Auxiliary Material: 100-year glacier mass changes in the Swiss Alps linked to the Atlantic Multidecadal Oscillation

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Auxiliary methods

Mass balance model

Surface melt rates $M(x,y,t)$ at day t and for grid cell (x,y) of a digital elevation model (DEM) with a spatial resolution of 25 m are computed by

$$M(x,y,t) = \begin{cases} \left[f_{\mathrm{M}} + r_{\mathrm{snow/ice}}\, I_{\mathrm{pot}}(x,y,t)\right] T(x,y,t) & : \; T(x,y,t) > 0°C \\ 0 & : \; T(x,y,t) \leq 0°C \end{cases} \tag{1}$$

where f_{M} denotes a melt factor, $r_{\mathrm{snow/ice}}$ are radiation factors for ice and snow surfaces and $I_{\mathrm{pot}}(x,y,t)$ is the potential solar radiation [*Hock*, 1999]. The snow water equivalent at every grid cell is modeled continuously providing the surface type (snow/ice). Daily air temperature $T(x,y,t)$ is determined using the weather-station temperature T_{WS}, a constant lapse rate $\mathrm{d}T/\mathrm{d}z$ and the elevation of the station z_{WS}:

$$T(x,y,t) = T_{\mathrm{WS}}(t) + (z(x,y) - z_{\mathrm{WS}})dT/dz. \tag{2}$$

Snow accumulation $C(x,y,t)$ is computed based on the measured daily precipitation at the weather station $P_{\mathrm{WS}}(t)$, an altitudinal precipitation gradient dP/dz, a precipitation correction c_{prec} accounting for gauge undercatch and a dimensionless snow redistribution matrix $D_{\mathrm{snow}}(x,y)$ as

$$C(x,y,t) = \begin{cases} P_{\mathrm{WS}}(t) c_{\mathrm{prec}} [1 + (z(x,y) - z_{\mathrm{WS}}) dP/dz] D_{\mathrm{snow}}(x,y) & : \; T(x,y,t) < 1.5°C \\ 0 & : \; T(x,y,t) \geq 1.5°C \end{cases} \tag{3}$$

$D_{\mathrm{snow}}(x,y)$ has an average of 1 over the glacier and accounts for effects of avalanching, wind drift and the regional precipitation field [*Huss et al.*, 2008, 2009].

Model parameters are calibrated for each glacier individually based on a semi-automated procedure. For each period with geodetic ice volume changes the melt factors are varied so that the simulated agrees with the observed mass change. In-situ mass balance measurements and discharge data (see Auxiliary Table 1) are used to constrain the accumulation parameters. Combination of the different field data sets allows the determination of the long-term mass change, the year-to-year variability and the altitudinal mass balance gradients based on the distributed model running in daily resolution. Average parameter values for all glaciers and units are given in the Auxiliary Table 2. For further details on the calibration procedure and the mass balance model refer to *Huss et al.* [2008]. Auxiliary Table 3 provides selected model results for all investigated glaciers.

Uncertainty analysis

The uncertainty in the presented glacier mass balance time series is mainly given by the accuracy of the DEMs used for the calculation of the geodetic mass change. The uncertainty in the geodetic mass change σ_{geod} is calculated as

$$\sigma_{\mathrm{geod}} = \sqrt{\Delta z^2 \sigma_{\rho}^2 + \rho^2 \sigma_{\Delta \mathrm{z}}^2}, \quad (4)$$

where ρ=850 kg m^{-3} is the density used to convert ice volume to mass change [*Sapiano et al.*, 1998; *Huss et al.*, 2009] and σ_{ρ}=50 kg m^{-3} is the uncertainty. Δz is the geodetic elevation change, assumed to be uncorrelated to ρ, $\sigma_{\Delta \mathrm{z}}$ is the uncertainty related to the DEMs defined by

$$\sigma_{\Delta \mathrm{z}} = \sqrt{\sigma_{\mathrm{DEM}_1}^2 + \sigma_{\mathrm{DEM}_2}^2}. \quad (5)$$

The uncertainties σ_{DEM_1} and σ_{DEM_2} given by the accuracies of the two DEMs are independent of each other. σ_{DEM} depends on (i) the geolocation and orientation of the individual aerial photographs or topographic maps (before 1950) used to produce the DEM, (ii) the accuracy of the elevation information and (iii) the interpolation to unmeasured grid points [*Thibert et al.*, 2008; *Huss et al.*, 2009]. σ_{DEM} is estimated as 2-5 m for topographic maps and as 0.3-1 m for aerial photographs [*Bauder et al.*, 2007; *Huss et al.*, 2009].

