Supplementary information

Saharan dust exacerbates the present sensitivity of alpine glaciers to climate change

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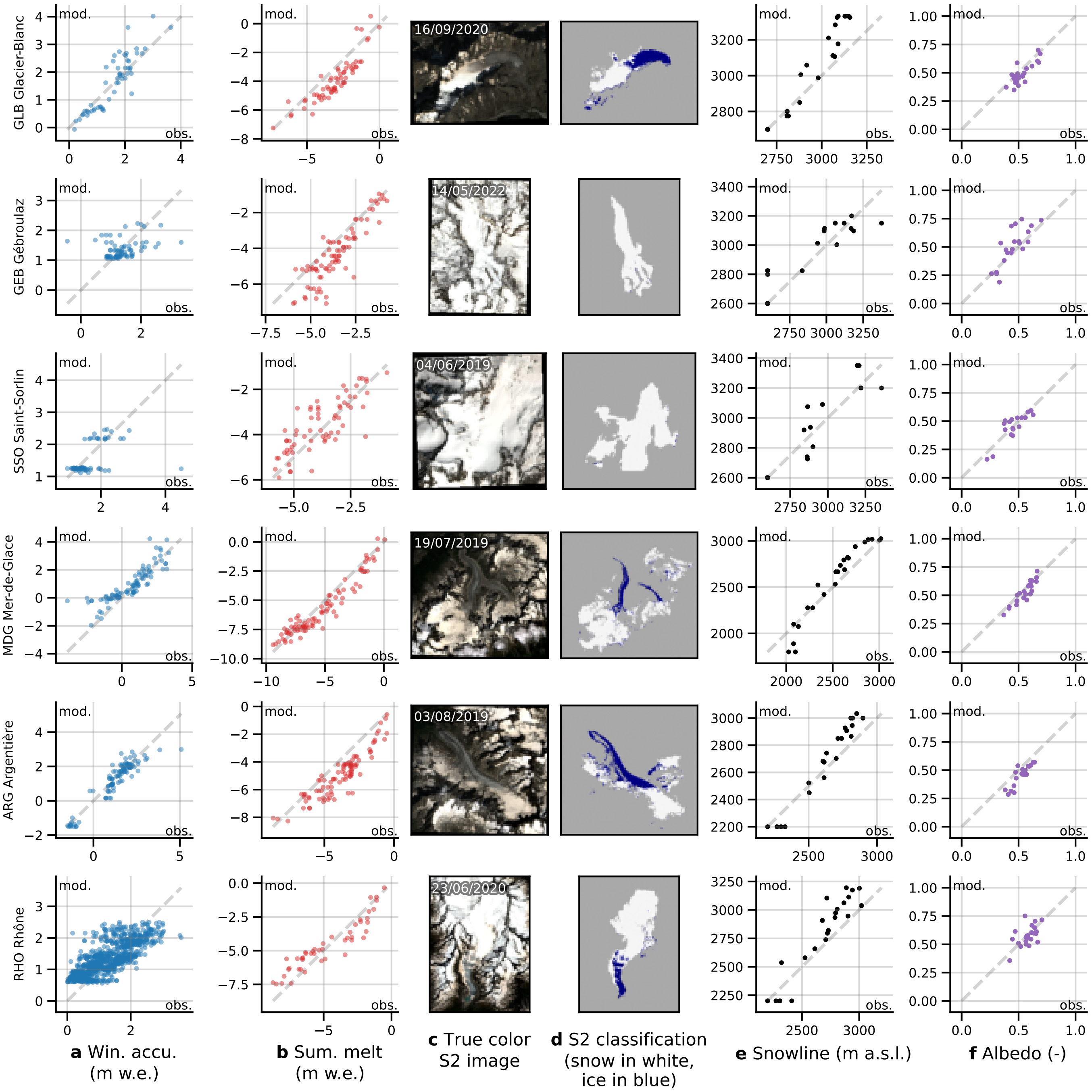
Abbreviation	Full glacier name	Country	Lat, lon (°)	Aspect	Elevation min-max[a] (m a.s.l.)	Area (km^2)
GLB	Glacier-Blanc	France	44.942, 6.384	NE	2450-4050	5
SSO	Saint-Sorlin	France	45.157, 6.159	N	2700-3450	2
GEB	Gébroulaz	France	45.290, 6.631	N	2600-3450	3
MDG	Mer-de-Glace	France	45.898, 6.939	NW	1550-4250	35
ARG	Argentière	France	45.941, 7.004	NW	1700-3560	11
FIN	Findel	Switzerland	45.993, 7.875	W	2600-3800	13
ALE	Aletsch	Switzerland	46.485, 8.055	SE	1700-4150	77
GRI	Gries	Switzerland	46.431, 8.321	E	2450-3350	4
RHO	Rhône	Switzerland	46.621, 8.399	S	2250-3600	14
CLA	Clariden	Switzerland	46.838, 8.886	SE	2450-3250	5
PER	Pers-Morteratsch	Switzerland	46.407, 9.931	N	2000-3960	15
SIL	Silvretta	Switzerland	46.852, 10.079	W	2450-3100	3

