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100-year mass changes in the Swiss Alps linked to the Atlantic Multidecadal Oscillation

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[1] Thirty new 100-year records of glacier surface mass balance, accumulation and melt in the Swiss Alps are presented. The time series are based on a comprehensive set of field data and distributed modeling and provide insights into the glacier-climate linkage. Considerable mass loss over the 20th century is evident for all glaciers, but rates differ strongly. Glacier mass loss shows multidecadal variations and was particularly rapid in the 1940s and since the 1980s. Mass balance is significantly anticorrelated to the Atlantic Multidecadal Oscillation (AMO) index assumed to be linked to thermohaline ocean circulation. We show that North Atlantic variability had a recognizable impact on glacier changes in the Swiss Alps for at least 250 years.
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1. Introduction

[2] The response of mountain glaciers to climate change is crucial to the projection of sea level rise [*Meier et al.*, 2007], the management of water resources, and the anticipation of natural hazards triggered by glacier retreat. Long data series are a key element in the glacier-climate linkage. However, only about 250 glacier mass balance time series are currently available worldwide [e.g., *Dyurgerov and Meier*, 2005]. These series have been extrapolated globally, generally assuming that they represent large areas, in order to assess the total contribution of mountain glaciers and ice caps to observed sea level rise [*Kaser et al.*, 2006]. Furthermore, mass balance time series rarely start before the 1960s and often only span a few years. Some series show variations in phase with atmospheric indices such as the North Atlantic Oscillation [*Reichert et al.*, 2001; *Rasmussen*, 2007], however, the glacier records are normally too short to establish a link to natural multidecadal oscillations in the climate system.

[3] This study combines surface elevation data and a comprehensive set of in-situ measurements with mass balance modeling to compute 100-year time series of daily melt, snow accumulation and surface mass balance for thirty Swiss glaciers (Figure 1) on a 25 × 25 m grid for the period 1908 to 2008.

2. Data and Methods

[4] The thirty investigated glaciers cover 30% of the total glacierized area of Switzerland and include different sizes, exposures and regional climate conditions. For each glacier, up to 9 high-accuracy digital elevation models (DEMs) are available from different dates over the 20th century (Table S1 of the auxiliary material), mostly originating from aerial photogrammetry.[5] Differencing of successive DEMs allows the calculation of changes in ice volume over periods of several years to decades [*Bauder et al.*, 2007]. In addition, almost 10,000 direct point mass balance measurements for both seasonal and annual periods are available. They cover most of the investigated glaciers and span from the 1910s to present for some sites (Figure 1b).

[5] The surface mass balance of alpine glaciers is determined mainly by solid precipitation (accumulation) and melt (ablation). In order to quantify these components of the mass budget with high temporal and spatial resolution, we apply a distributed accumulation and temperature-index melt model [*Hock*, 1999; *Huss et al.*, 2008] forced with daily mean air temperature and precipitation recorded at various weather stations (Figure S1). The model is constrained by in-situ field data for each glacier individually (Figure 1b): (i) ice volume changes obtained from DEM differencing, and, where available, (ii) in-situ point annual balance and (iii) winter accumulation, and (iv) discharge data. For details on the model and the calibration procedure refer to the auxiliary material or to *Huss et al.* [2008]. We evaluate 'conventional' specific mass balances in water equivalent, defined as a glacier's snow accumulation minus melt over one year divided by that year's glacier surface area.

