Response to Reviewers
TC-2016-61
Local reduction of decadal glacier thickness loss through mass balance management in ski resorts

A. Fischer[1], K. Helfricht[1] and Martin Stocker-Waldhuber[1]

[1]Institute for Interdisciplinary Mountain Research, Austrian Academy of Sciences, Innsbruck, 6020, Austria
Correspondence to: Andrea Fischer (andrea.fischer@oeaw.ac.at)

We thank all the reviewers and the editor for spending their time and effort for providing comments, which are much appreciated. According to the reviewer suggestions, we reorganized and rephrased large parts of the manuscript (see the attached change track version of the final manuscript) and worked on the figures. We implemented a better description of uncertainties, improved the analysis of the data (presenting an overview instead of all the results at the specific sites), and shifted the results at the specific sites to the supplementary material. In addition to that, the suggested changes in the specific comments were done, and some additional work on grammar, spelling, and smaller corrections.

This file is organized in the following way:

- Response to the anonymous reviewer 1
- Response to the anonymous reviewer 2
- Response to the comments of Mauri Pelto
- Change track version of the final manuscript

Response to Anonymous Referee #1

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General comments :

This paper deals with the impact of mass balance management on glacier thickness changes in ski resorts. From photogrammetry, laser scanning and GPS measurements, the authors compared the thickness changes on profiles with and without mass balance measurements over the last 20 years. The authors conclude that thickness changes could be reduced by 35-65% thanks to the mass balance management. This paper shows a large dataset given that 16 profiles on 5 glaciers have been measured since 1997 or 1999. These comparisons are rare on the alpine glaciers and these results certainly deserve to be published. It does not concern the scientific community only but also many people involved in the mass balance management.

However, this manuscript has large weaknesses and did not reach a sufficient maturity. This manuscript is difficult to read and confusing.

First, the authors should revise the structure: -

We restructured the manuscript as suggested by the reviewer, extended the descriptions of the data, added more details on measurement accuracies and added a more detailed description of the method.

Data: a lot of information should be included in Data and not elsewhere in the paper: for instance, the information related to the uncertainties on photogrammetry, GPS.., measurements given in Discussion (lines 5-15 p 10) should be reported in Data section. The authors should check that, everywhere in the manuscript. Seven lines in "Surface elevation data" are not sufficient to describe the measurements given these data are the basis of the paper. The authors should explain here clearly that DGPS measurements of 2014/2015 are compared to DEM from 1997/1999 and 2006/2007. It is not obvious at this stage of the mansucript.

-The techniques of management on each glaciers should be summarized in a Table (maybe in the Table 2).

done

-In Data and Methods section, the explanations about the emergence velocities (p.5, lines 1-20) should be removed from Data and Methods: first, the authors do not provide any explanations here why and how they used these equations. At this stage, the reader wonders why the authors introduce these Equations relative to the emergence/submergence velocities. These equations should be moved to the Discussion (lines 16-29, p10) where the authors provide a discussion about the relationship between the surface mass balance and the elevation changes.

However, I am not sure these Equations are helpful given the authors do not use them. In any case, the authors should use the classical way to present the equation related to emergence velocity (Cuffey and Paterson, 2010, equation 8.65). Equations 2 and 3 are not necessary in any case, given these equations are not used for calculations in this paper.

The equations of Cogley et al. were replaced by the suggested equation in Cuffey and Paterson. As suggested by reviewer #1, this part was shifted to the discussion.

-Study sites: the authors should replace the long (and indigestible) description by a Table.

The Table was improved. The detailed description went to the supplement and were described by a shorter and more illustrative descriptions of the sites.

-Results: this section is indigestible. The reader does not need the full and detailed description of elevation changes at each pylons, skilifts, pistes. Here, the description seems to come directly from a technical report. It is not useful for the scientific community.

This part was shifted to the supplement.

The number of Figures which show the elevation changes (Fig 3, 4, 56,7,8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23,24 and 25 !!) should be considerably reduced and most of them should be moved in a supplementary material.

Done

For this section, the authors should make a strong effort to sum up the results, to analyze them and to make a new Figure to show the summarized results.

We now present three figures summarizing the results of all sites and all periods. Only one figure presents the types of measurements was kept as an example.

From my point of view, it is absolutely necessary and this kind of Figure would be useful for the scientific community.

Second, the analysis of results is poor. I am aware of the difficulties given that the data come from different techniques and different areas. In this way, it is very difficult to compare elevation changes for areas with different altitudes and different aspect.

We revised the presentation of the results to give a better overview by adding mean elevations of the test sites, by calculating annual values with the respective error bars and by separating sites with higher and lower thickness losses.

However, despite on Table 3, there is a lack of quantitative results. I think that Table 3 is not sufficient to analyze the results. In addition, I am not sure that results given in relative reduction % are relevant.

We removed the relative reduction from the Table.

Some figures in Table 3 seem to me strange or wrong: for instance, at ST2, the authors reported a relative reduction of -396% despite on the fact that the elevation change is +0.2 m for the reference profile and -0.7 m for the profile with mass balance management.

The mass balance management mainly influenced surface elevation changes at this location in period 2. We tried to clarify this point in the introduction: during the first period (~1997 to 2006), mass balance management was applied only after 2003. During the second period, mass balance management was applied continuously. This explains why the area mbm in period 1 shows higher thickness losses than the reference area, but lower ones in the period 2. The explanation was in the text, but very well hidden – we apologize and hope that the explanation in the introduction makes it easier to follow the interpretation. We only interpret the differences between period 1 and 2, and the differences between mbm and ref areas in period 2. We removed the relative numbers, as dividing by zero results in odd values.

Did I miss something? If not, the authors should check the whole results. Again, I do not think the relative reduction in % is meaningfull.

We removed that.

When the value of elevation changes are close to zero (close to ELA), the relative reduction can reach very large values but it does not mean that the impact is more important. This way of presenting the results is not convincing. I believe that the percentages given in the manuscript (and in Abstract) are easy to understand for the general public but are probably no relevant.

We replaced them by absolute numbers and added mean values of thickness change by Abermann et al 2010 for comparison.

Third, I am not convinced by the conclusions relative to the impacts of mbm. For instance, the authors claimed that "the submergence and emergence should be similar so that a large impact resulting from different or changing ice flow regimes is unlikely". It can be questioned from the results shown in this study.

Here we have a small misunderstanding, which we hoped to improve by rephrasing the text. We have to assume that submergence and emergence at mbm and ref profiles is similar and not changing too much with time. Otherwise, one could argue that the investigated thickness changes are not resulting from the mass balance management, but from ice flow dynamics. We now show in the study that the shape of the reduced thickness changes exactly fits to the covers for Schaufelferner. We think that this is a good indication that these sharp and rectangular bumps are not caused by changes in ice dynamics.

For instance, it seems very difficult to make conclusions about the impact of mass balance management when the measurements have been done at very different altitudes (Fig. 3, Fig 5, Fig. 7.) and for different aspects.

Our approach is to compare areas with mass balance management to areas without mass balance management at various altitudes. High elevations show low thickness changes, low elevations high thickness without mass balance management. With mass balance management, thickness loss is reduced in all elevations, but at different rates. We agree that modeling the effects of mass balance management would be difficult, as the full energy balance is needed and the course of ablation and accumulation during season can result in huge differences. Nevertheless, we think that this is a further step, but not the aim of this study: We wanted to show that there are effects by a relative comparison.

Moreover, I do not understand how the submergence/emergence velocities spatial distribution can be neglected in this study.

We investigate thickness changes, not mass balance, as this is the parameter which ski resorts are most sensitive or vulnerable. Horizontal flow velocities on Austrian glaciers are a few meters/year only, so that the differences in vertical flow velocities between the first and the second period and mbm and ref profiles located only few meters apart should be small. At least there is no known proof of rapid velocity changes between the first and the second period, and no indications of extremely changing flux divergence at the profiles. This should be evident from cracks and crevasses. In addition to that, pylons mounted at the glacier surface would have to be repositioned in case of such an event, leading to an official report on that event.

A reduction of ice flow velocity at the glacier tongues lead to increased thickness loss even at constant melt rates. A partially reduction of thickness loss in mbm areas at glacier tongues caused by changes in ice flow would be related to increasing flow velocities, which is not observed.

The authors wrote that "Interannual differences in emergence/submergence velocities are less than 0.5 m a-1 at Kesselwandferner", but, here, this is the spatial distribution of emergence velocities which is questioned. Or I missed something.

We need booth assumptions for our study. For Kesselwandferner, we actually measured emergence velocity of stakes separated only a few meters. The differences in emergence or submergence are small, unless ice flow velocities are ~100 m/year and the stake is located in a crevasse zone. This type of motion is clearly indicated by surface features as crevasses, and therefore we can exclude that. We did not include that in the discussion, as this topic is far from the main focus of the paper.

The results shown TCD in Fig 3 to 25 are confusing and again, a thorough analysis and a synthesis are missing to provide relevant results and to convince the reader.

We added the summary Figures and shifted the raw data figures to the supplement.

Many things should be improved but I think it is not necessary to make a list at this stage given that the structure of the manuscript and the analysis of the results should be strongly revised first. Detail information should be removed from the manuscript when there are not used in the manuscript (GPR data, history of ski tourism). The authors should check that carefully.

We removed the section on GPR data, but kept the evolution of glacier ski resorts, because it would not be quite straight forward to understand why the infrastructure is located at the current positions now causing the need for adaptation (at least for someone which is not too familiar with length and thickness changes on Eastern Alpine glaciers in last 40 years).

Response to the *anonymous referee #2*

General Comments

The paper presents a valuable, comprehensive and comprehensible overview about the medium-term (decadal) effect of technical modifications of the glacier surface mass balance within Austrian Skiing resorts. The application of these measures started around the year 2004 and the related physical processes and short-term effects were already investigated in detail in a number of earlier studies. The authors analyze digital elevation model differences as well as DGPS measurements at selected spots of different glaciers with and without application of such measures between multiple years in order to quantify the effect of these intentional modifications on surface elevation changes within this timescale. Results indicate the clear medium-term benefit as well as the limitations of these technical measures on a larger scale in terms of costs and efforts.

Although the uncertainty of their method is discussed in the manuscript, the latter should be done in a more thorough, quantitative way, thereby also using an appropriate and exact terminology. In a revised version of the manuscript, the individual uncertainty sources should not only be named but all of them also be estimated and Interactive the resultant combined expanded uncertainty as well as its impact on the main results comment of the paper calculated.

We restructured the manuscript and added thorough calculation of measurement uncertainties as well as a better description of other uncertainties.

Therefore I suggest accepting the paper after the points listed in the specific comments and some minor ones in the technical corrections have been implemented by the authors.

Specific Comments (in decreasing order of importance)

1. *In the discussion section (p10. Lines 5-15) the Authors indicate a maximum uncertainty for their method of 1.1 m for both the DGPS and the DEM differences. It is not clear a) how this number is calculated exactly (uncertainty components), b) what confidence interval it is referred to (e.g. standard (66%) or expanded (95% level) uncertainty), c) what the impact of the combined expanded uncertainty is on the main results of the paper. For clarity and consistency, I very much encourage the Authors to study and use the Guide to the Expression of Uncertainty in Measurement (GUM; JCGM, 2008)) as well as the terminology that is defined therein.*

The discussion of errors and uncertainties was shifted to the section on Data and methods and expanded, discussing systematic and measurement errors separately.

(2) It is not clear how areas with long-term mass balance management were exactly identified (onsite location) in the study (own (GPS) records or data from skiing resorts?). Please add this information.

The criteria for the selection of the test sites are now part of the paragraph on test sites. The locations have been clearly indicated by previous (own) GPS records and documents of the pre-projects. Of course only own DGPS measurements are presented here.

(3) Concerning the single effect of grooming on snow and ice ablation, the authors should add that the observed effect was in the order of only 5 % rather than 10% and that this number was very close to the measurement uncertainty (Olefs and Fischer, 2008; Fischer et al., 2011; ;Olefs, 2005;Olefs and Obleitner, 2007).

Done – we changed the number to the original 6% and added the information that this is close to the measurement accuracy.

It is also worth to clarify the following in the paper: Based on previous studies, it is still not clear what exact physical mechanism(s) leads to the observed effect. Beside the reduction of surface layer erodibility through compaction (stronger bonding of the snow crystals), there may be other effects, e.g. a modification of surface albedo due to a reduction of average grain size of the surface snow layers induced by the snow-cat or a modification of snow thermal conductivity (Olefs and Obleitner, 2007). If there are new studies that separate those exact effects on the ablation reduction known to the authors, they should cite them.

We changed the wording to distinguish measurements and unknowns.

(4) I strongly suggest adding units (SI) to all variables whenever formulas or variables are used in the manuscript (e.g. p.5).

The formula is replaced.

(5) The physical effect of water injection in the snow cover is mainly to add mass to the existing seasonal snow (if there is enough cold content in the snow to refreeze the injected water). After injection, the release of latent heat due to refreezing of the water decreases the absolute value of the cold content of the existing snow cover (as e.g. shown in Fig.7 of Olefs and Fischer, 2008). Firstly, I do not understand why the cold content should be increased by this method (p.3, line 19).

Secondly, the authors could also add the two main resulting limitations of this method apart from the large effort: enough cold content before injection and timing problem (enough time between applications).

We agree with that points (cold content can increase only if small amounts of water are injected and cold air can penetrate the snow cover through the holes for a longer time; no skiing and no grooming and no snow falls after the injection). As injection is not used as mass balance management method, but mainly for ski racing, we decided for shortening that part rather than going to deep into that topic.

Technical corrections

p1 (1) l30: ":::depth height:::??"

height removed

(2) l4: Fischer et al., 2011 a or b?

a, J Glac

p2 (3) l6: please explain the first occurrence of the shortcut “GI” (4)

done

l9: 1987 in the manuscript, 1986 in Tab.1 ??

1986

(5) l13: They noticed::.

Section rephrased

(6) l18 and others: I would prefer “t-bar lift” instead of “tow lift” throughout the paper

replaced

p3 (7) l19: increase or decrease cold content? you could use the absolute value to clarify::.

Water injection is not discussed any more

p4 (8) l19: please use consistent naming for “Austrian glacier inventory” (GI?)

ok

p5 (9) please add units to all variables (SI)

The section is removed

p6 (10) For DGPS (?) profiles::.

The section is removed

P7 (11) L20: here the single effect of grooming (compaction of the surface layers) is mixed with the potential effect of snow farming (lateral transport of snow mass by snow cats), please clarify.

The section was rewritten. In any case, we can not separate the effects of various measures in this spatially distributed study.

(12) L27: (Tab.3)

changed

P8 (13) L29-30: “On average” instead of “In mean”

changed

p12 (14) l5::::ski tourism in the year 2100::.

changed

(15) L12: “Fujita and Ageta, 2000” is missing in the references

added

(16)L16: I would suggest to write “(e.g. without glacier cover)” as a) in other regions of the world glaciers do exist at low altitudes and b) the fact that the effectiveness of surface textiles to reduce ablation decreases with altitude is not tied to the surface type (glacier or not) but it is due to the Interactive energy balance being dominated by sensible/latent heat fluxes at lower altitudes.

changed

(17) L18: at the end of this sentence you could again cite the work of Skogsberg as well as Grünewald and Wolfsperger).

done

References

P15, l21: The year of publication should be placed at the end.

Done

Figures

Fig.1: In the caption please specify whether DGPS measurements are indicated by

the red lines.

Not all the red lines show DGPS data, in case recent LiDAR DEMs have been available, these have been analyzed. The red lines thus denote survey profiles (either DGPS/DEM or DEM/DEM comparison). This note was added to the caption.

Fig.3 and following: it is not clear what you mean with "surface elevation

changes plotted for surface elevation in 2007" ? Do you mean the difference 2007 –

1999 and 2015-2007 ? Please clarify in the captions and also in the ordinate label.

The Figures have been shifted to the supplement. Y axis has not been changed for the various surveys, every point is displayed with its elevation in the year 2007. Otherwise, if every point had been displayed with the surface elevation during the surveys, we would compare different locations.

Fig3.: It shoud be 25th /75th percentile (and not %!)

Changed

The captions of all following figures could be reduced:::there is a lot of redundant

information.

As this is part of the supplementary material now, we decided to keep the full caption, as the main manuscript is much shorter and straight forward.

Fig.13 and 18: on the right subplot "mbm" and "ref" is missing as label

The indices "mbm" and "ref" are added to the corresponding profiles (Figures shifted to supplementary material and numbers changed).

References

Joint Committee for Guides in Measurements (JCGM): Evaluation of

measurement data – Guide to expression of uncertainty in measurement,

JCGM 100:2008, GUM 1995 with minor corrections, available at:

http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf, 2008.

Reviewer comments of M. Pelto mauri.pelto@nichols.edu are italic and underlined

responses

Fischer et al (2016) provide by far the most extensive examination of the impact of ski area management on local glacier mass balance. This is a unique data set that cannot be matched elsewhere; hence this contribution provides a valuable snapshot at a critical moment for ski areas with glacier terrain response to climate change. Most of the comments below are quite minor. Considerable figure consolidation could be completed. Brief reference to the practice in other nations is warranted. Also the impact of new snow and grooming on increasing albedo should be mentioned, even though, the point of this study was not to quantify that impact.

The figures now contain overview graphs and just few examples of the different data sets. The original Figures are shifted to the supplement still as a part of the draft.

