

Supplementary materials to “Disaggregating geodetic glacier mass balance to annual scale using remote-sensing proxies”

Argha Banerjee, Ujjwal Singh, Chintan Sheth

Table S1: Available records of glaciological mass balance b_{gla} (Mandal et al., 2020), ELA (Mandal et al., 2020), SLA (Chandrasekharan et al., 2018), minimum albedo (Brun et al., 2015), and the two NDS1-based proxies introduced in the present study for Chhota Shigri glacier. The last two columns contain the multi-proxy reconstructed mass balance b_{rec} and its uncertainty.

Year	b_{gla} (m w.e. a ⁻¹)	ELA (m)	SLA (m)	Minimum Albedo	NDSI ₁	NDSI ₂	b_{rec} (m w.e. a ⁻¹)	Uncertainty (m w.e. a ⁻¹)
2001			5171	0.22	-0.06	-0.02	-0.67	0.32
2002			4974	0.24	-0.11	-0.03	-0.54	0.27
2003	-1.43	5235	5124	0.22	-0.07	-0.04	-0.66	0.32
2004	-1.24	5105	5069	0.25	-0.08	-0.03	-0.58	0.27
2005	0.13	4905	4888	0.32	0.08	0.18	-0.02	0.3
2006	-1.43	5230	5155	0.24	-0.05	0.02	-0.59	0.42
2007	-1.00	5125	5119	0.29	-0.03	0.04	-0.48	0.27
2008	-0.95	5110	5036	0.24	-0.07	-0.02	-0.55	0.33
2009	0.12	4920	4936	0.36	0.08	0.16	-0.04	0.28
2010	0.32	4925	4851	0.45	0.11	0.20	0.20	0.51
2011	0.06	4940	4927	0.47	0.04	0.10	0.00	0.48
2012	-0.46	5025	4955	0.29	-0.03	0.05	-0.33	0.23
2013	-0.77	5090	5145	0.27	-0.05	0.02	-0.55	0.32
2014	-0.08	5010	5009		0.06	0.19	-0.09	0.26
2015	-0.16	4985	5014		0.03	0.13	-0.20	0.28
2016	-0.84	5106	5190		-0.07	-0.03	-0.71	0.34
2017	-0.28	5085	5220		-0.06	0.02	-0.68	0.35
2018	-0.40	5080	5134		-0.05	0.00	-0.58	0.27
2019	0.54	4930	4839		0.09	0.26	0.21	0.5
2020					0.02	0.13	-0.16	0.31

Table S2: The available b_{geo} records for Chhota Shigri Glacier for different periods and the corresponding references. The mean b_{gla} and b_{geo} for the corresponding periods, and the uncertainties in the geodetic and reconstructed data are also given. The b_{geo} value marked with a ‘†’ was taken to be an outlier, and was not considered in this study. The symbols B_{gla} , B_{geo} and B_{rec} denote corresponding the cumulative values. All the mass balance and the uncertainties are in m w.e. a^{-1} . The cumulative balances are in m w.e.

Start Year	End Year	b_{gla}	b_{geo}	b_{rec}	B_{gla}	B_{geo}	B_{rec}	References
1999	2018	-0.53	-0.48 ± 0.05	-0.37 ± 0.34	-10.1	-9.1	-7.0	Shean et al., 2020
1999	2011	-0.60	-0.24 ± 0.12	-0.30 ± 0.36	-7.2	-2.9	-3.6	Mukherjee et al., 2018
2005	2014	-0.41	-0.23 ± 0.28	-0.25 ± 0.35	-3.7	-2.1	-2.3	Brun et al., 2017
2005	2014	-0.41	-0.27	-0.25 ± 0.35	-3.7	-2.4	-2.3	Brun et al., 2017
2000	2016	-0.55	-0.27 ± 0.13	-0.33 ± 0.3	-8.8	-4.3	-5.3	Brun et al., 2017
2002	2014	-0.56	-0.77^\dagger	-0.31 ± 0.34	-6.7	-9.2	-3.7	Garg et al., 2017
2000	2012	-0.59	-0.46 ± 0.34	-0.30 ± 0.35	-7.1	-5.5	-3.6	Vijay and Braun, 2016
2000	2011	-0.60	-0.37 ± 0.18	-0.30 ± 0.36	-6.6	-4.1	-3.3	Gardelle et al., 2013

