

On the imbalance and response time of glaciers in the European Alps Harry Zekollari^{1,2,3,4},
Matthias Huss^{1,2,5}, and Daniel Farinotti^{1,2}

1 Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zürich, Zürich, Switzerland

2 Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland

3 Department of Geoscience and Remote Sensing, Delft University of Technology, Delft, Netherlands

4 Laboratoire de Glaciologie, Université libre de Bruxelles, Brussels, Belgium

5 Department of Geosciences, University of Fribourg, Fribourg, Switzerland

Contents of this file

Figures S1 to S9

Table S1 and S2

Introduction

The supporting information consists of 8 figures and 1 table. These illustrate general concepts (Figure S1), the committed loss for a few selected individual glaciers (Figure S2) additional experiments with precipitation forcing (Figure S3), detailed simulations at the individual glacier level (Figure S4), response times derived from transient experiments (Figure S5), correlations between individual glacier characteristics and the glacier response time (Figures S6, S7 and S9), correlations between various glacier characteristics and the glacier response time (Figure S8), uncertainty analyses for selected glaciers (Table SX) and equations from various regressions analyses (Table S2).

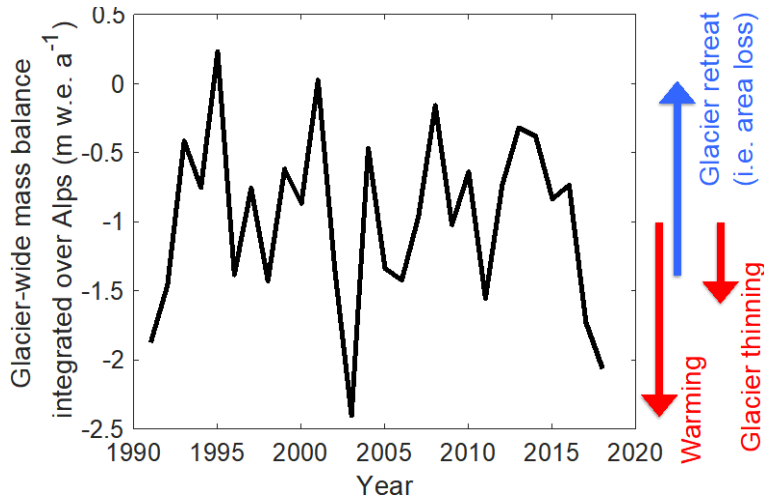


Figure S1. Evolution of the glacier-wide mass balance integrated over the European Alps as modelled with GloGEMflow (Zekollari et al., 2019). The coloured arrows indicate the main processes that occur, their direction indicating the correlation with the glacier-wide mass balance (downwards is negative, upwards is positive). The length of the arrows is indicative for the relative importance, i.e. the effect of glacier thinning is smaller than the effect of climate warming and of glacier retreat.