We cited all the papers we could find on practice in glacier ski resorts in other nations, and would really like to add additional literature to this topic. Is there citable literature describing the mass balance management on the sites you mention?

We added the following citation to describe the effect of grooming on albedo:

Keller, T. Pielmeier, C. Rixen, C. Gadient, F. Gustafsson, D. Stähli, M., 2004. Impact of artificial snow and ski-slope grooming on snowpack properties and soil thermal regime in a sub-alpine ski area. Annals of Glaciology, 38, 1, 314-318.

Unfortunately, Keller et al. do not find empirical data on the effect of grooming on snow albedo. Measurements of this effect might be difficult for various reasons, amongst them:

- Bidirectional reflection of snow requires careful consideration of all combinations of grooming tracks and incidence angles
- During operation, ski tracks replace grooming tracks, with even more difficult to capture changes in optical properties.

Figure 1: A single skier changes surface albedo on 26.05.2005 in 2850 m.

Taking into account, that grooming during the investigated period ended with mid to end of May, and surface melt processes had been observed mainly from beginning of May onwards, the effect of grooming on albedo during melting season is thus small, which was the reason for skipping that topic initially.

2-1: to store and maintain snow:::.

changed

2-13: The to They

changed

2-17: Not only has visitor demand developed over time but cable car technology has advanced::.

changed

3-3: Crevassed reduced not just at ski areas but on other glaciers too, for example Colgan et al (2016) Pelto and Hedlund (2001).

We agree, this is stated also for example in Fischer, A. (2010) Glaciers and climate change: Interpretation of 50 years of direct mass balance of Hintereisferner, Global and Planetary Change 71, 1-2: 13-26.

3-5: Is removal of rock, sand and dirt from the piste not a goal? Grooming and new snow production oth increase the albedo. This is a goal noted by some of your previous research.

These measures have been included in the first point which comprises measures to decrease surface roughness. We added explicit examples to that point. The albedo topic is included in the third point, reduction of mass loss, as the high albedo is not an aim on its own purpose, but for its influence on mass balance. But as stated before, grooming during ablation season is rare.

7-26: I assume the 35% and 65% reduction are compared to adjacent areas of the same glaciers, if so more clearly state this. Somewhere it would helpful to reference typical thickness loss values from either WGMS reporting Austrian glaciers or from the inventory, as a wider reference.

We restructured the article including a better description of the reference measurements. Typical losses from the glacier inventory have been added.

Abermann, J., Lambrecht, A., Fischer, A., and Kuhn, M.: Quantifying changes and trends in glacier area and volume in the Austrian Ötztal Alps (1969-1997-2006), The Cryosphere, 3, 205-215, doi:10.5194/tc-3-205-2009, 2009.

The thickness of Ötztal glaciers reduced by 0.95 m/year in average between 1969 and 1997, and -0.91 m/year between 1997 and 2006.

9-2: Continuous grooming will increase albedo.

This section was restructured. The albedo discussion was included in the state of the art report. Unfortunately we do not have data on surface albedo.

10-26: I agree with this assertion "In any case, submergence and emergence should be similar for the profiles and the reference profiles"

We rephrased this part.

11-2: Grooming would also reduce albedo.

We added the information that grooming takes place during winter, and the effect is measured in summer, so that a direct influence of grooming on albedo is not very likely.

12-3: It is worth noting that mass balance management extends to Tignes, France; Whistler, BC and Mount Hood, OR.

We added this information together with other ski resorts from our personal knowledge.

12-28: The enhanced prominence of managed area versus managed areas, generates steeper slopes as noted. This in turn should increase ablation. Will also act both as a wind scour and potentially wind trap for accumulation. Is this observed?

Yes, both effects are observed, but not quantified in detail. The removal of snow from previously covered platforms leads to their rapid meltdown once the maintenance stops. The separation of radiative and wind drift effects is hard to measure and drawing general conclusions included high uncertainties.

Figure 1: Ski area boundary line should be more distinct color.

changed

Figures: The number of profile figures is impressive. However, collectively they are redundant and also detract from highlighting important overall trends. The variation from profile to profile becomes the focus. I would suggest utilizing only two sets from each glacier, or focusing more on the central panel. The central panel alternative takes TCD advantage of the fact that Table 3 provides the data from the third panel for each glacier.

We restructured the Figures.

Figure 1 provides profile location. Hence, you could just use the middle panel for all but two profiles on each glacier.

Figure 1 is changed, and we hope that you find it benfical.

Colgan, W., H. Rajaram, H., Abdalati, W., McCutchan, C., Mottram, R., Moussavi, M. and Grigsby, S: Glacier crevasses: Observations, models, and mass balance implications, Rev. Geophys., 54, 119–161, doi:10.1002/2015RG000504, 2016.

included

Pelto, M.S., and Hedlund, C.: The terminus behavior and response time of North Cascade glaciers. Journal of Glaciology 47: 497–506, 2001.

included

Local reduction of decadal glacier thickness loss through mass balance management in ski resorts

A. Fischer[1], K. Helfricht[1] and Martin Stocker-Waldhuber[1]

[1]Institute for Interdisciplinary Mountain Research, Austrian Academy of Sciences, Innsbruck, 6020, Austria
Correspondence to: Andrea Fischer (andrea.fischer@oeaw.ac.at)

Abstract. For Austrian glacier ski resorts, established in the 1970s and 1980s during a period of glacier advance, negative mass balances with resulting glacier area loss and decrease in surface elevation present an operational challenge. Glacier cover, snow farming and technical snow production were introduced as adaptation measures based on studies on the effect of these measures on energy and mass balance. After a decade of the application of the various measures, we studied the transition from the proven short-term effects to long-term effects by comparing elevation changes in areas with and without mass balance management. Based on LiDAR DEMs and DGPS measurements, decadal surface elevation changes in 16 locations with mass balance management were compared to those without measures (apart from piste grooming) in five Tyrolean ski resorts on seven glaciers. The comparison of surface elevation changes presents clear local differences in mass change, and it shows the potential to retain local ice thickness over one decade. Locally up to 2~~0~~1.1 m±0.4 m of ice thickness was preserved compared to non-maintained areas at glacier tongues over a period of nine years. In this period, mean annual thickness loss in 15 of the mass balance managed profiles is in average 0.57 m/y ± 0.04 m/y lower than in the respective reference areas.

~~At 11 out of 16 profiles with mass balance management measurements, surface elevation loss could be reduced by more than 35%. At six profiles, surface elevation loss was reduced by over 65%.~~ At two of these profiles the surface elevation was preserved altogether, which is promising for a sustainable maintenance of the infrastructure at glacier ski resorts. Features like former covered pistes and installations in fun parks have rapidly evened out with the surrounding surface elevation as soon as maintenance was stopped. In general the results demonstrate the high potential of the combination of ~~piste grooming and~~ mass balance management by snow production and glacier cover, not only in the short term, but also for multi-year application to maintain the skiing infrastructure.

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1 ~~1~~ Introduction

~~1.1~~ During the last three decades, alpine glaciers have retreated drastically and increasingly, with current annual rates at historically unprecedented levels (Zemp et al., 2015). Globally, glacier mass balances have been increasingly negative (Vaughan et al., 2013), leading to additional river runoff in glacier-covered basins (Kovats et al. 2013). In Asia glacier retreat is likely to affect water scarcity (Hijioka et al., 2013).In the European Alps, glaciers are part of the national economy, contributing to hydropower production and as part of ski resorts. Glacier ski resorts are located at high elevations and thus are less affected by a decrease in ~~depth height~~depth and duration of seasonal snow cover than lower ski resorts (Kovats~~,~~ et al., 2013). Recently, mass balance management methods have been developed to store and maintain snow in ski resorts (Skogsberg and Lundberg. 2005; Spandre et al., 2016; Grünewald and Wolfsperger, 2016) and manage meltwater production (Nestler et al., 2015; Norphel and Padma, 2015). In the Austrian Alps, mass balance management in glacier ski resorts started after the extreme melt in the summer of 2003 (Fischer et al., 2011a) to compensate for the negative effects of glacier retreat on ski resort infrastructure. This paper presents the long-term effects of the measures on local glacier elevation change.

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~~1.2~~ Austria's glaciers experienced a reduction by 26% in area in recent decades (~~GI1~~First glacier inventory GI1 1969 – third glacier inventory GI3 2006/2012; Fischer et al., 2015). Abermann et al. found mean thickness changes of 0.95 m/year between 1969 and 1997, and -0.91 m/year between 1997 and 2006 for the glaciers in Ötztal. Since the extreme summer of 2003, we have seen several years with negative mass balances in all elevation zones. The glacier changes of the last three decades were challenging for the eight Austrian glacier ski resorts (Table 1), which are located on 15 glaciers. They were opened between 1969 to 198~~7~~6, when up to 72% of the Austrian glaciers were advancing (Fischer et al., 2013b). During the early years of the glacier ski resorts, the main skiing season was during summer, with some of the resorts even being closed during winter. In recent decades there has been less demand for summer skiing ~~-~~and the main season has shifted to autumn and spring. Most resorts open during summer for hikers and mountaineers only. Diolaiuti et al. (2006) investigated glacier evolution and summer skiing at Vadretta Piana (Stelvio Pass, Italy). They noticed that, although the glacier has receded, single years of exceptional good conditions for glacier summer skiing can still result in a high number of skiers. A comparative study on the impact of glacier changes on mountain tourism was presented by (Smiraglia et al., 2008)

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~~1.3~~ Not only the visitor demand developed over time but also cable car technology has advanced and with it the demands on glacier conditions. Initially it was mainly tow-lifts operating on the glacier, low installations with adjustable pylons to compensate for glacier flow and mass balance. As these lifts transport the skiers along the ground, they are technically easier to maintain and have less strict corridors for compensating glacier motion and mass balance. However, tow-lifts need a route with a gentle slope. Nowadays, chair lifts and circulating ropeways are built with much higher pylons and bearing loads. While these lift types can also be built in complex terrain of steep slopes or rock cliffs, there are strict

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limits on the acceptable inclination of the pylons. Apart from lift infrastructure, pistes on the glacier surface have to fulfil specific requirements regarding width and steepness. The transition of the ski tracks from glacier to the bare ground changes constantly with variations in glacier surface altitude and snout position.

~~1.4~~ The loss of firn reservoirs, increase of debris on the glacier surface by melt and rock falls (Fischer, 2010) as well as more and deeper supraglacial channels increase surface roughness on glaciers, so that more snow is needed in grooming to smooth pistes (Fischer et al., 2011a). Where glacier ice has disappeared, bare ground is often steeper than and not as smooth as the former glacier surface, so that pistes have had to be rerouted to meet the requirements on width and difficulty. Sinking glacier surfaces often make exit and entrance to summit or valley lift stations difficult. Steeper glacier surfaces complicate the maintenance of traverse pistes and increase the danger of avalanches. As the ropeway pylons are mounted on sledges designed for specific pylon shifts, changes in the flow regime, i.e. velocity and/or direction shorten maintenance windows. In the worst case, sinking surfaces lead to angles and bearing loads which are out of the approved range for that installation, so that the ropeway has to be replaced or adapted. One positive effect of the years with negative mass balances was the decrease of ice flow velocities which led to a reduction of the number and size of crevasses (Colgan et al., 2016; Fischer, 2010; Pelto and Hedlund, 2001) also in glacier ski resorts (e.g. Fischer et al., 2011a; Diolaiuti et al., 2006).

~~1.5~~ Therefore, mass balance management in glacier ski resorts has three aims:

~~1.6~~ i) Decrease surface roughness by keeping snow over the summer (including keeping smooth firn or snow cover on bare and rough glacier ice, crevasses and supraglacial rivers, rock and debris).

~~1.7~~ ii) Keeping surface elevation around infrastructure

~~1.8~~ iii) Prevent or reduce ice melt to keep bedrock ice-covered.

~~1.9~~ In previous studies at the glacier ski resorts in Tyrol (Austria), later also at Dachstein Glacier ski resort, several methods for mass balance management in glacier ski resorts were investigated by extensive field work and modelling (Olefs and Fischer, 2008; Olefs and Obleitner, 2007; Olefs and Lehning, 2010):

~~1.10~~ - Glacier covers

~~1.11~~ - Grooming

~~1.12~~ - Water injection

~~1.13~~ - Snow-farming

~~1.14~~ Glacier covering means insulating the glacier surface with an approx. 2 mm thick white polypropylene fabric in the period between peak accumulation (mid-May) and the start of the accumulation season (early September). Piste grooming comprises regular mechanical preparation of the ski piste by snow cat during operation (i.e. between September and May). Water injection aims at the infiltration and refreezing of liquid water in the snow layer to increase density and is used rather for preparing pistes for ski races than for mass balance management.~~ and cold content~~. Snow-farming summarizes efforts to amass snow accumulated from wind drift, technically produced snow and snow from avalanche deposits, which is relocated by snow cats to create snow depots or increase accumulation on the piste.

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~~1.15~~ In the study of Olefs and Fischer (2008), glacier cover was by far the most effective method and reduced ablation by 60%. In case enough snow was accumulated during the winter or brought in with snow cats or wind drift, local annual mass balance even went positive during the experiments. Grooming without other measures reduced ice ablation by ~~10~~6% which is close to measurement uncertainty. The exact physical mechanism is unclear. We measured a higher accumulation at the groomed areas at the end of the winter, potentially caused by limited~~ing~~ wind erosion of snow (Fischer et al., 2011a). We can not exclude other reasons for increased accumulations, such as modification of surface albedo or modifications of thermal conductivity. Fahey et al. (1999) observed up to 45% more water available on groomed pistes compared to non-groomed slopes. The application of water injection into the snowpack was not developed further. It increases the mechanical resistance of the piste, but has little effect on local glacier mass balance (Olefs and Fischer, 2008). As all measures are costly and need much manpower, application is limited to small areas, which have been identified as areas where sinking surface elevation, bare ground or steep slopes would do the most harm to the infrastructure. Thus mass balance management is applied only on less than 10% of the ski resorts glacier area, with mean values of about 3%, limiting the impact of the measures to hydrology and total glacier mass balance. As an additional method, snow production facilities have by now been installed at a number of ski resorts, providing snow on pistes for an early season start even on bare ice surfaces, when firn cover is missing, and to reduce ice ablation in summer.

~~1.16~~ After a decade of measuring the glaciers, the question arises of the long-term outcome of these measures: Although the short-term effect has been proven, it could be that measures have not been applied frequently enough to return a sustainable result, or that ice dynamics lead to a redistribution of masses so that, for example, no effect on surface elevations would be measurable. From this basic research question, this study aimed at assessing long-term net effects by comparing surface elevation changes in areas which have been subject to different types of mass balance management and neighbouring areas without such management. Surface elevation changes in mass balance managed areas were compared ~~-~~to neighbouring areas of the same elevation and exposure without such measures (apart from some grooming of pistes). The comparison was done for two time periods. The first is given by the date of the glacier inventory DEMs. Mass balance management measures started at the end of the first period. The effect of the mass balance management is investigated by i) comparing the first period (mass balance management was only applied in the late years) to the second period (mass balance management in the full period) and ii) comparing managed and unmanaged areas in period 2. The investigated measures were accumulation by snow production and movement of snow with snow cats in combination with glacier covers. ~~Surface elevation changes were compared to neighbouring areas of the same elevation and exposure without such measures (apart from some grooming of pistes).~~

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2 ~~2~~ Data and methods

~~2~~2.1 Elevation data

For the calculation of thickness changes three different sources of elevation information have been used in this study (Table 2). For all test sites, digital elevation models (DEMs) from the ~~2.1 Surface elevation data~~ second (GI2, 1997 and 1999) and third (GI3, 2006/2007) glacier inventories were used. The DEMs of GI2 are based on photogrammetry, the DEMs of GI 3 on LiDAR imagery. All DEMs are referenced to the official Austrian geodata Three test sites have been covered by recent high precision LiDAR DEMs. To capture the thickness changes at all sites up to 2015, surface elevation was recorded with DGPS along profiles. ~~All elevation data are summarized in Table 2.~~

~~2.1~~2.1.1 Photogrammetric DEMs

~~2.2~~ The ~~digital elevation models (~~DEMs~~)~~ ~~which are part~~ of the 2nd (GI2) ~~and 3rd~~ Austrian glacier inventory (~~Fischer et al., 2015;~~ Lambrecht and Kuhn, 2007). are based on ortho-photo~~grammetrys~~ ~~for GI2 (~~ with 5 m grid size~~)~~. ~~and airborne laser scanning (ALS) surveys for GI3.~~ ~~For some of the ski resorts, DEMs exist from more recent ALS surveys (1 m grid size). Additionally, we performed DGPS measurements of the surface elevation along profiles using a TOPCON HiPer V Dual-Frequency GNSS Receiver. Raw DGPS data were corrected in post-processing with data of the reference stations Merano, Bolzano, Vipiteno and Malles Venosta provided by the autonomous province of South Tyrol / Alto Adige (http://www.stpos.it/SpiderWeb/frmIndex.aspx). All elevation data are summarized in Table 2.~~ The DEMs have been calculated with a semiautomatic method in a 20 m grid (Würländer and Eder, 1998). The requirement on vertical accuracy was defined as ±1.9 m (Lambrecht and Kuhn, 2007) and found to be better than ±0.71 m by Würländer and Eder (1998). In shadowed or oversaturated parts of the orthophotos, local errors can be larger, as shown by Abermann et al. (2007) comparing in situ measurements on Kesselwandferner in Ötztal Alps with DEM data. There is no indication that the DEMs of the test sites in this study are not lying within the error margin of ±0.71 m found by Würländer and Eder (1998), as the respective orthophotos did not show oversaturation or shadows. The orthophotos were taken in August and September, close to the seasonal minimum of snow cover.

