Reconstruction and visualization of the retreat of two small cirque glaciers in the Austrian Alps since 1850

From static maps towards dynamic computer animation

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Zusammenfassung

In diesem Beitrag wird die Rekonstruktion und Visualisierung des Gletscherrückganges von zwei Kargletschern (Gößnitz- und Hornkees) der Schobergruppe (Hohe Tauern, Österreich) seit dem neuzeitlichen Hochstand von 1850 erörtert. Die Ausführungen beziehen sich auf ein Forschungsprojekt, welches gemeinsam vom Institut für Angewandte Geographie der Universität Graz und vom Institut für Angewandte Geodäsie der Technischen Universität Graz ausgeführt und vom Kärntner Nationalparkfonds finanziell unterstützt wurde. Die Rekonstruktion des Gletscherhochstandes von 1850 erfolgte anhand von Ufermoränen. Alte Karten wurden zur Rekonstruktion der Stände von 1873 und 1929 herangezogen, wohingegen Luftbilder für die jüngeren Stände (1954, 1969, 1974, 1983, 1992 und 1997) photogrammetrisch ausgewertet wurden. Die Rekonstruktionsergebnisse der einzelnen Gletscherstände wurden in einer digitalen Datenbasis, welche (1) digitale Geländemodelle, (2) Gletschergrenzen bzw. –flächen, (3) Orthophotos und (4) Zusatzinformationen umfaßt, für weiterführende glaziologische und kartographische Arbeiten bereitgestellt. Die numerische Auswertung ergab u.a., daß das Gößnitzkees 51% und das Hornkees 61% seiner Fläche seit 1850 verloren hat. Die entsprechenden Volumenverluste sind 77,5 Mill. m³ bzw. 38,2 Mill. m³. Die Visualisierung der einzelnen Gletscherstände sowie des Gletscherrückganges umspannt die breite Palette der kartographischen Darstellungsmöglichkeiten (Orthophotokarte, Schichtlinienplan, Axonometrie, thematische Karte) bis hin zur Computer-Animation, wo der Gletscherrückgang als kontinuierlicher Prozeß synthetisiert wurde. Zum gestellten Thema liegt ein Videofilm vor.

Summary

This paper describes the reconstruction and visualization of the retreat of two small cirque glaciers since the Little Ice Age advance of 1850. The two neighboring glaciers, Goessnitzkees and Hornkees, are located in the Schober group (Hohe Tauern range, Austria). The detailed explanations refer to a research project which has been carried out by the Institute of Geography (University of Graz) and the Institute of Applied Geodesy (Graz University of Technology) with financial assistance from the Hohe Tauern National Park Service. On the basis of prominent moraines (1850), old maps (1873, 1929) and metric aerial photographs (1954, 1969, 1974, 1983, 1992, and 1997) 9 glacial stages of the recent history of the glacier were reconstructed. All relevant data are stored in a digital database (for glacier studies) which is composed of 4 layers, i.e., digital terrain model, glacier boundaries/masks, orthophotos, and collateral information. A comprehensive spatial-temporal analysis of the given time series was performed using the digital database. The evaluation reveals, e.g., that the surface areas of Goessnitzkees and Hornkees have decreased by 51% and 61%, respectively, since 1850. The corresponding reduction in volume amounts to 77.5 mill. m³ and 38.2 mill. m³. Furthermore, the digital database is also the data source for subsequent cartographic work, i.e. the visualization of glacier retreat. The presented examples of visualization cover traditional maps, e.g., orthophoto maps, contour line maps and thematic maps, and also modern techniques of computer animation. The latter has been implemented in a "glacier movie" which presents the glacial retreat as a continuous process over space and time.

1 Introduction

Scientific analysis of the glacier history of two small cirque glaciers (Goessnitzkees and Hornkees) was carried out in the framework of a research project (1996-1998) funded by the Hohe Tauern National Park, Austria. The Institute of Geography (University of Graz) was in charge of the project coordination (project leader G.K. LIEB) and the glaciological work, whereas the Institute of Applied Geodesy (Graz University of Technology) was responsible for the mapping and computing tasks. The main issue of the project was to quantify the areal and volumetric changes of the two glaciers from 1850 to 1997 with the highest possible temporal and spatial resolution. Details on methodology, practical implementation and results of the respective project are given in the final report (KAUFMANN, KROBATH, LIEB & SULZER 1999). Selected topics, e.g., photogrammetric mapping, orthophoto production and preliminary quantification of glacial retreat, are also discussed in KAUFMANN & LIEB 1998.

