



*Supplement of*

## **The glaciers of the Dolomites: the last 40 years of melting**

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(Sector ID) Name	RGI-ID <sup>(a)</sup>	CGI-ID	Elevation <sup>(a)</sup>	Aspect	Area <sup>(b)</sup>
<i>(1) Popera Alto</i>	-11.03918	978	2486	E	0.09
<i>(1) Popera Pensile</i>	-11.03919	977	2722	N-E	0.07
<i>(2) Cristallo</i>	-11.03903	937	2483	N	0.24
<i>(3) Sorapiss Occidentale</i>	-11.03902	975	2661	N	0.19
<i>(4) Antelao Superiore</i>	-11.03910	966	2617	N-E	0.27
<i>(4) Antelao Inferiore</i>	-11.03909	967	2441	N	0.19
<i>(5) Marmolada <sup>(c)</sup></i>	-	-	2918	N	1.49
<i>M. Principale</i>	-11.03887	941	-	N	-
<i>M. Punta Penia</i>	-11.03883	942	-	N	-
<i>M. Ovest</i>	-11.03880	-	-	N	-
<i>M. Centrale</i>	-11.03884	-	-	N	-
<i>(6) Fradusta <sup>(d)</sup></i>	-	950	2703	N	0.03
<i>F. Superiore-Inferiore</i>	-11.03889	-	-	N	-
<i>F. Superiore</i>	-11.03888	-	-	N	-
<i>(6) Travignolo</i>	-11.03871	947	2529	N	0.04

5 **Table S1. Remaining mountain glaciers in the Dolomites region analysed in this study.** <sup>(a)</sup> RGI ID (RGI60-) and median elevation are retrieved from Randolph Glacier Inventory v 7.0 data (RGI Consortium, 2023). <sup>(b)</sup> Glacier area from Smiraglia and Diolaiuti (2015) inventory. <sup>(c)</sup> Marmolada Glacier includes data averaged from all its sectors, as they are now divided but considered as one here, as they were in the 1980s. <sup>(d)</sup> Fradusta Glacier was formerly a single glacier that split into two (F. Superiore and F. Inferiore), with the latter not existing anymore.

Year - Archive Images	Date <sup>(a)</sup>	Campaign name	Size	Format	Coverage <sup>(b)</sup>
1980	23-25 Jul	<i>Reven Belluno</i>	23 x 23 cm	A (BW)	3
1982	-	<i>Reven M. Veneta</i>	23 x 23 cm	A (BW)	4, 5, 6
1991	19 Sep	<i>Reven M. Veneta</i>	23 x 23 cm	A	4
1992	8-21 Aug	<i>Reven M. Veneta</i>	23 x 23 cm	A	1, 2, 3, 5, 6
1999	8-28 Oct	<i>Reven Cadore</i>	23 x 23 cm	A (BW)	4
2001	14-15 Oct	<i>Reven Belluno</i>	23 x 23 cm	A (BW)	-
2010	21-22 Sep	<i>Reven Cadore</i>	10368 x 5760 px	D	4
2012	21 Aug	<i>Reven Agordo</i>	12983 x 8483 px	D	5
Year - Other Surveys	Date	Survey Type	Sensor		Coverage
2010	1 Aug – 10 Oct	Airborne LiDAR	Optech ALTM 3100 EA		All
2014	23-26 Sep	Airborne LiDAR	Optech ALTM 3100 EA		All
2023	9 Sep – 1 Oct	UAV	DJI Mavic 2, DJI Air 2		1, 2, 3, 4, 6
2023	10 Oct	Aerial photos	Canon 6D MkII		5

10 **Table S2. Information regarding the dataset used in this study.** All the aerial photos are available online under the licence *Italian Open Data License 2.0 (IODL 2.0)* and are the property of *Regione del Veneto – L.R. n. 28/76 Formazione della Carta Tecnica Regionale*. 2010 and 2012 photos have been used only for visual reference and not for mass balance reconstructions. Format of archive imagery is Digital (D) or Analogue Scan (A), with some scans in black and white (BW). <sup>(a)</sup> Date related only to the portion of

the flight used in this work. <sup>(b)</sup> Area IDs as for Fig. 1 represent only the successfully reconstructed scenes. The complete coverage of the aerial imagery is shown in Fig. S2.

