Supplement of The Cryosphere, 17, 2343–2365, 2023
https://doi.org/10.5194/tc-17-2343-2023-supplement

Supplement of

Strategies for regional modeling of surface mass balance at the Monte Sarmiento Massif, Tierra del Fuego

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1. Quantification of model sensitivity and related uncertainty

Uncertainties in the surface mass balance estimation come from three different sources in this study: a) uncertainties related to the climatic forcing, b) model-inherent uncertainties related to the choice of model parameters and c) uncertainties related to the choice of model type. We will in the following discuss the model sensitivity to the respective calibration parameters and the associated uncertainty.

a) Uncertainties in the climatic forcing stem from the climatic input data, with the largest contribution coming from precipitation and air temperature. We consider both variables in the model calibration via the parameters TLR and τ. In Fig. S1, we see that the modeled ablation at the stakes is hardly sensitive to both variables (Fig. S1a, b). However, the mass budget of Schiaparelli (Fig. S1c) and, thus, the aggregated model skill with Strategy A (Fig. S1d) as well as the B_{MSMnc} (Strategy B) (Fig. S1e) are very sensitive to both TLR and τ.

To assess the uncertainty of the SMB based on the chosen parameters related to the climatic forcing, we compare the results of the 10 best ranked PDD runs where different combination of TLR and τ are used (Table S5). The ranking differs depending on the calibration strategy applied. Overall, the uncertainty following Strategy A is larger than following Strategy B for the B_{MSMnc} (Fig. S6). The largest range of uncertainty is found at glacier 149 with Strategy A (0.36 m w.e. yr^{-1}) and at glaciers Schiaparelli and 152 with Strategy B (0.59 m w.e. yr^{-1}). The width of uncertainty of the B_{MSMnc} is 0.21 m w.e. yr^{-1} and 0.06 m w.e. yr^{-1} for Strategy A and B, respectively (Fig. S6, Table S5).

The ranges of uncertainty of the B_{MSMnc} in the best 10 ranked runs related to the climatic forcing are larger if we rank the runs following Strategy A than following Strategy B. This shows that with a single-glacier calibration we face large difficulties to accurately calibrate the climate variables for an entire region. These can be overcome by a regional calibration, still, individual glaciers may be biased this way.

b) Model-inherent uncertainties relate to the choice of model parameterizations and limitations in the model calibration and are analyzed for each model individually. The uncertainties are assessed by considering the 10 best ranked parameter combinations for each model (5 best ranked for the PDD due to the significantly smaller sample size) after setting the climatic forcing.

For the PDD, the ablation at the stakes is very sensitive to the DDF_{ice} (Fig. S1a,b) but insensitive to the DDF_{snow} due to the neglectable amount of snowfall at these elevations. The mass budget of Schiaparelli (Fig. S1c) and, thus, the aggregated model skill with Strategy A (Fig. S1d) as well as the B_{MSMnc} (Fig. S1e) show high sensitivity to both parameters. The uncertainty range for the individual glaciers is between 0.35 (138) and 0.80 m w.e. yr^{-1} (Schiaparelli) (Table S6, Fig. S6). Also, the uncertainty around the B_{MSMnc} is large with 0.51 m w.e. yr^{-1} (Table S6, Fig. S6).

The SMB results of the SEB_Gpot and the SEB_G are very sensitive to both model parameters C_0 und C_1 (Fig. S2a,b). The range of uncertainty for the individual glaciers lies between 0.17 and 0.45 m w.e. yr^{-1} for the SEB_Gpot and between 0.19 and

0.40 m w.e. yr^{-1} for the SEB_G (Table S6, Fig. S6). The B_{MSMnc} can be determined rather accurately for both variants with an uncertainty range below 0.26 m w.e. yr^{-1} (Table S6, Fig. S6).

The simulated SMB from COSIPY is very sensitive to all three calibration parameters (Fig. S2c). The largest changes are observed by varying the z_0. The uncertainty range is largest for Schiaparelli Glacier with 0.19 m w.e. yr^{-1} and smallest for Conway Glacier with 0.05 m w.e. yr^{-1} (Table S6, Fig. S6). The B_{MSMnc} uncertainty (0.09 m w.e. yr^{-1}) is distinctly smaller as for the other SMB models.

