Author’s response tc-2016-61-rev2

We thank the reviewer and the editor for their valuable comments, which are very much appreciated. We went through general and detailed comments. Unfortunately, they referred to the change track version, which was very confusing as large parts of the manuscript have been redone. This was the reason why the final work in the previous submission was done on the ‘changes accepted’ version. This was intended to state in the comments to the editor, but obviously got lost somewhere. Unfortunately we did not communicate this in the response of the authors. We are sorry for the reviewer and the editor that they spent their time on a pre-final version. Most of the comments refer to mistakes which had already been corrected, or text parts/formula which have been removed in the final version.

List of relevant changes:

We rewrote the sections Discussion and Conclusion, skipped Figure 7, skipped the profiles of the third category, extended the description of the categories, renamed all Figures/Captions/Profiles/Tables as suggested. Therefore, the numbering of the remaining profiles changed (Short comment in the supplementary file, SOE3a-> SOE3, KT5-> KT1).The suggested detailed changes were done, and some minor additional corrections.

General comments of reviewer:

Authors response

1) Compared to the first version, this manuscript has been largely improved. The presentation of data and results is clearer. However, the manuscript needs to be improved again and did not reach the sufficient maturity to be published in TC. Many points need to be clarified. Many sentences are obscure and need to be reformulated (see general and specific comments). Some words are missing. Some words are not English. There are mistakes in some Equations. The authors did not take time to reread thoroughly the revised manuscript.

We made final corrections and proof reading in the ‘changes accepted version’, as large parts of the manuscript were reorganized and we wanted to avoid the situation that incomplete sentences etc. are left in the final manuscript. This was based on the opinion that the change track version would be used for change tracking only, not as basis of the review.

I have the feeling to play the role of colleagues or co-authors to prepare a draft and make a submitted version. Although there are large improvements compared to the first version which was a kind of “technical report”, my feeling is that the authors did not take sufficient time to revise the first version. Could the authors be fair and take pity on Reviewers ?

We are sorry for the misunderstanding which version of the manuscript was used for review.

In any case, this manuscript deserves a publication in TC after the necessary following changes.

2) The results section is not clear enough although that I recognize it has been largely improved. The presentation of the 3 categories is unclear: which difference? Information about the first and the second category is needed. The captions of Fig 5 and Fig 6 are exactly the same and are not helpful. The authors wrote "in similar settings" (l. 12, p. 11) but it is very unclear.

Line 12 on page 11 change track version says:
'profiles close to the glacier terminus in similar topographic settings resulting at similar thickness loss at mass '
Is this referring to this text or another?

This is line 12 page 9 in the final version.

What we want to say is that in the same climatic regime, same exposure, same accumulation condition, same radiation conditions, the mass balance of two points at the glacier neighboring each other (few meters to tens of meters distance) should not differ significantly, as we see no driver for this difference in terms of accumulation or energy balance governing melt. Can we basically agree on the absence of sharp changes in mass balance fields, in absence of any topographic, radiative or hydrologic cause for sharp gradients? (Here I consider wind erosion as a topographic factor).

We tried to improve the description of the categories, and skipped the third category as suggested.

3) Results section: Did the authors remove every measurements where the ice has disappeared between the first and the second measurements?

As the authors surveyed the profiles in situ, during ablation season, the existence of ice in the profiles is certain.

In Figure 4, one can see that the elevation change close to the terminus (altitude close 2880 m, light blue) for the first period, is not very negative (the values are between -5 and 0). It could be due to the fact that the ice has disappeared before the end of the 1st period.

We agree that it makes no sense to investigate profiles without ice cover. This was never intended, nor done.

If it is the case, the results are biased and the elevation changes are not relevant. It is absolutely necessary to remove these values (Table 3 and Figure 4) to make a relevant analysis.

It is not entirely clear to me on which evidence the hypothesis of ice free profiles is based on. It is correct that the largest elevation changes in the Austrian glacier inventories are found close to glacier tongues (cf Kuhn et al., 2012). Not every glacier in fact does show very high elevation changes, and not at every part of the tongue. We have no indication that there is any error in the data, or that any parts are ice free, not even after the summer of 2015.

4) About the results on the third category: The elevation changes for these small features are very heterogeneous. I do not think such data are useful for this paper because the representativeness is strongly questioned. I think that the authors should remove Figure 7 and data of this third category in Table 3.

The intention was to show which effect the coverage of kickers and bumpers has. These features have become modern in the last decades, and originally needed loads of winter snow to be built. This is not the case any more, as on normal pistes the ground now is shaped, and on glaciers the shape is preserved with covers. We agree that this is not very relevant for this study, and skipped the third category.

5) Important: the results are confusing and the reader is lost because the authors wrote everywhere in the manuscript “with mass balance management” for the first period although there is not “mass balance management” during this period except the last years of this period (l. 25, p.4). The authors should reword it because it is very very confusing. For instance, the authors could use “reference areas” and “experimental areas”, and specify “experimental areas without management” for the first period and “experimental areas with management” for the second period….or something else. Check carefully the manuscript. Same thing in captions of Figure 5 and 6. In addition avoid deltaZmbm for the first period in captions of Fig 5 and 6. Change the name of the vertical axis in Fig 5 and 6. Very misleading. (by the way, Figures 5 and 6 are fine and it is a large improvement compared to the first version).

We hoped that it would be clarified by the detailed description, that only part of the first period is covered by mass balance management. Nevertheless, we changed the wording as suggested and hope that the article is less confusing.

This comment refers to line 23 page 4 in the final version. As in this sentence only the areas are described, the exp and ref are introduces later and changed in the whole manuscript and supplement.

7) L. 21-31, p. 12: This part should be rewritten or removed. It seems to come from a technical report with advices to ski resort managers.
We removed that part.

8) Discussion about the surface mass balance inferred from elevation changes: it is not convincing.
We did not aim at inferring mass balance from elevation change. This is stated more clearly in the introduction now:
'From this basic research question, this study aimed at assessing long-term net effects of mass balance measures on volume changes by comparing surface elevation changes in areas which have been subject to different types of mass balance management and neighbouring areas without such management. This study is not aiming at inferring mass balance from elevation changes.'
A whole section in the discussion is now used, with the help of the corrected formula, that we have too much uncertainties to infer mass balance from thickness changes.

The Discussion about this point is poor. The assumption relative to "In any case, submergence and emergence should be similar for the profiles and the reference profiles" (l. 22, p. 16) is not supported by any data or evidence.
That is true, as on only one glacier in Austria (Kesselwandferner) time series of ice flow velocities are measured. So the ski resort glaciers are not subject to measurements of emergence and submergence. We skipped that sentence. It was actually wrong, as we use that as a precondition to compare thickness changes in adjacent profiles with very low flow velocities.

In this Discussion, the Equations are not used.

There is only one equation? We now refer to the equation.

I think that the authors should do a thorough analysis (first, please, write Equation of Cuffey and Paterson correctly).
First: Done

The authors should use this Equation to calculate the uncertainties on mass balance derived from elevation changes, between periods 1 and 2.

We did not derive any mass balance, and we do not think that this makes any sense or adds some information, as we do not know u, v, or w. Without knowing ice thickness, density in the vertical columns and 3D ice flow velocity the uncertainty of inferring local mass balances from elevation changes is too high to make sense. Comparing local stake measurements of ablation from the previous project with thickness changes, we know that at that time (2004-2009) about 60 to 70 % of the melted ice was replaced by inflowing ice, with approx.. 4 m of ice melt resulting in 1 m thickness loss.

