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Terrestrial laser scanning for glacier monitoring: Glaciation changes of the Gößnitzkees glacier (Schober group, Austria) between 2000 and 2004

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Abstract

Monitoring of glacier behaviour is an important task in environmental research. For detailed detection of glacier surface and volumetric changes terrestrial laser scanning is a very effective and cheap observation method, due to the ability to acquire high-resolution 3D data. Since summer 2000 this method is applied at the Gößnitzkees glacier, a small debris-covered glacier located in central Austria (12°45'E, 46°58'N; size *c.*0.75km²). More than 60% of the glacier is covered by a prominent debris mantle. So far, five terrestrial laser scanning campaigns have been carried out focusing on the central part of the glacier including the glacier terminus (07-2000, 08-2000, 07-2001, 08-2001, 08-2004). These measurements allow the comparison of three different time scales (intermonthly, interannual, four years). The results demonstrate that accumulation and ablation (snow/firn/ice) can be monitored very accurately. The debris cover reduces net ablation at the glacier surface by up to 75% whereas the amount of incoming solar radiation is less important. A highly active feature is the retreating steep ice wall at the glacier terminus. Supraglacial meltwater causes further increase of local net ablation due to heat exchange at the meltwater-ice interface. It is shown that by use of this method it is easily possible to detect small changes on a glacier surface (clean and debris-covered) relevant for glacier-climate modelling but also for aspects in hydrology and natural hazard management.

Keywords

Gößnitzkees; Debris-mantled glacier; Glacier mapping and monitoring; Terrestrial laser scanning; Glacier surface and volumetric changes - intermonthly, interannual and four years.

Background and objectives

Advancing or retreating glaciers have a complex impact on their neighbouring environment, as e.g. on permafrost, geomorphic processes (thus natural hazards) or vegetation. In Austria, monitoring of glacier behaviour is an important task in environmental research. Since many decades the Austrian Alpine Association (OeAV) coordinates annual glacier measurement campaigns. Of the 925 Austrian glaciers according to the first Austrian glacier inventory from the year 1969 (Patzelt 1980) 107 glaciers are currently monitored on an annual basis by this program (Patzelt 2005); the majority of them only in a very general way (e.g. change of glacier terminus). In addition to these activities, annual mass balance measurements are carried out at a much smaller number of Austrian glaciers (Hintereisferner, Jamtal Ferner, Kesselwandferner, Sonnblickkees, Vernagtferner and Wurten Kees) within the framework of the World Glacier Monitoring Service (WGMS). Currently, a new Austrian glacier inventory is in progress. This inventory will also include for the first time volume and ice thickness data. For this purpose, 49 glaciers of different types have been surveyed between 1995 and 2003 with the aid of ground penetrating radar (Würländer & Kuhn 2000, Fischer & Span 2005, Lambrecht et al. 2005). Knowledge of glaciation changes is essential for the interpretation of glacier-climate interaction and glacier-climate modelling studies. Furthermore, the total volume of a glacier body is an interesting parameter for water resource management, in particular in areas where glacier water is essentially used for irrigation during the summer period (e.g. Hunza valley, Pakistan) or used for hydropower production (e.g. Kaprun, Austria). Numerical requirements on the quality of glaciological data are high in order to allow reliable predictions for all these issues. A number of different methods on a local, regional and global scale for glacier monitoring are available. For detection of glacier surface and thus volumetric changes in a very high spatial resolution terrestrial laser scanning is a very effective and cheap observation method, due to the ability to acquire high-resolution 3D data in a very short period of time. This paper describes first monitoring results of recent glaciaton changes (2000 to 2004) of the Gößnitzkees,

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the largest glacier in the Schober Group, Austria. The explanations refer to a research project which is carried out by the Institute of Digital Image Processing, Joanneum Research, Graz, with logistic assistance from the Hohe Tauern National Park Service. The scope of this ongoing project is to monitor surface and structure changes of glaciers and rock glaciers of different sizes with a very high accuracy by means of terrestrial laser scanning.