The sensitivity to the model-inherent parameters and the related uncertainty show model distinct magnitudes. However, apart from the PDD, all models produce rather stable results looking at the B_{MSMnc} as well as the individual glaciers (Table S6, Fig. S6). The most stable results for both, the B_{MSMnc} and the individual glaciers, are produced by COSIPY. The increased ranges for the PDD model may be due to the reduced sample size of the model-specific parameters in this case. To compensate for this disparity, we calculated the uncertainties of the PDD taking only the top 5 instead of the top 10 ranked model runs. Yet, a direct comparison with the other models might not be straightforward. This also shows that the spread around the best result depends strongly on the range and sample size of applied model parameters.

c) Uncertainties due to model type are linked to model capability to realistically represent the controlling factors on SMB and are outlined by the use of different SMB models. Comparing the results of the best ranked run of each model (Table S6), we observe that the minimum estimate of each glacier comes mostly from the PDD, or from COSIPY, whereas the maximum estimate comes often from the SEB_G. The estimates for the individual glaciers differ between 0.21 (144) and 0.69 m w.e. yr^{-1} (Conway). The B_{MSMnc} is simulated in a range between -0.49 and -0.32 m w.e. yr^{-1}.

Overall, the differences between the four model types are moderate for the B_{MSMnc}, however significant for several individual glaciers. The estimated SMBs of the SEB_Gpot and SEB_G are on average similar and more positive than the PDD and COSIPY.

In general, we see the largest sensitivity of the SMB models to the climatic forcing, thus causing the highest uncertainty to the results. The model choice also impacts the SMB estimates of individual glaciers significantly although the massif-wide average is similar. The sensitivity of the individual models to the respective calibration parameters is generally smaller. However, we have shown that there is a strong dependence on the parameter range and sample size. We conclude that the model choice is of large importance and want to highlight the significance of accurate downscaling of climatic forcing data.

