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
10 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 on elevation changes. Based on LiDAR DEMs and DGPS measurements, decadal surface elevation changes in 15 locations with mass balance
15 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 over a period of nine years. In this period, mean annual thickness loss in 15 of the mass balance managed profiles is 0.54 ±0.04 m/y lower (-0.23±0.04 m/yon average) than in the respective
20 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. 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, 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 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 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 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. 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 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)	Retaining surface elevation around infrastructure

iii)	Preventing or reducing 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 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.

5   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
10 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
15 short-term effect has been proven, it could be that measures have not been applied frequently enough to return a sustainable result. Moreover, ice dynamics might 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 not aim at inferring mass
20 balance from elevation changes, but at 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
25 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

5 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

10 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.

15 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

20 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

25 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 subtracting the altitude at the dates of the second survey from
those of a first survey. The mean thickness change of a profile is the average of the thickness changes of every point within
the profile. Elevation changes between DEM and DGPS data were calculated at every point recorded by DGPS 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 obtained from these values at every point in the attribute
table. Thickness changes 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). 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 four 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 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 Hintertux 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), 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.

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)

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.

5   **4   Discussion**

This study focuses on the analysis of glacier surface elevation changes, as these are a major challenge for the operation of the ski resorts. Although thickness changes for managed and unmanaged areas are compared, it is outside the scope of this study to infer information on (unmeasured) mass balances from (measured) thickness changes. The interpretation of surface elevation changes in terms of mass balance is not possible without additional information. In the ablation area emergence

10   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.

15   Surface elevation changes $\frac{\partial S}{\partial t}$ result from glacier dynamics, density (ρ) changes, point mass balance b and the components of ice flow velocity w, u, and v (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 surface 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.

20   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 between experimental and reference areas. Therefore, we have to presume that the components of the surface velocity at the point u, v, and w are similar in the experimental and the reference profiles, as well as over the two periods. Then the measured thickness changes are driven by the mass balance measures and not by glacier dynamics. This

25   assumption is not confirmed by measurements of mass balance, densities or flow velocities, but at least supported by some empirical evidence: i) the superficial forms at mass balance managed areas are stable during years of field surveys and in geodata ii) very low flow velocities measured generally at Austrian glaciers and in ski resorts glaciers at pylons mean that absolute velocity differences are small, and iii) the absence of crevasses on the margins of the superficial forms indicate

strong gradients of 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.

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 m/y on Kesselwandferner (Fischer et al., 2011b).

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.

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

5   (France), Whistler (BC), Mount Hood (OR) (all M. Pelto, comment to TCD discussion paper), Mölltal Glacier (AT), Kitzsteinhorn (AT), Dachstein (AT), Zugspitze (D), Saas Fee (CH), and Schnalstal Glacier (IT).

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

10   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

15   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 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

20   be reduced locally by more than 1.3 m/year. This is more than the long-term mean thickness 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. Largest thickness changes are found close to the glacier tongues, and here the highest absolute effects of measures are found.

25   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, surface elevation in mass balance managed areas increased, 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

30   glacier cover in the upper parts of the glaciers (e.g. ST1, ST2) may affect the existence of these glacier sections in future, because equilibrium line altitudes of glacier mass balances 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.

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 technical infrastructure like stations and pylons. This also limits the impact of local measures on total glacier mass balance.

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-term 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 (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 Figures 5 to 6.

