Documentation of the Retreat of Gössnitzkees and Hornkees Glaciers (Hohe Tauern Range, Austria) for the Time Period 1997-2006 by Means of Aerial Photogrammetry

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Abstract

Gössnitzkees and Hornkees are two small cirque glaciers (2006: 58.9 and 30.6 ha, respectively) located in the Schober group of the Hohe Tauern range of the Eastern Alps in Austria. The glacier history of both glaciers has already been documented for the time period 1850-1997 based on field evidence, historical maps and aerial photographs. The temporal change in area, surface height, and volume of both glaciers was presented numerically and graphically. In this paper we intend to extend the observation period to the present. Aerial photographs of 2002 and 2006 covering the area of interest were made available by the Tyrolean regional government and the Austrian Federal Office of Metrology and Surveying, Vienna. A digital photogrammetric workflow was applied to the image data provided. Based on these multi-temporal data we computed the volumetric and areal change of both glaciers along with the respective numerical values at elevational intervals of 50 m. The change in surface height and area of both glaciers is shown in thematic maps. The results include a new orthophoto map at 1:10,000 scale representing the glacial stage of 2006 and an estimation of the equilibrium line altitude.

1. Introduction

Gössnitzkees and Hornkees („kees“ is the local name for glacier) are two neighboring cirque glaciers (46°58‘ N, 12°46‘ E) situated quite remotely in the center of the Schober group (Fig. 1). Located south of the main crest of the Hohe Tauern range, the Schober group comprises more than 30 peaks higher than 3000 m a.s.l. – the highest peak being Petzeck at 3283 m –, and 29 relatively small glaciers (mean area 0.18 km², cp. Lieb, 1987: 74). Inner-alpine continental climate prevails. Touristic and scientific interest in this mountain group has always been relatively low compared to the well-known Glockner and Goldberg group to the north, which also includes Austria's largest glacier, Pasterze. The remoteness of the area and the lack of touristically attractive large glaciers are the two main reasons why the Schober group has received little attention to date. Today the main parts of the Schober group belong to the Hohe Tauern National Park (founded in 1981).

Lieb (1987) and Buchenauer (1990) were among the first scientists to study glacial and periglacial phenomena in this mountain group. Measurements on glacier length change were commenced at Gössnitzkees by Lieb and Kaufmann in 1982, and one year later at Hornkees (for more details see Kaufmann and Lieb, 1985). Since then the terminus positions of the two glaciers have been measured annually. The Institute of Geography and Regional Science, University of Graz, is still in charge of this long-term monitoring program. Glacier reports are submitted annually to the OeAV (Austrian Alpine Club) for documentation and further analysis.

The glacier history of both glaciers was reconstructed for the time period 1850-1997 within a research project carried out by the Institute of Geography and Regional Science, University of Graz, and the former Institute of Geodesy, Graz University of Technology, with financial support of the Hohe Tauern National Park Service. The results of this project were presented and published, for example, in Kaufmann et al. (1999) and Kaufmann and Lieb (2002). The project also included the production of an orthophoto map of the two glaciers at 1:10,000 scale (for the map see Lieb, 2000) and a video film showing the workflow and results such as computer animations of glacier retreat (Kaufmann and Plösch, 2001).

The glaciers in the Schober group have been shrinking significantly due to past and ongoing atmospheric warming (climate change). According to Wakonigg (2007: 103), the mean annual air temperature in Austria has increased by 1.8° C during the observation period 1885-2003. It is expected that the glaciers in the Schober group will have disappeared by the middle of this century if the current climate continues. The small size of the glaciers, their specific topographic situation (with small accumulation areas), and their comparatively low mean altitude are factors which amplify the rate of deglaciation even further. The present study intends to continue the existing glacier history record to the present time (2006). In this context it should be mentioned that the new Austrian glacier inventory of 1998 – the first one dates from 1969 – has been published recently (Lambrecht and Kuhn, 2007). As far as the Schober group is concerned, detailed information is only available on areal changes in glaciation (1969-1998). Glacier volume loss could not be quantified due to the lack of an area-wide digital elevation model (DEM) of 1969. One of the tasks of the ongoing ALPCHANGE project, which is coordinated by the Institute of Geography and Regional Science, University of Graz, and financed by the Austria Science Fund (FWF), is to reconstruct the glacier history of the Hohe Tauern range, which also includes the Schober group (for more information please see Alpchange, 2007). The latter work is carried out in close cooperation with the Institute of Meteorology and Geophysics, University of Innsbruck (Avian, pers. comm., 2007), and it could benefit from the study presented in this paper.