The scope of this paper is to highlight some aspects of mapping and visualization of time series of glacial stages and to present some practical results based on the data derived in the previously mentioned project.

1.1 Objectives

The geometric state (area, surface topography, etc.) of a glacier and its temporal change is best shown in images, which may be presented in analogue or digital form. The possibilities are manifold, as reported in literature (HÄBERLING 1998 and KÄÄB 1998), regarding the coding of the third dimension (height) and the fourth dimension (time). A visualization may be either *static* (one single frame shows the whole information content) or *dynamic*, where a sequence of frames is shown one after the other, e.g. at a video rate of 25 Hertz or at a comparatively low rate, comparable to the childhood flick book toy where a series of images seen in rapid succession present an animated cartoon of Mickey Mouse jumping up and down. This latter process is referred to as *animation*. Concerning height information we have the choice of presentations in 2D (no height information at all), 2½D, or even 3D (cp. BUCHROITHNER & KIRSCHENBAUER 1998).

In our understanding the aim of visualization should primarily be of a qualitative nature, at least in glacier studies. This implies that these visualizations are not used for measuring geometric properties, such as distances, areas, volumes, or their respective changes. Since we are working with digital models in a computer-based environment, quantitative analysis of spatial-temporal relations must be performed numerically using the original data set. Modern techniques of visualization (good overview in MACEACHREN & TAYLOR 1994) should be stimuli for new directions in providing the interested observer with glacier-related information.

1.2 Description of the study area

Goessnitzkees and Hornkees ("Kees" is the local name for glacier), both typical representatives of small cirque glaciers, are located in the Schober group, which belongs to the Hohe Tauern range (Eastern Alps) in Austria (Fig. 1). Both glaciers are labeled as *MO 11* and *MO 10*, respectively, in the Austrian glacier inventory. The Schober group is characterized by a rough topography with steep rock faces, narrow crests and lack of flat surfaces at high elevations. This is why the mean size of the glaciers in this area is less than 0.2 km². Avalanches typically cause a great amount of snow accumulation on both glaciers, whose lower parts are marked by a dense debris cover (see Fig. 2). More information on the geographical setting of the glaciers is given in LANG & LIEB 1993, and also in KAUFMANN & LIEB 1998.

Fig. 1: Location of the study area in Austria

Fig. 2: Computer-generated perspective view of the study area with Goessnitzkees (1) and Hornkees (2)

2 Reconstruction of the glacial stages

2.1 Glacial stages of 1850, 1873 and 1929

LANG & LIEB 1993 describe the possibilities of reconstruction of older glacial stages. They also give good examples (located in Carinthia, Austria) and discuss the pros and cons. In this project the glaciologist had to rely on field evidence, such as terminal and lateral moraines, and on two old maps. The areal extent of the 1850 stage was reconstructed quite well with the help of the Little Ice Age moraines, whereas the precise dating of the "maximum extent of 1850" was not feasible. The temporal uncertainty may be plus/minus several years. Due to the lack of other historical documents, e.g., text sources or maps, describing or showing the surface topography, the reconstruction of the glacier surface based on contour lines had to be done hypothetically using longitudinal transects and cross-sections. The first cartographic document showing the two glaciers is dated with 1872/73 (Fig. 3). The reconstruction of the 1873 stage follows the previously outlined procedure. The "Austrian Map" 1:25,000, sheet 179/2 North, of 1928/29 shows contour lines and glacier boundaries of good quality (Fig. 4) for the first time. This map content was integrated with minor corrections. The 1:5,000-scale photogrammetric manuscript of the year 1997 (cf. next section) served as a topographic reference, not only for the 1850 stage but also for the two other younger glacial stages. In fact, the reconstruction of the 3 glacial stages was an iterative procedure ending up with quite realistic and geometrically consistent results.

Fig. 3: Clip of the "Sektionsblatt" 1:25,000, sheet 5249/2, showing Goessnitzkees and Hornkees. Mapping year 1872/73. In this map Hornkees is referred to "Klamm Kees". Reproduction not to scale.

Fig. 4: Clip of the "Austrian Map" 1:25,000, sheet 179/2 North, showing Goessnitzkees and Hornkees. Mapping year 1928/29. Reproduction not to scale.