We relate σ_{geod} to the calculated mass balance time series and take into account higher uncertainties of the results for the period between 1908 and the first DEM (normally in the 1920s/30s, see Fig. 1b). We find an uncertainty in the rate of the 100-year mass loss of $\sigma_{\Delta \mathrm{M}}$=0.06 m w.e. a^{-1}.

The uncertainty in the interannual variability in mass balance between successive DEMs is higher due to uncertainties associated with the climate data and the simplifications in the model. Comparison with an independent set of seasonal mass balance data for two of the investigated glaciers [*Huss et al.*, 2009] yields a randomly distributed error in the annual mass balance variability of σ_{b}=0.38 m w.e. a^{-1} and an uncertainty in the accumulation variability of σ_{c}=0.25 m w.e. a^{-1}.

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Auxiliary Table AM 1. Time periods covered by field data. n_{DEM} is the number of DEMs available in 1908-2008; n_{b_a} and n_{b_w} are the total number of measurements of in-situ annual mass balance and winter accumulation, respectively, for each glacier. Gaps in the data series of mass balance measurement and discharge records are not stated explicitly.

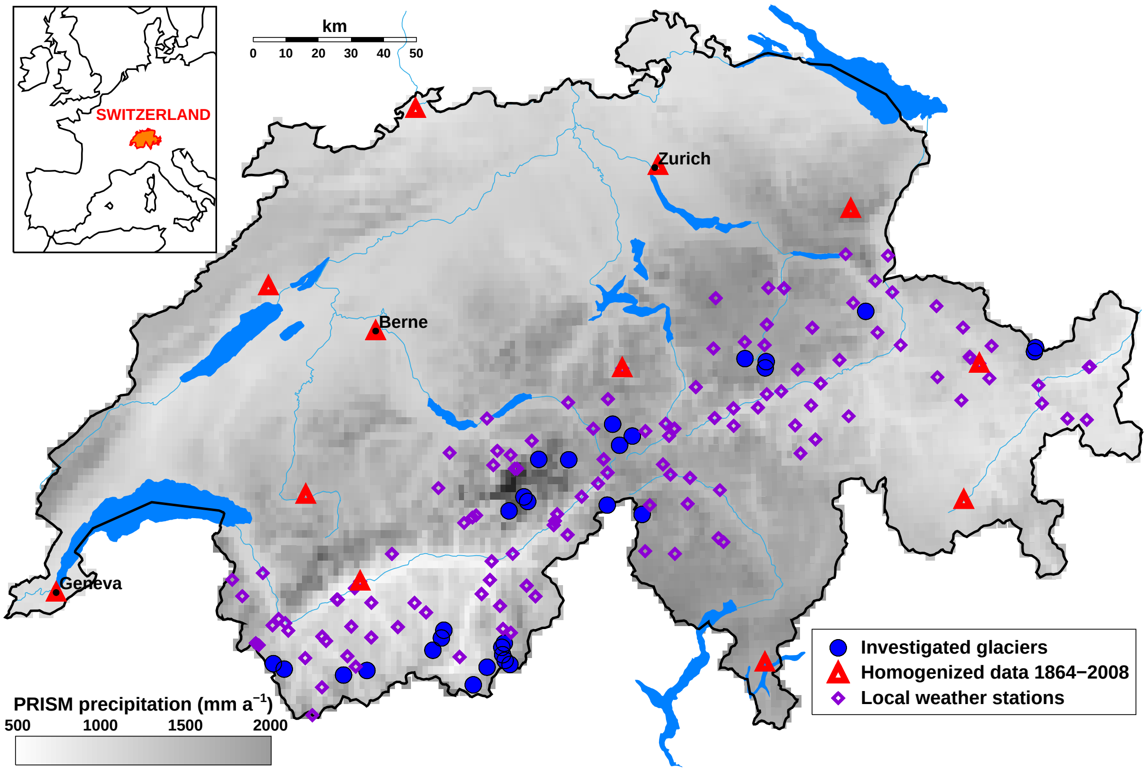
Glacier name	Vol. change	n_{DEM}	Annual bal.	n_{b_a}	Winter bal.	n_{b_w}	Discharge
Grosser Aletschgletscher	1926-1999	4	1921-2008	576	1919-2008	253	1923-2008
Gornergletscher	1931-2003	3	2004-2007	76	2004-2008	76	1969-2006
Unteraargletscher	1927-2003	6	1997-1999	129	-	0	-
Oberaletschgletscher	1926-1999	3	-	0	-	0	1923-2006
U. Grindelwaldgletscher	1926-2004	3	-	0	-	0	-
Findelengletscher	1931-2007	3	2005-2008	51	-	0	1962-2008
Glacier de Corbassière	1935-2003	3	1997-2008	77	-	0	-
Rhonegletscher	1929-2007	6	1980-2008	179	1980-2008	1447	1920-2006
Triftgletscher	1936-2003	6	2002-2003	20	-	0	-
Glacier de Zinal	1936-2006	5	-	0	2007-2007	149	1979-2005
Allalingletscher	1932-2008	9	1956-2007	298	1956-1996	109	-
Mittelaletschgletscher	1926-1999	3	-	0	-	0	1923-2006
Glacier du Trient	1931-2005	4	-	0	-	0	1919-2005
Glacier du Giétro	1934-2008	6	1967-2005	345	-	0	-
Glacier de Moming	1936-2006	5	-	0	-	0	1979-2005
Schwarzberggletscher	1946-2008	8	1956-2007	111	1956-1996	57	-
Claridenfirn	1936-2003	5	1915-2008	188	1915-2008	189	-
Griesgletscher	1923-2007	9	1962-2008	1539	1998-2008	177	1957-2004
Dammagletscher	1939-2007	3	-	0	2008-2008	227	-
Glacier du Weisshorn	1936-2006	5	-	0	-	0	1979-2005
Silvrettagletscher	1938-2007	7	1918-2008	1231	1915-2008	288	1933-2004
Hohlaubgletscher	1946-2008	8	1956-2004	46	1956-1996	70	-
Limmerngletscher	1947-2000	5	1949-1984	983	1964-1985	65	1964-1990
Ghiacciaio del Basódino	1929-2002	7	1993-2006	103	1993-2006	114	-
Seewjinengletscher	1946-2008	6	-	0	-	0	-
Glacier d'Orny	1931-2005	3	-	0	-	0	-
Verstanklagletscher	1959-2003	3	-	0	-	0	1933-2004
Plattalvagletscher	1947-2000	5	1949-1984	335	1964-1985	110	1964-1990
Chessjengletscher	1946-1999	6	1956-1982	37	1956-1997	65	-
Pizolgletscher	1961-2006	8	2006-2008	6	2006-2008	201	-
Total		156		6330		3597	