Study area

Gößnitzkees is located to the south of the main crest of the Hohe Tauern range in the central part of the Schober group at the valley head of the Gößnitz valley and is thus in the inner zone of the Hohe Tauern National Park at 12°45' E and 46°58' N (fig. 1). 'Kees' is the regional term for glacier. Gößnitzkees was included into the network of the mentioned annual glacier measurements of the OeAV in 1982. Due to the unsuitable topographic (steep rock faces, narrow crests, lack of flat surfaces at high elevations above the regional ELA) and climatic conditions (continental climate: low precipitation *c.*1500mm at 2000m asl., 0°C at 2300m asl.) of the Schober group, the glaciation is limited to a few positions at the foot of rock faces in northern expositions. The mean size of the glaciers does not exceed 0.18km² (N=29) and making Gößnitzkees with its *c.*0.75km² in 1997 the largest glacier of this mountain group (Lieb 2000, Kaufmann & Ladstädter 2004a). The general exposure of the glacier is NW with high crests and mountain tops to the S. The accumulation area of the glacier is very small. A high amount of snow accumulation originates from avalanches, in particular at the western head of the glacier at the foot of some pronounced couloirs (fig. 2). More than 60% of the glacier is covered by a prominent debris mantle with variable thickness. The rock material originates from the rock faces to the S consisting of crystalline rocks such as gneisses, amphibolites (Hornkopf peaks) and in particular schists (Western Klammerköpfe). The uppermost parts of the glacier – as e.g. the more-or-less separate glacierette just below the cirque on the W-facing slope of Großer Hornkopf (*cf.* fig. 1) – feature no pronounced bergschrunds, thus hinting a warm based glacier even at the uppermost limit. The overall appearance of the Gößnitzkees indicates a very inactive glacier also expressed by low mean annual flow velocities of 30-60cm/a (Kaufmann & Ladstädter 2004b). Due to the described topographic and climatic situation in the Schober group the entire area favours permafrost conditions. In NW-, N- and NE-aspects discontinuous permafrost can be expected above 2600 m with frequent occurrence of creeping permafrost features, i.e. active rock glaciers. The existence of the 77 intact rock glaciers is further enhanced by the mentioned lithologies; some of them may also contain some glacier ice (Lieb 1991, Krainer et al. 2000, Lieb et al. 2004, Avian et al. 2005a). Summing up, relief and geoecological elements of the Schober group are highly representative for the Central Alps and thus for the National Park Hohe Tauern.

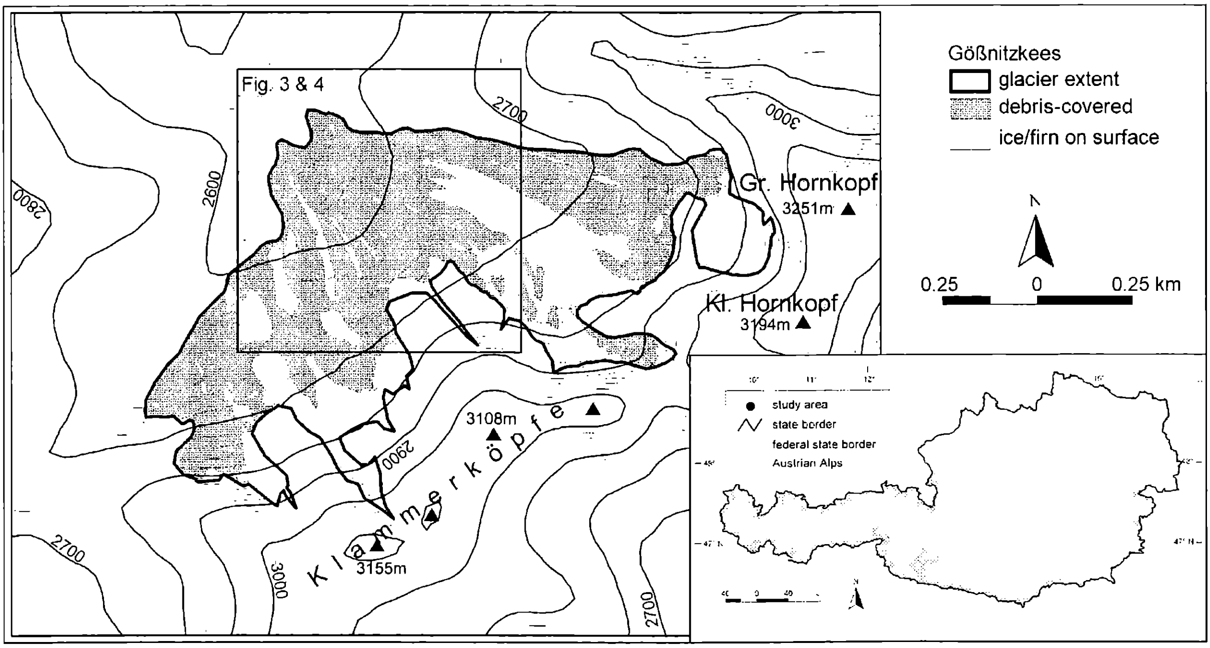


Fig. 1: Location and setting of the study area Gößnitzkees. The delineation of the glacier and the distribution of debris-covered and clean surfaces are based on the aerial photographs from the year 1998. The square in the main map indicates the location of the maps shown in figures 3 and 4.

