The new remote sensing derived Swiss glacier inventory: II. First results.

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ABSTRACT. Complete Swiss glacier inventories are available for 1850 (reconstructed) and 1973 (from aerial photography). Connected to the GLIMS project a new Swiss glacier inventory for approximately the year 2000 (SGI 2000) is compiled mainly based on satellite imagery. The developed and applied remote sensing and GIS methods are described in part I of the contribution. In part II, the inventory design, first result analyses and comparisons with former glacial conditions are presented. As basic entries SGI 2000 contains the individual glacier identification, planimetric glacier boundaries as derived from image analysis, digitised central flowlines and polygonal glacier basin maps. All other parameters are automatically deduced from the above entries and a DEM within a GIS. Here, we analyse a set of small Bernese and Valais glaciers of < 10 km^2. These glaciers lost about 21% of area from 1973 to 1998, in addition to ca. 80% during 1850–1973, both with respect to the 1973 area. In order to track the latest trend in more detail, an intermediate glacier condition has been compiled from satellite imagery of 1985. This analysis gave an increasing speed of area loss (19%) for 1985–1998.

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INTRODUCTION

Glacier changes are among the clearest signals of ongoing warming trends existing in nature. In view of today's rapid environmental changes, combined with the high thermal sensitivity of earth's mountain glaciers, detailed, repeated and up-to-date information of any glacierised region of the world is of growing interest. Space- and airborne remote sensing and geo-informatics play an important role for such glacier inventorying and monitoring work. Steps are now being undertaken to make worldwide glacier monitoring part of the Global Terrestrial Observing System (GTOS) by WMO, ICSU, FAO, UNEP and UNESCO. Such a worldwide collection of standardised observations includes repeated compilation of statistical information on the distribution and topographic characteristics of perennial surface ice in space (glacier inventories). Glacier inventory work is repeated at time intervals comparable to characteristic dynamic response times of mountain glaciers (a few decades), and helps with analysing and assessing changes at a regional scale (e.g. Haeberli and Hoelzle, 1995; Haeberli and others, 2000).

The highest information density and most complete historical record of glaciers exists in the European mountain ranges. In Switzerland, a complete glacier inventory was compiled from aerial photography taken in 1973 (Müller and others, 1976). This inventory was revised in detail and completed with a reconstruction of the 1850 glacierisation (Maisch and others, 1999). Comparison of the two data bases together with long-term observations at individual sites and regional studies using more recent imagery indicate major mass losses with an acceleration tendency in the last 20 years. Now the time has come to compile a new glacier inventory for the Swiss Alps. This task fits into the USGS-led GLIMS project (Global Land Ice Measurements from Space) for worldwide glacier mapping, using satellite imagery in combination with digital elevation information. GLIMS is about, for the first time, to compile a global remote sensing derived inventory of land ice masses. Connected to this project, a new Swiss glacier inventory for approximately the year 2000 (SGI 2000) is based on Landsat 5 TM. Later Landsat 7 ETM+, SPOT imagery , IRS (Indian Remote Sensing Satellite) and aerial imagery, and also ASTER images (Advanced Spaceborne Thermal Emission and Reflection Radiometer on board Terra) will be applied. This work continues the long Swiss tradition of glacier monitoring, but also serves as a GLIMS pilot study.

In view of this global perspective, it was decided not to use aerial photogrammetric approaches (cf. Würländer and Eder, 1998) for SGI 2000, but to develop and apply remote sensing and GIS (Geographical Information System) technology suitable for glacier inventorying over large areas. Although of much greater spatial resolution, glacier inventories derived from aerial photogrammetry do not allow for a high degree of automated glacier detection because of the panchromatic information. They are more cost- and time-consuming and substantially restricted by the availability of suitable aerial photography. Space-borne remote sensing, on the other hand, is the only technology suitable for standardised global glacier inventorying and monitoring.