2. Supplementary figures

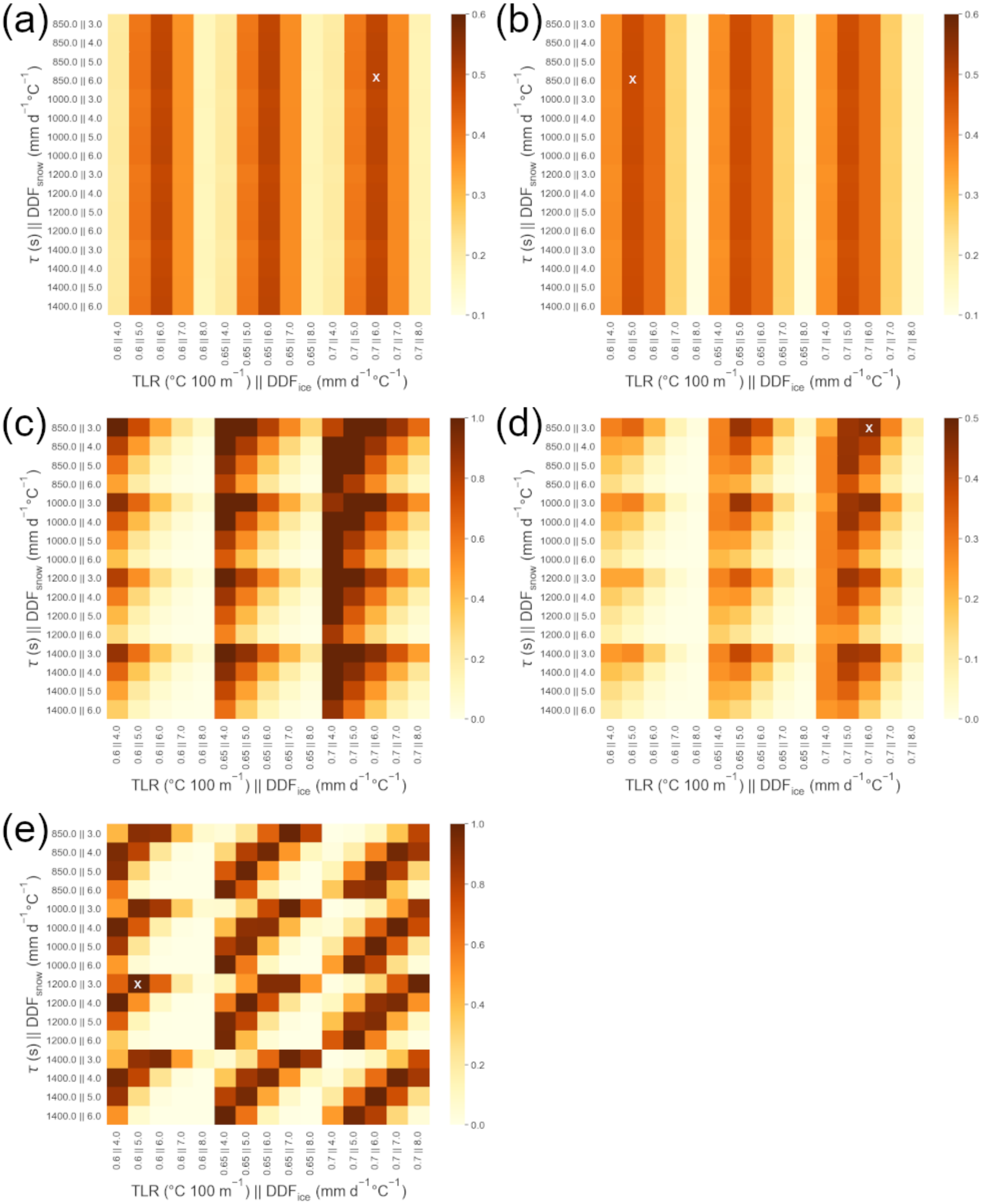

Fig. S1: Heat plots of the PDD calibration showing the skill scores of individual measurements and aggregated model skill. Displayed are skills of (a) S1toS5, (b) Sauto, (c) mass budget of Schiaparelli Glacier, (d) aggregated model skill with calibration Strategy A, and (e) geodetic B_{MSMnc} (Strategy B). The one highest performing run is highlighted with a white cross. For the Schiaparelli mass budget (c) in total 30 runs reach perfect agreement.

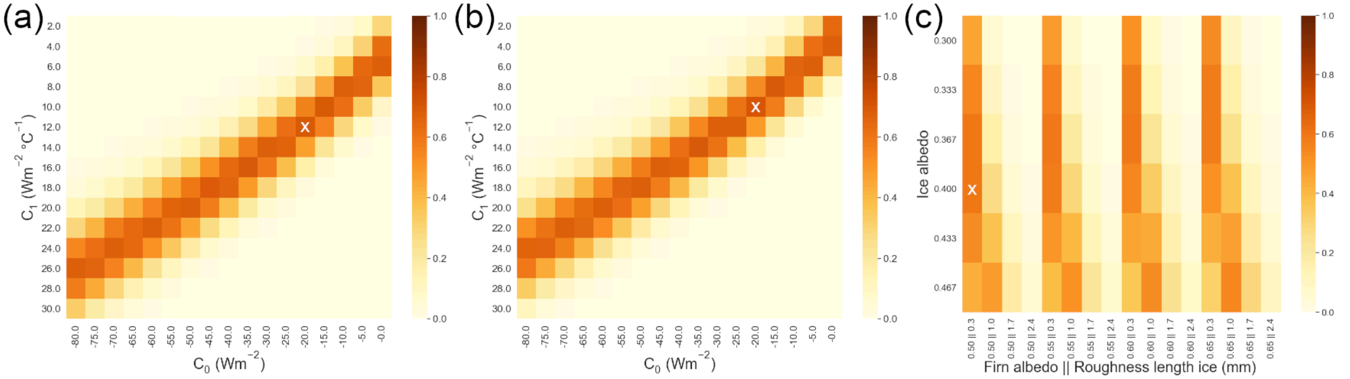

Fig. S2: Heat plots of the model-inherent calibration showing the aggregated model skill for the (a) SEB_Gpot, (b) SEB_G, and (c) COSIPY. The highest performing run is highlighted with a white cross.

