Dear editor and reviewers

Many thanks for your constructive comments. We have worked on the manuscript with the following main changes:

- The introduction was newly written emphasizing on studies in complex terrain with only minor vegetation effects on snow distribution and including a larger diversity of studies to this topic
- We are now focusing more on the missing correlation between HS0 and dHS as well as on explanations for this missing correlation. For this a new set of figures was included showing the correlation between HS0 and dHS (Fig. 5 c-e). For the same purpose, we were also deleting some paragraphs (e.g. the comparison with other studies, which is now more concisely mentioned in the introduction, as well as the regression analysis)
- With the gained knowledge at this site we formulated prerequisites for a strong correlation between melt and SWE in other areas. With these paragraphs we think we can show that we do not show only nice data from a new study site but that we can learn something from this high-resolution data set which is useful for the development of models and the design of further investigations on this topic

Point-by-point response to the reviews

Reply to reviewer 1

We thank the reviewer for the constructive comments. We copied the reviews comments in this reply for a better readability and marked them using italic fonts.

General comments
The objective of the study is to analyse factors which control areal snow ablation and snow cover depletion in a small study area in the Canadian Rocky Mountains. The analysis is based on very detailed maps of snow depth and snow depth differences obtained by several flights of UAV in one winter season 2014/2015. The results indicate that ablation rates differed in space and were mainly related to the spatial patterns of solar irradiance and albedo. The most important factor controlling snow cover depletion was the initial distribution of SWE, which was five time s more variable than melt variability. The authors conclude that in near summer solstice conditions the snow cover depletion curves can be calculated only from SWE spatial distribution. Generally, the topic of the manuscript is interesting and within the scope of the journal. The manuscript has a good structure and is clearly written. However, the analysis is based on only a few observations in one winter season, so the significance and generality of results are rather small. This is very well documented by the authors, who conclude that: ". . . clear advice to modellers is still not possible" and "Thus longer time series of spatially detailed SWE observations need to be made . . .".

Moreover the methodology used (UAV snow depth mapping) is not new.

We agree with the reviewer that there are papers on UAV snow depth mapping, but mainly on the accuracy of this method. This is one of the first using this methodology to answer snow-hydrological questions.

These facts raise a question whether the presented results provide a significantly novel contribution satisfying the HESS requirements for a scientific paper. In my opinion, the presented results are in its current form rather premature and more systematic and longer datasets are needed to justify interpretations made and to allow a transferability of results to other regions.

The novelty is given with the high-resolution data set. Since snow depth is known to vary largely below a scale break of tens of meters in alpine environments we think that a replication of studies which relied on manual probing in a much coarser resolution is needed. Manual probing with a spacing at or larger this scale break may complicate the interpretation of the results (Clark et al., 2011), since the dominant spatial structure can hardly be captured. A similar high resolution data set was only presented by Grünewald et al. (2010) and Egli et al. (2012), which only covers one study region and two different seasons. A replication of these studies to other areas is urgently needed to show the transferability of results. Furthermore, we present an explanation on the missing correlation between SWE and melt. This is now more precisely mentioned in a more focused way in the revised manuscript.

While we feel that this paper makes a significant movement forward in our understanding of the relationships between snow accumulation and snowmelt patterns at multiple scales, final answers can only be given if more replications like this study are available. Given the large effort in field data acquisition and processing of this high-resolution data set to good quality levels (the signal of a melt period needs to overcome the noise) and the rare availability of long melt events without snowfall, this can only be a stepwise process. However, this study may initiate more replications with indicating the urgent need for this to better guide snow-hydrological model design.

During our field work in 2015 there was nearly no knowledge of the spatial noise inherent to this method. Thus, we ended up with more field days than in the final paper (9 days instead of 5). Since the noise is site and weather dependent, as well as the signal, i.e. the melt amounts, also in 2018 we would probably include much more flight days than what can be finally use. Post-processing of one field day can be done within one day, however, only if the data is acceptable with standard settings. In our case, it took us several days to achieve acceptable data quality with changing post-processing settings. This shows the tremendous effort to achieve good results, which implies that single studies using this technology can only add to existing knowledge.

We formulated prerequisites for a strong correlation between melt and SWE in other areas. With these paragraphs we think we discussed the transferability of these results to other regions.

1) I found a little bit confusing connecting snow depth change directly to snow water equivalent. How valid/uncertain is the assumption of uniform snow density at 10cm spatial scale?

First of all we only use HS and dHS in the final manuscript. However, this still implies that they can be used as proxies for SWE and melt. In the newly written introduction we point to other studies which rely on spatial model results. Spatial modelling of snowmelt in complex terrain inherits a large amount of uncertainty. For example, energy balance modelling relies on assessment of turbulent fluxes, which is dependent on local wind fields. Those wind fields in complex terrain are very difficult to estimate (e.g. Mott et al., 2010; Musselman et al., 2015). To be independent of model uncertainties, we chose semi-direct measurements of melt and SWE. These also have uncertainties, e.g. one has to either apply no density (depth only) or just a few density measurements or modelled densities. However, it is well known that snow depth varies to a much larger degree than density (e.g. Pomeroy and Gray, 1995; López-Moreno et al., 2013). As a consequence, it is common to estimate areal SWE with a small number of representative density measurements and a high number of snow depth data (e.g. Steppuhn and Dyck, 1974; Pomeroy and Gray, 1995; Rovansek et al., 1993; Elder et al., 1998; Jonas et al., 2009). We were able to take a few SWE measurements, but we did not multiply dHS with snow density to estimate the ablation rate, because we think that our SWE measurements were neither representative for the whole area nor for the time between the measurements. This is why we analysed and interpreted HS and dHS as proxies of SWE and ablation rate.

This does not answer your question on snow density variations at a 10 cm scale. There are very few measurements assessing the density variability at smaller scales. For example, Proksch et al. (2015) showed SnowMicroPen measurements along a transect with 0.5 m spacing in the Antarctica (cp. their Fig.

12), which shows density variations resulting from different deposition and metamorphic processes. Given this lack of knowledge, we think that in our study region, which has large differences in HS and rather deep snowpacks, density differences are mainly driven by larger scale deposition processes (~tens of meters) rather than smaller scale metamorphic processes driven by e.g. summer terrain or vegetation differences as it may be the case in shallow snowpacks. Thus, we suggest that the results of López-Moreno et al. (2013) also apply in our study area at the 10 cm scale as an increase of variability of density at this scale seems unlikely.

2) P.7, l.27: ". . .increase? of R2". Please check.

Many thanks for finding this error. However, we decided on excluding the topic stepwise regression in the revised version.

3) Fig. 5. Perhaps consider to switch x and Y axes (to plot dHS on Yaxis as a prediction variable). Is a simple linear relationship robust enough?

We will switch the axis and delete the regression lines. A new Figure 5 including the relationship to HS0 was requested by reviewer 2.

4) References: I understand that the authors wrote many papers about the subject and are expert in the field, but I feel that the references are too biased to their own work. I wonder whether all the cited works of the authors are really relevant for the topic and/or if there are some other relevant studies evaluating snow cover depletion curves and factors controlling them on different scales.

The introduction has been changed substantially following this comment and the suggestions of reviewer 3. This will include a diversification of cited authors, as well as focusing on relevant work for this topic.

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Reply to reviewer 2

We thank the reviewer for the constructive comments. We copied the reviews comments in this reply for a better readability and marked them using italic fonts.

The study of Schirmer and Pomeroy used high-resolution aerial photographs of a mountain ridge to determine the spatial distribution and height of the snowpack (HS) during the melt season. Several surveys were undertaken at different times and the differences in snow height measurements (dHS) were used as proxies for ablation. The spatial patterns of ablation (dHS) was compared with pre-melt snow water equivalent (SWE, measured manually) and several topographical variables. Albedo (i.e., brightness of the snow) and solar radiation differences (i.e., deviation from North or soral irradiance) were identified at the dominant controls on dHS, whereas there was no correlation between dHS and initial SWE. The authors explain this lack of correlation with the difference in spatial scales at which dHS and initial SWE are affected by topographic and climatic variables. The high-resolution measurements of dHS further allow to estimate the spatio-temporal variability of ablation. The authors find that the variability in ablation (dHS) is much smaller than that of initial snow depth (HS0). Consequentially, snow cover depletion curves (SCD) are less sensitive to the spatiotemporal variability of ablation and most sensitive to the HS0 of the area. The authors show this by determining and comparing SCD's from combining either uniform or variable initial HS0 with uniform or variable dHS.

The high-resolution data set of spatial snow depth distribution is unique and potentially allows interesting analyses, however, I find it difficult to identify the novel scientific contribution of this study. One of the main findings, that initial snow depth (HS0) is not correlated with changes in snow depth over time (dHS) is only briefly mentioned in Sect. 3.3.

This and finding an explanation for the lack of correlation is a focus in the revised manuscript.

The second finding, SCD curves for the study area are largely affected by HS0 and less by dHS, has been studied extensively previously (P2L21-24, P3L31-32). I would thus recommend to revise the manuscript in a way that brings out the novelty of the authors' findings more clearly and to help the reader to learn something.

The novelty is given with the high-resolution data set. Since snow depth is known to vary largely below a scale break of tens of meters in alpine environments we think that a replication of studies which relied on much coarser manual probing is needed. Manual probing with a spacing at or larger this scale break may complicate the interpretation of the results (Clark et al., 2011), since the dominant spatial structure can hardly be captured. A high resolution data set was presented by Grünewald et al. (2010) and Egli et al. (2012), but only covered one study region and two different seasons. Testing of these studies in other areas is urgently needed to show the transferability of results. Furthermore, we present an explanation on the missing correlation between SWE and melt. This is now more precisely mentioned in a more focused way in the revised manuscript.

In addition, the language of the manuscript needs to be improved as some sentences are confusing and hard to understand (e.g., p11L27: "However, no study showed consistent and persistent fine-scale association between ablation and SWE suggested that they can be considered uncorrelated in modelling at fine scales."). Please find some more detailed comments below.

We have revised the language throughout the manuscript.

Introduction:
P2L30 – P3L33: It is difficult to follow the authors' train of thought here as this paragraph seems like a random collection of studies without an overarching theme that help the reader to get to the same conclusions as the authors. Is the overall point of this paragraph to show that SWE and melt are variable over time and space or that it is challenging to determine an accurate SCD curve? If so, it would help to state this as a theme at the beginning of the paragraph.

We have re-written the introduction to focus on studies with minor vegetation effects on snow depth distribution and on found correlations between SWE and melt.

Please explain briefly what a SCD curve is.

Done (p. 2 l. 19f).

Methods: 2.1 Site description: Why was this study site chosen, given that the snow distribution was strongly affected by ski slopes and strong winds?

We have written a better explanation on why we chose this study area (new section 2.1). The strong winds were the attractive point of this location. The skiers influence was small and spatially limited so that impacted zones could be excluded in the study area.

2.2 UAV Data acquisition: please don't use abbreviations in the headings or write as "Unmanned aerial vehicle (UAV) data acquisition"; How many flight were made in total? Can you please provide the dates of the individual flights in this section?

Done as suggested. The UAV was flown 18 times over snow from 15 May to 24 June 2015 at eight different days with substantial depth differences between these days and four flights over bare ground on 24 July 2015. However, as stated in the manuscript, we had to restrict analysis to two melt periods.

Your statement on p5L20 is not clear enough: "Ideally, four flights in total were made each sampling day, two for each subarea with perpendicular flight plans. Weather conditions and technical problems often allowed only a part of this program."

We have clarified this topic and now mention why perpendicular matter, why subareas were defined, and what weather conditions and technical problems restricted the surveys.

2.3 Accuracy evaluation and manual measurements: From this description of the methods I understand that for each (4?) sampling day, snow depth and density (i.e., SWE) were measured at up to 7 locations over the entire field site. Were these SWE estimates assumed to be representative for the times between measurements? Did you multiply snow density with dHS to estimate the ablation rate? This is not at all clear from your statement: p6L5-9 "At these GPS measurement points, snow depth was also manually measured and snow density was measured at approximately each third of these points. Density measurements were not sufficient to confidently estimate SWE from snow depth into SWE and ablation rates from differences in snow depth. As such the originally measured quantities are analysed and interpreted as proxies for ablation and SWE in the text." Also, what do you mean by "originally measured quantities"? Please be more precise.

We have clarified this in the revised manuscript. We did not multiply dHS with snow density to estimate the ablation rate, because we think that our SWE measurements were neither representative for the whole area nor for the time in between the measurements. This is why we analysed and interpreted HS and dHS as proxies SWE and ablation rate.

Results and discussion: 3.3 Spatial differences in dHS: It would be nice if you could also provide the correlation results for the remaining variable Slope, as well as the p-values for all correlations, for completeness (Table 1).

We have included slope. P-values are not very meaningful for these large numbers of observations since statistical significance is almost always achieved.

In Section 3.3. you use dHS (change in snow depth) equivalent to melt (or ablation), although nowhere before was explained what this assumption is based on and how melt was estimated. This important bit of information only comes later (Sect. 3.4, P12L28-30); please include this description into the Methods section. Also, if you simply multiply HS and dHS with a uniform and temporally constant snow density, the variability of the resulting SWE values and melt volumes are the same as for HS and dHS multiplied by snow density.

We used the words melt and SWE for a better readability in the original submission, lines P12L28-P13L2. However, in the revised manuscript we will only use the “words” dHS and HS.

P11L29-32: Your main finding, that is that initial HS is not correlated with dHS, is somewhat hidden in section 3.3. Given that this is a major result of your study, I would suggest to include a figure similar to Fig.5 that actually shows this lack of correlation.

This is done as suggested.