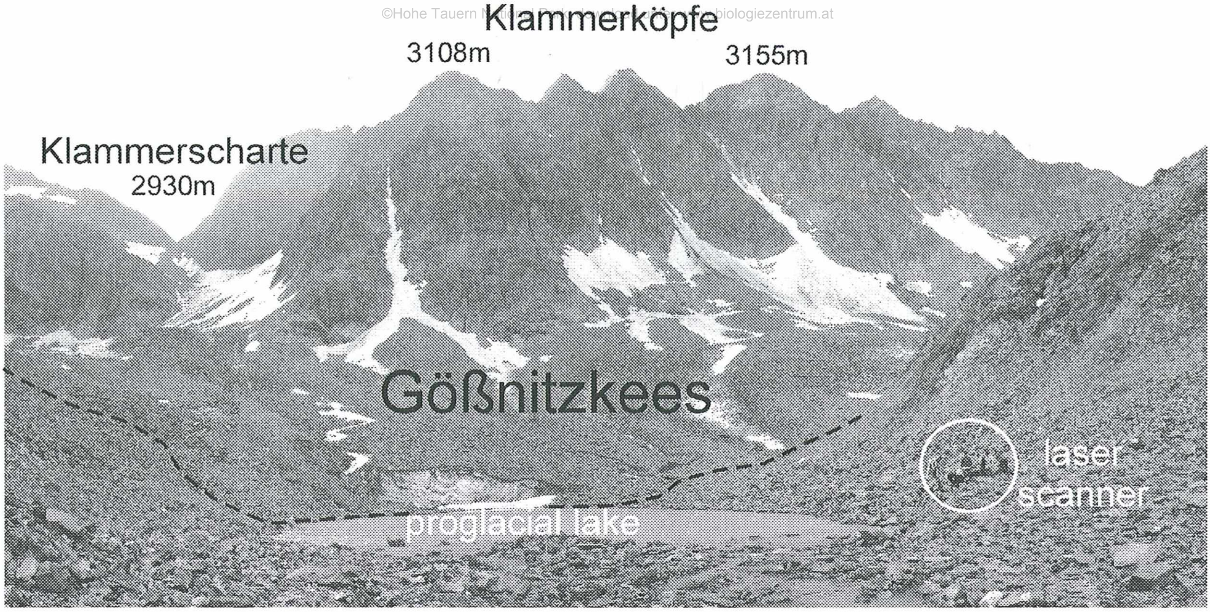
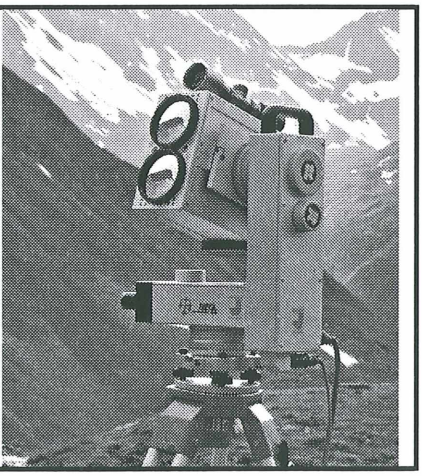


Fig. 2: Terrestrial overview of the study area. Note the steep ice front of the mostly debris-covered glacier adjacent to the proglacial lake and the group of people standing next to the location of the laser scanner; view towards SE (Photo: Kellerer-Pirklbauer 20-08-2004).

Methods and experimental setup

For the past few years, terrestrial 3D laser scanning systems have been employed very successfully in the design and manufacturing industries as well as in industrial surveying (Pfeifer et al. 2004). Further development of long range scanners with high precision allows them to be applied in terrain surveying. 3D laser scanners produce point clouds, sampled representations of 3D scenes, from range and angle measurements that are converted into accurate 3D models. The ability to acquire high-resolution 3D data of surface structures makes this technique a very interesting instrument for measuring glacier (Avian et al. 2005b; this volume) as well as rock glacier dynamics (Bauer et al. 2003, 2005). The integrated measurement system is capable of describing 3D motion and deformation of glacier surface within a single day's measurement campaign including logistics and evaluation. Table 1 gives technical information concerning the used instrument Riegl LPM-2k Long Range Laser Scanner.

