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

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

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

Abstract. For Austrian glacier ski resorts, established in the 1970s and 1980s during a period of glacier advance, negative mass balances with resulting glacier area loss and decrease in surface elevation present an operational challenge. Glacier cover, snow farming and technical snow production were introduced as adaptation measures based on studies on the effect of these measures on energy and mass balance. After a decade of the application of the various measures, we studied the transition from the proven short-term effects to long-term effects by comparing elevation changes in areas with and without mass balance management. Based on LiDAR DEMs and DGPS measurements, decadal surface elevation changes in 16 locations with mass balance management were compared to those without measures (apart from piste grooming) in five Tyrolean ski resorts on seven glaciers. The comparison of surface elevation changes presents clear local differences in mass change, and it shows the potential to retain local ice thickness over one decade. Locally up to 21.1 m±0.4 m of ice thickness was preserved compared to non-maintained areas at glacier tongues over a period of nine years. In this period, mean annual thickness loss in 15 of the mass balance managed profiles is on average 0.57 m/y ± 0.04 m/y lower than in the respective reference areas.

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, 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. 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 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 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 pistes have had to be rerouted to meet the requirements on width and difficulty. Sinking glacier surfaces often make exit and entrance to summit or valley lift stations difficult. Steeper glacier surfaces complicate the maintenance of traverse pistes and increase the danger of avalanches. As the ropeway pylons are mounted on sledges designed for specific pylon shifts, changes in the flow regime, i.e. velocity and/or direction shorten maintenance windows. In the worst case, sinking surfaces lead to angles and bearing loads which are out of the approved range for that installation, so that the ropeway has to be replaced or adapted. One positive effect of the years with negative mass balances was the decrease of ice flow velocities which led to a reduction of the number and size of crevasses (Colgan et al., 2016; Fischer, 2010; Pelto and Hedlund, 2001) also in glacier ski resorts (e.g. Fischer et al., 2011a; Diolaiuti et al., 2006).

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

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

ii) Keeping surface elevation around infrastructure

iii) Prevent or reduce 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 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 ice dynamics lead to a redistribution of masses so that, for example, no effect on surface elevations would be measurable. From this basic research question, this study aimed at assessing long-term net effects by comparing surface elevation changes in areas which have been subject to different types of mass balance management and neighbouring areas without such management. Surface elevation changes in mass balance managed areas were compared to neighbouring areas of the same elevation and exposure without such measures (apart from some grooming of pistes). The comparison was done for two time periods. The first is given by the date of the glacier inventory DEMs. Mass balance management measures started at the end of the first period. The effect of the mass balance management is investigated by i) comparing the first period (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 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 is calculated by subtracting the altitude at the dates of the second survey (t_1) from of a first survey (t_0)

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

The mean thickness change of a profile was calculated as average of the thickness changes of every point within the profile. The thickness change between DEM and DGPS data was calculated at every point recorded by DGPS. The differences were calculated with ArcGIS (version 10.2.2) 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 from these values at every point in the attribute table. Thickness changes calculated from 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, i.e. 0.7 m for the thickness change between the second and the third glacier inventory DEMs, 0.27 m for the thickness change calculated from the third glacier inventory DEMs and DGPS data and 0.4 m for LiDAR DEM differences.

Systematic errors of the thickness change result from positioning of the DGPS antenna above ground, different information content in raster and point data of elevation, 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 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 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 high elevations could be achieved by snow grooming and by covering the glacier. At profile ST5 (Figure 4), a nearly constant surface elevation at the glacier terminus during the second period is a consequence of constant piste grooming, relocation of snow and glacier cover. In the reference area, without application of mass balance management, surface elevation loss of the second period was in the same magnitude as in the first period. Graphs similar to Figure 4 are shown in the supplementary material for all profiles.

To provide 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. 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 from subglacial erosion, internal and basal melt and density changes

(Cogley et al., 2011). These factors are usually neglected in glacier wide geodetic mass balance studies, and we have no indication that they would play a major role in our study.

Much more importantly, surface elevation changes $\frac{\partial S}{\partial t}$ result from glacier dynamics, density (ρ) changes and point mass balance b (Cuffey and Paterson, 2010).

