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Comparative study of technical measures to reduce snow and ice ablation in Alpine glacier ski resorts

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Abstract

We present technical methods aiming at a reduction of snow and ice ablation within an Austrian glacier ski resort. From April 2004 to September 2005 we carried out field studies at Schaufelferner (2870 m a.s.l.) and Gaiβkarferner (3100 m a.s.l.), two glaciers situated in the Stubai Alps. We injected water into the winter snow and studied the effects of compaction and artificial surface cover blankets. Results demonstrate a high efficiency of special blankets (geotextiles) that are placed on the snow surface in spring. Average melt rates and total ablation are reduced by 60%, conserving around 300 $\mathrm{kgm^{-2}}$ of winter snow over the ablation periods 2004 and 2005, respectively. Crucial material properties are identified that play an important role in the performance. It is possible to increase glacier mass balance using a 0.004 m thin cover material.

Keywords: Ablation control; Snow farming; Glacier; Snow engineering; Ice engineering; Glacier covers

1. Introduction

The mass balance of most glaciers in the European Alps as well as of many mountain glaciers all over the world has been strongly negative in the last decades (IUGG(CCS)/UNEP/UNESCO/WMO, 2005; Dyurgerov and Meier, 1997; Dyurgerov, 2002). Between 1969 and 1998, Austrian glaciers lost about 15% of their area (Lambrecht and Kuhn, in press). Glacial recession resulted in glacier area and volume loss, thus glaciated surfaces lowered significantly and firn areas were reduced (Fischer, 2005). Fig. 1 shows mean altitudinal profiles of the specific mass balance of Hintereisferner. For Austrian glacier skiing resorts, which have been established during years of glacier advance in the late 1970s and early 1980s, these changes in glacier size and elevation have attracted increasing attention in recent years. Glacier retreat and mass wastage have isolated lift stations and ski-lift pylons, and exposed bed prominences and nunataks. These changes have required the relocation of some ski-lift tracks and skiing slopes. Due to the recession of firn areas to higher elevations and an increase in ice free areas, more snow is needed in early season to ensure good skiing conditions. Maintenance costs for the preparation of ski-lift tracks and slopes are rising. In some cases, lifts have had to be shortened and displaced. Where glacier slopes are becoming steeper, ski-lift tracks occasionally were abandoned.

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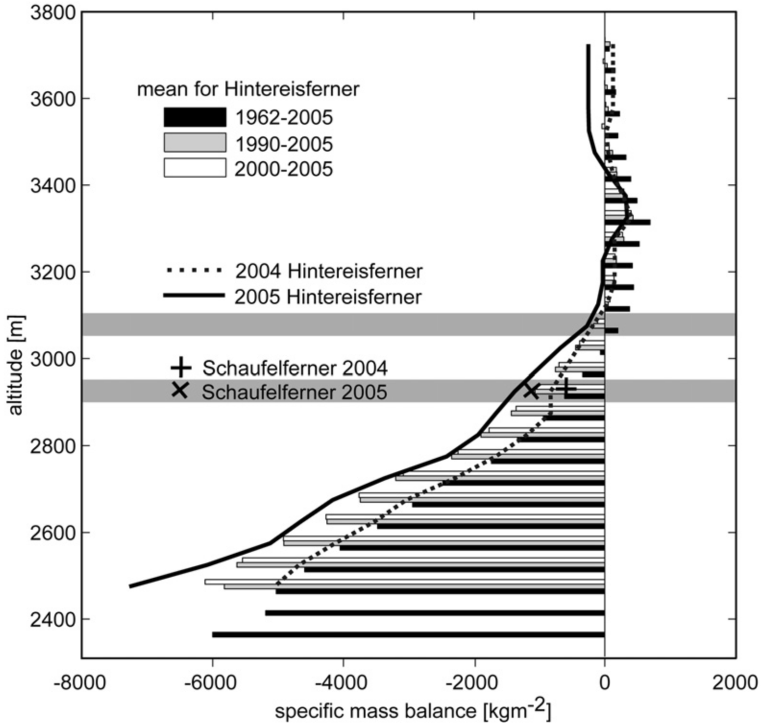

Fig. 1. Altitudinal profiles of specific mass balance of Hintereisferner; Mean values for the period: 1962–2005, 1990–2005 and 2000–2005 as well as for the individual years 2004 and 2005. The corresponding mass balance values of 2004 and 2005 within the test areas Schaufelferner (Stubai) are indicated by crosses. Thick grey horizontal bars indicate the altitudinal belts of the test areas Schaufelferner (2900 m a.s.l.) and Gaißkarferner (3100 m a.s.l.).

Therefore the application of technical measures to reduce snow and ice ablation in critical areas of glacier ski resorts gained new attention to keep the glacier locally at steady state.

This study summarizes the first comparative results of the effectiveness of different methods for reducing snow and ice melt within small areas of ski resorts. The measurements were carried out on a northerly slope of glacier Schaufelferner, Stubai Alps during 2004 and 2005 melt seasons (Fig. 1).

1.1. Previous studies on methods to reduce snow and ice melt

During the 1960s and 1970s considerable engineering effort was undertaken to ensure the year-round use of Arctic ice islands and sea–ice areas for scientific and military purposes, especially during the Arctic summer. High melt rates within these areas complicated the usage. Therefore, protective coverings for ice and snow were developed, tested and optimized (Herrmann and Stehle, 1966). Natural coverings (sawdust) and diverse types of foams with different sorts of additives were extensively investigated, reducing the ablation rates of ice very effectively by 50%–96%, compared to natural melt (Grove et al., 1963).

Beside the historical application of such methods in Arctic operations, similar techniques are currently being applied in the framework of sustainable energy use, e.g. the insulation of stored seasonal snow for the operation of a snow cooling plant during summer in a Swedish hospital (Skogsberg, 2005). Large wood chips are used to provide thermal insulation of the conserved snow mass. They report that melt rates could be reduced by 70% to 85%, depending on the thickness of the wood chip layer (0.025–0.075 m).

Notably, the melt rate reduction of a natural debris-covered glacier ranges from 35% to 85% for debris thicknesses of 0.1 m and 0.4 m, respectively, as compared to debris-free surfaces. These values are summarized in Skogsberg and Lundberg (2005), based on the work of Mattson and Gardner (1991), Mattson et al. (1993), Kayastha et al. (2000), Pelto (2000) and Takeuchi et al. (2000). The debris-layer effect on the ablation is an example of a natural modification of the glaciers mass balance.