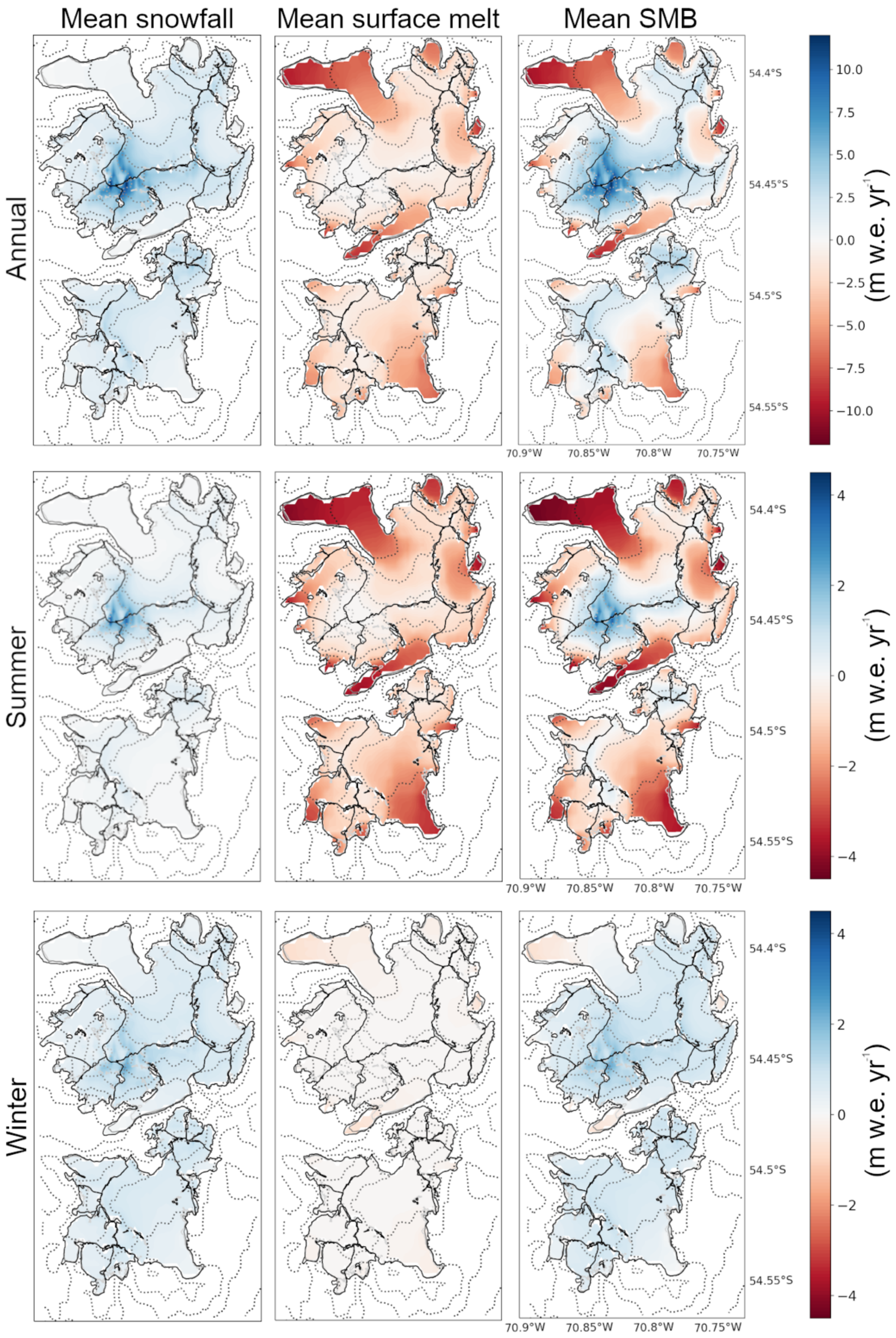

Fig. S3: Mean annual and seasonal snowfall, surface melt and SMB from COSIPY. Outlines represent 2004 (black), 2013 (darkgrey) and 2019 (lightgrey) extents.