Part I of this contribution (Paul and others, this issue) describes the evaluation of remote sensing algorithms for automatic glacier detection, the selection of remote sensing procedures suitable for SGI 2000, and the fusion of the classification results with digital elevation models (DEM) using GIS technology towards the SGI 2000 data base. Here, in Part II we present regional examples of SGI 2000, and a first comparison of SGI 2000 with the 1973 inventory and an intermediate 1985 stage.

GLACIER INVENTORY

The basic entries of the new Swiss glacier inventory SGI 2000 are (1) the individual glacier identification (ID), (2) planimetric glacier outlines as derived from image analysis, (3) manually (or semi-automatically) digitised central flowlines, and (4) polygonal glacier basin maps (Tab.1). The polygons of glacier basin map broadly surround the actual glaciers, but are also used for separating contiguous ice masses into individual glaciers, typically along firn divides as estimated from DEM information within the 1973 inventory. Thereby, the glacier ID (1) is connected to the according polygon of the glacier basin map (4). The planimetric glacier outlines (2) are, besides some pre- and post-processing procedures, basically deduced by thresholding ratio images of Landsat 5 TM bands 4 and 5, or equivalent bands of other sensors, respectively (Paul, in press b; Paul and others, this issue). For the results presented here, TM scenes of 12. Sept. 1985 and 31. Aug. 1998 were used. Central flowlines (3) were assessed within the 1850 and 1973 inventories (Maisch and others, 1999), and digitised from the inventory maps. Automatic delineation of centerlines from DEMs was tested by F. Keller (Haeberli and others, 1999; personal communication from F. Keller, 1997) based on tracking maximum local slope direction. It turned out that a number of operator interactions would be necessary to ensure acquisition of consistent flowlines without gross errors. From the above works we conclude that a semi-automatic approach, however, seems promising for large areas with an accurate DEM available.

Figure 1 shows the remote sensing results for a test region in the Swiss Alps (Mischabel range, approx. 7°50'E, 46°5'N). Here, we briefly point out some phenomena, typical also for other regions of the inventory. We want to stress that the depicted stages of 1973 (digitised inventory), 1985 and 1998 (both satellite derived) represent only three points in time of continuous glacier evolution. Conclusions for the entire development 1973–1998 have, therefore, to be drawn carefully. For Findelenglacier a clear retreat of the terminus and lateral zones can be recognised. Even some parts of the glacier bed within the glacier became free of ice. The northern parts of Feeglacier also lost significant amounts of area, with the tongue not only retreating longitudinally, but even more laterally. This mass loss was partially accompanied by increase of debris cover which was then mis-classified as non glacier, and, thus, leading to apparent but not actual glacier retreat. The southern parts of Feeglacier show an advance between 1973 and 1985, as observed for many Swiss glaciers around the 1980s (Herren and others, 1999). This advance is followed by a significant retreat 1985–1998. The southern parts of Feeglacier are comparably steep and the ice is estimated to be thin, both resulting in a sensitive relation between mass balance and area change, in that a given thickness loss leads to a comparable strong horizontal retreat for geometric reasons. At Allalinglacier (which was responsible for the catastrophic ice avalanche in 1965) a drastic slide of the tongue happened shortly before the 1985 satellite image acquisition. Since then, the glacier has retreated to its pre-slide extent. The north-western part of Schwarzbergglacier is debris-covered and, thus, not classified as ice from the satellite imagery. The tongue of this glacier ends above a steep edge, stabilising the lower extent. Finally, most small glaciers in the region drastically diminished or even totally disappeared in the time period observed. The latter phenomenon is discussed in more detail in the following section.

The major problem for deriving the glacier extents from satellite imagery (also affecting the results in Fig. 1) is presently to detect debris-covered ice. In the perspectives, we sketch out some possible remote sensing solutions for that problem. Here, we classify the glaciers as debris-free or significantly debris-covered. Thereby, 'debris-free' is defined in terms of the classification by the applied remote sensing algorithms. Since the mass-balance of debris-covered glaciers, or glacier parts, respectively, is different from debris-free ones, a separation of both types in the inventory and subsequent analyses is advisable anyway. Furthermore, it seems questionable if tracking of area changes of debris-covered glaciers is possible at all with useful accuracy and reliability. Fluctuations of debris-covered Swiss glaciers are not considered for the first inventory analysis presented here.