3. Alpine Glacier Mass Loss

[6] All glaciers show a considerable decrease in ice mass throughout the 20th century (Figure 2). However, large differences in the magnitude of mass loss between the individual glaciers are evident with the cumulative specific mass balance varying by a factor of more than three. We thus caution against assuming single glacier mass balances to represent entire mountain ranges in regional and global scale glacier change assessments. The strong differences (Figure 2) in the rate of mass change do not follow a clear regional pattern (Figure S2); multiple regressions with geographic location,

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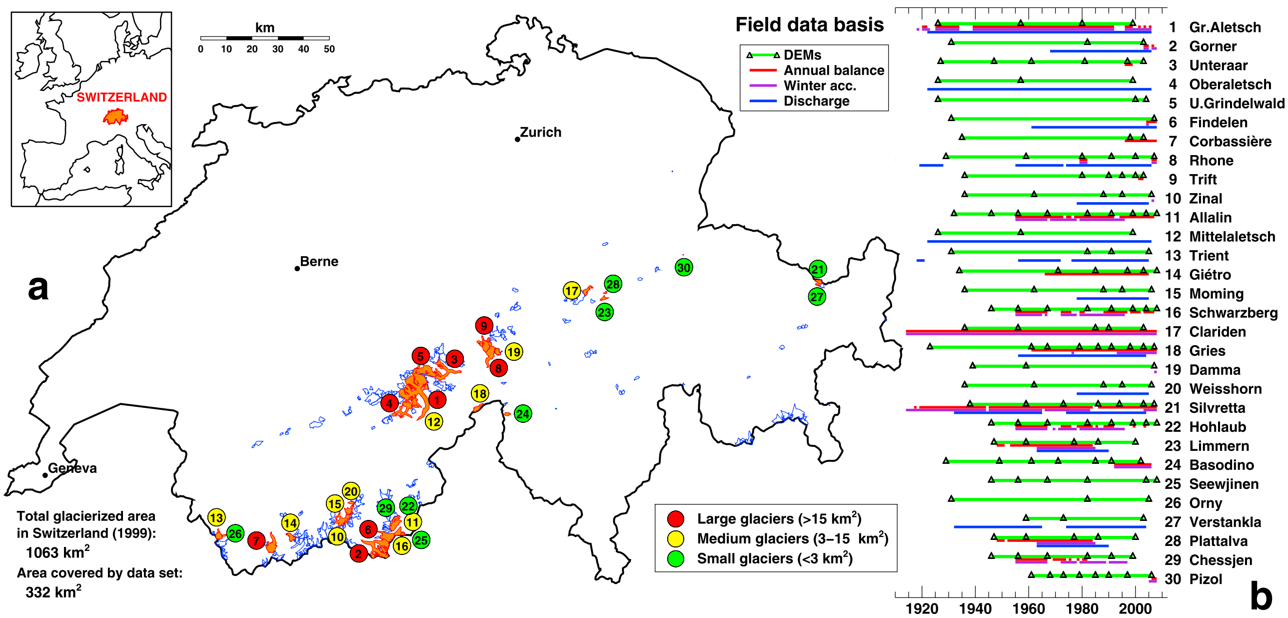

Figure 1. (a) Overview map. Investigated glaciers (orange) are numbered according to their size indicated by the color of the dots. (b) Periods covered with field data displayed by bars: (i) ice volume changes (dates of DEMs shown with triangles), (ii) point annual balance, (iii) winter accumulation, and (iv) discharge.

glacier area and exposure did not reveal any straightforward relations. However, large and more gently-sloping glaciers tend to have more negative mass balance. They take more time to adjust their size to the changed climatic conditions and hence (in the present climate) have a disproportionately large area fraction at low elevation with high ablation. In addition, regional variations in snow deposition due to changes in large-scale atmospheric flow paths over time [*Beniston*, 1997], and differences in melt rates due to positive and negative feedback mechanisms, e.g., enhanced dust concentration on bare ice surfaces [*Oerlemans et al.*, 2009] or increased debris coverage on glacier tongues, may contribute to the observed spatial variability in specific mass balances.