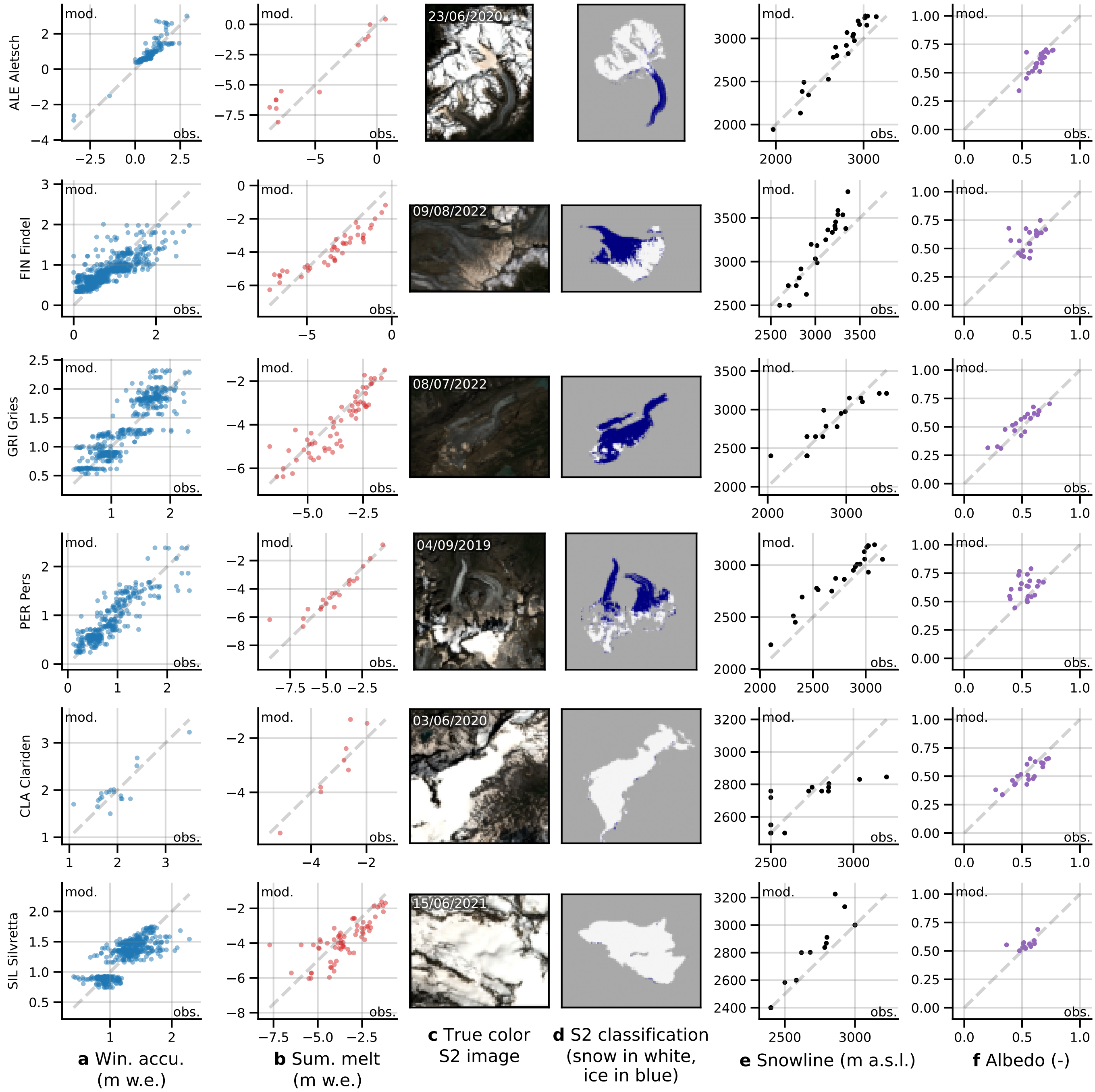
Supplementary Table 1: **Geographic and topographic information about the 12 selected glaciers.** [a]Minimum and maximum elevation of each glacier based on the outlines used in this study.