A first study on the intentional reduction of snow and ice melt within glacier ski resorts considering the effect

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and possible physical mechanisms of glacier covering and snow compaction was recently done by Olefs and Obleitner (2007). Numerical modeling results indicate a large potential of covering the snow surface in spring using geotextiles, which was confirmed by preliminary field measurements in 2004. This paper describes advances and new results.

1.2. Test site, characteristics of the ablation periods 2004 and 2005

Our main investigation areas are located on glaciers Schaufelferner and Gaiβkarferner (46°59′N and 11°07′ E) in the Stubai Alps, Austria. The sites are situated in the glacier skiing resort Stubai at altitudes between 2870 m and 3100 m a.s.l. (Fig. 2). The areas are considered typical neuralgic zones of Austrian glacier skiing resorts. Most of the glaciers within Austrian ski resorts have a gentle northerly exposition with ice thicknesses of some tens of meters (Span et al., 2005; Fischer et al., 2007). High losses of ice volume are observed near lower glacier margins. The areas that are subject to fast steepening of slopes and loss of area are located either near the terminus or along ice divides in the uppermost parts of the glaciers, where ice is thin and accumulation is small due to the steepness of the terrain and/or wind effects.

The test site Schaufelferner is a gently, northerly exposed slope near the lower margin of the glacier at an elevation of 2870 m a.s.l. It is partly shaded by the ridges of Schaufelspitze. The test site Gaiβkarferner is located near the ice divide between these glaciers at an elevation of about 3100 m .a.s.l.

Field experiments started in 2004 (at Gaiβkarferner and Schaufelferner). A complete monitoring system with automatic weather stations and a webcam was set up in January 2005 (at Schaufelferner). Data presented in this paper were derived from two years of measurements, which ended in September 2005.

Ablation occurred at testsite altitudes of 2900 m a.s.l. and 3100 m a.s.l. during the 105 day period from 9 June 2004 to 22 September 2004. A total amount of 3.8 m of snow and ice (1760 kgm^{-2}) melted in 2900 m a.s.l. In a comparative time period, between 22 June and 7

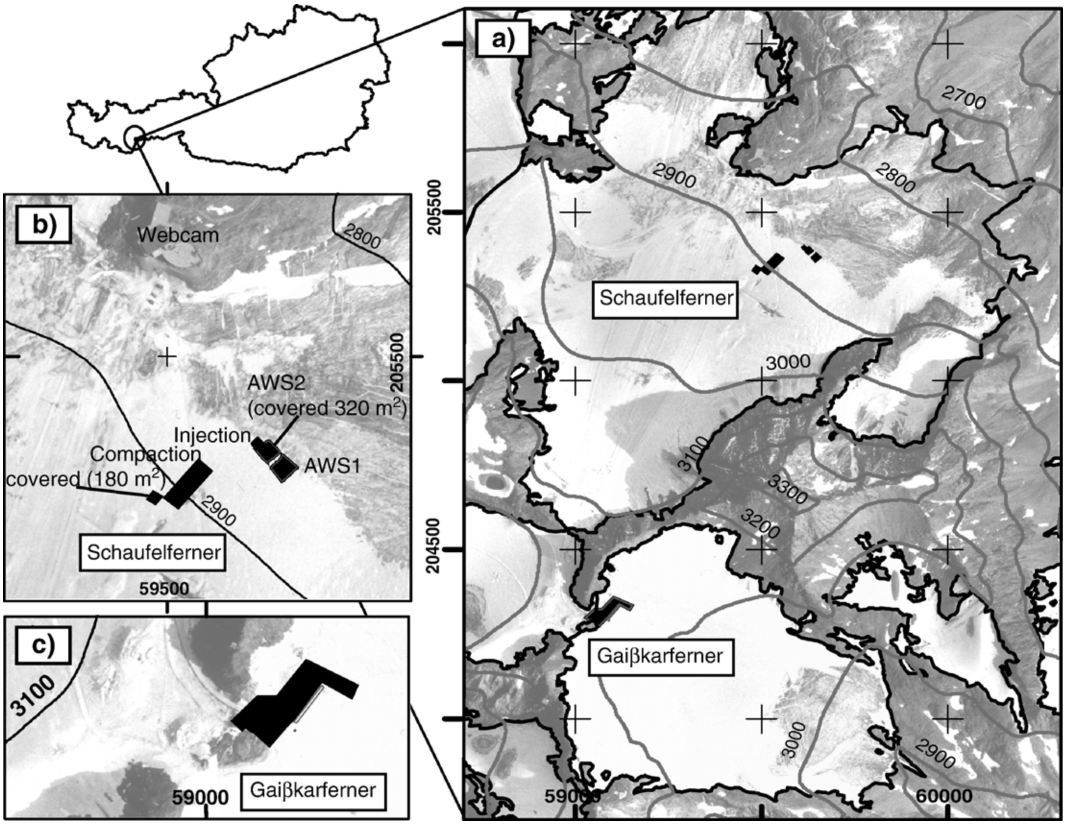

Fig. 2. Map of the test areas within the glacier ski resort Stubai, Austria, namely: a) overview of the two main investigation sites and detailed view of b) Schaufelferner (covered area of 180 m^2 during 2004 and detailed investigations during 2005) and c) Gaißkarferner (material tests during 2004).

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September 2004, this value amounted to 3.26 m and 2.88 m, respectively (2900 m a.s.l. and 3100 m a.s.l.). Bare ice begun to appear at the surface around 2 September 2004 at 2900 m a.s.l., resulting in 0.6 m of ice melt in that altitude (540 kgm^{-2}) (see Fig. 9).

The 2005 ablation period was markedly different. Fig. 3 shows measured air temperature from the automatic weather station, together with the time-series of natural snow and ice ablation, both on the lower site at 2900 m a.s.l. Melt stopped three times, coinciding with five cold spells, visible in the temperature records in June, July and August. Therefore, ice ablation amounted to 1 m (900 kgm^{-2}), and a total value of 3.8 m including both snow and ice ablation (2032 kgm^{-2}), during the 121 day ablation period.

Comparison of the specific mass balance data of 2004 and 2005 at nearby glacier Hintereisferner (Ötztal Alps) to its long-term record allows general conclusions with respect to the field measurement results at Stubai. Hintereisferner is a typical alpine valley glacier located approximately 32 km distance southwest of our investigation site. The long-term annual mean specific mass balance equals −517 kgm^{-2} (data since 1952) (Kuhn et al., 1999; Fischer and Markl, in preparation). Specific mass balance of Hintereisferner at the elevation of our test site in Stubai (2850 m–2900 m a.s.l.) was −826 kgm^{-2} (2003/04) and −1664 kgm^{-2} (2004/05), respectively. In 2002/03, the value at Hintereisferner amounted to −2780 kgm^{-2}. Assuming an ice density of 900 kg/m3, these values show a similar trend from 2004 to 2005, compared to ice thickness loss measured within our test areas in 2900 m a.s.l. (0.6 m in 2004 and 1 m in 2005). Namely, there is an increase of 67% (Stubai) and 100% (Hintereisferner), respectively, from 2003/04 to 2004/05.