[7] We detect two short periods of mass gain (1910s and late 1970s) and two periods of rapid mass loss (1940s and late 1980s to present). Due to a lack of sufficient data, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [see *Kaser et al.*, 2006] does not present mass changes of mountain glaciers and ice caps prior to 1941 and the global estimates prior to 1961 are highly uncertain. The

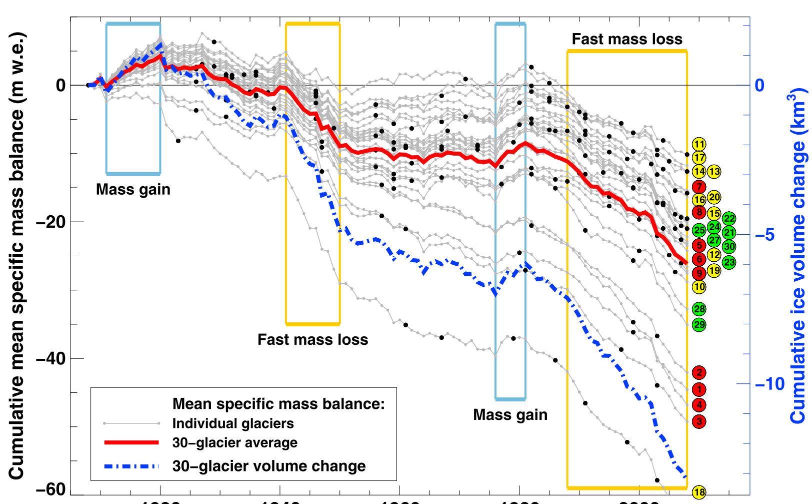

Figure 2. Cumulative mean specific mass balance of 30 Swiss glaciers and their total cumulative volume change in the 20th century. Series for the individual glaciers are shown in grey; black dots indicate the dates of DEMs. The solid red line represents the arithmetic average. Numbered symbols at the right-hand side indicate glacier size (color), name (Figure 1b) and location (Figure 1a). The dash-dotted blue line (right-hand side axis) shows the cumulative total volume change of the 30 glaciers. Two short periods with mass gain and two periods with fast mass loss are marked.

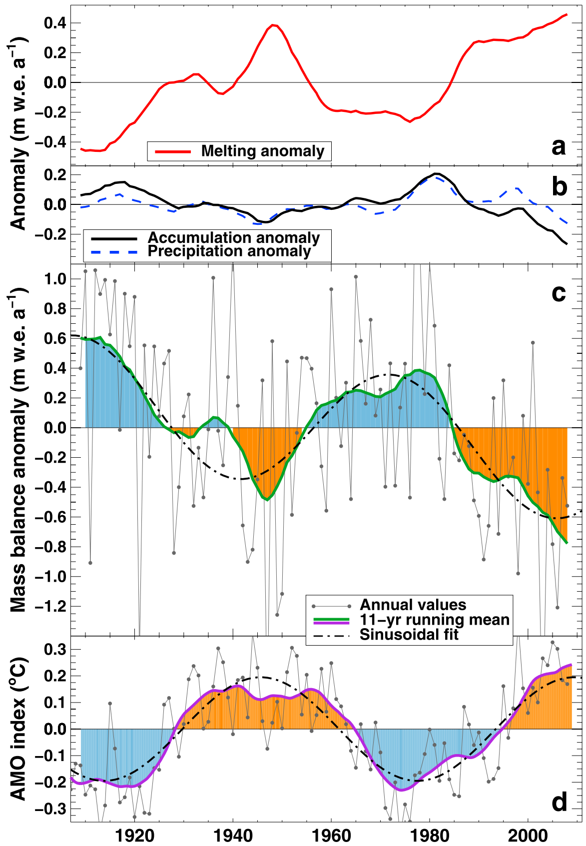

Figure 3. (a) 11-year running mean of the annual glacier melt anomaly averaged over the 30 glaciers, and (b) annual accumulation and precipitation anomaly (deviations from the 1908–2008 average). (c) Annual mass balance anomaly. A sinusoid superimposed on a linear trend is shown. (d) Atlantic Multidecadal Oscillation index [*Enfield et al.*, 2001]. Parameters of the sine function in Figures 3c and 3d are based on least square fits.

trends in the mass balance of Swiss glaciers generally coincide with the global trends for the period 1961–2004 (moderate mass loss, followed by fast loss). Our results indicate that glaciers in the European Alps gained mass in the 1910s followed by a period of moderate decrease before very rapid glacier wastage occurred in the 1940s (Figure 2).

