

VANISHING GLACIERS IN THE EUROPEAN ALPS

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Introduction

With the romantic enthusiasm of the 18th century, the seemingly ‘pure, untouched and eternal’ snow and ice of glaciers in the European Alps became an important international tourist attraction and, in combination with the cultivated Alpine garden landscapes of the surrounding habitats, were also more and more perceived as a strong symbol for an intact relation between humans and their environment (Figure 1; cf. Nussbaumer *et al.* 2007). In the meantime, the continued and worldwide shrinking of such ice bodies and their possible disappearance in a rather near future turned mountain glaciers into unique demonstration objects of fast climate change at a global scale in policy-oriented observing systems (UNEP 2007, WGMS 2008). The two basic reasons for this are the facts that a broad public can easily recognize the ongoing changes in nature (glacier shrinkage) and also understand the major physical principles behind the phenomenon (melting of ice with rising temperatures). The task of scientific glacier research and monitoring concerns the detailed understanding of the complex physical processes involved and the quantification of the observed developments. In this contribution, the quantitative documentation of recent, ongoing and possible future glacier changes in the European Alps represents the main focus.

Glaciers of the European Alps play a central role in internationally coordinated glacier observations. For historical reasons, systematic glacier observations were initiated in this densely populated high-mountain region, and over more than a century of idealistic and patient work also provided an especially rich documentation (Haeberli 2008). Concepts of integrated glacier monitoring over entire mountain chains can be especially well demonstrated for the European Alps (Haeberli *et al.* 2007). The following overview relates to (a) the documented changes since the mid 19th century, (b) their relation to pre-industrial variability in glacier extent during historical times and the Holocene, and (c) modeled scenarios for the coming decades and the 21st century. It is primarily based on comprehensive quantitative studies concerning the entire sample of glaciers in the European Alps and regular assessments by the European Environment Agency. The

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corresponding publications (Haeberli and Hoelzle 1995; Haeberli *et al.* 2007; Levermann *et al.* 2011; Paul *et al.* submitted; Zemp *et al.* 2006, 2007, 2008, 2010) contain a large number of references to detailed process-oriented studies and local/regional observations.



Figure 1. Glacier extent in the Little Ice Age: The valley of Chamonix (French Alps) around 1810-1820 with the advancing 'Mer de Glace' glacier, painted by Jean-Antoine Linck ('La chaîne du Mont-Blanc vue de la Flégère'; signed at bottom 'Jn Ante Linck fec. '); water colour and gouache; 62.0 x 85.5 cm; Musée d'art et d'histoire, Genève, Inv. Nr. 1915-75; Photo H.J. Zumbühl).

Documented changes

The most direct signal of glacier change is the annual mass balance, i.e. the difference between accumulation of snow and ablation (mainly melting) of snow and ice during the warm part of the year; the resulting value is expressed as an annual thickness change averaged over the entire glacier surface and given in water equivalent (to correct for density effects and to make it intercomparable with other glaciers). The mean value obtained from continuous long-term measurements at nine glaciers in the Alps (Gries, Silvretta, Vernagt, Hintereis, Kesselwand, Sonnblick, Careser, Saint Sorlin,

Sarennes) can be considered to be well representative for the entire glacier surface area in the Alps, as indicated by the results from comparing digital elevation models for a large number of glaciers in Switzerland (Paul and Haeberli 2008). The plot of cumulative mass balances (Figure 2) reliably documents the evolution since about the mid-1960s. Following a time interval with small overall mass changes between 1965 and 1985, accelerating and sustained mass loss took place with decadal mean loss rates increasing to more than 1 m per year today. Such values strikingly exceed the reconstructed long-term average loss rates of 0.2 to 0.3 m per year (with extremes of about 0.1 to 0.6 m per year) for the 1850-1985 time period. These values from the past were reconstructed from cumulative length change measurements and repeated photogrammetric precision mapping of selected glacier surfaces (Haeberli *et al.*, 2007). As most glaciers of the mass balance network are comparably small with characteristic mean thicknesses of a few tens of meters only, they may vanish in a near future and, hence, bring important long time series of mass balance measurements to an end. In order to save

