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# Alpine glaciers to disappear within decades?

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[1] Past, present and potential future glacier cover in the entire European Alps has been assessed from an integrated approach, combining in-situ measurements, remote sensing techniques and numerical modeling for equilibrium line altitudes. Alpine glaciers lost 35% of their total area from 1850 until the 1970s, and almost 50% by 2000. Total glacier volume around 1850 is estimated at some 200 km$^3$ and is now close to one-third of this value. From the model experiment, we show that a 3°C warming of summer air temperature would reduce the currently existing Alpine glacier cover by some 80%, or up to 10% of the glacier extent of 1850. In the event of a 5°C temperature increase, the Alps would become almost completely ice-free. Annual precipitation changes of ±20% would modify such estimated percentages of remaining ice by a factor of less than two. **Citation:** Zemp, M., W. Haeberli, M. Hoelzle, and F. Paul (2006), Alpine glaciers to disappear within decades?, *Geophys. Res. Lett.*, *33*, L13504, doi:10.1029/2006GL026319.

## 1. Introduction

[2] Impacts on cold mountain ranges from ongoing climate change are especially pronounced in regions above the timberline where effects related to perennial surface ice reflect increasing atmosphere/earth energy fluxes with extraordinary clarity [*Royal Swedish Academy of Sciences*, 2002]. Many mountain ranges have lost a significant proportion of their glacierization during the past 150 years with strong acceleration occurring in the past two decades [e.g., *Haeberli et al.*, 2005a, 2005b]. The shrinking of mountain glaciers is indeed the most obvious indication in nature of fast if not accelerating climate change on a worldwide scale. The predicted global temperature increase [*Intergovernmental Panel on Climate Change (IPCC)*, 2001] is likely to induce dramatic scenarios of future glacier developments including complete deglaciation of entire mountain ranges. Such future scenarios of glacier vanishing have thus far not been assessed quantitatively from spatial climatologies on an Alpine-wide scale, but are likely to affect landscape appearance, slope stability, the water cycle, sediment loads in rivers and natural hazards far beyond the range of historical and Holocene variability [*Watson and Haeberli*, 2004; *Barnett et al.*, 2005].

[3] In this study we apply an integrated approach, combining in-situ measurements, remote sensing techniques and numerical modeling to the European Alps. These techniques allow to quantitatively assess past as well as potential evolutions of area and volume of a glacier ensemble within an entire mountain chain. Glacier cover in the entire European Alps has been computed for different climate-change scenarios using satellite-derived glacier changes and a digital terrain model (DTM) together with a distributed model for equilibrium line altitudes (ELA). We thereby demonstrate the possibility of fast glacier disappearance within the European Alps, as well as the potential of new technologies to use information from glacier monitoring in mountain regions for quantification of global climate-change scenarios (Figure S1[1]).

## 2. Glacier Fluctuations From 1850–2000

[4] Information on glacier fluctuations in the European Alps is available from earlier and recent glacier inventories [*Haeberli et al.*, 1989; *Maisch et al.*, 2000; *Kääb et al.*, 2002; *Paul et al.*, 2002] (Figure S2) together with data compilations on past glacier fluctuations [*Zemp et al.*, 2006a] (Figure S2). National glacier inventories in the 1970s yield a total glacier area of 2909 km$^2$ [*Haeberli et al.*, 1989]. During the mid-1970s, glacier mass balances were close to zero or slightly positive [*Patzelt*, 1985] (Figure S3), many shorter glacier tongues slightly re-advanced and, hence, most glaciers were probably quite close to equilibrium conditions. The fact that the time basis for the corresponding inventory data is not uniform (Austria 1969, France 1967–71, Germany 1975, Italy 1975–84 and Switzerland 1973, cf. *Zemp et al.* [2006a]), therefore, plays a minor role: the center point of the corresponding time interval is thus defined as 1975. Detailed reconstructions of glacier areas around AD 1850 – the maximum extent for most glaciers in the European Alps at the end of the Little Ice Age – are available for the Swiss [*Maisch et al.*, 2000] and Austrian Alps (unpublished). The latest glacier inventory data based on satellite images is again available for most of the Swiss Alps in 1998/99 [*Kääb et al.*, 2002; *Paul et al.*, 2002], hereafter attributed to the year 2000 for the sake of simplicity. The Alpine glacier area in 1850 and 2000 is extrapolated by applying relative area changes for individual glacier size classes from the Swiss Alps to the corresponding entire Alpine glacier sample from 1975 (Table S1). This extrapolation reveals an overall loss in Alpine glacier area of 35% from 1850 up until 1975 ($-2.8\%$ per decade) and almost 50% by 2000 ($-3.3\%$ per decade). The area reduction between 1975 and 2000 is about 22% ($-8.8\%$ per decade), mainly occurring after 1985 (i.e., $-14.5\%$ per decade) as glacier fluctuation measurements and satellite-derived data have clearly shown [*Paul et al.*, 2004; *Zemp et al.*, 2006a] (Figure S3). Disintegration and

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2006gl026319.