[8] Periods of increased glacier melt coincide roughly with periods of accumulation decrease (Figure 3); both are fostered by higher air temperatures. Consequently, negative mass balance anomalies (deviations from the 100-year mean) due to stronger melt are amplified by reduced accumulation. We evaluate the percentage of the mass balance anomaly that is explained by accumulation and melt changes, and analyze the periods of positive and negative mass balance anomalies separately. The accumulation anomaly accounts for 19–25% of the mass balance anomaly indicating that changes in the melt rates are the dominant driver for the glacier mass fluctuations in the Swiss Alps.

[9] Accumulation is principally determined by precipitation, however its state – solid or liquid – is controlled by air temperature. During the last two decades in particular, accumulation and precipitation anomalies deviate (Figure 3b), indicating that an increasing amount of precipitation falls as rain. From the 1980s to present, the average fraction of snowfall relative to total annual precipitation over the glaciers decreased from 83% to 71% explaining 95% of the accumulation anomaly.

4. Large-Scale Forcing of Alpine Glacier Changes

[10] The changes in global air temperature over the last century have to a large extent been attributed to monotonically increasing greenhouse gas concentration, variations in solar irradiance and volcanic aerosols [*Mann et al.*, 1998]. Observed trends in dimming and brightening of global solar radiation in the European Alps are simultaneous with changes in the rate of snow and ice melt over the last 70 years [*Huss et al.*, 2009]. Decreasing concentration of atmospheric aerosols may explain a part of the strong climate warming since the 1980s [*Philipona et al.*, 2009]. Climate model experiments, however, have shown that natural multidecadal variability related to Atlantic Ocean circulation has a significant impact on global air temperature and explains a large portion of the observed detrended variations [*Zhang et al.*, 2007]. Oscillations in the global climate system with a period of 65–70 years have also been inferred from instrumental data [e.g., *Schlesinger and Ramankutty*, 1994].

[11] We find that this pattern is also reflected in our glacier mass records. In addition to a statistically significant 100-year trend in surface mass balance, multidecadal variations are evident (Figure 3c). Based on least squares we tentatively fit a sine function with constant phase and amplitude superimposed on the negative trend to the annual data points. The sinusoidal fit is able to describe the long-term course of the mass balance anomaly, although deviations in individual years are large, especially during the 1930s. The sine function with the best fit has a period of 65 years and an amplitude of 0.41 m w.e. a^{-1} explaining 94% of the variance of the low-frequency component of the mass balance anomaly (10-year means). Hence, about half of the mass loss since the year 2000 (−0.87 m w.e. a^{-1} on average) can be attributed to the oscillating behavior.

[12] Detrended anomalies in the sea surface temperature in the North Atlantic Ocean are referred to as the Atlantic Multidecadal Oscillation (AMO) (Figure 3d). The anomalies are explained by fluctuations in the thermohaline circulation in the North Atlantic [*Delworth and Mann*, 2000; *Knight et al.*, 2005]. This natural oscillatory mode persisted over the last centuries [*Gray et al.*, 2004] and has been shown to affect climate on both sides of the Atlantic Ocean [*Enfield et al.*, 2001; *Sutton and Hodson*, 2005; *Knight et al.*, 2006]. Positive AMO is associated with positive near-surface air temperature anomalies in Europe favored by changes in the intensity and predominant direction of propagation of cyclones and anticyclones [*Knight et al.*, 2006].