Auxiliary Table AM 2. Calibrated parameter values and units (see Equations AM1, AM2 and AM3). The average and the standard deviation σ_{param} of the parameters over all glaciers and time periods is given.

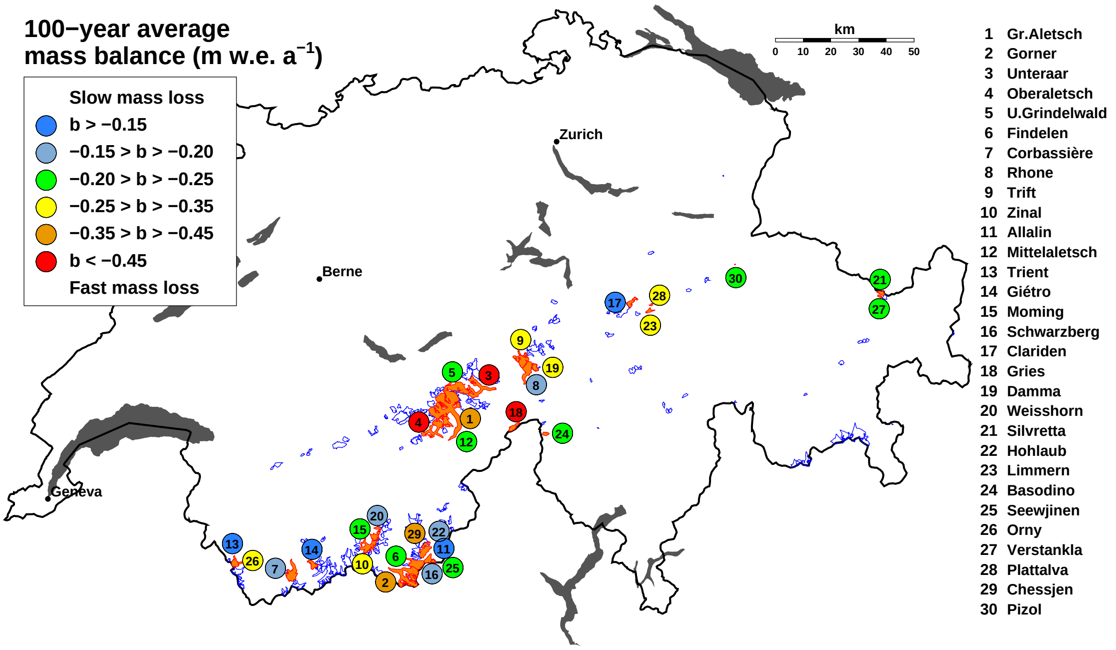
Parameter	Units	30-gl average	30-gl σ_{param}
f_{M}	$10^{-3}\,\mathrm{m\,d^{-1}\,{}^{\circ}C^{-1}}$	1.178	0.295
r_{ice}	$10^{-5}\,\mathrm{m^3\,W^{-1}\,d^{-1}\,{}^{\circ}C^{-1}}$	1.856	0.276
r_{snow}	$10^{-5}\,\mathrm{m^3\,W^{-1}\,d^{-1}\,{}^{\circ}C^{-1}}$	1.399	0.206
$\mathrm{d}T/\mathrm{d}z$	$\mathrm{{}^{\circ}C\,m^{-1}}$	–0.00541	0.00038
$\mathrm{d}P/\mathrm{d}z$	$\%\,\mathrm{m^{-1}}$	0.0102	0.0186
c_{prec}	–	1.376	0.328

