the effect of additional sawdust is minor.

The contribution of the different terms of the energy balance at the surface of the heap is shown in Figure 11a and Table 6, where positive values designate a flux towards the heap (energy source) and negative fluxes a direction to the atmosphere (energy sink). Note that the terms as presented here are net values cumulated over the entire simulation period. The huge effect of the covering layer on snow ablation is best illustrated when comparing the energy balance of the reference simulation (40 cm, 5th column in ~~Fig.~~Figure 11a) to a run without any cover (1st column). In total, energy available for ablation is nearly twelve times higher for the simulation without cover. In detail, shortwave radiation is by far the largest source of energy (Table 6, ~~Fig.~~Figure 11). Due to the much higher albedo of pure snow, net shortwave radiation reduces by about $1/5$ without sawdust. Contrary, longwave radiation acts as energy sink for both simulations but is nearly ~~13times~~ 13 times higher when a 40 cm sawdust cover is present. All other terms of the surface energy balance, namely net sensible and latent heat fluxes and precipitation ~~differ~~ change in sign: While they contribute to melting without cover, they remarkably cool the sawdust-covered

**Table 6.** Net energy fluxes at the surface of the Flüela snow heap summed for the entire simulation period without and with a 20 and 40 cm sawdust layer.

| Height of covering layer | 0 cm | 20 cm | 40 cm |
|---|---|---|---|
| Shortwave radiation [~~$kJ/m^2$~~$MJ/m^2$] | ~~336.5~~1212 | ~~410.0~~1476 | ~~410.0~~ 1476 |
| Sensible heat [~~$kJ/m^2$~~$MJ/m^2$] | ~~74.2~~ 267 | ~~-50.0~~-178 | ~~-73.1~~ -263 |
| Latent heat [~~$kJ/m^2$~~$MJ/m^2$] | ~~23.5~~ 84 | ~~-26.0~~-94 | ~~-22.7~~ -82 |
| Longwave radiation [~~$kJ/m^2$~~$MJ/m^2$] | ~~-21.5~~ -78 | ~~-237.6~~-855 | ~~-275.6~~ -992 |
| Precipitation [~~$kJ/m^2$~~$MJ/m^2$] | ~~5.4~~ 19 | ~~-1.7~~ -6 | ~~-2.9~~ -10 |
| Sum [~~$kJ/m^2$~~$MJ/m^2$] | ~~418.0~~ 1504 | ~~95.1~~ 343 | ~~35.5~~ 1295 |

snow heap and therefore limit snow ablation. The highest effect is clearly attributed to longwave emission, but sensible and latent heat fluxes also contribute ~~remarkably~~substantially. Precipitation only plays a minor role.

The cooling effect of the latent flux is mainly attributed to ~~sublimation~~ evaporation at the moist surface of the sawdust. As this layer remained wet for the entire summer and for all simulations shown in ~~Fig.~~Figure 10a, sawdust thickness appears less relevant for the magnitude of this flux.

~~Finally, Fig.~~Finally, Figure 11a points out that rain, even though only marginally, adds to cooling of the heap, at least when the covering layer exceeded 20 cm. This can again be explained by temperature differences between the warmer sawdust layer and the colder rain.

In addition effects of changed atmospheric forcing, namely ~~VW (Fig.~~WS (Figures 10b, 11b) TA (~~Fig.~~Figures 10c, 11c) and P (~~Fig.~~Figures 10d, 11d) have been analyzed. ~~VW~~ WS is an important parameter especially affecting turbulent fluxes (Schlögl et al., 2016). Figure 10b shows that higher ~~VW~~ WS slightly altered snow ablation. Triplicating ~~VW~~WS, for example, resulted in an increase of dHS from 15.5 to 17.6%. Setting the wind to ~~zero that is equivalent to a constant wind speed of~~ 0.3 m/s ~~, as hardcoded in SNOWPACK,~~ reduced dHS to 15.4%. As expected, rising TA also altered snow ablation (~~Fig.~~Figure 10c). For example, an increase in temperature of 5°C added 25 cm or 3% in dHS. On the contrary, additional rain did not affect snow ablation significantly (Figure 10d). Even five times higher amount of rain did not change melt considerably (23% for dHS). The reason is the wetness of the sawdust layer that never dried as already described earlier. Switching of P completely, however, increases the snow loss considerably. Smaller difference between HS and SWE for the simulation without P can be explained by less densification of the snow due to reduced moisture content in the snow pack.