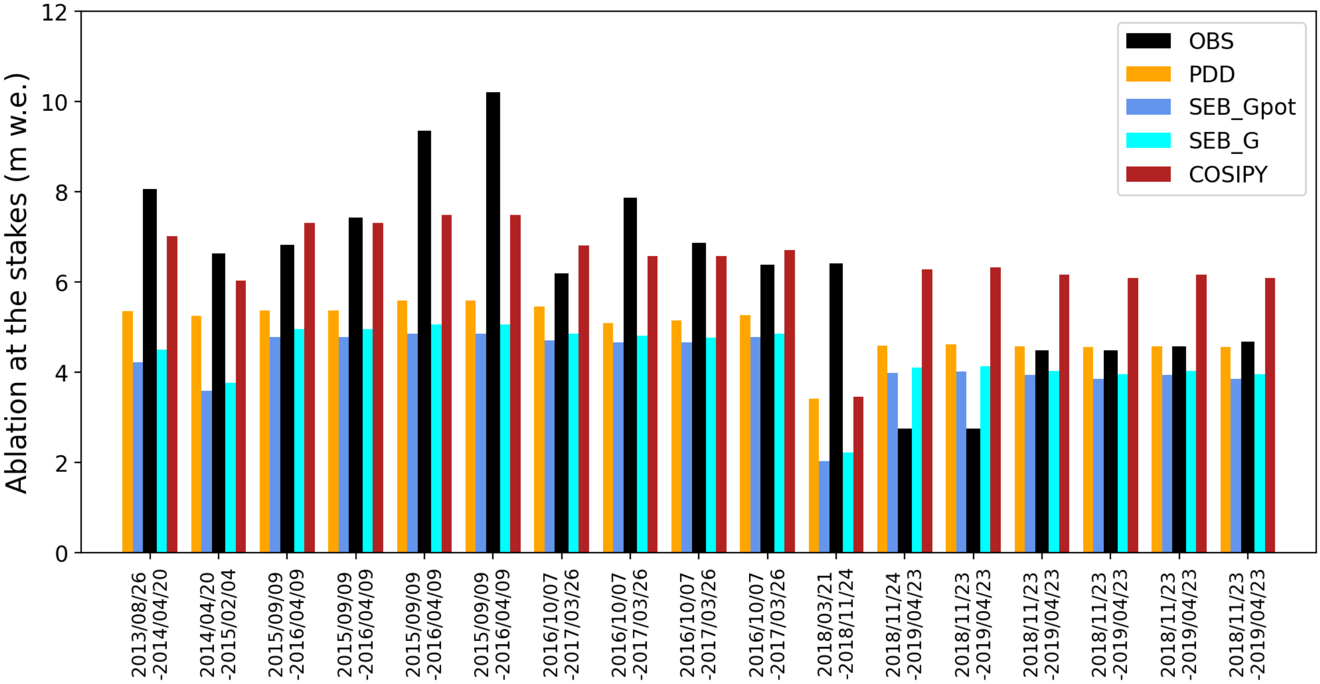

Fig. S4: Comparison of measured against modelled ablation at the individual ablation stakes (S1to5). The observation is displayed in black in the middle between the four models for each measurement period.

