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THE LONGTERM SIGNAL OF CLIMATE CHANGE IN THE SWISS ALPS: GLACIER RETREAT SINCE THE END OF THE LITTLE ICE AGE AND FUTURE ICE DECAY SCENARIOS

ABSTRACT: MAISCH M., *The longterm signal of climate change in the Swiss Alps: Glacier retreat since the end of the Little Ice Age and future ice decay scenarios*. (IT ISSN 0391-9838, 2000).

The study presented summarizes selected results of a nationwide glacier inventory project supported by the Swiss National Research Programme (NRP 31) on «Climate Changes and natural Catastrophes» completed in 1999. The data were obtained by the glaciological reconstruction and homogeneous parameterization of the 1850 glacier situation in the Swiss Alps (the last advance period of the Little Ice Age). The statistical comparison with the present-day glaciation (recorded in 1973) provides for the first time a complete synopsis of various glaciological and geographical aspects of longterm glacier retreat in the period since 1850. Attempts were made, based on the new inventory data, to model potential ice decay scenarios for the Swiss Alps and to estimate the glaciological consequences of an enhanced atmospheric warming.

Since the end of the Little Ice Age the mean vertical 2:1-ELA shift (AAR = 0.67) of glaciers with normal topographic characteristics is in the order of +90 m. This unfavourable change in mass balance conditions has led to a substantial glacier area loss in the Swiss Alps of approximataly 500 km^2 (27 percent) and to an ice volume loss of 33 km^3 (31 percent) The relative amount of ice-decay (area, volume, length) is highly variable on an individual scale but in general shows a significant inverse correlation with former glacier size. The simulation of different 2:1-ELA-rise scenarios outlines the high sensitivity of alpine glaciation in respect of future climate changes. A strongly accelerated but regionally differentiated glacier decay within the next few decades would be the result of the 21[st] century based atmospheric warming scenarios.

KEY WORDS: Late Glacial, Holocene, Little Ice Age, Swiss glacier inventory, glacier retreat scenarios

ZUSAMMENFASSUNG: MAISCH M., *Das langfristige Klimaänderungssignal in den Schweizer Alpen: Gletscherschwund seit dem Ende der Kleinen Eiszeit und zukünftige Eisschwund-Szenarien*. (IT ISSN 0391-9838, 2000).

Der hier vorgestellte Beitrag fasst ausgewählte Resultate eines nationalen Gletscherinventar-Projektes zusammen, welches im Rahmen des Nationalen Forschungsprogrammes (NFP 31) mit dem Titel «Klimaänderungen und Naturkatastrophen» durchgeführt und 1999 abgeschlossen worde. Die Datengrundlagen wurden durch eine vollständige glaziologische Rekonstruktion und Parametrisierung der 1850er-Vergletscherung, der letzten Vorstossphase der Kleinen Eiszeit mit einheitlicher Methodik erhoben. Der statistische Vergleich mit der aktuellen Vergletscherung (erfasst im Bezugsjahr 1973) ermöglicht erstmals einen vollständigen Gesamtüberblick zu den verschiedensten glaziologischen und geographischen Aspekten des langfristigen Gletscherschwundes seit 1850. Mit Hilfe der neu geschaffenen Gletscherdatenbank wurde ausserdem versucht, mögliche Gletscherschwund-Szenarien zu modellieren und die glaziologischen Folgen einer verstärkten atmosphärischen Erwärmung quantitativ abzuschätzen.

Seit dem Ende der Kleinen Eiszeit sind die Gleichgewichtslinien (2:1-GWL, AAR = 0.66) der Gletscher mit normalen topographischen Eigenschaften um rund 90 Meter angestiegen. Diese für die Ernährung der Gletscher ungünstige Veränderung im Massenhaushalt hat in den Schweizer Alpen zu einer Flächeneinbusse von annähernd 500 km^2 (27%) und zu einem Eisvolumenschwund von 33 km^3 (31%) geführt. Die prozentuale Anteile des Gletscherschwundes (Fläche, Länge, Volumen) zeigen auf der individuellen Ebene der Einzelgletscher eine ausserordentlich grosse Streuung. Generell verlaufen die relativen Schwundbeträge jedoch umgekehrt proportional zur ehemaligen Gletschergrösse.

Die Simulation verschiedener 2:1-GWL-Anstiegs-Szenarien unterstreicht die grosse Anfälligkeit der heutigen Alpenvergletscherung gegenüber der prognostizierten Klimaverschiebung. Als Resultat der für das 21. Jahrhundert vorhergesagten atmosphärischen Erwärmung wird in den kommenden Jahrzehnten mit einem deutlich beschleunigten, regional jedoch unterschiedlich stark ausgeprägten Gletscherschwund zu rechnen sein.

STICHWORTE: Spätglazial, Holozän, Kleine Eiszeit, Schweizerisches Gletscherinventar, Gletscherschwund.

RIASSUNTO: MAISCH M., *Il segnale di cambiamento climatico a lungo termine registrato nelle Alpi Svizzere: il ritiro dei ghiacciai dalla fine della Piccola Età Glaciale e gli scenari di futura ulteriore riduzione*. (IT ISSN 0391-9838, 2000).

Questo studio riassume alcuni risultati selezionati di un progetto di censimento nazionale dei ghiacciai, promosso dal Programma di Ricerca Nazionale Svizzero su «Cambiamenti climatici e catastrofi», completato nel 1999. I dati sono stati ottenuti a partire dalla ricostruzione glaciologi-

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ca e dalla parametrizzazione omogenea della situazione dei ghiacciai nelle Alpi Svizzere nel 1850 (l'ultima fase di avanzata della Piccola Età Glaciale). Il confronto statistico con l'attuale situazione dei ghiacciai (registrata nel 1973) fornisce per la prima volta un quadro completo dei diversi aspetti glaciologici e geografici della fase di ritiro glaciale a lungo termine dal 1850 ad oggi.

Sulla base dei nuovi dati ottenuti si è tentato di modellizzare gli scenari di potenziale ulteriore riduzione dei ghiacciai nelle Alpi Svizzere e di stimare le conseguenze glaciologiche del riscaldamento climatico.

Dalla fine della Piccola Età Glaciale la risalita media della Altitudine della Linea di Equilibrio (ELA), ottenuta usando il rapporto AAR = 0,67, nei ghiacciai con caratteristiche topografiche normali è stata dell'ordine di +90 m. Queste condizioni sfavorevoli di bilancio di massa hanno prodotto una sostanziale perdita di area coperta da ghiacciai nelle Alpi Svizzere, di circa 500 km^2 (27%), ed una perdita di volume di 33 km^3 (31%). Il valore relativo di perdita glaciale (area, volume, lunghezza) è molto variabile alla scala dei singoli ghiacciai ma in generale mostra una significativa correlazione inversa con le dimensioni di partenza. La simulazione di differenti scenari di risalita della ELA mostra la elevata sensibilità dei ghiacciai alpini ai futuri cambiamenti climatici. Con gli scenari di riscaldamento atmosferico previsti nel 21° secolo, si produrrebbe, nei prossimi decenni, una riduzione glaciale fortemente accelerata, sebbene regionalmente differenziata.

TERMINI CHIAVE: Tardiglaciale, Olocene, Piccola Età Glaciale, Censimento dei ghiacciai Svizzeri, Scenari di ritiro glaciale.