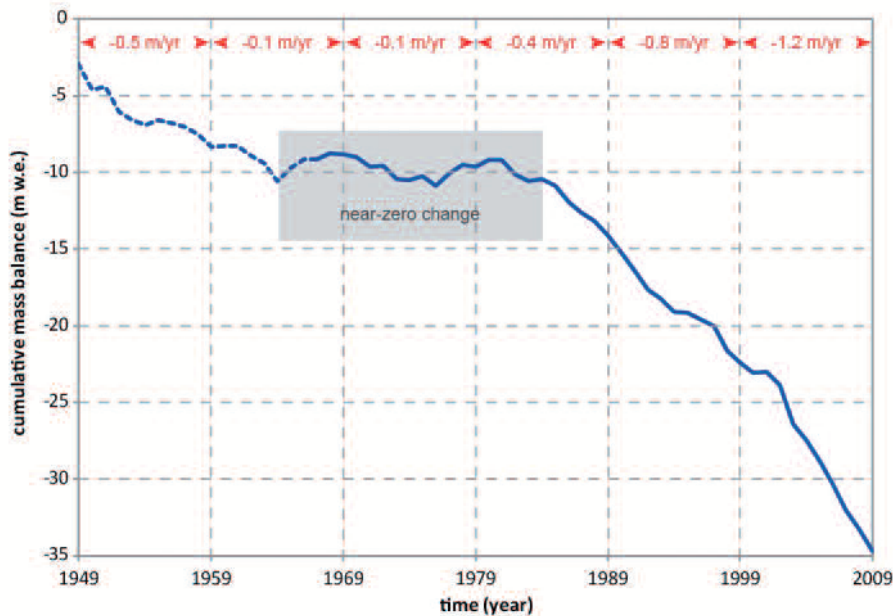


Figure 2. Cumulative mass balance (expressed as thickness change in m water equivalent averaged over the entire surfaces) of 9 Alpine glaciers with long-term observations (see text). Values for decadal means (in red) are rounded to the nearest tenth of a meter. Data source: WGMS (2009 updated, and earlier issues).

the continuity of observations, attempts are now made to start mass balance observations on glaciers, which are larger in size and elevation range.

The total glacier-covered surface area in the Alps decreased from some roughly estimated 4500 km² around 1850 to slightly more than 2900 km² in the 1970s, when systematic glacier inventories were compiled in all Alpine countries. The corresponding area loss rate of about 10 to 15 km² per year sharply increased after 1985 to about 40 to 45 km² per year, when the total glacier surface area was reduced to slightly more than 2000 km² in 2003. For that year, satellite images from the Landsat Thematic Mapper (TM) sensor enabled the compilation of a new, uniform and synchronous glacier inventory for the entire European Alps (Paul *et al.*, submitted). Simple extrapolation of the present loss rate indicates that the total glacier surface in 2010 is likely to be around 1800 km². With this area and average mass loss rates of -1.2 m per year, ongoing annual volume loss of the Alpine glaciers can be estimated at about 2 km³ per year. Estimates of the remaining glacier volume are more difficult and related to considerable uncertainty (probably ± 20 to 30%). First estimates based on tabular glacier inventory data and empirical relations between average basal shear stresses (maximum assumed: 150 kPa) and elevation ranges of individual glaciers were published in the 1990s (Haeberli and Hoelzle, 1995). They were recently further developed by a modeling approach using digitized glacier outlines and high-resolution digital terrain information (Linsbauer *et al.* 2009), creating a digital terrain model for the Swiss Alps 'without glaciers'. Slightly higher glacier volumes (but still within the estimated uncertainties) were obtained by model calculations for the 62 largest glaciers in the Swiss Alps using a combined surface mass balance and glacier flow approximation (Farinotti *et al.* 2009). The latter approach is calibrated using radar profiles across crevasse-free parts of glaciers, but leads to unusually high average basal shear stresses around 200 kPa. This is possibly due to an overestimation of ice thickness values in unmeasured steep/crevassed and thus shallower glacier parts. This latter approach may therefore provide 20–30% higher upper-bound volume estimates as given in brackets for the following rounded numbers. The total volume of the Alpine glaciers shrank from a very roughly estimated 200 to 300 km³ around 1850 at an average rate of about 0.5–1 km³ per year to 130 (170) km³ in the 1970s and to 100 (130) km³ around the turn of the millennium. With an annual volume loss of about 2 km³ per year since the year 2000 the total glacier volume in the Alps for the year 2011 can be estimated at some 80 \pm 25 km³ (cf. Levermann *et al.* 2011; Haeberli *et al.* 2007 most likely provide lower-bound values).