I think they should only use data with similar elevation changes during the first period (see my previous comment) for such analysis. Please remove the other equations which are not helpful (in addition, Equation named (1) is probably wrong given the density is not the same for the surface mass balance and the entire column and the surface mass balance (deltam).

There is no equation 1 nor 2?

Very confusing. Please remove the equations named (1) and (2) (the authors forgot to name Equation of Cuffey and Paterson). Discussion should be reworded completely.

The discussion is reworded. There is only one equation left.

9) The section "Conclusions" is not well written and should be reworded completely.

done

10) Table 3: did the authors remove every values for which the ice disappeared between the 1st and the 2nd measurements ?
There were no values to remove, as we did not include ice free areas.

11) Figure 3: It should be useful to show the "management areas" with dashed line (first panel). a) and b) should improve Figure 3 and caption. The coordinates are not necessary and the authors should add an horizontal scale. In caption, the authors should mention the name of the glacier (Stubai)
We decided not to show a dashed line, as then the sharp gradient in elevation change is not visible. We think that the margins of the mass balance management are clearly visible in the hillshade (b).
Stubai indeed is the name of a mountain range, or a glacier ski resort, and not a glacier. Table 1 and Figure 1 should explain that.

12) Figure 4: Provide a), b) and c) for each panel and provide full explanations in the caption about the colors (light blue, dark blue, pink, red)
done

13) Figures 5 and 6: In the caption, the authors used "median". Do the authors mean "median " or "mean" ? Change the vertical axis according my previous comments. Revise the captions according my previous comments
'Median' is intended to mean 'median', otherwise it would be phrased as 'mean'. Axis and captions changed.

14) Remove Figure 7. Not helpful for the manuscript.
done

15) I believe that the English of the manuscript should be checked by a native speaker. Many sentences seem to me obscure (although I am not native speaker).
The manuscript was checked by our English editorial office, Dr. Scott. As she is a professional language editor (although mostly working with literature), grammar and spelling should be ok. She had been going to this revision also.

Specific comments:
The number of lines correspond to the revised version with track changes

a) Check the ref Abermann et al (p. 2). Year ?
2009

b) Check the brackets for Smiraglia et al (p. 2)
this was corrected in the final version

c) L. 20, p. 2: "opened" ? I do not understand
changed to 'started operation''
d) L. 2 and 3, p.3: unclear
'The transition of the ski tracks from glacier to the bare ground changes constantly with variations in glacier surface altitude and snout position.'
Reworded to:
The transition of the ski tracks from glacier to the bare ground changes constantly, as the glacier area and elevation changes.

e) L 6 p 3: unclear
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.

We splitted the sentence.

f) L. 18 p 4: confusing
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.
Changed to
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 thatAlso ice dynamics can be considered to lead to a redistribution of masses so that, for example, no effect on surface elevations would be measurable.

g) L. 16-17, p 6: how did the authors check the accuracy ? It largely depend on the distance to reference station, to the time of acquisition and to number of satellites. The authors should add these information. Where does the standard deviation come from ? Vague

The 'Magnet Tools' software of TOPCON allows to calculate standard deviation, as any other GPS Software. The software is given in the line above. We added it once again.

h) Check the numbering of Equations
done, numbers removed (makes no sense using two equations).

i) L. 9, p 7: remove this Equation. Unuseful
done

j) L. 23-26 p 7: very confusing. Explain how you obtained the uncertainties
The line above says: 'The measurement errors of the thickness changes at one location are the sum of the measurements errors of each surface elevation data set' and the respective numbers are given in section 2.1.

k) P. 7 : some words are missing, check it. Please Re-read carefully the manuscript.
We and our editor carefully checked the manuscript (final version, not change track), but did not find too much errors – maybe this was a problem in the wrong version?

l) L. 2-3 p 8: reformulate please
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.
Rephrased to
The DEMs of the second glacier inventory were processed in a 20x20 m grid and resampled to a 5x5 m grid.

m) L.9-15: the text should be revised thoroughly. Finally the authors do not mention the real uncertainty on elevation changes (after interpolation). Very misleading.
Is this referring to page 8?
'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.'

We agree that the estimation of errors in elevation models is complex, but we are uncertain about the idea of a 'real uncertainty'. In lines 9-15, no interpolation is mentioned?

n) "Study sites " section: "high subsidence rates": not clear. Where does this result come from ? Reference ? Relevant in this section ?

We found two sentences with 'high subsidence rates':

i) Mass balance management takes place in areas where technical infrastructure located on solid ground is adjacent to ski pistes on glacier parts with high subsidence rates, and at pylons on glacier or boarder parks with jumps and pipes.

ii) The middle station at Schaufelferner (Figure 2 a) is located on a rock, with the surrounding glacier showing high subsidence rates.

Both describe why we investigated these locations. We consider this information relevant.

<u>o) L. 29 p 8: this glacier is not mentioned anywhere (except in Figure 1 in very small characters) and the reader is lost…</u>

The glacier is mentioned in Table 1, also displaying which glacier belongs to which ski resort.

<u>p) L. 33 p 8: which striking effect ? not relevant in this section</u>

<u>q) P. 9 words are missing.</u>

<u>r) L. 12, p 9: check the verb</u>

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.

This was corrected already in the final version.

<u>s) L. 29 p. 17: per year ?</u>

yes

<u>t) Please Reword Discussion and Conclusions (see my previous general comments)</u>

done

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

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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 of the measures on mass balance to long-term effects ~~by comparing elevation changes in areas with and without mass balance management~~on elevation changes. Based on LiDAR DEMs and DGPS measurements, decadal surface elevation changes in 1~~6~~5 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 21.1 m±0.4 m of ice thickness was preserved on mass balance managed areas compared to non-maintained areas ~~at glacier tongues~~ over a period of nine years. In this period, mean annual thickness loss in ~~15~~ 15 of the mass balance managed profiles is 0.54 ±0.04 m/y lower (~~, with~~ -0.23±0.04 m/y on average) ~~0.57~~0.54 ~~m/y ± 0.04 m/y lower~~ than in the respective reference areas (-0.78 ± 0.04 m/y).

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 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.

1 Introduction

During the last three decades, A~~a~~lpine 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 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.

Austria's glaciers experienced a reduction by 26% in area in recent decades (First glacier inventory GI1 1969 – third glacier inventory GI3 2006/2012; Fischer et al., 2015). Abermann et al. (2009) 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, Figure 1), which are located on 15 glaciers. They ~~were opened~~started operation between 1969 to 1986, 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).

Not only visitor demand has become more sophisticated over time but cable car technology as well and with it demands on glacier conditions have risen. 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 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, as the glacier area and elevation changes~~The transition of the ski tracks from glacier to the bare ground changes constantly with variations in glacier surface altitude and snout position~~.

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 p~~Pistes which became ice free 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). Therefore, mass balance management in glacier ski resorts has three aims:

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

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

iii) Preventing or reducinge ice melt to keep bedrock ice-covered.

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):

- Glacier covers
- Grooming
- Water injection
- Snow-farming

Glacier covering means insulating the glacier surface with an approx. 0.002 m thick white polypropylene fabric in the period between peak accumulation (mid-May) and the start of the accumulation season (early September). Piste grooming is~~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 more to prepare pistes for ski races than for mass balance management.~~.~~ 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.

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 6% which is close to measurement uncertainty. The exact physical mechanism is unclear. We measured a higher accumulation in the groomed areas at the end of the winter, potentially caused by limited 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.