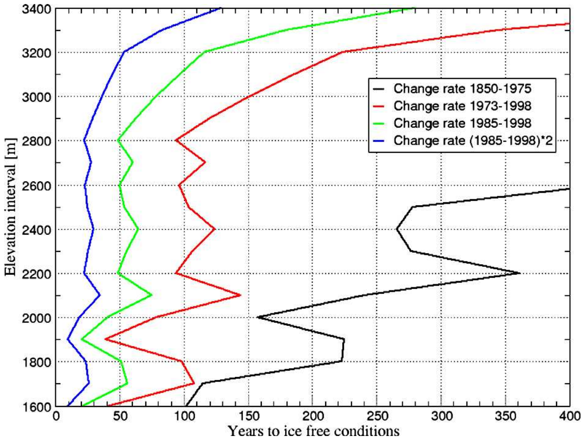

**Figure 1.** Years to ice-free elevation bands as obtained from the observed change in hypsography for two glacier samples (1850–1973 and 1973–1998, Figure S4). The glacier covered area in 1973 (1998) has been divided by the respective area loss per elevation band and multiplied with the number of years in the respective period (125, 25, 13, 6). Compared to the 1850–1973 period, there is not really a dependence of the change on elevation up to 2800 m a.s.l. for the more recent period.

'down-wasting' have been predominant processes of glacier decline during the most recent past [*Paul et al.*, 2004].

## 3. Assessment of Glacier Area Loss During the 21st Century

[5] Potential future area changes for the entire Alps are estimated by two independent methods. The first method is a purely empirical one that relates documented changes in glacier hypsography (i.e., rates of area change for altitudinal bands; see Figure S4) to scenarios of glacier shrinking, ranging from 'continued loss' (area reduction for the period 1850–1975), 'accelerated loss' (loss from 1975–2000), 'strongly accelerated loss' (period 1985–2000) and 'extreme loss' (using a doubled 1985–2000 loss rate). These scenarios cover the range of documented glacier shrinking rates and are related to a 20th-century warming of about 1°C in the European Alps [*Böhm et al.*, 2001]. The scenarios of future area losses (Figure 1) illustrate that the scenario of 'accelerated loss' would drastically reduce Alpine glacier areas within this century and that the scenario of extreme ice loss would cause most of the presently existing glaciers in the Alps to disappear within decades as large parts of the ice is located below 3000 m a.s.l. The 'extreme loss' scenario should be seen as an upper limit assumption but may not be unrealistic: hot-dry conditions like in the summer of 2003, which could occur at shorter and shorter intervals [*Schär et al.*, 2004] and involve strong reinforcing effects (albedo feedback, mass balance/altitude feedback, glacier down-wasting and collapse) could indeed soon bring about such a situation.

[6] The second method is based on the fact that, glacier health is primarily influenced by air temperature, while precipitation is the second most important climatic factor affecting their condition [*Kuhn*, 1981; *Oerlemans*, 2001]. The ELA on a glacier is a theoretical line which defines the altitude at which annual accumulation equals ablation. It represents the lowest boundary of climatic glacierization – that is, where the glacierization can begin. Hence, the second approach is a statistically calibrated and distributed model of ELA after *Lie et al.* [2003] that utilizes an empirical relation between 6-month summer air temperature ($T_{A-S}$, in degree Celsius) and annual precipitation ($P_a$, in millimeter) at the steady-state ELA ($\mathrm{ELA}_0$) [*Zemp et al.*, 2006b]:

$$P_a = 1773 \cdot e^{0.2429 \cdot T_{A-S}}$$

The relation is obtained from long-term mass balance data from 14 Alpine glaciers [*Haeberli et al.*, 2005a] in combination with gridded precipitation [*Frei and Schär*, 1998; *Schwarb et al.*, 2001] and temperature (interpolated from twelve high-altitude weather stations, cf. [*Zemp et al.*, 2006b]) climatologies of the period 1971–1990 and a DTM of 100 m cell size, resampled from the DTM of the Shuttle Radar Topography Mission [cf. *Rabus et al.*, 2003]. Its application to the entire European Alps enabled distributed modeling of the regional climatic ELA for zero mass balance ($\mathrm{rcELA}_0$) and the corresponding climatic accumulation area (cAA) above it (see Figure S5 for a diagram explaining this concept and *Zemp et al.* [2006b] for methodological details). The accumulation area over the entire Alps obtained from the reference model run (1971–1990) is 1950 km$^2$ and agrees well with accumulation areas of mapped glaciers (Figure S6).