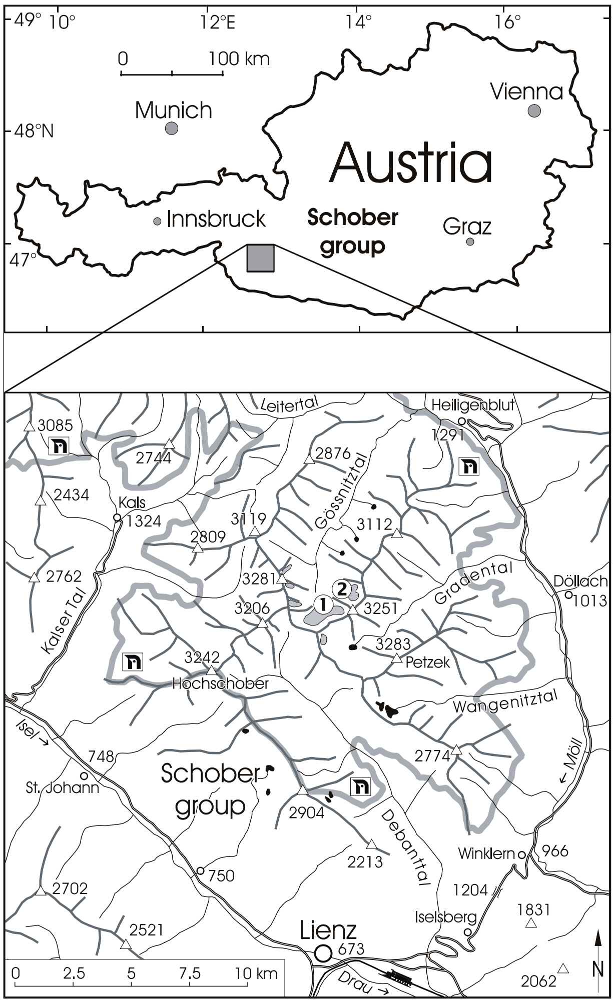

Fig. 1: Location of Gössnitzkees ① and Hornkees ② in the Schober group, Hohe Tauern range, Austria. Large parts of the Schober group are within the Hohe Tauern National Park

2. Study Area and its Glaciers

The mapping area of the present study covers the same extent as defined in the previously described glacier history project. As will be explained in more detail in the following chapter, aerial photographs of 2002 and 2006 were at our disposal. The area of interest (10.5 km², see Fig. 2) comprises not only Gössnitzkees and Hornkees but also several other smaller glaciers and at least three rock glaciers, including Weissenkar rock glacier. The Austrian glacier inventory of 1969 (as shown in Lang and Lieb, 1993) lists a total of 9 glaciers which are completely or partly located within the study area. Each glacier has a unique code number for identification but not always an official name. All of these glaciers are described in detail in Lieb (1987). Oblique aerial photographs reproduced in Lang and Lieb (1993) show very nicely the areal extent of glaciation in the mid-1980s. In 2006 only 6 glaciers were classified as glaciers by the authors of the present paper.

Glacier MO 15 no longer existed in 2006. This is also true for glacier MO 14, however, a shallow layer of debris-covered ice/firn (1.5 ha) and a small bergschrund was still visible. Kögele glacier (MO 9) was difficult to classify, since it is heavily debris-covered, and visual interpretation of the aerial photographs was hampered by low contrast. According to Kellerer-Pirklbauer and Kaufmann (2007) glacier ice still exists under the debris, preferably on the shady northern slopes.

The size of Gössnitzkees was 58.9 ha in 2006. Gössnitzkees is characterized by its distinct debris cover (over 2/3 of the area) and its seasonal proglacial lake (7095 m² in 2006). The cirque glacier is nourished mostly by avalanches coming from the steep cirque headwalls and couloirs, larger accumulation zones are missing. The coverage of Gössnitzkees at the time of 1850 (end of the so-called Little Ice Age) can be nicely traced based on the present-day photographs (see Fig. 2). Glacier area has decreased since then by 62.2%. The local distribution (layer thickness) of the supraglacial debris and the glacier surface topography (longitudinal ridges and furrows) cause differential melt of the glacier ice (cp. the terrestrial laser scanning study of Kellerer-Pirklbauer et al., 2005). Moreover, meltwater channels reshape the glacier surface, producing deeply incised meandering trenches. Since 1996 our Institute has been carrying out annual geodetic measurements in August. Two longitudinal profiles, the glacier terminus position, the areal extent of the proglacial lake, and 10 velocity markers are measured for reasons of comparison (Kienast and Kaufmann, 2004). The glacier flow velocity is rather low and ranges between 0.2 and 0.5 m a-1. Glacier surface mapping of a representative section of the glacier is also done on an annual basis applying terrestrial photogrammetry using low-cost digital consumer cameras (Kaufmann and Ladstädter, 2004). It is to be noted that a comparatively large area (2006: 3.3 ha) of the eastern extent of Gössnitzkees (located W of Gr. Hornkopf) became fully disconnected from the main glacier body at the end of the 1990s, causing an additional reduction in area and volume of the glacier.

