

SUPPLEMENTARY MATERIAL:

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

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The supplementary material consists of 6 tables and 5 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	rep2.6, rep4.5, rep8.5 (r1i1p1)					
ALARO-0	rep2.6, rep4.5, rep8.5 (r1i1p1)					
CCLM4-8-17	rep4.5 rep8.5 (r1i1p1)	rep2.6, rep4.5, rep8.5 (r12i1p1)		rep4.5 rep8.5 (r1i1p1)	rep4.5 rep8.5 (r1i1p1)	
HIRHAM5		rep2.6, rep4.5, rep8.5 (r3i1p1)		rep8.5 (r1i1p1)		rep4.5 rep8.5 (r1i1p1)
RACMO22E		rep2.6, rep4.5, rep8.5 (r12i1p1); rep4.5 rep8.5 (r1i1p1)		rep2.6, rep4.5, rep8.5 (r1i1p1)		
RCA4	rep4.5, rep8.5 (r1i1p1)	rep2.6, rep4.5, rep8.5 (r12i1p1)	rep4.5, rep8.5 (r1i1p1)	rep2.6, rep4.5, rep8.5 (r1i1p1)	rep2.6, rep4.5, rep8.5 (r1i1p1)	
REMO2009					rep2.6, rep4.5, rep8.5 (r1i1p1); rep2.6, rep4.5, rep8.5 (r2i1p1)	
WRF331F			rep4.5 rep8.5 (r1i1p1)			
WRF361H					rep8.5 (r1i1p1)	

Table S1. Overview of the 51 EURO-CORDEX RCM simulations utilised in this study. All available simulations at a 0.11° resolution (ca. 12 km) and with monthly temperature and precipitation series are considered. The simulations 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	8.0 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)

	RCP2.6	RCP4.5	RCP8.5
Glacier characteristic in 2017	2017-2100 relative volume change	2017-2100 relative volume change	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-simulation 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 the RCM multi-simulation 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 RCM multi-simulation means for a specific RCP.