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Area ID	Year	Date	Photos	Resolution (m/pix)	Tie Points	Dense Cloud points	GCP number
1 (Popera)	1992	21 Aug.	10	0.88	61,444	10,329,170	6
1 (Popera Alto)	2023	12 Sept.	144	0.05	99,047	63,057,487	12
1 (Popera Pensile)	2023	12 Sept.	66	0.14	13,634	11,108,717	12
2 (Cristallo)	1992	21 Aug.	6	0.87	28,503	17,319,719	6
2 (Cristallo)	2023	24 Sept.	218	0.13	94,549	50,806,741	12
3 (Sorapiss)	1980	23 Jul.	11	0.91	45,642	2,482,055	6
3 (Sorapiss)	1992	20 Aug.	12	1.01	133,237	12,785,764	15
3 (Sorapiss)	2023	9 Sept.	177	0.11	47,987	30,558,608	12
4 (Antelao)	1980	25 Jul.	7	1.57	109,269	10,832,894	8
4 (Antelao)	1992	19 Aug.	7	0.65	51,292	17,122,069	13
4 (Antelao)	1999	14 Oct.	4	0.83	45,538	14,662,362	17
4 (Antelao)	2010	21 Sept.	7	0.41	233,167	44,645,484	22
4 (Antelao Superiore)	2023	10 Sept.	553	0.06	729,420	192,905,021	12
4 (Antelao Inferiore)	2023	10 Sept.	138	0.15	23,018	23,174,756	12
5 (Marmolada)	1982	-	17	1.50	196,459	5,005,926	10
5 (Marmolada)	1992	19 Aug.	12	0.85	64,420	16,352,851	6
5 (Marmolada)	2001	15 Oct.	13	0.65	121,102	18,865,131	9
5 (Marmolada)	2012	20 Aug.	17	0.22	292,028	126,682,805	14
5 (Marmolada)	2023	10 Oct.	250	0.35	23,053	61,140,047	12
6 (Pale di S.M.)	1982	-	32	1.59	448,348	35,196,925	13
6 (Pale di S.M.)	1992	9 Aug.	28	0.71	494,427	45,856,617	18
6 (Fradusta)	2001	15 Oct.	16	0.74	210,548	25,732,223	16
6 (Travignolo)	2023	30 Sept.	130	0.09	43,916	31,107,078	12
6 (Fradusta)	2023	30 Sept.	71	0.06	30,193	25,419,814	12

**Table S3. SfM-MVS export report and dates divided by areas (see Fig. 1 for reference): Popera (1), Cristallo (2), Sorapiss (3), Antelao (4), Marmolada (5), Pale di San Martino (6); years of aerial acquisition and number of photos processed per year; Ground Resolution; Tie Points of the first alignment phase; GCP number used in the SfM pipeline, sometimes some of them have lately been excluded as not recognizable with precision in the aerial photos; RMSE error in m for Z only and XYZ (total) as computed by Metashape for the entire area, including poorly covered borders where photo coverage is less high (see Fig. S2).**

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Glacier	Area (km <sup>2</sup> )				
	1980-82	1991-92	1999-2001	2010	2023
<i>Popera Alto</i>	-	0.11	-	0.10	0.10
<i>Popera Pensile</i>	-	0.05	-	0.05	0.03
<i>Cristallo</i>	-	0.19	-	0.11	0.06
<i>Sorapiss Occidentale</i>	0.27	0.19	-	0.18	0.17
<i>Antelao Superiore</i>	0.31	0.28	0.25	0.24	0.19
<i>Antelao Inferiore</i>	0.20	0.16	0.13	0.11	0.09
<i>Marmolada</i> <sup>(a)</sup>	2.52	2.28	-	1.64	1.00
<i>Travignolo</i>	0.24	0.23	-	0.17	0.14
<i>Fradusta</i> <sup>(a)</sup>	0.27	0.24	-	0.09	0.03

30 **Table S4. Areas of the Dolomites glaciers during different intervals (km<sup>2</sup>).** <sup>(a)</sup> Marmolada and Fradusta Glaciers are treated as one even after segmentation.