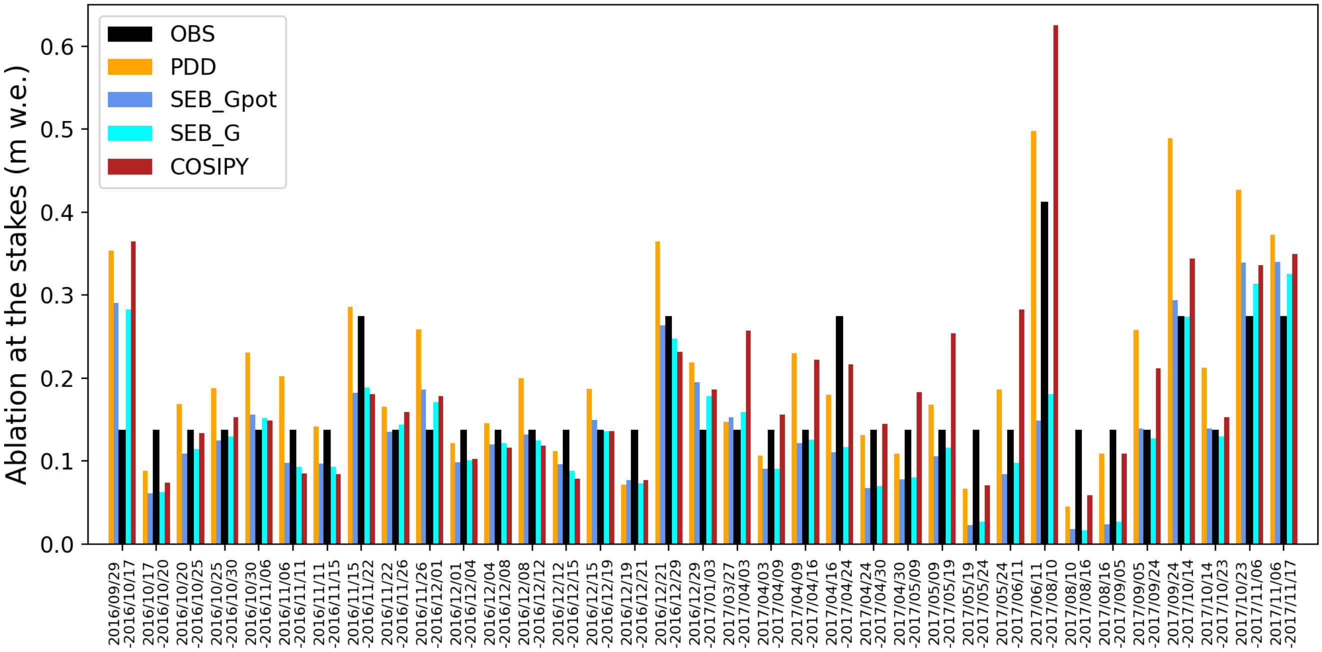

Fig. S5: Comparison of measured against modelled ablation at the automatic ablation sensor (Sauto). The observation is displayed in black in the middle between the four models for each measurement period.