Figures

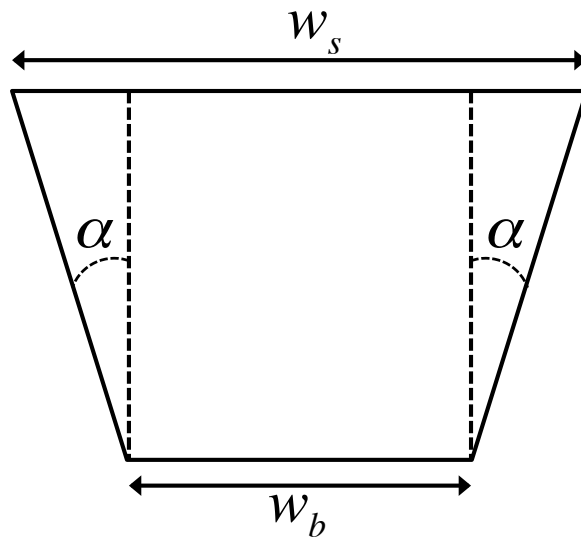


Fig. S1. Parameterization of glacier cross section with slope angle α

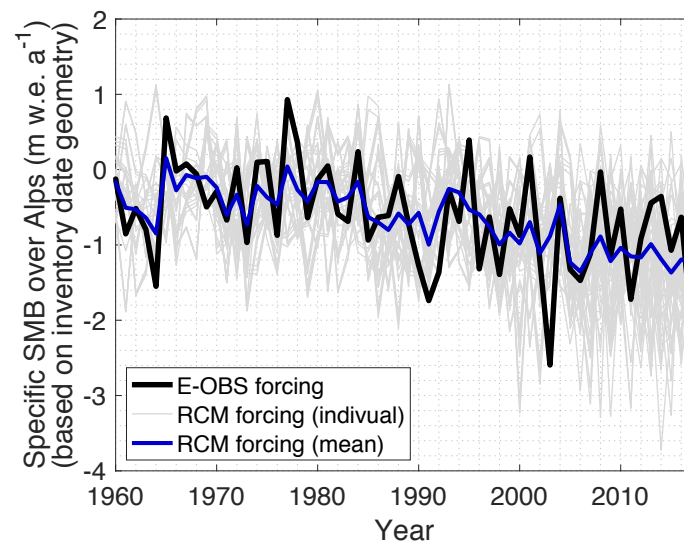


Fig. S2. Past specific surface mass balance (SMB) over glaciers in the European Alps, as derived from E-OBS data and from historical RCM simulations. SMB calculations are based on reference geometry at inventory date.

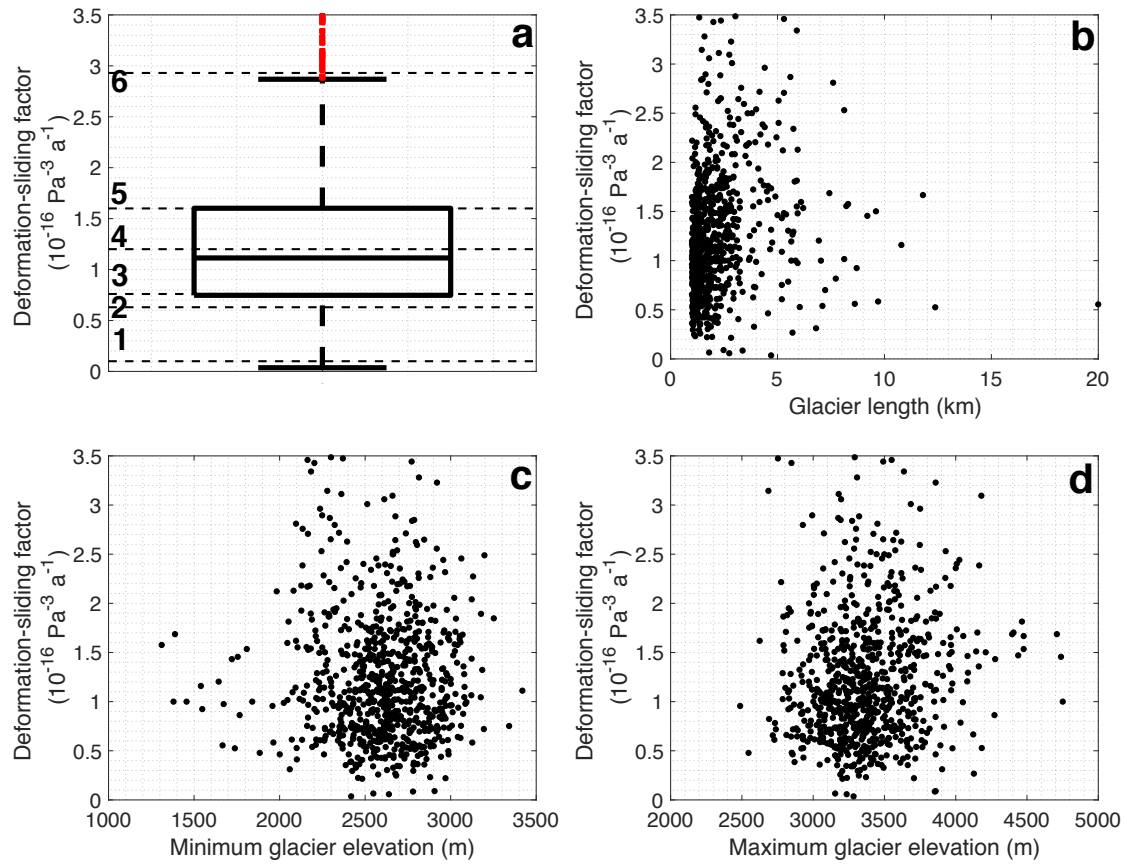


Fig. S3. Deformation-sliding factor obtained from model calibration (a) boxplot and as a function of various glacier characteristics: (b): glacier length, (c): minimum glacier elevation, (d): maximum glacier elevation. In panel (a), the horizontal dotted lines correspond to selected values from the literature: (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)