2.2 Glacial stages of 1954 - 1997

The reconstruction of the other younger glacial stages of 1954, 1969, 1974, 1983, 1992, and 1997, is based on the evaluation of aerial photographs (Tab. 1) which were obtained from the Austrian Federal Office of Metrology and Surveying on the one hand and acquired during an additional aerial survey in 1997, on the other hand. Aerotriangulation and photogrammetric mapping at 1:5,000 scale was carried out using the analytical plotter DSR-1 of Kern. The delimitation of the glacier boundaries was occasionally hampered by the lack of geomorphologic evidence resulting from the uniform debris cover on glaciated and ice-free areas in some places. However, glacier boundaries can be easily validated and corrected, if necessary, by overlaying appropriate contour line plots of successive glacial stages. Only the youngest glacial stage of 1997 cannot be controlled absolutely in its areal extent since the true topography of the glacier bed is not known beforehand. Such control is only possible with a more recent aerial survey under the assumption of continuous glacial retreat. In general, the inhomogeneous disintegration of glacier ice at the outer limits of the glacier often generates hummocky areas with dead ice in it. In these areas the glacier limits are difficult to draw. Another problem was encountered especially in the higher elevations where high albedo of snow covering the glacier surface prevented proper stereoscopy and therefore drawing of contour lines. To a certain extent "moving shadows" caused some minor problems in relief perception. Additional information concerning photogrammetric mapping can be found in the final report of KAUFMANN et al. 1999 mentioned above.

3 Digital database for glacier studies

This chapter deals with the elements and specifications of a digital database for glacier studies as implemented in the present study. In principle, the database should contain at least 4 different layers as shown in Fig. 5. Additional layers, e.g., containing photogrammetric manuscripts (".dxf",".dwg" or ".dgn"), rectified satellite images, digital terrain models as triangulated irregular network (TIN), value-added products, etc., can be added easily. All elements of the various layers should refer to a common three-dimensional (3D) cartesian coordinate system and should have a unique time tag T representing the temporal domain. With these assumptions the spatial-temporal analysis of one or more glaciers (2 in our case) located within a rectangular area, i.e. the study area, is straight forward and can be completely automated using standard GIS packages (cp. VOLK and KOLEM 1998) or in-house developed software. In the present glacier study the digital database was organized using appropriate file names and working directories, which is sufficient for a small project like this one. The set-up of the digital database for the concrete project will be given in the following subsections.

Fig. 5: Layer structure of the digital database for glacier studies

3.1 Digital terrain model

The digital terrain model (DTM) is a prerequisite for the anticipated spatial-temporal glacier analysis (cp. RENTSCH et al. 1990, KERSTEN & MEISTER 1993, SCHÖNER 1996) and also for orthophoto production. After an editing phase using AutoCad 14 and MicroStation 95, consistent 3D graphical data sets of all 9 glacial stages were obtained. High-resolution DTMs with a grid spacing of 2.5 m were derived using the software "MGE Terrain Analyst" of Intergraph (in fact, a TIN was first computed and afterwards gridded). The study area covers a rectangular area of 10.5 km² and includes both glaciers. Each DTM consists of 1200 lines and 1400 columns of height data. In order to save disk space the height values are stored using only 2 bytes, which allows a height resolution of 1 dm. This adds up to a total disk space of 3.2 MB for each DTM.

3.2 Glacier boundaries

The areal extent of the glaciers is described by closed polygons. In the case of the three oldest glacial stages height data for each vertex of the polygons was interpolated from the respective DTM. In order to be consistent with the computed DTMs the photogrammetrically derived *z*-values of the polygons were also replaced by the respective height values of the DTM. In a further step the areas defined by the polygons were gridded to fit the pixel geometry of the DTM. As a result we obtained binary *glacier masks* with 0.2 MB allocated disk space each. If we want to analyze each glacier of the study area separately, a corresponding glacier mask must be generated additionally. Moreover, the use of glacier masks facilitates the evaluation of "islands", i.e. ice-free areas within the glacier limits.

3.3 Orthophotos

The digital database for glacier studies should also include multi-temporal orthophotos because of three reasons: (1) it allows detailed photo interpretation of glaciological, periglacial and other geomorphologic features, e.g., crevasses, firn line, perennial snow patches, ice lakes, landslides, avalanches and many more; (2) in addition to orthophoto maps, secondary products, such as axonometric/perspective views or stereo-orthophotos can be produced (see KAUFMANN 1996); (3) tandem orthophotos, i.e., 2 orthophotos derived from a stereopair or 3 orthophotos derived from a stereotriplet, can be used to improve the existing DTM and to derive 3D deformation/flow vectors by means of modern techniques of digital photogrammetry, e.g. point transfer based on least-squares-matching.