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~~~~Also~~ Moreover, ice dynamics might ~~can be considered to~~ 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 of mass balance measures on volume changes by comparing surface elevation changes in areas which have been subject to different types of mass balance management and neighbouring areas without such management. This study does ~~is~~ not aim~~ing~~ at inferring mass balance from elevation changes, but at~~on~~ comparing elevation changes on experimental and reference areas. Surface elevation changes in mass balance managed (i.e. experimental) areas were compared to neighbouring (i.e. reference) 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 (with mass balance management only applied in the last 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.

2 Data and methods

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 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.

2.1.1 Photogrammetric DEMs

The DEMs of the 2nd (GI2) Austrian glacier inventory (Lambrecht and Kuhn, 2007) are based on orthophotos with 5 m grid size. The DEMs have been calculated with a semiautomatic method in a 20 m grid (Würländer and Eder, 1998). The minimum vertical accuracy had been defined as ±1.9 m (Lambrecht and Kuhn, 2007), but turned out 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) who compared in situ measurements on Kesselwandferner in the Ötztal Alps with DEM data. There is no indication that any of the DEMs of the test sites in this study are outside the error margin of ±0.71 m found by Würländer and Eder (1998), as the respective orthophotos did not present oversaturation or shadows. The orthophotos were taken in August and September, close to the seasonal minimum snow cover.

2.1.2 LiDAR DEMs

The airborne LiDAR DEMs of the third glacier inventory were recorded by the Federal Government of Tyrol with ALTM 3100 and Gemini sensors at a density of four points per square metre. The vertical accuracy is ±0.1m (Abermann et al., 2010). Studies on the accuracy of LiDAR DEMs by 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 snow cover. LiDAR DEMs of the years 2012 and 2014 have been produced on the basis of ALS surveys in close cooperation with the glacier ski resorts.

2.1.3 GPS measurements

We 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 (as calculated by Magnet Tools) of the corrected data is 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.

2.2 Calculation of thickness changes

The thickness change at a single location Δz results from~~is calculated by~~ subtracting the altitude at the dates of the second survey ~~(t_1)~~ from those of a first survey. ~~(t_0)~~

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

The mean thickness change of a profile ~~was calculated as~~is the average of the thickness changes of every point within the profile. ~~The thickness change~~Elevation changes between DEM and DGPS data ~~was~~ were calculated at every point recorded by DGPS~~. The differences were calculated with~~ using ArcGIS (version 10.2.2) and MATLAB R2014b~~:~~. Elevation values were extracted from the DEM rasters of the different dates using “extract values to points” and surface elevation changes were ~~calculated~~ obtained from these values at every point in the attribute table. Thickness changes ~~calculated from~~between two DEMs were calculated along a profile line at equidistant nodes 1 m apart, which show similar point densities to the DGPS measurements.

The measurement errors of the thickness changes at one location are the sum of the measurements errors of each surface elevation data set (to find a maximum error)~~,~~. ~~i.e~~This results in ~~.~~ 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, as well as seasonal snow cover. To prevent shading of the signal, the DGPS antenna was mounted on a stake or a backpack 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 within a range of centimetres. The DEM altitude is the mean altitude within the pixel located at the DGPS measurement point. As the LiDAR data are based on 4 pixels/m² and have a spatial resolution of 1x1 m, the spatial resolution can be considered similar to the DGPS measurements (acquired every second at walking speed, resulting in a point density of 1-2 points per metre. The DEMs of the second glacier inventory were processed in a 20x20 m grid. This grid was then and resampled to a 5x5 m grid. As these were recorded before mass balance management started, the glacier surface was 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. Therefore the difference of point altitudes from the mean within the grid cells is less than 1.3 m for slopes with 20° and less than 0.08 m for slopes with 5°.

All the elevation data were recorded during ablation season, with major parts of the glacier presenting 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 its individual minimum of mass. Although minor impacts of old snow (from the winter) can not be excluded, all data were recorded in the absence of new snow, thus neglecting the effect of seasonal snow cover-. 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 less than 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 Study sites

During 2003-2009, areas with mass balance management on Stubai Glacier, Pitztal Glacier, Kaunertal Glacier and Sölden Glacier ski resort were monitored extensively, with at least two surveys per annum and a maximum of weekly surveys on Stubai Glacier. After finishing these projects, the sites were still monitored on an annual basis with some 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 were selected for this study. Although not included in the initial research projects 2003-2009, sites in the Hintertuxer Glacier ski resort were added to 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 is adjacent to ski pistes on glacier parts with high subsidence rates, and at pylons on glacier or boarder parks with jumps and pipes. Three representative 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 have been applied since 2004 to allow 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, where the photograph in Figure 2 b) was taken. The subsidence of glacier surface is most extreme at the tongues, but also takes place at highest elevations. The most disturbing effects are observed close to the cols and at the transition to solid ground in highest elevations. The exit from the top station, where the photo in Figure 2 c) was 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 in Figure 2a shows the location of the prominent glacier covers, with clearly lower thickness losses than the surroundings (Figure 3).

In the five glacier ski resorts (Table 1), ~~24~~15 sites with mass balance management were selected for comparing thickness changes in managed and reference areas. The comparison was carried out for two time periods. 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.~~

3 Results

In general, in the last decade a balance of the surface elevation at the highest investigated 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 a general overview, the thickness changes at all profiles during the two periods (Table 3) are divided into three categories for further analysis:

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

For the first category, during the first period reference and mass balance management, thickness changes are quite similar and range between -0.53 m/year and -2.03 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 0.01 m/year to -0.94 m/y. In contrast to the smaller thickness losses in mass balance managed areas, reference areas lost a thickness of -0.55 m/y to -1.81 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 -1.12 m for the first period and -0.34 m/y in the second period. The respective losses in reference areas are -1.19 m/year and -1.12 m/year. Thus the difference in thickness loss between managed and unmanaged areas is 0.77 m/year on average during the second period.

The profiles SOE1 and 2 comprise the entire slope on Rettenbachferner and range between the 25th and the 75th percentile of all surface elevation changes. Profile SOE1a is located at the lowest part of the glacier tongue. It presents the largest spread between mean annual surface elevation changes of both periods in the mass balance management area, while mean annual surface elevation losses in the reference area were nearly constant.

For the second category, interpretation of surface elevation changes at these profiles is more complex with respect to their location on the glaciers. In period 1 thickness losses in both managed and unmanaged areas of category two are within a mean of -0.38 m/y and -0.57 m/y lower than in category one. In period 2, reference areas show a mean thickness loss of -0.57 m/y, managed areas of -0.20 m thickness loss.

The profiles ST4 and ST3 already had less negative surface elevation changes in the managed area compared to that of the reference area in the first period. Mean surface elevation changes at profile ST2 were similar in managed and reference 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 0.57 m lower than in the respective reference areas, with a maximum difference of 1.31 m/y between reference and managed areas in profile SOE1a.

The profiles in the third category (Figures 6) are not discussed separately for managed and reference areas. The small-scale features are discussed in more detail in the supplementary material. The mean annual surface elevation changes were almost 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).

At highest elevations, thickness changes are generally smaller than on glacier tongues, as is the absolute difference between managed and unmanaged profiles (e.g. profiles HI1, ST4). The spatial heterogeneity of surface elevation changes was levelled out by the use of 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). Where snow is gathered for piste maintenance, mass gain on the piste is balanced against mass loss in the areas where the snow is taken from. (e.g. SOE4, KT4). At two of these profiles the surface elevation could be preserved altogether (ST1, HI4).