Also, your conclusion “These values indicate much larger SWE variability than ablation variability in this period.” is equivalent to a larger variability of HS relative to dHS (in other words: the relative standard deviations of HS and dHS are same as for SWE and melt volumes). Thus, it seems confusing to use SWE instead of HS and melt instead of dHS, because SWE and melt are not measured the same way as HS and dHS.

In the revised manuscript we only use HS and dHS.

Minor comments:
- P4L5: What results of what models? A reader not familiar with snow hydrology literature has no idea what it meant by that.

We have re-written the introduction to address this.

- P6L18: Please explain what SfM means.

The abbreviation SfM was explained in P4L15.

- P11L24: “The correlation of. . .” What? “. . . with. . .”

This is included in the revised manuscript. The correlation of dHS with …

- P16L22:
“. . .varying exposures of vegetation, which is not a factor in this study.” Earlier in the manuscript you state that vegetation has a strong effect on snow distribution. Please explain.

We have indeed written in P4L29ff that vegetation had an effect on snow distribution, but that these areas were exluded from the analysis. We will change the wording to clarify this topic.

- P7L27: Shouldn’t it be “decrease of R2”?

Yes, many thanks for finding this error.

- P12L23: “Relative importance of ablation and initial SWE” Relative importance for what?

Many thanks, we will change this into Relative importance of dHS and HS0 on snow cover depletion.

Reply to reviewer Charles Luce

We thank Charles Luce for his detailed review.

This paper examines whether uniform melt assumption applied to depletion curves is reasonable for a site in northern Canada. It takes a bit of reading to figure that out, but that is the essential scientific contribution being addressed.

Unfortunately, 1) it is not framed in the context of other related work showing how replication can be used well to advance the science in this particular area, and 2) there are a few questions about the statistical and sampling procedures that require addressing. These problems could be addressed with some effort.

The most important issue is that the paper does not make a strong or compelling argument for its primary purpose or the need to replicate earlier experiments. It could be written more efficiently so that the primary scientific contribution was more prominent and readily apparent. The purpose is described in the paper as "determine factors which influence areal snow ablation patterns in alpine terrain," which is a bit vague and overarching, and the paper does not fully accomplish that task. The abstract and introduction spend most of their opening lines on the general subject of heterogeneity in snow without narrowing down to the specific issue addressed in this paper. The paper eventually goes into some depth in the introduction about depletion curves and relative contributions of melt versus accumulation variability. This is a good subject and an important subject in this field. As the authors note in P4L2-5 this is still a debate for the modeling community. An important question for the authors is why one would raise this question on Page 4 and not Page 1. Upon raising the question then, it is important to bring to bear the various answers and measurements contributing to that uncertainty already in the literature.

If better framed, the introduction should also address the need for replication of experiments on this subject in multiple places. The primary problem here is that the background material presented is by-and-large based on citations of their work or that of close colleagues. This is maybe fine for a general discourse or more obviously unique contribution. However, if one needs to make a case that more replication is needed on a subject, one needs to make a specific effort to find as much of the related literature as can be reasonably applied and explain why this particular replication is useful.

I'll pick on one citation that is already used for a different subject (general heterogeneity), but which has a nearly identical conclusion as this paper, Luce et al. 1998. We stated several times and in various ways:

"This result implies that spatial variability in snow drifting has a greater effect on the behaviour of Upper Sheep Creek than spatial variability in solar radiation and temperature."

It would be great to discuss this and the four related papers also giving similar findings on P3L29-31 in more detail and explain why measurements in more places are useful to answer the questions brought up 3 lines later. Without some explanation (e.g. that these conclusions were derived based on only 4 sites) the lines saying that the answers are unclear following four (now five) articles that agree with each other seems almost contradictory. There is some text in the preceding page-long paragraph that describe some differences in findings, but again one has to tease out that apparently one set of findings is from forests and one from windswept areas.

I think it quite reasonable to summarize from the antecedent papers that the relative dominance of accumulation versus melt processes varies from place to place, and that adding information about another location to that list, particularly with some more detailed physical insights, could be useful. Certainly, one could bring up that there might be more value in a synthesis (e.g. along the lines of Clark et al., 2011) when trying to sort through that problem, but that requires many sites to have been sampled. Page 19 Lines 1-4 present the key problem needing to be addressed. One would hope that the paper advances the theory and process understanding necessary to solve this problem rather than simply presenting one more example, however. It looks like there is capacity to do so with these data, but I'm not entirely certain. A well written introduction could probably narrow the subject enough that one could ask whether the finding that accumulation distributions are more important than melt distributions is a general finding for windswept sites with primarily low vegetation, or whether there are other contextual variables or information that would alter that simple generality? Alternatively, is there capacity to explore processes or causes for the lack of correlation

that might otherwise be expected? For example, is the cause of low correlation a result of 1) the high sun angles during the melt, 2) dust deposition mirroring snow deposition (e.g. a process likely to cause a positive correlation between melt and accumulation anomalies), or 3) substantially greater variability in accumulation than in melt as might be predicted from an area dominated by low slope angles and southerly and windward aspect?
At least some degree of coherent synthesis is necessary to support the addition of another paper on this subject that shows results similar to others. The heavy reliance on one or two heritages for many of the citations throughout the paper hobbles it considerably. Many of the papers cited in Clark et al., 2011 have information relevant to the discussion in this paper, and there are a number of others. There is also a need to become better acquainted with the literature. Some papers are cited for one thing when they are more relevant for another argument, or even several throughout the paper. There are also several citations in the paper (of the authors own work) that provide relatively poor support of their sentence compared to other well-known work.

With respect to the analysis of correlation between HS0 and dHS, only Pearson (linear) correlation is tabulated. It would be useful to see the plots and better understand the causes for the apparent lack of correlation.

We have re-written the introduction to implement the suggestions by this reviewer. For example, we have narrowed the introduction to focus on alpine studies with primarily low vegetation. We added other related work as this reviewer suggested and discussed their findings in more detail in the introduction. We emphasized why a replication at this site is meaningful and instructive. The additional benefit of this contribution is now more clearly written: The novelty is shown in using high-resolution data set to permit multiscale analysis. Since snow depth is known to vary mostly below a scale break of tens of meters in alpine environments we think that testing previous coarse resolution manual probing based studies with high resolution observations was needed. Manual probing with a spacing at or larger this scale break may complicate the interpretation of the results (Clark et al., 2011), since the dominant spatial structure can hardly be captured. Similar high resolution datasets have only been presented by Grünewald et al. (2010) and Egli et al. (2012), and they covered only one study region. Testing in other areas was urgently needed to show the transferability of results. Furthermore, we present a novel explanation on the missing correlation between SWE and melt. This is now more precisely mentioned in a more focused way in the revised manuscript.

Grünewald et al. (2010) and Egli et al. (2012) were not able to provide an explanation about the lack of correlation between HS and dHS. We now contribute with an explanation why uniform melt is applicable at multiple scales at this site in southern Canada. Doing this we explored the causes of the lack of correlation as Charles Luce requested. The observed scale difference between melt and SWE prohibits a large correlation between both. Snow depth varies in this area on smaller scales than melt differences driven by aspect differences, which are the typical melt energy differences included in spatial models. Only small scale albedo differences (quite untypical for this and other areas) were responsible for small scale variations in melt. The short scale break in snow depth has been reported by other studies as well. The open question is if melt is in general a spatially much smoother field than HS in alpine areas. This can only be answered if more high resolution studies become available in other mountain regions to confirm the strong results shown here. Given the large effort in field data acquisition and processing of this high-resolution data set to a good quality (the signal of melt periods needs to overcome the noise) and the rare availability of long melt events without snowfall, this can only be a stepwise process. However, this study may initiate more replications by indicating the urgent need for this to better guide snow-hydrological model design.

To better focus on the lack of correlation between melt and SWE we changed the results section and included a figure showing the lack of correlation between HS0 and dHS. We also deleted parts less relevant for this main conclusion, e.g. the stepwise regression results.

There is a great deal that should be explained about the potential effects of the sampling on the results. On P8 L17-19: In addition, one can note that the ESE wind direction is subparallel to the main ridge line. Would this have anything to do with the results?

Also from Figure 2, most of the area does not look to be particularly steep, and it is by and large south facing. These do not seem like circumstances that would be likely to produce substantial variance in melt.

The wind directions varied widely and sometimes where perpendicular and sometimes parallel to the ridgeline – that variability is a characteristic of this region as it is subject to westerly Chinooks, cold northerly flows and wet upslope flows from the east. The area includes an initial snowcovered area which is steep with varying aspects, although the east aspect is overrepresented (Fig 2b). The two large drifts visible in Figure 3d have a southerly component and are over 30 degrees steep. The Northwest facing slopes of the ridge are similarly steep. Flat parts are on top of the ridge which is only partly snowcovered, mostly in the southern part of the study area. In contrast to Grünewald et al. (2010) we observed spatial melt differences to be dependent on aspect and slope (Figure 5b). We have included Figure 2c showing the slope distribution of the initially snow covered area to make this more clear.

Furthermore, most of the winds are from the south-ish, implying an expectation of relatively more scour on much of the area with only a few subdrainage/subridges causing enhanced deposition (Figure 3c) with only a little participation by the main ridge, and there mostly with slightly south facing (?) areas.

We do not fully understand this point. The winds were from the north and the south and also along the ridge. The south face had massive snow drifts and was not scoured.

And in Figure 3d, only a few areas are really analyzed. Given that areas with shallow snow tend to have more vegetation poking through (northern part of 3d), it seems like a lot of the locations with shallower initial snow are excluded from the analysis, and it is hard to sort through the impacts of that choice in finding a correlation between initial snow depth and melt rate.

We excluded vegetation effects independently from snow depth appearance, for the included area vegetation played no role as it was bare ground before the vegetation period allowed to grow a few centimeters of alpine grass. This is now more clearly stated. There were many sites with shallow snow to begin with.

On P7 L22-24: Stepwise regression is a notoriously poor method for model selection. See Burnham and Anderson (2002), for example. I would not be surprised to see similar results from a more formal model selection procedure, but it seems important to use our best understanding when applying statistics.

We agree with the reviewer to apply more appropriate statistical methods. Following the reviewers suggestions to focus on the main results, we have deleted this paragraph.

P2 Lines 8-10 appear to contradict lines 10-12. Lines 10-12 apply only to the special case where wind deposition occurs on multiple aspects.

We have clarified this topic.

P19 L5-9: I would like these authors (and, to be fair, a large number of other authors) to comment on how more time series in one place help us to transfer models to other places. This seems to be a fundamental underpinning of modern hydrological science as it is practiced, and I have not been presented with much in the way of evidence to support it.

In Fortress Mountain there are only a few papers existent as this is a rather new study site and no previous papers have studied this topic there. We also try to discuss the potential to extrapolate our results. Moreover, as discussed above, we see this study as an initiation of new multiscale studies in other areas where airborne snow depth data is available.

~~Factors influencing spring and summer areal~~Processes governing snow ablation ~~and snowcover depletion~~ in alpine terrain~~: detailed~~. Detailed measurements from the Canadian Rockies

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Abstract

The spatial distribution of snow water equivalent (SWE) and melt are important to estimating areal melt rates and snowcover depletion dynamics but are rarely measured in detail during the late ablation period. This study contributes ~~the result of~~results from high resolution observations made using large numbers of sequential aerial photographs taken from an Unmanned Aerial Vehicle on an alpine ridge in the Fortress Mountain Snow Laboratory in the Canadian Rocky Mountains from May to July. With Structure-from-Motion and thresholding techniques, spatial maps of snow depth, snowcover and differences in snow depth (dHS) during ablation were generated in very high resolution as proxies for spatial SWE, spatial ablation rates, and snowcover depletion (SCD). The results indicate that the initial distribution of ~~SWE~~snow depth was highly variable due to overwinter snow redistribution and the subsequent distribution of ~~ablation rates~~dHS was also variable due to albedo, slope/aspect and other unaccountable differences. However, the initial distribution of ~~SWE~~snow depth was five times more variable than that of subsequent ~~ablation rates, even though ablation differences were substantial, with variability~~dHS values which varied by a factor of two between north and south aspects~~, and~~. dHS patterns were somewhat spatially persistent over time~~. Ablation rate patterns~~ but had an insubstantial impact on SCD curves, which were overwhelmingly governed by the initial distribution of ~~SWE~~snow depth. The reasons for this are that ~~variations in irradiance to slopes on north and south aspects in the~~

~~near-summer solstice period are relatively small and~~ only a weak spatial correlation developed between initial ~~SWE~~snow depth and ~~ablation rates~~dHS. Previous research has shown that spatial correlations between SWE and ablation rates can strongly influence SCD curves. ~~The results presented here are in contrast to alpine, shrub tundra and forest observations taken during ablation at higher latitudes and/or earlier in spring but in agreement with other near-summer observations in alpine environments. Whilst variations in net solar irradiance to snow were due to small scale variations in localized dust deposition from eroded ridgetop soil and larger scale differences in slope and aspect, variations in SWE were due to intense over-winter blowing snow storms with deposition from multiple directions of snow transport to incised gullies and slope breaks. This condition differs considerably from situations where wind transport from primarily one direction leads to preferential SWE loading on slopes of particular aspects, which can lead to a spatial correlation between SWE and ablation rate. These findings suggest that in near-summer solstice conditions and environments where snow redistribution is substantial, then mountain SCD curves can be calculated using the spatial distribution of SWE alone, and that hydrological and atmospheric models need to implement a realistic distribution of SWE in order to do this~~Analysing the reasons for a missing correlation in this study area provided some prerequisites for large spatial correlations and for when these need to be taken into account by SCD curves. These findings suggest that hydrological and atmospheric models need to incorporate realistic distributions of SWE, melt energy and cold content and so must account for correlations between SWE and melt in order to accurately model snowcover depletion.