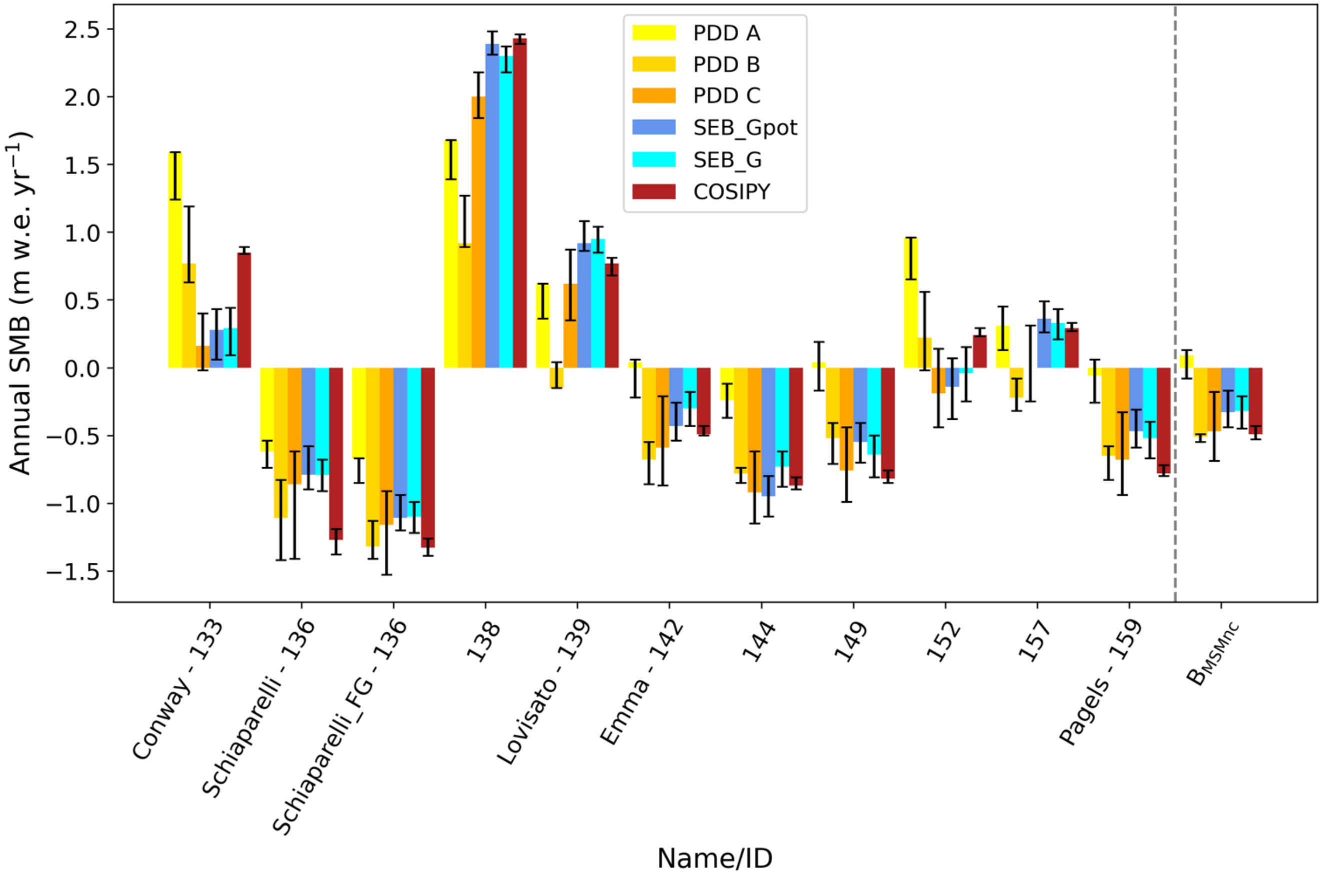

Fig. S6: Mean annual SMB and uncertainty for the individual glaciers and the B_{MSMnc}, (massif-wide annual average excluding glaciers with major calving losses). Results are shown for the three calibration strategies and the four models.

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3. Supplementary tables

Table S1: Statistical performance of input variables compared to observations at the AWS location (daily resolution). Given are the mean model bias (MMB), the root mean square error (RMSE) and the Pearson correlation (*r*). MMB and RMSE are given in the respective variable's unit.

	Quantile Mapping			ERA5 direct	Radiation model		OPM
	T	*RH*	*PRES*	*U*	*G*	*Gpot*	*RRR*
MMB	-0.06	-12.68	-0.26	-1.26	2.37	24.82	-1.28
RMSE	0.76	14.02	1.70	1.75	40.69	51.64	5.15
r	0.95	0.72	0.99	0.76	0.78	0.70	0.66

Table S2: Overview of model set-up and fixed parameter values

	Parameter	Value/Method	Unit	Source/Sensitivity tests (S)/Calculated (C)
Model set-up	Temporal resolution	3	hour	-
	Spatial resolution	200	m	-
OPM	Relative humidity threshold	90	%	S
PDD	Temperature threshold snow-rain	1.0	°C	S
	Temperature threshold melting	1.0	°C	S
SEB_Gpot	Temperature threshold snow-rain	1.0	°C	S
	Temperature threshold melting	1.0	°C	S
	Atmospheric transmissivity	0.38	-	C
SEB_G	Temperature threshold snow-rain	1.0	°C	S
	Temperature threshold melting	1.0	°C	S
COSIPY	Stability correction	Monin-Obukhov	-	S
	Center snow transfer function	1.0	°C	S
	Spread snow transfer function	1.0	-	-
	Albedo fresh snow	0.9	-	S
	Time constant snow albedo ageing	22	day	S
	Depth constant snow albedo ageing	3	cm	Oerlemans and Knap, 1998
	Roughness length fresh snow	0.24	mm	Mölg et al., 2012
	Roughness length firn	4.0	mm	Mölg et al., 2012

Table S3: Ice flux through the flux gate for the periods 2000-2013 and 2000-2019.

Period	Mean velocity (m day^{-1})	Mass flux (km^3 yr^{-1} i.e.)	Uncertainty (km^3 yr^{-1} i.e.)
2000-2013	0.18	0.0209	± 0.0044
2000-2019	0.19	0.0206	± 0.0036

Table S4: Average observed end of summer snow line altitudes (SLA) from satellite images (2003-2022) for four glaciers in the MSM.

Location	Average SLA (m a.s.l.)
133 – Conway	775
136 – Schiaparelli	645
139 – Lovisato	717
142 – Emma	612

Table S5: Comparison of geodetic and surface MB (m w.e. yr^{-1}) using Strategy A and B for the glaciers in the study site (> 3 km^2). For both strategies the best, minimum and maximum estimate are given. B_{MSMnc} gives the massif-wide annual average MB excluding glaciers with major calving losses. The asterisk marks lake termination.