Glacier	Common Area Surface Elevation Change (m)				
	1980s	1990s	2000s	2010s	Average Rate
	1980-82 to 1991-92	1991-1992 to 1999-01	1999-01 to 2010	2010 to 2023	All periods available
<i>Popera Alto</i>	-	-11.2 ± 2.6		-8.7 ± 0.3	-19.9
<i>Popera Pensile</i>	-	-10.2 ± 2.6		-6.8 ± 0.3	-17.0
<i>Cristallo</i>	-	-11.3 ± 1.8		-10.1 ± 0.4	-21.4
<i>Sorapiss Occidentale</i> (a)	-3.0	-19.6		-3.4 ± 0.3	-26.0
<i>Antelao Superiore</i> (b)	-6.6	-4.7	-12.7	-7.5 ± 0.3	-31.5
<i>Antelao Inferiore</i> (b)	-1.4	-5.7	-8.6	-11.7 ± 0.3	-27.4
<i>Marmolada</i> (c)	-8.9	-14.7		-10.6 ± 0.3	-34.2
<i>Travignolo</i>		-21.4 ± 4.8		-10.0 ± 0.4	-31.4
<i>Fradusta</i> (d)	-6.2	-28.5		-15.0 ± 0.4	-49.7

35 **Table S5. Average surface elevation change measured on common glacier area (for each comparison) for the 9 Dolomites glaciers.** 1980s reference year is 1982 (1980 for *Sorapiss*); 1990s is 1992 (1991 for *Antelao*), 2010s is 2010 and 2020s is 2023. Maps of the surface elevation change of the first period (1980s-2010) retrieved from historical SfM and the modern data (2010-2023) are presented respectively in Fig. 6 and 7. Surface Elevation Change uncertainty ( $\delta_s$ ) is calculated for cumulative periods comparisons and during 1980s-2010 was (a) ± 1.7 m, (b) ± 3.1 m, (c) ± 2.9 m, (d) ± 1.4 m.

