SUPPLEMENTARY MATERIAL:

Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble

Harry Zekollari[1,2]*, Matthias Huss[1,3] 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 Geosciences, University of Fribourg, Fribourg, Switzerland

* corresponding author: zharry@ethz.ch

The supplementary material consists of 6 tables and 4 figures

Tables

GCM RCM	CNRM-CERFACS-CNRM-CM5	ICHEC-EC-EARTH	IPSL-IPSL-CM5A-MR	MOHC-HadGEM2-ES	MPI-M-MPI-ESM-LR	NCC-NorESM1-M
ALADIN53	rcp2.6, rcp4.5, rcp8.5 (r1i1p1)					
ALARO-0	rcp2.6, rcp4.5, rcp8.5 (r1i1p1)					
CCLM4-8-17	rcp4.5 rcp8.5 (r1i1p1)	**rcp2.6**, rcp4.5, rcp8.5 (r12i1p1)		rcp4.5 rcp8.5 (r1i1p1)	rcp4.5 rcp8.5 (r1i1p1)	
HIRHAM5		rcp2.6, rcp4.5, rcp8.5 (r3i1p1)		rcp8.5 (r1i1p1)		rcp4.5 rcp8.5 (r1i1p1)
RACMO22E		rcp2.6, rcp4.5, rcp8.5 (r12i1p1); rcp4.5 rcp8.5 (r1i1p1)		rcp2.6, rcp4.5, rcp8.5 (r1i1p1)		
RCA4	rcp4.5, rcp8.5 (r1i1p1)	rcp2.6, rcp4.5, rcp8.5 (r12i1p1)	rcp4.5, rcp8.5 (r1i1p1)	rcp2.6, rcp4.5, rcp8.5 (r1i1p1)	rcp2.6, rcp4.5, rcp8.5 (r1i1p1)	
REMO2009					rcp2.6, rcp4.5, rcp8.5 (r1i1p1); rcp2.6, **rcp4.5**, rcp8.5 (r2i1p1)	
WRF331F			rcp4.5 rcp8.5 (r1i1p1)			
WRF361H					**rcp8.5** (r1i1p1)	

Table S1: Overview of the 51 EURO-CORDEX GCM-RCM chains utilised in this study. All available chains at a 0.11° resolution (ca. 12 km) and with monthly temperature and precipitation series are considered. The chains in red are the ones with a future volume evolution that is the closest to the multi-model mean.

Glacier name	Location	Area at RGI inventory date (2003)	
Grosser Aletschgletscher (Switzerland)	8.019°E 46.503°N	82.2 km^2	Three values correspond to (i) near-front, (ii) first velocity peak, and (iii) peak velocities (Fig. 5a). Observations are 1950/85 point measurements from Zoller (2010).
Mer de Glace (France)	6.934°E 45.883°N	24.2 km^2	Four values correspond to four peaks in surface velocities (Fig. 5b). Observations from SPOT imagery for the years 2000/2001 (Berthier and Vincent, 2012).
Rhonegletscher (Switzerland)	8.396°E 46.624°N	15.8 km^2	Values correspond to peak velocity. Visually interpolated between the 1981-82 and the 1999-2000 velocities from Fig. 8 in Nishimura et al. (2013).
Vadret da Morteratsch (Switzerland)	9.925°E 46.3893°N	15.8 km^2	Value corresponds to peak velocity. Observation from stake network, taken from Table 1 from Zekollari et al. (2013).
Unteraargletscher (Switzerland)	8.219°E 46.564°N	23.8 km^2	Peak velocity under the confluence (4 km from the front at inventory date). Observation from 1996/97 from Fig. 5.1. in Bauder (2001)
Hintereisferner (Austria)	10.758°E 46.800°N	8.03 km^2	Two values correspond 'line 6' and 'line 7' from Stocker-Waldhuber et al. (2018, Fig.3, which were visually interpolated to 2003), and are respectively located at about 1 km upstream and 2 km upstream from the front at the inventory date.
Kesselwandferner (Austria)	10.791°E 46.842°N	4.0 km^2	Peak velocity for the 1990-2010 period (Fig.4 in Stocker-Waldhuber et al., 2018)
Taschachferner (Austria)	10.855°E 46.896°N	5.4 km^2	Peak velocity in the 2000s (Fig.5 in Stocker-Waldhuber et al., 2018)
Gepatschferner (Austria)	10.757°E 46.849°N	16.6 km^2	Peak velocity in the 2000s (Fig.5 in Stocker-Waldhuber et al., 2018)
Careser (Italy)	10.708°E 46.451°N	2.8 km^2	Peak velocity in the 1970s (Carturan et al., 2013)
Argentière (France)	6.985°E 45.951°N	13.8 km^2	Peak velocity in the summer of 2003 (Fig. 2 in Rabatel et al., 2018)