Scanner parameter	*Value (range)*	
Measuring range for: - good diffusely reflective targets - bad diffusely reflective targets	up to 2500m >800m	
Ranging accuracy	±50mm	
Positing accuracy	±0.01gon	
Measuring time / point	0.25s to 1s	
Measuring beam divergence	1.2mrad	
Laser wavelength	900nm	
Scanning range - horizontal - vertical	400gon 180gon	
Laser safety class	3B, EN 60825-1	
Power supply	11-18V DC, 10VA	
Operation temperature range	-10 to +50°C	

Tab. 1: Scanner parameters and values of the used instrumentation Riegl LPM-2k Long Range Laser Scanner.

Between July 2000 and August 2004 five terrestrial laser scanning campaigns have been carried out (11.07.2000, 22.08.2000, 27.07.2001, 25.08.2001, 20.08.2004) covering the central part of the Gößnitzkees including the glacier terminus. The area that has been investigated during each laser scanning campaign covers 0.09 to 0.13km^2 or 11.8 to 17.1% of the entire glacier surface. Figure 3 gives the spatial coverage during the 5 campaigns as well as the locations of the laser scanner and the reflective reference targets relevant for sensor orientation. During each of the 5 campaigns a high-resolution geo-referenced digital elevation model (DEM) in form of a regularly grid has been generated. The resulting DEM for each measurement campaign represents a dated state of the region covered by the sensor measurements. Since the data is geo-referenced, simple differences between the DEMs reflect the changes in surface elevation (volume) between the campaign dates. This has been performed for three different time scales (intermonthly, interannual, four years). Postprocessing and visualisation has been fulfilled by the house-own software GeoScanner and ArcGIS (data resampled to a 1m grid for visualisation in fig. 3, 4 & 6). Further description of measurement procedure and data processing is found in Bauer et al. (2003). To compare the potential short-wave solar radiation (PSWR) highly relevant for glacier ice melting and the measured glacier net ablation rates at the Gößnitzkees, a map of PSWR for each month and inferred from that for the summer season (June-July-August) was modelled using a 25m-DEM and the Solar Analyst extension (Fu & Rich 2000) in ArcView.