INTRODUCTION

Glaciers are undoubtedly among the most spectacular features of high alpine environments. It's obvious that glaciers respond to climate and its long-term variations although the interactions between climate, mass balance and glacier response (advance and retreat periods) are rather complex and not completely understood. Nevertheless glacier changes, especially the ongoing recession period, are among the clearest signals of longterm changes in energy and mass balance. In the context of the «greenhouse problem» data from glacier inventories form a very useful tool that allows the calibration of the sensitivity of the alpine glaciation with respect to past and possible future climate changes (cf. VAW-ETH Zürich, 1990; Kuhn, 1990; Patzelt & Aellen, 1990; Haeberli, 1990, 1991, 1994; Haeberli & Hoelzle, 1995; Haeberli & Beniston, 1998; Haeberli & *alii*, 1997, 1998, 1999a/b; UNESCO, 1998; Maisch, 1992, 1995, 1997; Maisch & *alii*, 1999a/2000).

Advancing glaciers deposit moraines or pass over soils and trees that emerged during the ice-free periods. It is possible to trace the history of glacier changes far back to prehistoric times by analyzing and dating these «silent witnesses» (Gamper & Suter, 1982). Present knowledge holds that the pleistocene glacier systems of the Alps retreated very quickly at the end of the last cold period («Würm» Late glacial period). The overall disintegration of glaciers thereby followed the main trend of the warming process that began about 18,000 years ago and can be divided into various steps and stages. The Egesen stage in the eastern Alps or, for example, the regional Pontresina stage in the Bernina region of Upper Engadine in the Younger Dryas period (10,800 to 10,000 years BP), represent distinctive advance as well as rapid retreat phases (Maisch, 1992, 1995). With the beginning of the Holocene (Post-Glacial) about 10,000 years ago and the final melting back of the Alpine glaciers far into the upper reaches of the mountains, there appears evidence of an extraordinarily steady climatic and glacial development with minimal fluctuations (fig. 1). Compared with the Late glacial period, it is now possible to document a much «higher», that is, warmer, climate level. Eight clearly provable advancing cycles can be compared with the same number of phases with minimal glacial extent similar to that found today. The maximum extent period of 1850 with its moraine systems thus represents a dimension of glacial history which is not only typical for that period of the Little Ice Age (1350-1850), but also for almost all older maximum extent periods of the Holocene Epoch (Patzelt, 1973, 1995; Furrer, 1991; Holzhauser, 1995).

However, there is much more uncertainty in the knowledge about the «warm period» minimum extents than about the geomorphological-stratigraphic periods of advance, for which clear proof can usually be given. Various indicators from recent research into glaciological history point to the increasing likelihood that during the warmer or drier climatic periods of the Holocene, the extent of the glaciers might have been slightly, but perhaps more distinctly than previously assumed, smaller than the extent of the glaciers at the end of the 20th century.

Thus it was possible to provide proof for the period 8,000 to 5,000 years ago, based on the peat profiles found near the edge of the ice at the Rutor Glacier (Porter & Orombelli, 1985; Burga, 1991) and at the Gauli Glacier (Wäspi, 1993), that the glacial extent was smaller then than during the 1980s. Field evidences on reduced ice extents in this time period were also found in the forefield of Pasterze Glacier in the Austrian Alps (Slupetzky, 1993; Slupetzky & *alii*, 1998; Nicolussi & Patzelt, 2000). According to results from fossilized, centuries-old wood debris of trees grown in situ that recently emerged from under the ice edge, the sluggish and slowly reacting terminus of the Great Aletsch Glacier was probably shorter approx. 3,200 years ago (just following the final phase of the Löbben fluctuation of 3,600 to 3,100 years ago) and approx. 2,000 years ago than it was in the 1990s (Holzhauser, 1995, 1997).

The period of the last 10,000 years or so since the end of the last Ice Age seems to be a period of glacial and climatic variations that, although numerous, were always of similar size, and of comparably slight amplitude (±1 °C). Within the post ice-age glacial variation, the large extent of the glaciers around the year 1850 marks a characteristic order of magnitude which was reached repeatedly in the case of glacier advancing, but was surpassed only rarely. In terms of size and dynamics, the speed of glacier melt since 1850 is not very different from that in earlier retreat phases. It is possible that at the end of the Younger Dryas (following the Egesen phase), there were already many, more distinct phases of ice disintegration (Maisch, 1995). It is quite possible that glacier dimensions in the earlier warm phases of the post-glacial period, the time of the «pre-industrial», that is, mainly «natural» greenhouse climate, were smaller than those of the present time. The current glaciation situation is thus within the holocene extent of variation, while being clearly in the warm transition area of

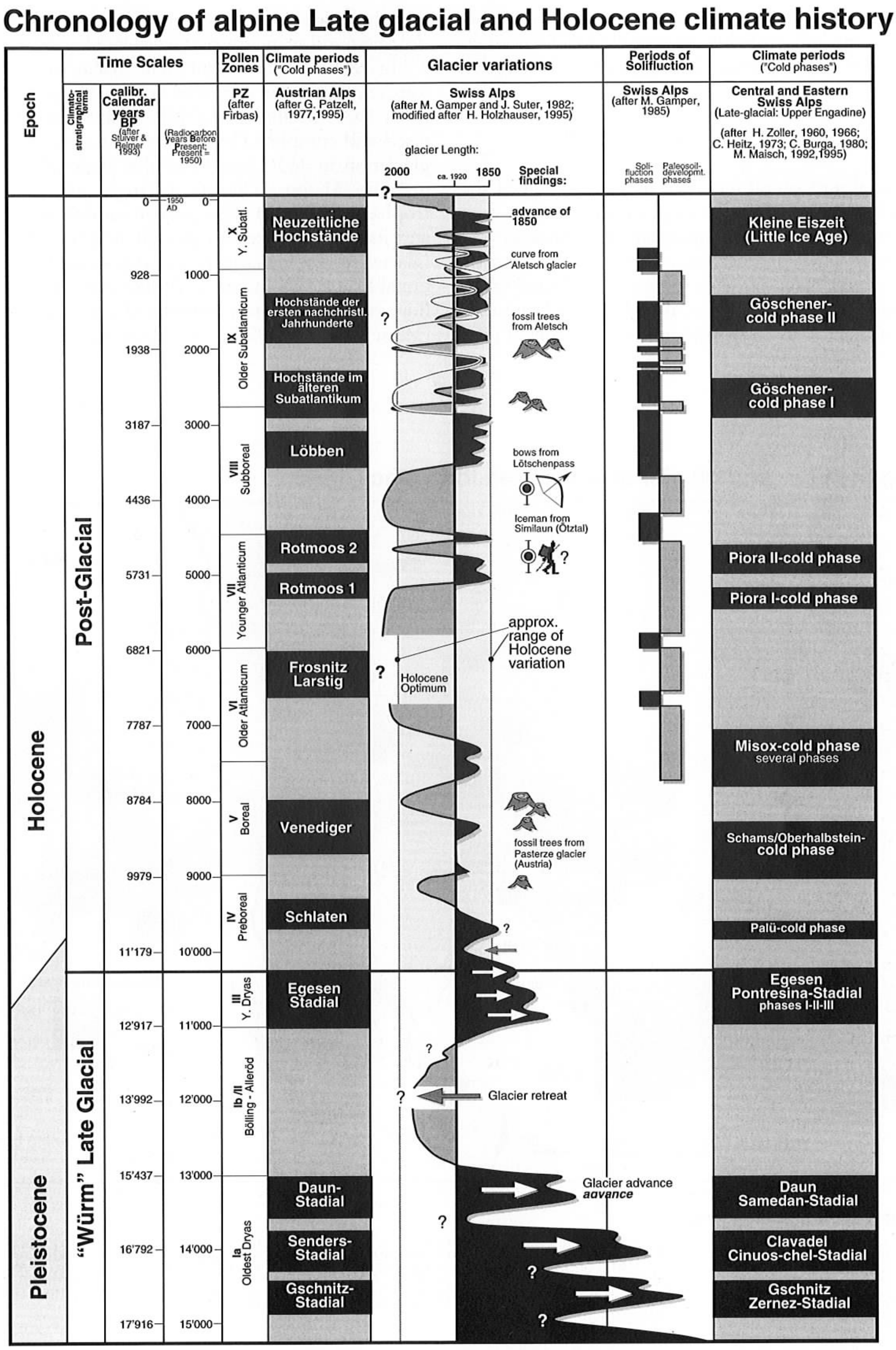


FIG. 1 - Chronology of the Holocene glacier and climate variations in the Alps. The dimension of the present-day glaciation lies at the «warm» boundary and is still within the range of Holocene variations (compiled after various sources by Maisch & *alii*, 1999/2000, updated).