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2.1.2 LiDAR DEMs

The airborne LiDAR DEMs of the third glacier inventory were recorded by the Federal Government of Tyrol with a density of four points per square meter with ALTM 3100 and Gemini sensors. The vertical accuracy is given as ±0.1m (Abermann et al., 2010). Studies on the accuracy of LiDAR DEMs by ~~For some of the ski resorts, DEMs exist from more recent ALS surveys (1 m grid size).~~ Bollmann et al. (2011), Joerg et al. (2012), Deems et al., (2013) and Sailer et al. (2014) confirm measurement accuracies better than ±0.2 m for flat areas. Fischer et al. (2011) compared in situ measurements and LiDAR altitudes of 51 periglacial ground control points, suggesting an accuracy of the LiDAR DEM better than ±0.3 m. The LiDAR DEMs were recorded in late August and September, close to the seasonal minimum of snow cover.

2.1.3 GPS measurements

~~Additionally, we~~We ~~performed DGPS measurements of the~~recorded the surface elevation along profiles using a TOPCON HiPer V Dual-Frequency GNSS Receiver. Raw DGPS data were corrected in post-processing (software: Topcon Magnet Tools) with data of the reference stations Merano, Bolzano, Vipiteno and Malles Venosta provided by the autonomous province of South Tyrol / Alto Adige (http://www.stpos.it/SpiderWeb/frmIndex.aspx). The standard deviation of the corrected data was calculated with as 0.07 m (vertical) and 0.15 m (horizontal). The uncertainty of the vertical component of the DGPS location is assumed to be 1 m (e.g. Monteiro et al., 2005). The DGPS surveys took place in July and August, with a snow covered area similar to the DEM data. In rather steep terrain, horizontal dislocation increases the vertical error.

~~2.3~~

~~2.2~~

~~2.4~~2.2 Calculation of ~~Surface elevation~~thickness changes

~~Local glacier thickness changes (Δh) result from mass changes caused by surface or basal mass balance (Δm), from the densification of snow and firn (Δρ), and from changes in submergence or emergence resulting from ice flow (Δv) (Cogley et al., 2011).~~

~~$\Delta h = \Delta m/\rho + h\cdot\Delta\rho + \Delta v$ (1)~~

~~Assuming that the mean density (ρ) of the entire column containing ice, snow and firn is constant (Δρ = 0) and glacier thickness changes (Δh) are similar to surface elevation changes (Δz) caused by mass changes and changes in ice flow between two dates of surveys t0 and t1:~~

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~~ht1-ht0= zt1 – zt0 = (mt1-mt0)/ρ + ((vt1-vt0)/2)·(t1-t0) (2)~~

~~In the ablation area, thickness change can be positive if ablation decreases between t0 and t1 and/or emergence velocity increases. In the accumulation area, positive thickness changes occur when accumulation increases and/or submergence velocity decreases.~~

The ~~geodetic surface elevation changes~~thickness change at a single location Δz ~~are~~ is calculated by subtracting the altitude at the dates of the first survey (t0) and of a second survey (t1) ~~at every DGPS measured point of the profile~~

$$\Delta z = z_{t1} - z_{t0} \quad (3)$$

The mean thickness change of a profile was calculated as average of the thickness changes of every point within the profile. The thickness change between DEM and DGPS data was calculated at every point recorded by DGPS. The differences were calculated with ArcGIS (version 10.2.2): Elevation values were extracted from the DEM rasters of the different dates using “extract values to points” and surface elevation changes were calculated from these values at every point in the attribute table.

Thickness changes calculated from ~~In case~~ two DEMs, ~~were used, the elevation changes were calculated for the~~were calculated along a profile line at equidistant nodes ~~(~~with a spacing ~~=~~ of 1 m)~~ along a profile line~~, which show similar point densities as the DGPS measurements.

~~The DGPS-measured altitude represents the altitude of the measurement point within the horizontal measurement uncertainty which was better than 0.2 m after post-processing. The DEM altitude represents the mean altitude within the pixel located at the DGPS measurement point. Seasonal snow cover was neglected.~~

The measurement errors of the thickness changes at one location is the sum of the measurements errors of each surface elevation data set, i.e. 0.7 m for the thickness change between the second and the third glacier inventory DEMs, 0.27 m for the thickness change calculated from the third glacier inventory DEMs and DGPS data and 0.4 m for LiDAR DEM differences.

Systematic errors of the thickness change result from positioning of the DGPS antenna above ground, different information content in raster and point data of elevation, the and well as seasonal snow cover. To prevent shading of the signal, the DGPS antenna ~~ha~~was ~~to be~~ mounted on a stake or at a ~~rucks~~bagpack during the measurements. Penetration of the stake in the snow, deviations from the perpendicular or other deviations from the recorded mounting positions can affect individual measurements in range of centimeters. The DGPS-measured altitude represents the altitude of the measurement~~ point within the horizontal measurement uncertainty which was better than 0.2 m after post-processing~~. The DEM altitude represents the mean altitude within the pixel located at the DGPS measurement point. As the LiDAR data is based on 4 pixels/m² and has a

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spatial resolution of 1x1 m. The spatial resolution can be considered similar to the DGPS measurements (acquired every second at walking velocity resulting in a point density of 1-2points per meter~~ XXXXX)~~. The DEMs of the second glacier inventory have been processed in a 20x20 m grid. This grid was then resampled to a 5x5 m grid. As ~~tehse~~these have been recorded before mass balance management started, the glacier surface has been smooth, so that the deviations within one pixel from the pixel mean result from the surface slope, which is lower than 20 ° in the test sites. Therfore, the difference of point altitudes from the mean within the grid cells is lower than 1.3 m for slopes with 20 ° and lower than 0.08 m for slopes with 5°.

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All the elevation data was recorded during ablation season, with major parts of the glacier showing bare ice. As every year and every region show a different course of accumulation and ablation, it is not possible to survey each site at it's individual minimum of mass. Although thus minor impacts of old snow (from the winter) can not be excluded, all data were recorded in absence of new snow. Therefore, the effect of seasonal snow cover is neglected. In any case, the time span of one decade includes considerable interannual variability in glaciological and meteorological parameters. The effect of old snow, confined to highest elevations at the survey dates, is lower than this the year to year variability, as the early date of the survey in 2015 coincides with extreme melt rates and early recession of snow cover.

~~2.3 **The s**~~

~~2.5~~2.3 Study sites

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During 2003-2009, areas with mass balance management on Stubai Glacier, Pitztal Glacier, Kaunertal Glacier and Sölden Glacier ski resort have been monitored extensively, with at least two surveys per anno and a maximum of weekly surveys on Stubai glacier. After finishing these projects, the sites were still monitored on an annual basis with few ablation stakes and a photographic documentation of the evolution of the glacier surface. Based on this documentation, areas with continuous mass balance measured within these ski resorts have been selected for this study. Although not being subject of the initial research projects 2003-2009, sites in the Hintertuxer glacier ski resort have been included in this study, as these are the sites with the longest history of mass balance management by on-glacier snow production. Mass balance management takes place in areas where technical infrastructure located on solid ground borders to ski pistes on glacier parts with high subsidence rates, at pylons on glacier or boarder parks with jumps, jibs and pipes. Exemplarily, three locations with mass balance management are shown in Figure 2. The middle station at Schaufelferner (Figure 2 a) is located on a rock, with the surrounding glacier showing high subsidence rates. Glacier covers are applied since 2004 to allow the access to and exit from the station. The steepening tongue of Rettenbachferner is kept in shape with a combination of snow production and covers to provide easy access to the valley station, from which the photography in Figure 2 b) is taken. The subsidence of glacier surface is highest at the tongues, but also takes place in highest elevations. Most striking effects are observed close to the cols and at the transition to solid ground in highest elevations. The exit from the top station from which the photo in Figure 2 c) is taken crosses a steepening and subsiding slope, which is kept in shape and at the same altitude by covers. The upper left side of the photo shows covered snow/firn hills used as jumps for snow boarders and free skiers.

The LiDAR DEM hillshade of the site ST5 shown Figure 2a shows the location of the prominent glacier covers, which clearly show lower thickness losses than the surroundings (Figure 3).

~~The investigated glaciers where chosen with respect to data availability from previous studies in these glacier ski resorts, i.e. Stubai Glacier, Pitztal Glacier, Kaunertal Glacier and Sölden Glacier ski resort (Tab. 1). In addition to these ski resorts, Hintertux Glacier was chosen because this resort has one of the first on-glacier snow production facilities. Within the resorts we identified areas with long term mass balance management (Figure 1). Examples of such areas are presented in the pictures of Figure 2.~~

In the five glacier ski resorts (Table 1), 24 sites with mass balance management have been selected for comparing thickness changes in managed and reference areas. The comparison was carries out for two time periods~~ for each profile~~. Reference profiles are located within the pistes close to the mass balance managed profiles in similar settings in terms of slope, aspect, shade and snow accumulation. Several smaller features are presented in additional profiles.

~~For profiles in these areas, altitude changes in neighbouring profiles with and without snow and mass balance management were compared. All measured profiles are subject to grooming during winter. During summer, only the Hintertux Glacier ski resort operates summer skiing and grooms the pistes. In addition to that, the glacier is covered during summer and/or technical snow is produced in winter at the profiles, but not at the reference profiles which are located nearby in similar settings in terms of slope, aspect, shade and snow accumulation. In the Hintertux Glacier ski resort on the Gefrorene Wand Kees (Tuxer Ferner), surface elevation changes for the periods 1999 to 2007 and 2007 to 2015 were analysed for individual parts of a DGPS profile. The profile HI1 (Fig. 3) follows a piste, which is groomed with technical snow and partly covered with sheets in summer. The lowest points in the profile belong to an off-piste traverse towards another piste. Profile HI2 (Fig. 4) follows a piste across a flat area, where the glacier ice is covered in summer. Profiles HI3 and HI4 (Fig. 5 and 6) cross a piste from the off-piste glacier surface towards the glacier margin. In this area a combination of technical snow production and glacier cover in summer is applied to reduce ablation at the glacier margin. Profile HI5 (Fig. 7) is located on a small glacier tongue, which is covered.~~

~~For Stubai Glacier ski resort, the latest available DEM for the glacier ski resort dates from 2006. In 2015, DGPS measurements were performed at locations where different measures have been used since 2004.~~

~~Profile ST1 (Fig. 8) is located along a ski traverse from the cable car mountain station to the glacier col. This traverse is necessary to exit from the lift station. Ongoing reduction in glacier surface elevation and thus steeper slopes or even melt-out of rocks between the station and the piste on the glacier would disconnect those two. The traverse is packed with additional snow and subsequently covered with sheets every summer. Profile ST2 (Fig. 9) is located on an ice divide which connects~~

~~the two glaciers Gaißkarferner and Windacher Ferner. Profile ST3 (Fig. 10) comprises an area next to a mountain lift station. In this area surface elevation is preserved to maintain the gentle slope at the start of the piste. To receive reference data, the analysed profile was extended further down the piste.~~

~~A very local application of the glacier cover is presented in profile ST4 (Fig. 11). The base of a pylon of the cable car has been covered every summer since 2008, when the pylons were last replaced to compensate for the ice flow. Reference data were collected around this spot and along a profile on the piste nearby.~~

~~Data of profile ST5 (Fig. 12) mark an area essential for the operation of the Stubai Glacier ski resort. The cable car station is built on a rocky outcrop which originally divided the ice flow of Schaufelferner. The glacier surface elevation next to the cable car station was decreasing so that skiers would have to walk up to the station. The area has been covered every summer since 2004, with additional snow being deposited there. Reference data were collected from the piste above this location and from an area to the side of this location.~~

~~In the Sölden glacier ski resort, profiles SOE1 and SOE2 (Fig. 13) show elevation changes along a piste on Rettenbachferner. In the area around profile SOE1, technical snow is added to the natural snow cover, whereas along SOE2 the influence of these technical snow loads is reduced.~~

~~At profile SOE1a (Fig. 14), avalanche snow is moved from the periglacial area onto the glacier tongue. The area has been covered every summer for 12 years to maintain the piste connection from the glacier to the valley station.~~

~~Profile SOE3 (Fig. 15) is a length profile located on Tiefenbachferner. Detailed DGPS surveys were performed directly on this glacier tongue in 2015 (SOE3a, Fig. 16). Profile SOE4 (Fig. 17) presents data from a traverse in the upper part of Tiefenbachferner.~~

~~As an up-to-date DEM is available, no additional DGPS measurements were performed in the Pitztal glacier ski resort. Profiles PI1 and PI2 (Fig. 18) present surface elevation changes on a tow lift~~t-bar lift~~ route compared to the piste area. Profile PI3 (Fig. 19) is the corresponding cross section in this area.~~

~~In Pitztal Glacier ski resort profile PI4 (Fig. 20), mass balance management was applied until 2006 to preserve a tow lift~~t-bar lift~~ track and a piste. As the cable car was rebuilt as a detachable gondola lift on a new ice-free route and the ski piste relocated, no measures were applied after 2006. Profile PI5 (Fig. 21) shows the maintenance of the piste in the highest parts of Mittelbergferner.~~

~~In the Kaunertal Glacier ski resort profiles KT1 and KT2 (Fig. 22) present the evolution of huge kickers built in a fun park on Weissseeferner. Profile KT3 (Fig. 23) was recorded at a huge snowboarder bump with an ice cave inside. This bump was created by amassing snow and covering it with sheets during summer. Profile KT4 (Fig. 24) presents a ski traverse in the upper part of Weissseeferner. DGPS data of profile KT5 (Fig. 25) were collected along a tow lift~~t-bar lift~~ track.~~

~~3~~

3 Results

~~3~~

~~3.1 General Results~~ In general, in the last decade a balance of the surface elevation at high elevations could be achieved by snow grooming and by covering the glacier. At profile ST5 (Figure 4), a nearly constant surface elevation at the glacier terminus during the second period is a consequence of constant piste grooming, relocation of snow and glacier cover. In the reference area, without application of mass balance management, surface elevation loss of the second period was in the same magnitude as in the first period. Graphs similar to Figure 4 are shown in the supplementary material for all profiles. To provide ~~an~~a general overview, the thickness changes at all profiles during the two periods (Table 3) are divided in three categories for the further analysis:

- profiles close to the glacier terminus in similar topographic settings resulting at similar thickness loss at mass balance management and reference profiles during the first period (Figure 5).
- profiles with differences in thickness loss at mass balance management and reference profiles during the first period (Figure 6)
- profiles at small scale features as kickers, jumps, pipes, pylons (Figure 7)

For the first category, during the first period reference and mass balance management thickness changes both are quite similar and range between -0.5 m/year and -2.0 m/year. During the second period, reference area thickness losses increased for SOE 1+2 and HI 4, and decreased for the other profiles (all values within measurement uncertainties). In all profiles, mass balance management thickness losses decreased between the first and the second period, ranging from 0.1 m/year to -0.9 m/y. In contrast to the smaller thickness losses in mass balance managed areas, reference areas lost a thickness of -0.6 m/y to -1.8 m/year. The calculated changes for the second period are larger than the measurement errors. The mean thickness loss in mass balance managed profiles is -1.1 m for the first period and -0.3 m/y in the second period. The respective losses in reference areas are -1.2 m/year and -1.1 m/year. Thus the difference in thickness loss between managed and unmanaged areas is in average 0.8 m/year during the second period.

The profiles SOE1 and 2 comprise the entire slope on Rettenbachferner and, thus, have a large range between the 25th and the 75th percentile of all surface elevation changes. The profile SOE1a is located at the lowest elevated part of the glacier tongue. It shows the largest spread between mean annual surface elevation changes of both periods in the *mbm* area, while mean annual surface elevation losses in the *ref* area were nearly constant.

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For the second category, interpretation of surface elevation changes at these profiles is more complex with respect to their location on the glaciers. Thickness losses in both managed and unmanaged area are with a mean of - 0.4 m/y and -0.6m/y in period 1 lower than in category one. In period 2, reference areas show a mean thickness loss of -0.6 m/y, managed areas of -0.2 m thickness loss.

The profiles ST4 and ST3 already had less negative surface elevation changes in the *mbm* area compared to that of the *ref* area in the first period. Mean surface elevation changes at profile ST2 were similar in *mbm* and *ref* areas, but heterogeneity of surface elevation changes between both parts of the profile could be reduced. Thickness loss in the mass balance managed profiles of category one and two is in average 0.6m lower than in the respective reference areas, with a maximum difference of 1.3 m/y between reference and managed areas in profile SOE1a.

The profiles in the third category (Fig. 6) are not discussed separately for in *mbm* and *ref* areas. The small scale features are discussed in more detail in the supplementary. The mean annual surface elevation changes were nearly similar in both periods. Only the surface elevation changes of the profiles in Kaunertal ski resort show a shift towards more negative surface elevation changes in the second period. This is caused by a mass gain at lower elevations of the glacier due to increase of ice flow from glaciers in the rock walls of Weissseeepitze Northface in the first period. However, small features like artificial bumps and kickers do not have any long-term influence on glacier surface elevation, because they disappear within a short time (e.g. ST4, PI5, KT1, KT2).