Table S2: Information and references for surface velocities used for model evaluation (Fig. 5 and Fig.6)

Glacier characteristic in 2017	RCP2.6 2017-2100 relative volume change	RCP4.5 2017-2100 relative volume change	RCP8.5 2017-2100 relative volume change
volume	$r^2 = 0.03$	$r^2 = 0.06$	$r^2 = 0.06$
area	$r^2 = 0.06$	$r^2 = 0.11$	$r^2 = 0.11$
length	$r^2 = 0.13$	$r^2 = 0.23$	$r^2 = 0.20$
median elevation	$r^2 = 0.07$	$r^2 = 0.07$	$r^2 = 0.03$
mean elevation	$r^2 = 0.07$	$r^2 = 0.07$	$r^2 = 0.03$
minimum elevation	$r^2 = 0.18$	$r^2 = 0.20$	$r^2 = 0.19$
maximum elevation	$r^2 = 0.38$	$r^2 = 0.41$	$r^2 = 0.30$
centre of mass	$r^2 = 0.06$	$r^2 = 0.05$	$r^2 = 0.02$
elevation range	$r^2 = 0.57$	$r^2 = 0.63$	$r^2 = 0.51$

Table S3: Correlation (r^2) between modelled present-day (2017) glacier characteristics and relative future volume changes (2100 vs. 2017). The values are based on the RCM multi-chain mean for the respective RCP.

	Ice flow	Δh	SMB calibration	Calibration	RCP 2.6	RCP 4.5	RCP 8.5
Standard	✓		local	V-L	36.5 (-70%)	21.1 (-83%)	5.5 (-95%)
Δh-parameterization		✓	local		31.9 (-74%)	18.4 (-85%)	6.1 (-95%)
region-wide MB calibration			regional	V-L	42.3 (-65%)	23.1 (-81%)	6.5 (-95%)

Table S4: 2100 glacier volume and relative loss (vs. 2003) for (i) the standard (dynamic) model, (ii) the model forced with the Δh parameterization and (iii) the dynamic model for which the SMB component is calibrated with a regional SMB estimation. All numbers correspond to multi-chain mean values.

	Sum Sq.	Degrees of Freedom	Mean Sq.	F	p-value
GCM	1092.8	5	218.6	6.9639	1.68×10^{-4}
RCP	6654.7	2	3327.4	106.02	7.64×10^{-15}
Realization	188.1	3	62.7	1.9976	0.134
RCM	593.6	8	74.2	2.3643	0.040
Error	1004.3	32	31.4		

Table S5: Analysis of variance (ANOVA) of linear model with categorical data for describing 2017-2100 volume change based on EURO-CORDEX data. For every category (GCM, RCP, Realization, RCM) the degrees of freedom correspond to the number of possible values minus 1.

Glacier and study	Ice flow model type	Scenario considered in detailed study and corresponding scenario here	Modelled glacier changes (detailed 3-D study vs. our flowline model)	Notes
Rhonegletscher; (Jouvet et al., 2009)	full-stokes model	median scenario (+4°C vs. 1990); between RCP4.5 and RCP8.5	-95% volume change over 2007-2100 vs. -90±6% under RCP4.5	In Jouvet et al. (2009), two scenarios without major precipitation changes are considered. Good (qualitative) agreement between changes from 3-D model and our study.
		Strong warming scenario (+6°C vs. 1990): warmer than RCP8.5	95% of the 2007 volume is lost by 2075 vs. 95% of the 2007 volume is lost by 2079.5±11.5 under RCP8.5	
Grosser Aletschgletscher (Jouvet et al., 2011)	full-stokes model	+2°C (1980-2009 → 2100); close to RCP2.6	1999-2100 volume change: -66% vs. -60±19% under RCP2.6	Good (qualitative) agreement between changes from 3-D model and our study.
		'ENSmin' (+2.9/+3.7°C annual/summer temperature increase in 2100 vs. 1980-2009); between RCP4.5 and RCP8.5	1999-2100 volume change: -76% vs. -68±14% under RCP4.5 and -90±10% under RCP8.5	
		'ENSmed' scenario (annual/summer temperatures increase by +4.3°C/+5.5°C by 2100 vs. 1980-2009); close to RCP8.5	1999-2100 volume change: -90% vs. -90±10% under RCP8.5	
Vadret da Morteratsch (Zekollari et al., 2014)	higher-order model	+1°C over period 2010-2100; approx. RCP2.6	2010-2100 volume change: -48%; vs. -63±14% under RCP2.6	(Qualitative) comparison suggests that simulations with our flowline model result in higher mass losses compared to those from detailed modelling study.
		+2.5°C over period 2010-2100; approx. RCP4.5	2010-2100 volume change: -69%; vs. -80±8% under RCP4.5	
		+4°C over period 2010-2100; approx. RCP8.5	2010-2100 volume change: -80%; vs. -95±4% under RCP8.5	