1 Introduction

The spatial variability of snow water equivalent (SWE) ~~during melt~~ exerts an important control on catchment or grid~~-scale meltwater generation~~-averaged snowmelt (Pomeroy et al., 1998~~). Terrain-induced~~; Liston, 1999). When focussing on complex terrain with only minor vegetation effects on SWE distribution, differences in precipitation~~ and terrain and vegetation-induced differences in~~ , snow redistribution, melt energy and freezing levels lead to a spatially variable distribution of SWE (e.g. Clark et al., 2011). For modellers of snow-hydrological applications the question arises as to which of those processes need to be considered. It is well known that south-facing slopes receive more melt energy than do north-facing slopes due to differences in solar radiation. At 50°N on April 1, the differences are already 40% for a slightly inclined slope of 10°, however, these differences decrease as summer solstice approaches (Figure 1, Gray and Male, 1981). It is also well known that SWE distribution at ~~the start of the melting season. In many environments~~peak accumulation is highly variable in alpine terrain. Liston et al. (2004) presented maps with regional differences of coefficients of variation (CV) of snow depth. For alpine regions a CV of 0.85 is suggested. Both, the variability in melt energy and SWE influence snow cover depletion. This can be visualized in snow-cover depletion curves, which are a function of snow-covered area (SCA) over time or grid-averaged SWE (e.g. Essery and Pomeroy, 2004; Clark et al., 2011). Both studies illustrate with theoretical simulations how increasing melt rate and peak SWE variability change the rate of areal snow-cover depletion. From their theoretical illustrations (Fig. 3 and 4 in Clark et al., 2011), it is clear that in alpine regions with a large variability in melt rate and peak SWE, ignoring SWE rather than melt rate variability would be the greater modelling mistake. However, as Pomeroy et al. (2004) pointed out, the importance of melt variability on SCD increases if a spatial correlation between melt and SWE exists. This suggests that in alpine terrain the question of relative contribution of spatially variable melt rates or snow redistribution on SCD can be reduced to the question of whether such a correlation between melt and SWE exists and how large it is.

Besides theoretical considerations, there are a number of existing field and modelling studies on the relative importance of spatially variable melt or snow redistribution on SCD. There are studies have found the temporal progression of snow-cover depletion (SCD) ~~has been found~~ to be governed primarily by the ~~premelt distribution of SWE~~variability caused by snow redistribution rather than the variability caused by melt rate differences (Shook and Gray, ~~1996; Donald et al., 1995; Marsh and Pomeroy, 1996~~1994; Luce et al., 1998~~, 1999; Pomeroy et al. 1998; Pomeroy et al. 2001~~; Anderton, 2004; Egli et al., 2012). These studies show with spatial observations that snow cover depletion (SCD) can be modelled with statistics derived during peak accumulation. Luce et al. (1998) modelled snow cover depletion with a spatially distributed energy balance model which integrated drifting snow redistribution based on an empirically derived drift factor. Ignoring this drift factor deteriorated model results, which suggests the relative importance of snow redistribution over melt variability. Grünewald et al. ~~All of these studies have explained the observations by~~ (2010) made indirect measurements of spatial melt rate and SWE via snow depth (HS) and the change in HS (dHS) by terrestrial LiDAR by and applying a few measured bulk densities to estimate SWE and ablation rates. They found that SWE and melt rate were spatially uncorrelated over most of their ablation season, except for a correlation coefficient of r = -0.4 for one sub period. They noted that the variability of SWE was much larger than the variability of melt rates. In the same study area over an additional winter season Egli et al. (2012) calculated SCD curves that assumed correlations between HS and the change in HS (dHS), however these curves deviated substantially from observations, suggesting that ~~the main deposition patterns remained during melt and that the statistical properties of SWE distribution control SCD. This is parameterised as the SCD curve in many hydrological and land surface models (Kuchment and Gelfan, 1996; Verseghy, 2000; Essery and Pomeroy, 2004) where a spatially uniform ablation rate is applied to a frequency distribution of SWE to calculate areal ablation rates and SCD during melt.~~ such correlations did not exist. Neither study examined why such correlations were absent.

~~However~~On the other side, spatially varying melt rates – caused by differences in insolation due to aspect (Marks and Dozier, 1992), net solar irradiance due to albedo differences (Skiles et al., 2015), internal energy storage due to deep, cold snow (DeBeer and Pomeroy, 2010~~), turbulent transfer (Pohl et al., 2006~~) and advected energy due to bare ground ~~or exposed vegetation~~ (Mott et al., 2011; 2013~~; Ménard et al., 2014~~) can alter this pre-melt SWE distribution and, when correlated to SWE, result in a spatial variability to SCD (~~Faria et al., 2000;~~ Pomeroy et al., ~~2001~~2004; Essery and Pomeroy, 2004; ~~Dornes et al., 2008a, b;~~ DeBeer and Pomeroy, 2010).~~ For instance in the boreal forest, snow interception by needleleaf trees reduces SWE accumulation, but higher ablation rates near tree trunks accelerate melt – this induces a negative spatial covariance between premelt SWE and melt rates that causes a strong bias in SCD (Faria et al., 2000).~~ Pomeroy et al. (2003) took measurements of energy fluxes to snowpacks using eddy correlation and slope based radiometers and snow ablation using spatially distributed snow surveys in a Yukon mountain valley in April and found that whilst ablation was proceeding rapidly on south facing slopes where snow was initially shallow, snow accumulation was still occurring on north facing slopes where a large drift had formed. ~~The different snow surface states and impact of prevailing winds and slope and aspect resulted in energy fluxes melting snow on south facing slopes and cooling snow on north facing slopes. As a consequence, a common SCD was not viable over the whole valley.~~ In Yukon and the Canadian Rockies, subsequent studies found melt variations to be important in controlling snow ablation and SCD (Pomeroy et al., 2003; 2004; Dornes et al., 2008a, b; DeBeer and Pomeroy, 2009; 2010). Pomeroy et al. (2004) reported that different spatial scales and landscape classes influence melt rates to be positively or negatively correlated to pre-melt SWE throughout melt in a wide variety of cold regions mountain environments. Dornes et al. (2008a, b) found that hydrological models and land surface schemes that did not consider slope and aspect impacts on melt as well as initial SWE could not be calibrated to produce realistic SCD curves or streamflow discharge hydrographs. Most interestingly, DeBeer and Pomeroy (2010) found in a windswept alpine catchment subject to substantial snow redistribution, that melt rate variations were ~~quite~~ important in the Canadian Rockies ~~in~~during early melt. ~~In contrast,~~Winstral and Marks (2014) found modelled SWE and ~~Grünewald et al. (2010) observed only a weak relationship between topographic and meteorological variables to spatial~~ melt rates ~~in a Swiss mountain valley; the relationship decreased later in the~~were correlated with r = -0.66 in the mountains of southern Idaho. Such a large correlation between modelled melt ~~season. They found using Terrestrial Laser Scanning (TLS)~~and SWE would indicate that ~~the variability of pre-melt SWE was much more variable than~~ spatial melt differences~~. Winstral and Marks (2002), Magnusson et al. (2011) and Winstral et al. (2013) concluded that spatial melt models which do not include spatial SWE variations caused by wind effects were not sufficient~~ are relevant to model ~~runoff in mountains. Anderton et al. (2004) found that pre-melt SWE was more important than spatial melt differences for explaining~~ SCD correctly in ~~the Pyrenees~~some regions.

~~When focusing on studies in alpine terrain without a larger vegetation effect on melt (e.g. DeBeer and Pomeroy, 2010; Egli et al. 2012) it still remains unclear whether spatial variable snowmelt in addition to spatially variable SWE should be considered in calculating SCD. Much of this uncertainty is due to the limited number of detailed measurements available and the uncertainty of distributed model results. There are likely to be fundamental differences in the sequence of ablation between relatively warm and cold mountain environments due to the effect of internal energy deficits in delaying melt of deep snowpacks (DeBeer and Pomeroy, 2010). But there are also substantial differences in solar irradiance as the summer solstice is approached – as shown in Fig. 1 in April at 50° N there is a 17 MJ m^{-2} difference between irradiance on 30% N and S facing slopes, but by solstice this decreases to 2.5 MJ m^{-2}. The variation in observations and model results for alpine terrain creates uncertainty in the relative importance of spatial melt rates and SWE to determine SCD and areal ablation rates. To address this uncertainty an extremely high spatial resolution digital surface model dataset was collected over an alpine ridge in the Canadian Rockies using an Unmanned Aerial Vehicle (UAV) and Structure from Motion (SfM) analysis to repeatedly determine snow depth and snow depth differences during a melt season as proxies of initial~~

~~SWE and sequential, spatial melt rates. Analysis over several spatial scales was conducted to correlate variables that might influence melt to measured spatial melt rates and investigate the influence of initial SWE and spatial variation in melt on SCD and areal mean melt over an alpine ridge in high mountain terrain.~~

Regional differences, e.g. the complexity of the terrain and wind redistribution, will alter the dominance of SWE variability on SCD and may thus explain part of the different findings of various studies. Not all cited studies fall in the highest CV category suggested by Liston et al. (2004). Furthermore, in study regions with a large elevation gradients, altitudinal melt energy differences as well as precipitation phase differences will play an important role in governing SCD (Blöschl and Kirnbauer, 1992; Elder et al., 1998).

From a practical modelling perspective, it is simpler to explicitly calculate melt energy differences in a model (Marks and Dozier, 1992) than to calculate snow redistribution mechanistically over complex terrain (Liston and Sturm, 1998; Mott et al., 2010; Fang et al., 2013; Musselman et al., 2015). Empirical modelling of SWE variability (Luce et al., 1999; Winstral and Marks, 2002; Liston et al., 2004, Essery and Pomeroy, 2004; Helbig et al., 2015) has therefore been a preferred choice. However, Dornes et al. (2008a, b) showed substantial interannual variability of SWE distributions and correlations to melt rate which invalidated empirical assumptions in some years and caused predictive failure of land surface hydrology models. Without explicit information on the effects of redistribution on the distribution of SWE, it is not possible to estimate the impact of correlations between SWE and melt rate on SCD curves.

This study aims to show the influence of peak SWE variability and melt rate variability and their spatial correlations on SCD in alpine terrain using high-resolution distributed measurements rather than sparse manual sampling or relying on model results. The use of high resolution measurements is potentially important because peak alpine snow depth, and thus also peak SWE, is known to vary most substantially below the scale of tens of metres in alpine environments. The coarse-resolution manual probing of previous studies may have missed important spatial structures which may determine the results (Clark et al., 2011). Most studies on this topic have relied on modelled melt rates, even though there are substantial uncertainties in melt modelling over complex terrain. For instance, Mott et al. (2011) were only partly successful in high resolution modelling of alpine melt rate variations. Those studies which have used high-resolution distributed snow depths, such as Egli et al. (2012) did not attempt to diagnose the variation of and correlation between SWE and melt rates.

2 Data and methods

2.1 Site description

A study region was chosen which showed substantial differences in aspect and slope to ensure spatial melt differences. In a nearby study site DeBeer and Pomeroy (2010) found spatial melt rates to be important for snowcover depletion, at least during early melt. Large drifts commonly form on south facing slopes in this area (MacDonald et al., 2010; Musselman et al., 2015) suggesting a correlation between melt energy and SWE. The study area is located in the Canadian Rocky Mountains in southern Alberta, Canada. Figure 2a shows a topographic map of the study area, an alpine ridge in a NE – SW orientation. ~~On both sides of the ridge the slope steepens to up to 40 deg.~~ Gullies and small scale aspect variations can be found in the slopes on both sides of the ridge. Extreme south and north aspects are underrepresented in the ~~snow covered area~~ terrain snowcovered at the beginning of the study period (Fig. 2b). The snowcovered area is reasonably steep with two peaks in the slope distribution at 10^{o} and 25^{o} (Fig. 2c). On both sides of the ridge the slope steepens to up to 40^{o}. Vegetation played a role in snow deposition patterns, mainly in the lee of shrubs and clusters of small trees in krummholz with heights up to 2 m. Areas within these vegetation clusters were excluded from the study as vegetation degraded the digital surface models (DSMs) derived from UAV SfM photogrammetry (see section 2.4). The included area only covered bare or sparsely vegetated ground so that vegetation effects can be excluded.

Two weather stations are located at the ridge, one on top of the ridge (Fortress Ridge - FRG) and one in a south facing slope (Fortress Ridge South - FRS, Fig. 2a). The local Fortress Mountain Snow Laboratory within the regional Canadian Rockies Hydrological Observatory provided five more weather stations within less than 2 km distance of the ridge, which were used to interpret weather situations and for quality control.

2.2 ~~UAV~~Unmanned aerial vehicle (UAV) Data acquisition

A “Sensefly Ebee RTK” fixed wing UAV was used with a modified consumer-grade Canon Elph compact RGB camera. As a base station a Leica GS15 differential GPS system

~~was used, which~~ communicated with the UAV to tag captured images with corrected geolocations. Additionally, ground control points were measured with this differential GPS system, which improved the quality of the Digital Surface Models (DSMs) generated. For a more detailed description of the UAV and the usage please refer to Harder et al. (2016). An area of 0.31 km^2 (666 x 470 m) was separated into two subareas because of battery restrictions on flight ~~areas~~coverage (Fig. 2a, red polygons). Each flight lasted approximately 20 min. The flight altitude was ~~chosen to be~~ 100 m over the ~~ridge top~~ridgetop, which resulted in an approximate resolution (ground sampling distance) of ~~smaller~~less than 4 cm. A lateral overlap of the images of 85% and a longitudinal overlap of 75% was chosen as suggested by the manufacturer for difficult terrain. Ideally, four flights in total were made each sampling day, two for each subarea with perpendicular flight plans~~.~~, which is suggested by the manufacturer for complex terrain. Weather conditions and technical problems often allowed only a part of this program. Wind speeds over 14 m/s or occurrence of precipitation restricted flying, while camera malfunctions or connection issues with the Leica GPS base station were the most typical technical limitations. In total, the UAV was flown over snow from 15 May to 24 June 2015 at eight different days with substantial depth differences and four flights over bare ground on 24 July 2015. However, as stated section 3.2, we had to restrict analysis to two melt periods.

