Potential SLR estimates from the glacierisation of an entire mountain range as exemplified with observations from the European Alps

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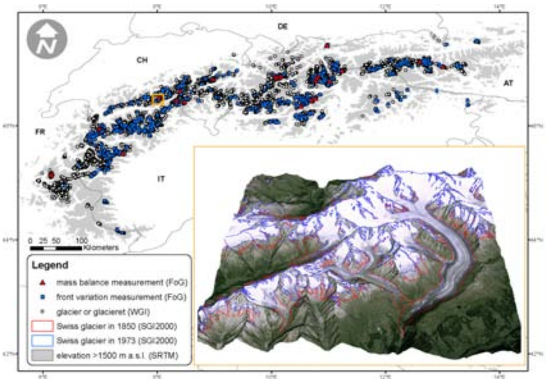
Introduction

Total ice volume of glaciers and ice caps (excluding Greenland and Antarctica) corresponds to a sea level rise (SLR) equivalent of about 0.5 m (e.g., Meier & Bahr 1996, Dyurgerov 2002). The ice cover of the European Alps thereby only contributes by about 0.3 mm.

However, the extensive amount of available information on glacier distribution and fluctuations (Figure 1), dating back to 1850, allows to apply and validate common scaling approaches for the estimation of glacier area and volume changes and its projection into the 22nd century.

Figure 1



Conclusions

Modern strategies of glacier monitoring combine in-situ measurements, remote sensing techniques and numerical modelling (cf. Haeberli 2004). This approach allows to assess past as well as potential evolutions of area and volume of a glacier ensemble within an entire mountain range.

Overall area loss of glaciers in the European Alps amounts to almost 50% between 1850 and 2000. The Alpine ice volume is now close to one third of the value back in 1850. The model experiment shows that the possibility of Alpine glacier to disappear within decades is far from slight.

The main uncertainty of these estimations comes from the representativity of the available measurements for the entire Alpine glacierisation, and the volume estimations.

Area extrapolations

Complete Alpine ice coverage can be compiled for the 1970s, when the about 5,150 glaciers covered a total area of 2,909 km^2 (Haeberli et al. 1989). In the 1970s, 90% of the glaciers were smaller than 1 km^2 and corresponded to about 30% of the Alpine glacierisation. The 34 largest glaciers make out almost 25% of the overall ice cover. This Alpine inventory is used together with digital outlines from the Swiss Glacier Inventory (Kääb et al. 2002, Paul et al. 2002) and in consideration of relative changes* of different glacier size classes (Table 1) to extrapolate total Alpine glacier covers in 1850§ and 2000§ which amount to 4,475 km^2 and 2,270 km^2, respectively. This corresponds to an overall loss from 1850 up until the 1970s of 35%, and almost 50% by 2000. Thereby, the relative loss of area decreases with glacier size.

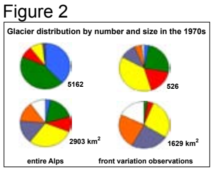
Haeberli & Hoelzle (1995) estimated glacier area loss between 1850 and the 1970s from an empirical relationship between glacier area and length, derived from the 1970s inventory and cumulative front variation measurements, resulting in an area loss of 35% as well.

The major sources of error of these approaches are the assumption that the used subsamples (Swiss glaciers and glaciers with front variation measurements, respectively) are representative for the entire Alps (cf. Table 1 and Fig. 2) and that the empirical relationship between glacier area and length is constant over time. The used sample of Swiss glaciers covers all glacier size classes and corresponds to about 45% of the Alpine glacierisation.

Table 1

class	Switzerland (SGI2000)								Alps			
	1850		1973		2000		1850–1973*	1973–2000*	1970's		1850§	2000§
[km^2]	num.	area [km^2]	num.	area [km^2]	num.	area [km^2]	area change [%]	area change [%]	num.	area [km^2]	area [km^2]	area [km^2]
< 0.1	297	17.3	1022	40.1	164	3.6	-55.4	-64.6	1953	100.7	225.5	35.6
0.1–.5	715	181.3	673	153.9	448	60.3	-52.9	-45.6	2254	497.0	1055.0	270.4
0.5–1	249	172.5	151	104.1	131	63.5	-44.3	-29.1	430	299.8	538.0	212.6
1–5	253	524.4	157	296.0	141	217.1	-33.2	-17.9	425	862.3	1291.1	707.9
5–10	26	195.5	35	249.4	36	232.6	-19.7	-10.8	66	461.7	574.8	412.1
10–20	18	259.9	14	216.3	13	192.8	-14.8	-8.2	27	387.9	455.1	356.1
> 20	9	270.5	5	225.9	5	213.0	-12.3	-5.7	7	293.6	334.8	276.9
Total	1567	1621.4	2057	1285.7	938	982.9	-27.1	-16.1	5162	2902.9	4474.3	2271.6