From the primary inputs such as 2D glacier outline, 2D flowlines, 2D glacier basin map and DEM, a number of secondary parameters are derived automatically, either directly from the primary data, and/or after combining the planimetric data with a DEM (Tab.1). For SGI 2000 we used the 25m-spaced DEM of the Swiss Federal Office of Topography, which turned out to be mostly of suitable precision. A major problem, however, is that the DEM is collected from aerial photography over a longer time period and, thus, does not reflect a well-defined point in time, and in any case does not coincide with the time for the used satellite imagery. This error mainly affects the parameter 'minimum glacier elevation'. All parameter-derivation procedures are performed within the GIS Arc/Info (Paul and others, this issue).

In Figure 2, the share of glacier number within different area size classes compared to the total number of Swiss glaciers (a), and the share of glacier area within the area classes compared to the total glacierised area (b) is depicted. As is well known, and reflecting general characteristics of alpine type glacierisation, most glaciers are small, and cover a small total area (cf. Maisch and others, 1999; Paul, in press a). However, we want to point out that small glaciers, not included in most monitoring networks, still sum up to a significant total area. Note, that glaciers of 0.01–1km^2 cover 25% of glacierised area (Fig. 2b). The raw inventory data were used to compute the percentages, and some small glaciers combined to larger ones as occasionally done for glacier inventorying.

GLACIER CHANGES

First results of glacier changes derived from the 1973 Swiss inventory and observed from 1985 and 1998 satellite imagery were computed for a sample of about 300 debris-free glaciers of the Bernese and Valais Alps. Thereby, the decision whether a glacier is debris-covered or not was made based on visual inspection of the applied satellite imagery. The large glaciers of the region are not included because they all show significant debris cover. Thus, the sample analysed here can be viewed as representative for glaciers < 10 km^2. Figure 3 shows the percentage area loss 1973–1998 of the sample, additionally averaged for the area-size classes used in Figure 2. As expected and already found by other authors (e.g. Maisch and others, 1999; Serandrei-Barbero and others, 1999; Paul, in press a), the smaller the glaciers are, the larger is the variance of their relative area change. This relation might reflect the larger sensitivity of small glaciers to the local variability of processes involved in glacier mass balance, but is also substantially influenced by the highly individual reaction of small glaciers to external forcing (cf. Haeberli and Hoelzle, 1995; Herren and others, 1999). The fast reaction leads to the effect that the area of small glaciers as mapped from one inventory snapshot only reflects the mass balance of a few preceding years. The larger glaciers change more likely represents the average change between two inventory snapshots. In that context, also the very different time periods investigated here have to be considered. Whereas the period 1850–1973 might exceed the response time of all investigated glaciers, the 1973–1985–1998 periods might not do so for a number of glaciers. Furthermore, the smaller the glaciers are, the worse becomes the signal-to-noise ratio from detection and processing, for instance due to the limited pixel size, and, thus, the variance of the sample.

Figure 4 summarises the area changes of the test set of debris-free glaciers for the periods 1973–1985–1998 for the individual glacier area classes. The area changes 1850–1973 were added for comparison from Maisch and others (1999). The 1850–1973 changes are based on a larger glacier sample, which we consider to be, however, comparable to the 1973–1985–1998 sample. Note that all area changes given in Figure 4 are relative to the 1973 glacier areas.