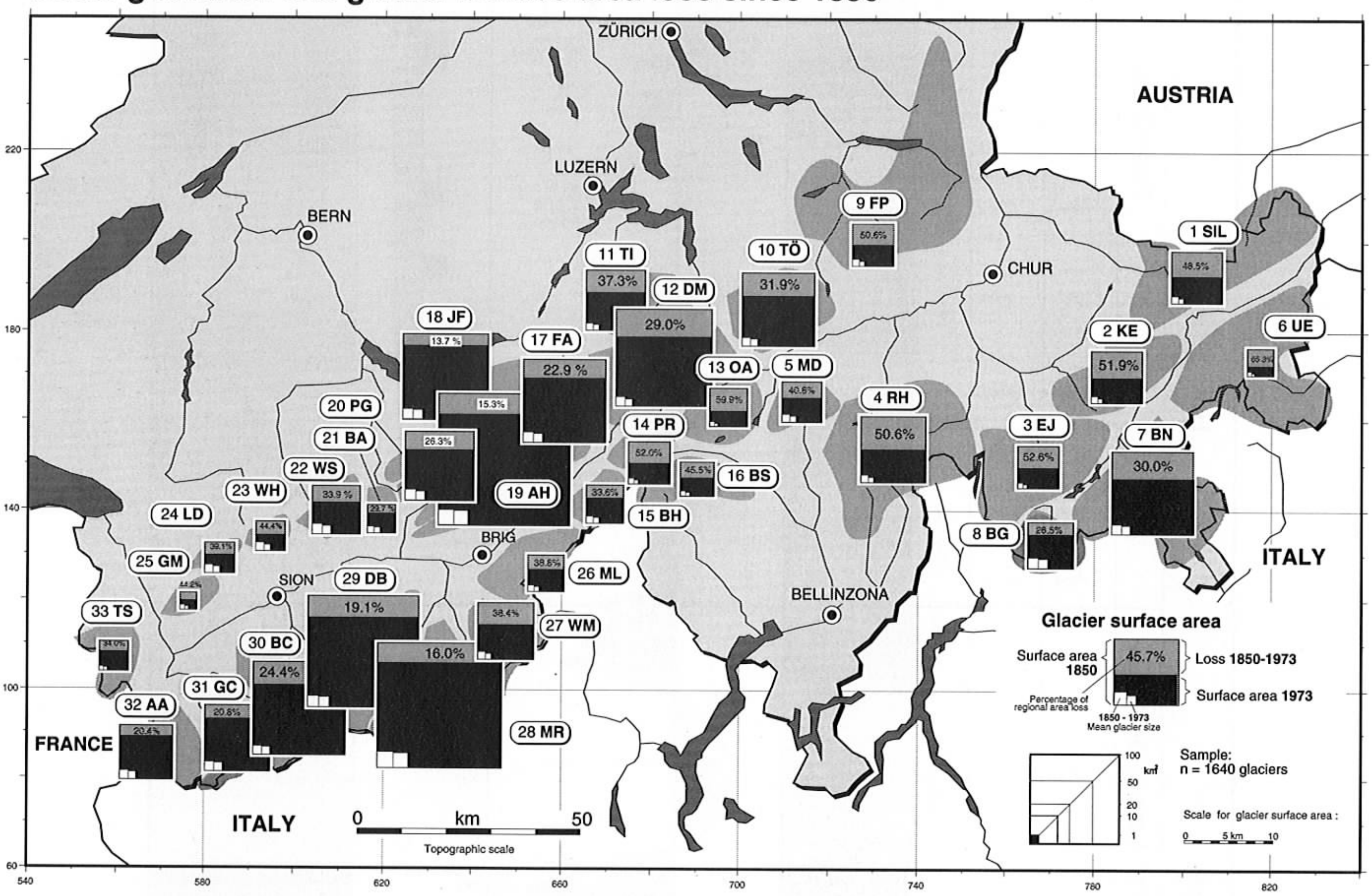
all reconstructable post-glacial glacier and climate fluctuations. This range will probably be exceeded if the predicted temperature rise scenarios occure (IPCC, 1990, 1995).

SWISS GLACIER INVENTORY 1850/1973

The frontal and lateral moraines and the extent of the forefield areas of the 1850 advance in the Alps can be easily seen during field work mapping and are especially recognisable with aerial photography. These fresh and mostly unstable new landscapes are now opened to a broad variety of natural processes. As a special and very delicate new life zones the forefields attract the interest not only of geomorphologists and glaciologists, but also of botanists, pedologists and many tourists as well (Maisch & *alii*, 1999b).

In Switzerland, a complete glacier inventory of the «present day» was compiled from aerial photographs taken in 1973 (Müller & *alii*, 1976). This first dataset was revised and completed with a detailed reconstruction of the glaciation in 1850 as part of the National Research Programme 31 on «Climate Changes and natural Catastrophes» (NRP 31). The project entitled «Climate change and its consequences on glaciers and their forefield areas (glacier retreat scenarios)» was supported by the Swiss National Science Foundation (Project No. 4031-033412). The final report was lately completed and recently puplished (Maisch & *alii*, 1999a/2000). Regional summaries of selec-

Swiss glaciation and glacier surface area loss since 1850



Glacier regions (mountain ranges):

26 **ML** MONTE LEONE
27 **WM** WEISSMIES
28 **MR** MONTE ROSA
29 **DB** DENT BLANCHE
30 **BC** MONT BL. DE CHEILON
31 **GC** GRAND COMBIN
32 **AA** AIG. D'ARGENTIÈRE
33 **TS** TOUR SALLIÈRE

17 **FA** FINSTERAARHORN
18 **JF** JUNGFRAU
19 **AH** ALETSCHHORN
20 **PG** PETERSGRAT
21 **BA** BALMHORN
22 **WS** WILDSTRUBEL
23 **WH** WILDHORN
24 **LD** LES DIABLERETS
25 **GM** GRAND MUVERAN

11 **TI** TITLIS
12 **DM** DAMMA
13 **OA** OBERALP
14 **PR** PIZ ROTONDO
15 **BH** BLINNEHORN
16 **BS** BASÒDINO

6 **UE** UNTERENGADIN
7 **BN** BERNINA
8 **BG** BERGELL

9 **FP** FLIMS-PIZOL
10 **TÖ** TÖDI

1 **SIL** SILVRETTA
2 **KE** KESCH
3 **EJ** ERR-JULIER
4 **RH** RHEINWALD
5 **MD** MEDEL

FIG. 2 - Glaciation and glacier retreat since 1850 in the Swiss Alps as recorded in the CH-INVGLAZ inventory database. The glaciers are grouped into 33 mountain ranges. The rectangles represent the regional totals of surface area in 1850, 1973 and the difference (area loss) since. Note the different map scale for the glacier surface area.

ted results and first attempts at modelling future ice retreat scenarios are given in Battaglia (1994), Benz (1995), Denneler & Maisch (1995) and Maisch (1992, 1997). The inventory of the Bernese Alps has been worked out and analyzed by WIPF (1999). A complete revision of this existing Swiss glacier inventory now based on Landsat and SPOT satellite imagery is being established by a project at the Geography Department of University of Zürich (Paul, 1995).