Figure 2



Volume estimations

Changes in glacier volume can be calculated by multiplying representative mass balance values with the average surface area of a given time period. Thereto, average mass balance values as reconstructed from cumulative glacier length changes (-0.25 m w.e. a^{-1}; Haeberli & Hoelzle 1995) and from mass balance measurements (-0.5 m w.e. a^{-1}; Figure 3) were used for the periods 1850–1975 and 1975–2000, respectively. The cumulative balance of -12 m w.e. over a mean glacier area of 2,590 km^2 during the same time interval (1975–2000) indicates a volume loss of 30 km^3. As average slope and equilibrium line altitude have increased, but glacier size, altitude extent, mass flux and driving stress decreased, the percentage of volume loss must be even greater than the calculated area loss of 22%. On this basis, the total Alpine ice volume can be roughly estimated as 200 km^3 in 1850, 105 km^3 in the 1970s, and 75 km^3 in 2000. The crucial element of this estimation is the representativity of the reconstructed/measured mass balance values for the entire Alpine glacierisation (Figure 4).

The often used, straigthforward volume-area scaling (e.g., Bahr et al. 1997) is simple but problematic due to autocorrelation and, hence, masks the large scatter (~ ±30%) in glacier thickness as related to glacier area. A more process-oriented approach computes mean glacier thickness along the central flowline from mean surface slope as related to the average shear stress (Haeberli & Hoelzle 1995; Figure 5). These approaches result in volumes of 140 km^3 and 130 km^3 for the 1970s. The resulting range of estimated volumes corresponds to one third of the potential SLR equivalent.

Figure 3

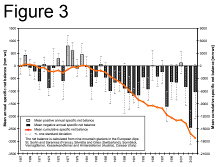


Figure 4

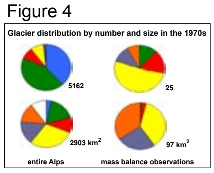
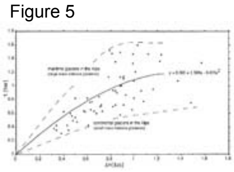


Figure 5



Future projections

A numerical model, based on an empirical relationship between annual precipitation and summer temperature at the glacier steady-state equilibrium line altitude, is used in combination with a digital terrain model and GIS-techniques to model the climatic accumulation area over the entire European Alps (Lie et al. 2003, Zemp et al. accepted). Based on the reference model run (1971–1990) the impact of the range of IPCC (2001) scenarios of changes in precipitation and temperature on the Alpine glacierisation was investigated (Zemp et al. submitted).

The study shows that a 3 °C warming of summer air temperature would reduce the Alpine ice 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 2.

The model uncertainties include the neglect of topographic effects (e.g., snow drift, avalanches, radiation) and the assumption of a constant glacier accumulation area ratio over time.

Figure 6

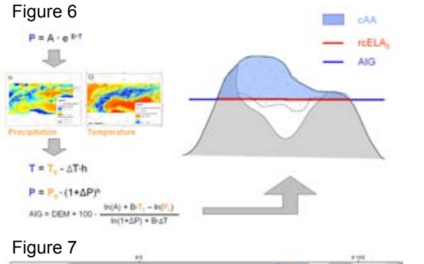
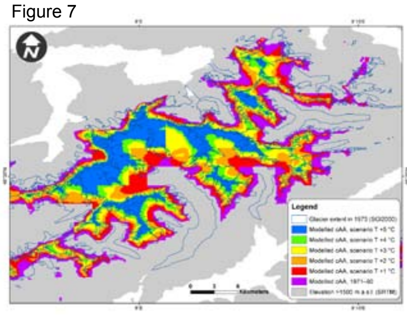


Figure 7



Perspectives

International glacier monitoring programmes such as the World Glacier Monitoring Service (www.wgms.ch) and the GLIMS project (www.glims.org) aim at compiling inventory and fluctuation information for all glacierised mountain ranges, so that sound worldwide estimations of glacier area and volume should become available one day (cf. Raper & Braithwaite 2005). With increasing availability of digital terrain models and gridded climatologies with high temporal and spatial resolution, simple but robust modeling approaches can help to quantify the impact of potential climate change on glaciers and corresponding SLR of the different mountain ranges of the world.

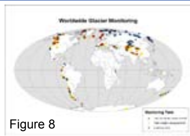


Figure 8

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