The 15-year average specific mass balance (1989/90–2004/05) of Hintereisferner amounts to −1432 kgm^{-2} at 2900 m, thus the average mass loss of 2004 and 2005 at Hintereisferner corresponds to the 15-year average within 15% (see also Fig. 1). Most importantly, this indicates that both melt periods in Stubai are quite representative for the last 15 years. Therefore, both time and location of the measurements in Stubai are typical and representative for the situation of Austrian glacier skiing resorts in the last decade.

1.3. Monitoring system and available dataset

The evolution of the winter snow cover and the effect of the measures were surveyed continuously with a total number of 7 vertical snow profiles for the year 2004 and 20 profiles from January to September 2005 at different locations. Snow density, temperature, liquid water content and water equivalent of the snow cover were measured.

Ablation was measured during 2004 and 2005 by means of ablation stakes (Hoinkes, 1970). The time resolution of this ablation data is one week. Fig. 4a shows the

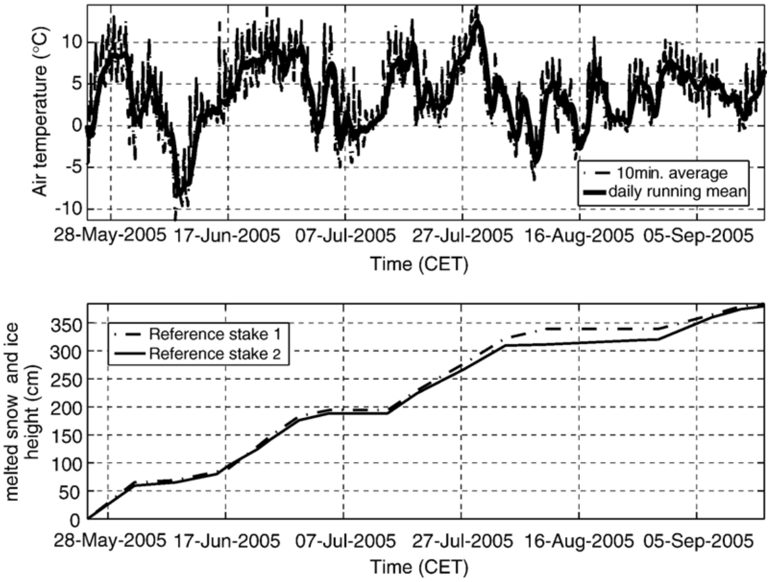

Fig. 3. Time-series of measured air temperature (top) and natural snow and ice ablation (bottom) over the ablation period 2005 (24 May 2005–16 September 2005) within the test site Schaufelferner (Stubai Alps). Time resolution of the ablation stake data is one week. Total ablation equals 3.8 m in height or 2032 kgm^{-2} water equivalent comprising 1 m of ice thickness loss (height).

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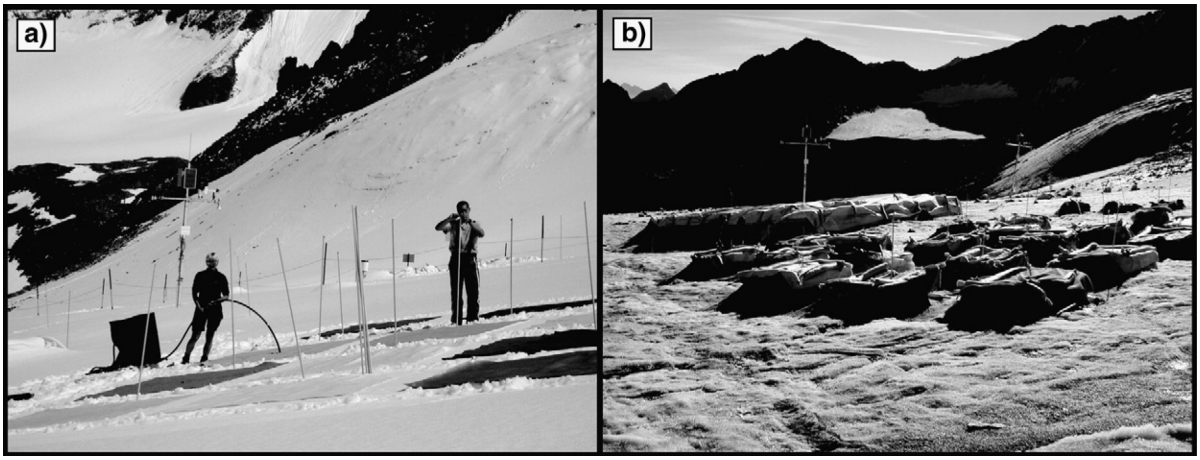

Fig. 4. During both years 2004 and 2005 a total number of 42 different cover materials were tested and compared using one ablation stake per sample. This figure illustrates a) the setup of the material intercomparison in 2005 and b) the result at the end of the ablation period 2005.

setup of a cover material intercomparison in the year 2005, using one ablation stake per tested material.

Since January 2005 two automatic weather stations were set-up, enabling the examination of the energy and mass balance of the underlying snow and ice. The recorded meteorological parameters were air temperature and pressure, relative humidity, wind speed and direction, snow height (using an ultrasonic sounder), rain, shortwave and longwave incoming and reflected (emitted) radiation and snow temperatures at each station (for details see: http://imgi.uibk.ac.at/IceClim/alpS/index_engl.html). The snow cover surrounding the automatic weather stations was groomed during winter 2005. Finally an area of 320 m^2, surrounding one of the two stations was covered from 24 May 2005 until 16 September 2005.

2. Materials and methods

Any effort to increase the local mass balance on a glacier needs to consider either promoting an increase of accumulation or a reduction of ablation. Three promising technical methods with the potential to influence snow- and ice mass balance were tested:

- Injection of water into the winter snow cover using an injection device (Fig. 5a).
- Compaction of the winter snow cover (Fig. 5b) using snow-cats or compaction devices to increase the density of the winter snow cover (increase the snow thermal conductivity).
- Covering of the snow surface between the time of snow height maximum and the end of the ablation period using geotextiles (Fig. 5c,d).