Table S3: Available records of b_{gla} (<https://wgms.ch/>), SLA (Davaze et al., 2020, <https://www.theia-land.fr/en/homepage-en/>), minimum albedo (Davaze et al., 2018), and the two NDSI-based proxies introduced in the present study for Argentière glacier. The last two columns contain the multi-proxy reconstruction b_{rec} and its uncertainty.

Year	b_{gla} (m w.e. a ⁻¹)	NDSI ₁	NDSI ₂	Minimum albedo	SLA (m)	b_{rec} (m w.e. a ⁻¹)	Uncertainty (m w.e. a ⁻¹)
2000	-1.23	0.06	0.08	0.41	2820	-0.64	0.49
2001	0.32	0.09	0.20	0.48	2760	0.18	0.58
2002	-1.18	0.03	0.06	0.47	2820	-0.56	0.5
2003	-1.91	-0.01	-0.01	0.38	2840	-1.35	0.49
2004	-1.16	0.06	0.06	0.38	2840	-0.84	0.52
2005	-1.71	-0.01	-0.01	0.40	2860	-1.33	0.56
2006	-1.21	-0.04	-0.01	0.40	2820	-1.34	0.56
2007	-0.47	-0.01	0.02	0.44	2820	-0.92	0.48
2008	-1.17	0.02	0.03	0.41	2820	-0.94	0.59
2009	-2.02	-0.03	0.01	0.35	2850	-1.50	0.54
2010	-0.56	0.05	0.10	0.47	2800	-0.30	0.57
2011	-1.71	0.00	-0.03	0.42	2900	-1.28	0.6
2012	-1.48	0.01	0.00	0.38	2880	-1.33	0.5
2013	-0.54	0.10	0.13	0.44	2800	-0.21	0.55
2014	-0.69	0.07	0.06	0.43	2820	-0.53	0.48
2015	-2.24	-0.07	-0.05	0.37	2840	-1.72	0.7
2016	-0.57	0.09	0.08		2820	-0.35	0.65
2017	-1.44	-0.06	-0.07			-2.02	0.69
2018	-1.41	-0.02	0.01			-1.40	0.52
2019	-1.43	-0.04	-0.01			-1.62	0.54
2020	-1.00	-0.03	-0.01			-1.52	0.58

Table S4: The available b_{geo} records for Argentière Glacier for different periods and the corresponding references. The mean b_{gla} and b_{rec} for the corresponding periods, and the uncertainties in the reconstructed data are also given. All the above quantities are in m w.e. a⁻¹. The symbols B_{gla} , B_{geo} and B_{rec} denote the corresponding cumulative mass balances (m w.e.).

Start Year	End Year	b_{gla}	b_{geo}	b_{rec}	B_{gla}	B_{geo}	B_{rec}	Reference
1998	2008	-1.08	-0.80	-0.86 ± 0.53	-10.8	-8.0	-8.6	Vincent et al., 2018
2003	2012	-1.34	-1.12	-1.11 ± 0.54	-12.1	-10.1	-10.0	Vincent et al., 2018
1999	2010	-1.11	-1.03	-0.87 ± 0.54	-12.2	-11.3	-9.6	Sommer et al., 2020
2000	2014	-1.12	-0.74	-0.86 ± 0.54	-15.7	-10.4	-12.1	Sommer et al., 2020
2000	2020	-1.18	-1.05	-1.02 ± 0.56	-23.6	-21.0	-20.4	Hugonnet et al., 2021