Table S6: Modelled glacier changes compared to other 3-D detailed studies including non-local stresses. All values from our study corresponds to multi-chain means for a specific RCP.

Figures

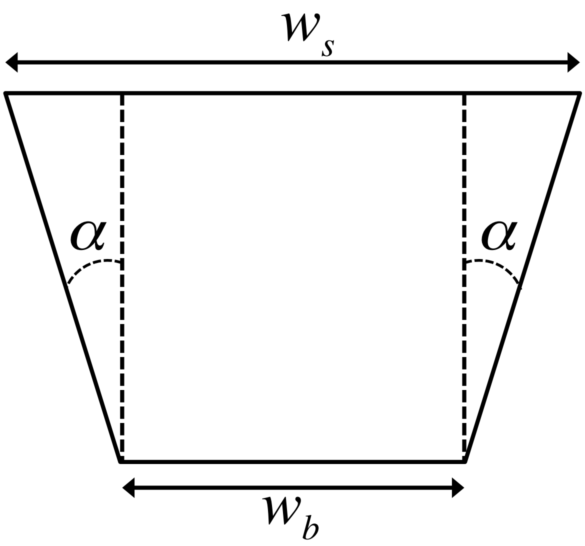

Fig. S1: Parameterization of glacier cross section with slope angle α

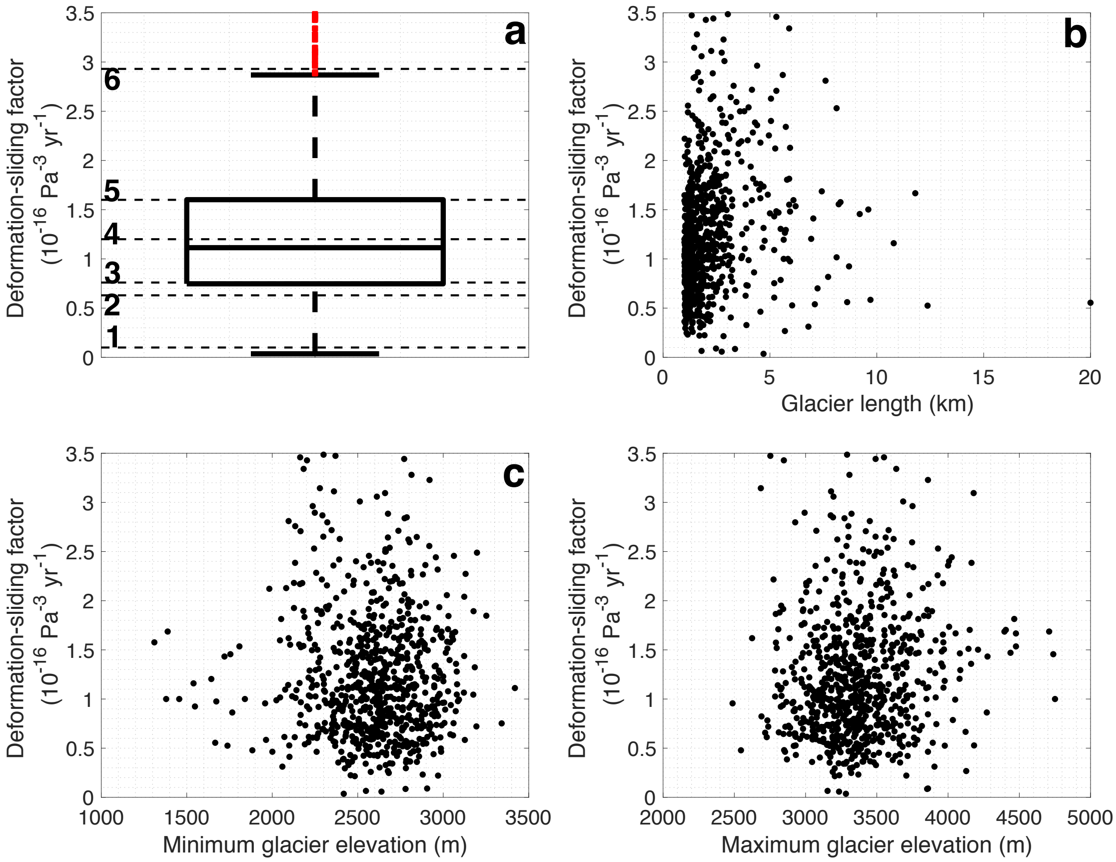

Fig. S2: Deformation-sliding factor obtained from model calibration (a) boxplot and as a function of various glacier characteristics: (b): glacier length, (c): minimum glacier elevation, (d): maximum glacier elevation. In panel (a), the horizontal dotted lines correspond to selected values from the literature: (1) Modelling of Pasterze (Austria) (Zuo and Oerlemans, 1997), (2) Glacier de