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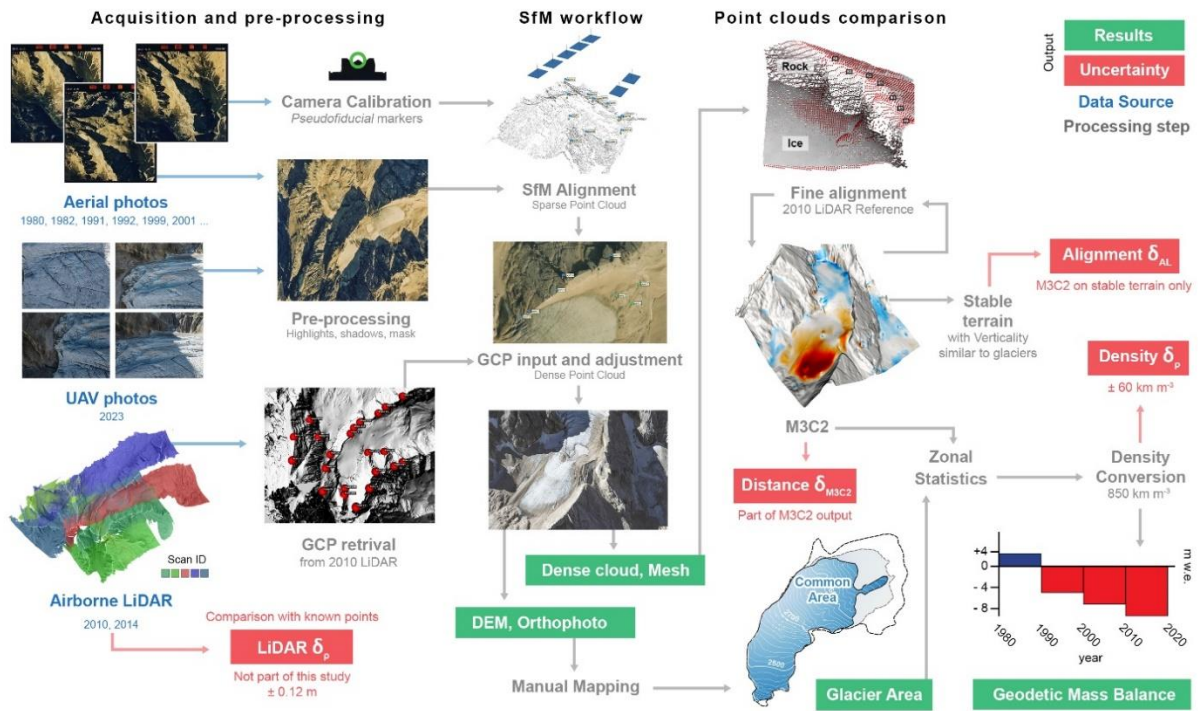
Glacier	Geodetic Mass Balance Rate (m w.e. yr <sup>-1</sup> )				
	1980s	1990s	2000s	2010s	Average Rate
	1980-82 to 1991-92	1991-1992 to 1999-01	1999-01 to 2010	2010 to 2023	All periods available
<i>Popera Alto</i>	-	-0.31 ± 0.13		-0.57 ± 0.04	-0.55
<i>Popera Pensile</i>	-	-0.28 ± 0.13		-0.44 ± 0.04	-0.47
<i>Cristallo</i>	-	-0.31 ± 0.09		-0.66 ± 0.05	-0.59
<i>Sorapiss Occidentale (a)</i>	-0.21	-0.54		-0.35 ± 0.02	-0.51
<i>Antelao Superiore (b)</i>	-0.62	-0.57	-0.98	-0.77 ± 0.04	-0.65
<i>Antelao Inferiore (b)</i>	-0.13	-0.69	-0.66	-0.49 ± 0.04	-0.57
<i>Marmolada (c)</i>	-0.75	-0.70		-0.69 ± 0.05	-0.71
<i>Travignolo</i>	-0.65 ± 0.15			-0.65 ± 0.05	-0.65
<i>Fradusta (d)</i>	-0.52	-1.34		-0.73 ± 0.07	-1.03

50 **Table S6. Mass Balance rates (m w.e. yr<sup>-1</sup>) of the Dolomites glaciers during the last four decades. The mass balance uncertainty  $\delta_{mb}$  is calculated for cumulative periods comparisons and during 1980s-2010 was (a) ± 0.07 m, (b) ± 0.11 m, (c) ± 0.10 m, (d) ± 0.07 m. *Sorapiss Occidentale* values have been corrected removing the positive elevation gain portion for 2010-2023; Marmolada and Fradusta mass balance are based on the average of all (now segmented) parts of the former glacier. All calculations are based on common areas.**