2.3 Accuracy evaluation and manual measurements

The accuracy assessment of this rather new method to determine snow depth was given a high priority and is described in detail by Harder et al. (2016) for this environment and others. In short, 100 differential GPS measurements on bare ground were taken. Approximately 60% of the area was bare at the beginning of the study period which allowed distribution of GPS ground measurements over a large part of the study area (Fig. 3a) and thus widespread detection of any general misalignment of DSMs or local tilts. These points could be used for all available flights. Differential GPS measurements were also taken at the snow surface on the day of the specific flights, but technical problems often allowed only limited additional time for these surveys. For most of the days up to 20 differential GPS measurements on snow could be taken. At these GPS measurement points, snow depth was also manually measured and snow density was measured at approximately each third of these points. Density measurements were not sufficient to confidently estimate SWE from snow depth into SWE and ablation rates from differences in snow depth. As such ~~the originally~~

~~measured quantities~~HS and dHS are analysed and interpreted as proxies for ~~ablation and~~ SWE and melt in the text.

Harder et al. (2016) described errors and accuracies of the UAV measurements in detail. In short, from 100 measurements on bare ground, the root mean square errors of bare ground surface elevation ranged between 4 and 15 cm with a mean of less than 9 cm. Over snow with fewer measurements an increase in these error measures could not be detected. A signal-to-noise ratio (SNR) was used to ensure that the signal of the UAV was sufficiently larger than the error, defined as mean of the signal divided by the standard deviation of the error~~-~~. The potential impact of this error on the results presented is discussed in section 3.2.

2.4 Spatial data generation

Digital Surface Models (DSMs) and orthomosaics were created by application of SfM techniques (Westoby et al., 2012) using the software Postflight Terra 3D, which was provided with the UAV. Default settings likely resulted in overexposed pixels, which created erroneous points in the point cloud over snow that appeared several metres above the real snow surface. This issue could partly be solved with a semi-global-matching option within the software, which reduced the number of affected areas. Remaining areas with errors were manually excluded (Harder et al., 2016). DSMs and orthomosaics were resampled to a common grid and resolution of 10 cm, which increased the speed of subsequent data analysis substantially.

Subtracting DSMs provided both snow depth (HS) and differences in snow depth (dHS). dHS was scaled by the time interval between observations for comparison of varying observation periods. Snow~~–~~-covered area (SCA) was defined using individual thresholds in RGB values for different flights using the orthomosaics. Manual adjustment was needed to ensure that very dark snow was classified correctly (see for example Fig. 3b). HS was masked by the SCA of the date of the flight, whilst dHS was masked by the SCA on the dates of the first and subsequent flight. Figure 3c and 3d show examples of HS and dHS maps of a part of the study area. Several areas such as ski lifts and snow cat tracks and erroneous points as mentioned above were excluded from the analysis. Furthermore, large errors were detected in areas close to vegetation, which were manually excluded. The marked green area in Fig. 3d indicates the excluded area for this part of the study area.

To explain the observed differences in snow depth, several topographical variables were created using the DSMs. *Deviation from North* and *Slope* were calculated on a 1 m resolution to exclude small-scale noise of the DSMs. *Solar Irradiance* was calculated for a 1 m resolution for each flight day with the Area Solar Radiation function in ArcGIS. To account for albedo differences the *Brightness* of the orthomosiac pixels was abstracted on a 10 cm resolution. The blue value was chosen since it was least affected by unwanted illumination differences due aspect variations. *Brightness* and *Solar Irradiance* are temporal averages based on the first and the last flight and, if available, flights within the periods.

2.5 Data analysis

To ~~identify~~diagnose reasons for spatial differences in snow depth change (dHS), Pearson correlation coefficients were calculated with several potential explaining variables as *Slope*, *Deviation from North*, *Solar Irradiance*, *Brightness*, current snow depth (HS) and snow depth at the beginning of the study period (HS0). Scatter plots also were visually inspected to detect reasons for strong or weak correlations or non-linear dependencies. The scatter plots were too dense to interpret visually because of the high resolution and so instead of plotting point pairs, the density of point pairs in a limited area of the plot was visualized (e.g. in Fig. 5a).

~~In addition to this univariate analysis, a stepwise forward-backward linear regression was used to define a small subset of variables and to calculate the coefficient of determination r^2 and coefficients of normalized explaining variables. Regular tests for including or excluding variables in a regression will fail given the large number of data ($N > 10^5$). Instead, a threshold for an increase in R^2 of 0.2 was defined to include an additional variable. A variable was excluded for any increase of R^2.~~

Spatial dependencies of the spatial structure of dHS and its correlation with explaining variables were analysed with variograms and correlograms. Variograms were calculated with

$$\hat{\gamma}_x(h) = \frac{1}{2\,|N(h)|} \sum_{(i,j)\in N(h)} (x_j - x_i)^2 , \qquad (1)$$

for point pairs x_i and x_j in a lag distance class $N(h)$ (e.g. Webster and Oliver, 2007). Correlations between two variables x and y in a certain lag distance h were calculated with the cross-variogram as an estimator of the covariance (Webster and Oliver, 2007).

$$\hat{\gamma}_{xy}(h) = \frac{1}{2\,|N(h)|} \sum_{(i,j)\in N(h)} (x_j - x_i)(y_j - y_i) , \qquad (2)$$

This covariance was scaled with estimators of the variance $\hat{\gamma}_x$ (Eq. 1) using

$$\rho_{xy}(h) = \frac{\hat{\gamma}_{xy}(h)^2}{\hat{\gamma}_x(h)\hat{\gamma}_y(h)}, \qquad (3)$$

to obtain a correlation measure (Webster and Oliver, 2007). Variograms and correlograms were calculated only with a random subset of 10% of available data points to save computational resources. Smallest number observations were N > $5\text{x}10^4$, which was large enough to obtain consistent variograms and correlograms with different randomly chosen subsets.

3 Results and discussion

3.1 Overview and meteorology

Fortress Ridge is well exposed to the wind, with peak hourly wind speeds over 20 m/s and a mean of 4.6 m/s over the winter 2014/15 at the FRG station. Two dominant wind directions can be identified, WSW and ESE, the latter is approximately perpendicular to the ridge. The wind direction parallel to the ridge is associated with the highest wind speeds. During precipitation and high wind events both directions were frequent. During late melt in 2015, wind speeds were substantially lower with a higher frequency of very calm days, providing more frequent flying conditions for the UAV.

Due to high wind speeds, large parts of the ridge were snow~~-~~-free during most of the exceptionally warm and dry winter season. After a large late November 2014 snow storm, the FRG station rarely documented snow on the ground and shallow snowpacks that did form were regularly eroded by wind within a few days. The snow covered area (SCA) reached the seasonal maximum in late November after this substantial snowfall (80 mm) with light winds and dropped dramatically due to subsequent wind redistribution from blowing snow storms. When aerial measurements began on 19 May 2015, SCA was slightly below its typical winter value as spring ablation was under way. Without excluding any areas (see section 2.4) SCA was approximately 0.45 in both subareas (Fig. 3a).

Dust-on-snow was an obvious feature in late winter and the beginning of the melt season (Fig. 3b). It ~~has~~had not been observed to such extent in over a decade of observations in the region. This dust was locally eroded from the fine frost-shattered and saltation-pulverized shale particles at the ridge-top and was transported by wind to adjacent lee slopes and into gullies, similarly to wind-transported snow. Hence dust was deposited preferentially to snow drifts. Subsequent snow accumulation and melt processes led to a dust-on-snow pattern of high small-scale variability. The lower albedo from dust deposition may have influenced snowmelt energetics, but its high variability is different from the large scale, areally uniform dust deposition reported by Painter et al. (2010) where the dust source is in upwind arid zones and very fine aerosols are evenly deposited on snow.

Blowing snow transport and redistribution during the high wind speeds also caused a highly variable snow depth (Fig. 3c) as is expected in the region (~~MacDonald~~Fang et al., ~~2010~~2013; Pomeroy et al., ~~2012; Musselman et al., 2015~~2016). Snow was redistributed to the SE facing slopes of the ridge and also in gullies on the NW facing slopes, which are perpendicular to the ridge. Areas of bare ground and very deep snow (> 4 m) were only separated by a few metres distance. This high variability of snow depth at scales of from a few to tens of metres is a typical feature for wind-swept alpine snow covers (e.g. Pomeroy and Gray, 1995, p.22-27; Deems et al., 2006; Trujillo et al., 2007; Schirmer et al., 2011; Schirmer and Lehning, 2011). There is no avalanching redistribution of snow in the study domain.

An example of reductions in snow depth (dHS) due to ablation over a period of 13 days is shown in Fig. 3d. At the first glance differences between aspects are obvious, as well as smaller scale impact of albedo variations (cf. Fig. 3b). The driving forces to differences in ablation inferred from the observed differences in depth change will be examined in section 3.3.

The study ~~period~~ covered the late melt period, when the highest ablation rates occurred. Peak SWE of 500 mm was measured with a weighing snow lysimeter (Sommer “Snow Scale”) in a nearby forest clearing on 20 April 2015. By the start of the study period on 19 May, SWE had gradually decreased to 300 mm, often interrupted by snowfall. During the study period after 19 May no significant (>3 cm) snowfall was observed. The much higher ablation rates compared to the previous weeks caused the snow to disappear at this station on 30 May. A very similar development could be observed at two other stations using snow depth sensors within the Fortress Mountain Snow Observatory, including the FRS station (c.f. Fig. 2a). On 30 May a SCA of 0.2 was measured from the UAV over the whole flight domain.

Considering a typical pre-melt SCA of approximately 0.45, the presence of a significant SCA illustrates the value of spatially distributed measurements of snow ablation and cover, when all seven meteorological stations in the ~3 km^2 region were snow-free.

A meteorological overview during the study period is given in Fig. 4 at the FRG station (cf. Fig. 2a). Measurements of incoming shortwave radiation and air temperatures are shown on the left, and resulting modelled results with ~~SNOBAL in~~ CRHM using Snobal as the melt module (cf. Fang et al., 2013) for a flat field simulation on the right. Although the FRG station was snow-free, CRHM was initialized with a hypothetical SWE amount of 800 mm in order to represent deeper nearby snow patches. Energy fluxes were summed and scaled for comparison over the indicated dates with UAV flights. The energy balance was dominated by inputs of net shortwave radiation. ~~Melt~~Modelled melt accelerated around 8 June when high incoming shortwave radiation was accompanied by smaller longwave radiation losses and larger sensible heat fluxes driven by air temperatures often in excess of 10^{o} C.

3.2 Selection of melt periods

Melt periods were chosen to include sufficient ablation such that the dHS signal ~~of dHS~~ exceeded the measurement error from the UAV and data processing. A signal-to-noise ratio (SNR) was used, which relates the mean dHS with the typical standard deviation error (SD) found by Harder et al. (2016) for surfaces measured with the UAV to be 6.2 cm. Since two surface measurements are needed to achieve a dHS map, this SD value was doubled. For SNR $\geq$ 4, the signal is assumed to be sufficiently large to avoid mistaking it for a fluctuation in noise (Rose, 1973). Applying this criterion, mean dHS had to be larger than ~0.5 m. ~~This melt amount was reached when melt periods were longer than approximately eight days.~~ Given the availability of suitable flights in both subregions, this permitted two time periods for analysis; P1 from 19 May to 01 June 2015, and P2 from 01 June to 24 June 2015.

3.3 ~~Spatial~~Factors influencing spatial differences in dHS

Table 1 shows the Pearson's correlation coefficient for above mentioned melt periods and different subareas. This univariate analysis shows clearly two driving factors for the earlier melt period, P1, albedo and solar radiation differences, expressed respectively with *Brightness* and either *Deviation from North* or with *Solar Irradiance* ~~(Table 1).~~. The sign of the correlations is mainly as expected: More southerly and darker pixels ~~melted faster~~showed larger dHS values. Exceptions (e.g. during P2 in the southern subarea) may be explained with observable differences between a few remaining snow patches with different albedo values, slope, snow depths and sky view factors. Energy contributions from longwave radiation (DeBeer and Pomeroy, 2009) or altered turbulent heat fluxes because of cold air pooling (Mott et al., 2011; 2016) may override an obvious relationship with solar radiation. Also, faster settling rather than melt of deeper ~~snowis~~snow is possible, although the snowpack ~~is~~was quite ripe~~ at this time of the year~~.

In the first period, P1, *Brightness* had a large effect in the northern subarea (r = -0.66). Figure 5a visualizes this relationship between dark snow and ~~melt~~dHS. The high scatter especially for brighter snow pixels can partly be explained with radiation differences. For the same period and area *Solar Irradiance* and *Deviation from North* had a correlation of r = 0.57. Figure 5b illustrates the dependency with *Solar Irradiance* but for white pixels only (approximately 50% of the observations). A clear dependency is visible with a correlation coefficient of r = 0.66. Radiation effects were more substantial during P2 in this northern subarea with r = 0.84 for both *Solar Irradiance* and *Deviation from North*. This may be explained due to less scatter produced by albedo differences in this period (r = 0.03). Darker parts of the snowcover melted out by the end of this period.