profile name	mean elevation	mbm	thickness change in period 1 in m					thickness change in period 2 in m				
			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
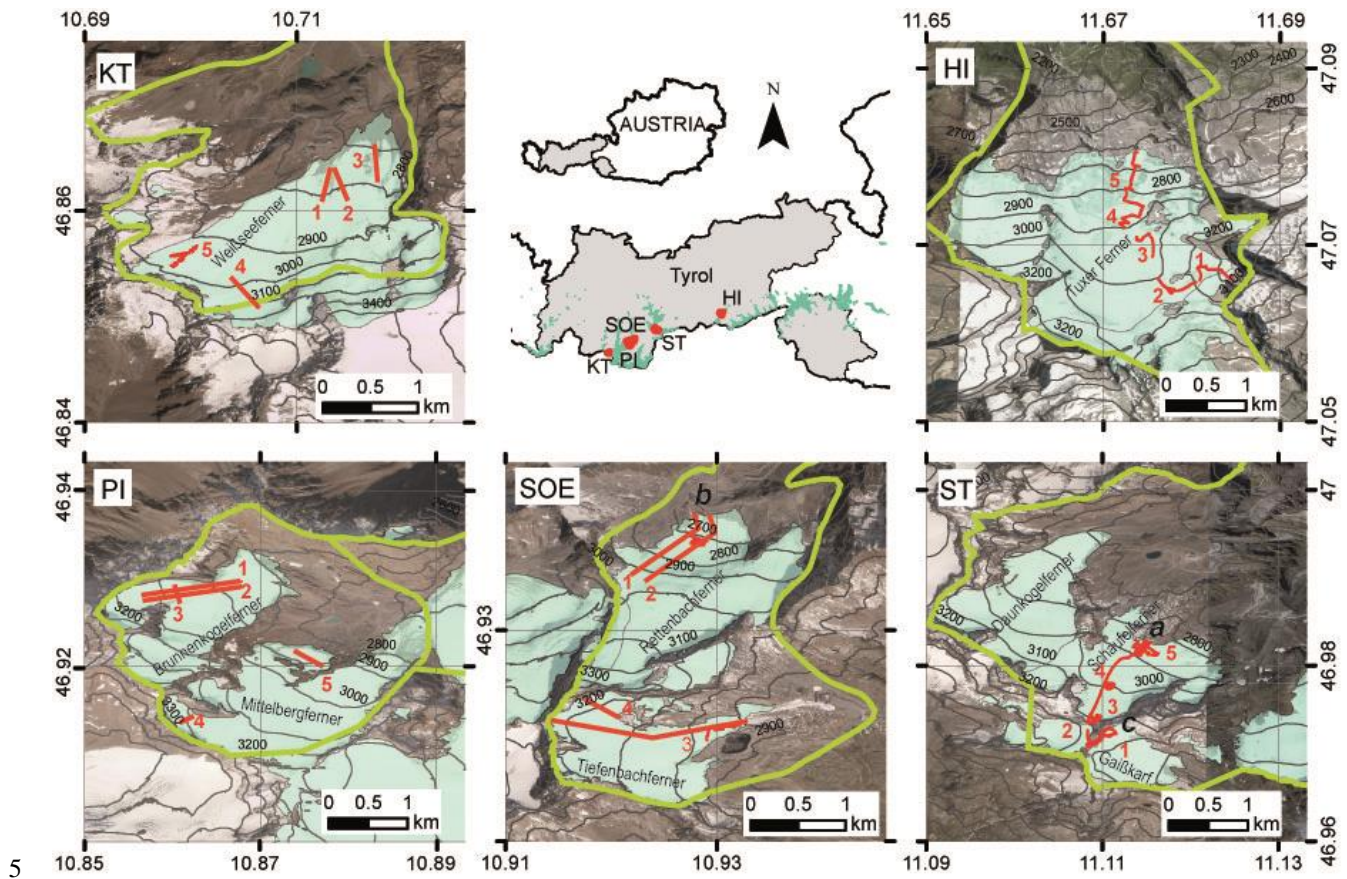
Figure 1. Overview of the Tyrolean glacier ski resorts of Kaunertal (KT), Pitztal (PI), Sölden (SOE), Stubai (ST) and Hintertux (HI). Measurement locations (red lines) with profile numbers (red), ski resort outlines (green lines), glaciers assigned to the resort (light green) and contour lines of the GI3 DEMs superimposed on orthophotos (tirol.gv.at). *a,b,c* …areas shown in Figure 2.
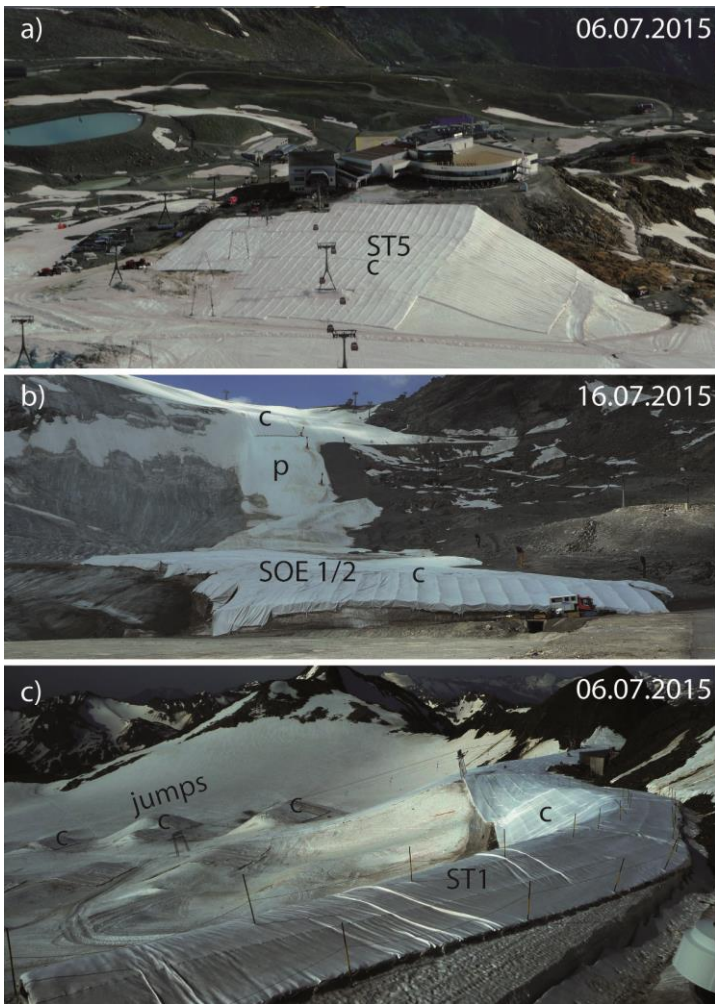