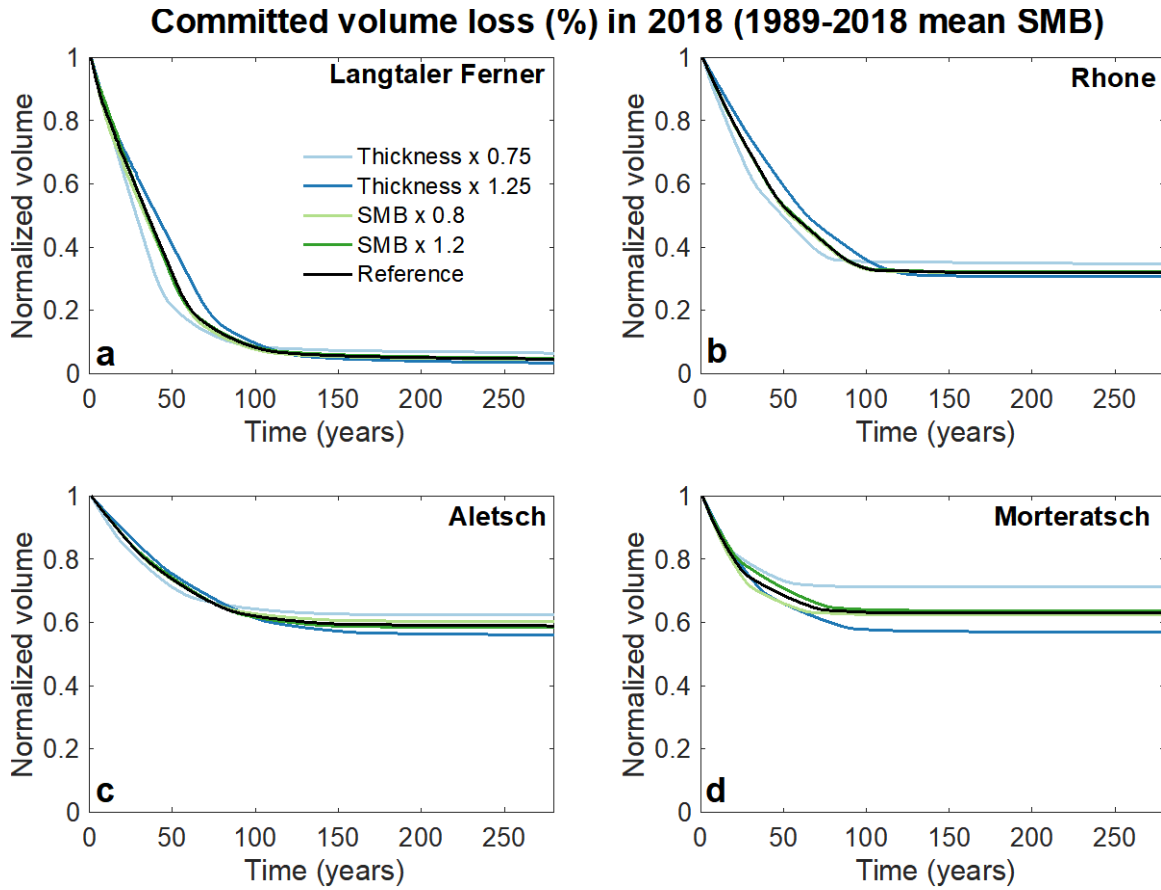


Figure S2. Committed volume loss (%) in 2018 under 1989-2018 mean SMB for (a) Langtaler Ferner (Austria, 3 km² in RGI), (b) Rhonegletscher (Switzerland, 16 km² in RGI), (c) Grosser Aletschgletscher (Switzerland, 82 km² in RGI) and (d) Vadret da Morteratsch (Switzerland, 16 km² in RGI). The lines represent the evolution for the reference run and for experiments in which the ice thickness and surface mass balance is perturbed (see Table S1 for details).