Name/ID	Area (km^2)	geodetic MB (m w.e. yr^{-1})	Uncertainty (m w.e. yr^{-1})	SMB (m w.e. yr^{-1})					
				Strategy A			Strategy B		
				best	min	max	best	min	max
133 – Conway*	8.45	-0.18	0.04	1.59	1.24	1.59	0.77	0.63	1.19
136 – Schiaparelli*	25.03	-0.79	0.19	-0.62	-0.74	-0.54	-1.11	-1.42	-0.83
136 – Schiaparelli_FG	23.15	-0.59	0.16	-0.67	-0.85	-0.67	-1.32	-1.41	-1.13
138*	3.89	-0.50	0.23	1.68	1.39	1.68	0.92	0.89	1.27
139 - Lovisato*	12.57	-1.30	0.35	0.62	0.36	0.62	-0.15	-0.15	0.04
142 - Emma	7.28	-0.21	0.04	0.04	-0.22	0.06	-0.68	-0.86	-0.55
144	3.83	-0.74	0.17	-0.24	-0.37	-0.12	-0.78	-0.85	-0.74
149	3.91	-0.65	0.16	0.04	-0.17	0.19	-0.52	-0.71	-0.41
152	3.60	-0.33	0.07	0.96	0.65	0.96	0.22	-0.02	0.56
157	3.55	-0.09	0.02	0.31	0.13	0.45	-0.22	-0.32	-0.08
159 - Pagels	18.69	-0.45	0.11	-0.06	-0.26	0.06	-0.65	-0.83	-0.58
B_{MSMnc}	78.23	-0.51	0.16	0.09	-0.08	0.13	-0.51	-0.55	-0.49

Table S6: Comparison of geodetic and surface MB (m w.e. yr^{-1}) (2000-2013) from the four different models for the glaciers in the study site (> 3km^2). For every model the best, minimum and maximum estimate are given. B_{MSMnc} gives the massif-wide annual average MB excluding glaciers with major calving losses. The RMSE is weighted by area and calculated from the land-terminating glaciers. Asterisk marks lake termination.

Name/ID	Area (km^2)	geodetic MB (m w.e. yr^{-1})	SMB (m w.e. yr^{-1})							
			PDD		SEB_Gpot		SEB_G		COSIPY	
			best	min max	best	min max	best	min max	best	min max
133 – Conway*	8.45	-0.18	0.16	-0.02 0.40	0.28	0.06 0.43	0.29	0.09 0.44	0.85	0.84 0.89
136 – Schiaparelli*	25.03	-0.79	-0.86	-1.41 -0.62	-0.79	-0.90 -0.58	-0.79	-0.91 -0.68	-1.27	-1.38 -1.19
136 – Schiaparelli_FG	23.15	-0.59	-1.16	-1.53 -0.91	-1.11	-1.20 -0.94	-1.10	-1.22 -0.99	-1.33	-1.39 -1.26
138*	3.89	-0.50	2.00	1.84 2.18	2.39	2.31 2.48	2.30	2.18 2.37	2.43	2.39 2.46
139 - Lovisato*	12.57	-1.30	0.62	0.35 0.87	0.92	0.86 1.08	0.95	0.85 1.04	0.77	0.68 0.81
142 - Emma	7.28	-0.21	-0.59	-0.87 -0.21	-0.43	-0.54 -0.26	-0.30	-0.43 -0.18	-0.49	-0.50 -0.43
144	3.83	-0.74	-0.92	-1.15 -0.62	-0.95	-1.10 -0.80	-0.73	-0.88 -0.62	-0.87	-0.90 -0.81
149	3.91	-0.65	-0.76	-0.99 -0.44	-0.55	-0.70 -0.41	-0.64	-0.81 -0.50	-0.82	-0.85 -0.76
152	3.60	-0.33	-0.19	-0.44 0.14	-0.14	-0.38 0.07	-0.04	-0.25 0.15	0.24	0.23 0.29
157	3.55	-0.09	0.00	-0.25 0.31	0.36	0.26 0.49	0.33	0.21 0.43	0.29	0.27 0.33
159 - Pagels	18.69	-0.45	-0.68	-0.94 -0.33	-0.47	-0.59 -0.31	-0.52	-0.67 -0.40	-0.78	-0.80 -0.72
B_{MSMnc}	78.23	-0.51	-0.47	-0.69 -0.18	-0.33	-0.44 -0.17	-0.32	-0.45 -0.21	-0.49	-0.53 -0.43
RMSE			0.17	0.17 0.75	0.19	0.19 0.23	0.16	0.16 0.21	0.31	0.30 0.34