The glacier data, used selectively in this paper, has been taken homogeneously with standardized methods and has been recorded in a new Swiss glacier inventory database called CH-INVGLAZ (Maisch & *alii*, 1999a/2000). As a first step in the inventarization each and every glacier was grouped hydrologically by catchment area (i.e. rivers Rhine, Reuss, Ticino and Inn) and geographically by 33 mountain ranges (fig. 2). Each glacier was classified by the categories of: aspect (orientation of the main axis), glacier type (i.e. valley glaciers, mountain glaciers, glacierets, firn patches etc.), shape of glacier front, longitudinal profile (i.e. normal, irregular with cascades, etc.) and the morphology of the forefield areas (i.e. sedimentary bed, bedrock or mixed bed; Maisch & *alii*, 1999c). After reconstructing the ice topography by drawing 100 m contour intervals (scale 1:25,000), nearly 50 parameters were measured and recorded for each glacier (for details see Maisch, 1992). This parameterization includes standardized data on surface area, volume losses, glacier length along the central flowline, elevations (minimum, maximum and mean elevations), mean slope of the ice surface and calculations on the equilibrium-line altitude (2:1-ELA, by using an AAR-ratio of 0.67; cf. Gross & *alii*, 1978). Detailed and partially GIS-based (ARC/INFO) datasets are available also for the area-altitude distribution of both observation periods. The statistical comparison of the datasets, calculated as simple difference of the situations in 1850 and 1973, gives the absolute and relative amount of glacier retreat on a secular time scale. Spatial analysis reveals interesting geographical patterns on different regional levels (Swiss Alps, mountain regions and subregions, catchment areas, regional climate zones, aspect and orientation).

GLACIER RETREAT AND ELA-RISE SINCE 1850

In the Swiss Alps more than 2000 «glacier units» with a minimum size of 0.01 km^2 in 1850 could be detected, reconstructed and inventoried. The spatial distribution of Swiss glaciation is typically very asymmetric in that ice is concentrated in the larger mountain ranges such as Bernina, Damma, Finsteraarhorn, Aletschhorn, Monte Rosa and Dent Blanche (fig. 2). The glaciated surface area gives a total of 1800 km^2 for 1850 and 1300 km^2 for the present-day situation. Overall, since the end of the Little Ice Age the Swiss Alps show an area loss of 500 km^2 or 27 percent of the formerly glaciated area. More than 100 small glacierets have disappeared completely. The absolute amount of area loss reaches its maximum in the Damma region (–34 km^2) and its minimum in the Balmhorn area (–2.9 km^2). The regional area loss varies between 65.5 percent (Unterengadin: weak glaciation with below average mean glacier sizes) and 13.7 percent (Jungfrau: strong glaciation with above average mean glacier size) and is dependent obviously on mean glacier size and the regional degree of glaciation.

Absolute ice volume loss in the Swiss Alps is in the order of 33 km^3 which is close to one third of its former dimensions (1850: 107 km^3; 1973: 74 km^3). The percentage of volume loss seems small (31%) but is mainly influenced by the strong statistical weight of the much more densely glaciated regions in the southwestern parts of Switzerland (i.e. Monte Rosa, Dent Blanche, Aletschhorn). These mountain ranges have lost only a small portion (13-20%) of their glaciations in respect of their still large reserves. Most of the other regions typically show much higher volume loss (40-60%), 17 out of the 33 Swiss mountain ranges have lost more than 50 percent of their ice mass since 1850.

In fig. 3 the Bernina region at the Swiss/Italian border has been chosen to illustrate on an individual scale the glaciation and the glacier retreat bahaviour since 1850 (Maisch, 1992). Glacier size and glacier distribution are clearly connected with mountain topography (altitude of the accumulation zones), which gives much stronger glaciation in the north facing valleys of the Bernina massif. On the other hand glacier size tends to decrease towards the outer edges of the Bernina mountains which offer much lower elevated cirque headwalls and provide less favourable conditions for glacier feeding.

Fig. 4 and fig. 5 outline that single glacier size distribution is, for natural reasons, dominated by small and very tiny glaciers or «glacierets» (Switzerland: mean glacier size 1850 = 1.06 km^2; 1973: = 0.77 km^2). In 1850 about 80% of the Swiss glaciers were smaller than 1 km^2, in 1973 more than 90%. Only 28 glaciers (~1.5%) were larger than 10 km^2 in 1850, in 1973 this number is reduced to 21 valley glaciers (~1%). The largest and also the longest glacier in the Grisons area is Morteratsch glacier (1850: 19.3 km^2; 1973: 16.4 km^2; Maisch, 1992), the famous Grosser Aletsch glacier is well known to be the largest ice stream in the Alps (1850: 105.6 km^2; 1973: 96.1 km^2; Wipf, 1999).

The ice-decay reveals a surprising variety in individual glacier behaviour mainly due to local effects (differences in aspect, glacier bed and cirque catchment topography, wind effects, avalanches etc.) which are not easy to quantify. In general a significant inverse correlation with former glacier size can be observed (Gross, 1987; Maisch, 1992; Lieb, 1993). This correlation can be clearly seen also on the Bernina map (fig. 3). The group of small and tiny glaciers in 1850 tend to disappear completely. Glacier size is strongly connected with vertical glacier extension and therefore with size and topography of the ablation zone. A significant long-term 2:1-ELA shift affects quite large and important parts of the ice surface area to become an ablation zone for smaller rather than for larger glaciers. The latter still have much more extended accumulation areas in higher and cooler positions.

The glaciological cause of the remarkable glacier retreat since 1850 is a significant vertical shift of the equilibrium line (2:1-ELA) as the result of an estimated atmos-