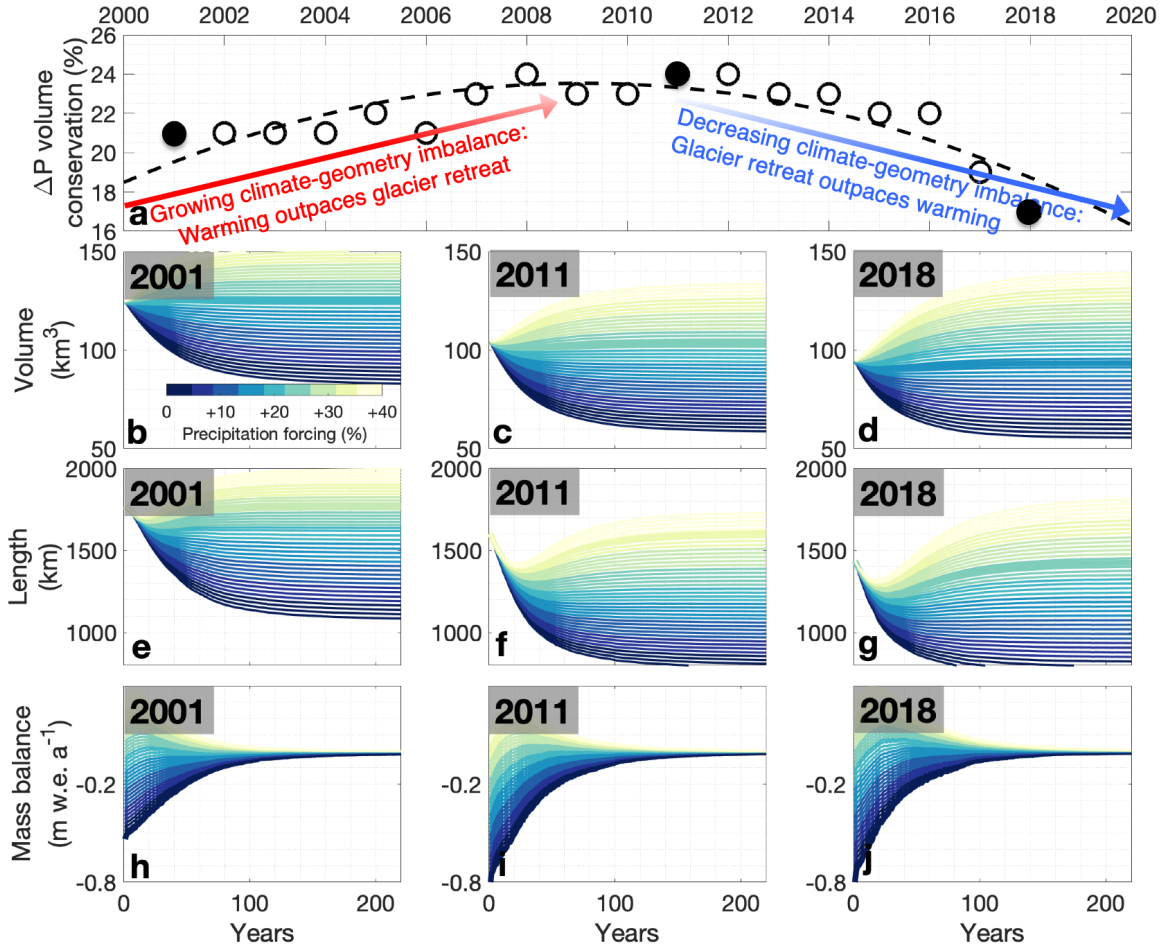


Figure S3. Same as Figure 2 in the main text but for experiments with precipitation anomaly instead of temperature anomaly. (a) Precipitation forcing needed at any given point in time to maintain the total glacier volume at that time. The black circles indicate the precipitation forcing needed to maintain the volume in 2001, 2011 and 2018. Evolution of glacier volume (b, c, d), glacier length (e, f, g), and glacier-wide mass balance (h, i, j) for conservation experiments starting in 2001, 2011 and 2018. The values are integrated over all glaciers of the European Alps. Colours depict different precipitation forcing (legend in panel b).

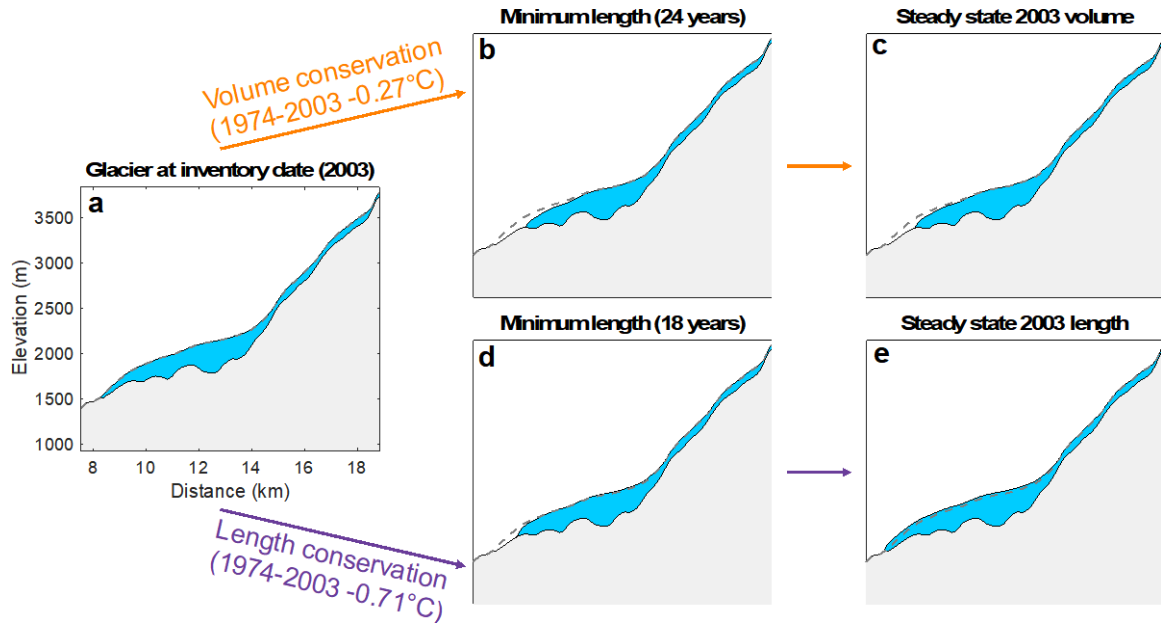


Figure S4. Evolution of glacier geometry of Mer de Glace (France) starting from the reference geometry at inventory date (2003, panel a). Perturbing the reference (1974-2003) climate with -0.27°C results in a steady-state glacier with the same volume as in 2003. This steady state (panel c) is reached after ca. 50 years. Perturbing the reference climate with -0.71°C , instead, results in a steady-state glacier with the 2003 length (steady-state reached after ca. 80 years, panel e). The geometries with minimum glacier length that occur during the transient evolution from the initial state (panel a) to the steady states of panels c and e are shown in panels b and d, respectively.