Abbr.	End-of-summer snowline elevation (m a.s.l.)[a]	Mean glacier-wide SMB (m w.e. yr^{-1})[b]	Rank SMB 2020 vs. 2008-2017	Number of stakes summer measurements[d]	Number of stakes winter measurements[c]	Sentinel-2 tile	Ice albedo from Sentinel-2
GLB	3180	-1.30	11th	13-18	16-20	T31TGK	0.22
SSO	2970	-1.96	8th	9-23	18-27	T31TGL	0.23
GEB	3070	-1.30	7th	16-24	24-25	T32TLR	0.25
MDG	3080	-1.49	7th	18-26	26-42	T32TLR	0.22
ARG	2860	-1.49	7th	19-28	30-40	T32TLR	0.23
FIN	3280	-1.18	8th	8-13	140-275	T32TMR	0.26
ALE	3100	-1.63	6th	2-5	2-74	T32TMS	0.22
GRI	2990	-1.59	7th	13-17	114-168	T32TMS	0.21
RHO	2930	-1.39	6th	11-13	273-373	T32TMS	0.25
CLA	2840	-1.24	7th	2-2	2-15	T32TMS	0.23
PER	3070	-1.64	8th	9-11	136-168	T32TNS	0.26
SIL	2810	-1.81	5th	16-18	174-198	T32TNS	0.23

Supplementary Table 2: **Glaciological information about the 12 selected glaciers.** [a]Mean over the period 2000-2025 using end-of-summer snowline elevation from Sommer et al. (2026). [b]Average of annual SMB over the period 2019-2022 from the WGMS time series of annual mass-change estimates for the world's glaciers (Dussaillant et al., 2025). [c]Rank of the SMB of the year 2020 among the 10 years of the period 2008-2017, using also the WGMS time series. [d]Minimum and maximum numbers over the 4 years between 2019 and 2022.