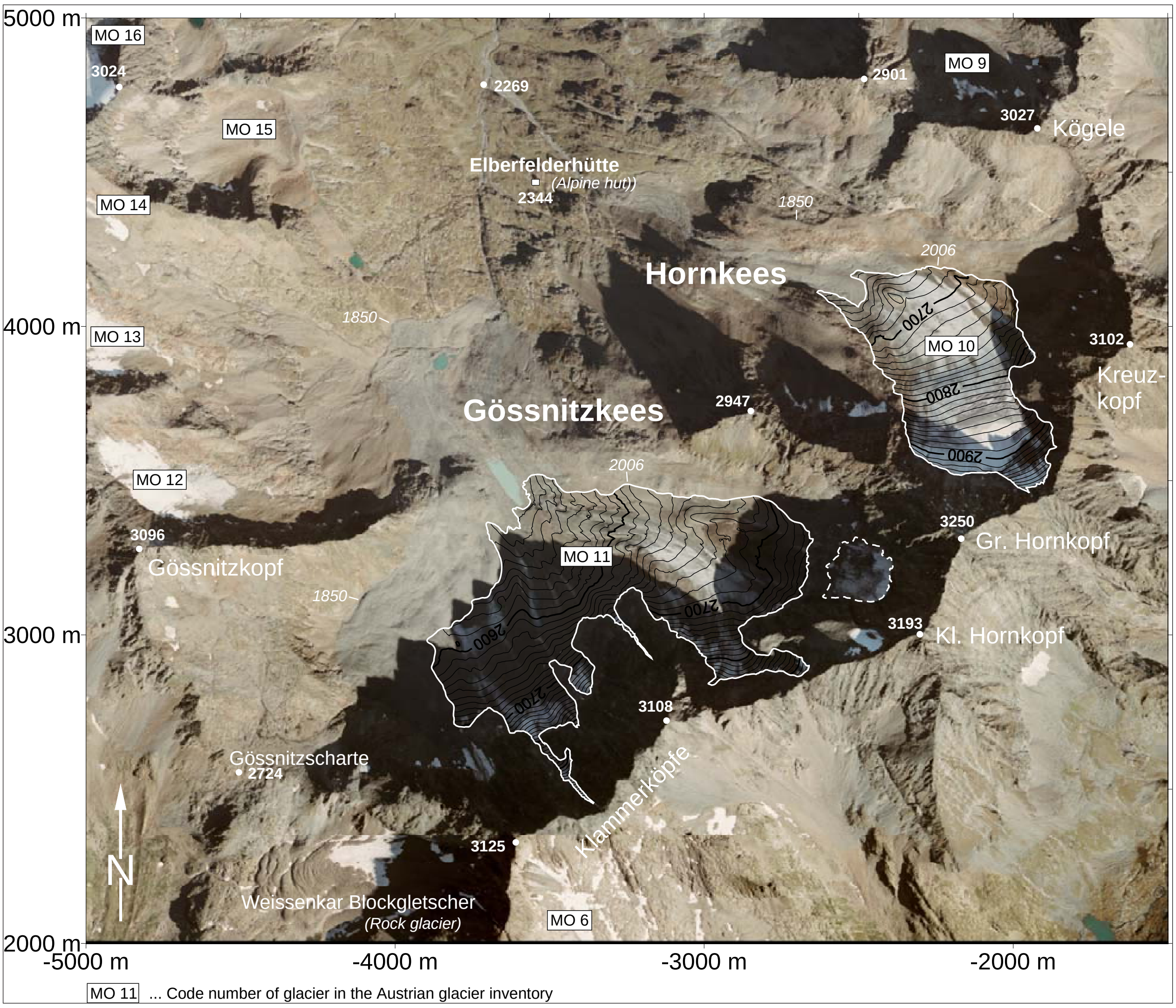

Fig. 2: Orthophoto of the study area. The color photographs forming the orthophoto mosaic were taken on September 1 and July 20, 2006 (area south of Gössnitzscharte and Klammerköpfe), respectively. Photographs © BEV, Vienna. Elberfelderhütte is a mountain hut maintained by the German Alpine Club (DAV). The letters „MO" of the glacier code numbers refer to the catchment area drained by the river Möll (cp. Fig. 1).