2.1. Covers

Covering the snow surface in spring has a direct impact on the energy balance components of the underlying snow surface, decreasing the energy available for melt (see Olefs and Obleitner, 2007 for more details about possible physical mechanisms). Ideally, the covers are placed on the glacier surface between the time of the snow height maximum and the end of the ablation period. This maximizes the mass of snow under the cover and avoids problems with cover removal. The covers are not left under the snow cover during winter but are removed before the first persistent snow fall in late summer or early autumn occurs. Special fixing systems were developed to keep the covers in place even in case of strong winds.

We tested 16 and 24 different cover materials in 2004 and in summer 2005 respectively. The goal of these tests was to identify the cover materials with the best performance, and to assess the most relevant snow-mass balance processes within the covers. These samples included biodegradable and non-biodegradable materials, geotextiles as well as highly reflecting plastic tarps (see Fig. 4a,b). Each sample cover material was 4 m^2, which limited the duration of the experiments due to increased lateral melt.

Additionally the mass balance of larger covered areas was measured. Since July 2004, an area of 180 m^2 was covered at an altitude of 2900 m a.s.l. This cover was left on the glacier during the period of snow accumulation to investigate the winter-effects on the cover material. Slightly below this site, a 320 m^2 area was covered during the entire 2005 ablation period. This cover was removed at the end of the ablation period in September

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2005. To investigate the effect of cover thickness on the reduction of the ablation, 3 patches were covered with additional layers using the same material (single, double, triple) during 2005.

Besides mass balance measurements at each covered patch and at its undisturbed surroundings (reference areas), the reflectivity of the cover materials was quantified, using a Fieldspec Handheld Spectroradiometer from Analytical Spectral Devices, Inc.. It exhibits a sensitivity range between 325 nm and 1075 nm wavelength and a spectral resolution of 3 nm at 700 nm. About 71% of the energy of the incoming solar radiation is included within that range. The measured albedo differences of the cover materials indicate significant differences in the radiation balance and therefore in the energy available for snow and ice melt under and beneath the cover. The albedo was measured before and after the application of cover materials during fair, clear-sky weather conditions.

2.2. Water injection

A water-injection device, as used in the preparation and maintenance of alpine ski racing courses, allows the injection of liquid water into the winter snow cover. To reach the most effective gain of mass, all the water injected need to refreeze within the snow body or on the underlying glacier ice substrate at the test site. Therefore, low snow temperatures are required to allow the water to effectively release its heat content and the latent heat discharged during freezing. Cloud free nights tend to promote a depression of air and snow cover temperatures caused by high longwave emission of snow covered surfaces. The amount of injected water has to be

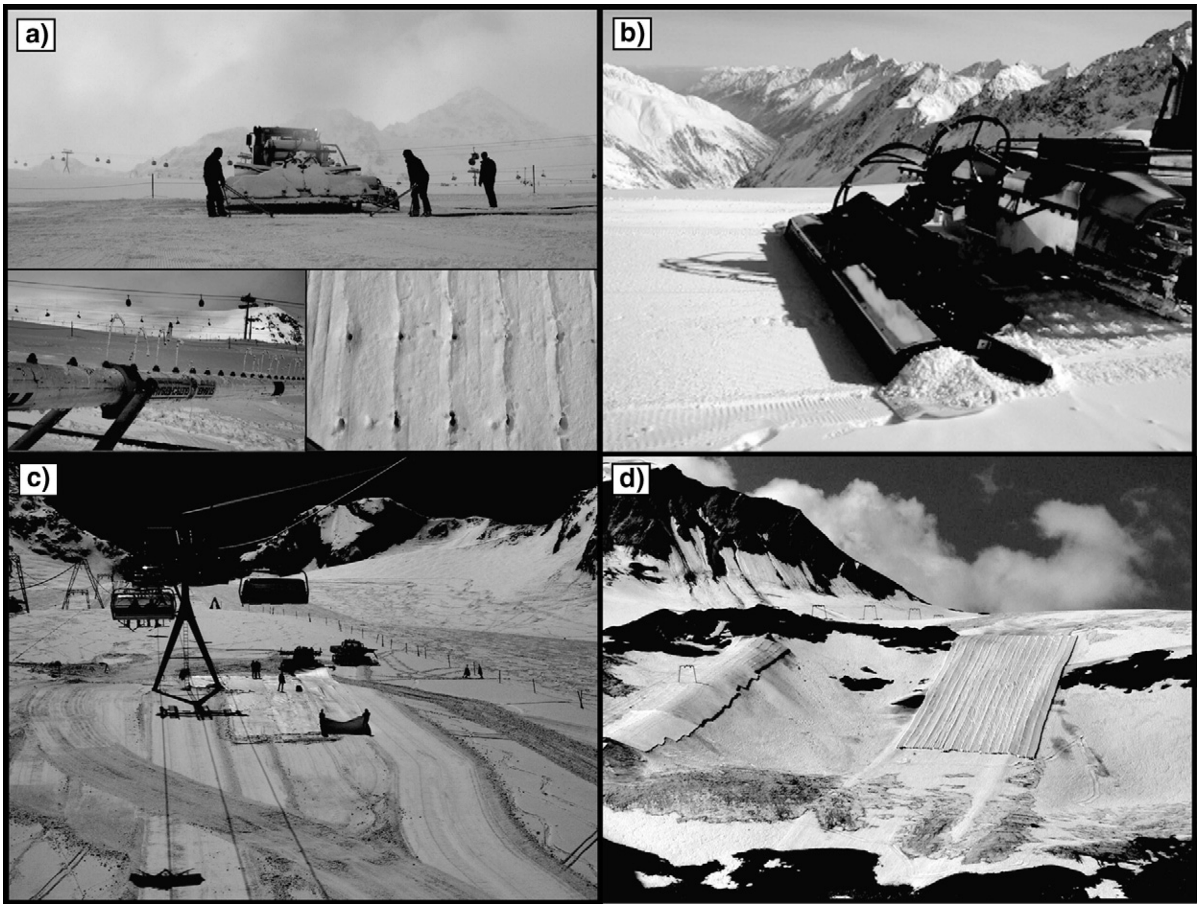

Fig. 5. Three technical methods with a potential to modify the mass balance of snow and ice were investigated during the project: a) injection of water inside the winter snow cover using a water injection device at test site Schaufelferner, b) compaction of the winter snow cover using snow-cats equipped with either the traditional molding-cutter and finisher or an oscillating plate (shown here) at Schaufelferner, c) and d) covering of the snow surface in spring using diverse types of materials at glacier Schaufelferner and Mittelbergferner (Pitztal), respectively.