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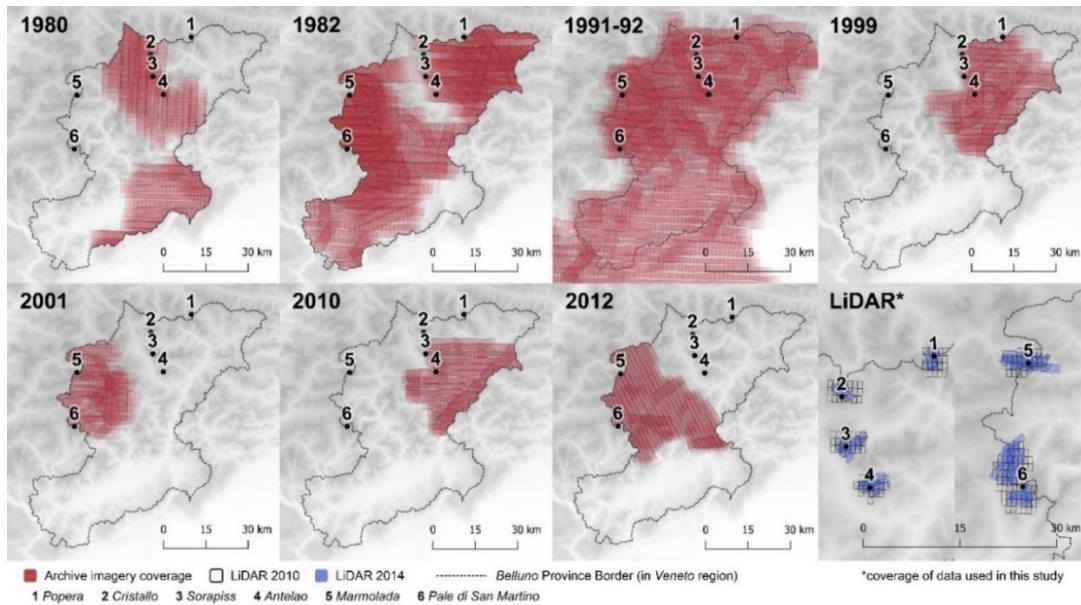
Glacier	Total Ice Mass Loss (Mt) Entire Period available in this study	% of the Total Dolomites Loss
<i>Popera Alto</i>	0.95	1.6
<i>Popera Pensile</i>	0.43	0.6
<i>Cristallo</i>	1.36	2.1
<i>Sorapiss Occidentale</i>	5.08	5.3
<i>Antelao Superiore</i>	6.07	7.9
<i>Antelao Inferiore</i>	3.57	4.0
<i>Marmolada</i>	54.41	65.7
<i>Travignolo</i>	4.37	5.5
<i>Fradusta</i>	6.86	7.3

**Table S7. Total ice mass loss (Mt) during the observation period available in this study and % of the dataset.**



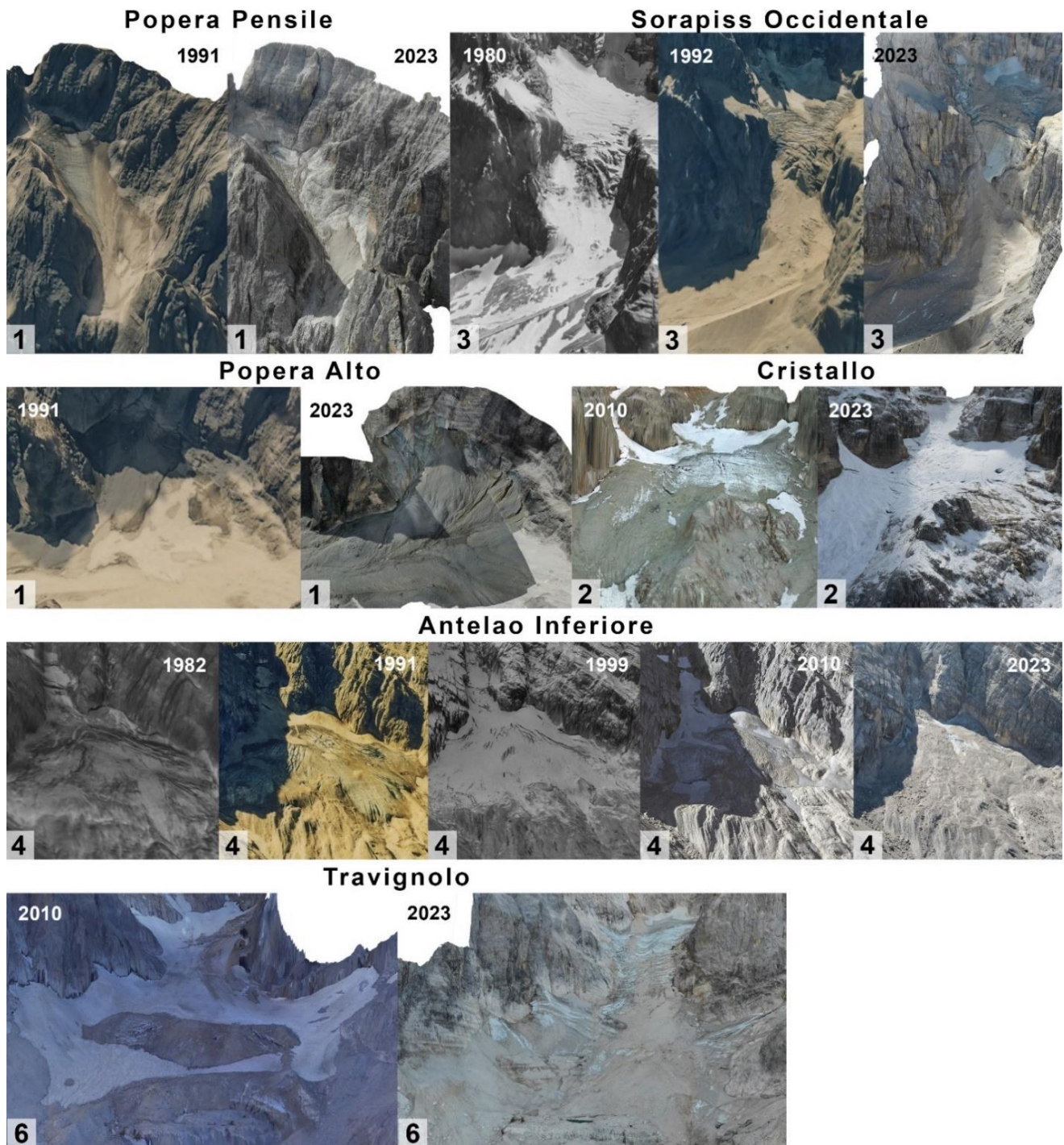
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Figure S1: Visual representation of the processing workflow described in Manuscript Section 3. Green boxes (results) and red boxes (uncertainties) represent the output of the processing workflow.