The latter reason refers to a future high mountain long-term monitoring system, fully based on digital photogrammetry. The basic ideas have already been outlined by KAUFMANN 1998. Recently, a prototype version has been implemented by LADSTÄDTER 1999 for monitoring rock glaciers. He could prove that the system also works on debris-covered glaciers, such as Goessnitzkees (see Fig. 5).

3.4 Collateral information

The fourth layer comprises project-relevant parameters and descriptions, i.e. non-graphical information, which is needed for proper interpretation of all other layers in the course of immediate and future evaluations. General parameters define the limits of the study area, the geometric properties of the cartographic projection, the various spatial resolutions (pixel size and grid spacing), and possible co-ordinate offsets and scaling factors. Most important, this layer should hold numbers for the assessment of the relative (inner) and absolute (outer) accuracy of each multi-temporal element. These numbers are needed for calculating the error budget (cp. SCHÖNER 1996 and KAUFMANN et al. 1999) of derivatives, e.g. volumetric changes. Absolute accuracy refers to the geometric datum, which generally is a result of photogrammetric orientation (model set-up or aerotriangulation, both using control points). In his database, LADSTÄDTER 1999 also included information for each tandem orthophoto, such as focal length and the elements of outer orientation of the photograph used for the generation of the orthophoto, and the source of the DTM. The descriptions are supposed to be a loose collection of text files, progress reports, and computer listings.

4 Quantification of glacier retreat

In a first attempt, "Idrisi for Windows", a raster-based GIS from Clark University, was used to numerically explore the existing database. With the help of Idrisi Macro Language (IML) the areal and volumetric changes of Goessnitzkees and Hornkees were computed. This also included tables of respective values for successive height intervals, e.g. 50 m, as needed by glaciologists. However, subsequently a more dedicated software was written (in Fortran programming language) in order to better address the wide scope of requirements, i.e., glaciological questions, cartographic needs, output formats (readable listings and tables), batch processing, and computing speed. Through intensive "data mining" all relevant glaciological parameters describing each glacial stage and the respective changes were computed (for details see KAUFMANN et al. 1999). Changes in volume and surface height according to elevational intervals were determined stringently as explained in REINHARDT & RENTSCH 1986 and SCHÖNER 1996. For reasons of comparison the classical methods of FINSTERWALDER 1953 and HOFMANN 1958 were also implemented. In short, the quantification of glacier retreat is shown in Tab. 2 and Tab. 3. Referring to Tab. 2, Goessnitzkees has lost 52% and Hornkees 61% of their respective surface areas since 1850. Other results, shown in tables and graphs, as well as a comprehensive glaciological interpretation (given by LIEB) can be found in KAUFMANN et al. 1999 as well as in LIEB 2000.

5 Visualization of the glacial stages in a static mode

Within the framework of the glacier study an orthophoto map "Gößnitz- und Hornkees, Schobergruppe" at 1:10,000 scale was published in order to show the present glaciation. A copy of the black-and-white combined image-line map can be found in LIEB 2000. Technical notes on the map generation (using CorelDraw 6.0) are given in the final report mentioned above. This orthophoto map also includes a computer-generated perspective view (Fig. 2) of the study area (for reasons of comparison see LANG & LIEB 1993, Fig. 36, 38 and 40, which show oblique areal photographic views in color). Various possibilities exist for the visualization of single glacial stages (cp. HÄBERLING 1998). Since the production of most of the (traditional) maps – this also includes the above mentioned orthophoto map – is quite time-consuming and cost-intensive, alternative solutions have to be found, especially, if a time series of many glacial stages has to be presented cartographically. We used the low-cost grid-based graphics program SURFER as a cartographic authoring tool. SURFER offers the possibility to import, merge and visualize all digital data of the glacial database.

A more challenging task was to come up with thematic maps showing the spatial-temporal changes of both glaciers. We will present 2 thematic maps (Fig. 6 and Fig. 7) from the variety of experimental maps produced. The first map is a black-and-white version showing the temporal change in area of both glaciers. A mapping scale of 1:20,000 was selected for printing on A4-sized paper. In order to keep the map readable the most important glacial stages, at least from a glaciological point of view, were selected. The relief of the surroundings of the glaciers is shown using contour lines, which were re-interpolated from the DTM of 1997. A modification of this map also includes lines indicating selected longitudinal and cross profiles of the glacier in order to visualize the vertical change of surface height of the glaciers in separate profile plots (shown in KAUFMANN et al. 1999). The second map is a color-coded thematic map showing the elevational change of the glacier surfaces for the time period 1850-1997. The legend of Fig. 7 also includes positive values since the same layout allows all other combinations of glacial stages to be visualized by just substituting the respective input files. Further cartographic variations show, e.g. annual values of vertical change in ice thickness over the permanently glaciated areas of both stages. The simultaneous presentation of elevational changes of more than one time period in a single static map (image) is questionable (cp. KÄÄB 1998).