As known from other inventory analyses (cf. Maisch and others, 1999; Serandrei-Barbero and others, 1999; Paul, in press a), the smaller the glaciers, the larger their percentage area loss. This fact is partially due to simple geometric reasons in that a certain mass balance change leads to larger area changes for the small, mostly thin glaciers than for large glaciers with often steeper flanks. Furthermore, the overall uplift of the equilibrium line altitude, as indicated by the measured area loss, shifts the equilibrium line above the altitudinal extent of a number the small glaciers, such crossing the threshold necessary for glacier persistence. In addition, a positive feedback could be observed with markedly decreasing albedo and increasing long-wave radiance from rock headwalls, and, thus, enhanced negative mass balance especially for small glaciers loosing their accumulation area to a large or even total extent. The counteracting fact that small glaciers might retreat into more shadowy cirque situation seems not to govern the above system of influences, at least not for our glacier sample.

The area loss 1973–1985 as observed for the Bernese and Valais glaciers (Fig. 4) is markedly smaller than the 1985–1998 loss. In addition, the 1973–1985 decadal loss is smaller than the average decadal 1850–1973 area loss, except for the glaciers < 0.5 km^2. This exception has to be interpreted carefully due to the complex reaction of the small glaciers in connection with especially high solid precipitation in the late 1970's. In contrast to the moderate area loss 1973–1985, a drastic loss as compared both to 1850–1973 and 1973–1985, can be observed for 1985–1998. For all glaciers < 10 km^2 the 1985–1998 area loss is approximately four times higher than the average decadal 1850–1973 loss. Compared to 1973–1985 the 1985–1998 loss is approximately four times higher for the glaciers < 0.5 km^2, and more than eight times higher for the glaciers 0.5–10 km^2. The total sample area of 205 km^2 in 1973 was reduced by 21% between 1973–1998 (2% for 1973–1985; 19% for 1985–1998).

Glaciers < 1 km^2 contributed over 55% to the total area loss 1973–1998 of the sample. This drastic area loss manifests ongoing warming trends even more clearly than reactions of large glaciers but with a higher temporal and spatial variability. To estimate the average thickness reduction connected with the observed area loss we calculated the ratios between area loss and volume loss obtained for the 1850–1973 period by Maisch and others (1999) for different size categories. The average mass balance 1850–1973 for the glaciers < 10 km^2 was approximately –0.09 ma^{-1} (Maisch and others, 1999), –0.17

ma^{-1} for the entire 1973–1998 period, and –0.35 ma^{-1} for the last period 1985–1998. Thereby, one should note that the above estimated mass balance values are dominated by small glaciers and become more negative by a factor of 1.2-1.3 for the large glaciers (> 10 km^2) not considered here (cf. Hoelzle and Haeberli, 1995; Maisch and others, 1999). The above numbers can be compared with (even more negative) direct mass balance measurements (Haeberli and others, 1999) and assessments from glacier length changes for the Alps (ca. -0.17 to -0.25 ma^{-1} for 1850-1970 from Haeberli and Hoelzle, 1995; Hoelzle and Haeberli, 1995; ca. -0.13 ma^{-1} for ca. 1900-mid-1990s from Hoelzle and others, 2000) as well as with global averages (e.g. ca. -0.13 ma^{-1} for 1961-1990; Dyurgerov and Meier, 1997; Cogley and Adams, 1998).

Extrapolating the observed area loss 1973-1998 for the sample glaciers < 10 km^2 until 2025 would give an area loss of 45% for 1973-2025. Even if considering that glaciers > 10 km^2 are missing in our sample, this extrapolation would give higher area losses than the ca. 33% area-loss scenario given by Haeberli and Hoelzle (1995) based on the IPCC-scenario ‘business as usual’. Extrapolating the observed 1985-1998 area-loss acceleration would exceed the IPCC scenario markedly (Haeberli and others, 2001).

CONCLUSIONS AND PERSPECTIVES

The new Swiss Glacier Inventory 2000 confirms the clear trend in area-loss of Alpine glaciers. A drastic acceleration of retreat since 1985 can be observed for the entire glacier sample analysed here (< 10 km^2). Although this drastic area loss of small glaciers is not equivalent to drastic volume loss with respect to the total ice volume (which is predominantly influenced by the larger glaciers; cf. Bahr, 1997) it has significant effects on processes involved in surface energy balance, hydrology or landscape evolution. The behaviour of the small glaciers shows a high spatial and temporal variability which can completely be assessed only by remote sensing methods.