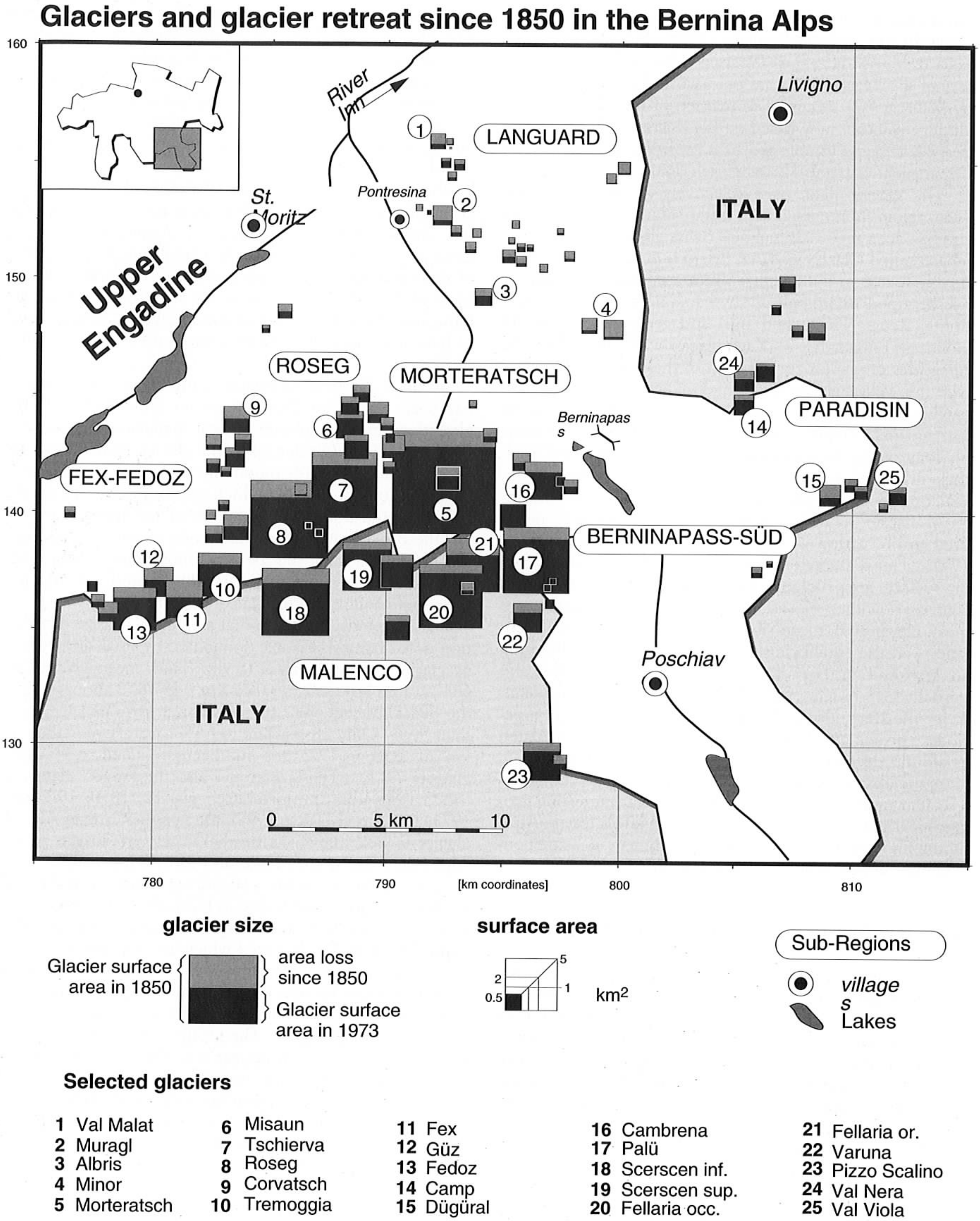


FIG. 3 - Glaciation and glacier retreat since 1850 in the Bernina region (Upper Engadin and adjacent regions of Italy) as recorded in the CH-INVGLAZ inventory. The rectangles represent every single glacier and its surface area in 1850, 1973 and the difference (area loss) since 1850.

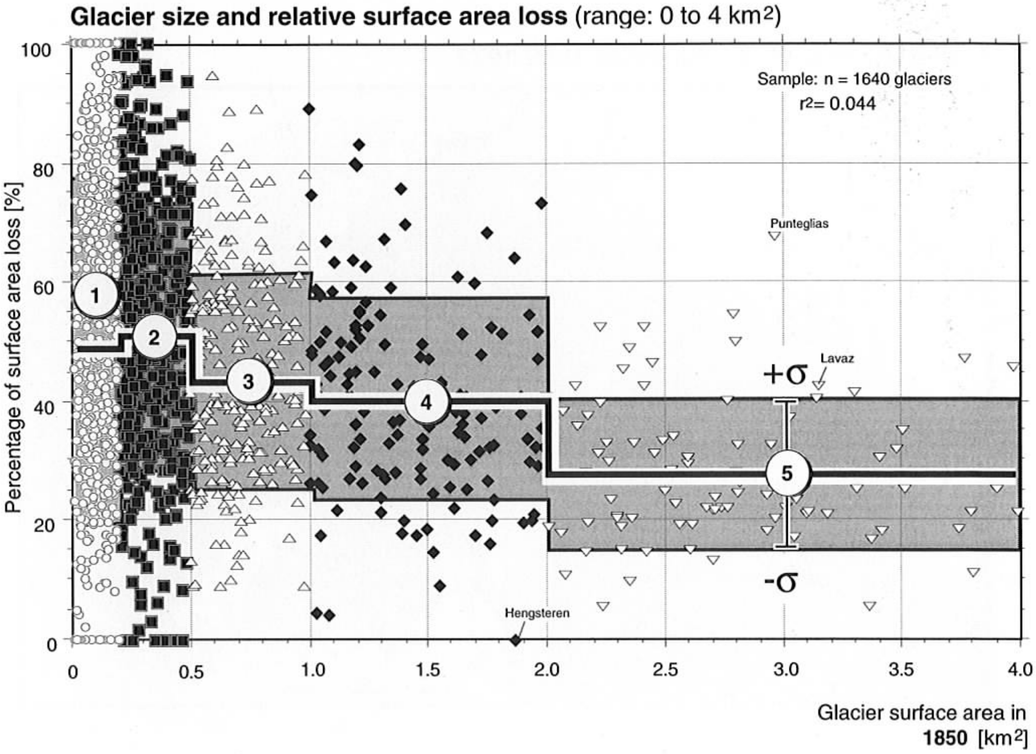


FIG. 4 - Regression plot of glacier size in 1850 and the percentile area loss since 1850 in the Swiss Alps (sample n = 1640 glaciers). The diagram shows the glacier size range between 0 to 4 km². Beside the wide variety in the reaction of the small and tiny glaciers the tendency to relatively smaller area losses with increasing glacier size can be clearly recognized.

pheric warming of about +0.5 °C - +0.7 °C. The 2:1-ELA, calculated with an AAR of 0.67 (Sc:Sa ≈ 2:1), determines in a complementary way the extent of the accumulation and ablation zones on the glaciers surface. Since the end of the Little Ice Age the mean vertical 2:1-ELA shift of glaciers with normal longitudinal profiles is in the order of +90 m. On an individual scale the parameter of 2:1-ELA shift displays a widely scattered variation, this is mainly due to the differences in ice topography interfering with the geometry of the 2:1-ELA method (Maisch, 1992). Re-

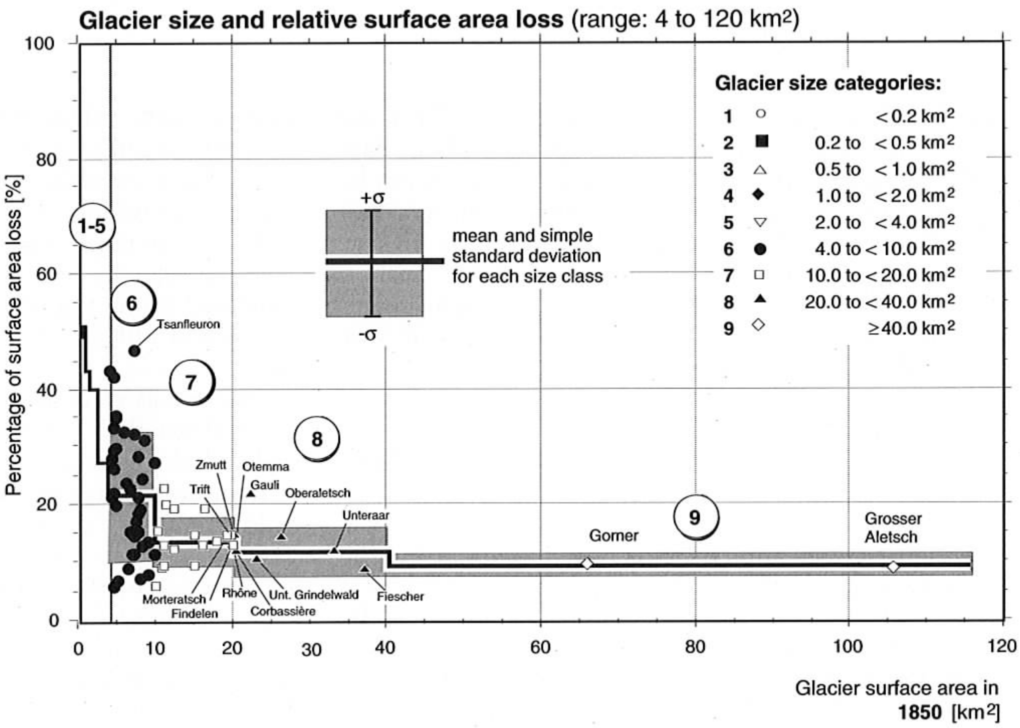


FIG. 5 - Regression plot of glacier size in 1850 and the percentile area loss since 1850 in the Swiss Alps (sample n = 1640 glaciers). The diagram shows, in addition to Figure 4, the glacier size range between 0 up to 120 km².