Fig. 6: Thematic glacier map showing the change in area of Goessnitzkees and Hornkees since 1850

Fig. 7: Thematic glacier map showing the change in ice thickness of Goessnitzkees and Hornkees since 1850

6 Visualization of the glacial stages in a dynamic mode

Computer animation is used to visualize dynamic processes (good overview is given in WATT 1992). In contrast to computer simulation, where mathematical models provide numerical results, i.e. geometric properties are measurable, animation focuses on the graphical display of these results for visual perception (cp. section 1.1). Therefore data accuracy is not of prime importance. Furthermore, the amount of data has to be limited in order to keep the data manageable and processing time low.

In the present study the dynamic change of glaciation has to be shown in a time-accelerator. All necessary data for this type of visualization is available through the digital database. The grid spacing of the DTMs has been increased to 15 m by means of averaging over a 6 by 6 window. Since only 9 glacial stages are available, irregularly distributed over the whole time period of 147 years, other intermediate glacial stages have to be interpolated from them, either based on a scientific glacier flow model (WAGNER 1996) or any other simplified geometric model. The first refers to computer simulation, whereas the second is adequate for the proposed task, especially because there was no theoretical glacier flow model available, at least for this type of small cirque glacier. In short, appropriate wireframe models (Fig. 5) of the surfaces can be generated on the basis of the DTMs. Any other "in between" glacial stage must be linearly interpolated in vertical direction in respect to the given time mark. The computation of this dynamic (glacier) model was accomplished by the interpolation module of the animation software (Tab. 4). For the visualization the software computes images of the 3D model for the pre-defined time interval, i.e. the frame rate. The latter depends on the media used for presenting the animation, e.g. 25 frames/sec for PAL video, and it also defines the total amount of frames for a single animation sequence, e.g., 10 sec of animation require 250 (= 10 times 25) frames. The visualization does not only need the dynamic geometric model as input but also information on illumination and surface properties of the 3D object, both the glaciated and non-glaciated area. The animation software allows the selection of an appropriate light source, which can be positioned anywhere in the virtual space. The light source produces shades based on a Phong reflection model and, moreover, the relief of the surface casts shadows, which increase the visual perception of the 3D scene content. Surfaces are also associated with material properties, i.e. either procedural or mapped shaders. Glaciers are shown using procedural shaders, i.e. without texture in cyan color, and non-glaciated areas are mapped by means of a draped digital image, i.e. the orthophoto of 1997 with a spatial resolution of 1 m. Once all those settings have been defined, a virtual camera can be positioned in the scene (Fig. 8). Finally, the rendering program calculates all frames within the specified time lapse as seen from the camera position. Each frame is stored in a single file, and subsequently transferred to a mass storage, i.e. a harddisk recorder. Animated sequences or even individual frames can be retrieved from this recorder, e.g. for producing a video film. Since the video resolution of 720 by 576 is not sufficient for high-quality printouts, higher resolution renderings are necessary for this purpose (see Fig. 9).

The association with time in the animation is achieved visually by an inserted animated icon, i.e. a digital clock counting the years, like a mileage indicator in a car. In fact, an educational video film "glacier movie" has been produced which covers the scope of this paper and, as a highlight, shows the retreat of both glaciers as a very realistic animation. The chosen monotonic sound track to the animation intensifies quite well the visual impression of the continuous glacier retreat. Short sequences of the computer animation can be downloaded from `http://www.cis.tu-graz.ac.at/photo/viktor.kaufmann/`.

Fig. 8: Scheme of the rendering process

Fig. 9: Single frame of the computer animation produced by rendering

7 Conclusion and outlook

The aim of this presentation was to convey methods in reconstruction and visualization of the glacier history of two solitary glaciers in the Austrian Alps since 1850. Ongoing global warming will definitely change our climate. In order to study climatic change and its impact on our environment long-term monitoring programs must be installed and maintained. Concerning glaciers (= ice glaciers and also rock glaciers) a future monitoring system should run on an operational basis, not only for some selected glaciers but for many glaciers evenly distributed in the high mountains of the globe. All data has to be stored in digital databases for direct access by the user community. The costs will be a limiting factor. In this respect, alternative remote sensing techniques, e.g., SAR interferometry or laser scanning, must also be considered. Public awareness for our environment can be strengthened by computer-based information systems, which should present scientific research results in an easily understandable way. The World Wide Web (WWW) could be a suitable presentation media. The presented computer/video animation of the glacier retreat may be a good example to begin with.