In conclusion ~~Figure~~Figures 10 and 11 clearly show the effects of the covering layer on the one hand and of the atmospheric forcing on the other hand. This underlines the high ~~correlation between sawdust thickness and~~ impact of sawdust thickness on energy available for snow melt. Higher ~~VW~~ WS and warmer TA also altered snow melt significantly while additional P did not play a decisive role.

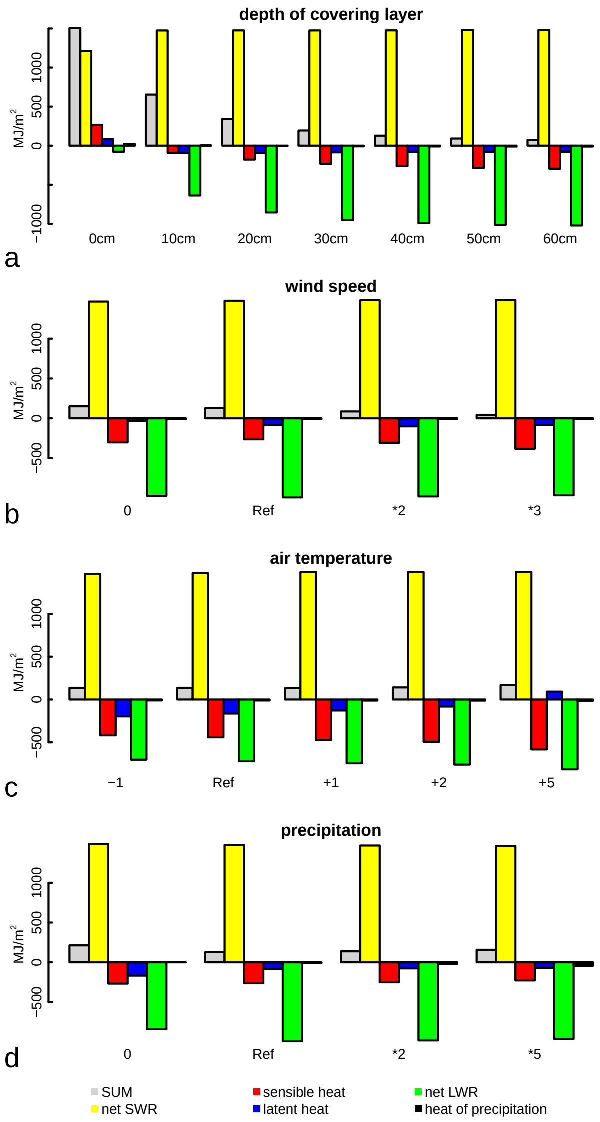


**Figure 11.** ~~most~~ Most important terms of the energy balance of the Flüela snow heap and their contribution to melt for the different model runs of the sensitivity study (a: depth of covering layer, b: wind speed, c: air temperature, d: precipitation).

# 4 Discussion

## 4.1 Data quality of the measurements and resulting error estimates

In general, we rate the accuracy of the snow volumes calculated from TLS data as very high. As described before (Sect. 2.2.1), short measurement distances, convenient scan angles, high point densities, and overlapping of multiple scan positions provide favorable conditions for a high accuracy of the measurements. Based on operating experiences with similar settings we estimate the vertical accuracy of the TLS measurements to about 1 cm. Nevertheless, scan shadows still caused some data gaps, especially at the crown of the heaps for the two surveys in autumn (~~Fig.~~Figures 5b, 6b). These data gaps were ~~determined~~ caused by a rougher surface such as local depressions. They had therefore to be closed by linear interpolation introducing some uncertainty. The extent of the gaps is, however, limited to few square meters, meaning that the effect on the total mass balance can be rated as marginal (below 0.1% if we assume an area of 10 $m^2$ mean deviation of 10 cm).

Another source of potential error is introduced by the lack of (accurate) bare ground elevation models. For Flüela no such model could be monitored but the flat and only slightly sloped ground area allowed for a good approximation with a sloped plane defined by the margins of the snow heap. For Martell, a bare ground elevation model was measured after most of the snow had been distributed in autumn. The remaining snow in the depot, however, could only be estimated based on visual impression and the rating of the local expert. As described in Sect. 2.2.1 we assumed snow volume to be in the range of 600 to 1000 $m^3$ and used 800 $m^3$ for the corrections. Applying the maximum or minimum estimates would reduce/alter relative snow volume loss by one to two percent. Nonetheless, this correction only affects snow volumes. Snow volume changes or dHS calculations do not require a bare ground elevation model and are therefore not concerned. Finally, thickness of sawdust and fresh snow were obtained from a limited number of probe measurements (see Sect. 2.2.1). Nevertheless, a bias of few centimeters would be small regarding its relation to the large volume and HS of the snow heaps.