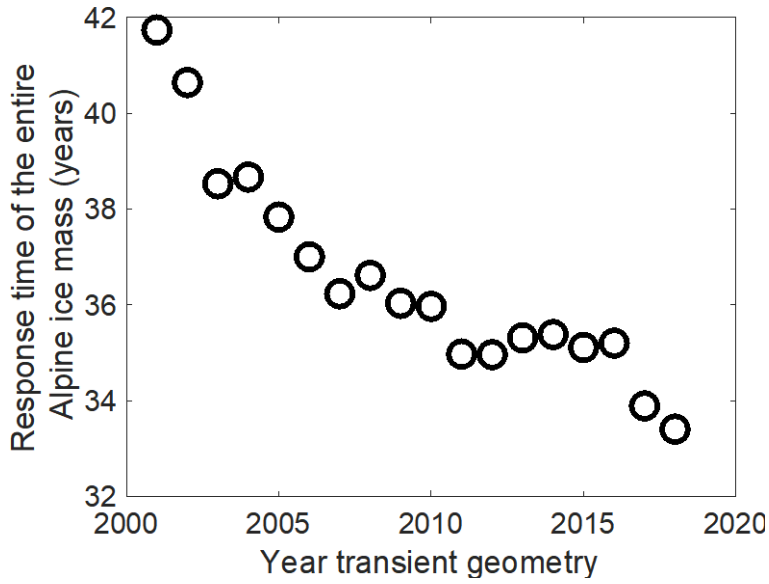


Figure S5. e-folding volume response times for the entire Alpine ice mass as derived from the committed loss experiments (Figure 1a). The indicated year (x-axis) corresponds to the transient geometry for which the response time is derived. Response times are obtained by (i) imposing the mean SMB conditions of the previous 30 years to that geometry, (ii) running the model forward until a steady state is reached, and (iii) determining the e-folding time scale from the so-obtained volume evolution.