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date of acquisition	number of photographs	focal length [mm]	image scale	film type
September 9, 1954	8	210.230	1:12,600-1:17,100	BW
October 10, 1969	3	152.670	1:25,000-1:31,200	BW
September 5, 1974	11	210.440	1:6,900-1:11,400	BW
July 23, 1983	3	213.790	1:27,800-1:32,300	CIR
September 18, 1992	4	214.760	1:11,400-1:15,800	CIR
September 1, 1997	3	152.383	1:15,600-1.21,900	BW
September 16, 1997	2	152.700	1:28,300-1:34,500	BW

Annotations: The frame size of the photographs of 1954 is 18 cm by 18 cm, otherwise 23 cm by 23 cm. For 1992 there is no full stereoscopic coverage of Hornkees. The photographs of September 16, 1997 were only used for orthophoto production.

Tab. 1: Aerial photographs used in the mapping of glacial stages

	Goessnitzkees		Hornkees	
time period	change in area [ha]	change in area [ha/a]	change in area [ha]	Change in area [ha/a]
1850 – 1873	-9.5 ±0.9	-0.41	-7.2 ±0.7	-0.31
1873 – 1929	-13.8 ±0.8	-0.25	-13.9 ±0.6	-0.25
1929 – 1954	-35.0 ±0.8	-1.40	-26.6 ±0.5	-1.06
1954 – 1969	-4.0 ±0.7	-0.27	-1.7 ±0.5	-0.11
1969 – 1974	-3.4 ±0.6	-0.67	-0.5* ±0.5	-0.10
1974 – 1983	0.2* ±0.6	0.03	-0.4* ±0.5	-0.05
1983 – 1997	-14.7 ±0.6	-1.05	-5.2 ±0.4	-0.37
1850 – 1997	-80.1 ±0.8	-0.55	-55.6 ±0.6	-0.38
1983 – 1992	-11.9 ±0.6	-1.32	.	.
1992 – 1997	-2.9 ±0.6	-0.57	.	.

* ... no statistically significant change in area
Annotations: 1 hectar (ha) = 0.01 km². The evaluation of entire Hornkees for the 1992 stage was not possible (cp. Tab. 1).

Tab. 2: Change in area of Goessnitzkees and Hornkees since 1850

	Goessnitzkees		Hornkees	
time period	change in volume [10^{-6} m³]	change in ice thickness [cm/a]	change in volume [10^{-6} m³]	change in ice thickness [cm/a]
1850 – 1873	-12.0	-33	-7.8	-37
1873 – 1929	-17.1	-22	-12.6	-27
1929 – 1954	-30.7	-107	-12.5	-77
1954 – 1969	-3.1 ±0.2	-20 ±1	-0.40 ±0.09	-3* ±2
1969 – 1974	-2.5 ±0.2	-54 ±4	-0.36 ±0.08	-17 ±4
1974 – 1983	0.6* ±0.2	7* ±3	0.87 ±0.11	24 ±3
1983 – 1997	-8.8 ±0.2	-111 ±3	-5.35 ±0.11	-99 ±4
1850 – 1997	-77.5	-44	-38.2	-36
1983 – 1992	-12.8 ±0.2	-116 ±3	.	-136 ±4
1992 – 1997	-3.9 ±0.1	-103 ±3	.	-137 ±5

* ... no statistically significant change in volume
Annotations: The change in ice thickness refers to the area which was glaciated in both glacial stages. The evaluation of entire Hornkees for the 1992 stage was not possible (cp. Tab. 1).

Tab. 3: Change in volume of Goessnitzkees and Hornkees since 1850

Software	Animation program:	Maya of Alias|Wavefront
	Postprocessing:	Composer of Alias|Wavefront
	Image processing:	Adobe Photoshop
Hardware	Workstation:	Silicon Graphics Indigo2 R10000 576MB Ram
	Render server:	Silicon Graphics Power Challenge 8 x R10000 4GB Ram
	Hardisk recorder:	Pronto Video PV 24
	Interface to video recorder:	Microvideo D/A Converter

Tab. 4: Software and hardware used for the computer animation