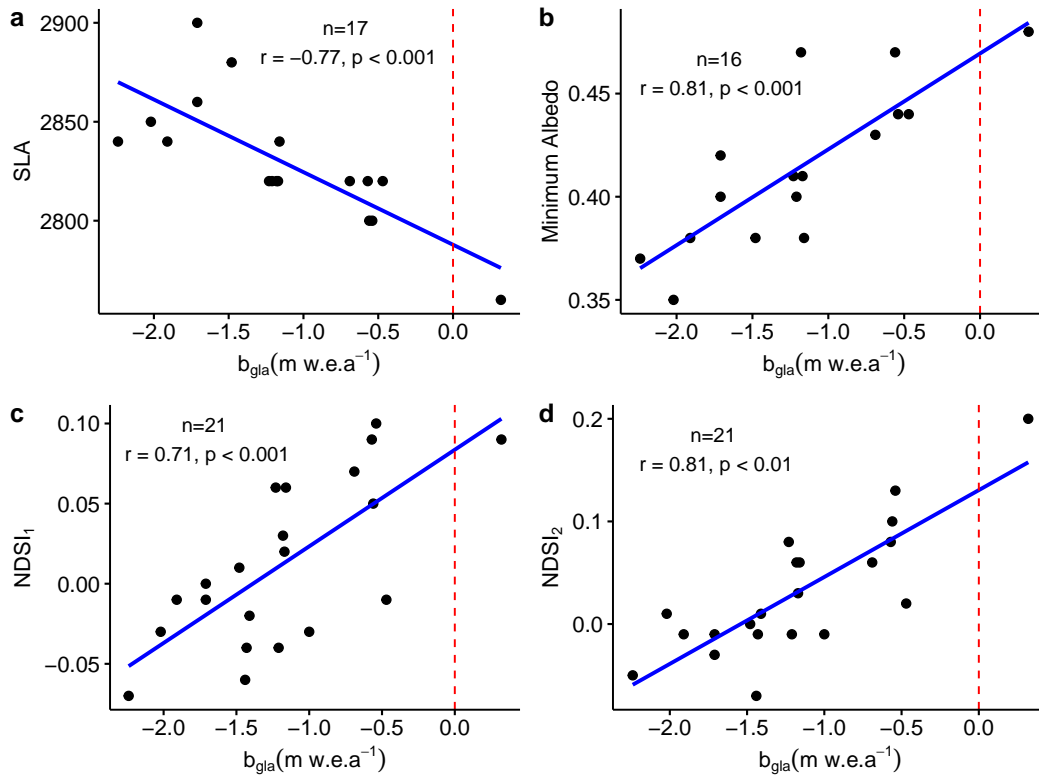


Figure S1: Comparisons between glaciological mass balance and the four different remotely-sensed proxies on Argentière Glacier. In all the sub-figures, the number of data points n , the correlation coefficient (r), and its statistical significance (p) are indicated.