Beyond past variability ranges

Knowledge about glacier fluctuations during times before the Holocene maximum glacier extent around 1850 are based on length changes (advance and retreat of the glacier terminus) as documented from historical sources (paintings, etc.), lichenometry, moraine mapping, pollen analysis and tree studies (radiocarbon dating and dendrochronology). Corresponding mass balances for this period can be inferred using simple glacier models (mass conservation for step changes between equilibrium conditions) or statistical relations calibrated with modern measurements. Though the length of Alpine glaciers is not yet in balance with the current climate, it is partly already now more reduced than ever since the Middle Ages and even since Roman times. During these two millennia, characteristic long-term averages of mass balance have been ± 0.5 m, i.e. about half the sustained value observed since the turn of the millennium. In addition to the extraordinary rate of current mass losses, the length of the time interval of presently ongoing retreat and mass loss also appears to be unusual.

At some locations, glacier lengths now even reach conditions comparable to their minimum extent since the end of the Last Ice Age. In view of the delayed dynamic response of glacier length with respect to climate change, thickness and volume of smaller glaciers may already have reached previous minima. Remarkable findings in cold ice patches and miniature ice caps frozen to the permafrost at high elevation, confirm that ice disappearance in the Alps has developed beyond conditions of the past about 5000 to 7500 years (Oetztal Ice Man, several archeological findings at Schnidejoch, dating of a cold ice crest at Piz Corvatsch; May 2009). Ice conditions may now approach assumed minimum ice extent during the generally warmer early Holocene (ca. 6000–8000 years before Christ), when incoming solar radiation on the northern hemisphere was considerably higher than at present. Despite remaining uncertainties in detail, there is hardly any doubt that glacier shrinkage as an expression of increasing energy content in the climate system is about to leave – at extraordinarily high and even accelerating rates – the range of natural, pre-industrial variability.

Scenarios for the future

Simple comparison of ongoing loss rates (40–45 km² annual area loss, 2 km³ annual volume loss) with remaining glacier area (1800 km²) and ice volume (80 \pm 25 km³) indicates that the ice-vanishing process could essentially be complete within about 30 to 50 years only. There are, however, many ‘ifs’ and ‘buts’ which must be considered concerning such straightforward extrapolation of documented trends. Decreasing areas tend to re-

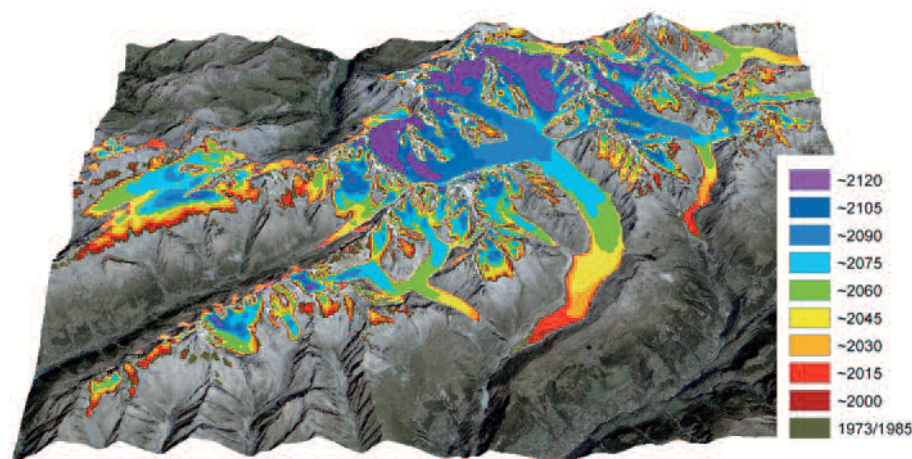


Figure 3. Example of modelled glacier extents in the Aletsch region (Swiss Alps) for a warming scenario of 4°C by 2100 (with unchanged precipitation and without lake formation). North is to the top, Rhone Valley at bottom right and Lötschen Valley at bottom left. This model assumes a continuation of the elevation loss rate as observed for the 1985-2000 period. The satellite images (Landsat and IRS-1C) are from the Swiss National Point of Contact (NPOC). DEM25: © 2011 swisstopo.