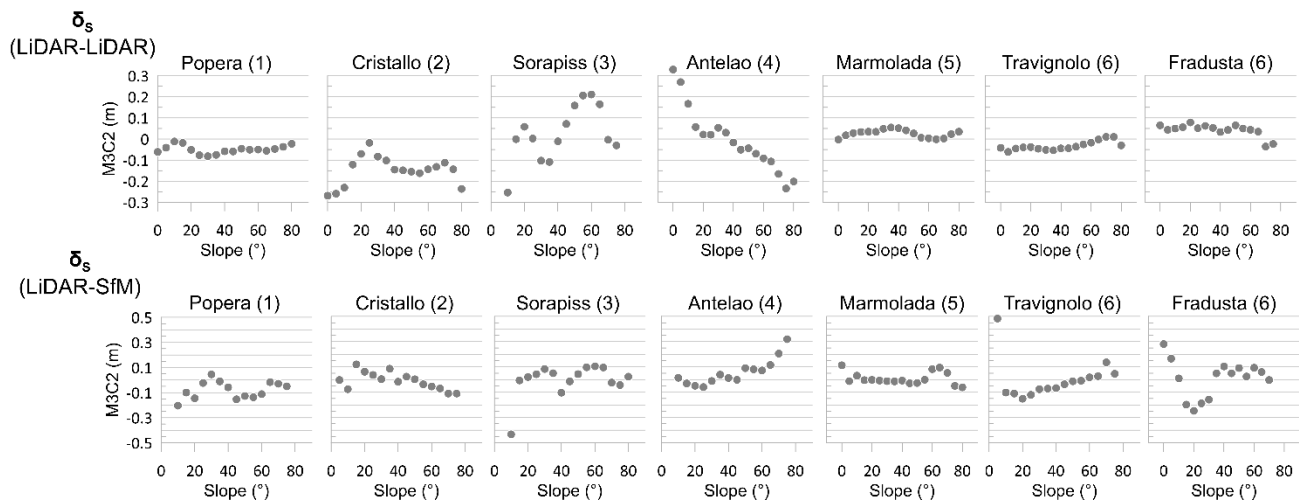
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Figure S2: Archival imagery (1980, 1982, 1991-92, 1999, 2001, 2010, 2012) and LiDAR (2010, 2014) data coverage in the Veneto Region (Bolzano province, black line). Most of the archival imagery extends with some frames across the administrative border. Reference dates and data description are available in Table 2.