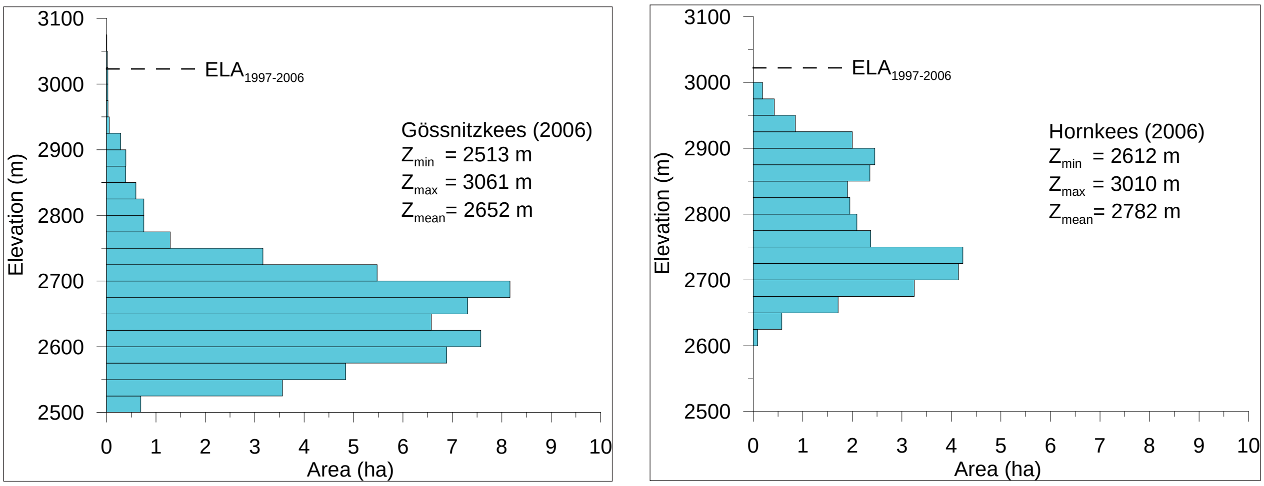

Fig. 3: Area-elevation distribution of Gössnitzkees and Hornkees for 2006. The dashed line shows the mean equilibrium-line altitude (ELA) for the time period 1997-2006.

Date of acquisition	Camera type	Mean image scale	Film type	Pixel size (μm)
September 18, 2002	Zeiss RMK TOP 30	1:14,000	color positive	15
September 21, 2006	Leica RC 30	1:15,900	color positive	15

Fig. 4: Technical parameters of the aerial photographs
Notes: In the 2006 data set, the southern part of the project area (south of Gössnitzkees and Klammerköpfe/MO 6) is covered by photographs taken on July 20, 2006. Therefore, these regions (around Weissenkar rock glacier and Klammerkees) show much more snow in the orthophoto mosaic than the main part in the north.

Hornkees, which is also a good example of a cirque glacier, covered an area of 30.6 ha in 2006. Its area-elevation relationship is more favorable in terms of future glacier survival as compared to Goessnitzkees. See Fig. 3 for comparison. Some of the prominent moraines of the 1850 glacial stage can be easily identified in the orthophoto (cp. Fig. 2). Based on the reconstruction of the maximum glacial extent given in Lieb 2000, the areal reduction in glacier size is about 66.6 % with respect to present glaciation. Debris cover on Hornkees is far less extensive than on Gössnitzkees and is limited to the border areas in the W, N and E of the glacier. Delimitation of the glacier boundary was quite difficult especially in the northern parts of the glacier.

3. Aerial Photographs of 2002 and 2006

The basis of the present study are digitized metric aerial photographs provided by the Tyrolean regional government and the Austrian Federal Office of Metrology and Surveying, Vienna. The technical parameters of both data sets are given in Fig. 4. The color photographs were taken more or less at the end of the hydrologic/balance year and are thus ideal for glaciological studies. Moreover, there is no snow cover except for some perennial snow patches. The long cast shadows visible in both data sets are due to the acquisition time late in the year and, most of all, due to early flights in the morning.

4. Photogrammetric Mapping

In the preceding (glacier history) project the photogrammetric work, i.e. aerotriangulation and feature extraction, was still done on an analytical plotter based on analog photographs (for technical details see Kaufmann et al. 1999). This time we pursued a digital photogrammetric workflow using a digital photogrammetric workstation from Intergraph.

4.1. Photogrammetric orientation

The elements of exterior orientation of all photographs were additionally provided by the owner of the photographs. Since the aerotriangulation of the preceding project was carried out in a local coordinate system (approximate to the Austrian Gauss-Krüger coordinate system), we finally decided to keep this local coordinate system as a reference in order to avoid time-consuming data conversions and recalculations. For the sake of simplicity, a set of evenly distributed stable ground control points, which had already been used for image orientation in the preceding project, were measured in the 2002 and 2006 stereo models. Coordinate offsets of the 1997 system to the other two "georeferenced" systems were determined. No significant planimetric shift was detected between the local system and the given photogrammetric, i.e. Gauss-Krüger, coordinate systems. However, two different systematic offsets in height were detected and appropriately taken into account for height adjustment.

4.2. Feature extraction

The primary goal of the photogrammetric mapping workflow was (1) to obtain high-resolution DEMs of Gössnitzkees and Hornkees for the two epochs 2002 and 2006, and (2) to update the DEM of 1997 for orthophoto production. The first step was to update the photogrammetric manuscript of 1997 to generate a new one for 2006. This was accomplished interactively using stereoscopic vision at the digital photogrammetric workstation. 3D superimposition made it possible not only to check the perfect geometric fit of the 1997 data against the 2002 and 2006 terrain situation but also to detect areas where surface height change had occurred, for example, areas which were snow-covered in 1997 and, of course, areas affected by glacier melt. As already mentioned, data capture and editing was done interactively. Continuous contrast enhancement was indispensable in dark areas (shadow areas) and also in bright areas (glacier surfaces). For the convenience of the photogrammetric operator, the mapping area around Gössnitzkees and Hornkees was limited by the glacier boundary of 1997. The digital manuscripts comprise contour lines, ridge lines, drainage lines and spot heights. The glacier boundaries of Gössnitzkees and Hornkees were traced in a second step.