When analyzing SWE instead of HS or volume, uncertainty in snow density measurements must also be considered. We showed that the range of snow densities was considerable (541 to 681 $kg/m^3$) with higher densities near to the ground. Throughout the storage period a ~~load and time dependent~~ load- and time-dependent densification must be assumed due to creep and wet snow metamorphism. As in spring only densities near to the surface could be measured, an adequate initial density profile with an expectable increase with depth could not be captured. This limits the capability to assess the temporal evolution of densification based on measurement but also from the simulation results as the initial snow profile had to be defined with a constant density.

## 4.2 Comparison of the sites

As described earlier, the results of the snow-volume measurements suggested large differences in terms of snow-volume loss between the two sites. While only 22,6% of the volume disappeared at Flüela, the decrease was more than 10% larger at Martell (Table 5). Considering the large similarity in terms of initial volume, surface area (Table 5) and also meteorological conditions (~~Fig.~~Figures 3, 4) this huge difference appears surprising. Possible explanations are different properties of the covering materials (see Sect. 2.1). If we, however, consider the very similar dHS at the position of maximal HS (15% at Flüela and 16% at Martell) and the fact that the simulations reproduced this amount very well, this explanation appears insufficient. A second possible reason is a potential warming effect of the black paved road at Martell (Fig. Figure 2) resulting in lateral advection of heat as described earlier (Mott et al., 2013)(Mott et al., 2013, 2015, 2017). The relatively high dHS near to the edges of the heap (Fig. Figure 6) supports this hypothesis. Other mico-meteorological characteristics, such as deviating local wind fields and their implication for energy balance might be present and could well also play a role. Unfortunately, due to lack of measurement stations directly at on the heaps, such effects could not be detected and therefore not proofed. An other explanation for increased melt could be insufficient covering of the heap at the edges. Areas with shallow cover were partly visible during our surveys.

### 4.3 SNOWPACK

The excellent agreement of measurements and model results indicates that SNOWPACK is well capable to reproduce dHS of sawdust covered snow heaps at the point scale. A direct transferability of these results to total mass loss of the heaps happening in the three dimensional space requires caution. As shown in Section 3.3 Sect. 3.3, the total mass loss was much higher than the loss measured and simulated at the point scale. Spatial effects such as variability of radiation and wind and lateral effects at the edges of the heap would need to be considered to simulate total mass losses. Distributed models such as Alpine3D (Lehning et al., 2006) could be used for this task but would require also more distributed information on meteorological forcing, which was not available in this study.

In principal, it needs to be considered that SNOWPACK incorporates some simplifications that might influence simulation results. Such, the sawdust cover represented The sawdust cover was modeled as homogenous layer, discriminated to eight elements in the model. Potential internal heterogeneity such as variable temperature or water content in the layer and its implication to energy balance are not considered. Furthermore, model outcomes are strongly influenced by the accuracy of the input parameters. For example, small-scale variability in meteorological conditions might be present at the test field but not be represented in the recorded meteorological measurements. Moreover, several initial settings such as sawdust properties and the initial state of the snow pack are only based on estimations or little limited measurements (see Sect. 2.2). However, sensitivity runs (not shown) that had been performed for the most important parameters (thermal conductivity, water content, texture of sawdust) showed no significant effect on the mass balance. Initial snow pack characteristics (density, water content) were more important but still only marginally changed final results.

## 5 Conclusions and Outlook

A detailed study on snow farming for touristic applications has been presented. Mass balances of two snow heaps covered with a 40 cm thick layer of sawdust and chipped woods wood respectively have been calculated from repeated TLS surveys in 2015. More than 75% of the snow volume of a 7000 $m^3$ snow pile could be conserved in the Flüela valley near Davos, Switzerland (Table 5). At the Martell heap, only two thirds of the snow remained in autumn, even though settings and conditions were quite similar at both study sites. We assume that this reduced performance is attributed to heat advection from a surrounding paved road or from insufficient cover thickness at some locations on the heap. Moreover, we applied the physically based snow cover model SNOWPACK to simulate snow ablation at the point scale. A comparison of measurements and simulation results showed excellent agreement: At Flüela dHS of 15.1% (Martell: 16.6%) was measured at the point of maximal snow height. Simulations of relative losses (15.6% for Flüela and 17.1% for Martell) were only marginally higher. In summary, the magnitude of these results is well in line with operating experiences of different snow farming sites (12-50%).