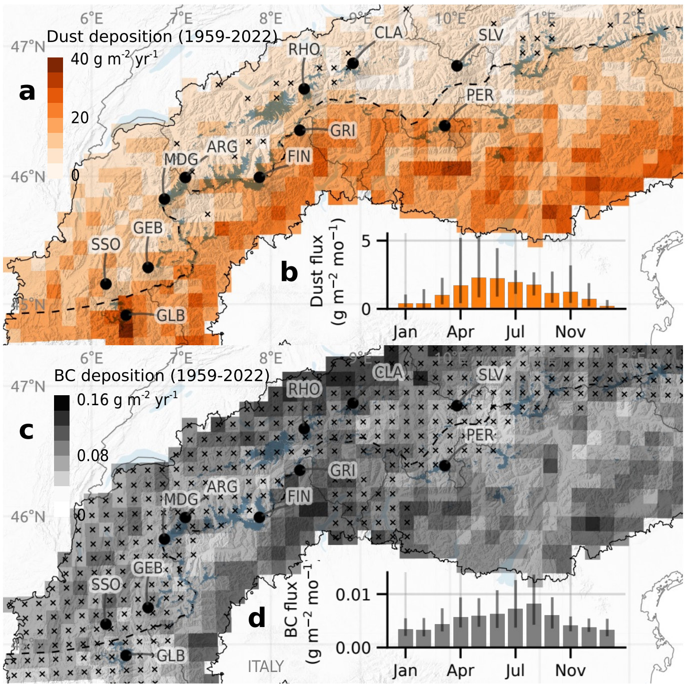
Supplementary Figure 1: **Evaluations of the simulations**, for 6 of the 12 selected glaciers, except for winter accumulation which is used for calibration (see Methods). (a) Winter accumulation, observed using stakes vs. simulated. (b) Summer melt, observed at stakes vs. simulated. (c) Randomly chosen Sentinel-2 (S2) true color image used as an example. (d) S2 classification of the corresponding S2 image (see Methods), snow in white and ice in blue. (e) Snowline elevation for all selected S2 images, observed using S2 classification (see Methods) vs. simulated. (f) Mean observed albedo of snow vs. mean simulated albedo for each S2 image (see Methods). For S2 image, only simulation points without ice exposed in the model and with snow retrieved in the S2 classification are considered. Grey dotted line corresponds to the 1:1 line.



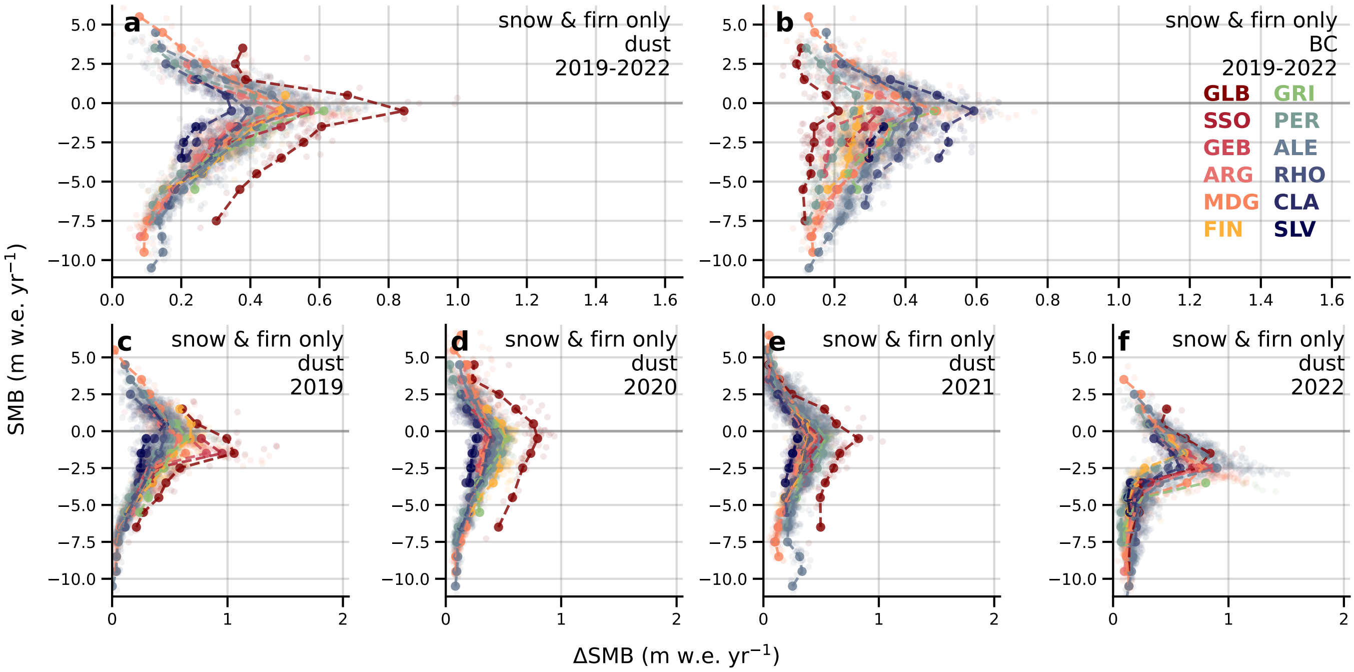
Supplementary Figure 2: **Evaluations of the simulations.** Same as Supp. Fig.1 for the 6 other glaciers.