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~~3.1~~

In ~~general, in the last decade a balance of the surface elevation at~~ highest elevations~~.~~, thickness changes are generally smaller than on glacier tongues, and so is the absolute difference between managed and unmanaged profiles.~~could be achieved by snow grooming and by covering the glacier at the highest elevations~~ (e.g. profiles HI1, ST4~~,~~). The spatial heterogeneity of surface elevation changes was levelled out by using glacier cover sheets (e.g. ST2). ~~-~~At the glacier tongues the body of ice could be protected against total mass loss by this method (e.g. HI5, ST5, SOE1a, SOE3a). ~~However, small features like artificial bumps and kickers do not have any long-term influence on glacier surface elevation, because they disappear within a short time (e.g. ST4, PI5, KT1, KT2).~~ Where snow is gathered for piste maintenance, mass gain on the piste is balanced with mass loss in the areas where the snow is taken from. (e.g. SOE4, KT4). ~~At 11 of the 16 profiles with mass balance management measurements, surface elevation loss could be reduced by more than 35% (Tab. 2). At 6 profiles surface elevation loss could even be reduced by more than 65%.~~ At two of these profiles the surface elevation could be preserved altogether (ST1, HI4).

~~3.2 3.2 Hintertux Glacier ski resort~~

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~~Profile HI1 shows a constant surface elevation along the piste with mass balance management (*mbm*) within the last 4 years (Fig. 3). Prior to that, the surface elevation changes were negative from 1999 to 2011 in the same profile. In the lowermost parts of this profile, the traverse between the two pistes lost a total of 8 m in surface elevation over the second period.~~

~~Profile HI2 shows a higher surface elevation loss in the reference areas (*ref*) compared to the middle part of this profile, which is covered in summer (Fig. 4). However, this local reduction is also visible in the data of the first period, but more pronounced in the second period with up to 4 m. The surface elevation changes in the second period were higher compared to surface elevation changes in the longer 12-year first period. A distinct reduction of glacier surface elevation loss is achieved by technical snow production along the glacier margin in the lower part of Gefrorene Wand Kees. Profiles HI3 and HI4 present mean differences in surface elevation changes of 5 m between the reference and the mass balance management areas for the second period, whereas surface elevation changes were within 2 m of difference between *mbm* and *ref* areas (Fig. 5 and 6, Tab. 2). Surface elevation of the 2011 surface could be kept constant at the glacier tongue over the second period (HI5, Fig. 7).~~

~~**3.3** 3.3 Stubai Glacier ski resort~~

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~~The differences between *mbm* parts and *ref* parts of profile ST1 show that maintenance of the traverse started before 2006 (Fig. 8, Tab. 2). In both periods, surface elevation changes were more negative in *ref* parts compared to surface elevation changes in *mbm* parts, while the difference between them stayed nearly similar for both periods. Some surface elevation gain can be seen in the *mbm* part of profile ST1 in the second period.~~

~~Mean surface elevations changes are almost equal at both parts of the profile (Fig. 9). However, the variation of surface elevation changes is distinctly reduced in the second period. The standard deviation of surface elevation changes (Tab. 2) is reduced from 2.9 m in the first period to values below 1 m in the second period.~~

~~In the area of profile ST3 a positive surface elevation change can be observed in the second period, whereas surface elevation was rather constant in the first period (Fig. 10). However, surface elevation changes of the second period come close to the surface elevation changes of the first period following the profile down-glacier along the piste.~~

~~The very local application of glacier cover to preserve the ice body for the pylon of the ropeway in profile ST4 caused differences of up to 9 m in surface elevation (interquartile range of *mbm* p2, Fig. 11). The achieved mean reduction in surface elevation around the pylon (compared to the piste nearby) was 2.5 m in (Tab. 2).~~

~~The area of profile ST5 presents some mass gain as a consequence of constant piste grooming and glacier cover (Fig. 12). In mean the surface elevation in the mbm area could almost be preserved in the second period, whereas in the ref area surface elevation loss of the second period was in the same magnitude as in the first period.~~

~~**3.4** 3.4 Sölden Glacier ski resort~~

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~~The continuous grooming of the piste on Rettenbachferner with technical snow production resulted in distinct differences in surface elevation changes of profiles SOE1 and SOE2 in the second period, whereas mean surface elevation changes were~~

~~nearly the same between 1997 and 2006 (Fig. 13, Tab. 2). Between 2006 and 2014, mean surface elevation change at profile SOE1 was nearly half that of profile SOE2 (Tab. 2). Locally more than 10 m of glacier surface elevation could be preserved in profile SOE1a (Fig. 14) using piste grooming and glacier cover at the glacier tongue.~~

~~On Tiefenbachferner, surface elevation losses were reduced locally on the glacier tongue. This is obvious at the lowest parts of profile SOE3 (Fig. 15) and in more detail in profile SOE3a (Fig. 16). Mean surface elevation loss was reduced by 65% (Fig. 16, Tab. 2). Profile SOE4 presents a large variability of surface elevation changes along a ski traverse on a slope. Less elevation change can be found on the traverse compared to surface elevation changes above and below it (Fig. 17). However, mean surface elevation changes of the two periods are approx. similar.~~

~~3.5 3.5 Pitztal Glacier ski resort~~

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~~Both PI1 and PI2 present less negative surface elevation change in the second period than in the first period (Fig. 18). As a result of covering the glacier rim to maintain the lift traverse along PI1, surface elevation changes in the lower part of this profile were distinctly less compared to those in PI2 at the same elevations. A small dislocation of the tow lift~~t-bar lift~~ line in PI3 caused large surface elevation changes at its south facing slope (Fig. 19). Also the dominance of the lift traverse compared to the glacier surface was more pronounced in 2006. The overdeepening next to the rocks in the southern part of PI3 appeared in the second period (Fig. 19). Despite the high elevation location of profile PI4 in the accumulation area, changes are obvious in the position of the wind kolk (Fig. 20). The retreat of the edge of the piste caused high surface elevation losses at the old slope. Whereas these surface elevation changes in the second period were in the magnitude of those of the first period, the piste grooming and amassing of snow reduced surface elevation changes compared to the unprepared slope in a mostly snow-covered area. In profile PI5 the technical maintenance of a piste (western part) and a lift traverse (eastern part) between 1997 and 2006 as well as the abandonment of this maintenance are obvious (Fig. 21). The technical features on the glacier surface in 2006 were completely reduced to the surrounding surface in 2014.~~

~~3.6 3.6 Kaunertal Glacier ski resort~~

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~~Profile KT1 presents the construction of large kickers in a ski fun park before 2006 and the decay of these features after 2006 (Fig. 22). Profile KT2 shows mean surface elevation changes similar to those of KT1 in the second period, with the only difference that the kickers were reduced in KT1 and newly constructed in KT2. Both profiles show higher surface elevation loss in the second period. The top of the bump in profile KT3 was built after 2006 and still reaches the original surface elevation of 1997 (Fig. 23), whereas surface elevation decreased sharply above and below the bump in the second period. This may have been caused by the use of the surrounding snow for the bump itself, which increases ice melt in these areas.~~

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4 Discussion

~~The uncertainty of surface elevation changes stems from the uncertainty of the DEMs and the uncertainty of the DGPS measurements. DEMs from stereo-photogrammetric surveys have an uncertainty of surface elevation of 0.5 m, whereas DEMs from Airborne Laser Scanning (ALS) surveys have higher accuracy and thus lower uncertainty (e.g. Abermann et al., 2010). Especially on glacier surfaces, slopes are gentle and thus uncertainty of ALS elevations is small, with typical values of less than 0.2 m (e.g. Bollmann et al.,2011; Joerg et al., 2012, Deems et al., 2013). The uncertainty of the vertical component of the DGPS location is assumed to be 1 m (e.g. Monteiro et al., 2005). For the difference between the DEMs and DGPS data, a maximum uncertainty of 1.1 m can be calculated. Seasonal snow cover was neglected. Especially at high-elevation profiles, the state of the snowpack may influence the results. For instance, the mean surface elevation change in the *mbm* part of profile ST1 of 2.2 m can partly be explained by the seasonal snow pack under the glacier cover at the time of measurement. The LiDAR DEMs were recorded in late August and September. The DGPS surveys took place in July and August.~~

This study focuses on the analysis of glacier surface elevation changes, as these are a major challenge for the ski resorts. Differences between mass balance managed and reference area are in the range of uncertainty of the first period DEM differences, but not in the second period involving only high accuracy geodata.

The interpretation of surface elevation changes in terms of mass balance is not possible without additional information. In the ablation area emergence reduces surface elevation loss by ablation, so that ablation generally is higher than surface elevation decrease. In the accumulation area, accumulation is higher than surface elevation change as submergence takes place. ~~Potential sources of uncertainty on a local and glacier-wide scale are~~Local surface elevation changes can result from subglacial erosion, internal and basal melt and density changes (Cogley et al., 2011). These factors are usually neglected in glacier wide geodetic mass balance studies, and we have no indication that they would play a major role in our study.

Much more importantly, ~~according to eq. 2,~~ surface elevation changes $\frac{\partial s}{\partial t}$ result from ~~submergence and emergence and~~glacier dynamics, density (ρ) changes and -point mass balance *b* (Cuffey and Paterson, 2010).

$$\frac{\partial S}{\partial t} = \frac{b}{\rho} + w - u\frac{\partial S}{\partial x} - u\frac{\partial S}{\partial x}$$

Local glacier thickness changes (Δh) result from mass changes caused by surface or basal mass balance (Δm), from the densification of snow and firn (Δρ), and from changes in submergence or emergence resulting from ice flow (Δv) (Cogley et al., 2011).

For our analysis, we presume that the components of the surface velocity at the point u, v, and w are similar in the mass balance managed and the reference profiles, and during the two periods. Then, the measured thickness changes are driven by the measures and not glacier dynamics. This hypothesis is confirmed by i) evidence and stability of the suprafical forms at

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mass balanced areas also visible in the photographs and the LiDAR hillshade, and ii) very low flow velocities measured at Austrian glaciers.

$$\Delta h = \Delta m/\rho + h\cdot\Delta\rho + \Delta v \qquad (1)$$

Assuming that the mean density (ρ) of the entire column containing ice, snow and firn is constant (Δρ = 0) and glacier thickness changes (Δh) are similar to surface elevation changes (Δz) caused by mass changes and changes in ice flow between two dates of surveys t0 and t1:

$$h_{t1}-h_{t0}= z_{t1} - z_{t0} = (m_{t1}-m_{t0})/\rho + ((v_{t1}-v_{t0})/2)\cdot(t_1-t_0) \qquad (2)$$

In the ablation area, thickness change can be positive if ablation decreases between t0 and t1 and/or emergence velocity increases. In the accumulation area, positive thickness changes occur when accumulation increases and/or submergence velocity decreases.

~~In the ablation area emergence reduces surface elevation loss by ablation, so that ablation generally is higher than surface elevation decrease. In the accumulation area, accumulation is higher than surface elevation change as submergence takes place.~~ Horizontal ice flow velocity on Austrian glaciers generally decreased (Fischer, 2015) and so did submergence and emergence (e.g. Span and Kuhn; 2003, Fischer et al., 2011b; Helfricht et al., 2014). Interannual differences in emergence and submergence are less than 0.5 $\mathrm{ma^{-1}}$ on Kesselwandferner (Fischer et al., 2011b). In any case, submergence and emergence should be similar for the profiles and the reference profiles. The shape of elevation changes in the DEM differences fits the location of the measures, so that a large impact resulting from different or changing ice flow regimes is unlikely.

However, this study does not focus on the absolute values of surface elevation changes, nor mass balance. The aim is to analyse the differences between maintained glacier areas and areas with limited maintenance nearby. In the profile plots all measurement points are shown along the elevation range of the profile, so that differences caused by the measurement setup are obvious. ~~Some~~ All~~of~~ ~~the~~ reference surfaces are subject to grooming during winter, ~~some are not~~ only in Hintertux glacier ski resort pistes are also groomed in summer. Local mass balance measurements indicate that grooming in winter without other measures reduces ice ablation in summer by 10% by limiting the wind erosion of snow (Fischer et al., 2011a). This study did not investigate the effect of grooming in summer (without application of other measures) on albedo, which is presumed by e.g. Keller et al. (2004). Relocation of snow by snow cats is mainly taking advantage of periglacial snow or even, in addition to that, deposits gained by blasting of avalanches in periglacial slopes.

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In general the absolute values of the mean surface elevation changes strongly depend on the chosen path or profile line and do not represent mean glacier mass balance at these elevations. Often the basis of pylons and lift traverses are covered to retain them over a period of several years, until the pylons have to be relocated to compensate for the ice flow. After stopping the mass balance management, these features, at first standing proud from the glacier surface, disappear fast. This can be explained by the enlarged surface of the feature in relation to its volume. Thus the increase of energy exchange will cause higher melt until the surface is minimized and evens out with the nearby surfaces. Additionally, less snow is accumulated on it, because the surface is more exposed to wind.

~~In general it is not feasible to reconstruct the snow volume onto the piste. The locations of multi-year use of glacier cover are better known. Thus these areas where selected for the mbm areas along the DGPS profiles (blue colour, e.g. ZT1-5). However, these areas may also change slightly over the years so that the transition between maintained and non-maintained areas is more fluid than the manual separation in mbm parts and ref parts shows. In addition to the geodetic analysis, GPR measurements have been carried to out to find the transition from new firn to the glacier ice at the glacier tongues. GPR data were recorded with a 500 MHz antenna to complement the DGPS measurements. However, while the glacier bed could be detected in most of the data, internal layering was not visible. This can be caused by the reduced differences in snow and firn layering caused by steady piste grooming, or by a lack of layers with low density.~~

Mass balance management at the glacier tongues may be feasible as long as the area to be managed remains small and needs not to be extended to larger areas upglacier. However, mass balance management shows the potential to keep the surface constant at highest elevations of the glaciers and thus conserve the firn reservoirs. This might have a long-term impact on the future existence since the natural glacier ELA in recent years often exceed peak elevation (Fischer et al., 2013a; Fischer et al., 2014a; Fischer et al., 2014b). Thus, specific mass balance management in the typical firn areas is more sustainable with respect to future glacier extent than mass balance management at the tongues.

Apart from the effects on mass balance, the economic benefit of mass balance management is often discussed, as well as the sustainability of measures in the light of current glacier retreat.

The economic benefit results from costs and gains, with costs for all investments being easier to capture than the gains. The total costs of glacier covers are those of material and maintenance. Material/investment costs include sheets and bags filled with gravel for fixing the sheets on the glacier, and storage space. Maintenance costs include transport, mounting, maintenance on the glacier and removal of the material, both personnel and machinery costs. Depending on individual settings, total costs are about 1.5 €/m², divided about 50:50 between material and maintenance. The uncertainty about the economic benefits is much higher, as, even with detailed visitor questionnaires, the costs of loss of glacier area for ski slopes is hard to quantify. In addition to that, the costs of the loss of glacier area or altitude are highly individual: If a ski lift has to be rebuilt, economic costs of glacier loss are quite high. Currently, mass balance management extends to Tignes (France), Whistler (BC), Mount Hood (OR) (all M. Pelto, pers. communication), Mölltaler Gletscher (AT), Kitzsteinhorn (AT), Dachstein (AT), Zugspitze(D), Saas Fee (CH), and Schnalstaler Gletscher (IT).

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Another fact to keep in mind is the sustainability of measures on glaciers: Glaciers are constantly changing, so that some maintenance effort is always needed for adapting to retreat or, as was the case in the 1980s, to advance. Taking into account that snow cover duration is high in today’s glacier-covered regions, ski tourism in the year 2100 might focus on these high-altitude regions, even if no glacier at all was left by then. The history of ski tourism is not very old. It started about 1900 and boomed in the 1970s in terms of infrastructure and turnover. In the light of changing markets, demands and politics, the climatic changes might introduce fewer uncertainties than the socioeconomic ones. In general, investments and facilities are budgeted for a time frame of than less than 20 years.

A wider application of the methods for meltwater management has been proven for Armenia (Nestler et al., 2014). An application in high lying regions in Central Asia could be feasible: Albedo has been shown to be a major factor governing mass balance (Fujita and Ageta, 2000), so that the application of geotextiles will reduce melt in the absence of seasonal snow falls. As the covers can be placed and removed at nearly any time (unless superimposed ice forms on them), an effective water management seems possible. Drawbacks of the method are the need for machinery for an application on areas larger than about 100 x 100 m, and the costs.

An application of geotextile covers to ski resorts at lower elevations (e.g. without glacier cover) is not straightforward, as the sensible rather than the radiative energy flux is decisive here. This makes mass balance management by relocation of snow often combined with insulating measured as wood chips more effective than the albedo increase by geotextiles (Skogsberg and Lundberg. 2005; Grünewald and Wolfsperger, 2016).

5 ~~5~~ Conclusions

The use of snow grooming and technical snow production as well as glacier covering in selected areas on glaciers, which are important for the infrastructure and the pistes in glacier ski resorts, show good results in preserving the surface elevation on the decadal time scale. Distinct differences between surface elevation changes in maintained areas and surface elevation changes in nearby areas without technical intervention are presented in this study. Small-scale ice ridges arising from very local mass balance management melt down within a few seasons when mass balance management is stopped.