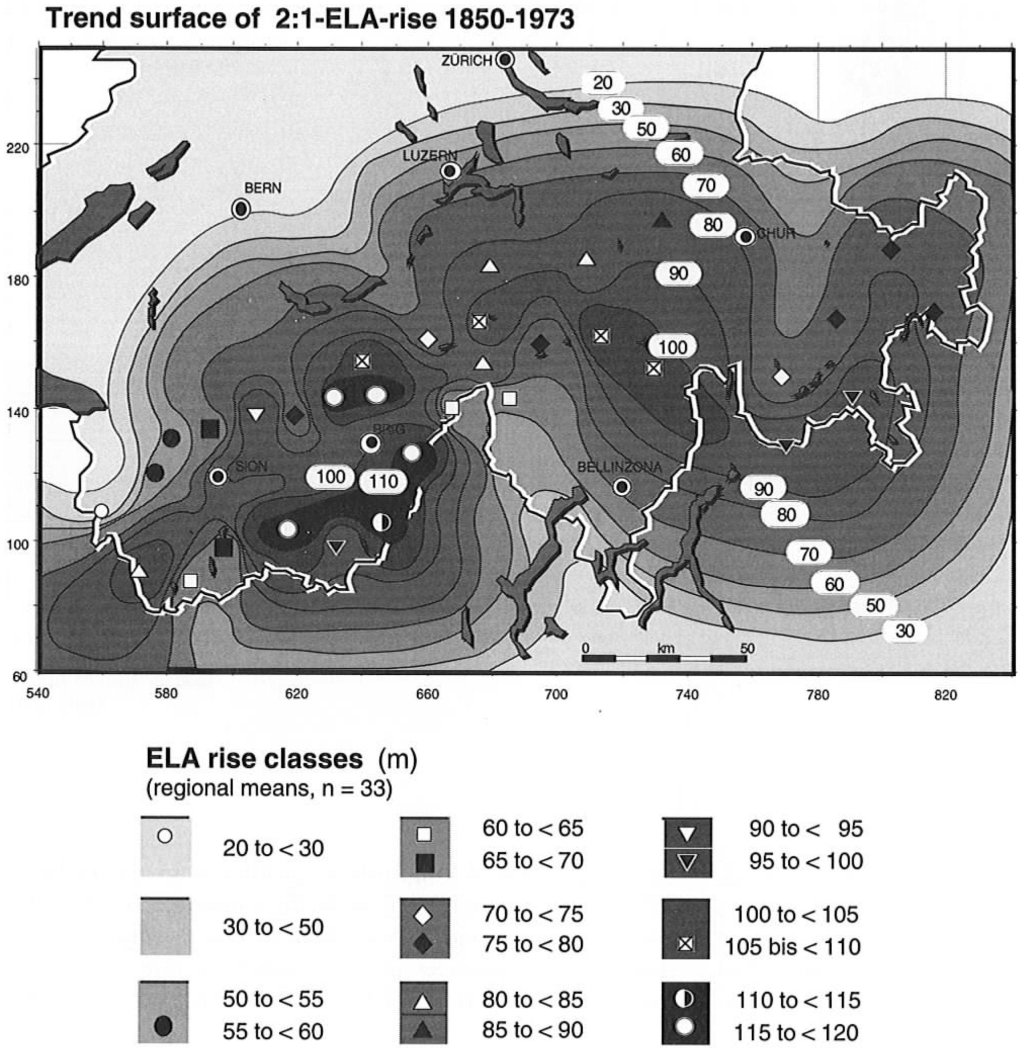


FIG. 6 - Trend surface map with spatial variation of the ELA-rise 1850-1973. The map is based on the regional means of north-facing glaciers with normal longitudinal profiles (n = 33 mountain ranges).

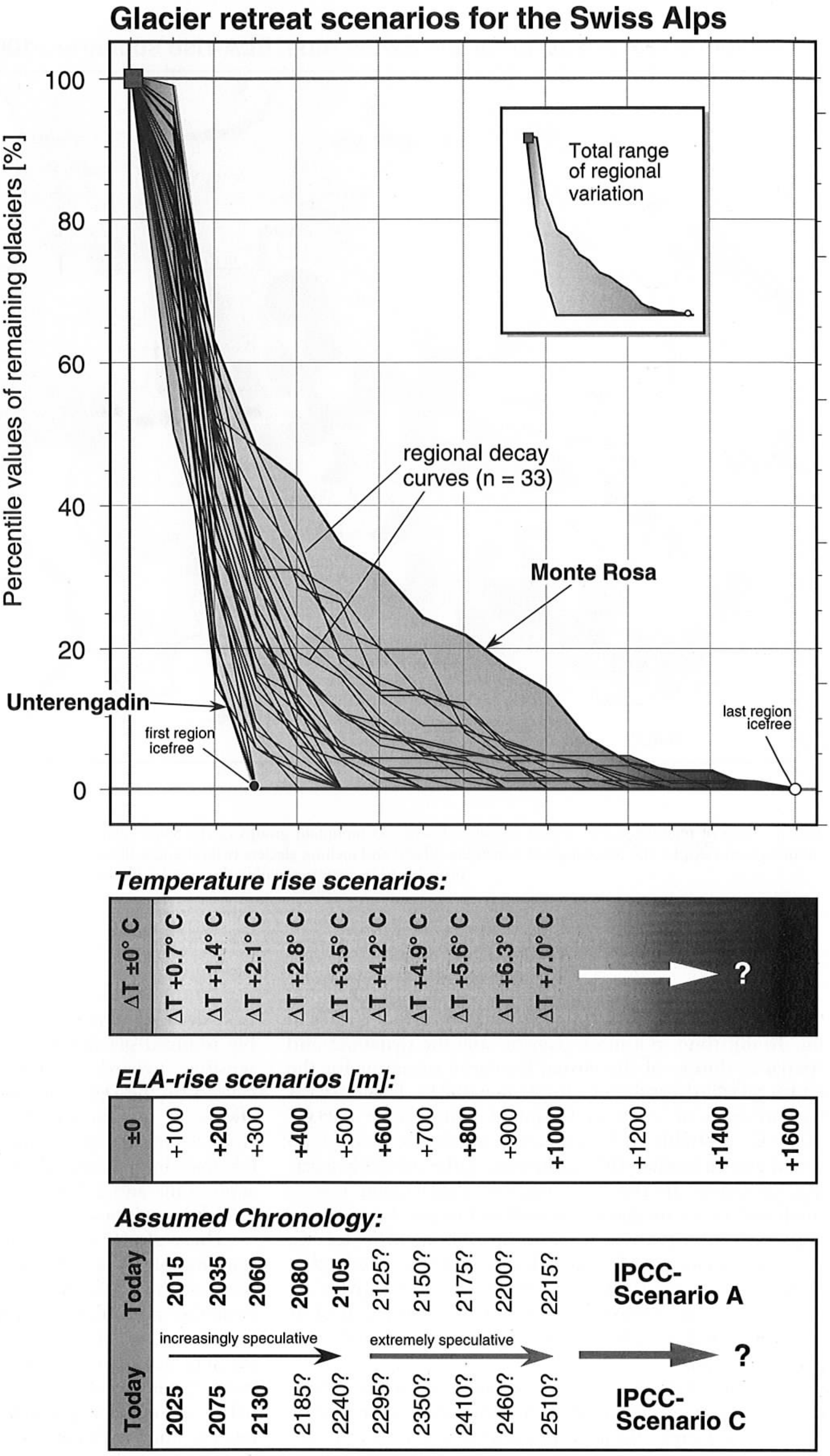
gional analysis show a tendency of smaller 2:1-ELA rise values at the northern border of the Alps and higher values in the southern parts (fig. 6). This slight tendency can be explained climatologically by a reduction in precipitation of 10-20% since 1850 in the southern parts of the Alps or, looking back in time, by a higher precipitation level in 1850. The differences in ELA rise vary from region to region and their statistical significance is, indeed, still very questionable (Maisch & *alii*, 1999/2000).