Abbr.	Summer melt MAE (m w.e.)	Summer melt RMSE (m w.e.)	Mean snowline elevation MAE (m)	Mean snowline elevation RMSE (m)	Albedo MAE (-)	Albedo RMSE (-)
GLB	0.99	1.09	98	131	0.05	0.07
SSO	0.64	0.79	69	99	0.05	0.06
GEB	0.81	1.05	74	109	0.08	0.11
MDG	0.67	0.82	112	138	0.04	0.05
ARG	1.13	1.30	97	112	0.07	0.08
FIN	0.81	0.93	164	197	0.07	0.10
ALE	0.99	1.26	146	164	0.06	0.07
GRI	0.50	0.65	122	153	0.05	0.06
RHO	0.81	0.95	140	173	0.06	0.08
CLA	0.44	0.56	79	126	0.06	0.07
PER	0.39	0.71	134	147	0.11	0.14
SIL	0.74	0.92	81	130	0.04	0.06

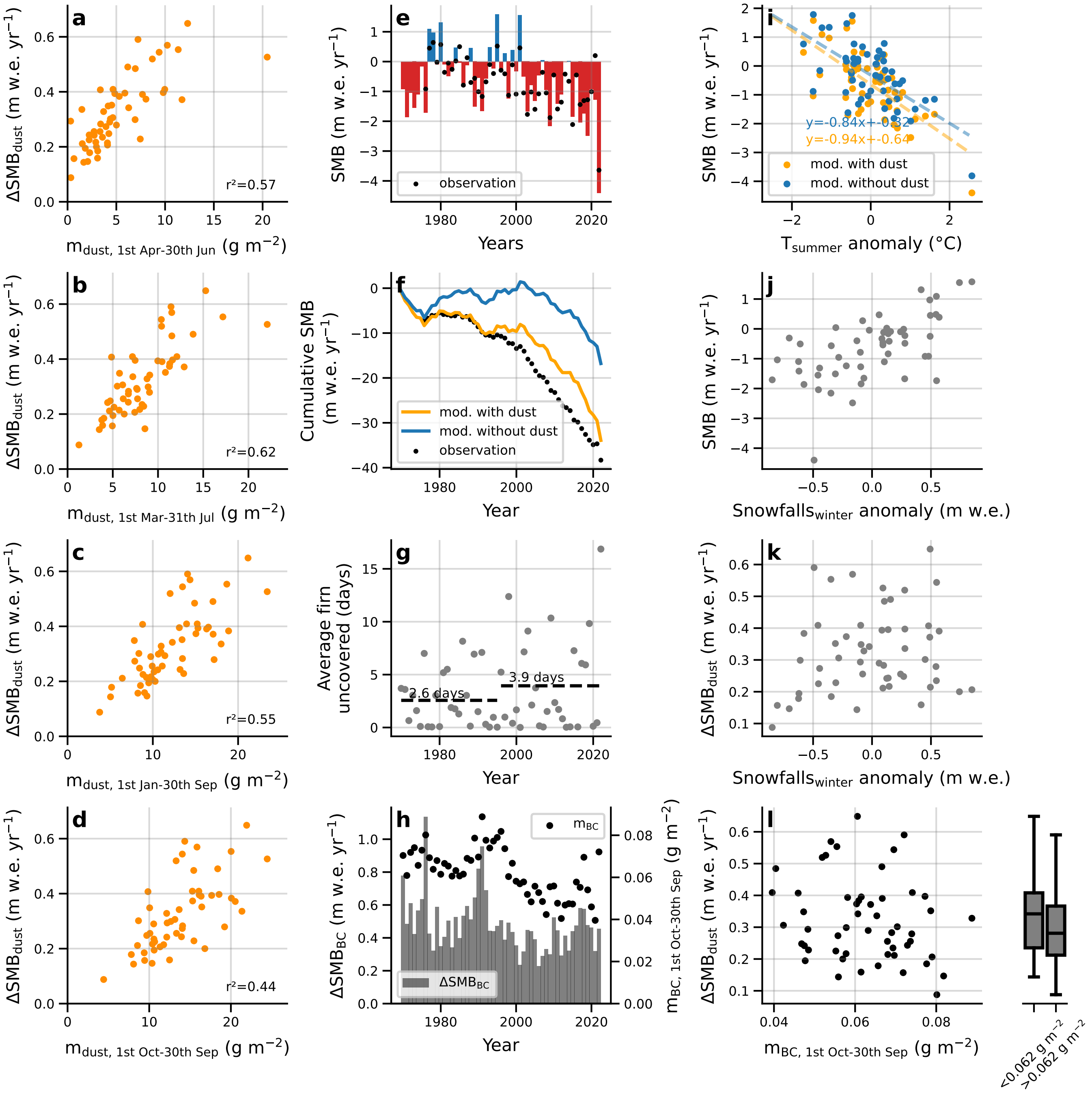
Supplementary Table 3: **Evaluation metrics of the simulations for each glacier.** Metrics related to Supp. Fig. 1-2. MAE stands for mean absolute error. RMSE stands for root mean square error.