[7] The impact on glacier areas as related to scenarios of temperature and precipitation change is illustrated in Figure 2. Atmospheric warming of 3°C in summer accompanied by an increase of 10% in annual precipitation would,

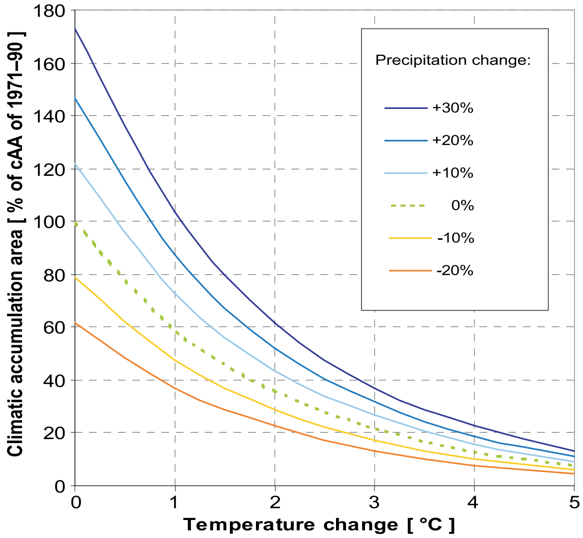

**Figure 2.** Modeled climatic accumulation area (cAA) according to changes in 6-month summer temperature and/or annual precipitation. The total of 100% refers to the cAA of the reference model run (1971–1990) and amounts to 1950 km$^2$. The changes in temperature and precipitation cover the range of the IPCC-scenarios [*IPCC*, 2001]. The dotted line refers to pure summer temperature changes (order of the lines correspond to legend).

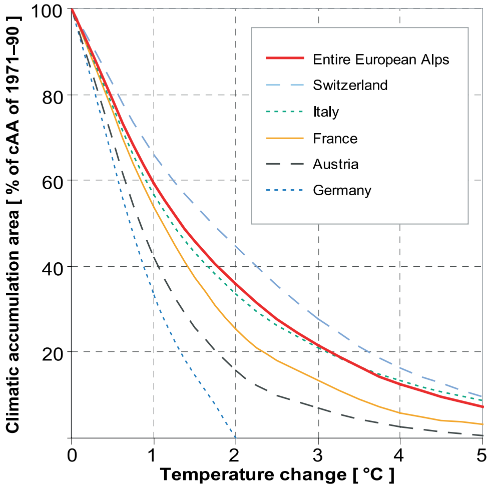

**Figure 3.** Modeled remains of Alpine glacierization as a consequence of a 1–5°C warming of the 6-month summer temperature. The total of 100% refers to the cAA of the reference model run (1971–1990) and amounts to 1950 km$^2$ for the entire European Alps. The 100%-marks of the other lines refer to the fraction of glacierization of the corresponding Alpine country.

for instance, raise the rcELA$_0$ by 340 m and reduce the cAA by 75% compared to the 1971–1990 reference period. Depending on the climate scenario chosen, this could take place toward the middle or the end of this century [*IPCC*, 2001]. Due to the strong warming in the past two decades, more than one-third of this glacier area reduction has already been taking place [*Paul et al.*, 2004; *Zemp et al.*, 2006a]. An increase in summer air temperature of 5°C would reduce the glacier cover by more than 90% as compared to the reference period. Precipitation changes of ±20% would modify such estimated percentages of remaining ice by a factor of less than two. Many individual mountain ranges within the Alps would become ice-free under such conditions and only rather small glacier remnants would persist in a few regions with the highest mountain peaks (Figure 3 and Figure S6). Because Alpine glaciers were close to equilibrium conditions during the reference period (1971–1990), the model is able to compute plausible rises of the rcELA$_0$ and corresponding cAA for the range of climate change scenarios for the 21st century. Present ablation areas, however, will respond with a certain delay to such fast changes and glacier mass balance will be far away from steady-state conditions. The presented results confirm earlier (independent) estimates from modeling of statistical glacier data [*Haeberli and Hoelzle*, 1995; *Maisch et al.*, 2000] and show that the calculation is robust.