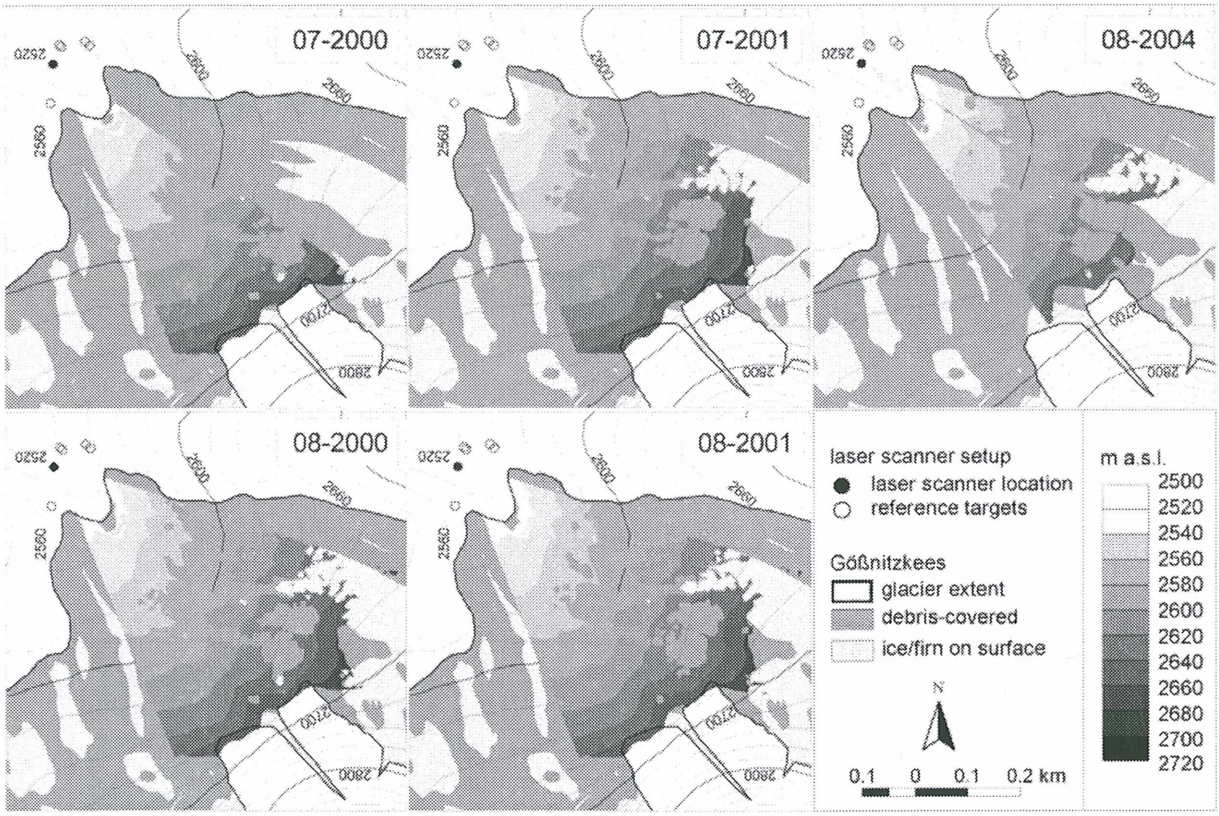


Fig. 3: Spatial extent of the five terrestrial laser scanning campaigns at the central part of the glacier including the glacier terminus: open circles mark the used reference targets for sensor orientation; the dot indicates the location of the laser scanner illustrated in table 1 (*cf.* fig. 1).

Results

Based on the measured terrain data glaciation changes over 3 different time scales have been calculated: 2 x intermonthly – 07 to 08-2000, 07 to 08-2001, 2 x interannual – 07-2000 to 07-2001, 08-2000 to 08-2001, and 1 x over four years – 08-2000 to 08-2004. The results are presented in figure 4. Table 2 gives a numerical overview of the calculated results and an estimation of volume changes for the total glacier for each time interval. The scanned area covers a profile sector from the cirque headwall to the glacier terminus and is representative for the entire area. Thus, it is assumed that the detected changes are not only valid for the measured sector but also can be – more or less - extrapolated on the entire glacier.