The correlations of dHS with *Brightness*, *Deviation from North* and *Solar Irradiance* were often strong. dHS increased from 5 to 7 cm/d (nearly 60% increase) as aspect shifted about 115 deg from north to south or snow from clean to dusty (c.f. Fig. ~~5~~5b). This shows the importance of spatial variation in net solar irradiance to melt energetics – as exemplified by the ~~model~~modelled energy budget shown in Fig. 4b.~~-~~ The impact of dust on albedo and slope on solar irradiance is well established in the snow literature and so this is expected. ~~What is a more unique finding here is that dHS is not correlated largely with initial SWE (HS0, Table 1) as found by DeBeer and Pomeroy (2009, 2010), Pomeroy et al. (2003, 2004), Dornes et al. (2008 a, b) and other mountain studies in Canada. This indicates a lack of covariance between melt rate and SWE in late melt that should have important implications for SCD curves (Pomeroy et al., 2001, section 3.4.3).~~

~~All previous studies in the Canadian Rockies, Alberta and Coast Mountains, Yukon focussed on the full melt period rather than the late melt period that is measured in this study and so the importance of season differences in irradiance to slopes as shown in Fig. 1 and the late-melt isothermal snowpacks may be important to explaining the missing spatial correlation~~

~~between melt and SWE. During early melt the cold content is related to snow depth, which likely will result in a spatial correlation between SWE and melt (c.f. DeBeer and Pomeroy, 2010, 2017). Furthermore, the observed two dominant wind directions related to precipitation and strong wind speeds have influenced spatial SWE patterns and reduced the likelihood of a spatial correlation of SWE and melt. In contrast, areas with wind transport from primarily one direction and hence preferential SWE loading onto slopes will affect particular aspects, which in turn may be southerly, and hence induce a spatial correlation between SWE and ablation. Another reason for a missing spatial correlation is discussed in section~~ What is a more interesting finding here is that dHS was not correlated with initial HS0, Fig. 5c, Table 1), as was observed in other cold regions mountain studies in Canada such as DeBeer and Pomeroy (2009, 2010), Pomeroy et al. (2003, 2004), and Dornes et al. (2008 a, b). A lack of covariance between HS0 and dHS in late melt has important implications for SCD curves (Pomeroy et al., 2001), which will be highlighted in section 3.5. Figure 5c shows the areal mean values for HS0 and dHS for flat areas (slope < 5°) and areas on both sides of the ridge (threshold aspect is 235°, slope $\geq 5^{\circ}$). The hypothesis for this study period was that large drifts on south-facing parts of the ridge cause a correlation between melt energy and SWE. Indeed, the southeast part showed larger HS0 and dHS compared to the flat and northwest part of the study area. This suggests a correlation between HS0 and dHS, which was not apparent when analysing all pixels. In each subarea the range of snow depth was large, which diminished the observed correlation. More importantly, on the south-eastern face a mild negative correlation of r = -0.35 developed (Fig. 5d), which may be explained by a remaining cold content in deep drifts. This negative correlation is not apparent for smaller dHS values, in the northwest part of the ridge (Fig. 5e). The lack of correlation in the Fig. 5c point cloud was contributed to by compensation between the positive correlation driven by melt energy and the negative correlation from a cold content.

To aid in analysing the reasons for the lack of correlations between Hs and dHS in this study area one can formulate some prerequisites for large spatial correlations in general. For instance, cold content has the potential to establish a negative correlation since deeper snowpacks take longer to warm up to 0 $^{\circ}$C and so shallower snowpacks start melting earlier. This results in greater melt for shallower snowpacks. The spatial distribution of SWE and melt energy on slopes may result in a negative or positive correlations, which depend on whether deep drifts are found on north-facing or south-facing slopes. For a large correlation between Hs and dHS, either snow redistribution to slopes or deep snow cold content processes needs to be present and need to not counteract each other. In such a case the sign of the correlation driven by spatial distribution of SWE melt energy must be negative (drifts on north-facing slopes) and hence similar to the negative correlation driven by greater cold content in deeper snow. Remote sensing techniques such as remote sensing can determine where deep drifts occur on north-facing slopes (Wayand et al., 2018; Painter et al., 2016) and these are quite prevalent in many regions. DeBeer and Pomeroy (2010) showed that spatial variation in cold content was large only in early melt and was unimportant to SCD later in the melt season when isothermal snowpacks predominate.

Given these scenarios some guidelines for modelling areal SCD can be provided. Models must be able to represent realistic correlations between SWE and melt in order to model the effect of this correlation on SCD (Essery and Pomeroy, 2004). Potential pitfalls are incomplete modelling representations that might neglect a governing process. To capture the spatial correlations, models need to include snow redistribution, internal snowpack energetics and melt rate variability on slopes at fairly fine scales (<100 m) in complex terrain. Semi-distributed models with homogenous snow distribution over large areas or distributed models that neglect blowing snow redistribution may misrepresent spatial correlations of SWE and melt.

Another reason for models misrepresenting spatial correlations between HS0 and dHS is discussed in section 3.6~~3.56~~, in which the mismatch of scales of ~~ablation~~dHS and ~~SWE~~HS0 patterns ~~are~~is discussed.

~~The stepwise linear regression results shown in Table 2 confirm that the most important variables explaining ablation variation are solar irradiance and albedo. Combinations of solar irradiance and albedo increased the explanation compared to univariate regressions (Table 1). For example for P1 in the northern subarea, a model with *Deviation from North* and *Brightness* explained nearly 70% of the total ablation variance with nearly equally large (normalized) coefficients, indicating equal effect contributions of irradiance and albedo to explaining variations in dHS.~~

~~3.4 Relative importance of ablation and initial SWE~~

~~3.4.1~~3.4 Variability of ~~ablation~~dHS in relation to ~~(initial) SWE~~HS0 and temporal persistence

Table ~~3~~2 shows mean, standard deviation and CV values of HS and dHS in different periods and subareas. Throughout the melt season CV values of dHS were about five times smaller than those of HS. At the start of the study period, the variability of dHS was smaller than that of HS by a factor 3.7 to 6.7~~, for the whole area approximately by a factor 5. Applying the mean measured snow density from 19 measurements between 19 May and 22 May (413 kg/m^3) to HS provides an estimate of mean initial SWE of 520 mm with a standard deviation of over 480 mm. Ablation amounts in period P1 were in mean 334 mm, with a standard deviation of only 65 mm. These values indicate much larger SWE variability than ablation variability in this period~~.

~~3.4.2 Persistence of ablation patterns~~

For the whole area only a weak correlation (r = 0.36) was found between ablation patterns ~~between~~over the two long periods P1 and P2. Larger correlations were found for the northern subarea (r = 0.60). Ablation patterns in certain sub-periods with similar weather conditions were correlated to each other. For instance, ablation patterns in the cool and cloudy period between 05 May and 01 June were correlated with two other rather cloudy sub-periods at the end of the study period with r = 0.49 and r = 0.64, and to the later combined period P2 (r = 0.70). ~~Closer investigations~~Further investigation on how these correlations responded to weather ~~conditions were~~was not possible given the reduced signal-to-noise ratio for shorter time periods~~. Larger periods always included~~ and the inclusion of several ~~types of~~ weather ~~patterns~~types over longer periods.

~~3.4.3~~3.5 Depletion curves

Maximum differences in ~~melt rate~~dHS of up to 100% were measured (section 3.3) and ~~melt rates~~ were spatially persistent especially in the northern subarea. Similarly to Pomeroy et al. (2001) and Egli et al. (2012) the impact of spatial ~~melt rates~~dHS on snow-cover depletion ~~and areal melt~~ were analysed in several scenarios:

1. Variable HS0/uniform ~~melt~~dHS: This scenario started with the measured distribution of HS at the start of the study period (HS0) and a spatially uniform ~~melt rate~~dHS value was applied for each pixel. This ~~melt rate~~value was determined with observed mean ablation values shown in Table 3. Each pixel was reduced by this mean ~~melt rate~~value and any negative values in HS were set to 0. SCA was defined as the ratio of the number of grid points with HS > 0 to all pixels.
2. Uniform HS0/variable ~~melt~~dHS: In this scenario, the mean initial snow depth as shown in Table 3 was uniformly distributed in the whole snow-covered area. Spatially variable ~~melt rates~~dHS values as measured with the UAV were applied to each pixel. To obtain the exact melt-out time this scenario was calculated ~~in a~~ daily ~~resolution with~~ using a temporally constant ~~melt rate~~dHS value between flights. No exact ~~melt~~dHS amounts ~~are~~were available for pixels which ~~have~~ melted out between flights. For those pixels the mean ~~melt rate were~~ areal dHS value was applied. The general shape of SCD curves ~~can be~~ obtained when this scenario ~~is~~was also calculated on the time resolution of the UAV flights.
3. Uniform HS0/uniform ~~melt~~dHS: Similar to scenario 2, but a spatially uniform ~~melt rate~~dHS value was applied to each pixel~~.~~, each of which had a uniform HS0. This scenario was also calculated on a daily resolution.

In all scenarios, SCA was set to 1 for the area which was snow-covered at the start of the study period. Figure 6 shows mean HS ablation and SCD curves for the whole area and the northern subarea (top), for which more flights are available. Differences between measured development and the first scenario of uniform ~~melt~~dHS and variable HS0 were not large. However, a large difference between measurements and the second and third ~~scenario of~~ scenarios with uniform HS0 ~~with~~and either variable or uniform ~~melt~~dHS is obvious. Areal ~~melt~~dHS in those scenarios was overestimated before modelled melt-out because of ~~overestimating~~the overestimation of SCA. Later~~ during melt~~, areal ~~melt~~dHS was underestimated (or zero) since ~~nearly (~~most or all~~)~~ snow disappeared too early. This is particularly important when the aim is to model late rain-on-snow events in hydrological models~~. For this area these~~ (Pomeroy et al., 2016). These results indicate that it is possible ~~ignoring~~to not represent the spatial melt variability in late melt ~~to achieve~~and still simulate a realistic SCD curve, while this is not possible ~~ignoring~~if the spatial ~~HS0~~ variability of HS0 is not represented. This main feature is consistent with Egli et al. (2012).

The main reason why the observed dHS differences, which were substantial and partly persistent~~ melt differences were ~~, did not ~~largely influencing depletion~~influence SCD curves ~~compared to a homogeneous melt scenario ~~can be found in the small ~~or missing~~to negligible spatial correlation between ~~melt~~dHS and ~~initial SWE~~HS0 (cf. section 3.3 and Table 1). Large correlations substantially influence SCD: Negative correlation accelerates SCD at the beginning of melt and delays it in late melt lengthening the snowmelt season and vice versa with positive correlations (Essery and Pomeroy, 2004).

~~In case of weak to no~~Where correlation is insignificant, spatial melt differences can be quite large without affecting SCD curves~~ compared to homogeneous melt. The~~. In this case, spatially variable melt can be viewed as a nearly random process~~. There is still some impact because of the ~~ – it introduces noise into the log-normal frequency distribution of ~~SWE.~~HS, but does not affect the emergent behaviour of the SCD curve. Here, with a much larger variability of ~~SWE~~HS0 compared to ~~melt~~dHS (see section ~~3.4.1)~~3.4) and only small spatial correlations between them (see Table 1), ~~SWE must dominate~~HS0 controls the SCD.

~~3.5~~3.6 Scale dependencies of ~~melt~~dHS

Figure 7 and 8 show how the variance of dHS, the variance of explaining variables and correlations thereof, develop with larger lag distance between point pairs (variograms and correlograms, Eqs. 1 to 3). This gives further insights into the driving factors of ablation and why a correlation between dHS and initial HS0 was weak in this study area during late melt.

~~In Fig.~~Figure 7a~~ shows with,~~ the variogram of dHS, shows that the variance increased over two distinct length scales, one less than 50 m and one greater than 200 m. This implies that the driving ~~forces to~~processes which generate variance for ~~ablation~~dHS need to be ~~searched~~investigated at these two scales. In section 3.3 a strong correlation was found between dHS and *Brightness* and *Solar Irradiance*, but only small correlations ~~to~~between these and HS0. These variables were ~~also~~therefore analysed with variograms and correlograms.

The variogram of *Brightness* shown in Fig. 7b indicates a variance increase only at the small lag distances less than 50 m. This is consistent with the visual impression of a small-scale variability of albedo shown in Fig. 3b. The correlogram shown in Fig. 7c reveals a strong correlation of *Brightness* with dHS at these small scales ($\rho_{xy} \approx -0.6$ at 50 m lag distance). This demonstrates that albedo was largely responsible for the small-scale ~~melt~~dHS variability observed in Fig. 7a.

Figure 8a shows the variogram of *Solar Irradiance*. A small increase for length scales less than 100 m suggests radiation and aspect differences at those scales (within-slope variations), but the largest increase can be observed at lag distances longer than 200 m. This scale represents slopes on both sides of the ridge and coincides with the larger scale of ~~melt~~dHS variance. Indeed, the correlogram (Fig. 8b) confirms that the largest correlation with ~~melt~~dHS to $\rho_{xy} = 0.4$ was achieved at those larger distances.

The same analysis for initial snow depth (HS0) can be seen in Fig. 8c and d. Most of the variance for snow depth is at length scales less than 100 m. The periodic behaviour shown beyond that scale may be due to the patchy snow cover which has long snow-free patches. No ~~large~~substantive correlation with dHS is observable on all scales (Fig. 8d).