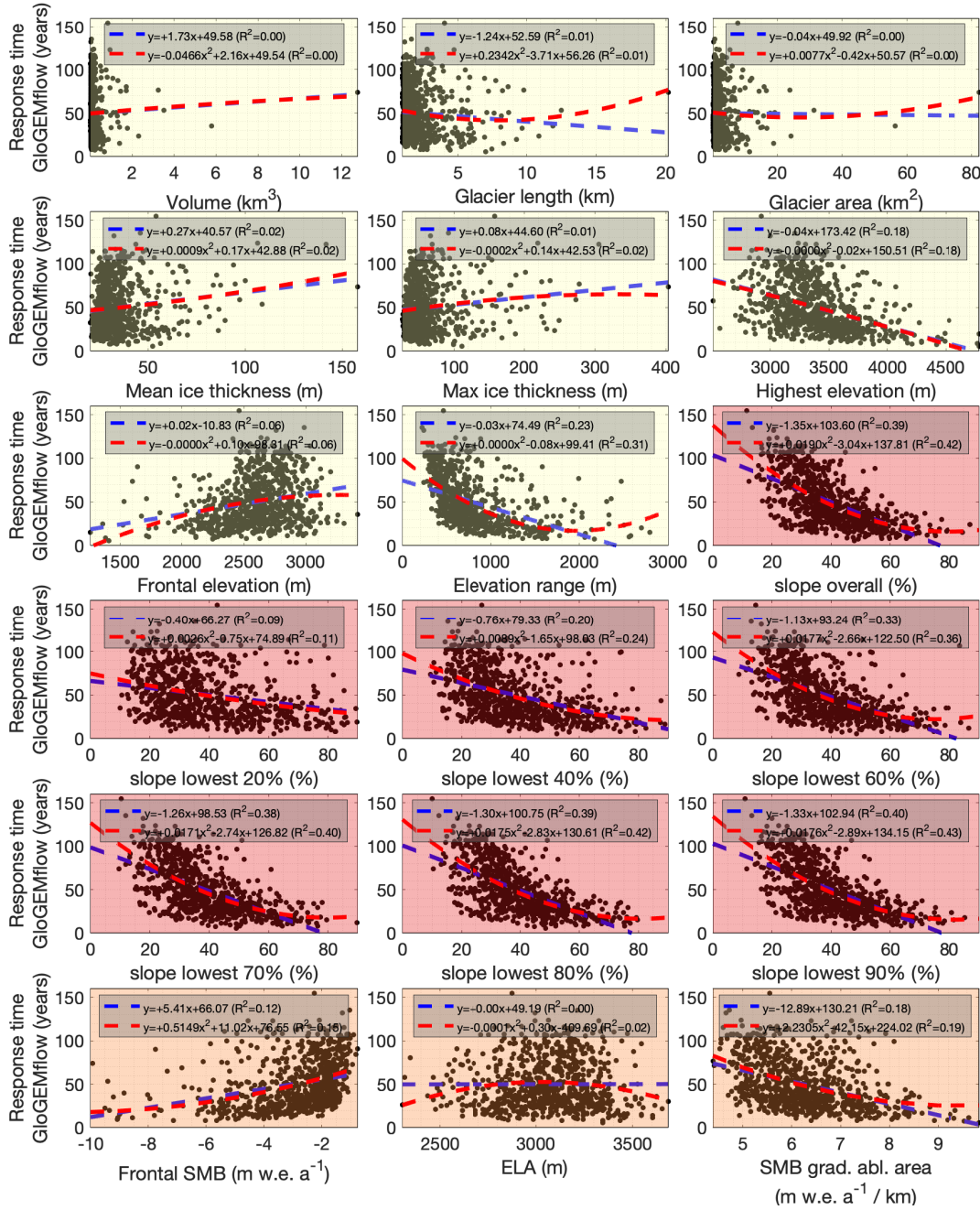


Figure S6. Modelled response time from numerical experiments (y-axis) as a function of various glacier characteristics. The glacier characteristics are subdivided in three main categories: (i) glaciers size (yellow), (ii) glacier slope (red) and (iii) surface mass balance (orange). “Slope lowest x%” is the average slope along the flowline of the lowest x% of elevation of the glacier. “ELA” is the equilibrium line altitude. “SMB grad. abl. area” is the gradient of the surface mass balance in the glacier’s ablation area. Blue and red lines are fitted through linear and quadratic regression, respectively. The corresponding equations are given in the panels’ upper insets. The correlation is significant at the 1% and 5% significance level when $R^2 > 0.09$ and $R^2 > 0.07$, respectively.