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

For our analysis, we presume that the components of the surface velocity at the point u, v, and w are similar in the mass balance managed and the reference profiles, and during the two periods. Then, the measured thickness changes are driven by the measures and not glacier dynamics. This hypothesis is confirmed by i) evidence and stability of the suprafical forms at mass balanced areas also visible in the photographs and the LiDAR hillshade, and ii) very low flow velocities measured at Austrian glaciers.

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.

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 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), Mölltaler Gletscher (AT), Kitzsteinhorn (AT), Dachstein (AT), Zugspitze(D), Saas Fee (CH), and Schnalstaler 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. Distinct differences between surface elevation changes in maintained areas and surface elevation changes in nearby areas without technical intervention are presented in this study. Small-scale ice ridges arising from very local mass balance management melt down within a few seasons when mass balance management is stopped.

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

Over the observed time periods, the reduction in surface elevation caused by glacier retreat could be reduced locally by more than 1.3 m/year. 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.

Acknowledgements

The authors thank the Austrian glacier ski resorts for the constructive cooperation, logistic help for in-situ measurements and providing the 2014 LiDAR DEM data. The LiDAR DEM data of 2012 were provided from the joint project PROSA funded by the German Research Foundation (DFG) (SCHM 472/17-1 and SCHM 472/17-2) and the Austrian Science Fund (FWF) (I 894-N24 and I 1646-N19). The constructive comments of two anonymous reviewers and Mauri Pelto were very helpful for improving the manuscript. We are grateful to Brigitte Scott for the English editing.

References

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

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

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

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

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

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

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

digitalen Gletscherkatasters. Zeitschrift für Gletscherkunde und Glazialgeologie 34(2), 167–185, 1998.

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

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

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

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

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

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

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

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

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

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

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

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

Fujita, K. and Ageta Y.: Effect of summer accumulation on glacier mass balance on the Tibetan Plateau revealed by mass-balance model. J. Glaciol. 46 (153), 244–252, 2000.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Wurländer, R. and Eder, K.: Leistungsfähigkeit aktueller Photogrammetrischer Auswertemethoden zum Aufbau eines

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A. P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L. N., Cáceres, B. E., Casassa, G., Cobos, G., Dávila, L. R., Delgado

Granados, H., Demuth, M. N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J. O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V. V., Portocarrero, C. A., Prinz, R., Sangewar, C. V., Severskiy, I., Sigurðsson, O., Soruco, A., Usubaliev, R., and Vincent, C.: Historically unprecedented global glacier decline in the early 21st century, Journal of Glaciology, 61, 745-762, 2015.