This analysis offers ~~an~~further explanation why ~~ablation~~dHS and ~~initial SWE~~HS0 were not spatially correlated in these observations. ~~Melt~~dHS variance ~~(ignoring the small-scale influence of albedo)~~ was related to large scale aspect changes on both slopes~~, while~~ and medium scale albedo change, whilst snow depth was ~~mainly~~ variable mainly at much smaller scales. This scale mismatch ~~prevented a stronger correlation.~~

~~3.6 Comparison with other studies in alpine terrain~~

~~The correlation coefficients~~leads to a larger scatter between dHS and ~~explaining variables found here are larger than those found by Grünewald et al. (2010) in a Swiss alpine catchment. They found maximum correlations of |r| ≈ 0.4 for altitude, slope, northing and initial SWE, mainly for the first of their ablation periods. This is despite the fact that they used a wider range of explaining variables such as wind fields from a high resolution wind flow model and accounted for time-variant diffuse radiation in modelling shortwave irradiance. The lower relation to explaining variables may be caused by regional differences, but can also be found in the slightly larger area (0.6 km²) studied by Grünewald et al. (2010), which can potentially include more effects. These local effects were observable in our study as correlations change strength and sign with time and space (c.f. Table 1). Grünewald et al. (2010) found correlations diminished with time and explained this by suggesting the increasing importance of local advection of heat. These diminishing correlations were not observed here. They also found more similar variance in ablation and SWE. This may be~~

~~explained by the particularly wind-swept study site.~~ HS0 values and thus prevented a substantive spatial correlation.

~~Egli et al. (2012) working in the same catchment as Grünewald et al. (2010) found that SCD curves were insensitive to the degree of heterogeneity of ablation. This can be explained as they also did not find a large correlation between SWE and melt. As also found here, Egli et al. (2012) observed that when correlations developed, they were temporally and spatially unsteady, disappeared or changed sign. This reduced the impact of these small-scale correlations on SCD over the ablation season in within a larger study area.~~

~~In a northern Canadian mountain basin (Yukon), Pomeroy et al. (2004) observed on their smallest scale (100 to 300 m) a large negative correlation between ablation and SWE of r = -0.95 at the valley bottom part of their 660 m long transect, a correlation of r = -0.63 on the south face and no correlation on the north face slopes (c.f. their Fig. 5). This is in agreement to findings here that correlations vary regionally. Pomeroy et al. (2004) explained those differences with by varying exposures of vegetation, which is not a factor in this study. When these three slopes are aggregated to the sub-basin, the areal multi-scale correlation is diminished (Fig. 5, Pomeroy et al., 2004). The large correlation of r = -0.86 over the sub-basin is driven by a slope-scale association between snow redistribution to north faces that also experience lower ablation rates (Fig. 6, Pomeroy et al., 2004). This is a meso-scale feature of southerly winds in the basin due to proximity of the Pacific Ocean to the south. Dornes et al. (2008) showed that representing differences in ablation rates amongst these slopes is critical to calculating accurate SCD, but did not suggest that small-scale ablation rate variation need to be considered. They found that by disaggregating the basin into slope units with averaged melt energy applied to each unit, then accurate SCD curves could be estimated within each slope unit using the variability of SWE alone.~~

~~DeBeer and Pomeroy (2010; 2017) concluded that multi-scale variable melt and SWE improved SCD modelling compared to aerial photography of SCA during early melt, but not mid or late melt seasons in the Canadian Rockies (Marmot Creek Basin). They included a spatial distribution of SWE within four slope-scale subareas, and modelled the cold content of snow, which introduced an early multi-scale correlation between SWE and melt in the model. Applying different melt rates within each of the slope-based subareas improved simulations of SCD compared to uniform melt rates during early melt. Considering the whole ablation season they concluded that "…the improvements from including simulations of~~

~~inhomogeneous melt over the entire snowmelt period in the spring were negligible (Table 3).” This refers to small scale inhomogeneous melt and is in agreement with the measurements presented here. Over Fisera Ridge in the same region, Musselman et al. (2015) showed a slope-scale but not fine-scale spatial association between ablation and SWE, and noted that the slope scale association was due to the localized wind-loading of this particular ridge (northerly winds) and would not apply to the larger basin studied by DeBeer and Pomeroy (2017) or Pomeroy et al. (2016) where wind directions varied.~~

~~Winstral and Marks (2014) found modelled SWE and melt rates were correlated with r = 0.66. This large modelled correlation of spatial patterns of SWE and melt may be realistic in this study area, since snow transport is dominated there by a rather homogeneous wind direction, both in space and time which leads to a coincidence between preferentially loaded slopes and melt energy. Such a large correlation between modelled melt and SWE would indicate that spatial melt differences are relevant to model SCD correctly in this area.~~

~~In summary, some studies found correlations between melt and SWE at slope scales, but not at fine scales. These associations were strongest early in melt and at higher latitudes and where wind redistribution occurred over consistent directions due to synoptic conditions during mesoscale wind loading of slopes and is consistent with the slope-based solar irradiance differences shown in Fig. 1. However, no study showed consistent and persistent fine-scale association between ablation and SWE suggested that they can be considered uncorrelated in modelling at fine scales. To address differences in melt energy at slope scales, modellers can chose to calculate averaged energetics to slope units and apply a mean ablation rate to a frequency distribution of SWE over the slope as was demonstrated by Dornes et al. (2008) and DeBeer and Pomeroy (2010; 2017). This is computationally more efficient than the fully distributed calculations employed by Winstral and Marks (2014) and Musselman et al. (2015) and is a promising and likely necessary direction for disaggregation of land surface schemes calculations of melt in mountain regions.~~

Two processes were previously discussed and described in Fig. 5c which could drive compensating correlations between HS0 and dHS; cold content and melt energy. Cold content likely acts on a similar scale as HS0, since it depends mainly on snow depth. As shown in Fig. 5d and 5e a negative correlation driven by cold content is not uniformly present. Melt energy differences, i.e. differences in net shortwave radiation, turbulent fluxes, and net longwave radiation, are not directly dependent on snow depth, but need to spatially coincide by chance (e.g. by direction of redistribution). Acknowledging that *Solar Irradiance* is a simple proxy of melt energy, spatial coincidences between accumulation and melt energy are only present over larger distances (Fig 8b). The large scatter between HS0 and dHS results from the observation that most of the variance of HS0 occurs at much smaller scales (Fig. 7a). Figure 8d illustrates variability in the compensating correlations. At small scales below 50 m, the differences in *Solar Irradiance* are small and the cold content is responsible for slight negative correlation between HS0 and dHS. This is counteracted by *Solar Irradiance* until the distance of 250 m (cp. Fig 8a).

There needs to be a match in scaling behaviour between SWE and melt rate for these variables to develop spatial correlations. Assuming melt is primarily driven by aspect and slope differences as in the proxy *Solar Irradiance*, SWE must vary on similar scales for a correlation to develop. This may be achieved if SWE varies primarily over larger scales, e.g. in a simple topography of a ridge without gullies and with one predominant wind direction during blowing snow, in which one slope face has much larger SWE values than the other. This may also be achieved if *Solar Irradiance* acts on a smaller scale similar to HS0. This might be possible in highly complex terrain in which most slope/aspects differences can be found on scales below 100 m but this does not correspond to the “ridge” in our study site.

4 Conclusions and outlook

The aim of this study was to determine factors which influence areal snow ablation patterns in alpine terrain~~.~~ using spatially intensive observation. The dependency of ~~SWE~~snow accumulation and topographic variables ~~on~~with spatial melt rates were analysed for an alpine ridge in the Fortress Mountain Snow Laboratory located in the Canadian Rocky Mountains. Detailed maps of snow depth~~ (HS),~~, snow depth ~~changes (dHS)~~change and snow-covered area ~~(SCA) ~~were generated during late season ablation with UAV~~—~~-based orthophotos, photogrammetry and Structure-from-Motion techniques. ~~HS~~Snow depth and ~~dHS~~its change served as proxies for ~~SWE~~snow accumulation and melt rates. ~~Ablation rates~~Snow depth change values were found to be spatially variable and mainly dependent on variation in solar irradiance and albedo~~.~~, and likely on the cold content of the snowpack which is a function of snow depth. Local and small-scale dust variations, which ~~have never~~had not previously been ~~observable to this degree~~observed in the area, increased the variability of ablation.

~~However, snow-cover~~Snowcover depletion ~~(SCD)~~ curves were ~~largely~~mostly dominated by the ~~SWE~~ variability of initial snow depth at the start of this study~~, which~~ rather than the variability in snow depth change. Initial snow depth variability was approximately five times larger than ~~melt~~the variability in snow depth change in this ~~extraordinarily~~ windswept environment. ~~More importantly, SWE and melt rates~~The scales of variability of snow depth and snow depth change were mismatched, with snow depth variability occurring at small scales (<10 m) and snow depth change associated with the medium scale (50 m) of albedo variation or the slope scale (100s of m) of solar irradiance variation. As a result, the initial snow depth and changes in snow depth were not strongly correlated over space, ~~which is a prerequisite for melt influencing SCD. Three reasons for lack of spatial association between ablation and SWE patterns here are: (1) the snowcover was isothermal during of the study period so that spatial differences in the depth dependent cold content as found by DeBeer and Pomeroy (2010), did not play a relevant role; (2) the SWE pattern was~~and so only initial snow depth influenced ~~by two dominating wind directions, preventing wind loading on particular slopes coincident with either larger or low energy input as found by Pomeroy et al. (2003), Dornes et al. (2008 a,b) and Musselman et al. (2015); (3) near summer solstice conditions limited differences of radiation energy input between slopes; (4) a scale mismatch between the variabilities of ablation and SWE was detected, with SWE varying mostly on smaller scales (in-slope gullies, ridges), while melt varied mostly on larger slope-scale aspect differences.~~ snowcover depletion.

~~These findings suggest that during those conditions SCD curves can be calculated without the spatial distribution of melt rates, while hydrological and atmospheric models need to implement a realistic distribution of SWE in order to do this. Comparison of these results to those found in Switzerland, Yukon, the Canadian Rockies and mountains in Idaho, indicates that clear advice to modellers is still not possible. It is not possible to determine without detailed modelling or measurements whether, when and where a catchment-wide multi-scale association between SWE and melt are capable to sufficiently alter SCD curves from those derived with an uniform melt assumption.~~

~~Thus~~The observations collected here show the prerequisites for strong correlations that can impact snowcover depletion curves. Correlation between melt and snow accumulation may be driven by cold content and melt energy distributions. Whilst cold content can create a negative correlation between melt and snow accumulation, melt energy variations can create either positive or negative correlations. In order to not compensate for each other, one process needs to be dominant, or the both processes need to create a similar negative correlations. It is also important that these variations occur at the same spatial scales.

To further investigate these arguments, longer time series of spatially detailed ~~SWE~~snowpack and snowcover observations need to be made in order to further test and examine the temporal evolution of the spatial covariance and variance of ablation and ~~SWE in order to~~accumulation in various global alpine environments. The results of such a study could suggest how to ~~efficiently and accurately model~~ parameterise snow-cover depletion and runoff ~~in snow-melt~~models for snowmelt dominated ~~catchment, and to deal with region variations in associations between SWE and melt~~alpine catchments, without relying on ~~powerful~~model calibration ~~routines~~. This will help to transfer snow-hydrological models to ungauged catchments and to model future climate scenarios where snow redistribution patterns might be vastly different.

5 Data availability

The data is available, upon request from the database manager (~~Branko Zdravkovic),~~Amber Peterson, in the ~~Changing Cold Regions (CCRN)~~Global Water Futures dataserver. (www.ccrnetwork.ca/outputs/data/index.php). Please refer to this website for contact details. The data involves all UAV derived grids for HS, dHS and SCA, as well as grids of explaining variables (Brightness, Deviation from North and Slope) in 1 m resolution (cp. section 2.4). Metadata is provided which explains the file naming convention of the grids (dates and variables).

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Figures

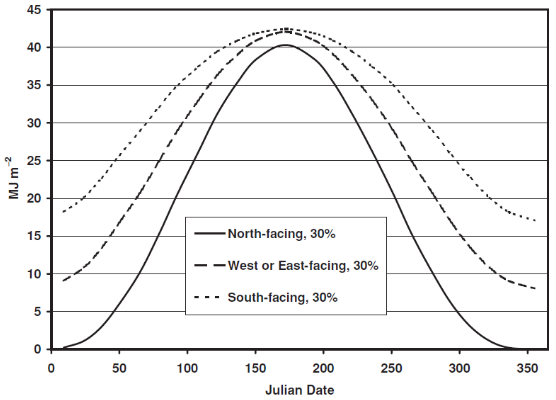


Figure 1. Extraterrestrial solar irradiance at 50° N for north, south and east/west facing 30 % slopes. Note the small differences as summer solstice is approached (~~Male~~after Gray and ~~Gray~~Male, 1981).