4 Discussion

This study focuses on the analysis of glacier surface elevation changes, as these are a major challenge for the ski resorts. Although thickness changes for managed and unmanaged areas are compared, it is outside not in the scope of this study to infer information on (unmeasured) mass balances from (measured) thickness changes. Differences between mass balance managed areas and reference areas are within the range of uncertainty for the first period DEM differences, but not for the second period, for which high accuracy geodata are available.

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. Local surface elevation changes can result not only from surface mass balance, but also 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.

To highlight why we do not claim to interpret thickness changes in terms of mass balance, we shortly [BS1]refer to basic glaciology: ~~Much more importantly, s~~Surface elevation changes $\frac{\partial S}{\partial t}$ result from glacier dynamics, density (ρ) changes and point mass balance *b* (Cuffey and Paterson, 2010).

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

In our study, we measured s~~S~~urface elevation changes $\frac{\partial S}{\partial t}$ at reference and experimental areas. All other parameters are unknown, and modelling results at such a small scale may be dominated by uncertainties of input parameters.

A necessary assumption for being able to compare $\frac{\partial S}{\partial t}$ for experimental and reference areas with obvious and photographically documented differences in mass balance b is that the other components $(\rho, w, u\frac{\partial S}{\partial x}, v\frac{\partial S}{\partial x})$ are largely unchanged ~~do not change much~~ between experimental and reference areas. Therefore, ~~For our analysis,~~ we have to presume that the components of the surface velocity at the point *u*, *v*, and *w* are similar in the ~~mass balance managed~~experimental and the reference profiles, as well as over ~~nd during~~ the two periods. Then~~,~~ the measured thickness changes are driven by the measures and not by glacier dynamics. This ~~hypothesis~~ assumption is not confirmed by measurements of mass balance, densities or flow velocities, but at least supported by some empirical evidence:~~is confirmed by~~ i) the superficial~~afical~~ forms at mass balance managed areas ~~evidence and~~ are stable ~~both~~ during years of field surveys and in geodata ~~stability of the suprafical forms at mass balanced areas also visible in the photographs and the LiDAR hillshade, and~~ ii) very low flow velocities measured generally at Austrian glaciers and in ski resorts glaciers at pylons mean that~~, keeping,~~ absolute velocity differences are small, and iii) the absence of crevasses on ~~at~~ the margins of the supera~~a~~ficial forms indicate~~ing~~ strong gradients o~~i~~f ice flow. 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.

~~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.~~ 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 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 show up immediately. All reference surfaces are subject to grooming during winter, only in Hintertux glacier ski resort are pistes also groomed in summer. Local mass balance measurements indicate that grooming in winter without other measures reduces ice ablation in summer by 10% because of 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 mainly takes advantage of periglacial snow or even, in addition ~~,~~ of deposits gained by blasting avalanches on periglacial slopes.

Differences between mass balance managed areas and reference areas are within the range of uncertainty for the first period DEM differences, but not for the second period, for which high accuracy geodata are available.

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.

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 annual 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, comment to TCD discussion paper), Mölltal~~er~~ ~~Gletscher~~Glacier (AT), Kitzsteinhorn (AT), Dachstein (AT), Zugspitze (D), Saas Fee (CH), and Schnalstal~~er~~ Glacier ~~Gletscher~~ (IT).

~~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 (e.g. 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 Conclusions

The use of snow production, relocation of snow~~-~~, and 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. 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. This is more than the long-term mean change of all ski resort glaciers of -0.8 m/y (1997-2006, Fischer et al., 2011). 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 differences between mass balance managed areas and reference areas cover a wide range of values, as do the thickness changes ~~itself do~~. Largest thickness changes are found close to the glacier tongues, and there ~~also~~ the highest absolute effects of measures are also found. Although the reduction of thickness changes is smaller in higher areas and areas with lower thickness losses in reference areas, this does not mean that measures are less effective there: In four of 15 profiles, thickness changes in mass balance managed areas were positive, ~~although~~while reference areas showed a continuous decrease of surface elevation.

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 sections~~parts~~ in future, because equilibrium line altitudes of glacier mass balances ~~in recent years~~ have exceeded peak elevations in recent years. 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. Practical limitations on the application of mass balance measures arise from the evolving small~~-~~-scale topography.

~~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. 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 measures have been carried out at small areas only, as costs and labour restrict the application to the most sensitive areas, i.e. the interface between subsiding parts of the glacier and~~to~~ technical infrastructure like~~as~~ stations and pylons~~-~~. ~~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~~This also limits ~~also~~ the impact of local measures on total glacier mass balance. ~~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. 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.~~

Our study complemented previous research on the positive effect of mass balance management on local mass and energy balance and was able to demonstrate that there is a positive long-erm impact of measures on elevation change. Nevertheless, in the light of technical and practical limitations of the measures, and the extreme melt rates of the early 21st century, such measures can only delay the decay of glaciers in ski resorts. The question remains whether the well investigated effect of thick enough debris cover reducing ice melt might be technically applicable for glacier ski resorts. Important points to investigate would be the stability of debris depending on slope inclination and liquid water (rain and melt water), the optimum size and structure of the debris and the potential to create smooth surfaces, prohibiting the evolution of melting ponds and steep ridges.

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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	Weissseeferner	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 Glacier	1997	2006	2012	23/07/2015
Pitztal Glacier	1997	2006	2014	-

Table 3. Mean elevation of the profiles and the applied mass balance management 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 Figures 4 to 6.

profile	mean	mbm				thickness change in period 1 in m					thickness change in period 2 in m				
name	elevation					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	-

Table 3. Mean elevation of the profiles and the applied mass balance management measures (mbm) 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 experimental areas (*exp*) and reference areas (*ref*) at the profiles in the periods without (p1) and with (p2) mass balance management are shown. Absolute differences (abs. diff, in m) of the *exp* mean values to the *ref* mean values are given. Note that the arrangement of the profiles corresponds to the segmentation of the profiles in ~~the~~ Figures 5 to 6.

profile	mean	mbm				thickness change in period 1 in m					thickness change in period 2 in m				
name	elevation					ref		exp		abs.	ref		exp		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
SOE3	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
KT1	2962		r	c	g	-4.7	1.6	-4.0	2.0	0.7	-12.4	1.0	-3.9	3.4	8.5