Figure 2. Mass balance management at profiles ST5 (a, Stubai glacier ski resort, for hillshade and thickness change see Figure 3), SOE1/2 (b, Sölden ski resort), and ST1 (c, Stubai Glacier ski resort) with applied measures: c…covers, p…snow production..
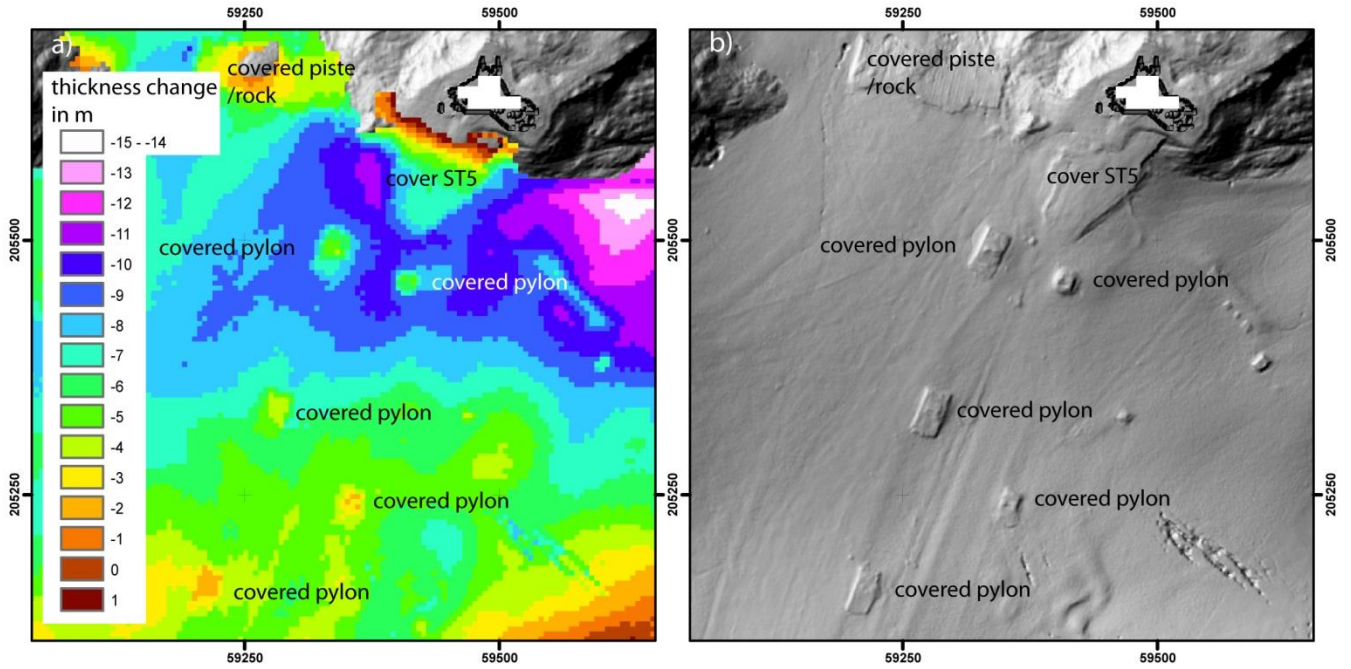
Figure 3: The thickness changes on Schaufelferner (Stubai glacier ski resort) at the location of the mass balances measures
5   (a) on the LiDAR DEM hillshade of 2006) are lower than in the surroundings (b).
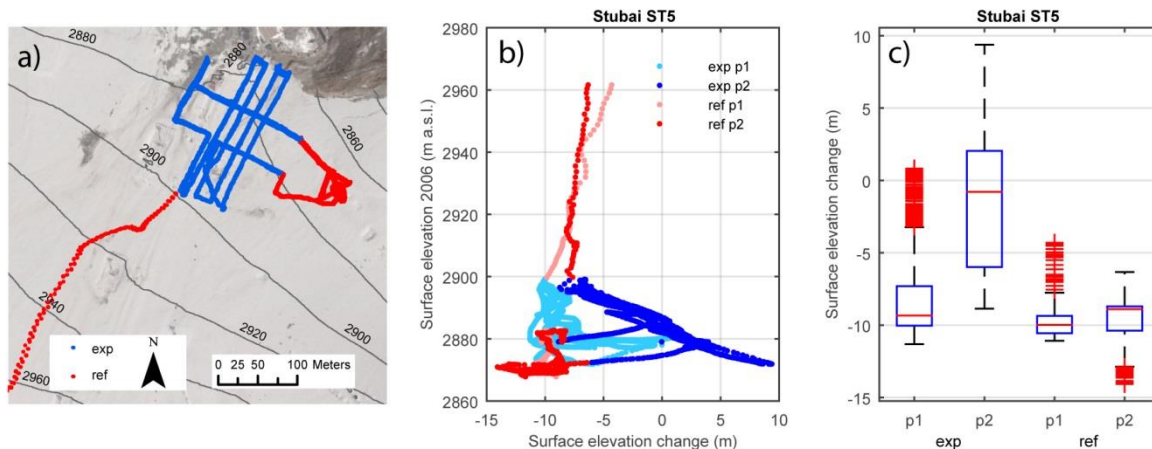
Figure 4. a) Location of profile ST5, b) surface elevation changes plotted for surface elevation in 