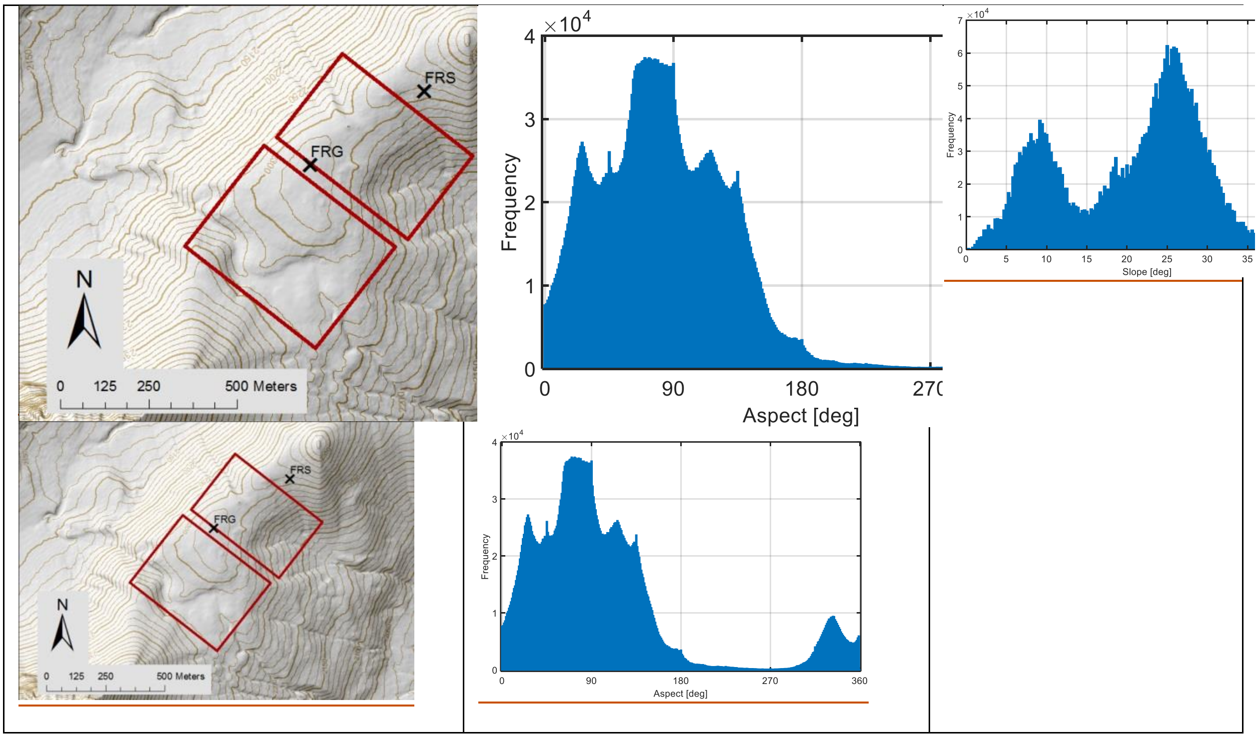


Figure 2. Topography of the study site, (a) Overview of the two areas of investigation (red rectangles) with the location of the two weather stations (black crosses) on the alpine Fortress Ridge, Alberta, Canada, and (b) aspect distribution of the snow covered area at 27 May 2015 (spatial resolution of 10 cm, N > 3 x 10^6).

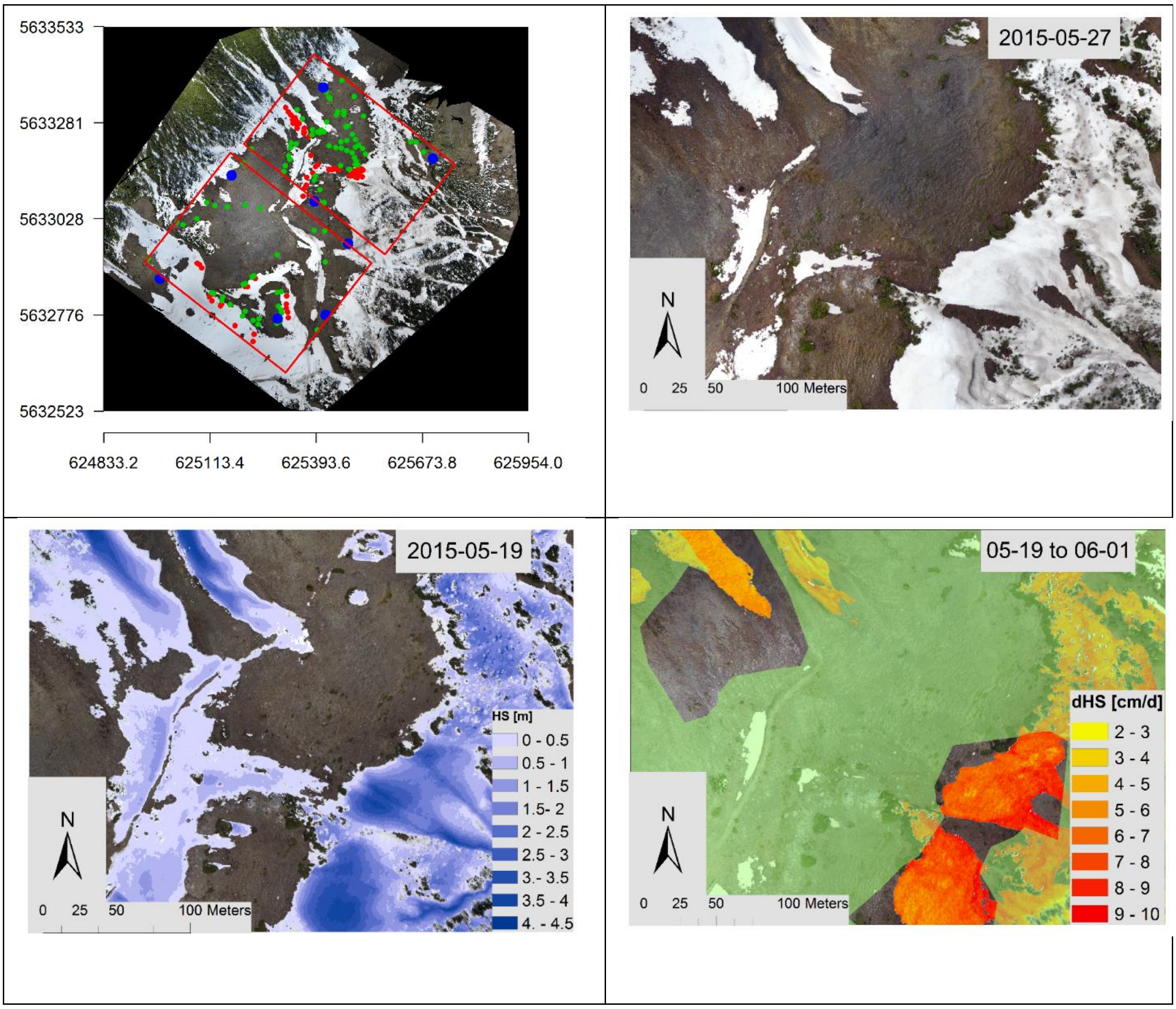


Figure 3. UAV photogrammetric data for the study site: (a) orthomosaic from images captured on 22 May 2015, showing the two N and S areas of investigation (red polygons). Points indicate locations of manual snow depth and differential GPS measurements over snow (red) and bare ground (green). (B) enlargement of part of the study area showing evidence of dust on snow, (c) snow depth (HS) on 19 May 2015 and d) differences in snow depth (dHS) between that date and 1 June. The green colour in (d) indicates areas excluded from analysis because of human impacts on snow or substantive vegetation.

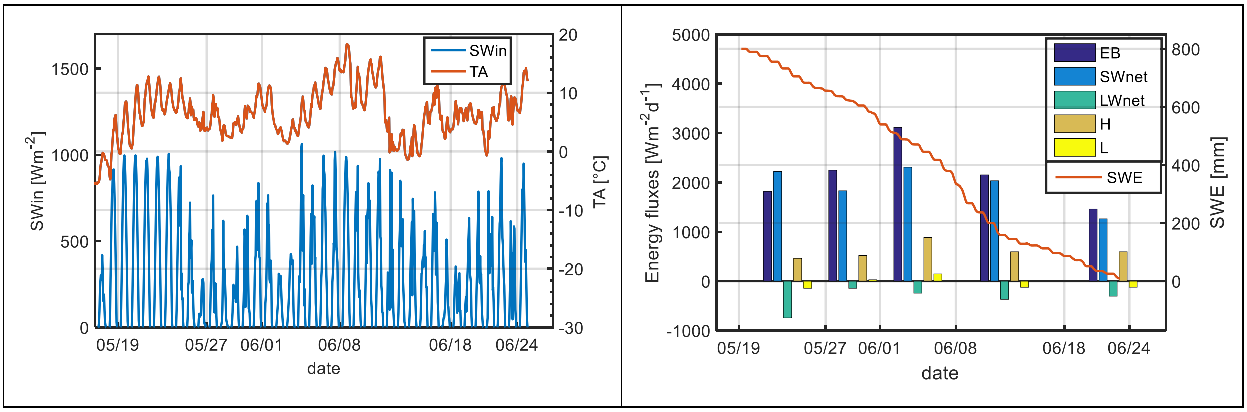


Figure 4: Measured (a) and modelled (b) values at the FRG station, energy fluxes per day for periods between UAV flights as modelled by ~~SNOBAL in~~ CRHM. EB is the total energy flux, SWnet and LWnet are net shortwave and longwave radiation, H and L are sensible and latent heat fluxes. Heat advected by rain and ground heat flux, with only small contributions are not shown.

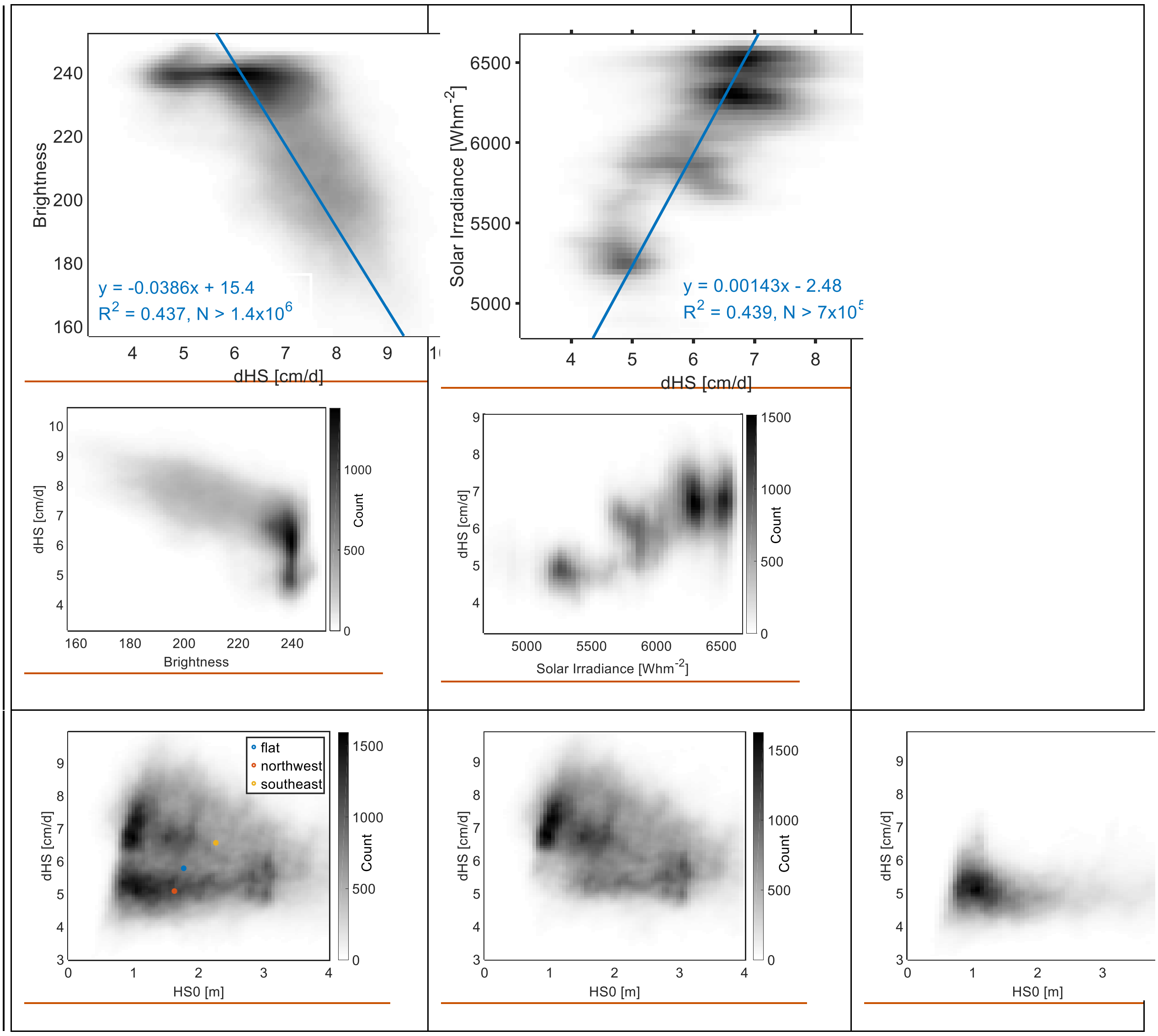
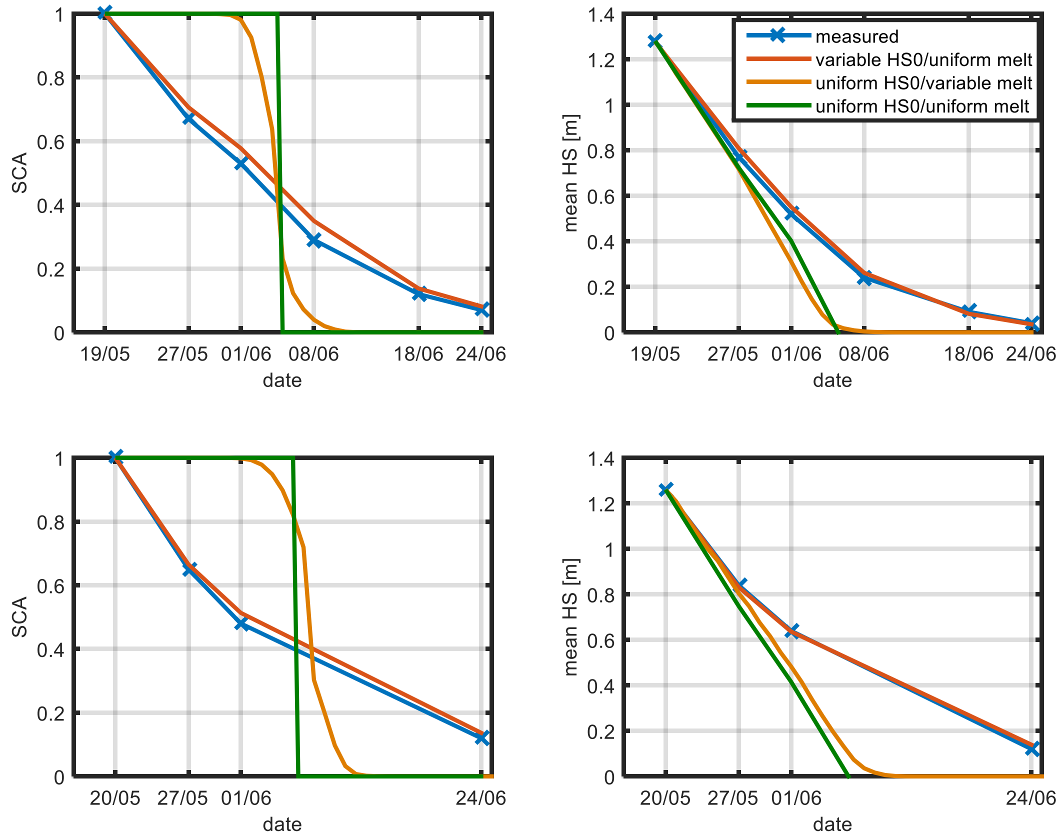


Figure 5. Scatter plots of (a) snow brightness and b) solar irradiance versus differences in snow depth (dHS~~).~~) for the northern subarea. Darker tones indicate a higher density of points. For (b) only bright snow pixels are used (brightness > 230). ~~Blue lines indicate the linear regression lines, which are highly significant (p = 0) because of the large number of observations.~~



Scatter plots (c-d) show the dependence of dHS and HS0 for the whole area with mean values of either side of the ridge and additionally flat pixels(c), and only on the northwestern (d) and southeastern part of the ridge (e).