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adjusted to account for best absorption due to capillary forces. The maximum water content per volume is largely a function of snow grain size. A value of 10% is reported for fine-grained snow (grain diameter below 0.0005 m) and one of 5% for coarser grains (grain diameter above 0.001 m), (Fauve et al., 2002). Water is injected under pressure using a series of small cones separated by approximately 0.1 m from each other. The device is manually placed on the snow surface every 0.2 m, the position is changed when the injection hole is finally filled with water (see Fig. 5a).

Between 23 February 2005 and 20 April 2005, water was injected into the snow cover twelve times, using 2300 l of water each. A total amount of 27600 l of water was injected at a test site with an area of 104 m^2. Vertical snow profiles with measurements of temperature, density and snow water equivalent before and after water injection documented the effects on snow properties.

2.3. Compaction of snow

The main effect of snow compaction on the snow cover is the increase of snow thermal conductivity (Yen, 1969; Kattelmann, 1985; Sturm et al., 1997). This can result in lower melt rates due to a colder snow cover at the onset of the melt. Preliminary model simulations with a bulk formulation of the compaction processes using data measured at glacier Hintereisferner indicate that the ice ablation was reduced by around 5%. Bare ice exposure was delayed by 2 days due to higher thermal conductivity of the winter snow cover (Olefs, 2005; Olefs and Obleitner, 2007).

Two devices were used for compaction of the snow cover during our field experiments. In spring 2004 a new special compaction engine was tested during one 1field experiment. This compactor is mounted on the rear of a snow-cat. The usual molding-cutter and finisher devices are replaced by a heavy plate oscillating at low frequency (see Fig. 5b). The second device is a snow-cat equipped with a molding-cutter and finisher for ordinary grooming of skiing slopes. It was used during all experiments of the year 2005, 86 times between 26 January 2005 and 30 April 2005.

During winter, vertical profiles of density, temperature, liquid water content as well as the water equivalent of the compacted snow cover were repeatedly measured in several snow pits.

3. Results and discussion

As a first result, Fig. 6 illustrates the melt pattern at the main investigation site of the year 2005, during the period of bare ice appearance. This gives a first impression of the efficiency of the distinct methods to modify the ablation of the winter snow cover.

3.1. Accumulation measures: injection of water into the winter snow cover

Water injection is the only method adding mass to the winter snow cover, and therefore increases total accumulation. Effects on snow properties such as thermal conductivity and changed microstructure were studied.

As mentioned previously, between 2300 l and 2500 l of water were injected into the snow cover per application within the test site of 104 m^2. The resulting mean mass gain calculated per unit area is in the order of 22.1–24.1 lm^{-2}. This was confirmed by measured snow water equivalents before and after the first application of the water injection device, 631.8 kgm^{-2} and 654.9 kgm^{-2}, respectively. A snow profile, dug after the 8th injection indicated a pronounced horizontal variability of the injected water. The measured snow water equivalent of 788.9 kgm^{-2}, differed by 28 kgm^{-2} from the value expected after seven additional injections. These variations are caused by horizontal flow of the liquid water within the snow cover and the slightly inhomogeneous use of the water injection device.

The time-series of four vertical temperature profiles in Fig. 7 show how the energy released by liquid water due to its heat content (injected water had a temperature of 4 °C) and phase shift is distributed in the snow cover at different times after the application. Before the addition of water, a linear temperature profile can be observed, with the lowest values (−17.3 °C) at the surface and the highest ones (−6.5 °C) at the bottom of the snow cover. Directly after the water is injected, the lower and middle parts of the snow cover heat up, the strongest signal being recorded at the snow–ice interface, where temperature increases from −6.5 °C before the application to 0°C afterwards. Near the snow surface and in the upper 0.4 m, temperature remains unchanged. Ninety minutes later, the strongest warming can be detected in the upper 0.2 m, where the greatest freezing potential was located. One day later, the upper and lower parts have reached the initial pre-injective temperatures, whereas the middle part is up to 5 °C warmer. Such a development indicates that the released heat is conducted in direction of lower temperatures (surface) during the hours following the application, which mostly heats up the surface. Finally, the energy can be effectively dissipated through longwave emission of the surface. This scenario indicates that the use of such a device has to be coordinated due to prevailing meteorological conditions.

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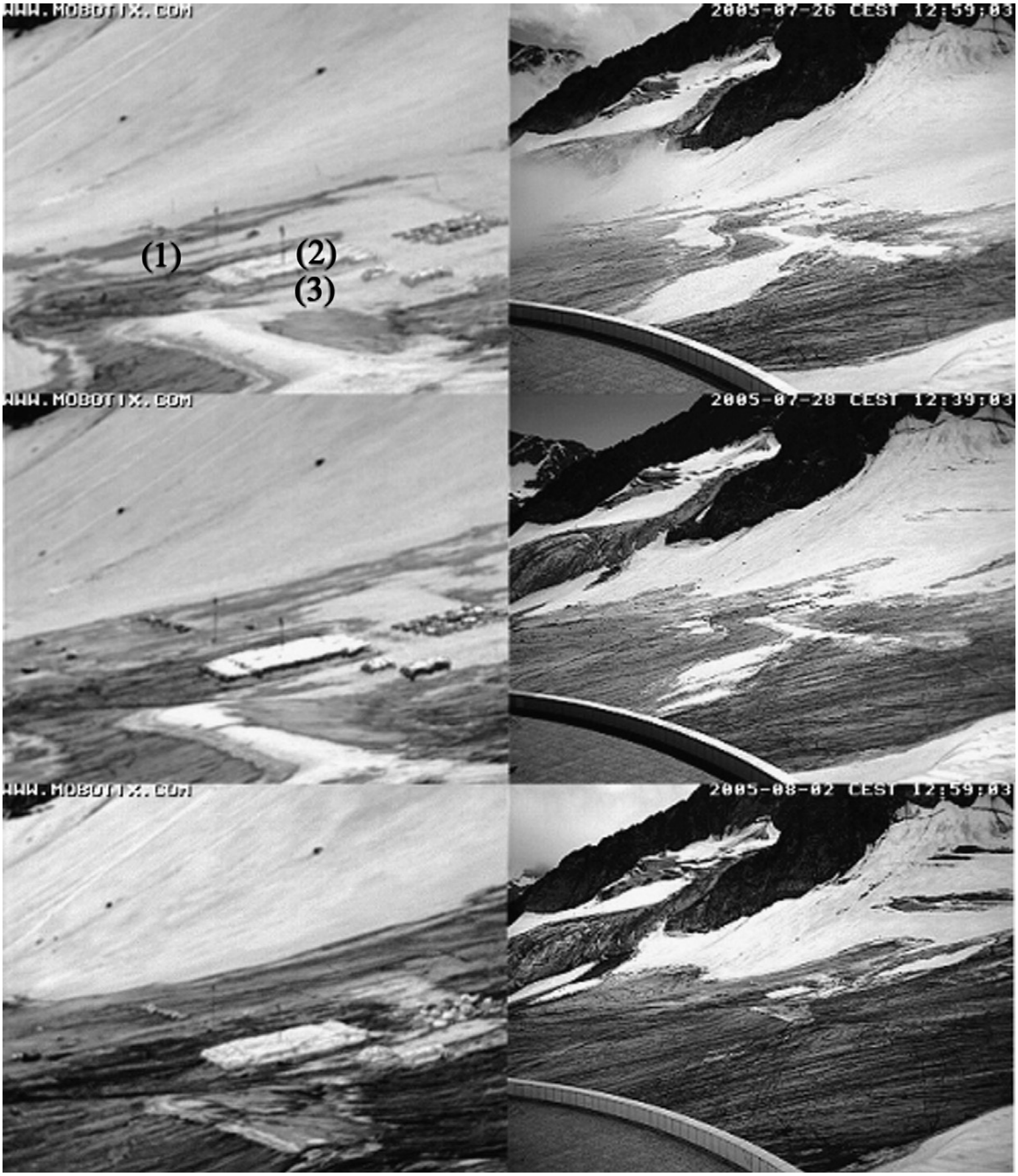