2006 and c) boxplot of surface elevation changes along the profile separated into experimental areas (exp; in blue) and reference areas (ref; in red) for the periods without (p1; in light color) and with (p;, in dark color) mass balance management. Note that similar plots for each profile are provided in the supplement.
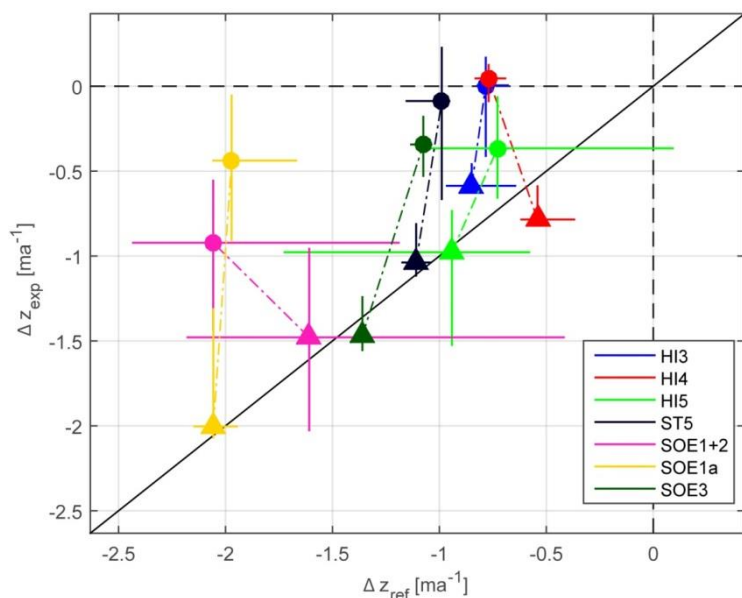
Figure 5. Median of the annual surface elevation changes in reference areas (Δz_{ref}) compared to the median of the annual surface elevation changes in experimental areas (Δz_{exp}) for the periods without (triangles) and with (circles) mass balance management. Periods are