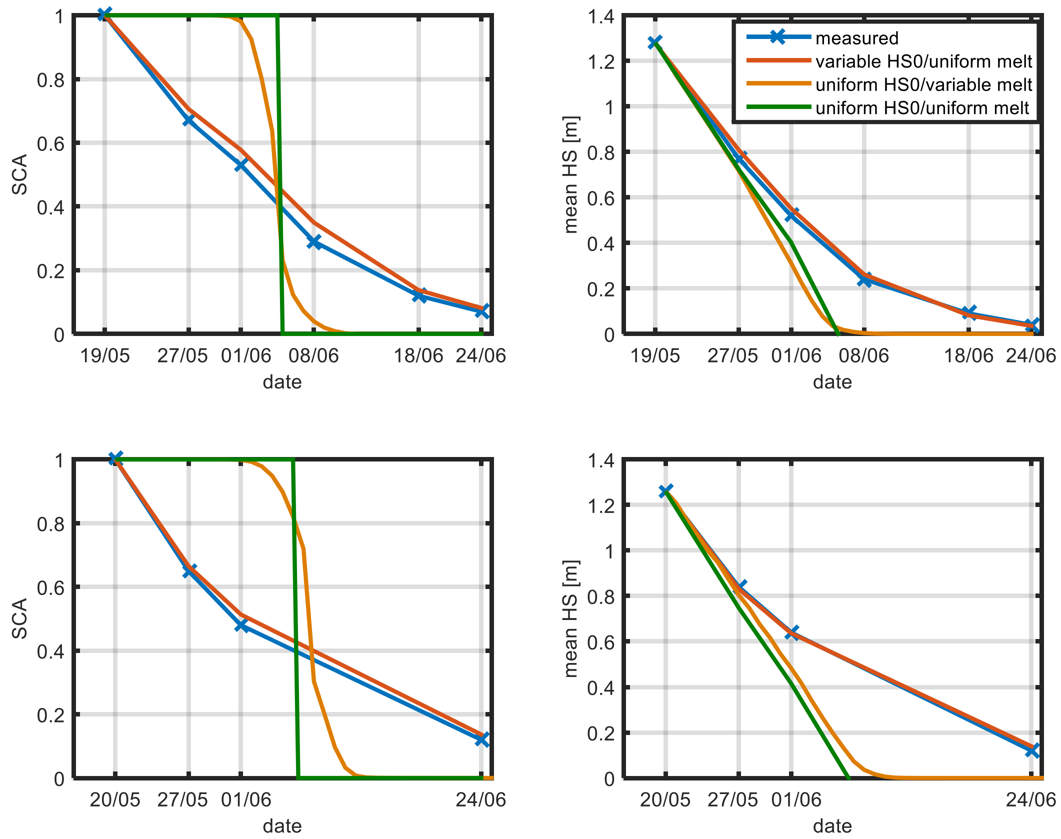


Figure 6. SCD and mean HS ablation for subarea N (a, b) and the total area (c,d). Blue are measured values, red are modelled values with initialized with measured HS distribution on May 19 and uniform melt, green are modelled values initialized with uniform snow depth distribution and uniform melt.

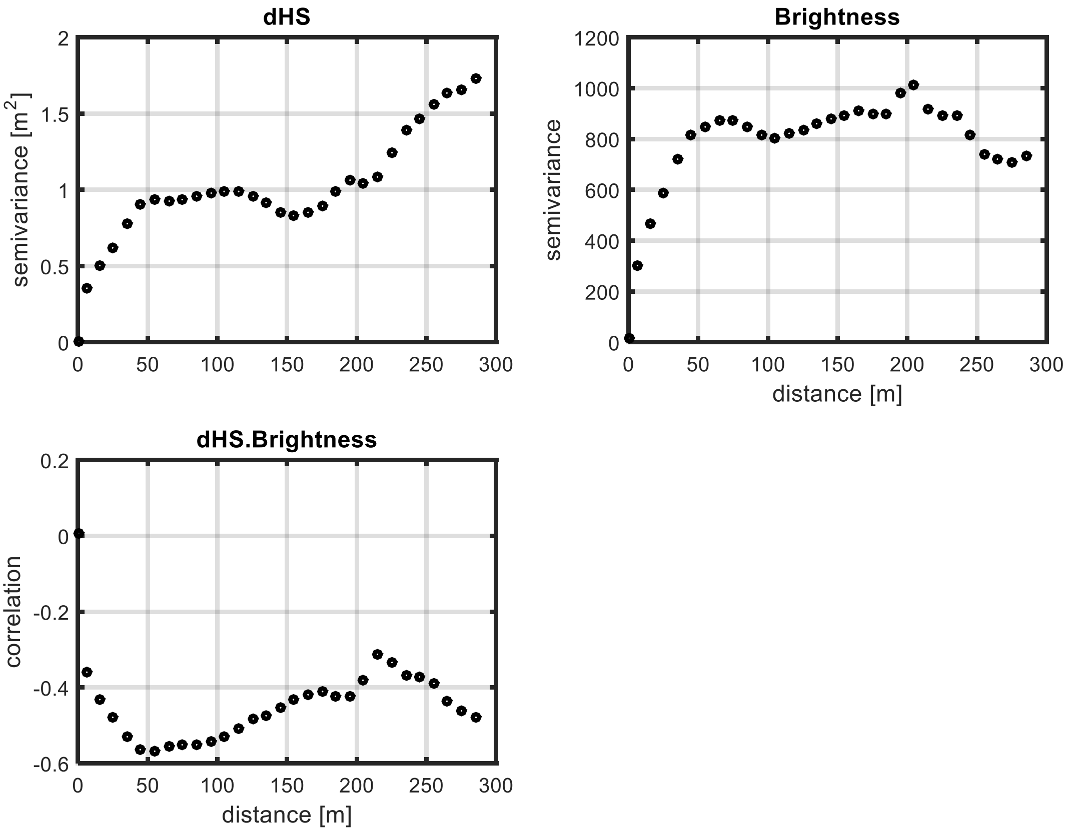


Figure 7. Variograms and correlogram for dHS and Brightness.

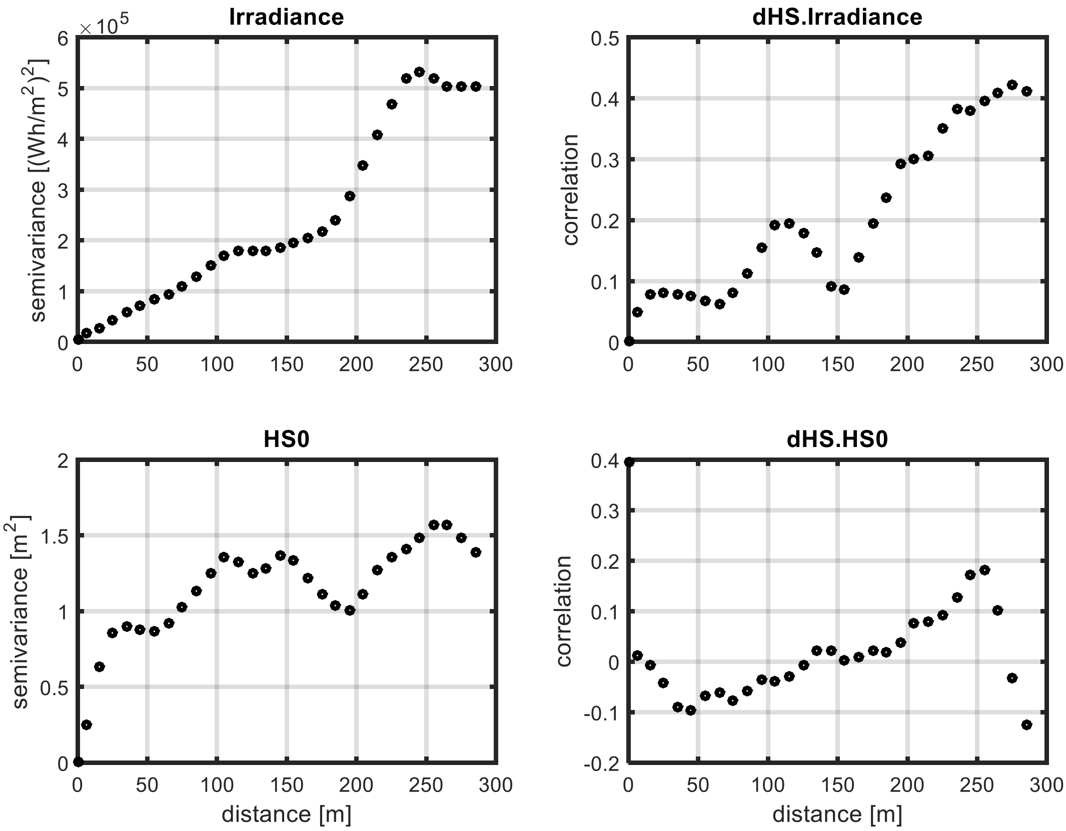


Figure 8. Correlograms with dHS and variograms for initial HS0 and modelled Irradiance.

Tables

Table 1. Pearson's correlations coefficient r between dHS and explaining variables. P1 is from 19 May to 01 June and P2 from 01 June to 24 June. N is number of observations.

Period	Area	Brightness	Degrees from North	Solar Irradiance	HS0	N
P1	all	-0.47	0.56	0.39	-0.12	3245837
P2	all	-0.59	0.30	0.01	0.33	706344
P1	N	-0.66	0.57	0.57	-0.24	1410768
P2	N	0.03	0.84	0.84	0.03	183822
P1	S	-0.43	0.39	0.33	0.01	1835069
P2	S	-0.68	-0.21	-0.61	0.30	522522

Table 2. ~~Results from stepwise linear regression. DegN stands for Degrees from North, Bright for Brightness, SolIrr for Solar Irradiance. Bright1 is the Brightness at the date of the first flight. The coefficients are normalized, which lead to negligible intercepts.~~

~~Period~~	~~Area~~	~~Regression equation~~	~~R^2~~	~~N~~
~~P1~~	~~all~~	~~dHS = 0.62·DegN - 0.54·Bright~~	~~0.60~~	~~3245837~~
~~P2~~	~~all~~	~~dHS = 0.25·Slope + 0.41·DegN - 0.60·Bright~~	~~0.52~~	~~706344~~
~~P1~~	~~N~~	~~dHS = 0.49·DegN - 0.59·Bright~~	~~0.67~~	~~1410768~~
~~P2~~	~~N~~	~~dHS = 0.84·DegN~~	~~0.71~~	~~183822~~
~~P1~~	~~S~~	~~dHS = 0.44·DegN + 0.18·Bright1 - 0.84·Bright + 0.23·SolIrr~~	~~0.52~~	~~1835069~~
~~P2~~	~~S~~	~~dHS = 0.42·Slope - 0.57·Bright~~	~~0.63~~	~~522522~~

~~Table 3.~~ Mean, standard deviation (SD), Coefficient of Variation (CV) for snow depth (HS) and snow depth change (dHS) for different periods and areas. P1 was from 19 May 2015 to 01 June 2015 and P2 from 01 June 2015 to 24 June 2015. Values are given for only snow-covered areas. Values for HS are given for the start date of the period. Values for dHS are given for the area which was snow covered at the end of the melt period.

Period	area	HS [m]			dHS [cm/d]		
		Mean	SD	CV	Mean	SD	CV
P1	all	1.26	1.16	0.92	6.22	1.22	0.20
P2	all	1.33	1.13	0.85	7.57	1.19	0.16
P1	N	1.28	0.93	0.73	6.86	1.22	0.18
P2	N	0.98	0.73	0.74	6.76	1.35	0.20
P1	S	1.25	1.27	1.01	5.72	0.97	0.17
P2	S	1.54	1.27	0.83	7.86	0.98	0.12