Up to now the areas under mass balance management represent only a small proportion of the total glacier area and thus have limited influence on the mass balance of the total glacier. Surface elevation differences between maintained and not technically prepared areas on the glaciers can be expected to increase with ongoing glacier retreat, which will cause steeper slopes on the glacier surface. In the uppermost parts of the glaciers the preservation of surface elevation by covering the glacier works well to retain the piste connection between ropeway mountain stations and the glacier surface over multi-year periods. The long-term use of glacier cover in the upper parts of the glaciers (e.g. ST1, ST2) may affect the existence of these glacier parts in future, because equilibrium line altitudes of glacier mass balances in recent years have exceeded peak elevations. In areas near the glacier terminus, the continuous combination of additional snow load and glacier cover helps to preserve the remaining ice body where, without mass balance management, the glacier would retreat rapidly.

Over the observed time periods, the reduction in surface elevation caused by glacier retreat could be reduced locally by more than 1.3 m/year~~75%~~.Mass balance management measures thus do a good job in stemming surface elevation decrease on a small proportion of the area of ski resort glaciers where the measures can be applied. The application is limited by the effort necessary as well as by the limited snow and water resources.

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~~7~~ References

Abermann, J., Fischer, A., Lambrecht, A., and Geist, T.: On the potential of very high-resolution repeat DEMs in glacial and periglacial environments, The Cryosphere, 4, 53-65, 2010.

Bollmann, E., Sailer, R., Briese, C., Stötter, J., and Fritzmann, P.: Potential of airborne laser scanning for geomorphologic feature and process detection and quantifications in high alpine mountains, Z. Geomorphol. Supp., 55, 83–104, 2011.

Cogley, J. G., Hock, R., Rasmussen, L. A., Arendt, A. A., Bauder, A., Braithwaite, R. J., Jansson, P., Kaser, G., Möller, M., Nicholson, L., and Zemp, M.: Glossary of Glacier Mass Balance and Related Terms. IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris, 124 pp., 2011.

Deems, J. S., Painter, T. H., and Finnegan, D. C.: Lidar measurement of snow depth: a review, Journal of Glaciology, 59, 467-479, 2013.

Diolaiuti, G., Smiraglia, C., Pelfini, M., Belò, M., Pavan, M., and Vassena, G.: The recent evolution of an Alpine glacier used for summer skiing (Vedretta Piana, Stelvio Pass, Italy), Cold Regions Science and Technology, 44, 206-216, 2006.

Fahey, B., Wardle, K., and Weir, P.: Environmental effects associated with snow grooming and skiing at Treble Cone Ski Field. Part 2. Snow properties on groomed and non-groomed slopes., Science for Conservation, 120B, 49-62, 1999.

Fischer, A.: Glaciers and climate change: Interpretation of 50 years of direct mass balance of Hintereisferner, Global and Planetary Change, 71, 13-26, 2010.

Fischer, A.: Sammelbericht über die Gletschermessungen des Österreichischen Alpenvereins im Jahre 2014., Bergauf, 02/2015, 26-33, 2015.

Fischer, A., Markl, G., and Kuhn, M.: Glacier mass balances and elevation zones of Hintereisferner, Ötztal Alps, Austria, 1952/1953 to 2010/2011., Institute for Interdisciplinary Mountain Research, A. A. o. S., Innsbruck (Ed.), PANGAEA, 2013a.

Fischer, A., Markl, G., Schneider, H., Abermann, J., and Kuhn, M.: Glacier mass balances and elevation zones of Kesselwandferner, Ötztal Alps, Austria, 1952/1953 to 2012/2013., Institute for Interdisciplinary Mountain Research, A. A. o. S., Innsbruck (Ed.), PANGAEA, 2014a.

Fischer, A., Olefs, M., and Abermann, J.: Glaciers, snow and ski tourism in Austria’s changing climate. Annals of glaciology, 52, 89-96, 2011a.

Fischer, A., Patzelt, G., and Kinzl, H.: Length changes of Austrian glaciers 1969-2014. Institute for Interdisciplinary Mountain Research, A. A. o. S., Innsbruck (Ed.), PANGAEA, 2013b.

Fischer, A., Schneider, H., Merkel, G., and Sailer, R.: Comparison of direct and geodetic mass balances on an annual time scale, The Cryosphere Discuss., 5, 565-604, 2011b.

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Fischer, A., Seiser, B., Stocker Waldhuber, M., Mitterer, C., and Abermann, J.: Tracing glacier changes in Austria from the Little Ice Age to the present using a lidar-based high-resolution glacier inventory in Austria, The Cryosphere, 9, 753-766, 2015.

Fischer, A., Stocker Waldhuber, M., Seiser, B., Hynek, B., and Slupetzky, H.: Glaciological Monitoring in the Hohe Tauern National Park, ecomont, 6/1, 55-62, 2014b.

Fujita and Ageta, 2000

Grünewald T., and Wolfsperger, F., Storing snow for the next winter: Two case studies on the application of snow farming, Geophysical Research Abstracts 18, EGU2016-8384, 2016.

Helfricht, K., Kuhn, M., Keuschnig, M., and Heilig, A.: Lidar snow cover studies on glaciers in the Ötztal Alps (Austria): comparison with snow depths calculated from GPR measurements, The Cryosphere, 8, 41-57, 2014.

Hijioka, Y., Lin, E., Pereira, J.J., Corlett, R.T., Cui, X., Insarov, G.E., Lasco, R.D., Lindgren, E., and Surjan, A.: Asia. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Eds.: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., and White, L.L. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1327-1370, 2014.

Joerg, P. C., Morsdorf, F., and Zemp, M.: Uncertainty assessment of multi-temporal airborne laser scanning data: A case study on an Alpine glacier, Remote Sensing of Environment, 127, 118-129, 2012.

Kovats, R.S., Valentini, R., Bouwer, L.M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M., and Soussana, J.-F.: Europe. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Eds.: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., and White, L.L. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1267-1326, 2014.

Lambrecht, A. and Kuhn, M.: Glacier changes in the Austrian Alps during the last three decades, derived from the new Austrian glacier inventory, Annals of Glaciolgy, 46, 177-184, 2007.

Monteiro, L. S., Moore, T., and Hill, C.: What is the accuracy of DGPS?, The Journal of Navigation, 58, 207-225, 2005.

Nestler, A., Huss, M., Ambartzumian, R., and Hambarian, A.: Hydrological Implications of Covering Wind-Blown Snow Accumulations with Geotextiles on Mount Aragats, Armenia. Geosciences 4, 73-92, 2014.

Norphel, C., and Padma, T.: Snow Water Harvesting in the Cold Desert in Ladakh: An Introduction to Artificial Glacier, In: Nibanupudi, K. H., and Shaw, R.: Mountain Hazards and Disaster Risk Reduction, 199-2010, Springer Japan, 2015. Doi:10.1007/978-4-431-55242-0_11.

Olefs, M. and Fischer, A.: Comparative study of technical measures to reduce snow and ice ablation in Alpine glacier ski resorts, Cold Regions Science and Technology, 52, 371-384, 2008.

Olefs, M. and Lehning, M.: Textile protection of snow and ice: Measured and simulated effects on the energy and mass balance, Cold Regions Science and Technology, 62, 126-141, 2010.

Olefs, M. and Obleitner, F: Numerical simulations on artificial reduction of snow and ice ablation. Water Resources Research 43~~ 2007~~, 43, W06405, doi:10.1029/2006WR005065, 2007.

Skogsberg, K., and Lundberg, A.: Wood chips as thermal insulation of snow. Cold Regions Science Technology 43, 207–218, 2005.

Smiraglia, C., Diolaiuti, G., Pelfini, M., Belò, M., Citterio, M., Carnielli, T., and D'Agata, C.: Glacier changes and their impacts on mountain tourism: two case studies from the Italian Alps. In: Darkening peaks: glacier retreat, science and society, Orlove, B., Wiegandt, E., and Luckman, B. H. (Eds.), University of California Press, Berkeley, CA, 2008.

Span, N. and Kuhn, M.: Simulating annual glacier flow with a linear reservoir model, Journal of Geophysical Research: Atmospheres, 108, 4313, 2003.

Spandre P., Morin S., Lafaysse M., Lejeune Y., Francois H., and George-Marcelpoil E.: Integration of snow management processes into a detailed snowpack model. Cold Regions Science Technology 125, 48-64, 2016. doi:10.1016/j.coldregions.2016.01.002.

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A. P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L. N., Cáceres, B. E., Casassa, G., Cobos, G., Dávila, L. R., Delgado Granados, H., Demuth, M. N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J. O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V. V., Portocarrero, C. A., Prinz, R., Sangewar, C. V., Severskiy, I., Sigurðsson, O., Soruco, A., Usubaliev, R., and Vincent, C.: Historically unprecedented global glacier decline in the early 21st century, Journal of Glaciology, 61, 745-762, 2015.

Colgan, W., Rajaram, H., Abdalati, W., McCutchan, C., Mottram, R., Moussavi, M. and Grigsby, S: Glacier crevasses: Observations, models, and mass balance implications, Rev. Geophys. 54, 119–161, doi:10.1002/2015RG000504, 2016.

Pelto, M.S., and Hedlund, C.: The terminus behavior and response time of North Cascade glaciers. Journal of Glaciology 47: 497–506, 2001.

Abermann, J., Lambrecht, A., Fischer, A., and Kuhn, M.: Quantifying changes and trends in glacier area and volume in the Austrian Ötztal Alps (1969-1997-2006), The Cryosphere 3, 205-215, doi:10.5194/tc-3-205-2009, 2009.

Wurländer, R. and Eder, K.: Leistungsfähigkeit aktueller Photogrammetrischer Auswertemethoden zum Aufbau eines digitalen Gletscherkatasters. Zeitschrift für Gletscherkunde und Glazialgeologie 34(2), 167–185, 1998.

Abermann, J., Lambrecht, A., and Schneider, H.: Analysis of surface elevation changes on Kesselwand glacier – Comparison of different methods, Zeitschrift für Gletscherkunde und Glazialgeologie, 41, 147–168, 2007.

Sailer, R., Rutzinger, M., Rieg, L., and Wichmann, V.: Digital elevation models derived from airborne laser scanning point clouds: appropriate spatial resolutions for multi-temporal characterization and quantification of geomorphological processes, Earth Surf. Proc. Land., 39, 272–284, doi:10.1002/esp.3490, 2014.

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Fischer, A., Schneider, H., Merkel, G., and Sailer, R.: Comparison of direct and geodetic mass balances on an annual time scale, The Cryosphere Discuss., 5, 565-604, doi:10.5194/tcd-5-565-2011, 2011c.

Keller, T. Pielmeier, C. Rixen, C. Gadient, F. Gustafsson, and D. Stähli, M.: Impact of artificial snow and ski-slope grooming on snowpack properties and soil thermal regime in a sub-alpine ski area. Annals of Glaciology 38, 1, 314-318, 2004.

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Table 1: Glacier ski resorts in Austria with opening year, federal state, glacier names, the total glacier area, the glacier area assigned to the ski resort and the relative area of the ski resort on glacier with mass balance management (mbm). An asterisk (*) denotes ski resorts with preparatory studies to mass balance management measures. A plus sign (+) denotes ski resorts with data analysed in this study.

Ski resort	Opening year	State	Glaciers	Total glacier area (km²)	Ski resort area on glacier (km²)	Area of mbm (%)
Kitzsteinhorn	1965	Salzburg	Schmiedinger Kees	1.16	-	-
Dachstein Glacier *	1969	Upper Austria	Schladminger Gletscher	0.71	-	-
Hintertux Glacier $^{+}$	1969	Tyrol	Gefrorene Wand Kees, Riepenkees	4.56	4.56	2.9
Stubai Glacier *$^{+}$	1972	Tyrol	Schaufelferner, Daunkogelferner, Fernauferner, Windacher Ferner, Gaißkarferner	4.48	4.10	2.4
Sölden *$^{+}$	1975	Tyrol	Rettenbachferner, Tiefenbachferner	2.76	2.76	2.2
Pitztal Glacier *$^{+}$	1983	Tyrol	Mittelbergferner, Brunnenkogelferner	10.94	3.39	2.1
Kaunertal Glacier *$^{+}$	1980	Tyrol	Weisssseferner	2.64	2.13	6.6
Mölltal Glacier	1986	Carinthia	Wurten Kees	0.05	-	-
			total	25.43	16.94	2.95

Table 2: Dates of the surface elevation information in the different glacier ski resorts from digital elevation models (DEM) based on orthophotos (O), airborne laser scanning surveys (ALS) and from differential GPS measurements (DGPS).

Ski resort	Period 1			
		Period 2		
	DEM GI2 (O)	DEM GI3 (ALS)	DEM (ALS)	DGPS
Hintertux Glacier	1999	2007	-	03/08/2015
Stubai Glacier	1997	2006	-	06/07/2015
Sölden Glacier	1997	2006	2014	16/07/2015
Kaunertal	1997	2006	2012	23/07/2015

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Glacier				
Pitztal Glacier	1997	2006	2014	-

Formatiert: Block, Zeilenabstand: 1.5 Zeilen

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~~Table 3. Mean (μ) and standard deviation (σ) of surface elevation changes [m] for areas of mass balance management (mbm) and no mass balance management (ref) at the profiles in the two periods (dates see Table1). Absolute difference (abs. diff, [m]) of the *mbm* mean value to the *ref* mean value and relative reduction (rel. red, [%]) in surface elevation change are given for the two periods.~~

~~Profile~~	~~Period 1~~						~~Period 2~~					
	~~ref~~		~~mbm~~		~~abs.~~	~~rel~~	~~ref~~		~~mbm~~		~~abs.~~	~~rel.~~
~~-~~	~~μ~~	~~σ~~	~~μ~~	~~σ~~	~~diff~~	~~red~~	~~μ~~	~~σ~~	~~μ~~	~~σ~~	~~diff~~	~~red~~
~~HI1~~	~~-1.3~~	~~2.8~~	~~-2.9~~	~~3.1~~	~~-1.6~~	~~127~~	~~-2.4~~	~~2.5~~	~~-0.3~~	~~1.5~~	~~2.0~~	~~-86~~
~~HI2~~	~~-4.2~~	~~0.5~~	~~-3.1~~	~~0.4~~	~~1.1~~	~~-26~~	~~-5.3~~	~~1.3~~	~~-4.3~~	~~0.9~~	~~1.1~~	~~-20~~
~~HI3~~	~~-6.0~~	~~2.1~~	~~-4.2~~	~~1.3~~	~~1.7~~	~~-29~~	~~-5.8~~	~~1.1~~	~~-0.9~~	~~2.5~~	~~4.9~~	~~-85~~
~~HI4~~	~~-4.2~~	~~1.4~~	~~-5.7~~	~~1.2~~	~~-1.4~~	~~34~~	~~-6.0~~	~~1.1~~	~~0.1~~	~~1.1~~	~~6.1~~	~~-101~~
~~HI5~~	~~-9.2~~	~~4.2~~	~~-8.9~~	~~3.2~~	~~0.3~~	~~-3~~	~~-4.4~~	~~4.7~~	~~-2.8~~	~~2.5~~	~~1.6~~	~~-37~~
~~ST1~~	~~-7.4~~	~~3.8~~	~~-0.7~~	~~3.1~~	~~6.7~~	~~-91~~	~~-4.7~~	~~2.4~~	~~2.2~~	~~1.9~~	~~6.9~~	~~-148~~
~~ST2~~	~~0.2~~	~~2.9~~	~~-0.7~~	~~2.9~~	~~-0.9~~	~~-396~~	~~1.2~~	~~0.4~~	~~1.6~~	~~0.8~~	~~0.3~~	~~28~~
~~ST3~~	~~-3.6~~	~~0.4~~	~~-0.2~~	~~2.0~~	~~3.5~~	~~-95~~	~~0.5~~	~~2.1~~	~~4.2~~	~~1.9~~	~~3.8~~	~~828~~
~~ST4~~	~~-5.8~~	~~0.8~~	~~-4.9~~	~~0.6~~	~~0.9~~	~~-15~~	~~-6.3~~	~~1.4~~	~~-3.8~~	~~1.8~~	~~2.5~~	~~-39~~
~~ST5~~	~~-9.8~~	~~1.0~~	~~-8.5~~	~~2.4~~	~~1.4~~	~~-14~~	~~-9.6~~	~~1.6~~	~~-1.2~~	~~4.5~~	~~8.3~~	~~-87~~
~~SOE1+2~~	~~-12.7~~	~~7.3~~	~~-12.8~~	~~5.0~~	~~-0.1~~	~~1~~	~~-14.5~~	~~6.5~~	~~-7.5~~	~~4.0~~	~~7.0~~	~~-48~~
~~SOE1a~~	~~-18.3~~	~~1.2~~	~~-15.3~~	~~3.9~~	~~2.9~~	~~-16~~	~~-16.1~~	~~3.6~~	~~-4.4~~	~~3.6~~	~~11.8~~	~~-73~~
~~SOE3~~			~~-7.4~~	~~3.7~~					~~-5.7~~	~~2.9~~		
~~SOE3a~~	~~-12.2~~	~~0.7~~	~~-12.6~~	~~1.9~~	~~-0.3~~	~~3~~	~~-10.1~~	~~1.1~~	~~-3.5~~	~~2.5~~	~~6.6~~	~~-65~~
~~SOE4~~			~~-6.4~~	~~3.9~~					~~-5.8~~	~~3.9~~		
~~PI1+2~~	~~-10.1~~	~~1.6~~	~~-10.0~~	~~2.0~~	~~0.1~~	~~-1~~	~~-9.6~~	~~1.6~~	~~-7.1~~	~~2.8~~	~~2.5~~	~~-26~~
~~PI3~~			~~-10.6~~	~~1.8~~					~~-11.0~~	~~2.4~~		
~~PI4~~			~~-7.6~~	~~1.9~~					~~-7.3~~	~~4.0~~		
~~PI5~~			~~-14.7~~	~~3.1~~					~~-16.3~~	~~3.5~~		
~~KT1+2~~	~~-8.6~~	~~4.1~~	~~-0.5~~	~~5.5~~	~~8.2~~	~~-95~~	~~-16.9~~	~~3.5~~	~~-15.0~~	~~3.3~~	~~1.9~~	~~-11~~
~~KT3~~			~~-3.7~~	~~2.8~~					~~-13.9~~	~~6.5~~		
~~KT4~~			~~-1.6~~	~~3.2~~					~~-6.2~~	~~3.2~~		