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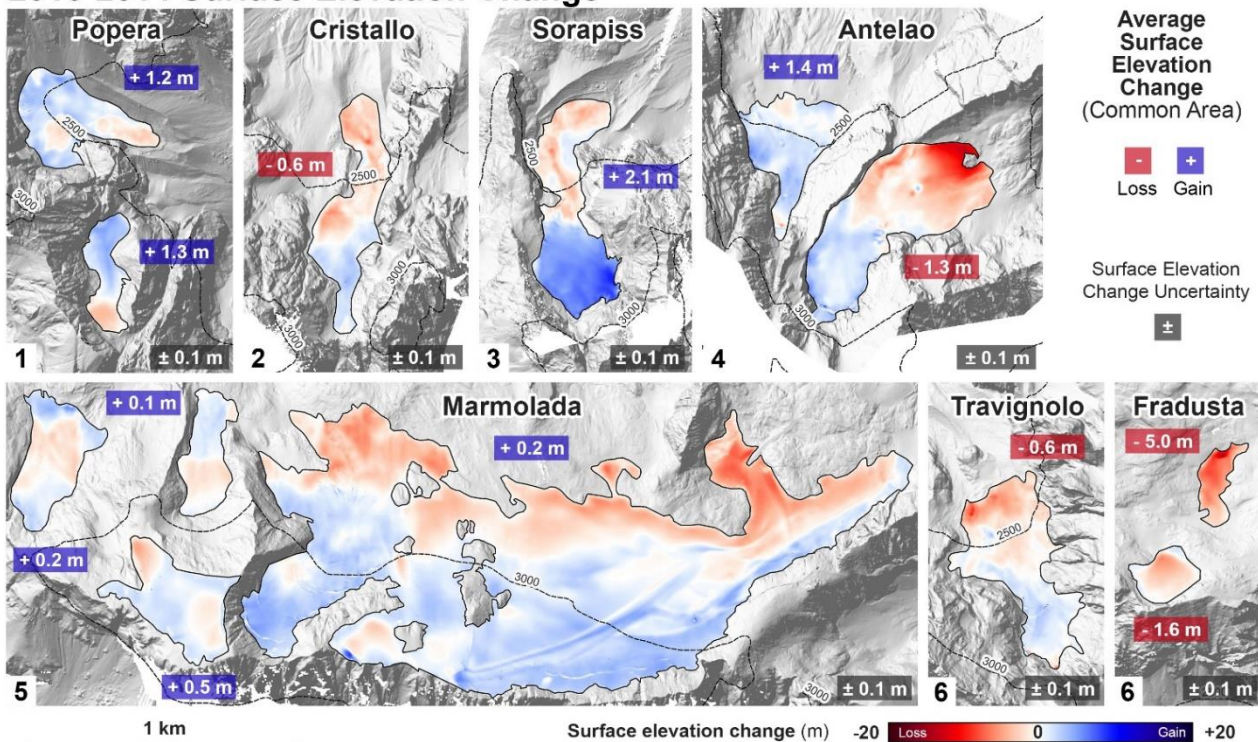
Figure S3. Examples of the reconstructed 3D textured models (i.e., triangular meshes derived from dense point clouds) of the Dolomites glaciers during different decades. Missing reconstructions from Marmolada, Fradusta and Antelao are shown in the manuscript (Fig. 3).



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Figure S4. Scatter plot of  $\delta_s$  (m), based on M3C2 distance measurements on stable terrain, and slope ( $5^\circ$  bins) for LiDAR-LiDAR comparisons (2010-2014) and LiDAR-SfM comparison in all the surveyed areas.

### 2010-2014 Surface Elevation Change



80 Figure S5. Surface elevation change (m) measured across the Dolomites glaciers from 2010 to 2014. Average surface elevation change, and its uncertainty, are reported for every glacier using common area.