given in Table 2. Solid lines show the interquartile range between the 25th and the 75th percentile. Dashed lines connect the corresponding values of one profile.
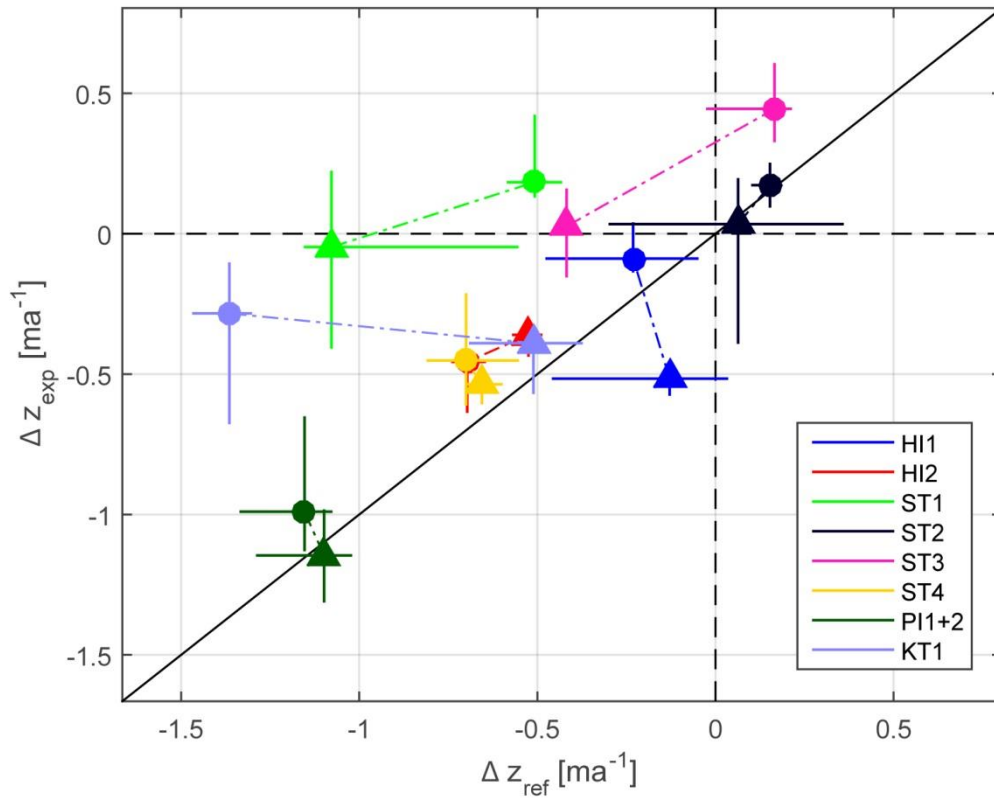
Figure 6. Median of the annual surface elevation changes in reference areas (Δz_{ref}), compared to the median of the annual surface elevation changes in experimental areas (Δz_{exp}) for the periods without (triangles) and with (circles) mass balance management. Periods are given in Table 2. Solid lines show the interquartile range between the 25th and the 75th percentile. Dashed lines connect the corresponding values of one profile.