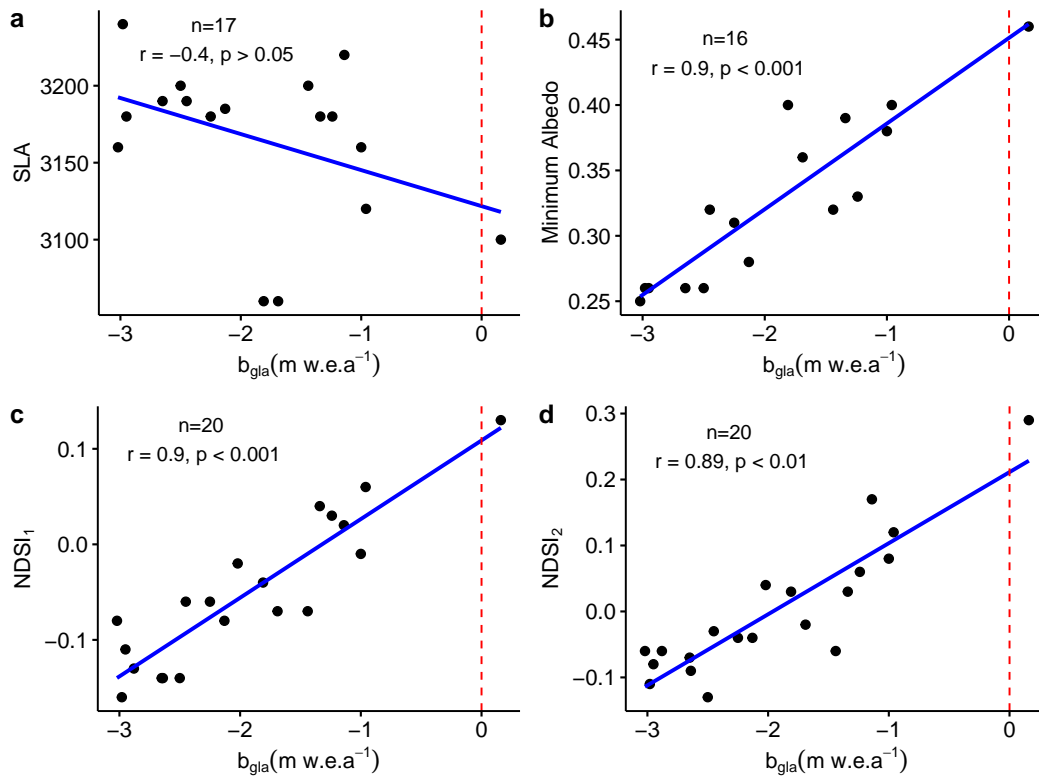


Figure S2: Comparisons between glaciological mass balance and four different remotely-sensed proxies on Saint-Sorlin Glacier. In all sub-figures, the number of data points n , the correlation coefficient (r), and its statistical significance (p) are indicated.

Table S5: The available records of glaciological mass balance b_{gla} (<https://wgms.ch/>), SLA (Davaze et al., 2020, <https://www.theia-land.fr/en/homepage-en/>), minimum albedo (Davaze et al., 2018), and the two NDSI-based proxies introduced in the present study for Saint-Sorlin Glacier. The last two columns contain the multi-proxy reconstruction of annual mass balance (b_{rec}) and its uncertainty.

Year	b_{gla} (m w.e. a ⁻¹)	Minimum Albedo	NDSI ₁	NDSI ₂	SLA (m)	b_{rec} (m w.e. a ⁻¹)	Uncertainty (m w.e. a ⁻¹)
2000	-1.24	0.33	0.03	0.06	3180	-1.48	0.7
2001	0.16	0.46	0.13	0.29	3100	-0.20	1.07
2002	-1.69	0.36	-0.07	-0.02	3060	-1.40	0.69
2003	-2.95	0.26	-0.11	-0.08	3180	-2.30	0.66
2004	-2.45	0.32	-0.06	-0.03	3190	-1.92	0.61
2005	-2.50	0.26	-0.14	-0.13	3200	-2.51	0.88
2006	-1.44	0.32	-0.07	-0.06	3200	-2.05	0.54
2007	-2.25	0.31	-0.06	-0.04	3180	-1.95	0.45
2008	-1.81	0.40	-0.04	0.03	3060	-1.13	0.99
2009	-2.65	0.26	-0.14	-0.07	3190	-2.39	0.59
2010	-1.00	0.38	-0.01	0.08	3160	-1.34	0.58
2011	-3.02	0.25	-0.08	-0.06	3160	-2.15	0.62
2012	-2.13	0.28	-0.08	-0.04	3185	-2.11	0.71
2013	-0.96	0.40	0.06	0.12	3120	-0.90	0.8
2014	-1.34	0.39	0.04	0.03	3180	-1.31	0.69
2015	-2.98	0.26	-0.16	-0.11	3240	-2.67	0.92
2016	-1.14		0.02	0.17	3220	-1.39	0.97
2017	-2.64		-0.14	-0.09		-2.51	0.83
2018	-2.02		-0.02	0.04		-1.43	0.63
2019	-2.88		-0.13	-0.06		-2.37	0.76

Table S6: The available b_{geo} records for Saint-Sorlin Glacier for different periods and the corresponding references. The mean b_{gla} and b_{rec} for the corresponding periods, and the uncertainties in the reconstructed data are also given. All the above quantities are in m w.e. a⁻¹. The symbols B_{gla} , B_{geo} and B_{rec} denote the corresponding cumulative mass balances (m w.e.). The b_{geo} values marked with a ‘†’ were taken to be outliers, and were not considered in this study.