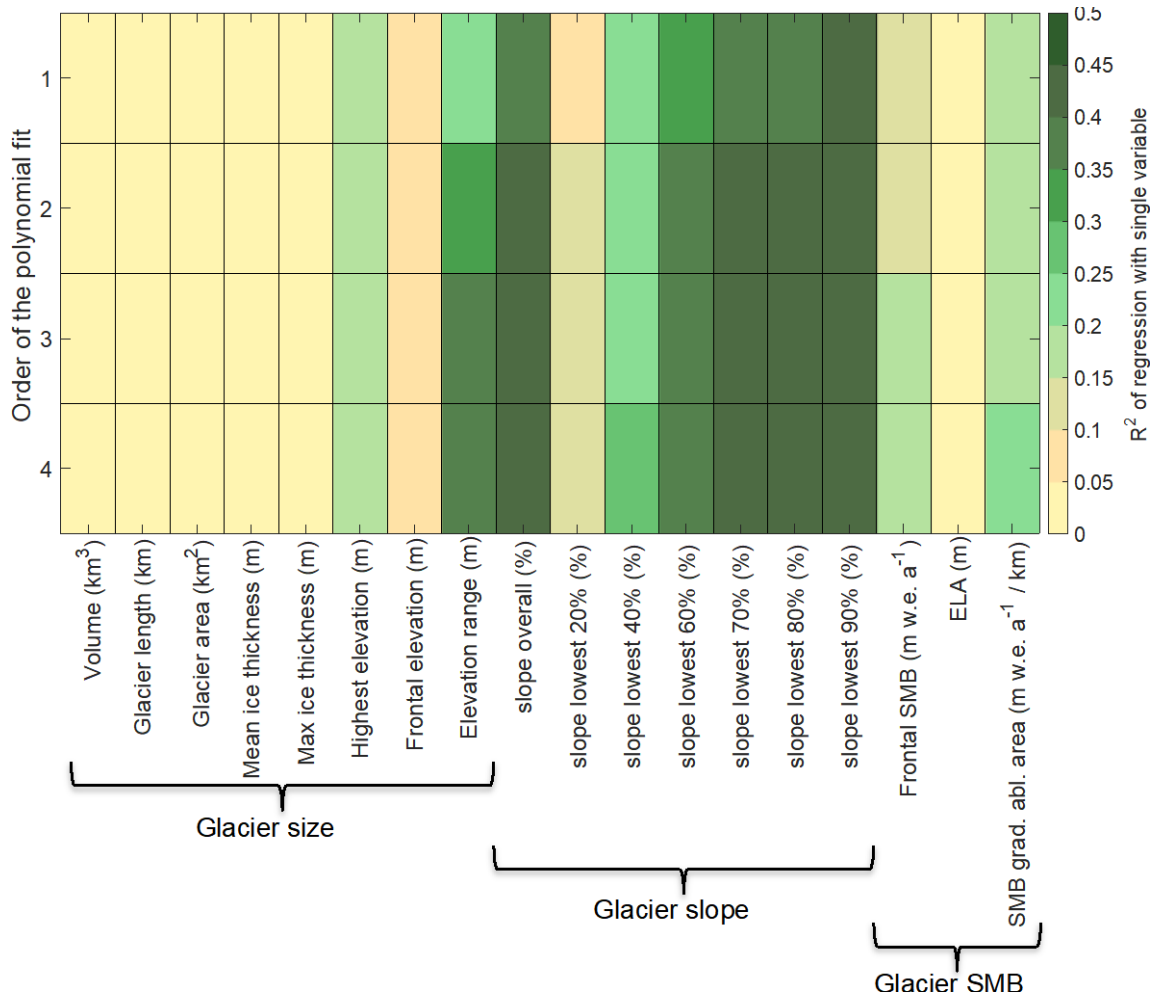


Figure S7. Fraction (expressed as R^2 value) of the response time variability explained by regression analyses with a single variable and a polynomial fit of order n ($n=1,2,3,4$). “Slope lowest $x\%$ ” is the average slope along the flowline of the lowest $x\%$ of elevation of the glacier. The correlation is significant at the 1% and 5% significance level when $R^2 > 0.09$ and $R^2 > 0.07$, respectively.

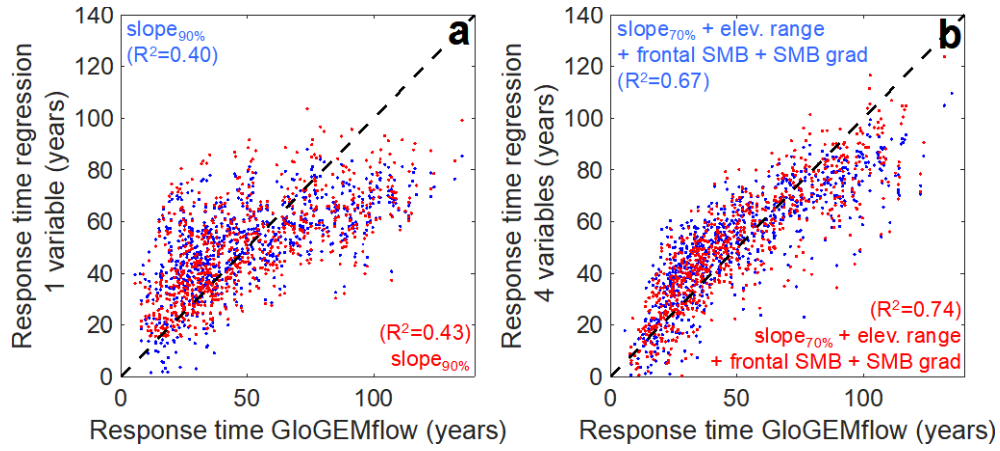


Figure S8. Best fit between numerically-derived response time and response time derived from regression analyses with one (a) and four (b) predictor variables. Linear (blue) and quadratic (red) regressions are shown separately. The predictors and portions of explained variance (R^2) are given in the panels' corners. An equivalent figure with two and three predictor variables is shown in Figure 4 of the main text. The equations for the best fit are given in Table S2.