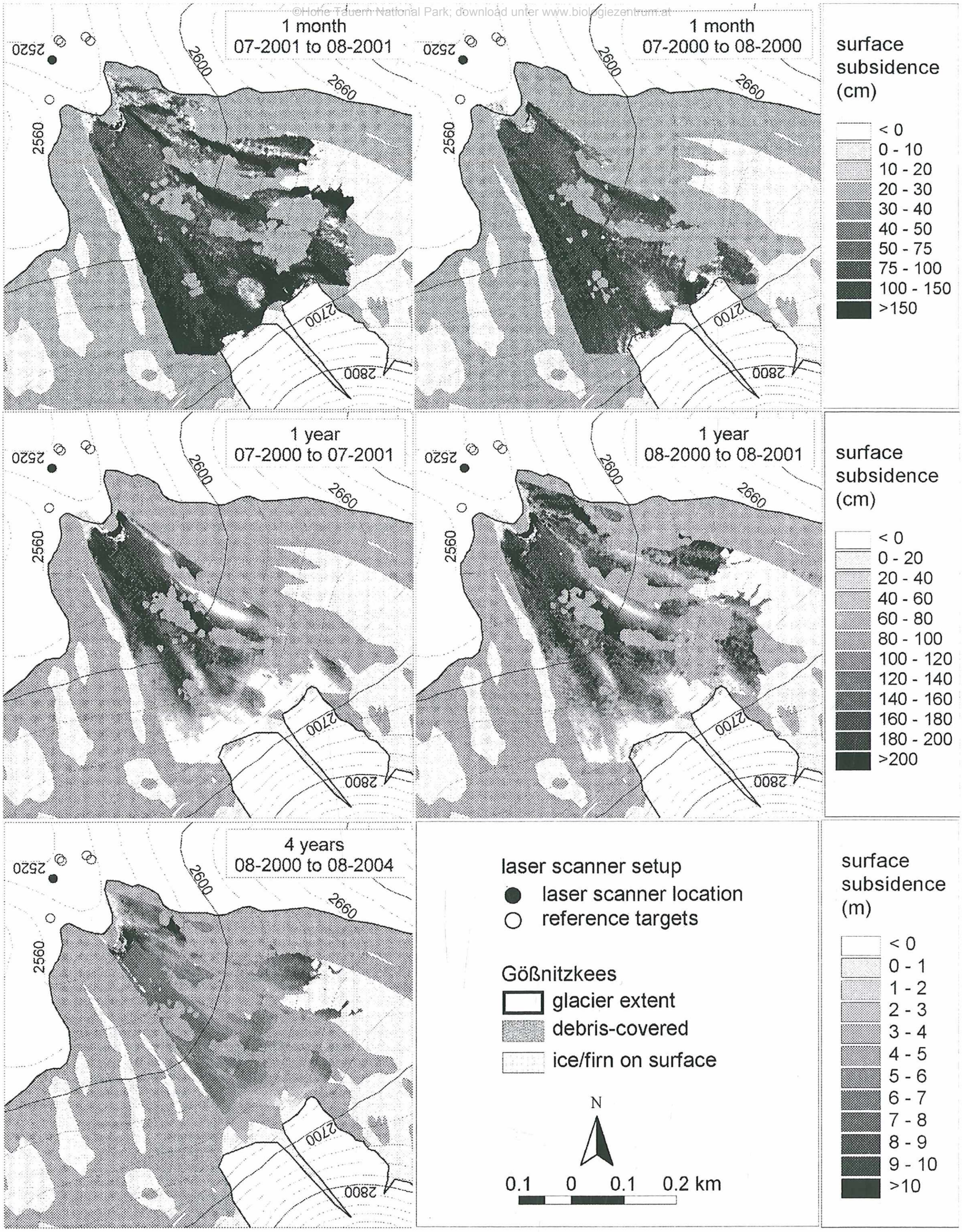


Fig. 4: Glacier surface changes during three different time scales (intermonthly, interannual, four years). Positive values indicate areas of thinning and <0 values indicate areas of thickening respectively (i.e. accumulation of snow/firn). Note the increase in thickness in some areas at the 1 year time scales due to a favourable glaciological year 2000/2001.

Difference calculations	Area considered in the difference calculations				Area considered on the entire glacier * (%)	Mean change in elevation (m)	Measured volume change at the monitored glacier section (m^3)	Estimated volume change for the entire glacier* (m^3)
	total [a] (m^2)	on the glacier [b]		δ of a & b (%)				
		(m^2)	(%)					
1 month: 07 to 08-2000	87,763	85,262	97.2	2.8	11.4	-0.971	-82,789	-728,250
1 month: 07 to 08-2001	120,241	118,175	98.3	1.7	15.8	-1.113	-131,529	-834,750
1 year: 07-2000 to 07-2001	86,262	84,224	97.6	2.4	11.2	-0.829	-69,822	-621,750
1 year: 08-2000 to 08-2001	119,962	117,896	98.3	1.7	15.7	-1.179	-138,999	-884,250
4 years: 08-2000 to 08-2004	63,083	62,894	99.7	0.3	8.4	-5.755	-361,955	-4,316,250

*glacier size 0.75km²

Tab. 2: Numerical overview of the calculated and estimated results for each time interval.

Discussion

The results shown in figure 4 clearly demonstrate non-uniform and peculiar retreat behaviour of the Gößnitzkees during all three studied time scales. This extremely uneven change pattern is related to a number of factors acting unequally at different areas on the glacier. These factors are: (i) temperature and (ii) PSWR during summer, (iii) distribution and characteristics of debris cover on the glacier, (iv) heat exchange at the meltwater-ice interface in supraglacial meltwater channels, and (v) specific accumulation and/or ablation history of snow/firn/ice between two compared time periods.

Temperature and PSWR during summer (modelling results in figure 5) are of minor importance for the unequal distribution of net ablation. Note the homogeneity of modelled PSWR at the relevant, central part of the glacier indicating the low influence of PSWR on the difference of glacier surface changes over short horizontal distances. The distribution and characteristics of the debris cover plays a crucial role in the behaviour of the Gößnitzkees. During all three time scales, glacier surface changes are greatly influenced by the presence or absence of a debris mantle (*cf.* fig. 4 & 6). In some areas the debris cover reduced net ablation at the glacier surface by up to 75% compared to clean ice surfaces in close neighbourhood. Glaciers mantled by a pronounced debris-cover behave differently to normal or 'clean' glaciers. First, debris-covered glaciers may deposit massive ridges of morainic debris around their snouts, which are capable of ponding large volumes of meltwater, but lack the mechanical strength to impound the water for more than a few decades. The breakage of such a dam may cause dangerous and catastrophic glacier lake outburst floods (GLOF) causing massive destruction of property and loss of live. Second, by insulating ice from solar radiation and daily temperature fluctuations, a thick debris cover effectively insulates the underlying ice and greatly reduces rates of ablation relative to that of uncovered ice, thus delaying the response of the glacier to atmospheric warming. During periods of climatic warming, debris-covered glaciers slowly melt down, until closed hollows and lakes begin to form on the glacier surface or at the margin (BENN & EVANS 1998, BENN et al. 2001). A further important aspect in this context is the increasing input of debris on glaciers; lower glaciation causes a higher input of debris on the remaining glacier body due to pressure release and paraglacial instabilities on adjacent slopes and the cirque headwall. Such an increase in debris input in combination with inefficiency of sediment transfer from the glacier ice to the meltwater may cause even complete debris coverage of a once 'clean' glacier and eventually the transformation into a glacier-derived or ice-cored rock glacier (KRAINER & MOSTLER 2000, SHRODER et al. 2000, BERGER et al. 2004, NAKAWO et al. 2000). Meltwater draining sub-, intra- or supraglacially enhances melting of ice due to heat exchange at the meltwater-ice interface ('thermo-erosion'; *cf.* BENN et al. 2001). At the Gößnitzkees this effect is most effective along supraglacial meltwater channels (fig. 6c). Finally and obviously, the specific accumulation and/or ablation of snow/firn/ice between two compared time periods greatly influence the calculated results.