Start Year	End Year	b_{gla}	b_{geo}	b_{rec}	B_{gla}	B_{geo}	B_{rec}	Reference
2003	2014	-2.04	-1.31 [†]	-1.84 ± 0.69	-22.4	-14.4	-20.2	Basantes-Serrano et al., 2018
1999	2010	-1.80	-1.24 [†]	-1.70 ± 0.73	-19.8	-13.6	-18.7	Sommer et al., 2020
2000	2014	-1.82	-1.69	-1.68 ± 0.72	-25.5	-23.7	-23.5	Sommer et al., 2020
2000	2010	-1.80	-1.78	-1.70 ± 0.73	-18.0	-17.8	-17.0	Hugonnet et al., 2021
2010	2020	-2.01	-1.29 [†]	-1.82 ± 0.76	-20.1	-12.9	-18.2	Hugonnet et al., 2021
2003	2014	-2.04	-1.83	-1.84 ± 0.69	-22.4	-20.1	-20.2	Vincent et al., 2018
1998	2008	-1.80	-1.57	-1.66 ± 0.76	-18.0	-15.7	-16.6	Vincent et al., 2018

Table S7: The best-fit glacier specific calibration constants α and β for the four proxies are listed for all the three studied glaciers.

glacier	SLA	Min. Albedo	NDSI ₁	NDSI ₂
	α, β	α, β	α, β	α, β
Chhota Shigri	16.31,-0.0033	-1.64,4.32	-0.30,4.45	-0.52,3.03
Argentière	26.62,-0.0097	-8.35,17.94	-1.22,17.10	-1.27,8.74
Saint-Sorlin	39.10,-0.013	-5.68,12.05	-1.17,11.61	-1.70,5.92