4.3. Delimitation of the glacier boundaries

As already indicated previously, the tracing of the boundaries of a debris-covered glacier may be troublesome or sometimes even impossible, not only in nature but also in photographic stereo models. When superimposing the 3D map of 1997 onto the more recent stereo models it was found that the delimitation of the glacier boundary of Goessnitzkees was slightly wrong in two areas. The 1997 glacier boundary could only be drawn approximately because delimitation was made difficult both by a uniform debris mantle and the absence of topographic evidence of underground glaciation. It should be noted that slopes with shallow glaciation or with dead ice, or sliding zones near recently deglaciated areas can also complicate the delimitation of debris-covered glaciers.

Assuming substantial glacier retreat (as observed in recent times), the glacier boundary of a certain glacial stage can be cross-checked or drawn in a supervised manner using the surface height information of a younger stage. If the glacier is growing and surface height is therefore increasing, the surface data of the previous (older) glacial stage can be used to immediately check the glacier boundary of the younger stage. However, the previous (minimum) glacial stage cannot be controlled in this specific case of glacier development.

In general, the intersection of the (modified) glacier surface with the stable terrain defines the (sometimes invisible) glacier boundary. This fact can be utilized interactively using a digital photogrammetric workstation, or, which is more convenient, off-line, by overlaying the contours of both stages derived from the respective DEMs. This procedure has already been successfully applied in the preceding project using transparent analog manuscripts and a light table. Following this general procedure, the glacier boundaries of 1997 could be updated appropriately, and the boundaries of 2002 could be traced with confidence. The glacier boundaries of the 2006 stage can only be cross-checked with upcoming topographic height information of a younger stage, presuming that glaciers continue to retreat. The requested height information can be provided either by another aerial survey or by airborne laser scanning (cp. Würländer et al., 2004). Terrestrial means of 3D surface data acquisition are also possible, such as tacheometry, terrestrial laser scanning, or terrestrial photogrammetry (references have already been given previously).

4.4. Glacier masks and digital elevation models

Glacier masks (binary images) and digital elevation models of both glacial stages, 2002 and 2006, were produced as a basis for analysis of glacier change in area and volume. As for the glacial stage of 1997, the already existing DEM of 1997 was adopted, but a new glacier mask had to be derived from the corrected glacier boundary polygon discussed in the previous section. DEMs were computed using the program Terrain Analyst of Intergraph. For the ease of further processing, raster-based DEMs with a grid-spacing of 2.5 m were derived from the primary TINs (triangulated irregular networks). Binary masks with a GSD of 2.5 m were derived from vector data (dxf-Autocad) defining the glacier areas.

4.5. Orthophotos

Finally, four aerial photographs of each epoch were needed to completely cover the study area. Orthorectification was accomplished using the software BaseRectifier of Intergraph. I/RAS C of Bentley/Intergraph was used as a mosaicking tool. Contrast and color balancing of the individual orthorectified photographs to be merged in a single orthophoto mosaic was quite difficult for both epochs, because some of the aerial photographs of 2002 had a red tint, and those of 2006 were taken in two different seasons of the year. The problem was best solved interactively using Photoshop. Orthophotos with a GSD of 0.25, 0.5, 1, and 2 m were provided for further analysis and visualization purposes.

5. Quantification of Glacier Change

Data evaluation was performed serving glaciological questions (cp. Fountain et al., 1997; Haeberli et al. 1998; Orlemanns, 2001; Kaser et al., 2003). Glacier change in area and volume was calculated using an in-house developed computer program (for more details see Kaufmann and Plösch, 2000). A similar computer program was used for the new Austrian glacier inventory of 1998 (cp. Lambrecht and Kuhn, 2007, Würländer and Eder, 1998). Volumetric change was quantified for (1) areas which became ice-free, (2) permanently ice-covered areas, and (3) newly ice-covered areas. Information concerning area and surface height change was also provided in elevational bands, e.g.,

	Gössnitzkees		**Hornkees**	
Period	**Change in area (ha)**	**Change in area (ha a-1)**	**Change in area (ha)**	**Change in area (ha a-1)**
1850/1873	-9.45	-0.41	-7.21	-0.31
1873/1929	-13.82	-0.25	-13.92	-0.25
1929/1954	-35.01	-1.40	-26.58	-1.06
1954/1969	-4.01	-0.27	-1.70	-0.11
1969/1974	-3.35	-0.67	-0.51	-0.10
1974/1983	+0.24	+0.03	-0.45	-0.05
1983/1992	-11.87	-1.32	.	.
1992/1997	-2.61	-0.52	-5.20 (1983/97)	-0.37 (1983/97)
1997/2002	-12.32	-2.46	-3.10	-0.62
2002/2006	-4.48	-1.12	-2.38	-0.60
1850/2006	-96.68 (-62.2 %)	-0.62	-61.03 (-66.6 %)	-0.39