As it is shown in figure6a-b, the accumulation of snow over a period of 1 year can be quantified in depressions close to glacier terminus, i.e. supraglacial meltwater channels still filled with wind-drifted winter snow, but also at the avalanche cones at the foot of the cirque headwall. This net accumulation results due to a very favourable glaciological year 2000/2001 at the Gößnitzkees with large areas of snow coverage even in late summer (Lieb et al. 2001). High ablation can also be quantified at different locations on the glacier as e.g. at the same supraglacial meltwater channel as mentioned before but over a different time scale (fig. 6c), at the glacier terminus (very active feature; retreat of 7-15m/a) and at the foot of the cirque headwall (fig. 6c-d). Figure 6b and d also shows nicely that on the lower part of this particular avalanche cone surface dynamics are lower as in the close vicinity due to a wind exposed and less avalanche prone location (*cf.* fig. 2).

The values given in table 2 reflect the recent glaciological history of the Gößnitzkees: unfavourable glaciological year 1999/2000 (Lieb et al. 2000), favourable glaciological year 2000/2001 (Lieb et al. 2001), unfavourable glaciological year 2001/2002 (Lieb et al. 2002), very unfavourable glaciological year 2002/2003 (Krobath 2003), and unfavourable glaciological year 2003/2004 (Krobath 2004). For the 1-month period 07 to 08-2000 the mean change in elevation over the entire glacier and the measured and estimated volume change is due to snow and ice melting; for 07 to 08-2001 mainly due to snow melting. Values for the 1-year periods are relatively low due to a favourable glaciological year 2000/2001. The difference between these two periods is mainly based on higher snow ablation in summer 2001 (due to snow availability!) compared to summer 2000. The results measured and calculated for the entire monitoring period give a mean elevation change of about *c.*-5.8m (-1.45m/a) and an estimated total volume loss of more than 4.3 Mio. m^3 (1.08 Mio m^3/a) strongly indicating once more a retreating glacier. It has to highlighted that if no debris cover would protect the glacier, the rates of glacier ice retreat would have been much higher. As an example of utilizing high resolution laser scanner data only a few glaciological aspects are pointed out in this paper. Further analysis and interpretations are in progress.