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

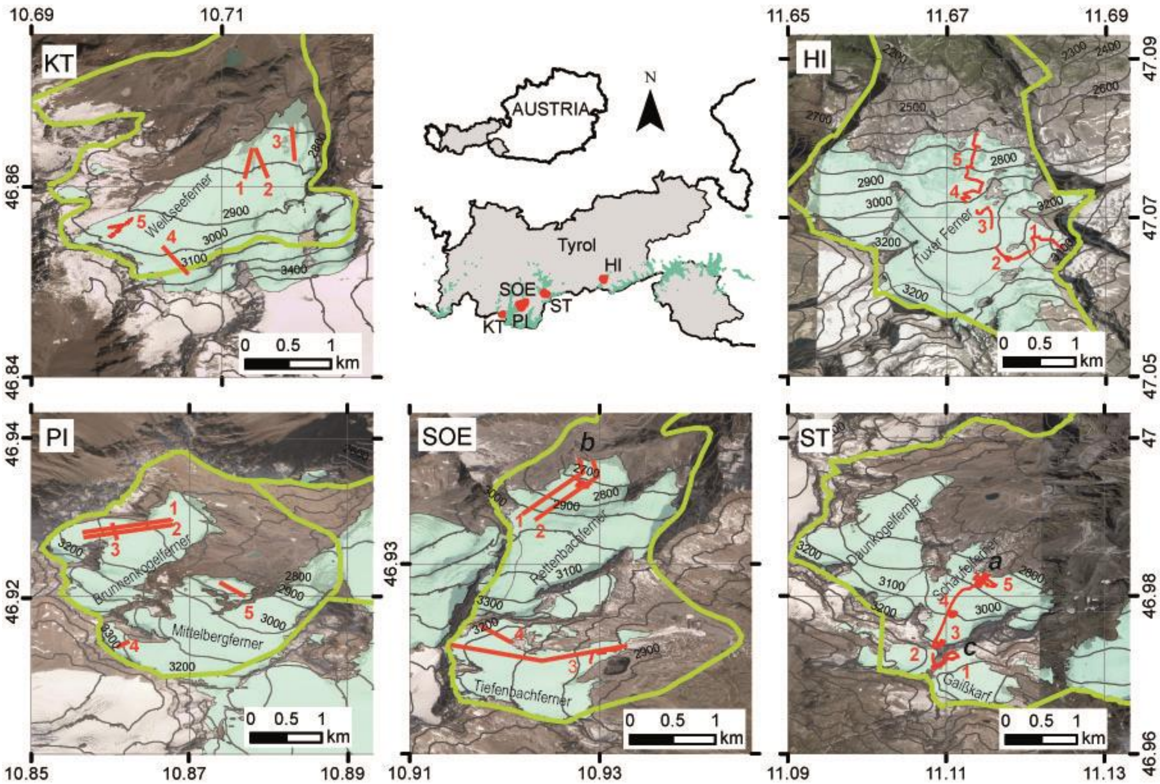

Figure 1. Overview of the Tyrolean glacier ski resorts of Kaunertal (KT), Pitztal (PI), Sölden (SOE), Stubai (ST) and Hintertux (HI). Measurement locations (red lines) with profile numbers (red), ski resort outlines (green lines), glaciers assigned to the resort (light green) and contour lines of the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

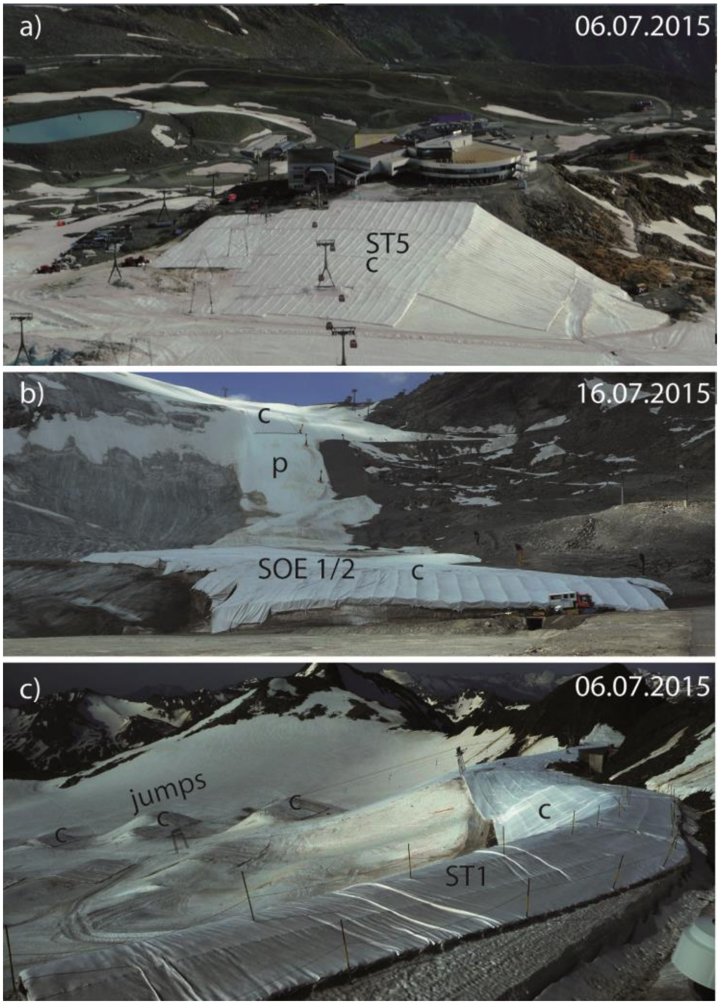

Figure 2. Mass balance management at profiles ST5 (a, Stubai glacier ski resort, for hillshade and thickness change see Figure 3), SOE1/2 (b, Sölden ski resort), and ST1 (c, Stubai Glacier ski resort) with applied measures: c…covers, p…snow production..