Saint-Sorlin (France) (Le Meur and Vincent, 2003), (3) Model mean from various calibrated numerical models (Cuffey and Paterson, 2010), similar value value obtained for Unteraargletscher (Gudmundsson, 1999); (4) Mean from various borehole tilt measurements (Cuffey and Paterson, 2010), (5) Modelling of Findelengletscher (Iken and Truffer, 1997); similar value obtained for Vadret da Morteratsch (Zekollari et al., 2013); (6) value obtained from various lab experiments (Budd and Jacka, 1989)

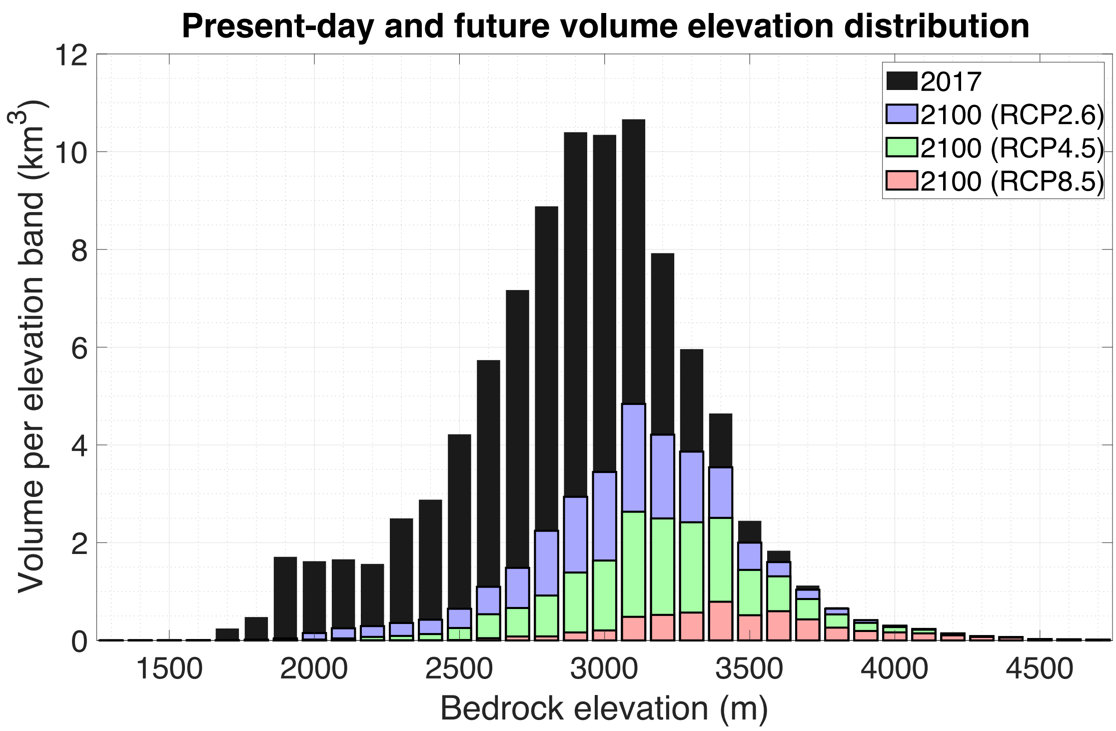

Fig. S3. Modelled volume elevation distribution in 2017 and in 2100 under three climate scenarios (RCP2.6, RCP4.5, and RCP8.5). The values in 2100 correspond to the multi-model mean under a specific RCP.