The next steps within the Swiss glacier inventory 2000 will be: inclusion of more satellite imagery for intermediate stages; expansion of the analysed glacier sample in terms of regions and glacier number; more extensive statistical analysis; comparison of observed trends with climate modelling and scenarios.

Besides the specific results for the Swiss glaciation, the compilation of SGI 2000 will reveale valuable conclusions for world-wide glacier inventorying and monitoring. In deed, the fusion of satellite image analysis and GIS technology turned out to be highly suitable for operational and repeated glacier inventorying of large and remote regions by comparably low expenditure, but nevertheless fulfilling glaciological standards (cf. Haeberli, 1998). Observation of areas often obscured by clouds (which was no major problem for SGI 2000) has to include more optical and also microwave sensors to obtain a more frequent or cloud-independent coverage. Exploiting satellite imagery of several different years seems advisable for inventorying and subsequent analysing of small glaciers due to their complex reaction. This strategy is greatly facilitated by the high degree of automation possible with space-borne glacier monitoring. The availability of suitable DEMs is a – slowly improving – bottleneck for deriving glaciological 3D-parameters. Especially ASTER with its along-track stereo capabilities opens the possibility of simultaneous glacier mapping and DEM generation. Debris coverage of ice still remains the largest technical problem, which has to be addressed by both sophisticated classification methods and special statistical measures in inventory analysis. For classification, we favour the inclusion of more spectral bands than the here-used two for example adding thermal bands to classification, and knowledge-based 2D- and 3D-algorithms (e.g. neighbourhood relations, and geomorphometric analysis based on DEMs; cf. Paul and others, this issue).

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TABLES AND FIGURES

Table 1. Glacier parameters of the Swiss Glacier Inventory 2000 data base. Primary data represent the original input, secondary data are automatically derived from the primary data within a GIS. Various 'on demand'- parameters can be derived automatically for special purposes, but are not included in the data base.

data level	*parameter*	*derivation*
	glacier ID	
description	name, mountain range, debris coverage, etc.	
primary:	2D glacier outline	remote sensing
	2D central flowline(s)	manual digitising, semi-automatic computation
	2D basin map	manual digitising
	DEM	remote sensing, contour line digitising
secondary:	3D glacier outline	DEM + 2D-outline
	3D flowlines	DEM + 2D-flowline
	glacier area	2D-outline
	glacier length	2D/3D-outline + flowline
	min./max. elevation	3D-outline
	median/average elevation	DEM + 2D-outline
	hypsography	DEM + 2D-outline
	direction and slope of different units	DEM + outline/flowlines
on demand	illumination/ shadow, etc….	DEM