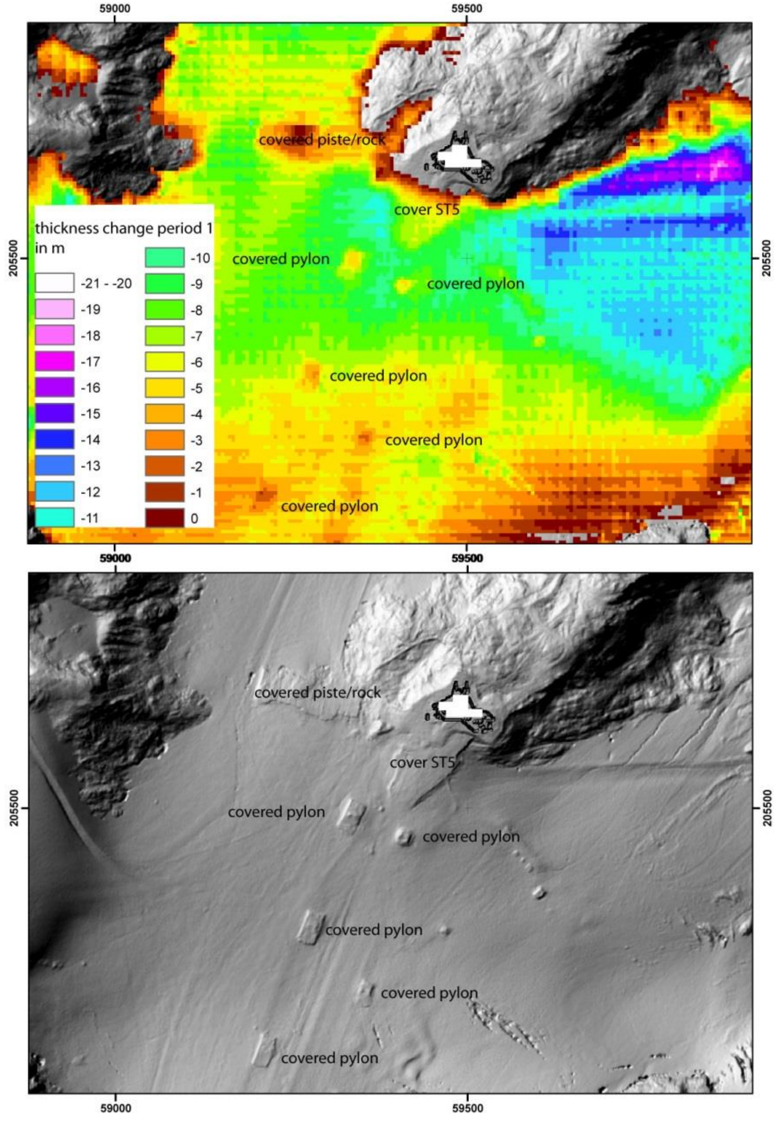

Figure 3: The thickness changes at the location of the mass balances measures (lower panel on the LiDAR DEM hillshade of 2006) are lower than in the surroundings (upper panel).