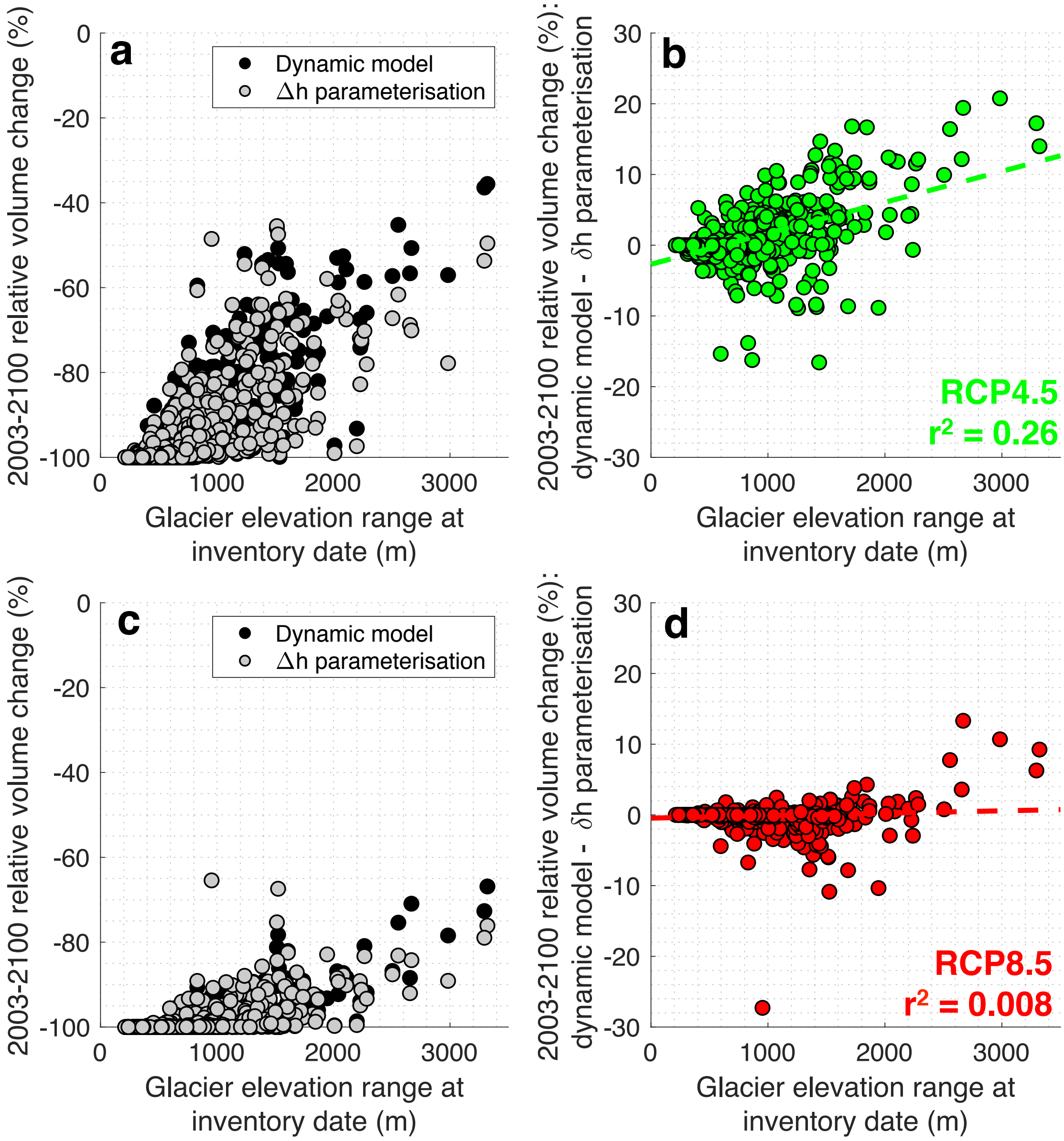

Fig. S4. Future glacier evolution for individual glaciers with dynamic model and corresponding glacier simulation with Δh-parameterisation. All values correspond to RCP4.5 multi-chain mean values (a,b) and RCP8.5 multi-chain mean values (c,d).