GLACIER RETREAT SCENARIOS 21ST CENTURY

In order to model potential future glacier scenarios a simple geometrical approach was used and applied to the whole Swiss glacier data set CH-INVGLAZ. The vertical interval between the 2:1-ELA 1973 and the maximum glacier elevation (highest glacier point) were taken as the key parameters in estimating the sensitivity of each glacier under different 2:1-ELA rise conditions. Those 2:1-ELA scenarios were calculated in 100 m «steady state» steps under the assumption that a glacier will disappear when its 2:1-ELA exceeds the upper glacier limit for long enough. According to this hypothesis each glacier was classified into the categories «melting» or «remaining» by checking step by step its remaining vertical extension compared to the virtual new 2:1-ELA position (2:1-ELA scenarios of +100 m, +200 m, +300 m, +400 m, ...+1000 m, etc.).

The results combined with given temperature rise scenarios (from IPCC, 1990, 1995) were regionally summarized and plotted in fig. 7. The simulation and the statistics of future ice retreat scenarios result in a dense bundle of regionally slightly different ice-decay curves. These curves indicate the percentage of remaining glacier bodies (y-axis) with respect to the assumed 2:1-ELA rise scenarios (x-axis). The steep slope of the outcoming curves in general leads to the conclusion that a tendency of accelerated ice decay may even start to occur as early as the first third of the next century.

FIG. 7 - Summary of different glacier retreat scenarios computed stepwise for the glaciation of the Swiss Alps. The curves display each of the 33 glacier regions with their individual ice-decay characteristics. In general the potential glacier retreat will be accelerated within the next decades according to the 2:1-ELA-rise scenarios to between +100 m (δT +0.7 °C) and +300m (δT +2.1 °C). The assumed temperature changes and time scales become increasingly hypothetical and are still very speculative.