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~~KT5~~	~~-4.7~~	~~1.6~~	~~-4.0~~	~~2.0~~	~~0.7~~	~~-15~~	~~-12.4~~	~~1.0~~	~~-3.9~~	~~3.4~~	~~8.5~~	~~-68~~

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Revised Table:

Table 3. Mean elevation of the profiles and the applied *mbm* measures snow production (p), snow relocation (r), snow covering (c) and piste grooming (g). The mean (µ) and the standard deviation (σ) of surface elevation changes in m for areas of mass balance management (*mbm*) and without mass balance management (*ref*) at the profiles in two consecutive periods (see Table 2) are shown. Absolute differences (abs. diff, in m) of the *mbm* mean values to the *ref* mean values are given for the two periods. Note that the arrangement of the profiles corresponds to the segmentation of the profiles in the Fig. 4 to 6.

profile name	mean elevation	mbm				thickness change in period 1 in m					thickness change in period 2 in m				
						ref		mbm		abs.	ref		mbm		abs.
						µ	σ	µ	σ	diff	µ	σ	µ	σ	diff
HI3	2976	p		c	g	-6.0	2.1	-4.2	1.3	1.7	-5.8	1.1	-0.9	2.5	4.9
HI4	2870	p		c	g	-4.2	1.4	-5.7	1.2	-1.4	-6.0	1.1	0.1	1.1	6.1
HI5	2742	p	r	c	g	-9.2	4.2	-8.9	3.2	0.3	-4.4	4.7	-2.8	2.5	1.6
SOE1+2	2769	p	r	c	g	-12.7	7.3	-12.8	5.0	-0.1	-14.5	6.5	-7.5	4.0	7.0
SOE1a	2703	p	r	c	g	-18.3	1.2	-15.3	3.9	2.9	-16.1	3.6	-4.4	3.6	11.8
SOE3a	2940		r	c	g	-12.2	0.7	-12.6	1.9	-0.3	-10.1	1.1	-3.5	2.5	6.6
ST5	2884		r	c	g	-9.8	1.0	-8.5	2.4	1.4	-9.6	1.6	-1.2	4.5	8.3
HI1	3167		r	c	g	-1.3	2.8	-2.9	3.1	-1.6	-2.4	2.5	-0.3	1.5	2.0
HI2	3038		r	c	g	-4.2	0.5	-3.1	0.4	1.1	-5.3	1.3	-4.3	0.9	1.1
ST1	3141		r	c	g	-7.4	3.8	-0.7	3.1	6.7	-4.7	2.4	2.2	1.9	6.9
ST2	3135			c	g	0.2	2.9	-0.7	2.9	-0.9	1.2	0.4	1.6	0.8	0.3
ST3	3102			c	g	-3.6	0.4	-0.2	2.0	3.5	0.5	2.1	4.2	1.9	3.8
ST4	3000		r	c	g	-5.8	0.8	-4.9	0.6	0.9	-6.3	1.4	-3.8	1.8	2.5
PI1+2	3041		r	c	g	-10.1	1.6	-10.0	2.0	0.1	-9.6	1.6	-7.1	2.8	2.5
KT5	2962		r	c	g	-4.7	1.6	-4.0	2.0	0.7	-12.4	1.0	-3.9	3.4	8.5
SOE3	3064		r	c	g			-7.4	3.7				-5.7	2.9	
SOE4	3189		r		g			-6.4	3.9				-5.8	3.9	
PI3	3057		r	c	g			-10.6	1.8				-11.0	2.4	
PI4	3202		r		g			-7.6	1.9				-7.3	4.0	
PI5	2878		r	c	g			-14.7	3.1				-16.3	3.5	
KT1	2779		r	c	g			-8.6	4.1				-16.9	3.5	
KT2	2779		r	c	g			-0.5	5.5				-15.0	3.3	
KT3	2738		r	c	g			-3.7	2.8				-13.9	6.5	
KT4	3036		r		g			-1.6	3.2				-6.2	3.2	

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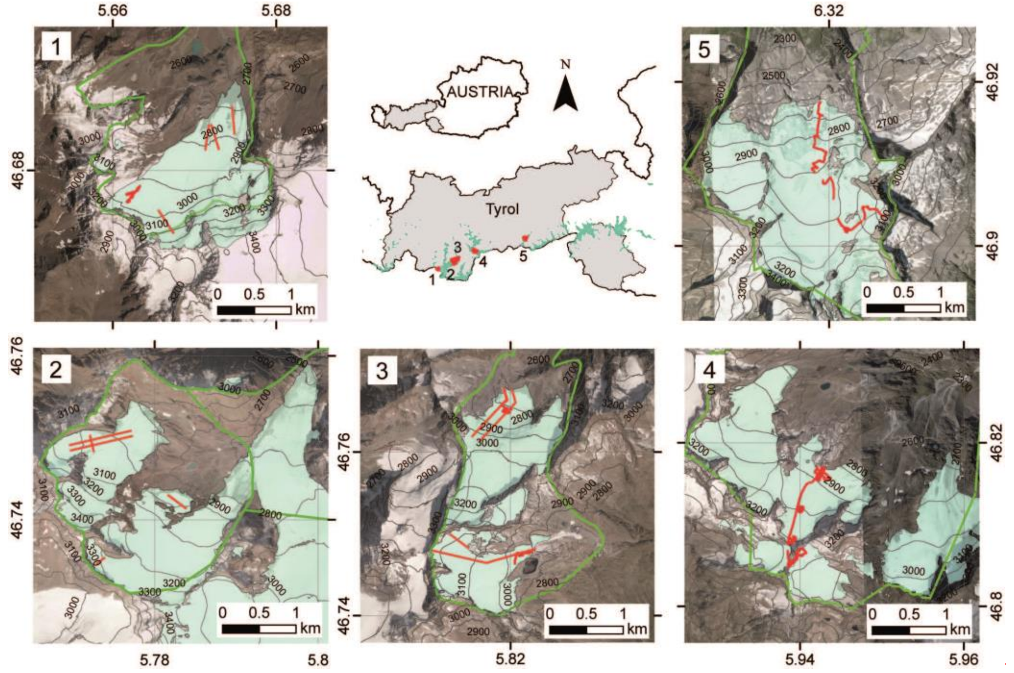
1
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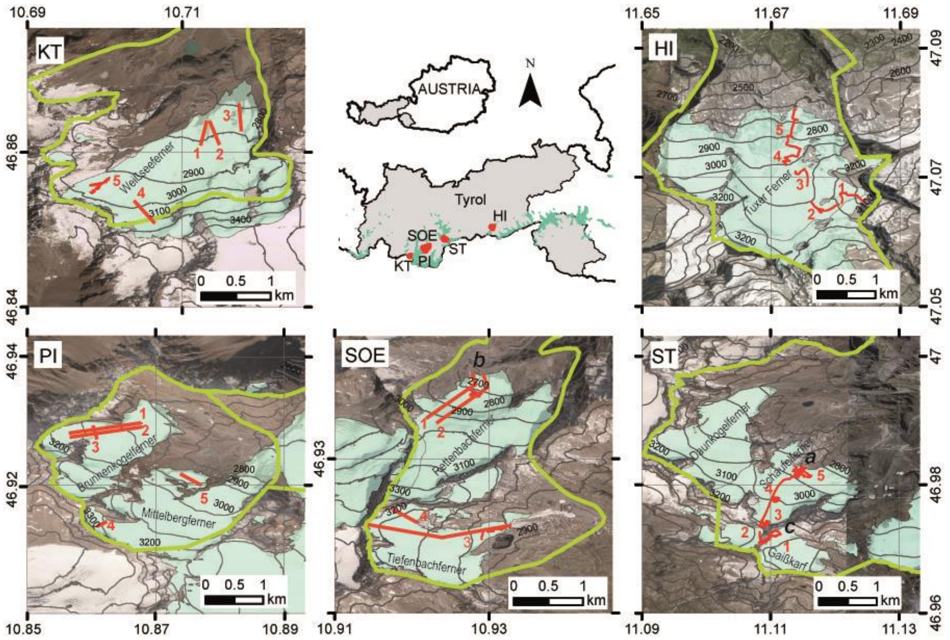
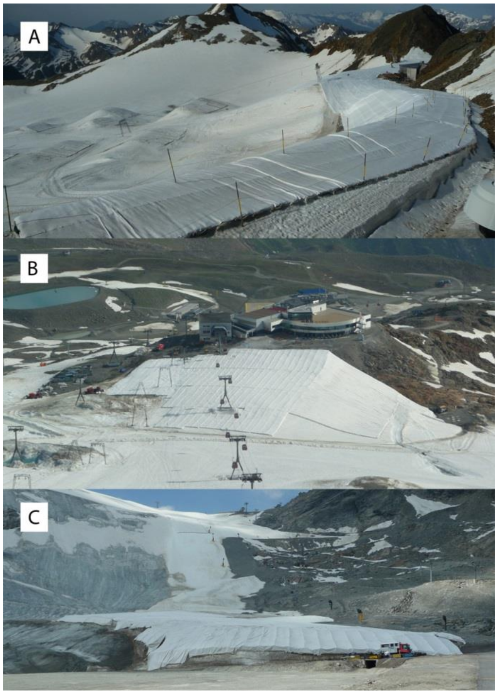


Figure 1. Overview of the Tyrolean glacier ski resorts of Kaunertal (~~1~~KT), Pitztal (~~2~~PI), Sölden (~~3~~SOE), Stubai (~~4~~ST) and Hintertux (~~5~~HI). Measurement locations (red lines) with profile numbers (red), ski resort outlines (green lines), glaciers assigned to the resort (light ~~blue~~green) and contour lines of the GI3 DEMs ~~are presented~~superimposed on orthophotos (tirol.gv.at). a,b,c …areas shown in Figure 2.


A
B
C

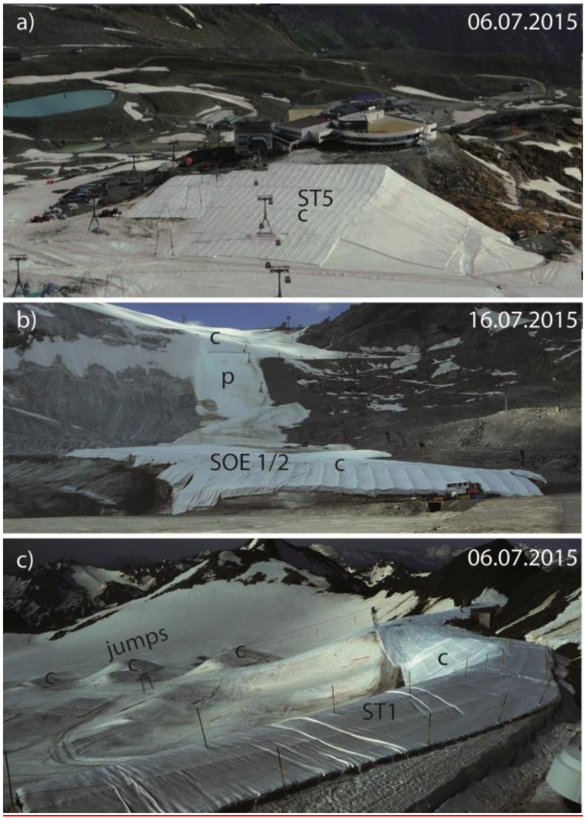


Figure 2. ~~Areas of ~~M~~m~~ass balance management at ~~(A)~~ profiles ST5 (a, Stubai glacier ski resort, for hillshade and thickness change see Figure 3), SOE1/2 (b, Sölden ski resort), and ST1 ~~and (B)~~ ~~profile ST5 in~~ (c, Stubai Glacier ski resort~~), and at profile SOE2 on Rettenbachferner in Sölden ski resort~~ with applied measures: c…covers, p…snow production..

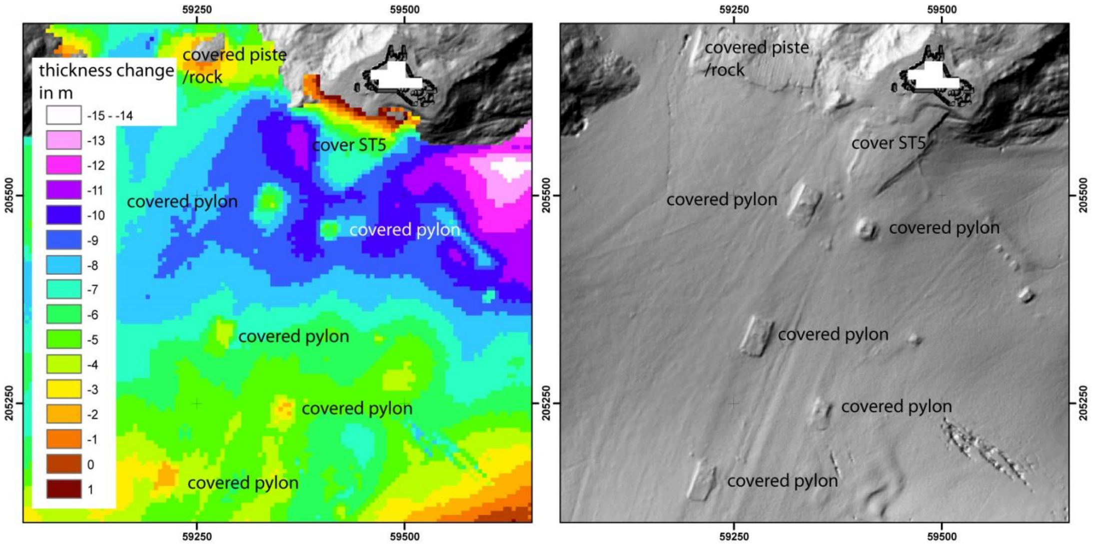


Figure 3: The thickness changes at the location of the mass balances measures on the LiDAR DEM hillshade of 2006 are lower than in the surroundings.

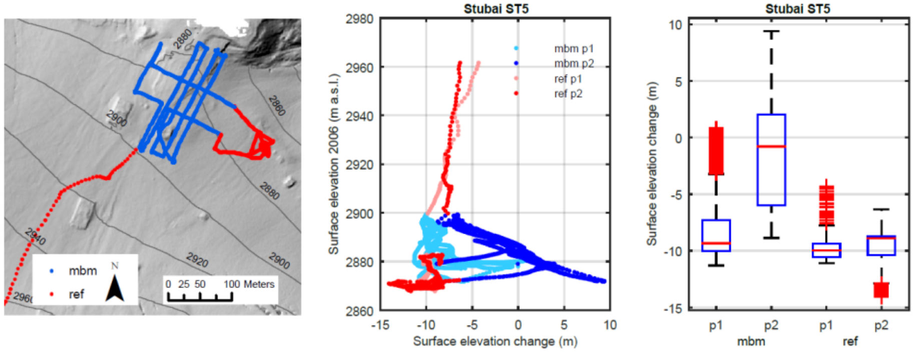


Figure 4. Location of profile ST5, surface elevation changes plotted for surface elevation in 2006 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red)

for the periods 1997 -2006 (p1) and 2006 – 2015 (p2). Note that similar plots for each profile are provided in the supplement~~ary material~~.

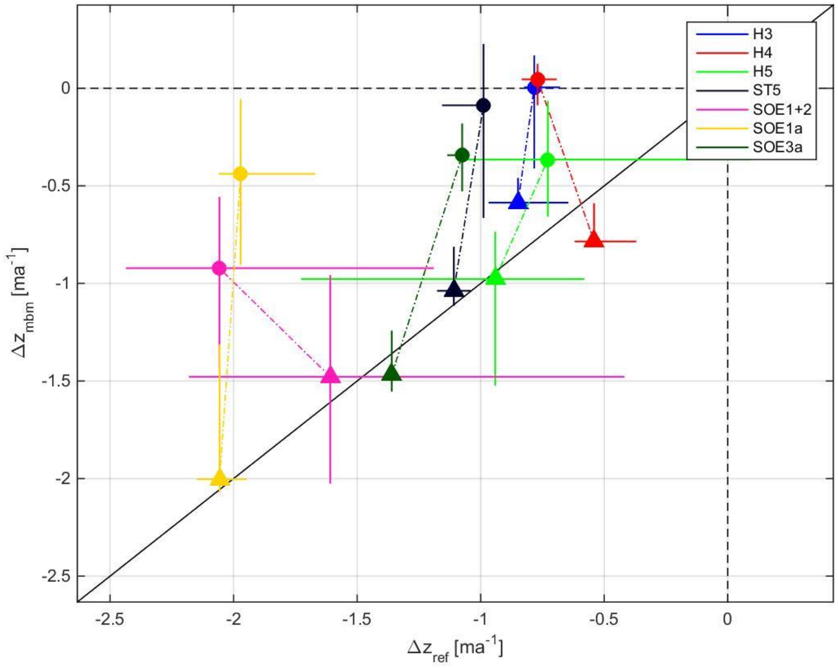


Figure 5. Median of the annual surface elevation changes of the reference profile (Δz_{ref}) compared to the median of the annual surface elevation changes of the profile with mass balance management (Δz_{mbm}) for the first (triangles) and the second (circles) period. Periods are given in Table 2. Solid lines show the interquartile range between the 25th and the 75th percentile. Dashed lines connect the corresponding values of one profile.