[13] The AMO index is inversely correlated with glacier mass balance in the Swiss Alps (Figure 3). Correlation of 10-year means of AMO and detrended decadal mass balance is high ($r = -0.78$, $n = 10$, significant at the 95% level according to the F-test). Decadal series of AMO and mass balance do not show significant autocorrelation. AMO also correlates significantly with 10-year means of glacier melt ($r = 0.72$) and accumulation ($r = -0.73$). A positive AMO index is associated with pronounced Alpine glacier mass loss; during periods with negative AMO, glaciers experienced reduced mass loss or even mass gain (Figure 3). Hence, long-term North Atlantic variability is likely to affect glacier changes

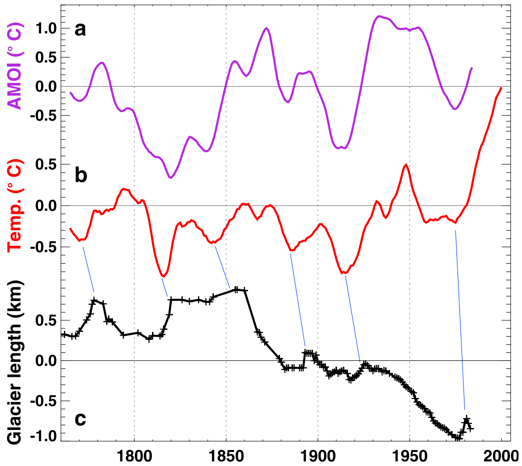

Figure 4. (a) Reconstructed AMO index [*Gray et al.*, 2004] and, (b) summer (JJA) air temperature from instrumental data in the Greater Alpine Region [*Auer et al.*, 2007] (11-year low-pass filtered). (c) Observed length change of U. Grindelwaldgletscher [*Holzhauser and Zumbühl*, 1999]; blue lines indicate phases of glacier advance in response to cooler temperatures.

in the European Alps. The rapid glacier wastage observed during the last two decades may thus have been amplified by natural multidecadal climate variations.

[14] Comparison of reconstructed AMO index [*Gray et al.*, 2004] and homogenized instrumental air temperature records for the Alps since 1765 [*Auer et al.*, 2007] shows that multidecadal variations in these variables are roughly in phase (Figure 4). Important local minima in air temperature in about 1820, 1910 and 1970 correspond to low AMO. The warming after 1850, contributing to the termination of the Little Ice Age in central Europe, is simultaneous with a high phase of the AMO. Periodic advances and subsequent retreats of termini of glaciers with long-term observations in the Alps [*Holzhauser and Zumbühl*, 1999] follow minima and maxima in air temperature with a time shift of one to several decades (Figure 4) corresponding to the delayed reaction of the glacier front to changed climatic forcing. This suggests that Alpine glaciers advanced and retreated in response to AMO-driven variations in regional climate at least over the last 250 years.

[15] Coupled ocean-climate model results indicate that over the next 30 years the oceanic thermohaline circulation will weaken [see *Knight et al.*, 2005, Figure 4c], possibly leading to lower AMO. This weakening is due to the oscillatory nature of ocean circulation, but may be further amplified by anthropogenic warming [*Stouffer et al.*, 2006]. The correlation of Alpine glacier mass budget with AMO implies that the rate of glacier mass loss might decrease over the next decades in comparison to the observed strongly negative trend of the last years. Nevertheless, higher air temperatures due to increasing greenhouse gas forcing will continue to contribute to a strong retreat of Alpine glaciers in the 21st century.

5. Conclusion

[16] Our 100-year glacier mass balance time series, unprecedented in length and coverage, provide a highly resolved data basis in the spatial and temporal domain for analyzing the response of mountain glaciers to the 20th century climate change, and for upscaling measurements from individual glaciers to entire mountain ranges. The data show that the glacier mass budget in the Swiss Alps varies in phase with the AMO, and is thus related to North Atlantic variability. This indicates that up to half of the recently accelerated mass loss might be due to natural multidecadal climate variations that might reduce the rate of Alpine glacier wastage in the next decades. Linking accumulation and ablation processes on mountain glaciers to multidecadal oscillatory modes and large-scale forcing is important for projections of future glacier change and associated impacts.

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