Auxiliary Table AM 3. Topographic characteristics and selected results from the 30 investigated glaciers. Glacier area, elevation range and average surface slope refer to the most recent DEM. $\overline{b_{1908-2008}}$ is the calculated annual mass balance as an average over the period 1908-2008, and $\overline{ELA}$ is the mean equilibrium line altitude.

Glacier name	Area (km^2)	Elevation (m a.s.l.)	Slope (°)	Exposure	$\overline{b_{1908-2008}}$ (m w.e. a^{-1})	$\overline{ELA}$ (m a.s.l.)
Grosser Aletschgletscher	83.02	1560-4085	15	S	–0.45	3008
Gornergletscher	39.03	2172-4605	17	N	–0.42	3240
Unteraargletscher	22.73	1936-3675	15	N	–0.49	2740
Oberaletschgletscher	19.68	2147-3776	20	S	–0.47	3012
Unterer Grindelwaldgletscher	19.55	1307-3901	23	N	–0.23	2721
Findelengletscher	16.31	2512-4112	14	N	–0.23	3233
Glacier de Corbassière	16.01	2217-4310	16	N	–0.15	3125
Rhonegletscher	15.94	2205-3596	14	SW	–0.20	2935
Triftgletscher	15.34	1625-3361	19	N	–0.27	2761
Glacier de Zinal	13.41	2056-3856	21	N	–0.29	3103
Allalingletscher	9.68	2604-4180	17	N	–0.10	3233
Mittelaletschgletscher	8.00	2304-4186	23	E	–0.24	3086
Glacier du Trient	5.87	1950-3442	16	N	–0.13	2984
Glacier du Giétro	5.55	2535-3811	12	N	–0.13	3187
Glacier de Moming	5.45	2524-4069	23	N	–0.20	3095
Schwarzberggletscher	5.31	2662-3564	15	N	–0.16	3059
Claridenfirn	5.13	2440-3207	14	E	–0.12	2832
Griesgletscher	4.97	2425-3324	12	N	–0.65	2950
Dammagletscher	4.60	2057-3312	25	E	–0.27	2830
Glacier du Weisshorn	3.10	2835-3714	20	W	–0.16	3179
Silvrettagletscher	2.79	2467-3069	13	NW	–0.21	2803
Hohlaubgletscher	2.18	2843-4030	19	N	–0.20	3193
Limmerngletscher	2.23	2200-3366	20	NE	–0.26	2760
Ghiacciaio del Basódino	2.21	2546-3203	19	NE	–0.20	2857
Seewjinengletscher	1.47	2719-3225	18	N	–0.21	2982
Glacier d'Orny	1.36	2646-3252	14	NE	–0.28	3001
Verstanklagletscher	0.92	2400-2987	22	N	–0.22	2700
Plattalvagletscher	0.58	2550-2996	17	E	–0.33	2808
Chessjengletscher	0.15	2869-3007	17	N	–0.35	3039
Pizolgletscher	0.08	2611-2786	22	N	–0.23	2676



Auxiliary Figure AM 1. Location of the investigated glaciers and weather stations used to force the mass balance model. Triangles represent weather stations providing homogenized and continuous temperature data since 1864 [*Begert et al.*, 2005]. Weather stations close to the glaciers used to obtain the temporal precipitation variability, as well as temperature and precipitation gradients with elevation are marked with diamonds. The spatial distribution of annual precipitation sums is given by the PRISM data set [*Schwarb et al.*, 2001] and is shown in grey scales. All data are provided by the observational network of MeteoSwiss and were used to produce composite daily temperature and precipitation series 1908-2008 scaled to each study site [*Huss et al.*, 2008].



Auxiliary Figure AM 2. Regional distribution of annual mass balance averaged over 1908-2008 for 30 Swiss glaciers. Colors indicate the magnitude of mass change.