Fig. 6. Melt pattern at test site Schaufelferner during the time of bare ice appearance for 26, 28 July and 2 August 2005. A visible height difference of the covered surface (2) compared with the natural one on 26 July 2005 indicates a high ablation reduction performance of this method. Compaction (1) and water injection measures (3) lead only to a delay of bare ice appearance.

This is especially important for repeated applications, since the snow cover requires a certain time to release the entire inserted energy, primarily depending on the snow temperatures and the cloud conditions.

Bare ice within the test area for water injection began to appear on 28 July 2005, 3 days later compared to the reference field (Fig. 6). On 3 August 2005, all the snow had melted. However this time delay had no

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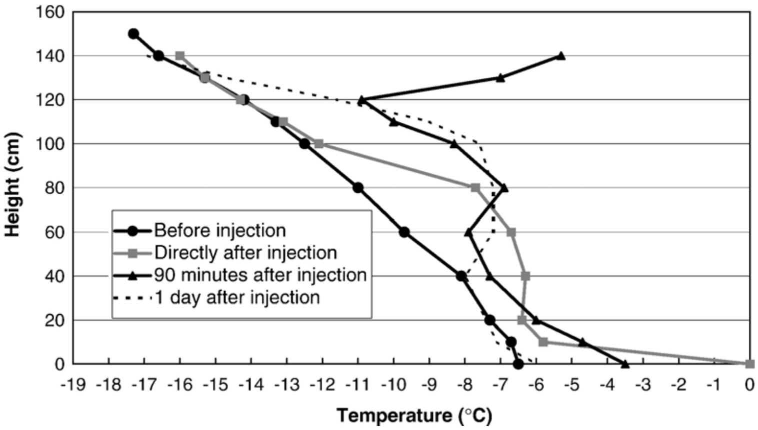

Fig. 7. Vertical profile of snow temperature taken at different times before and after one application of the water injection device. Following the injection of around 2400 l of water the heat is released in direction of lower temperatures (towards the surface) where it can be dissipated through longwave emission of the snow surface.

lasting consequence on the total ablation at the end of the melt period as can be observed in Fig. 8, which shows the mean values of two reference ablation stakes and two stakes inside the water injection test field.

In the experiment, no net mass gain was achieved using the water injection method.

3.2. Ablation measures: covering and compaction

Compaction influences the total mass balance by a modification of the snow thermal properties, whereas covering of the glacier directly manipulates the energy balance components at the snow or ice surface.

3.2.1. Properties of tested cover materials

Different material characteristics of the covers were identified as key parameters for the performance to reduce the ablation of snow and ice, namely:

- Radiative properties (shortwave reflectivity, longwave emissivity)
- Thermal properties (thermal conductivity)
- Permeability
- Tensile strength
- Surface roughness
- Thickness

These properties directly or indirectly influence the components of the energy balance of the underlying snow or ice surface in different ways.

The radiative properties of the cover material determine the short- and longwave radiation balance of the underlying snow or ice surface. Shortwave reflectivity (albedo) is of great interest, because of the high importance of solar radiation in melt processes of snow and ice in alpine regions. Longwave emissivity is crucial as well, since snow behaves nearly as a black body.

Thermal conductivity plays an important role for the exchange of sensible heat between the snow/ice surface and the atmosphere, this concerns the absorbed part of radiative energy as well as the heat content of the air.

The permeability of the cover materials was qualitatively tested, using water and blue ink. For practical purpose and efficiency of the covers, this material property turned out to be important in combination with liquid or solid precipitation. In fact, a totally impermeable material leads to the formation of “bathtubs” that heat up considerably, whereas an entirely permeable material does not protect underlying snow and ice from percolation of rain or melt water from the surface, meaning additional import of melt energy. Therefore, semi-permeable materials like our tested geotextiles were found to be a good compromise.

Tensile strength of the covers varied strongly, depending on the material composition. Many materials did not withstand strong wind gusts that occurred frequently within the test areas. Most tested geotextiles had high values of tensile strength and there was generally no problem related to this material property.

The surface roughness of the blankets also had decisive consequences on its effectiveness. In some cases, the shear strength between the cover and the underlying snow surface was too low, so that it was not possible to maintain the cover in its original position in spite of the used fixing systems. Additionally, this also had lasting consequences on an occasional snow layer (summer

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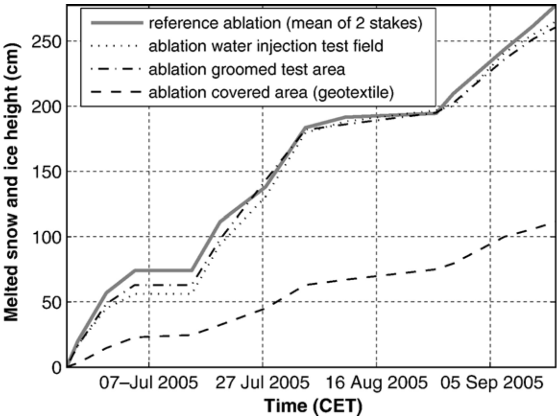

Fig. 8. Ablation in terms of snow and ice height between 22 June 2005 and 16 September 2005 within the test areas of the different technical methods to reduce snow and ice ablation. Covering of the snow surface is the only tested method with a clear reduction effect. Decreasing the ablation by around 60%.

snowfall) that is present at the cover surface, which could lead to potential snow slab avalanches if the materials are used in steep terrain. Possibly, the roughness has a further effect on the persistence of dirt layers (albedo) present at the surface of the material in combination with melt water or precipitation runoff. Here, the inclination of the slope is a supplementary factor. However, during the material intercomparison periods the slope inclination was equal for all tested materials.