Snowpack simulations were also applied to analyze the contribution of the different terms of the energy balance to snow ablation (Fig.Figure 11). It could be shown that shortwave radiation was by far the most important source of energy. Sensible and latent heat fluxes also contribute to melt if the snow heap was not protected by sawdust. The presence of such a covering layer, however, led to an inversion of the seasonal net fluxes of sensible and latent heat now contributing to cooling of the snow heap. The largest cooling effect was attributed to longwave emission at the surface of the sawdust. This insulting layer absorbs the solar energy during the day but strongly limits conduction to the snow. During night the absorbed energy is then emitted by longwave radiation. Such, about $2/3$ of the net energy input by solar radiation is compensated by long wave cooling. Additional 18% are balanced by net sensible and 6% by latent heat fluxes. In summary, only 9% of the net shortwave energy input remained available for snow ablation. The high amount of snow conserved over the summer is therefore attributed to these cooling and insulating effects of the covering layer. Moreover, the high influence of the thickness of the sawdust was evident from the simulations. The larger the covering layer, the smaller the temperature gradient and such therefore the heat flux into the snow. This increased insulation effect finally results in the higher amount of snow that can be conserved. The excellent insulation of sawdust is primary given by its high density and heat capacity rather than by its heat conductivity (factor two higher than conductivity of PP-insulation plate). This enables the sawdust to absorb large amounts of heat being re-emitted during night. Still, significant costs of sawdust and additional work load need to be considered when deciding about layer thickness. 40 cm seems a good compromise.

Finally, effects of varying meteorological conditions, namely VWWS, TA and P have been investigated. As expected, it could be shown, that higher TA and VW WS enhance snow ablation. Nevertheless, a resulting increase of a few percent appears small in relation to the effect of covering layer thickness. This finding points out that snow farming might also be feasible under much warmer climatic conditions indicating that it might also be applicable for lower situated, sub-alpine ski resorts and communities. Additional precipitation did not play a significant role, as the sawdust remained wet during the entire summer for all scenarios with rain. Switching off rain completely, however led to a clear increase of snow ablation. As a consequence, irrigation of snow heaps, as suggested by some practitioners, seems unnecessary as long a certain amount of rain is available.

In conclusion it could be shown that snow farming appears as appropriate method for the allocation of a basic snow offer in autumn. However, operating costs and space requirements are considerable limiting the amount of snow that can be stored. SNOWPACK proofed Operational costs have to be evaluated for each snow farming project specifically considering the applied technical and logistical solutions. For example in Davos 15 CHF per $m^3$ snow were estimated for the first snow farming project in 2008. Till 2016 these costs could be strongly reduced to about 9 CHF per $m^3$ thanks to larger snow volumes stored and improved infrastructure and work flow. Investments for structural measures at the storage location are not considered in this calculation. Two thirds of the expenses were caused by the distribution of the snow along the cross-country track followed by the removal of the saw dust (14%) and material costs for saw dust (10%) , assuming a five year operational live-time (Norbert Gruber and Werner Putzi personal communication). Generally, it can be stated that snow production costs are minor compared to covering and especially distribution costs and therefore cost-efficient snow farming remains limited to applications, for which technical snow production is impossible or too risky because of weather uncertainties.

SNOWPACK proved as appropriate simulation tool and can well be applied to study the suitability of potential snow farming sites, or to asses performance of different covering materials (see also Olefs and Lehning, 2010) or to simulate influences of changing climatological conditions on snow farming. The only prerequisite is the availability of adequate meteorological input data. Spatial distributed models such as Alpine3D could be used to investigate spatial effects. The application of multiple different snow models could be interesting to assess model sensitivity and uncertainty. Future research might also include detailed surveys of other snow farming projects, possibly in higher temporal resolution or the investigations of mass losses during different work steps, such as shaping or de-covering of snow heaps. Investigations of different types of covering material are currently running in Scandinavia and will contribute to knowledge about best practice of snow farming.

*Acknowledgements.* We are grateful to all people who contributed to the successful completion of this paper. We want to thank your reviewers, J. Garvelmann, S. Fassnacht and B. Nordell for their very positive and constructive suggestions. Norbert Gruber, Werner ~~Buzzi~~ Putzi (Davos) and Martin Stocker (Martell) are acknowledged for the good collaboration during field work and for fruitful exchange of ideas. We thank Thomas Rinderer for his work, providing many basic information for the simulations. We thank Mathias Bavay and Charles Fierz for their help with SNOWPACK, Nander Wever, Hansueli Rhyner and Rebecca Mott for their support and for good discussions. Parts of this study were conducted in the framework of the Swiss Competence Center for Energy Research - Supply of Electricity (SCCER-SoE) with funding from the Commission for Technology and Innovation CTI (grant 2013.0288).

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