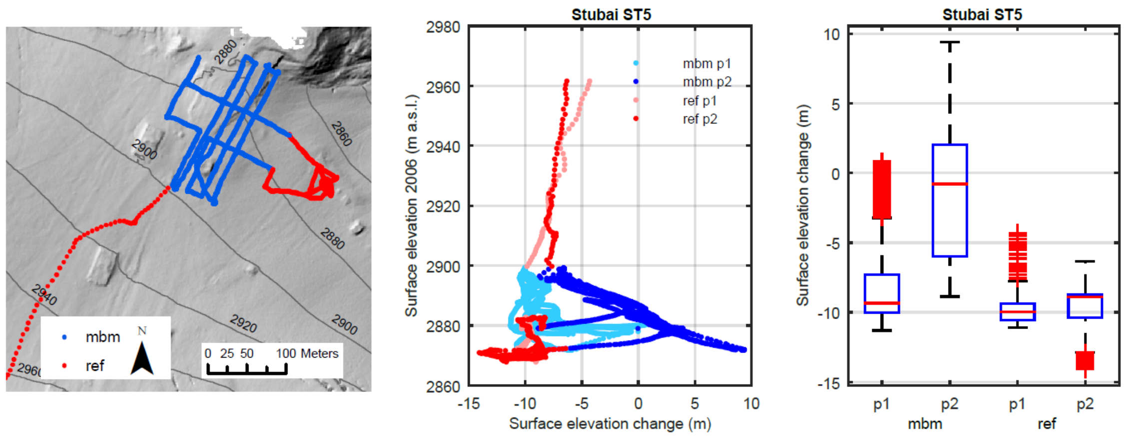

Figure 4. Location of profile ST5, surface elevation changes plotted for surface elevation in 2006 and boxplot of surface elevation changes along the profile separated into area of mass balance management (mbm; in blue) and area without mass balance management (ref; in red) for the periods 1997 -2006 (p1) and 2006 – 2015 (p2). Note that similar plots for each profile are provided in the supplement.

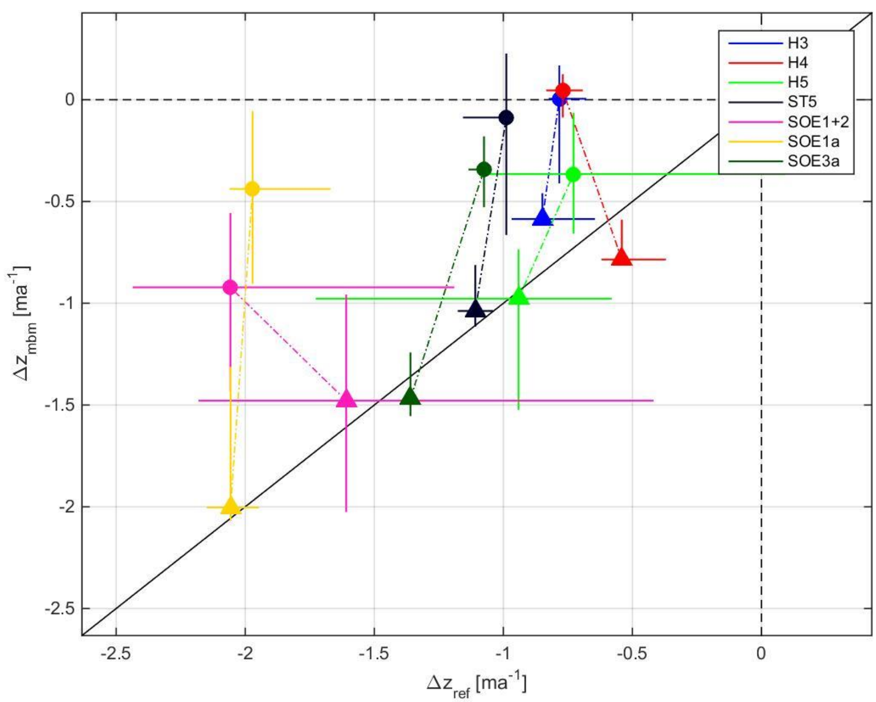

Figure 5. Median of the annual surface elevation changes of the reference profile (Δz_{ref}) compared to the median of the annual surface elevation changes of the profile with mass balance management (Δz_{mbm}) for the first (triangles) and the second (circles) period. Periods are given in Table 2. Solid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