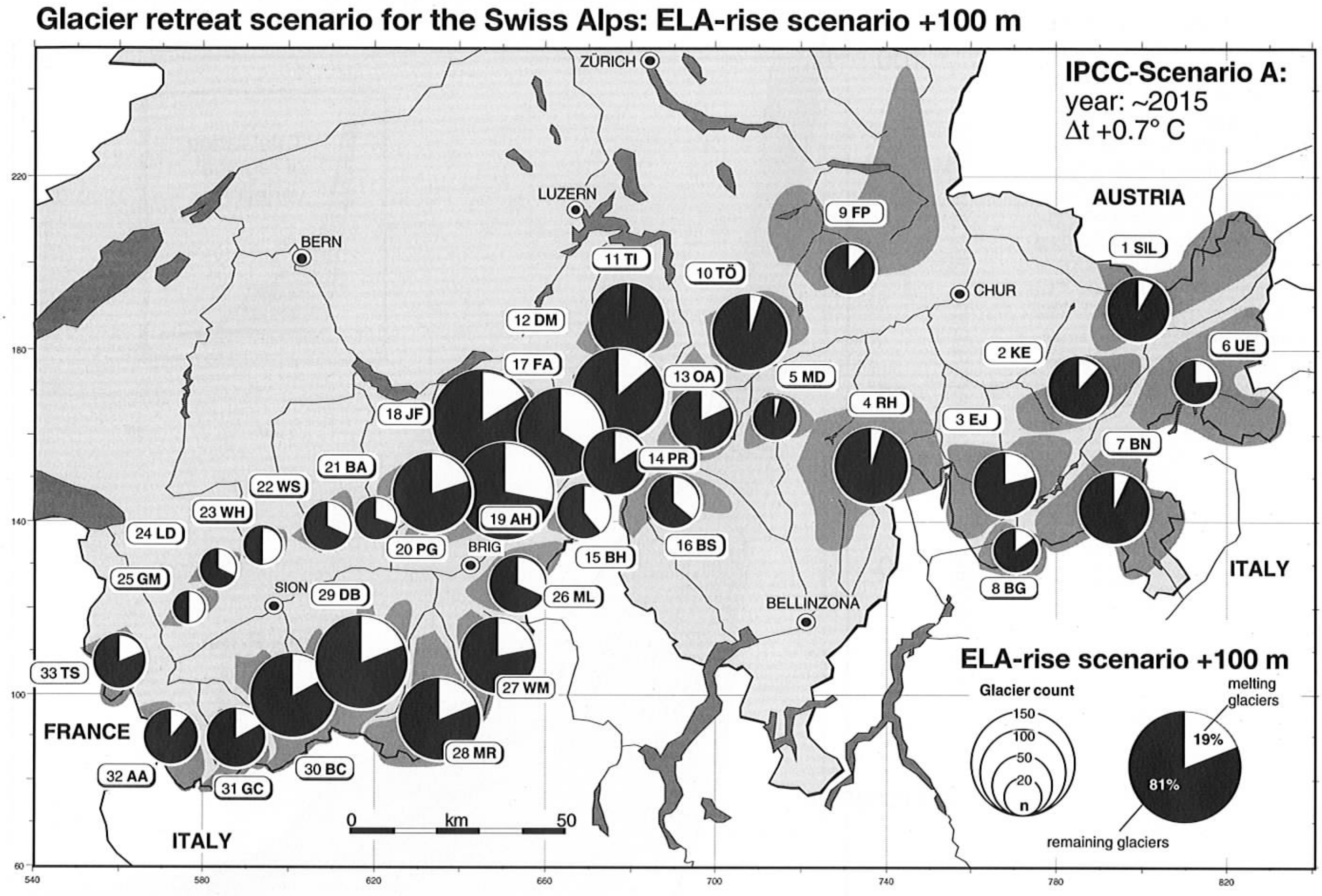


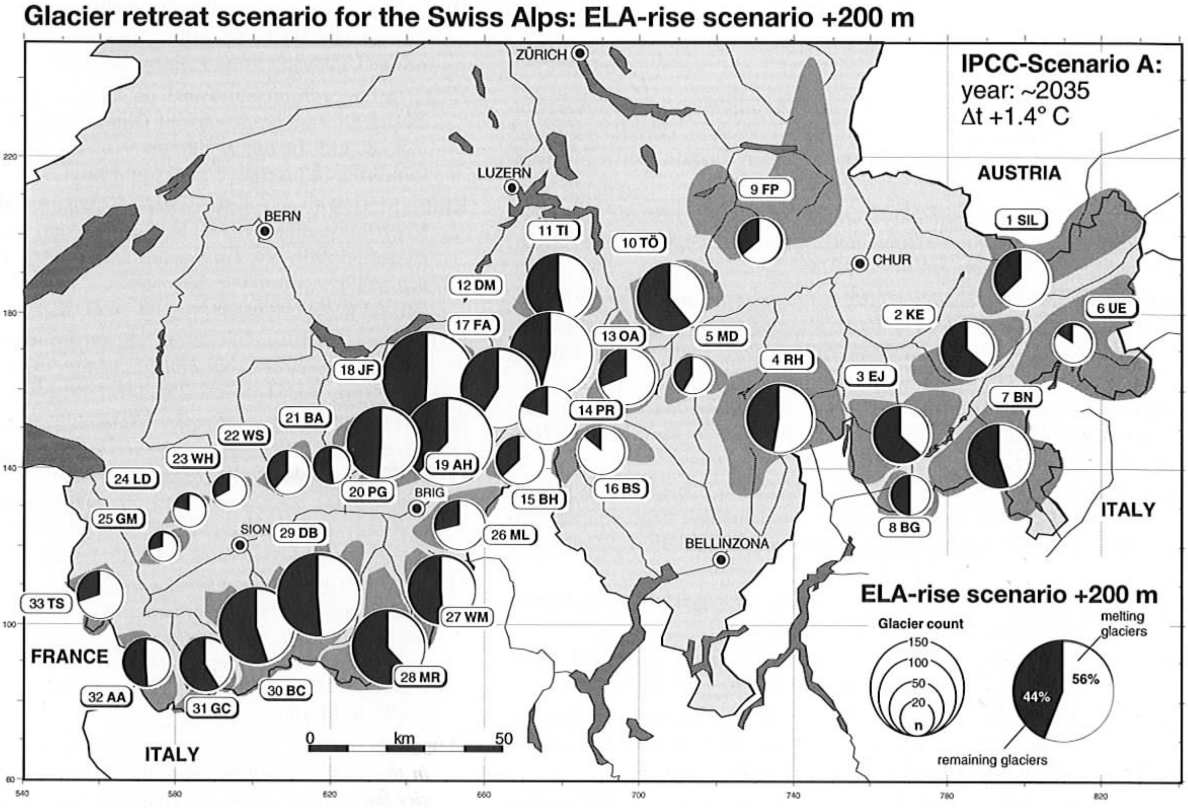
FIG. 8 - Map of regional glacier retreat scenarios for the 33 mountain groups of the Swiss Alps. The circles are proportional to the glacier sample (numbers) and display the percentage of remaining (black) and melting glaciers (white) under the assumed 2:1-ELA-rise scenario +100 m (δT + 0.7 °C; probably to be expected within the next 10-20 years).

The maps in fig. 8 and fig. 9 and with further details in fig. 10 illustrate in a more realistic way the dynamics and spatial evolution of the virtual ice-decay scenarios for the entire Swiss Alps (glacier sample n = 1923). The 2:1-ELA rise scenario of +100 m (assumed temperature rise δT +0.7° C, probably to be expected within the next 10-20 years) gives a further 19% reduction of the presently existing glaciation. In this first stage of deglaciation mainly small and very tiny glaciers as well as firn patches will disappear. A 2:1-ELA rise scenario of +200 m (δT +1.4 °C; perhaps realistic in a few decades) would give a reduction of nearly 60%, an ELA rise scenario of +300 m (δT +2.1 °C; end of 21st century?) will result in a reduction of at least 75% under such unfavorable climate and mass balance conditions.

The fact that the existing climate models still have many uncertainties means that the time table of the scenarios proposed here still is very speculative. One glaciological signal seems to come out very clearly: the phenomenon of potential ice-decay will be strongly accelerated in the next decades. The presently existing and already remarkably reduced glaciation seems to become more and more sensitive towards additional 2:1-ELA changes. This is caused by the significant loss in ice thickness since 1850, effects of albedo changes in the cirque headwall area (rock-ice interface) and the reduction of vertical extension (changes in area-altitude distribution), thus decreasing reaction time and enhancing the melting processes at higher 2:1-ELA positions.

These glacier retreat scenarios give us a better understanding of glaciers dynamics and the increasing vulnerability of the glacial and periglacial environments towards potential atmospheric warming scenarios. The process of continuing and probably accelerated glacier and ice melting (i.e. permafrost degradation) in high alpine environments could lead to a significant change in the risk potential of natural hazards (ice avalanches, debris flows, rock fall, etc.) under changed climate conditions (Zimmermann & *alii*, 1997; Haeberli & *alii*, 1998; Haeberli & Beniston, 1998; Haeberli & *alii*, 1999b).

FIG. 9 - Map of regional glacier retreat scenarios for the 33 mountain groups of the Swiss Alps. The circles are proportional to the glacier sample (numbers) and display the percentage of remaining (black) and melting glaciers (white) under the assumed 2:1-ELA-rise scenario + 200 m (δT + 1.4 °C; perhaps realistic in a few decades).



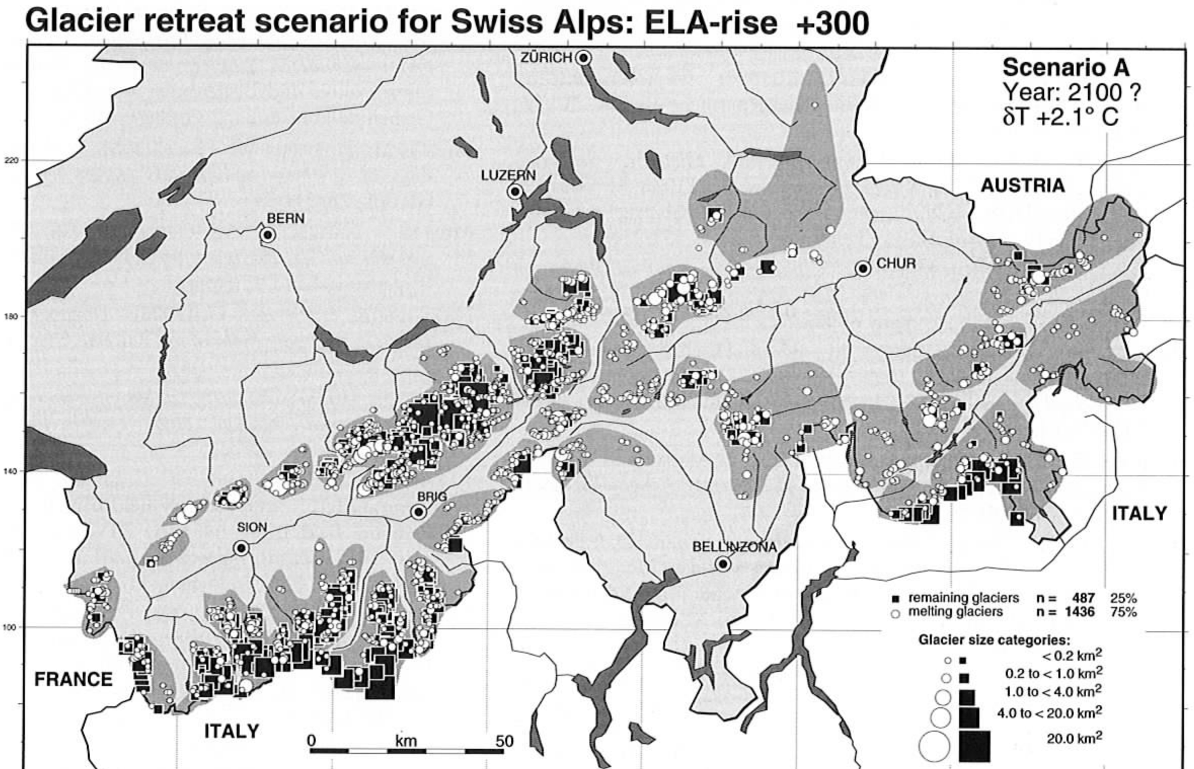


FIG. 10 - Map of the potential glacier retreat in the Swiss Alps within the next century. The black rectangles (grouped into size categories) represent the remaining glaciers the white circles indicate the melting glaciers under the assumed 2:1-ELA-rise scenario + 300 m (δT + 2.1 °C; end of 21st. century?).

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