Supplementary Figure 3: **(Extension of Figure 3) Deposition fluxes of LAPs, and illumination of the glaciers.** (a, c) Annual fluxes of (a) dust and (c) BC deposition from ALADIN over the period 1959-2022. (b, d) Monthly average of (b) dust and (d) BC deposition fluxes for the 12 selected glaciers over the period 1959-2022. Bars stands for the mean over the 12 glaciers, and the black lines for the minimum and maximum. Alpine glacier locations are highlighted in blue. Black crosses are drawn where the p-values corresponding to the Pearson, Spearman, and Kendal tests are under 0.05, assessing increasing trends for dust and decreasing trends for BC over the period 1959-2022. This shows a minority of increasing trends for dust depositions, while a majority of the BC depositions are decreasing.



Supplementary Figure 4: **Extension of Figure 3, considering only impacts on snow and firns.** Impacts on snow and firns of (a) dust and (b) BC for period 2019-2022 for the different glaciers aggregated over SMB bins of 1 m w.e. yr^{-1}. Bins are plotted if they contain at least 5 simulation points. Compared to Figure 3, the present figure only accounts for the difference in SMB between the simulation with all LAPs and the simulation without dust or BC when either snow or firn are at the surface of both simulations. Thus, the present figure does not account for the albedo feedback on ice.



Supplementary Figure 5: **Extension of Figure 4, long-term simulation on the glacier of Argentière (1970-2022).** (a-d) Relation between the deposited mass of dust from ALADIN over different periods (April-July, March-July, January-September and October-September) and the impact of dust on the SMB. (e) Simulated glacier-wide SMB of Argentière (including both dust and BC). (f) Cumulative glacier-wide SMB of Argentière (dust and BC for the orange line, only BC for the blue line). (g) Simulated glacier-wide time duration of firn at the surface with averages on two periods 1970-1995 and 1996-2022. For example, a value of 10 days can mean that firn covers a quarter of the glacier between 40 days. (h) Evolution of the annual deposition in BC deposited by ALADIN. (i) Summer air temperature anomaly vs. glacier-wide SMB with and without dust. (j) Winter snowfalls anomaly vs. glacier-wide SMB. (k) Winter snowfalls anomaly vs. impact of dust on the SMB due to dust. (l) Annual BC deposition vs. impact of dust on the SMB and associated boxplots of the same values divided into two bins.

References

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