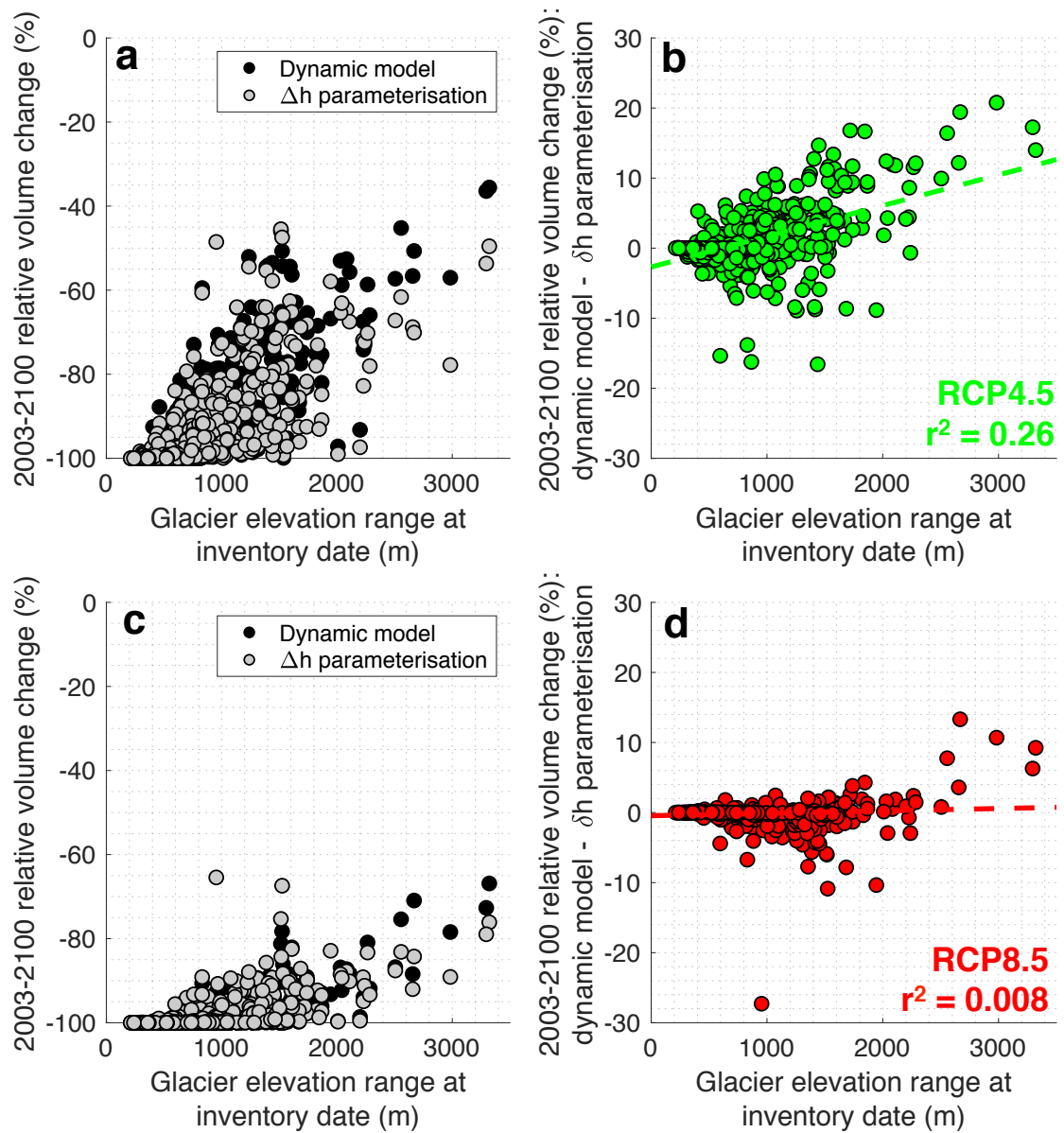


Fig. S4. Future glacier evolution for individual glaciers with dynamic model and corresponding glacier simulation with Δh -parameterisation. All values correspond to RCP4.5 multi-simulation mean values (a,b) and RCP8.5 multi-simulation mean values (c,d).

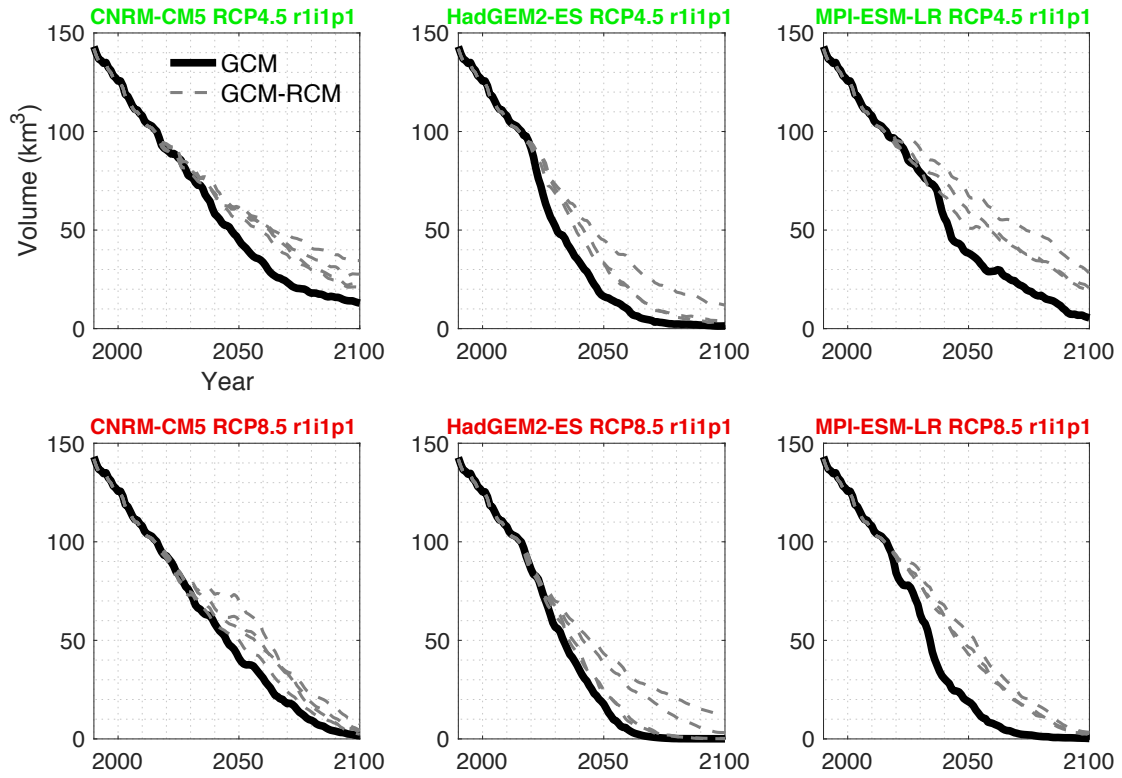


Fig. S5. Future evolution of glacier volume when the model is forced directly with GCMs vs. EURO-CORDEX GCM-RCM simulations. Results are shown for the GCMs that have the most corresponding RCM simulations in the EURO-CORDEX ensemble for a given realisation (CNRM-CM5 r1i1p1, HadGEM2-ES r1i1p1, MPI-ESM-LR r1i1p1).

References supplementary material

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