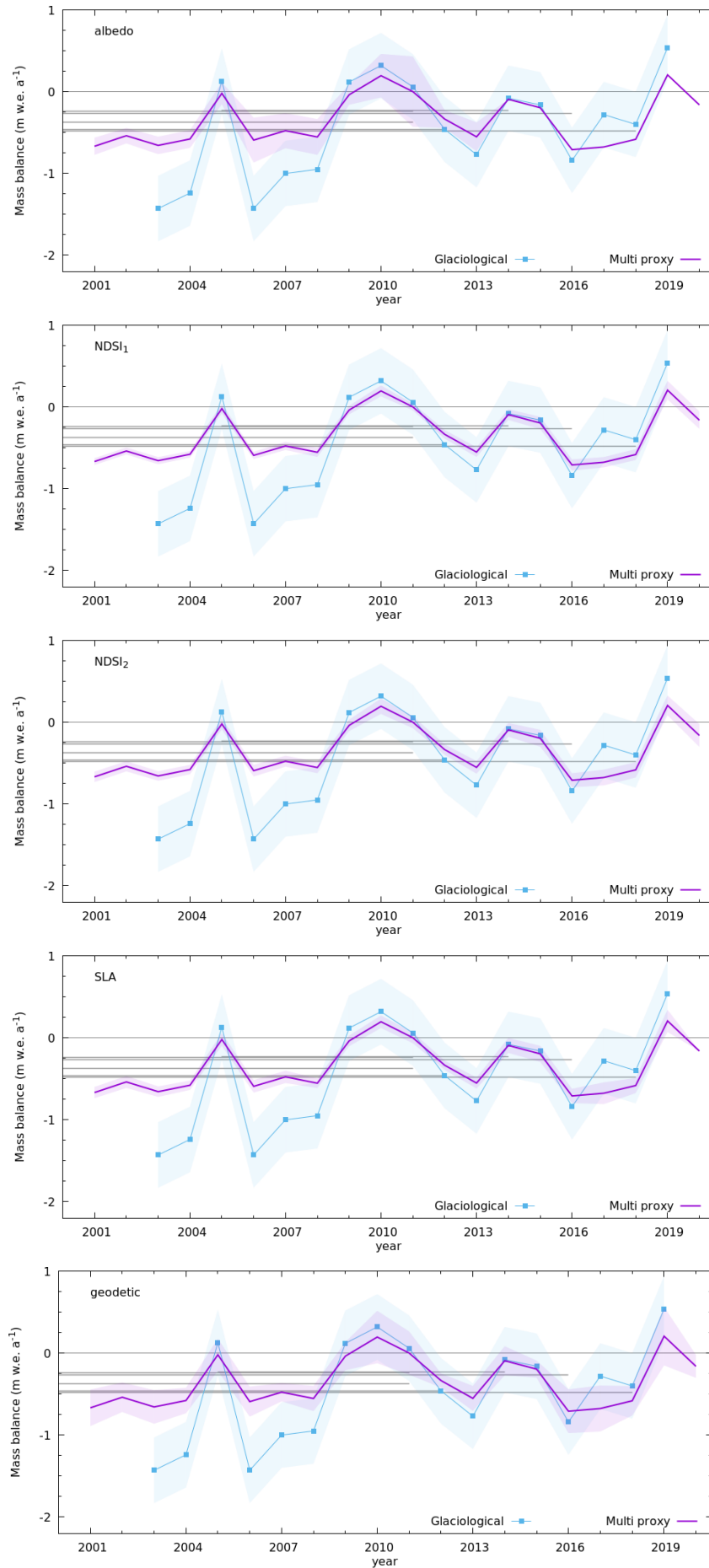


Figure S3: a) The uncertainties in multiproxy reconstructed mass balance b_{rec} when noise was added to the individual proxies and the geodetic data on Chhota Shigri Glacier. See main text for details of the noise added. The noise contributions from the geodetic mass balance and min. albedo dominate the overall noise on this glacier.