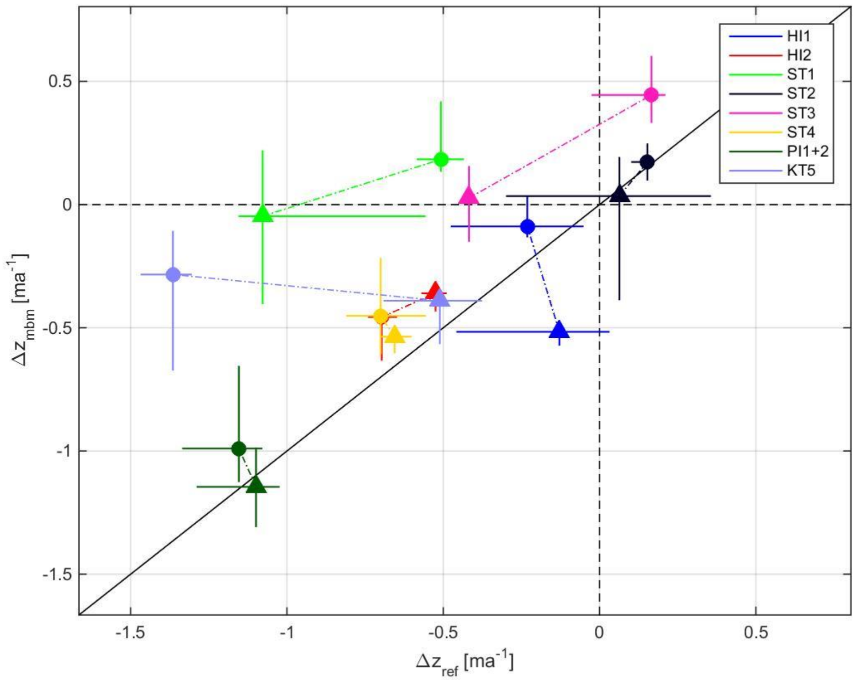

Figure 6. Median of the annual surface elevation changes of the reference profile (Δz_{ref}) compared to the median of the annual surface elevation changes of the profile with mass balance management (Δz_{mbm}) for the first (triangles) and the second (circles) period. Periods are given in Table 2. Solid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

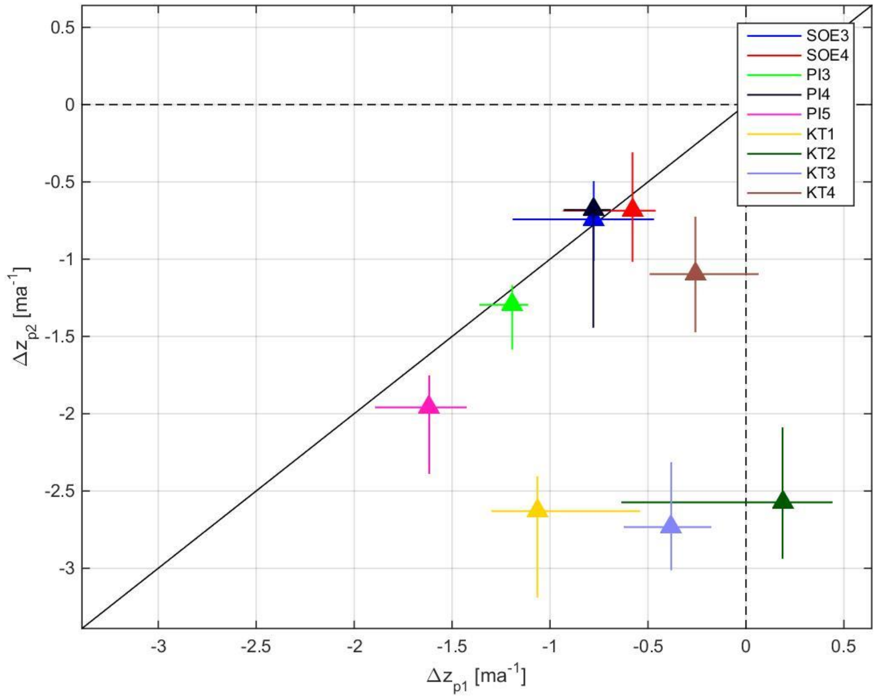

Figure 7: Median of the annual surface elevation changes of the profiles in the first period (Δz_{p1}) compared to the median of the annual surface elevation changes of the profiles in the second period (Δz_{p2}). Periods are given in Table 2. Solid lines show the interquartile range between the 25th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