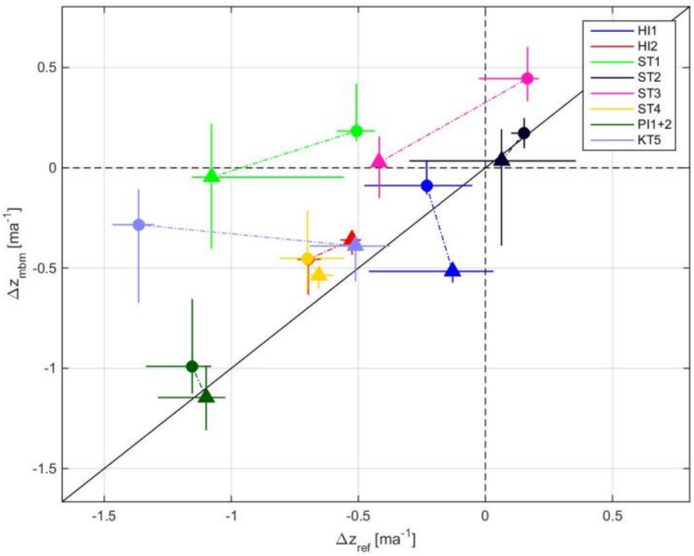


Figure 6. Median of the annual surface elevation changes of the reference profile (Δz_{ref}) compared to the median of the annual surface elevation changes of the profile with mass balance management (Δz_{mbm}) for the first (triangles) and the second (circles) period. Periods are given in Table 2. Solid lines show the interquartile range between the 25th and the 75th percentile. Dashed lines connect the corresponding values of one profile.

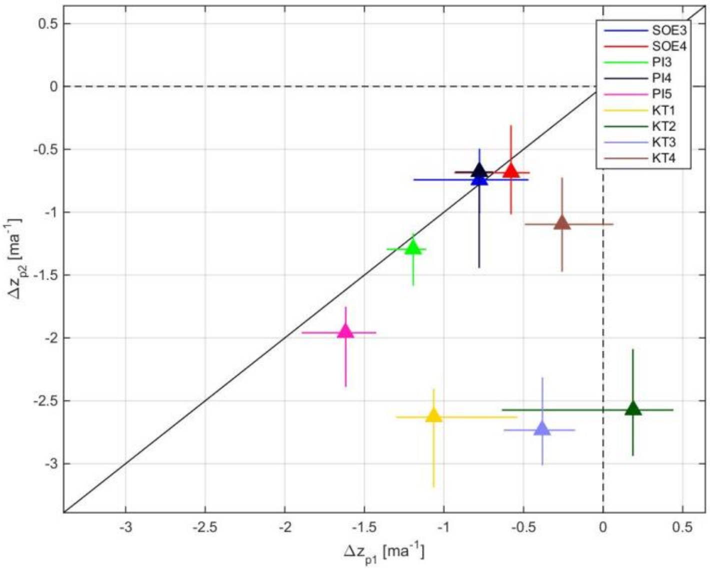
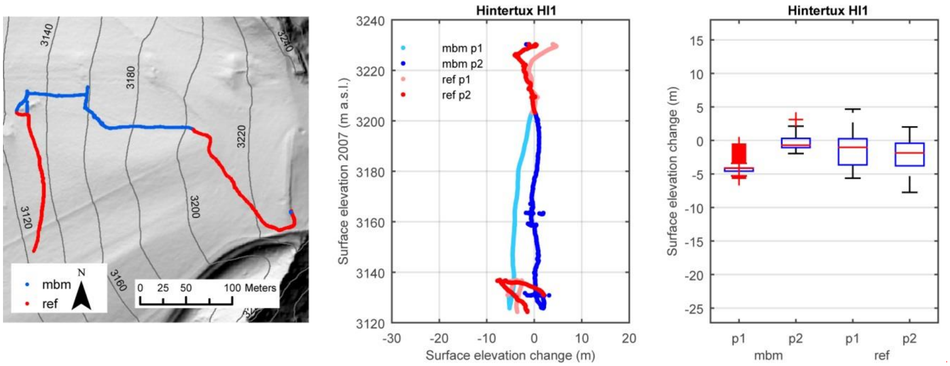
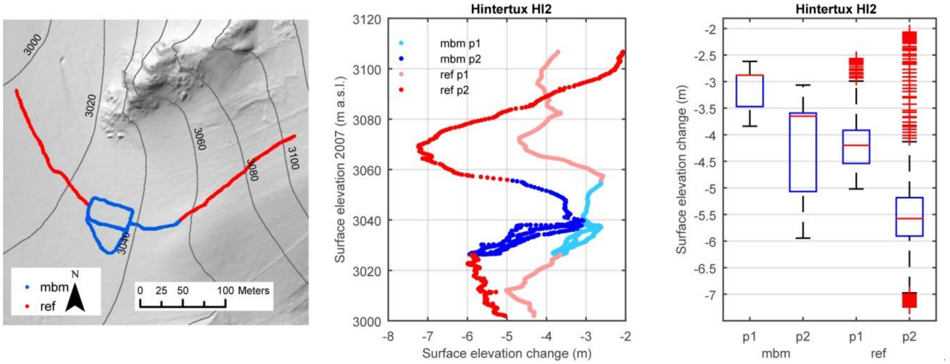


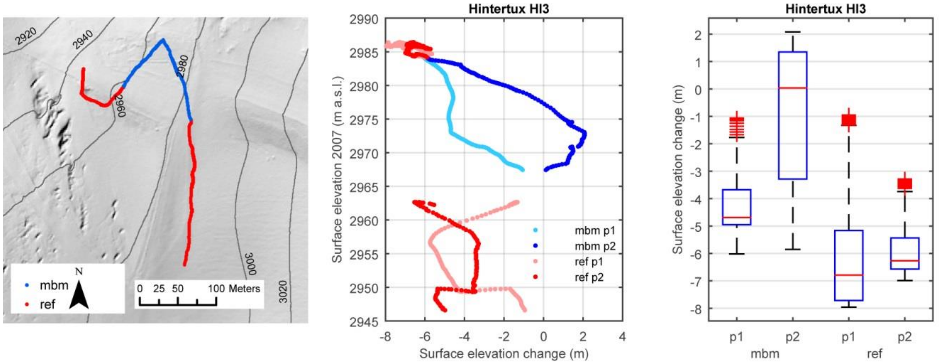
Figure 7: Median of the annual surface elevation changes of the profiles in the first period (Δz_{p1}) compared to the median of the annual surface elevation changes of the profiles in the second period (Δz_{p2}). Periods are given in Table 2. Solid lines show the interquartile range between the 25th and the 75th percentile.



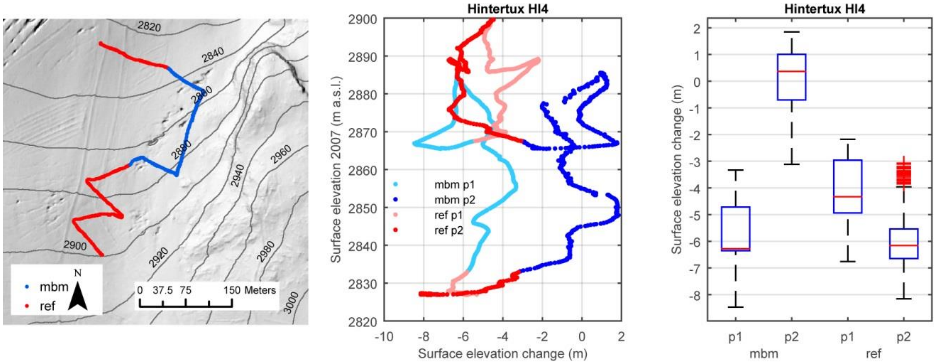
~~Figure 3. Location of profile HI1 (left), surface elevation changes plotted for surface elevation in 2007 (middle) and boxplot of surface elevation changes along the profile (right, red line: median, blue box: 25/75% percentile, whisker: 1.5 interquartile range, red cross: outliers) separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1999 -2007 (p1) and 2007 – 2015 (p2).~~



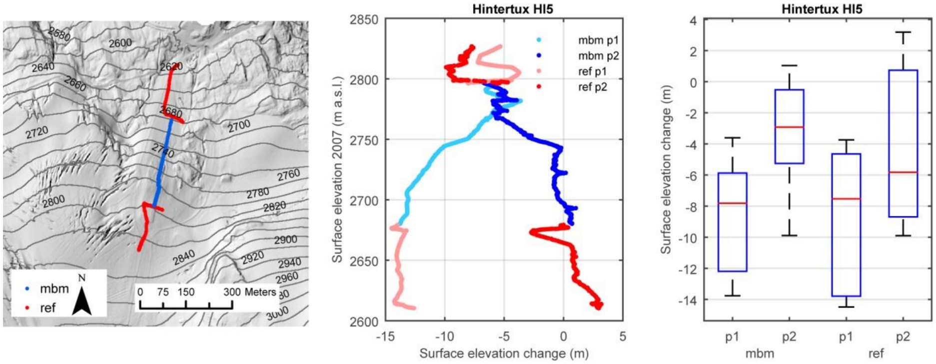
~~Figure 4. Location of profile HI2, surface elevation changes plotted for surface elevation in 2007 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1999 -2007 (p1) and 2007 – 2015 (p2).~~



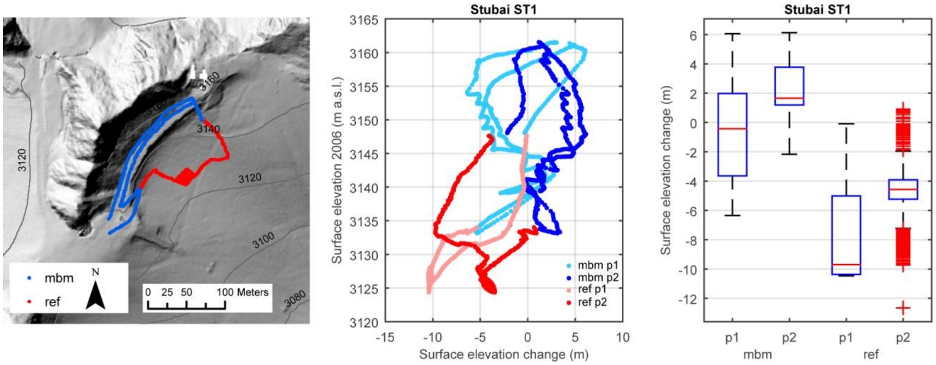
~~Figure 5. Location of profile HI3, surface elevation changes plotted for surface elevation in 2007 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1999–2007 (p1) and 2007 – 2015 (p2).~~



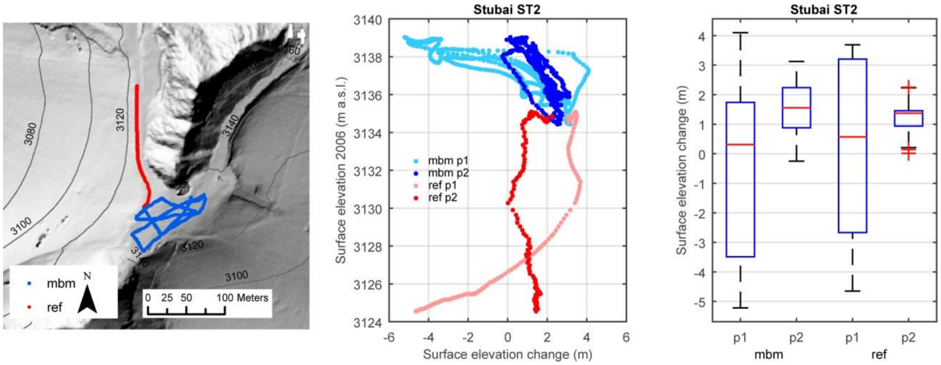
~~Figure 6. Location of profile HI4, surface elevation changes plotted for surface elevation in 2007 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1999–2007 (p1) and 2007 – 2015 (p2).~~



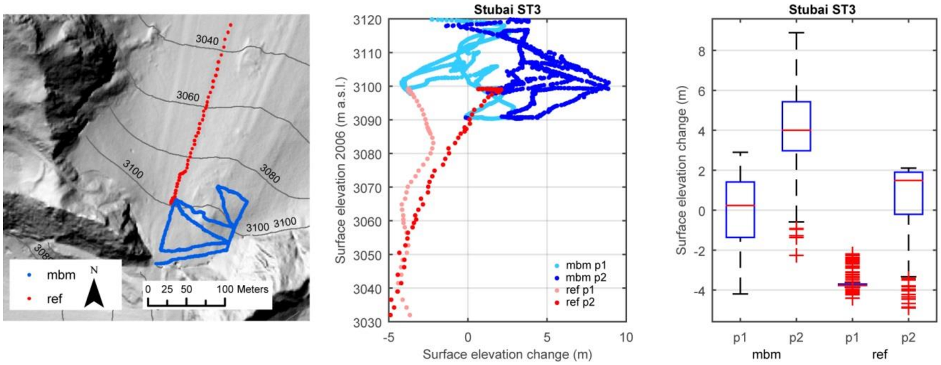
~~Figure 7. Location of profile HI5, surface elevation changes plotted for surface elevation in 2007 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1999–2007 (p1) and 2007 – 2015 (p2).~~



~~Figure 8. Location of profile ST1, surface elevation changes plotted for surface elevation in 2006 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1997–2006 (p1) and 2006 – 2015 (p2).~~

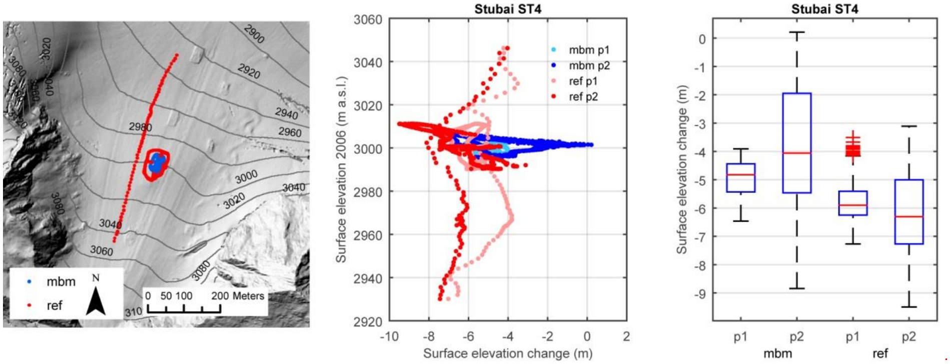


~~Figure 9. Location of profile ST2, surface elevation changes plotted for surface elevation in 2006 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1997–2006 (p1) and 2006 – 2015 (p2).~~

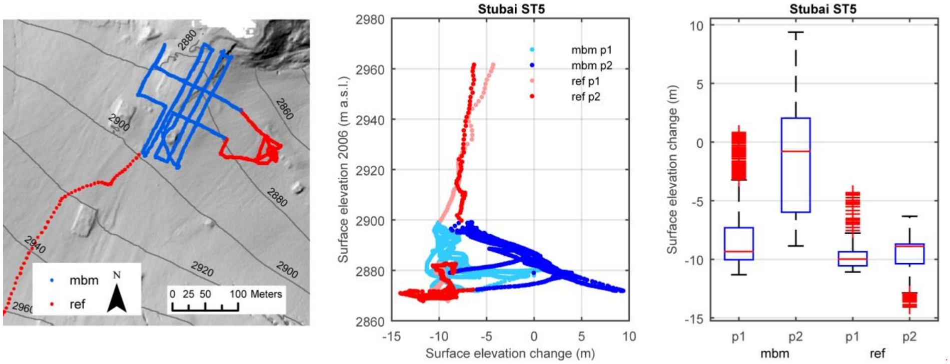


~~Figure 10. Location of profile ST3, surface elevation changes plotted for surface elevation in 2006 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1997–2006 (p1) and 2006 – 2015 (p2).~~