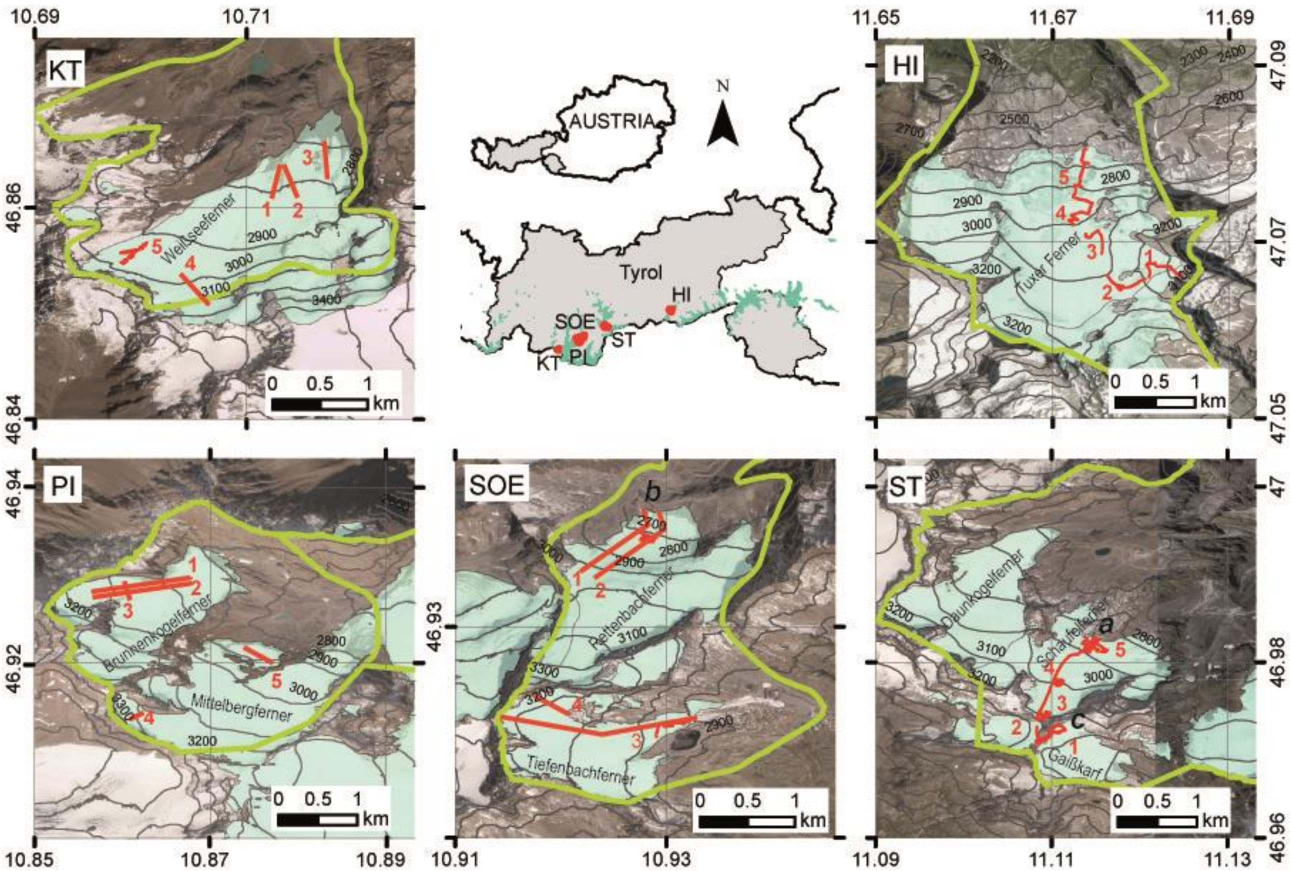


Figure 1. Overview of the Tyrolean glacier ski resorts of Kaunertal (KT), Pitztal (PI), Sölden (SOE), Stubai (ST) and Hintertux (HI). Measurement locations (red lines) with profile numbers (red), ski resort outlines (green lines), glaciers assigned to the resort (light green) and contour lines of the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