The cover thickness often expressed in terms of the material mass per unit area, influences the thermal and radiative properties in a clear but non-linear way, as will be shown later. For general logistical reasons and practical issues during the placement and removal of the covers an upper limit of this parameter has to be considered.

After all, this shows that for textile selection radiative and thermal properties and the material exposure to rough alpine environment has to be considered. The general performance of the cover materials with respect to ablation reduction and a quantitative assessment of two of these material properties (shortwave reflectivity and material thickness) is presented in the following section.

3.2.2. Results of cover experiments

Covering the snow surface with a geotextile is the only method tested, which had a net effect on the mass balance. During both melt periods 2004 and 2005, the ablation of snow and ice was reduced significantly (Figs. 8 and 9). The total average daily ablation rates for natural undisturbed conditions in 2900 m a.s.l. in terms of height were 0.037 md^{-1} in 2004 and 0.032 md^{-1} during 2005 (15.9 kgm^{-2} and 16.8 kgm^{-2}, respectively). Under the geotextile material net ablation was reduced to 0.014 md^{-1} and 0.013 md^{-1} in height (6.0 kgm^{-2} and 6.8 kgm^{-2}). This approximately corresponds to a 60% reduction of natural ablation. During both years, no ice ablation took place under the cover as 0.6 m of winter snow could be saved (315 kgm^{-2} in 2005). Fig. 10 shows the covered test area at the end of the ablation period 2005. During this year, the winter snow protected from melt had a mean density of 525 kgm^{-3} corresponding to a conserved mass of snow of around 100 t for the covered area of 320 m^2.

The effect of different thickness of cover materials on the ablation rates was investigated during the ablation period 2005. The same material was placed in a single (0.004 m), double (0.008 m) and triple (0.016 m) layer application, yielding daily average ablation rates of 0.013 md^{-1}, 0.009 md^{-1} and 0.009 md^{-1} in height, respectively. Interestingly enough, the performance of the cover material increases by about 10% if the thickness is doubled, but a triple thickness does not yield any effects on ablation reduction.

A small sample of shortwave spectral reflectivity measurements of the tested cover materials is shown in Fig. 11. The results indicate that new, unused cover materials with a high reduction of ablation (V0 and V7 in Fig. 11a) have both generally higher values of shortwave reflectivity than surrounding old snow in late July 2004. Fig. 11b demonstrates that a well performing geotextile material had always absorbed less solar

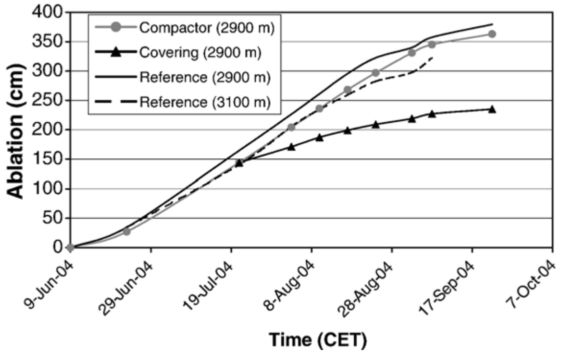

Fig. 9. Snow and ice ablation (height) for 9 June 2004 to 22 September 2004 at test site Schaufelferner (2900 m a.s.l.) and Gaißkarferner (3100 m a.s.l.). The single use of the compaction device has no lasting consequences on the ablation, whereas a geotextile placed on 21 July 2004 reduces natural ablation rate from 15.9 kgm^{-2} to 6.0 kgm^{-2} during that period, conserving 0.6 m of winter snow over the summer. Note, that the ablation curve for covering starts on 21 July 2004.

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Fig. 10. Cover test area Schaufelferner after the removal of the geotextiles at the end of the ablation period on 16 September 2005. Natural glacier ice ablation (900 kgm^{-2}) was completely stopped and 315 kgm^{-2} of winter snow were preserved over the ablation period.

radiation than nearby bare ice or rock, even if its albedo had decreased during the use on the glacier due to impurities which darken the surface of the material. In both years all measured covers showed such a reduction of the shortwave reflectivity, but the magnitude of the reduction was strongly diverse, which can be attributed to different surface characteristics of the covers.

The most efficient material tested during 2005 also has the highest reflectivity with 63% measured after 7 weeks of use on the glacier. In contrast, reflectivity of the least suited material was 5%. Generally, the relationship between the albedo and the ability of the material to decrease the ablation rate is better with thin materials. In such a way a material tested during 2005 with a thickness of a few centimeters and a very low albedo of 0.16 ranged between the best tested materials. This outcome can probably be attributed to a process of heat storage and demonstrates that the albedo of a material is not the only parameter that has to be considered to judge whether a cover effectively reduces the ablation rate or not. Table 1 gives measurement details of four different material types tested during diverse periods in 2004 and 2005.

3.2.3. Compaction

Between 2 and 6 April 2004, the snow cover was compacted layer-wise (0.2 m each) after its complete removal on a defined area using the special compaction facility (oscillating plate). Snow density vertical profiles taken three weeks later on 26 April 2004 inside and outside of the compacted area indicated a mean density difference of only 25 kgm^{-3} (420 kgm^{-3} vs. 395 kgm^{-3}). This negligible divergence indicated minor impact on the snow and ice thermal regime, due to a strong relationship between density and thermal conductivity (see Sturm et al., 1997). During the ablation period 2004, the ablation rates of the compacted and undisturbed area did not differ significantly, confirming the expectations from the snow profile data (see Fig.9).