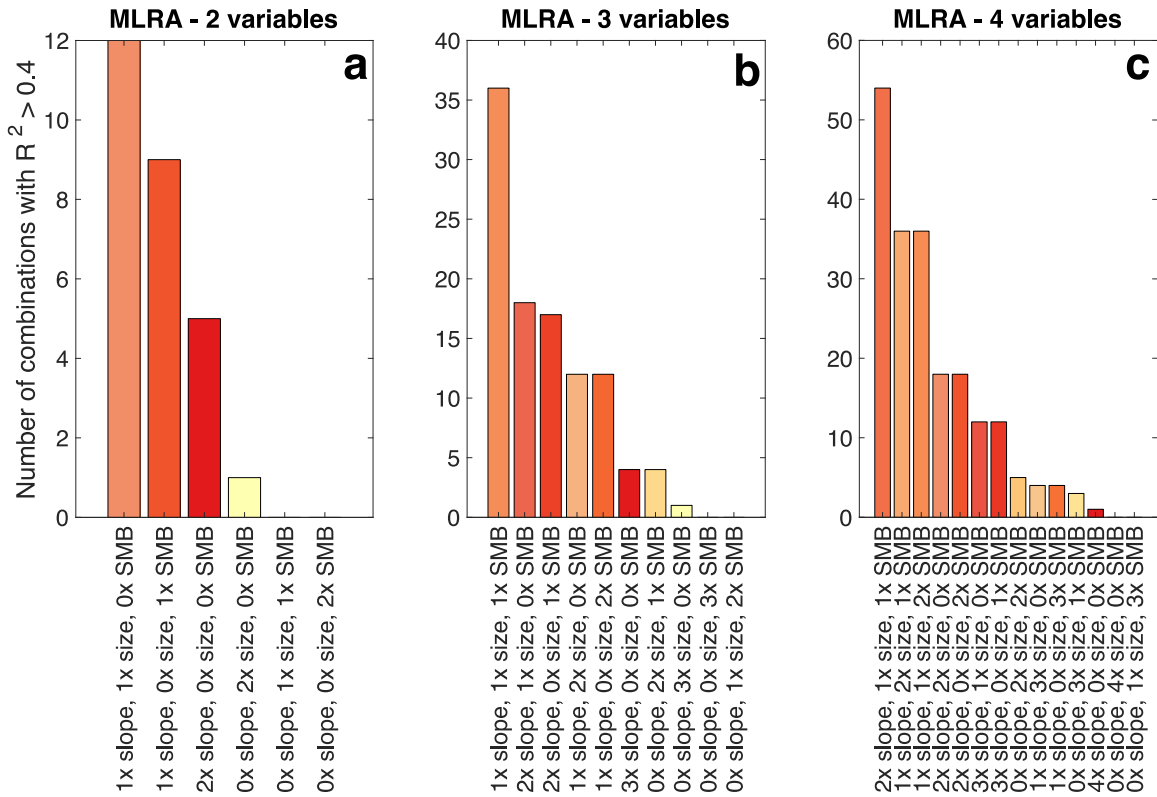


Figure S9. Number of times a given combination of glacier characteristics explains more than 40% of the inter-glacier variability in response time ($R^2 > 0.4$). 40% corresponds to the maximum variability that can be explained by a single variable. The tested combinations of characteristics are given by the x-labels. For example: “2 x slope, 0 x size, 1 x SMB” means that the Multiple Linear Regression Analysis (MLRA) was performed with two variables characterizing the glacier’s slope, no variable characterizing the glacier’s size, and one variable characterizing the glacier surface mass balance (SMB). The variables considered for every category (slope, size, SMB) are given in Figures S6 and S7. MLRA with two (a), three (b) and four variables (c) are shown separately. Notice different scales for the y-axes. Colours of the bars are based on a linear mixing between the colours of the three categories (slope=red, size=yellow, and SMB=orange; cf. Figure S6).

Glacier	Reference	Ice thickness -25%	Ice thickness +25%	More gentle SMB gradient (SMB x 0.8)	Steeper SMB gradient (SMB x 1.2)	Mean	Std. dev.	Std. dev / Mean (%)
Committed volume loss in 2018 (1989-2018 mean SMB)								
Langtaler Ferner	-95.5%	-93.6%	-96.7%	-95.7%	-95.2%	-95.3%	1.1%	1.1%
Rhone	-68.0%	-65.4%	-69.4%	-68.1%	-67.8%	-67.8%	1.5%	2.2%
Aletsch	-41.1%	-37.7%	-43.9%	-39.7%	-41.7%	-40.8%	2.3%	5.7%
Morteratsch	-37.0%	-28.9%	-43.0%	-37.6%	-36.5%	-36.6%	5.0%	13.8%
Temperature forcing needed for volume conservation (in 2018)								
Langtaler Ferner	-0.86°C	-0.77°C	-0.91°C	-0.88°C	-0.84°C	-0.85°C	0.05°C	6.2%
Rhone	-1.00°C	-0.86°C	-1.14°C	-1.00°C	-1.00°C	-1.00°C	0.10°C	9.8%
Aletsch	-0.94°C	-0.79°C	-1.07°C	-0.91°C	-0.96°C	-0.94°C	0.10°C	10.7%
Morteratsch	-0.78°C	-0.53°C	-0.90°C	-0.79°C	-0.76°C	-0.75°C	0.13°C	17.8%
Response time (years)								
Langtaler Ferner	114.6	110.0	128.6	115.1	114.2	116.5	7.1	6.1%
Rhone	81.4	82.3	101.2	83.0	80.1	86.2	8.6	10.0%
Aletsch	74.6	78	92.7	77.8	72.6	79.1	7.9	10.0%
Morteratsch	47.8	48.2	59.5	48.5	47.1	50.2	5.2	10.4%