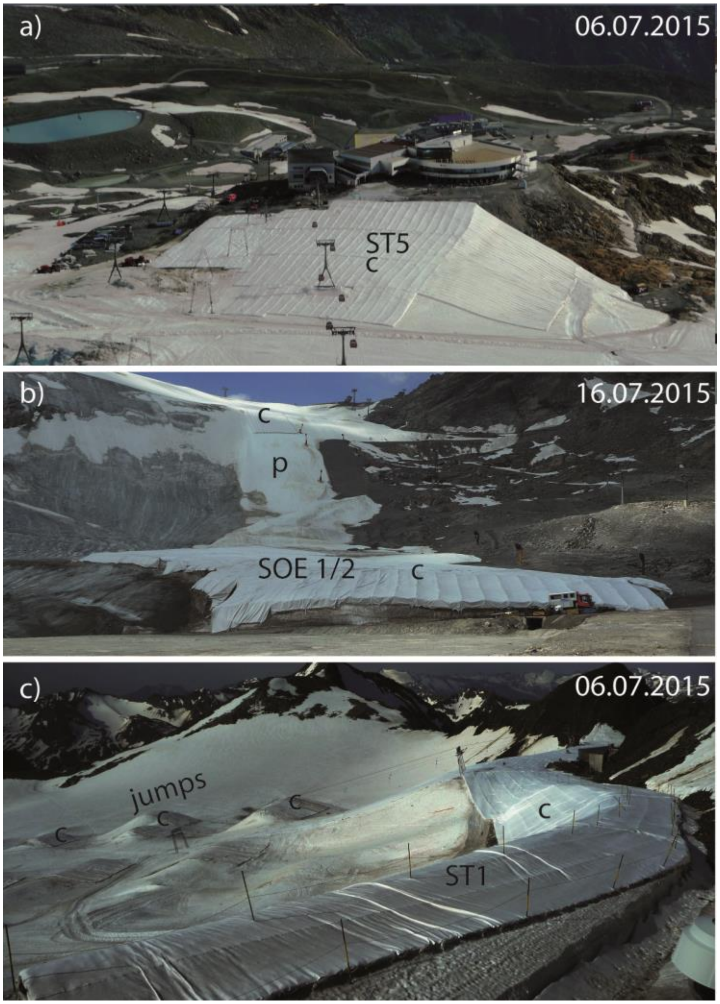
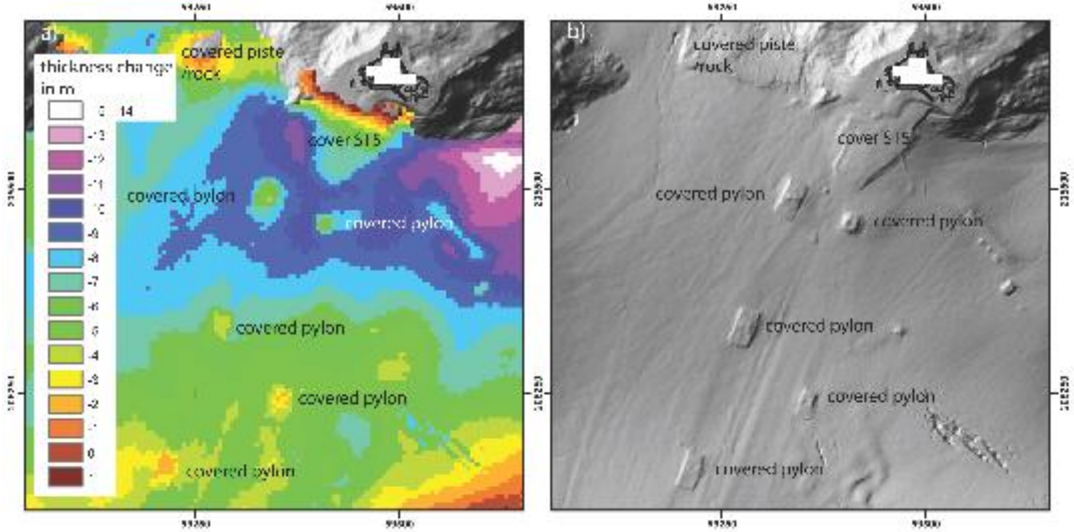
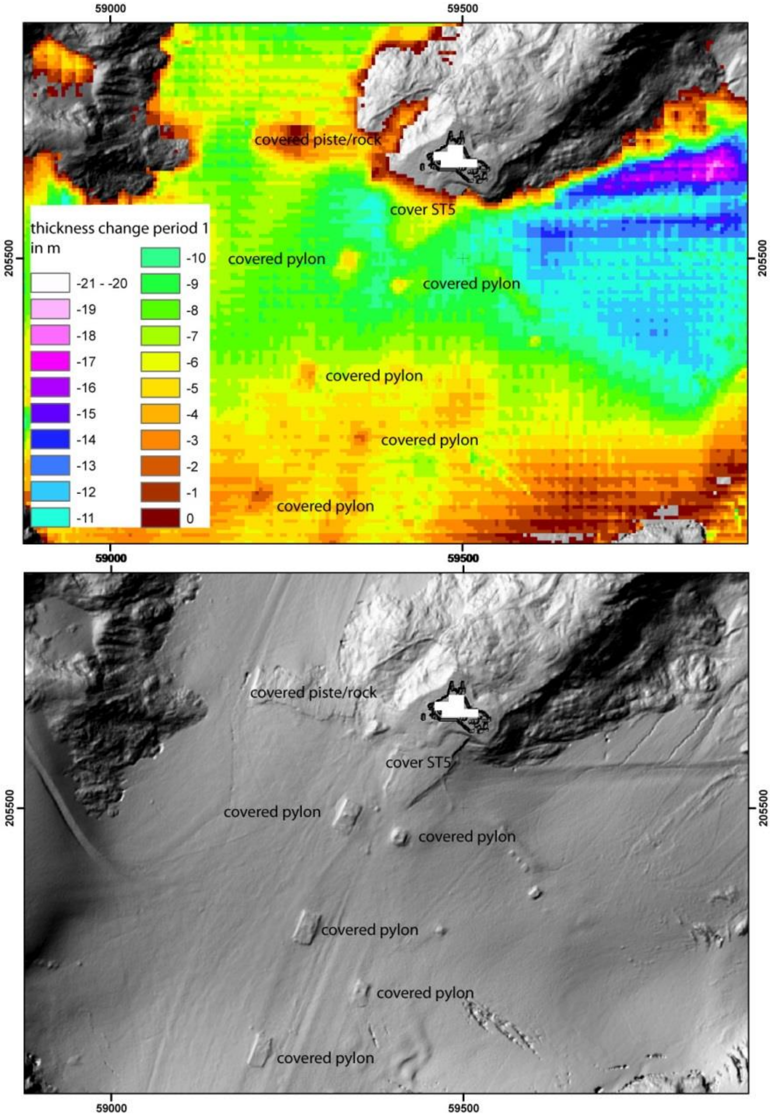
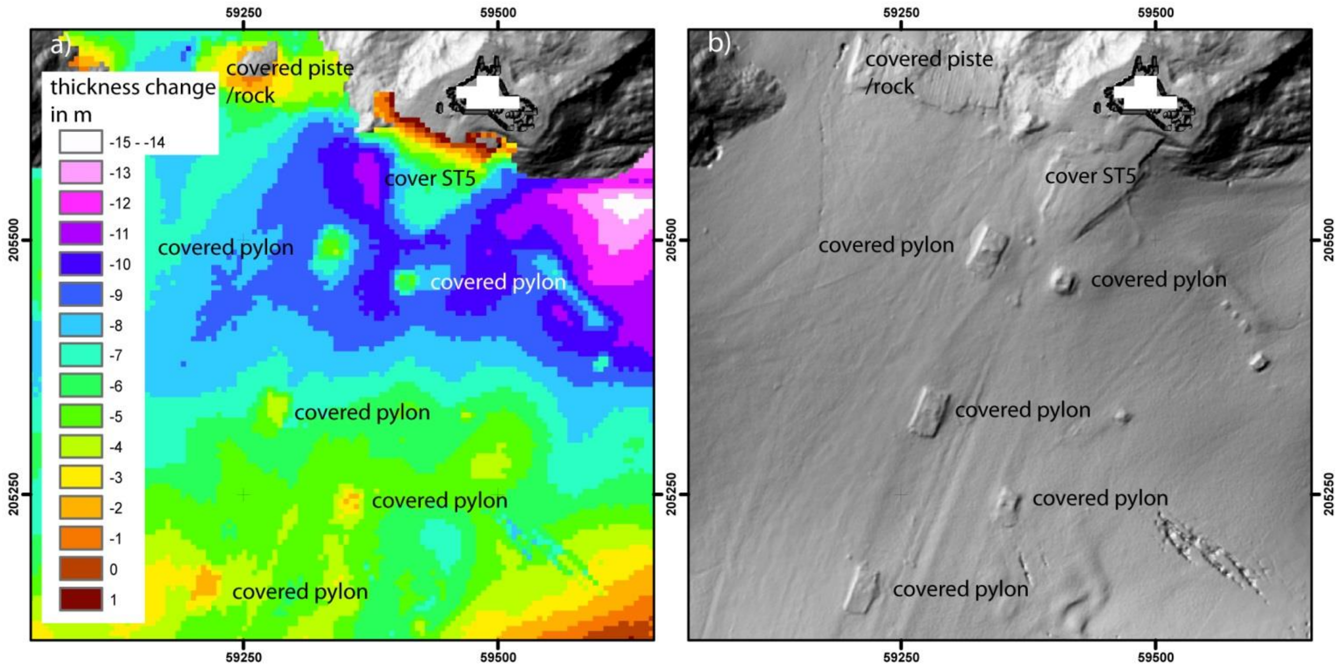


Figure 2. Mass balance management at profiles ST5 (a, Stubai glacier ski resort, for hillshade and thickness change see Figure 3), SOE1/2 (b, Sölden ski resort), and ST1 (c, Stubai Glacier ski resort) with applied measures: c…covers, p…snow production..


a)
thickness change in m
covered piste /rock
cover ST5
covered pylon
covered pylon
covered pylon
covered pylon
covered pylon
b)
covered piste /rock
cover ST5
covered pylon
covered pylon
covered pylon
covered pylon
covered pylon


59000
59500
covered piste/rock
cover ST5
thickness change period 1 in m
-21 - -20
-19
-18
-17
-16
-15
-14
-13
-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
covered pylon
covered pylon
covered pylon
covered pylon
covered pylon
205500
205500
59000
59500
covered piste/rock
cover ST5
covered pylon
covered pylon
covered pylon
covered pylon
covered pylon
205500
205500
59000
59500



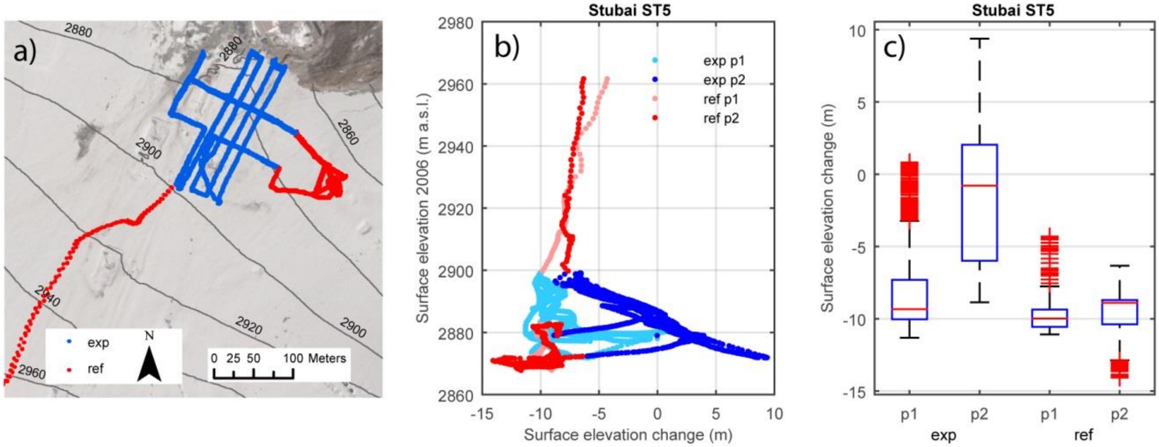


Figure 3: The thickness changes on Schaufelferner (Stubai glacier ski resort) at the location of the mass balances measures (~~lower panel~~a) on the LiDAR DEM hillshade of 2006) are lower than in the surroundings (~~upper panel~~b).