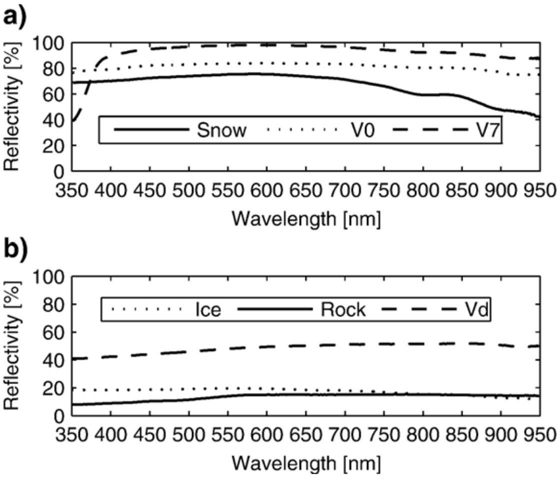

Fig. 11. Shortwave spectral reflectivity of a) new, unused geotextiles (V0 and V7) vs. surrounding old snow in late July 2004 and b) a used geotextile vs. surrounding bare ice and rock in September 2005.

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Table 1
Measurement details of four different cover materials tested during both ablation periods 2004 and 2005

Type	Tested period (total number of days spent on glacier)	Natural average ablation rate (10^{-2} md^{-1})	Average ablation rate with material (10^{-2} md^{-1})	Shortwave reflectivity (350–950 nm) in %	
				New	After *x* days of use
Geotextile I	2004 (42)	3.9	1.7	91.9	67.1 (42)
	2005 (33)	4.4	2.2		45.8 (75)
GeotextileII	2004 (42)	3.9	1.8	88.5	65 (42)
	2005 (33)	4.4	1.9		55.4 (75)
Biodegradable material	2005 (33)	4.4	2.3		41.9 (33)
Cotton sheet	2004 (28)	3.1	2.4		73 (28)
Canvas	2004 (42)	3.9	2.9		67.4 (42)

Average ablation rates are indicated in cm of height difference per day.

Contrary to these results of a single manipulation of the entire snow cover with the special compactor (oscillating plate), regularly grooming the test area between January and April 2005, using traditional devices (molding cutter, finisher), had a clear impact on snow density profiles as can be seen in Fig. 12. Actually, the two natural (not yet groomed) profiles taken in December and January show a mean density of 339 kgm^{-3} and 359 kgm^{-3}, increasing towards 429 kgm^{-3} and 444 kgm^{-3} after 40 and 61 runs of the snow-cat in March and April 2005. After a total number of 86 snow-cat runs, the mean density was 494 kgm^{-3} on 24 May 2005. The mean density of all 6 snow profiles taken within the groomed test fields between February and May 2005 was 439 kgm^{-3}, or 425 kgm^{-3} if only the four profiles during the cold period until mid-March, where densification through melt water percolation and refreezing plays no role, are taken. This number is in good agreement with the density range given by Fauve et al. (2002), 400 kgm^{-3}–600 kgm^{-3} and with seasonal mean density for groomed snow in New Zealand of 400 kgm^{-3} (calculated with values from Fahey et al. (1999)).

Considering the effect on snow and ice ablation, Fig. 6 demonstrates that the entire snow cover on the groomed area had completely melted until 29 July 2005, four days after the natural reference site and one day after the water injection test field. Like the injection of water, this has no significant impact on total ablation (Fig. 8).

4. Summary and conclusion

A comparative investigation of technical measures to increase the net mass balance of snow and ice within test areas of Austrian glacier skiing resorts was presented. Tested methods included: (i) compaction of the winter snow cover, (ii) injection of liquid water inside the

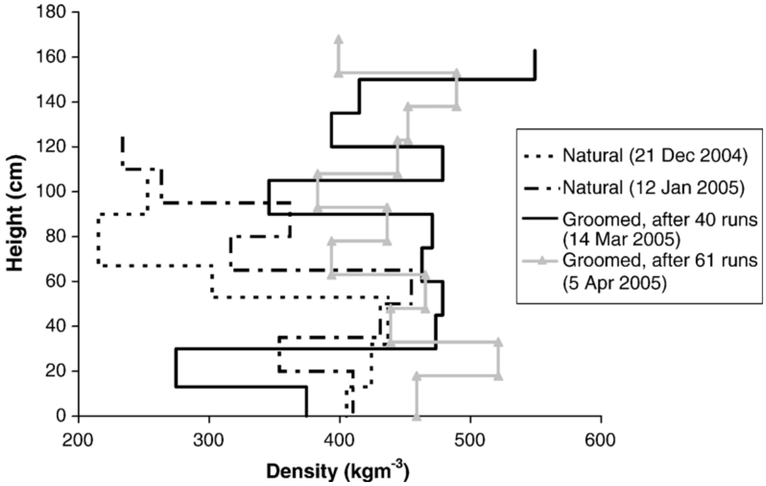

Fig. 12. Vertical profiles of snow density before and after regularly grooming, using traditional equipped snow-cats within the compaction test field Schaufelferner during Winter 2004/05 (for explanations see text). Note the different dates of the profiles.

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winter snow cover and (iii) covering of the snow surface in spring.

It was shown that the covering of the glacier in spring decreases total ablation of snow and ice by about 60% using geotextiles. A net mass gain was achieved, as it was possible to stop glacier ice melt completely and to save around 0.5 m of winter snow over the summer during both years. On the other hand, compaction of the snow cover and injection of water turned out to have a minor impact. The injection of liquid water inside the winter snow cover requires great amounts of water and work. Regular grooming of skiing slopes reduced snow ablation by delaying the time of bare ice appearance by four days.

The efficiency of the covering method is obviously strongly dependant on the material characteristics. An intercomparison of more than forty different cover materials tested, showed a wide range of performances related to the individual and specific material properties (thickness, permeability, surface roughness, tensile strength, radiative and thermal characteristics). Geotextiles merged most of the required properties to effectively reduce the ablation of snow and ice. Some of these crucial properties such as material thickness or shortwave reflectivity were already investigated. Others need additional examination (e.g. longwave emissivity, thermal conductivity). This is also essential in the scope of future studies.

Therefore, further efforts will consider a process-oriented adaptation of a physically based snow model, which is also based upon first experiences with bulk approaches (Olefs and Obleitner, 2007) and the presented measurement results within this study. Automatic weather station data, including both undisturbed and covered conditions, which has sparsely been used here, may serve as a solid verification basis. This also requires more detailed measurements of specific energy balance components related to cover materials (e.g. latent heat flux).

Such should enhance the understanding of the involved physical processes and is considered as valuable for further optimization purposes. Finally, it could allow spatial studies, investigating the consequences on mass balance and hydrological regime of the whole glacier.

Nevertheless, covering of glaciers will be restricted to small parts within glacier ski resorts due to the high effort, even though larger areas could be protected on the basis of a rotating shift. Such an approach would be most valuable in combination with data on the spatial distribution of ice thickness and its change in time and is as well subject of current and future investigations on this topic.

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