Fig. 5: Changes in area of Gössnitzkees and Hornkees since 1850.
Notes: The changes in area are given in hectares (ha = 0.01 km²); annual values were calculated by simply dividing the area by the number of years; evaluation of the entire Hornkees glacier was not possible for the 1992 stage. Numerical values for the period 1850-1997 are taken from Kaufmann and Lieb, 2002. Note that the values for Gössnitzkees covering the period 1992/1997 have been updated.

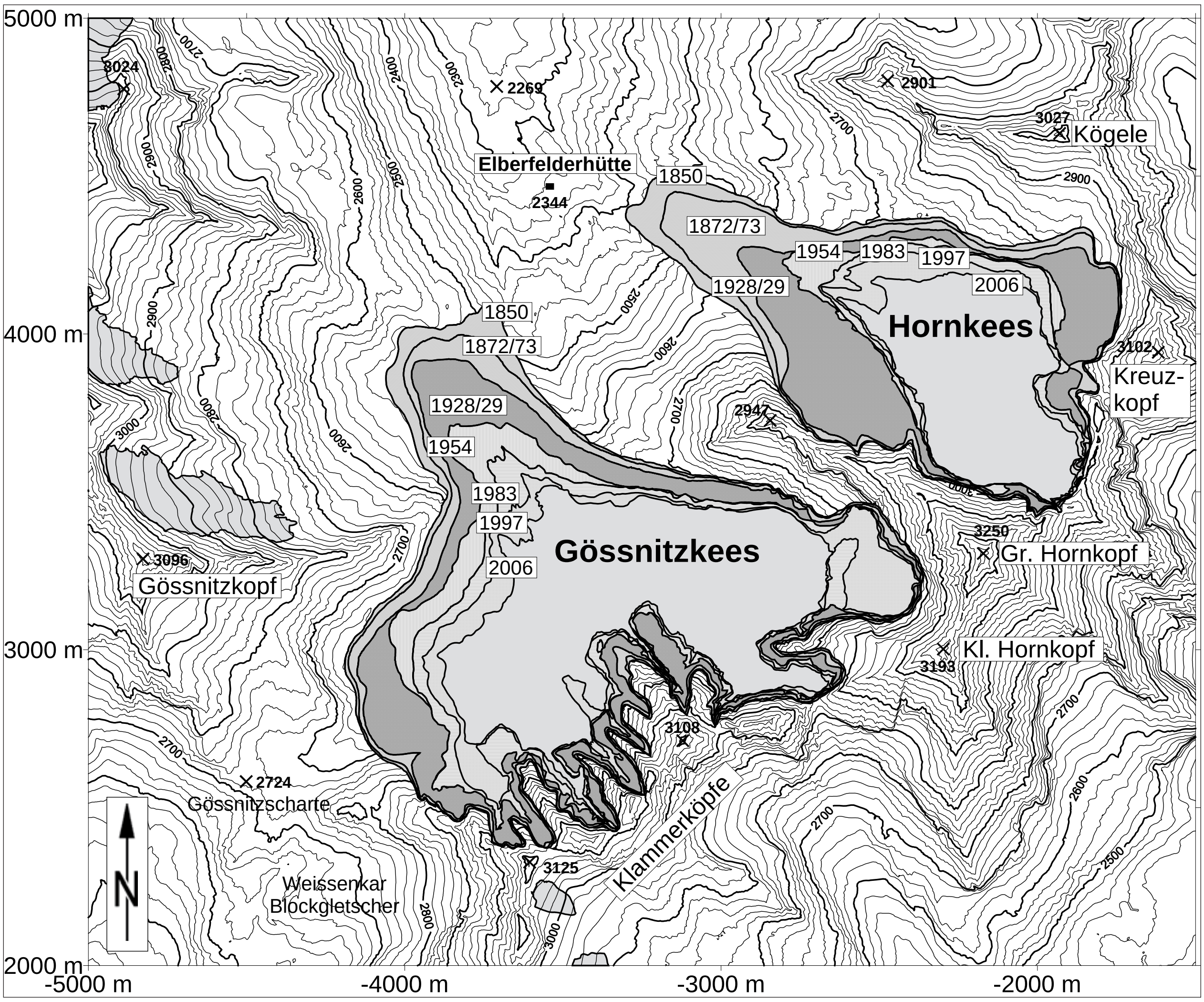

Fig. 6: Thematic map showing the changes in area of Gössnitzkees and Hornkees since 1850.