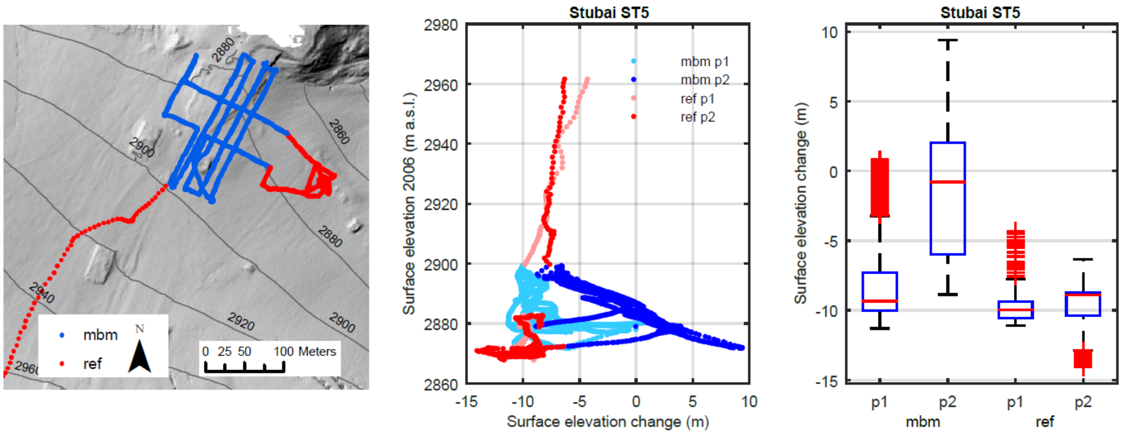
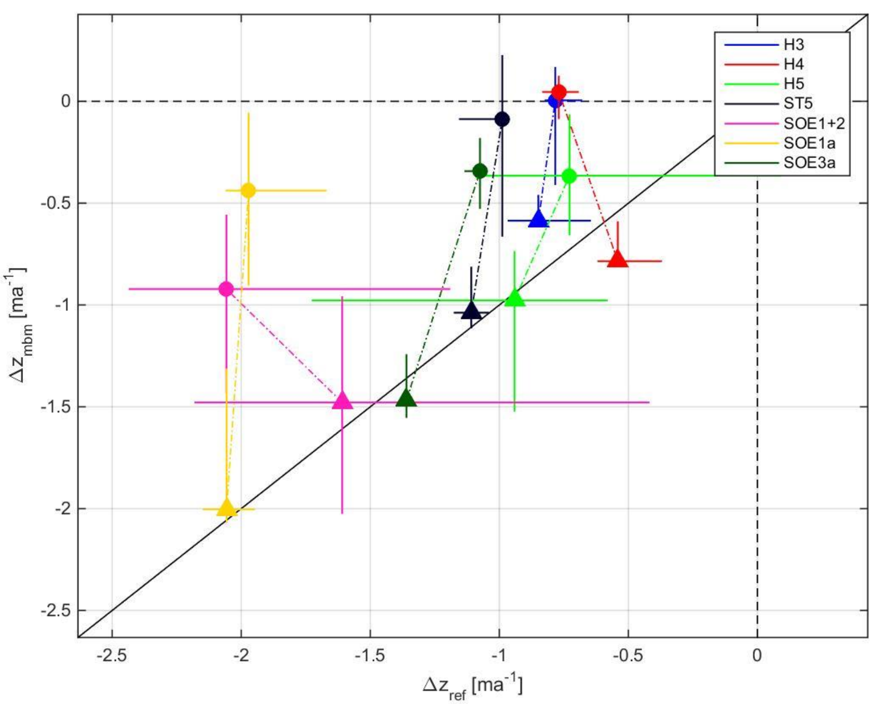
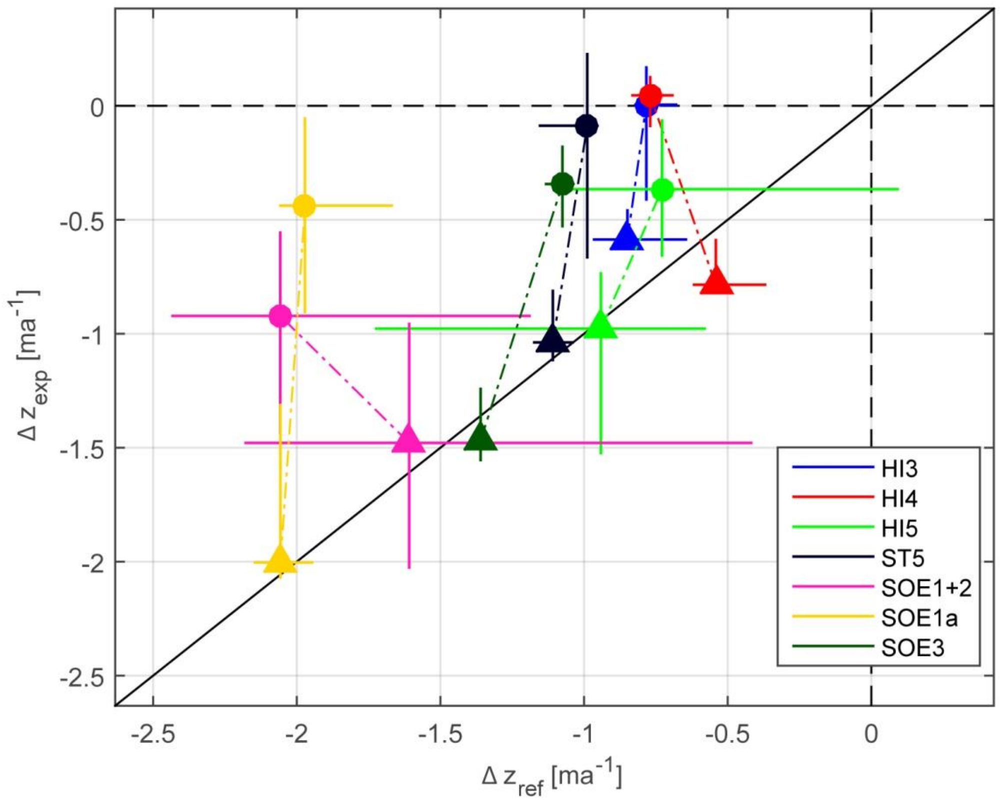


Figure 4. a) Location of profile ST5, b) surface elevation changes plotted for surface elevation in 2006 and c) boxplot of surface elevation changes along the profile separated into experimental areas (exp; in blue) and reference areas (ref; in red) for the periods without (p1; in light color) and with (p;, in dark color) mass balance management. Note that similar plots for each profile are provided in the supplement.,,erueruFigure 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.