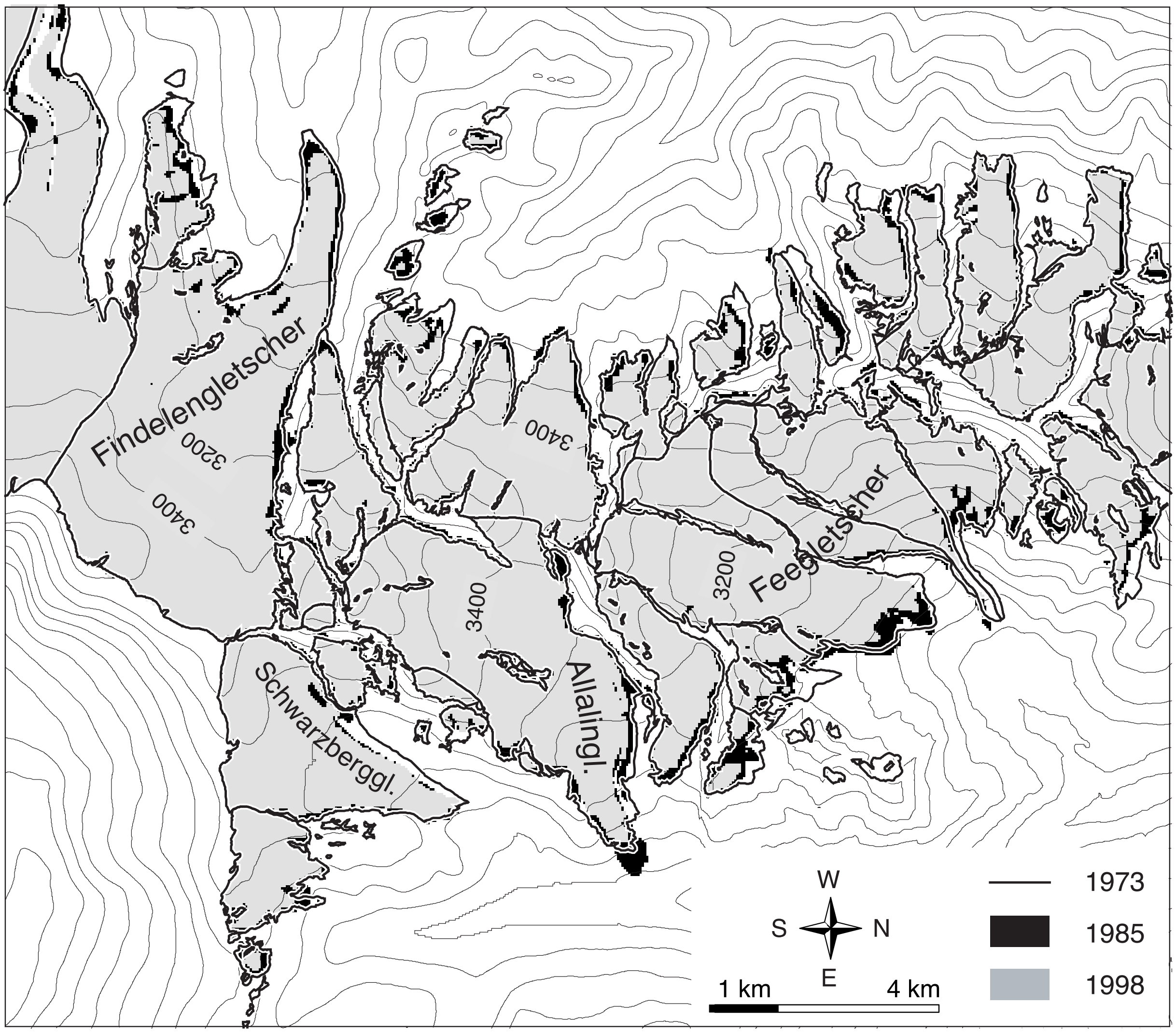

Fig. 1 Mischabel range, Valais, Swiss Alps. Glacier outlines from the 1973 inventory (Maisch and others, 1999), and glacier areas for 1985 and 1998 as automatically deduced from Landsat TM imagery. In addition to a general glacier retreat trend, the 1980s advance period can be recognised for some glaciers. A major problem, however, consists in detecting debris-covered ice.

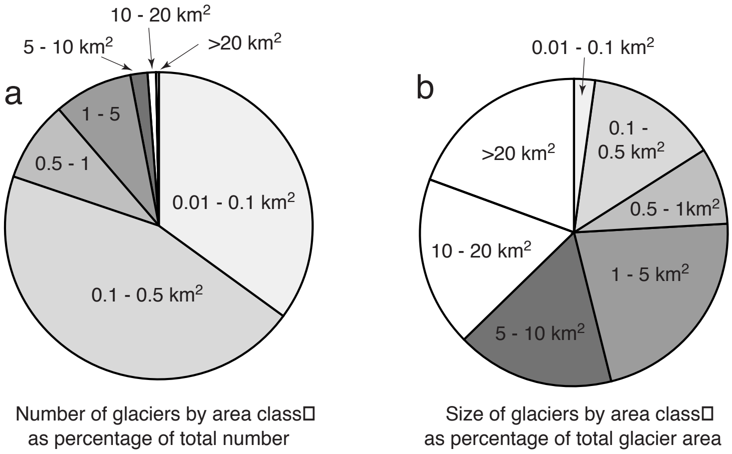

Fig. 2 Glacier number and area size classified by different area classes (in km^2) as percentage of the total number (a), or total area (b), respectively. The numerous small glaciers < 1km^2 cover about 25% of the total Swiss glacierised area.