## 4. Estimations of Past, Present, and Future Ice Volumes

[8] Changes in glacier volume are calculated by multiplying representative mass balance values with the average surface area (the mean of the areas at the beginning and end) of a given time period. Mean mass balance of nine Alpine glaciers between 1975 and 2000 was almost −0.5 m water equivalent (w.e.) per year (Figure S3). This is about twice the loss rate reconstructed from cumulative length change for the time period after 1850 [*Haeberli and Hoelzle*, 1995; *Hoelzle et al.*, 2003; *Steiner et al.*, 2005] and characteristic long-term mass changes during the past 2000 years [*Haeberli and Holzhauser*, 2003]. The cumulative balance of −12 m w.e. over a mean glacier area of 2590 km$^2$ during the same time interval (1975–2000) indicates a lower limit of the corresponding volume loss of 30 km$^3$. As average slope and ELA have increased, but glacier size (as well as altitudinal extent, mass flux and driving stress) decreased, the percentage of volume loss must be even greater than the calculated area loss of 22% (see remarks on volume estimations in auxiliary material). Based on this assumption, the estimated volume loss (30 km$^3$) corresponds to 25–30% of the total Alpine ice volume in the 1970s. This estimates show that the glaciers in the Alps have lost an average of 1% of their volume per year since 1975. On the same basis, total Alpine ice volumes can be estimated roughly as 105 ± 15 km$^3$ in 1975, and 75 ±10 km$^3$ at the turn of the century [*Paul et al.*, 2004], that is, considerably lower than the 130/100 km$^3$ estimated earlier [*Haeberli and Hoelzle*, 1995]. Total glacier volume for the end of the Little Ice Age (around 1850) with an extrapolated total glacierized area of 4475 km$^2$ is estimated at some 200 km$^3$ or more, and is now close to one-third of this value.

[9] Mean ice depth over the entire remaining glacier area of the Alps, calculated as the quotient of ice volume and area in 2000, is only about 30–35 meters. The average mass balance of −2.5 m w.e. in the extreme year 2003, therefore, eliminated an estimated 8% of the remaining Alpine ice volume within one single year [*Haeberli et al.*, 2005a; *Zemp et al.*, 2005]. The following year 2004 with an average mass balance of −1 m w.e. reduced an additional 3%, leading to about 10% volume loss in only two years. Extremely hot and dry summers such as 2003 thus not only induce strong positive feedbacks, but also eliminate increasing percentages of shrinking total ice volume. It is likely that five rather than ten repetitions within the coming decades of conditions as in 2003, would bring out this scenario of widely deglaciated Alps. As 90% of all Alpine glaciers are smaller than 1 km$^2$, the probability that most glaciers in the European Alps will disappear within the coming decades (Figure 3) is indeed not insignificant. The few largest valley glaciers with maximum ice thicknesses of several hundred meters will be able to resist such warming effect for somewhat longer. However, reinforcing mechanisms such as the mass balance/altitude feedback or the development of glacier lakes will also increasingly enhance their wasting.

## 5. Discussion and Conclusions

[10] The major sources of error and corresponding consequences for the three methods (a: scenarios for changes in glacier hypsography, b: distributed ELA model, c: volume estimations) are: for a), the representativity of the analyzed sub samples for the entire Alpine glacierization, which might bias the rates of ice loss due to regional peculiarities, for b), the neglect of topographic effects (e.g., snow drift, avalanches, radiation) leading to differences between the modeled rcELA$_0$ and the local topographic ELA$_0$, and the assumption of a constant accumulation area ratio, resulting in an uncertainty in the extrapolation of glacier changes

from the modeled cAA to the total glacier area, and for c) the representativity of average reconstructed/measured mass balance values from the used glacier samples for the entire Alpine glacierization in 1850/1975/2000, resulting in estimated thickness changes biased by mid-size glaciers [cf. *Zemp et al.*, 2006a].

[11] Glaciers in the European Alps lost almost 50% in area from 1850 to 2000. The area reduction between the 1970s and 2000 is about 22%, mainly occurring after 1985. Total glacier volume around 1850 is estimated at some 200 $km^3$ and is now close to one-third of this value. From the model experiment, we show that the probability of Alpine glaciers disappearing within the coming decades is far from slight.

[12] Modern strategies of glacier observations established within international monitoring programs make use of fast-developing new technologies and relate them to traditional approaches in order to apply integrated, multilevel concepts [*Haeberli*, 2004]. The combination of in-situ measurements with remote sensing, digital terrain information and numerical models thereby allows for comprehensive views by assimilating individual observational components over different scales in space and time. Glacier changes as a function of climate change are not only easily observed, they are also comprehensible, in their basic physical principles, to a large public. By simply looking at the evolution of glaciers in the mountain ranges of the world, coming generations will be able to define and to physically see whether and at what rate climate change has taken place.

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