Table S1. Effect of the ice thickness and SMB uncertainty on the modelled (i) committed volume loss, (ii) temperature forcing needed for volume conservation, and (iii) response time. In all experiments, the glacier-specific simulations are re-run by perturbing the two model parameters with the largest uncertainty: the SMB and ice thickness. Whereas the long-term losses in ice volume are constrained by direct observations (geodetic MB) the SMB gradients are a modelling result and are thus uncertain. To represent the SMB gradient uncertainty, the SMB is multiplied with 0.8 and 1.2, representing a gentler and a steeper SMB gradient respectively. The uncertainty in the modelled ice thickness individual glacier volume is estimated to be in the order of 20% (see section 3), and this is represented conservatively by applying glacier-wide ice thickness perturbations of -25% and +25%. For every perturbed experiment a new glacier-specific calibration of ice flow parameters occurs. These experiments thus also reflect the effect of uncertainties in ice flow parameters on the modelled results. Results are given for a small glacier (Langtaler Ferner, Austria; 3 km² in RGI), two medium-sized glaciers (Rhönegletscher and Vadret da Morteratsch, Switzerland; both 16 km² in RGI) and the largest glacier in the European Alps (Grosser Aletschgletscher, Switzerland; 82 km² in RGI). The resulting uncertainty (standard deviation from standard and perturbed experiments vs. mean value) is in the order of 1-15% for the committed volume (see also Figure S2), 5-15% for the temperature forcing needed for volume conservation and 5-10% for the response times.

Number of variables considered	Best linear fit	Best quadratic fit
1	$\tau_{\text{glac}} = -1.328 \text{ slope}_{90\%} + 102.9$ $[R^2 = 0.401; \text{Adjusted } R^2 = 0.401]$	$\tau_{\text{glac}} = 0.0176 (\text{slope}_{90\%})^2 - 2.891 \text{ slope}_{90\%} + 134.2$ $[R^2 = 0.427; \text{Adjusted } R^2 = 0.426]$
2	$\tau_{\text{glac}} = -1.239 \text{ slope}_{80\%} - 0.028 \text{ elev range} + 121.2$ $[R^2 = 0.585; \text{Adjusted } R^2 = 0.584]$	$\tau_{\text{glac}} = 0.025 (\text{slope}_{90\%})^2 - 3.356 \text{ slope}_{90\%} + 1.434 \times 10^{-5} (\text{elev range})^2 - 0.0661 \text{ elev range} + 179.2$ $[R^2 = 0.667; \text{Adjusted } R^2 = 0.665]$
3	$\tau_{\text{glac}} = -1.240 \text{ slope}_{70\%} - 0.020 \text{ elev range} - 7.167 \text{ SMB grad} + 159.4$ $[R^2 = 0.626; \text{Adjusted } R^2 = 0.625]$	$\tau_{\text{glac}} = 0.024 (\text{slope}_{90\%})^2 - 3.269 \text{ slope}_{90\%} + 1.169 \times 10^{-5} (\text{elev range})^2 - 0.0519 \text{ elev range} + 1.659 (\text{SMB grad})^2 - 27.693 \text{ SMB grad} + 275.7$ $[R^2 = 0.699; \text{Adjusted } R^2 = 0.697]$
4	$\tau_{\text{glac}} = -1.137 \text{ slope}_{70\%} - 0.053 \text{ elev range} - 9.960 \text{ frontal SMB} - 11.670 \text{ SMB grad} + 179.469$ $[R^2 = 0.674; \text{Adjusted } R^2 = 0.672]$	$\tau_{\text{glac}} = 0.0213 (\text{slope}_{90\%})^2 - 2.905 \text{ slope}_{90\%} + 2.01 \times 10^{-5} (\text{elev range})^2 - 0.1013 \text{ elev range} - 0.694 (\text{frontal SMB})^2 - 15.770 \text{ frontal SMB} + 1.579 (\text{SMB grad})^2 - 31.21 \text{ SMB grad} + 283.8$ $[R^2 = 0.739; \text{Adjusted } R^2 = 0.736]$

Table S2. Equations of the Multiple Linear Regression Analyses (MLRA) describing the highest portion of variability (R^2 values) in glacier response time (τ_{glac}). See Figure S6 for the definition of the variables. The many degrees of freedom lead to an Adjusted R^2 value that is almost identical to the R^2 value. For a given number of variables, the higher Adjusted R^2 values for the quadratic fit indicate an improvement of the regression compared to the linear fit, as opposed to overfitting (Miles, 2014).

References

- Miles, J. (2014). R Squared, Adjusted R Squared. *Wiley StatsRef: Statistics Reference Online*, (2), 2–4. <https://doi.org/10.1002/9781118445112.stat06627>
- Zekollari, H., Huss, M., & Farinotti, D. (2019). Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble. *The Cryosphere*, 13, 1125–1146. <https://doi.org/10.5194/tc-13-1125-2019>