Period	Gössnitzkees		Hornkees	
	Volumetric change (106 m³)	**Volumetric change (106 m³ a-1)**	**Volumetric change (106 m³)**	**Volumetric change (106 m³ a-1)**
1850/1873	-11.98	-0.52	-7.80	-0.34
1873/1929	-17.08	-0.31	-12.63	-0.23
1929/1954	-30.65	-1.23	-12.49	-0.50
1954/1969	-3.09	-0.21	-0.40	-0.03
1969/1974	-2.49	-0.50	-0.36	-0.07
1974/1983	+0.55	+0.06	+0.87	+0.10
1983/1992	-8.83	-0.98	.	.
1992/1997	-3.93	-0.79	-5.35 (1983/97)	-0.38 (1983/97)
1997/2002	-3.83	-0.77	-1.87	-0.37
2002/2006	-3.11	-0.78	-1.55	-0.39
1850/2006	-84.52	-0.54	-41.61	-0.27

Fig. 7: Changes in volume of Gössnitzkees and Hornkees since 1850.

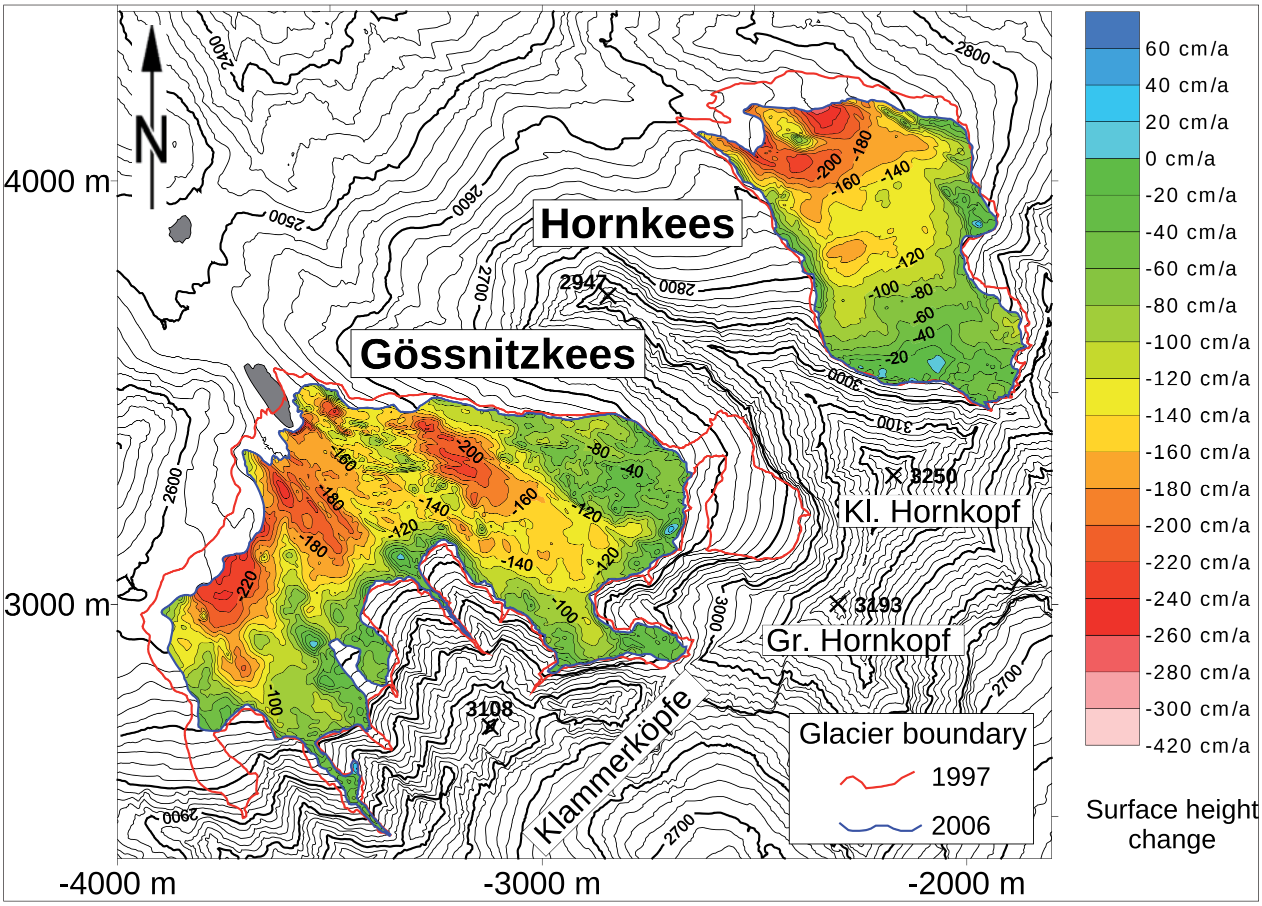

Fig. 8: Thematic map showing the mean annual surface height change of Gössnitzkees and Hornkees for the period 1997-2006.