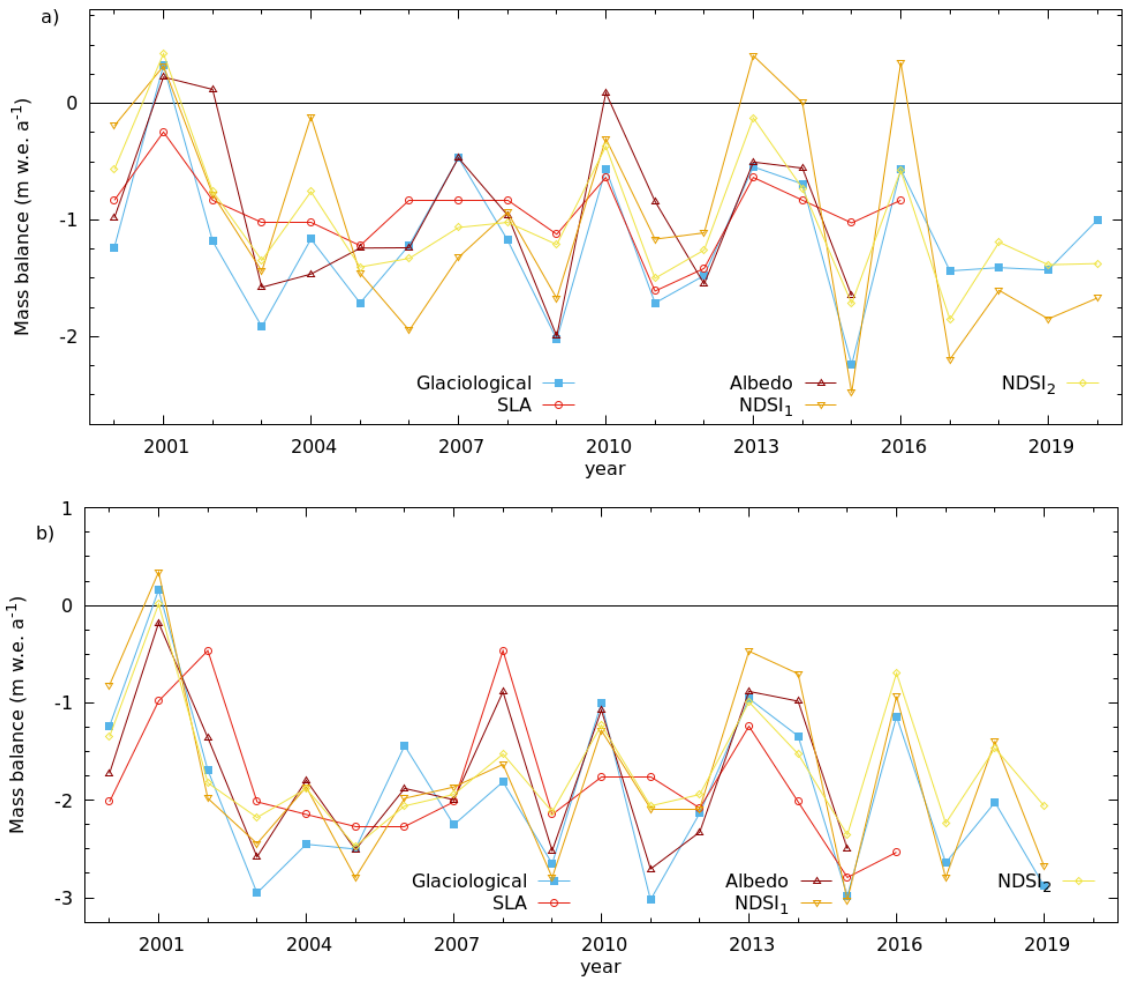


Figure S4: Comparison of the reconstructed mass balance for individual proxies and the observed mass balance on a) Argentière and b) Saint-Sorlin glaciers.

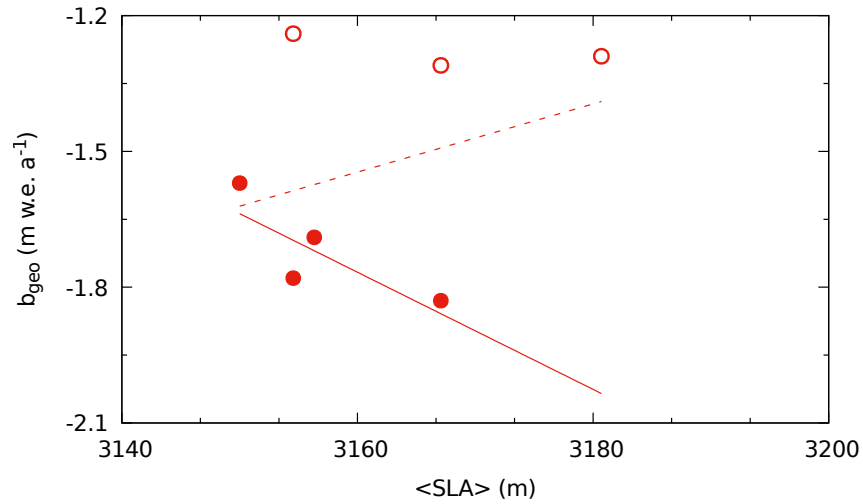


Figure S5: The linear fits to mean SLA and geodetic mass balance data with/without the three outliers (open symbols) for Saint-Sorlin Glacier. The solid line is the linear fit used in the present reconstruction where only the solid symbols were considered. The dashed line is the fit to all the data (solid+open symbols). The dashed line is unphysical as it implies a more positive mass balance for a higher SLA.

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