Δ z_exp [ma^-1]
Δ z_ref [ma^-1]
0
-0.5
-1
-1.5
-2
-2.5
HI3
HI4
HI5
ST5
SOE1+2
SOE1a
SOE3

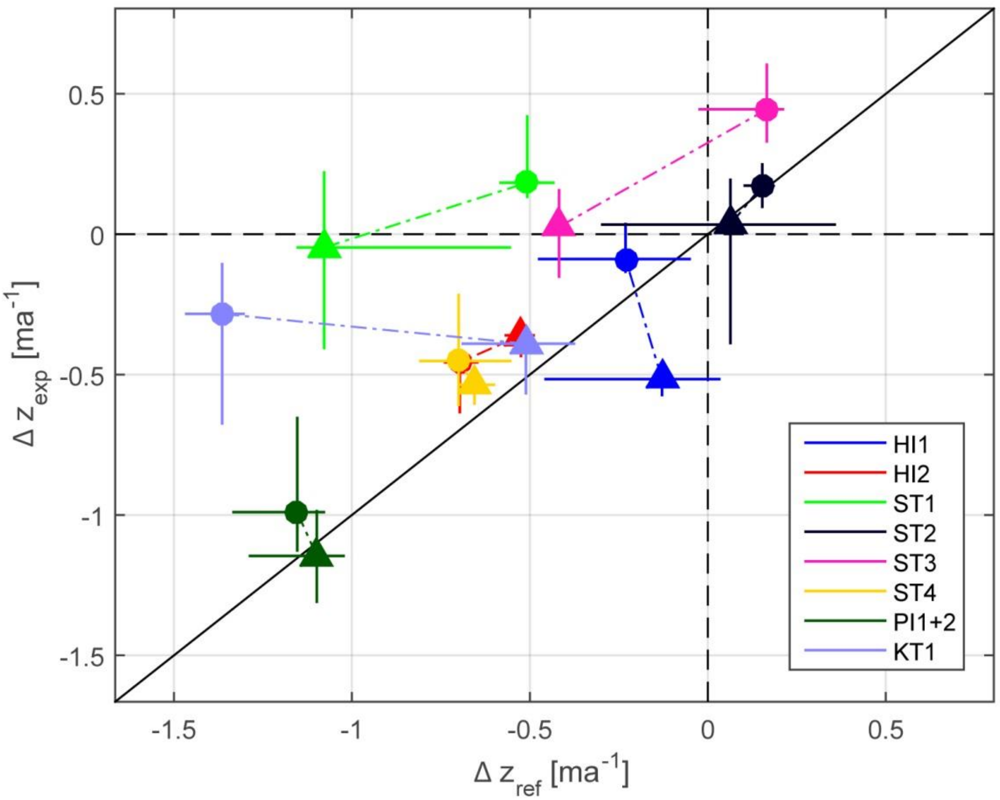


Figure 5. Median of the annual surface elevation changes in reference areas (Δz_{ref}) compared to the median of the annual surface elevation changes in experimental areas (Δz_{exp}) for the periods without (triangles) and with (circles) mass balance management. Periods are given in Table 2. Solid lines show the interquartile range between the 25th and the 75th percentile. Dashed lines connect the corresponding values of one profile.

~~Figure 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.~~

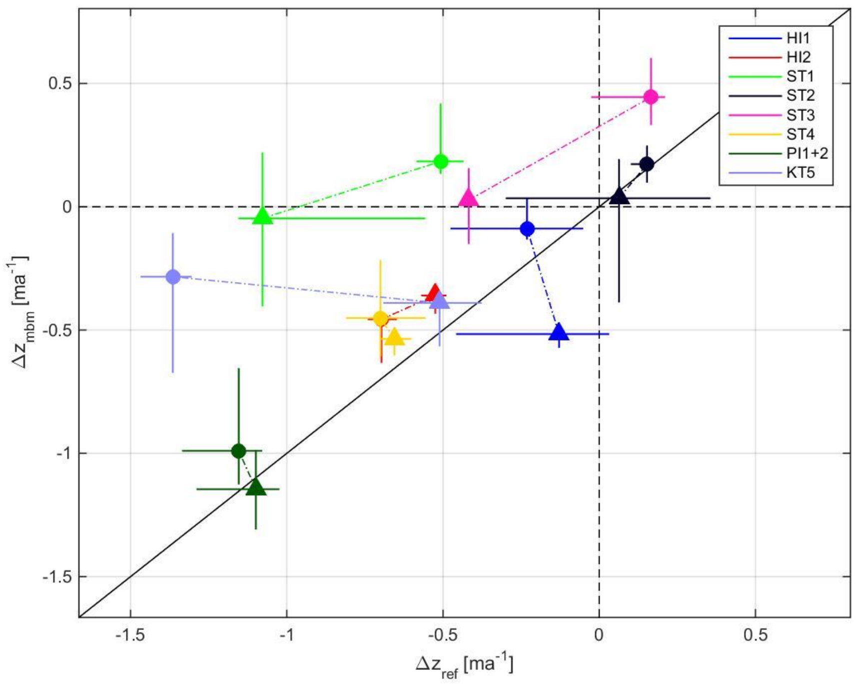


Figure 6. Median of the annual surface elevation changes in reference areas (Δz_{ref}), compared to the median of the annual surface elevation changes in experimental areas (Δz_{exp}) for the periods without (triangles) and with (circles) mass balance management. Periods are given in Table 2. Solid lines 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.

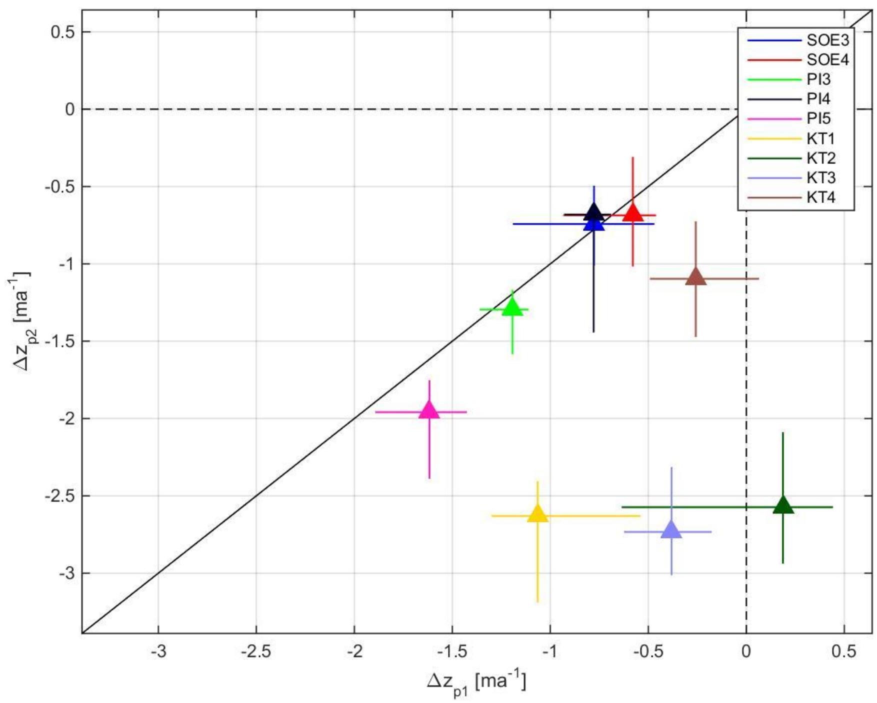


Figure 7: Median of the annual surface elevation changes of the profiles in the first period (Δz_{p1}) compared to the median of the annual surface elevation changes of the profiles in the second period (Δz_{p2}). Periods are given in Table 2. Solid lines show the interquartile range between the 25th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