References supplementary material

Bauder: Bestimmung der Massenbilanz von Gletschern mit Fernerkundungsmethoden und Fliessmodellierungen, ETH Zürich., 2001.

Berthier, E. and Vincent, C.: Relative contribution of surface mass-balance and ice-flux changes to the accelerated thinning of Mer de Glace, French Alps, over 1979-2008, J. Glaciol., 58(209), 501–512, doi:10.3189/2012JoG11J083, 2012.

Budd, W. F. and Jacka, T. H.: A Review of Ice Rheology for Ice Sheet Modelling, Cold Reg. Sci. Technol., 16, 107–144, 1989.

Carturan, L., Baroni, C., Becker, M., Bellin, A., Cainelli, O., Carton, A., Casarotto, C. and Fontana, G. D.: The Cryosphere Decay of a long-term monitored glacier: Careser Glacier (Ortles-Cevedale, European Alps), Cryosph., 7, 1819–1838, doi:10.5194/tc-7-1819-2013, 2013.

Cuffey, K. M. and Paterson, W. S. B.: The physics of glaciers, Butterworth-Heinemann, Oxford., 2010.

Gudmundsson, G. H.: A three-dimensional numerical model of the confluence area of Unteraargletscher, Bernese Alps, Switzerland, J. Glaciol., 45(150), 219–230, doi:10.3189/002214399793377086, 1999.

Iken, A. and Truffer, M.: The relationship between subglacial water pressure and velocity of Findelengletscher, Switzerland, during its advance and retreat, J. Glaciol., 43(144), 328–338, doi:10.1017/CBO9781107415324.004, 1997.

Jouvet, G., Huss, M., Blatter, H., Picasso, M. and Rappaz, J.: Numerical simulation of Rhonegletscher from 1874 to 2100, J. Comput. Phys., 228(17), 6426–6439, doi:10.1016/j.jcp.2009.05.033, 2009.

Jouvet, G., Huss, M., Funk, M. and Blatter, H.: Modelling the retreat of Grosser Aletschgletscher, Switzerland, in a changing climate, J. Glaciol., 57(206), 1033–1045, doi:10.3189/002214311798843359, 2011.

Le Meur, E. and Vincent, C.: A two-dimensional shallow ice-flow model of Glacier de Saint-Sorlin, France, J. Glaciol., 49(167), 527–538, doi:10.3189/172756503781830421, 2003.

Nishimura, D., Sugiyama, S., Bauder, A., Funk, M., Bauder, A. and Funk, M.: Changes in Ice-Flow Velocity and Surface Elevation from 1874 to 2006 in Changes in Ice-Flow Velocity and Surface Elevation from 1874 to 2006 in Rhonegletscher, Switzerland, Arctic, Antarct. Alp. Res., 45(4), 552–562, 2013.

Rabatel, A., Sanchez, O., Vincent, C. and Six, D.: Estimation of Glacier Thickness From Surface Mass Balance and Ice Flow Velocities: A Case Study on Argentière Glacier, France, Front. Earth Sci., 6, 112, doi:10.3389/feart.2018.00112, 2018.

Stocker-Waldhuber, M., Fischer, A., Helfricht, K. and Kuhn, M.: Ice flow velocity as a sensitive indicator of glacier state, Cryosph. Discuss., doi:10.5194/tc-2018-37, 2018.

Zekollari, H., Huybrechts, P., Fürst, J. J., Rybak, O. and Eisen, O.: Calibration of a higher-order 3-D ice-flow model of the Morteratsch glacier complex, Engadin, Switzerland, Ann. Glaciol., 54(63), 343–351, doi:10.3189/2013AoG63A434, 2013.

Zekollari, H., Fürst, J. J. and Huybrechts, P.: Modelling the evolution of Vadret da Morteratsch, Switzerland, since the Little Ice Age and into the future, J. Glaciol., 60(224), 1208–1220, doi:10.3189/2014JoG14J053, 2014.

Zoller, N.: Fliessbewegung des Grossen Aletschgletschers, Bachelor thesis, ETH Zürich., 2010.

Zuo, Z. and Oerlemans, J.: Numerical modelling of the historic front variation and the future behaviour of the Pasterze glacier, Austria, Ann. Glaciol., 24, 234–241, 1997.