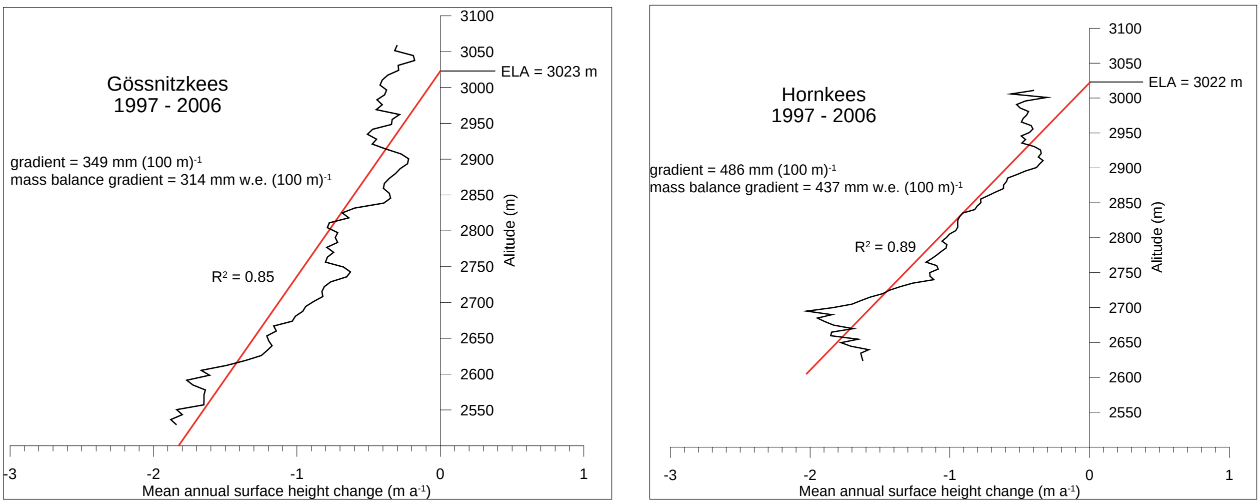

Fig. 9: Estimation of the equilibrium line altitude (ELA) for Gössnitzkees and Hornkees for the time period 1997-2006.

at intervals of 10, 25, 50, and 100 m. Numerical values were also given in relative numbers (%) and in cumulative notation for reasons of comparison. The listings and tables also include the specific net mass balance in water equivalent (w.e.). Finally, the whole glacier history of both glaciers comprising 11 glacial stages between 1850 and 2006 was re-calculated applying one single batch job obtaining all information for selective analysis by the glaciologist.

6. Results

In this paper we will present some of the most important results obtained numerically and/or graphically.

6.1. Glacier change in area

Gössnitzkees covered an area of 75.7 ha in 1997, 63.3 ha in 2002, and 58.9 ha in 2006; the corresponding values for Hornkees are 36.1 ha, 33.0 ha, and 30.6 ha, respectively. Fig. 5 lists the changes in area of both glaciers since 1850. Both glaciers have already lost almost 2/3 of their areal extent since 1850 (cp. Fig. 6).

6.2. Glacier change in volume

From a glaciological point of view, glacier change in volume is of great importance since it directly reflects glacier mass balance. The numbers given in Fig. 7 show the volumetric changes of both glaciers since 1850. The values given can be converted to specific net mass balances. Both glaciers have continuously retreated since the early 1980s. Fig. 8 and 9 confirm that the glaciological situation for both glaciers is quite dramatic. The mean annual vertical surface height change profile (i.e. vertical mass balance profile) was negative for all elevational zones for the period 1997-2006. This means that the accumulation zone has practically disappeared, and the whole glacier area is affected by ablation. The two glaciers are completely out of balance.

Annotations: See Fig. 5.

6.3. Estimation of ELA

The equilibrium line altitude (ELA) for the time period 1997-2006 was estimated at c. 3020 m for both glaciers by linear regression (cp. Fig. 9).

6.4. Scenario for the future

Based on the estimated mean ice thickness and the calculated mean annual surface height change (1997-2006) Gössnitzkees will probably be completely melted by 2033 and Hornkees by 2029.

7. Conclusions

In the present study the existing glacier history (1850-1997) of Gössnitzkees and Hornkees was updated by two additional glacial stages, 2002 and 2006, thus finally covering a time span of 156 years. 3D feature collection for deriving glacier DEMs and glacier boundaries was performed interactively. Strong cast shadows in the aerial photographs provided were a challenge for the photogrammetric operator. Delimitation of the glacier boundaries in the debris-covered areas would have been more difficult or even impossible without combined analysis of the available data, especially of the multi-temporal DEMs. Numerical values of glacier change in area and volume are presented. Ongoing glacier retreat suggests that both glaciers will vanish around 2030. This implies that all other glaciers of the Schober group will share the same fate, sooner or later.

Acknowledgments

Aerial photographs of 2002 (© Amt der Tiroler Landesregierung, Innsbruck, 2004) were given free of charge by the Tyrolean regional government with the help of H. Gspan. Aerial photographs 2006 © Austrian Federal Office of Metrology and Surveying, Vienna.

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