duce rates of area loss over time and major parts of the still existing ice volume are not directly exposed to rapid melting, because they are located deep below the surface within the thick ice of the largest glaciers. Increasing atmospheric temperatures, on the other hand, tend to intensify the melting process. Dust input during dry summers like 2003 markedly lowering the albedo of firn/ice surfaces (Paul *et al.* 2005, Oerlemans *et al.* 2009) and increasing signs of down-wasting, disintegration, collapse and subglacial cavity formation as well as the development of numerous new lakes also tend to increase the rate of ice vanishing (Paul *et al.*, 2007). Over the past two decades of intense mass reduction, many low-lying glaciers have lost their entire firn area, where normally accumulation should predominate over ablation. Without such a firn area, glaciers have no more possibility to survive. Accumulation area ratios as derived from mass balance measurements indicate that Alpine glaciers on average need to lose another third (600 km²) of their area in order to be in equilibrium with climatic conditions of the first decade of the 21st century. This means that – due to their delayed response – many (especially larger) glaciers in the Alps would continue to retreat far into the 21st century even with climatic conditions remaining constant from now on.

An increasing number of numerical glacier models are being applied to account – at least partially – for such effects. The simplest approximation using step changes between steady-state conditions (‘immediate’ response) provides robust results over time intervals corresponding to the dynamic response time (typically a few decades for Alpine glaciers). Transient model calculations treat effects of ‘delayed’ response but involve a number of uncertainties concerning details of dynamic processes (ice deformation and basal sliding) and of the mass- and energy fluxes at the surface. They nevertheless clearly show that – with plausible warming scenarios – even the largest glaciers can disintegrate within the coming decades (Figure 3) into a number of small glaciers, which might then rapidly disappear. An often-observed phenomenon is the separation of tributaries at steep slopes (where the ice is thin), partly leaving large dead ice bodies in the valley floors. In any case, both model types leave no doubt that the main vanishing phase of Alpine glacier ice will most probably take place within the first half of this century and that an almost complete deglaciation of the entire mountain chain could be completed towards the end of our century.

Perspectives

The possible to even probable disappearance of most Alpine glacier ice during the coming decades will have pronounced consequences for the high-mountain landscape, natural hazards and the water cycle. The latter primarily concerns the seasonal redistribution of water supply (Figure 4). Following a transitional time of enhanced runoff from high-mountain regions due to strong melting of still existing glaciers, water supply during the warm season will continuously decrease to much lower values than hitherto experienced. The influence of vanishing glaciers must thereby be considered in combination with earlier snowmelt and a trend towards hotter and dryer future Alpine summers in a generally warmer world (Huss *et al.*, 2008). Under such conditions – the extreme summer of 2003 may serve as an example – the lack of glacial melt water is likely to accentuate late summer droughts and impose critical limits to economic activities (river navigation, power production, irrigation for agriculture, etc.) even at a continental scale (cf. Huss 2011). At politically relevant time scales, such a development must be considered to be irreversible, because no more decision will be able to bring back – within useful times of months or years – the glaciers and their melt water during the hot/dry season.

Perhaps the most important aspect of Alpine glacier vanishing, however, relates to its signal function concerning much more general and more serious consequences of climate change. Coming generations will know what

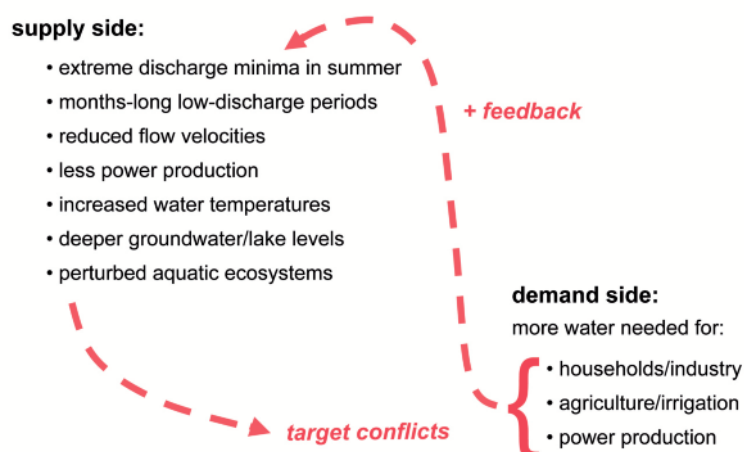


Figure 4. Possible future water stress: conditions of the extreme, hot/dry summer of 2003 in the last decades of our century with essentially deglaciated Alps and melting of the seasonal snow cover advanced in time by several weeks.

climate scenario indeed developed by looking at the fate of mountain glaciers all over the world. Their continued shrinking and vanishing can be seen as an important ‘writing on the wall’ – with the glaciers in the European Alps being among its best recognizable letters.

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