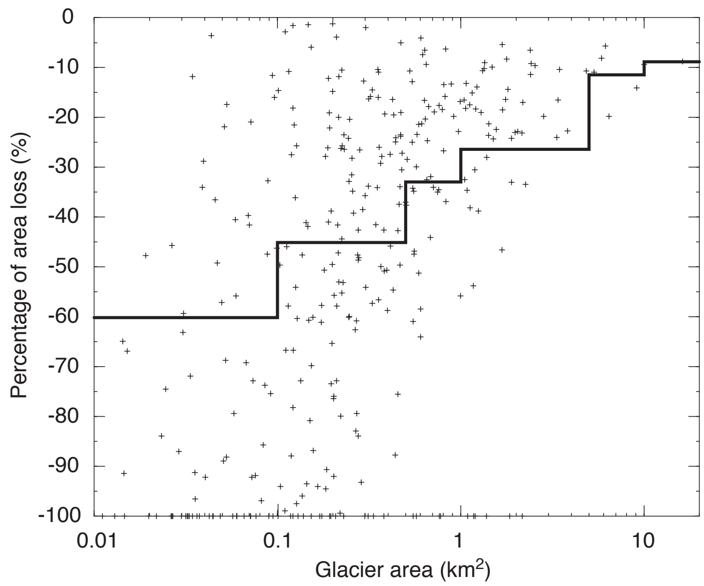

Fig.3: Area changes 1973-1998 for a sub-sample of debris-free glaciers in the Valais and Bernese Alps. Large glaciers > 10km^2 are not included because of their (often high) debris-coverage. The changes are averaged for the area classes shown in Fig 2 (bold line). The smaller the glaciers, the larger the variance of their behaviour, and the higher their average percentage area loss.

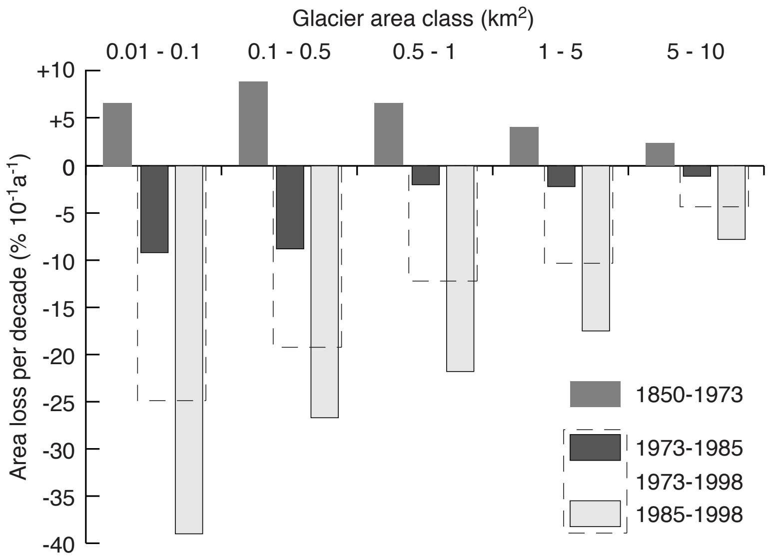

Fig. 4: Decadal area loss for the periods 1973-1985-1998 for the glacier sample of Fig.3. The 1850-1973 loss is taken from Maisch and others (1999). The total area loss 1973-1998 amounts to 9% per decade. All percentages refer to the 1973 area. The dashed columns represent the 1973-1998 average.