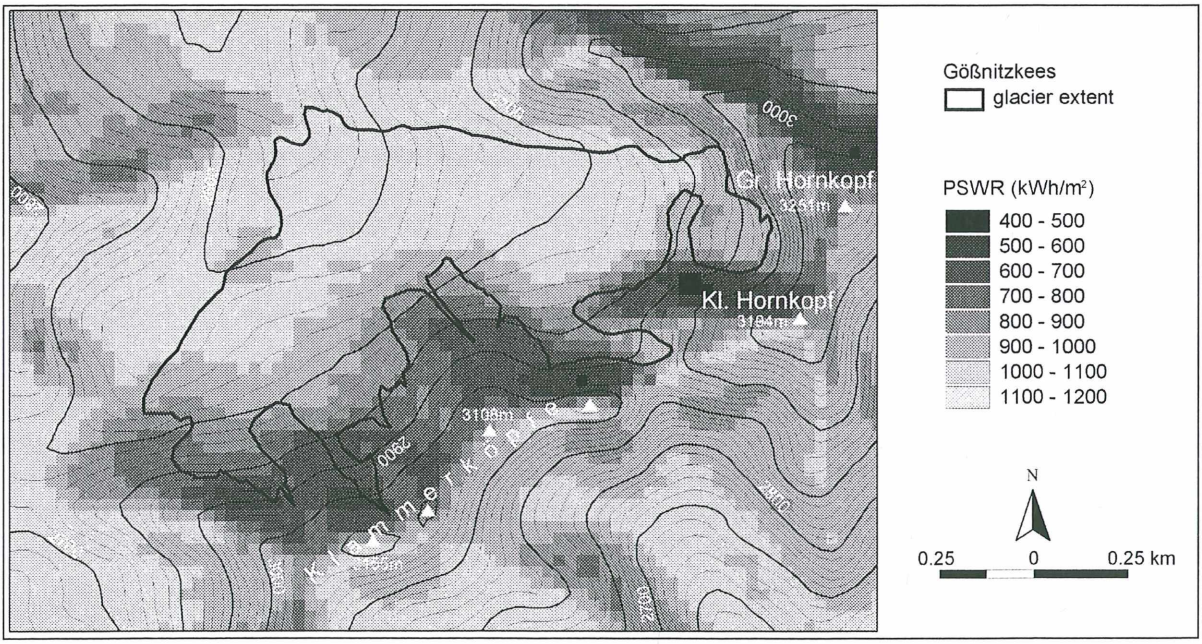


Fig. 5: The spatial distribution of the potential short wave radiation (PSWR) during summer (June-July-August) at the study area. Note the homogeneity of modelled PSWR at the relevant, central part of the glacier indicating the low influence of PSWR on the difference of glacier surface changes within short horizontal distances.

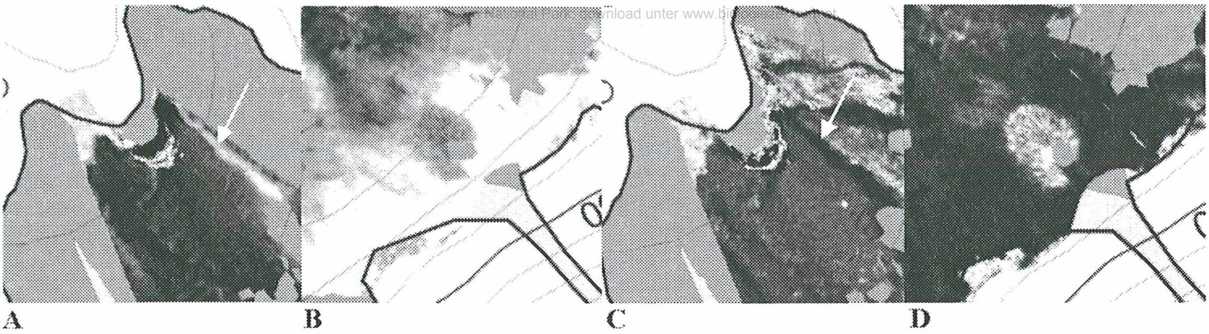


Fig. 6: Section examples of figure 4 showing surface changes both increase and decrease - at the glacier at different time scales and at different locations; (A and B): sections of 1-year change maps (07-2000 to 07-2001), bright areas indicate accumulation of snow – A: in the supraglacial meltwater channel (white arrow), B: at the foot of cirque headwall; (C and D): sections of 1-month change maps (07-2001 to 08-2001); dark areas indicate enhanced ice melting – C: at the supraglacial meltwater channel (white arrow) at the glacier terminus and in areas with a minor debris cover, D: melting of winter snow at the foot of the cirque headwall.

Technical and glaciological conclusions

- Monitoring of glacier surface changes with high temporal and spatial resolution in alpine terrain is feasible.
- Operational system is available as mobile or stationary unit.
- Results are available immediately after measurement.
- Accuracy depends on viewing geometry and footprint size of the laser beam.
- 3D high resolution surface change data (accumulation of snow and debris; ablation of snow/firn/ice) is obtained by DEM analysis.
- The same method can be applied to rock glaciers, snow cover thickness determination and rock slide monitoring.
- Both large scale (e.g. estimation of total glacier volume change) and small scale (e.g. quantification of supraglacial meltwater channel incision) glaciological features can be quantified.
- PSWR during summer plays a minor role in different ablation and accumulation behaviour on a heavily debris-covered glacier.
- An existing debris cover causes a striking difference in net ablation at areas mantled by debris relative to clean ice surfaces within close distance (up to 75%) , in particular at the debris-free vertical glacier terminus. A detailed analysis of the debris cover on the glacier (e.g. thickness of layer, spatial distribution, clast size) is planned in the near future.
- Obviously, the principal factor causing an uneven distribution of surface changes within a short horizontal distance between two compared time periods is the specific accumulation/ablation history.
- It is clearly shown that multi-temporal terrestrial laser scanning analyses provide a high potential for mass balance estimates and thus glacier dynamics studies.
- Detailed monitoring of retreating debris-covered glaciers helps to identify growing natural risks (e.g. GLOFs), thus may have a very high social relevance in terms of natural hazard prevention.

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