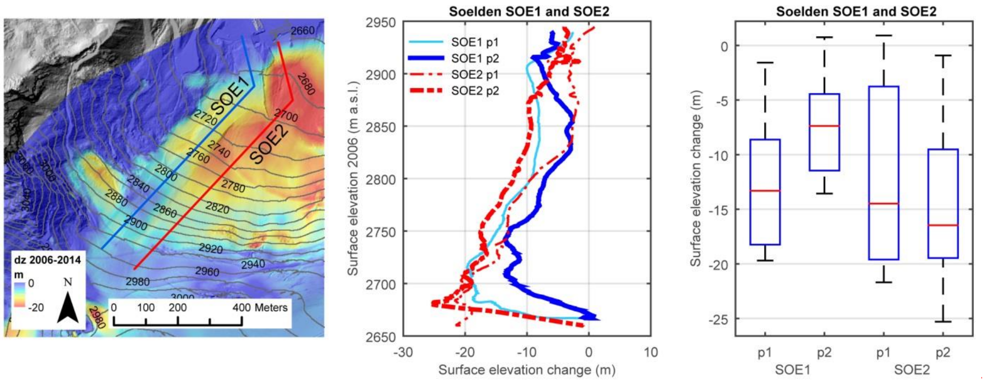
Formatiert: Block



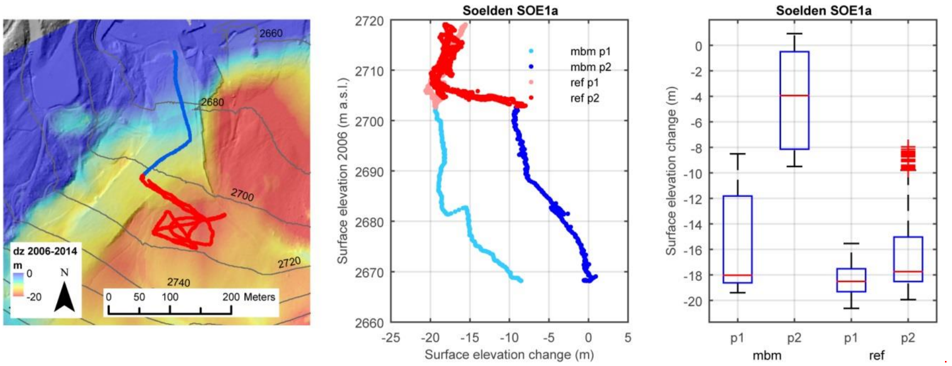
~~Figure 11. Location of profile ST4, surface elevation changes plotted for surface elevation in 2006 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1997–2006 (p1) and 2006 – 2015 (p2).~~



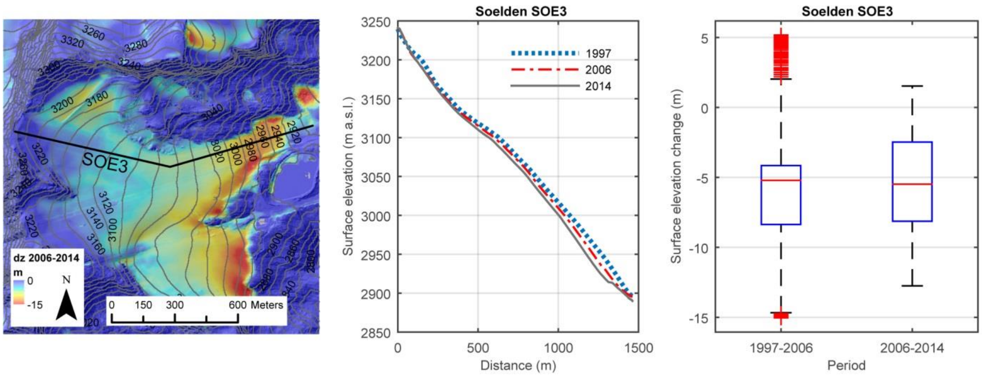
~~Figure 12. Location of profile ST5, surface elevation changes plotted for surface elevation in 2006 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1997–2006 (p1) and 2006 – 2015 (p2).~~



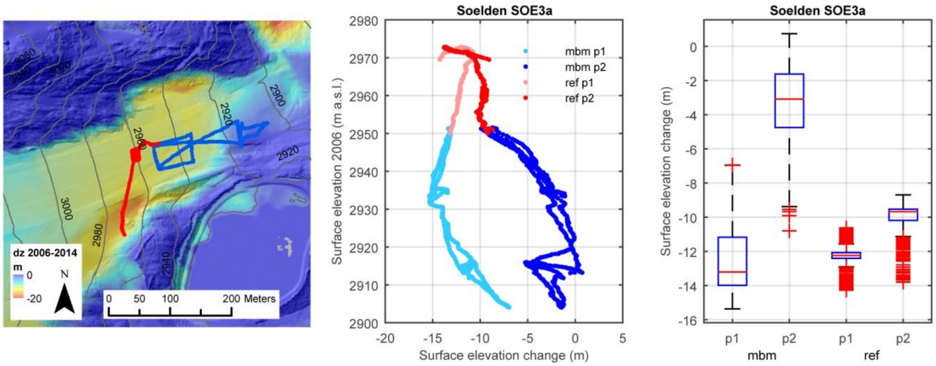
~~Figure 13. Location of the profiles SOE1 and SOE2 with spatial distribution of surface elevation changes between 2006 and 2014, surface elevation changes plotted for surface elevation in 2006 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1997 - 2006 (p1) and 2006 – 2014 (p2).~~



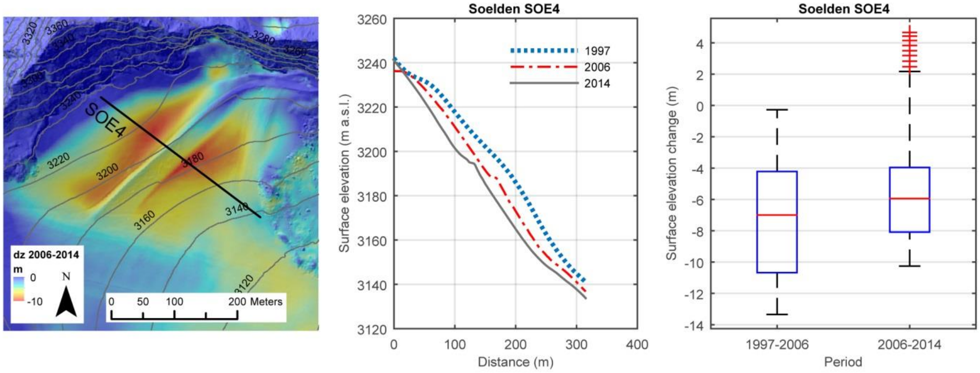
~~Figure 14. Location of the profile SOE1a with spatial distribution of surface elevation changes between 2006 and 2014, surface elevation changes plotted for surface elevation in 2006 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1997 - 2006 (p1) and 2006 – 2015 (p2).~~



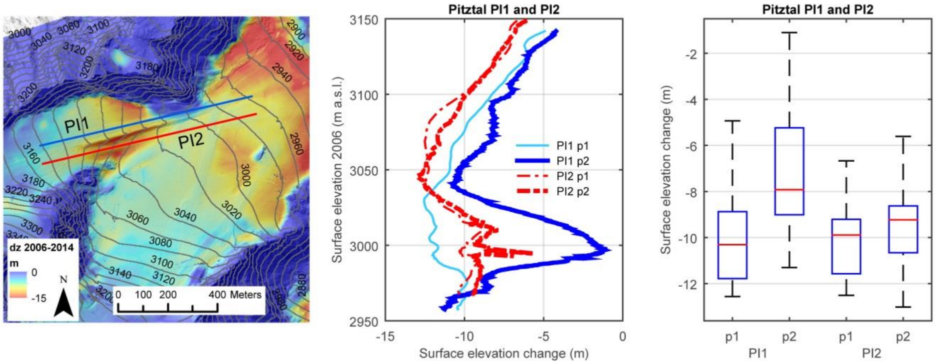
~~Figure 15. Location of the profile SOE3 with spatial distribution of surface elevation changes between 2006 and 2014, surface elevation along the profile and boxplot of surface elevation changes of the periods 1997 - 2006 and 2006 – 2014.~~



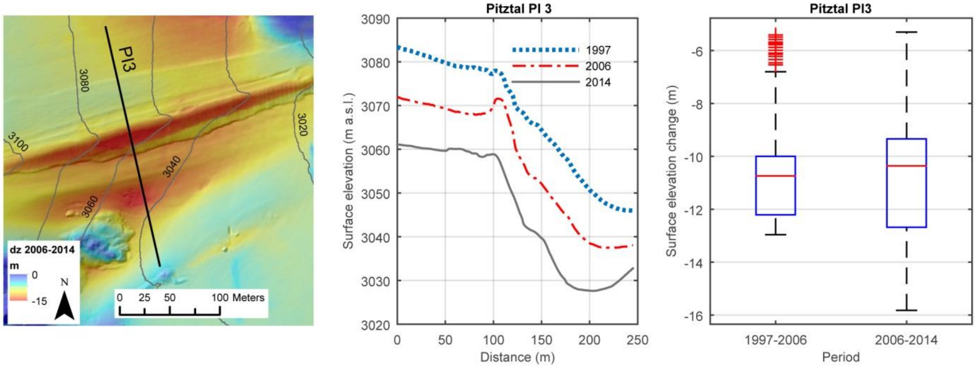
~~Figure 16. Location of the profile SOE3a with spatial distribution of surface elevation changes between 2006 and 2014, surface elevation changes plotted for surface elevation in 2006 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1997 - 2006 (p1) and 2006 – 2015 (p2).~~



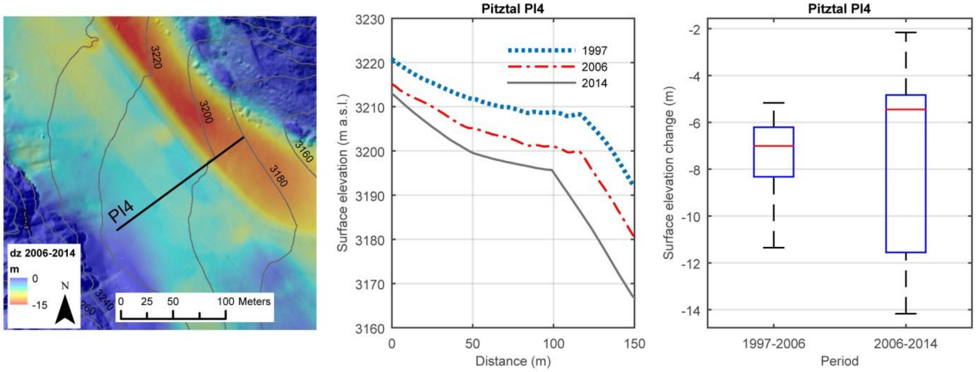
~~Figure 17. Location of the profile SOE4 with spatial distribution of surface elevation changes between 2006 and 2014, surface elevation along the profile and boxplot of surface elevation changes of the periods 1997 - 2006 and 2006 – 2014.~~



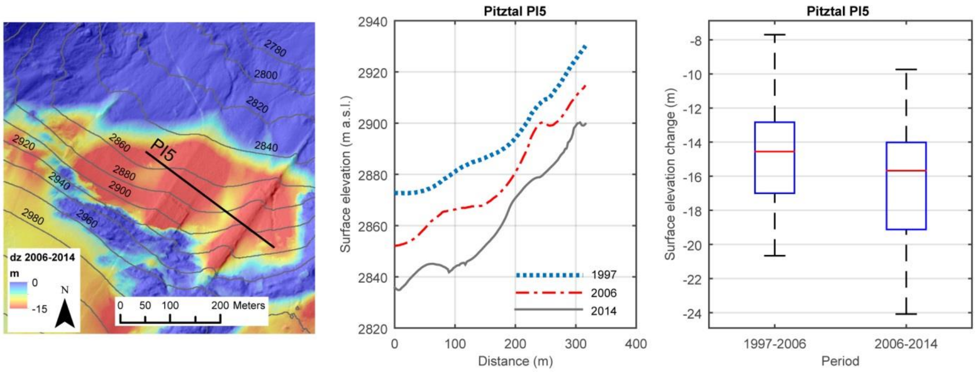
~~Figure 18. Location of the profiles PI1 and PI2 with spatial distribution of surface elevation changes between 2006 and 2014, surface elevation changes plotted for surface elevation in 2006 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1997 - 2006 (p1) and 2006 – 2014 (p2).~~



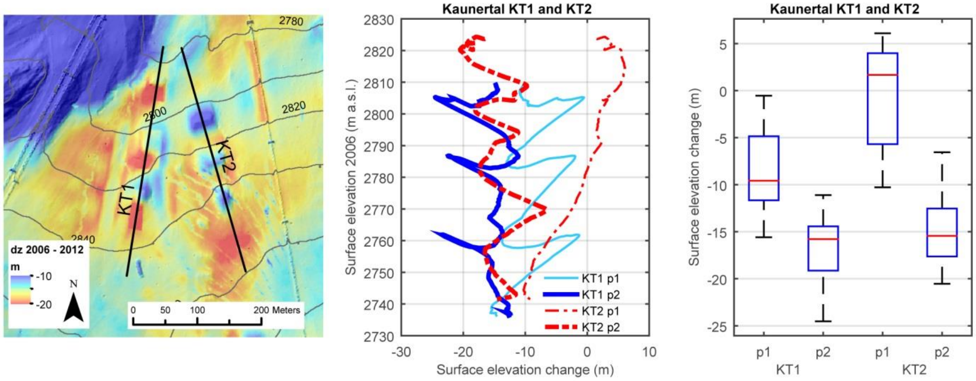
~~Figure 19. Location of the profile PI3 with spatial distribution of surface elevation changes between 2006 and 2014, surface elevation along the profile and boxplot of surface elevation changes of the periods 1997 – 2006 and 2006 – 2014.~~



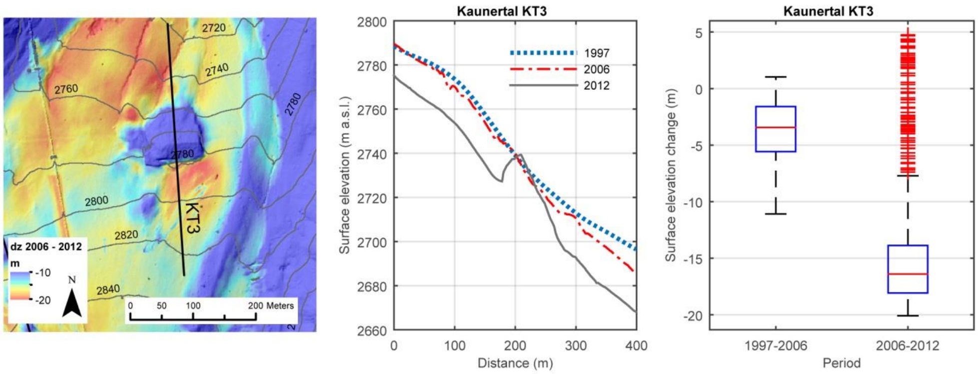
~~Figure 20. Location of the profile PI4 with spatial distribution of surface elevation changes between 2006 and 2014, surface elevation along the profile and boxplot of surface elevation changes of the periods 1997 - 2006 and 2006 – 2014.~~



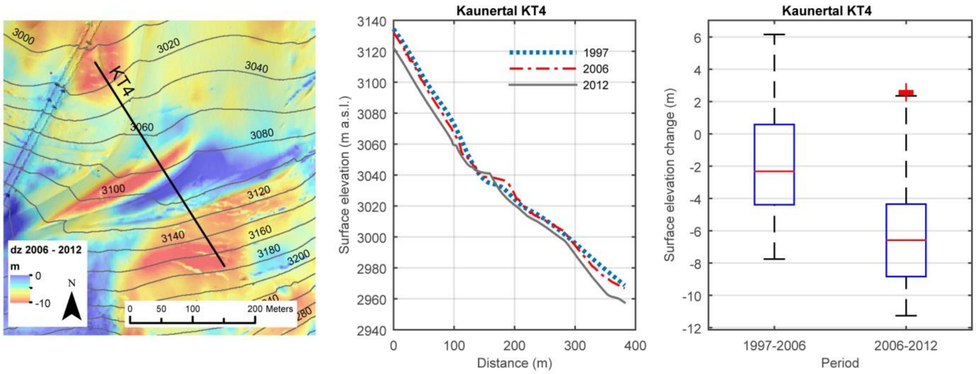
~~Figure 21. Location of the profile PI5 with spatial distribution of surface elevation changes between 2006 and 2014, surface elevation along the profile and boxplot of surface elevation changes of the periods 1997 - 2006 and 2006 – 2014.~~



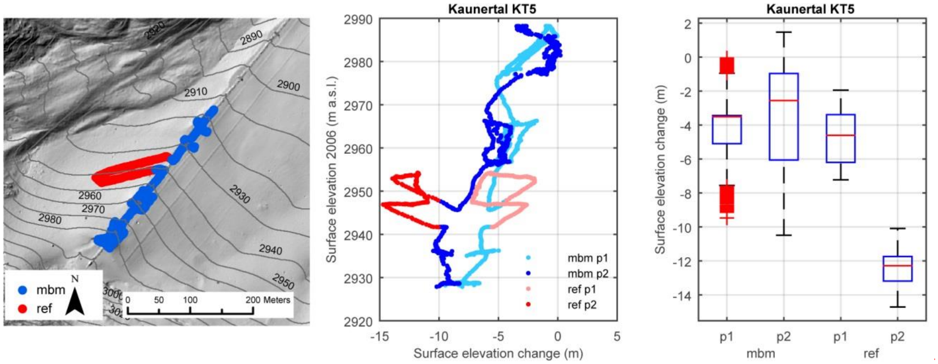
~~Figure 22. Location of the profiles KT11 and KT2 with spatial distribution of surface elevation changes between 2006 and 2012, surface elevation changes plotted for surface elevation in 2006 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1997 - 2006 (p1) and 2006 – 2012 (p2).~~



~~Figure 23. Location of the profile KT3 with spatial distribution of surface elevation changes between 2006 and 2012, surface elevation along the profile and boxplot of surface elevation changes of the periods 1997 - 2006 and 2006 – 2012.~~



~~Figure 24. Location of the profile KT4 with spatial distribution of surface elevation changes between 2006 and 2012, surface elevation along the profile and boxplot of surface elevation changes of the periods 1997 - 2006 and 2006 – 2012.~~



~~Figure 25. Location of profile KT5, surface elevation changes plotted for surface elevation in 2006 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1997–2006 (p1) and 2006 – 2015 (p2).~~