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Supplement of

High-resolution inventory to capture glacier disintegration in the Austrian Silvretta

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Supplement

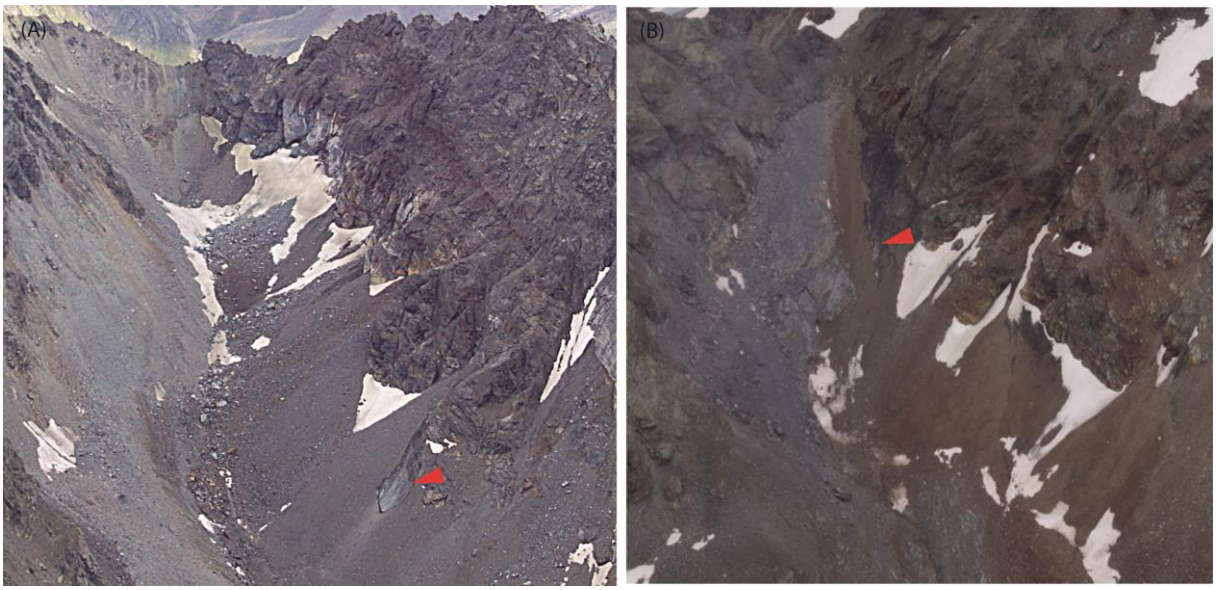

Figure S1: Enlarged views Schnapfenkuchl glaciers V (A) and H (B) from aerial photographs taken in 21.08.2020 (Andrea Fischer).

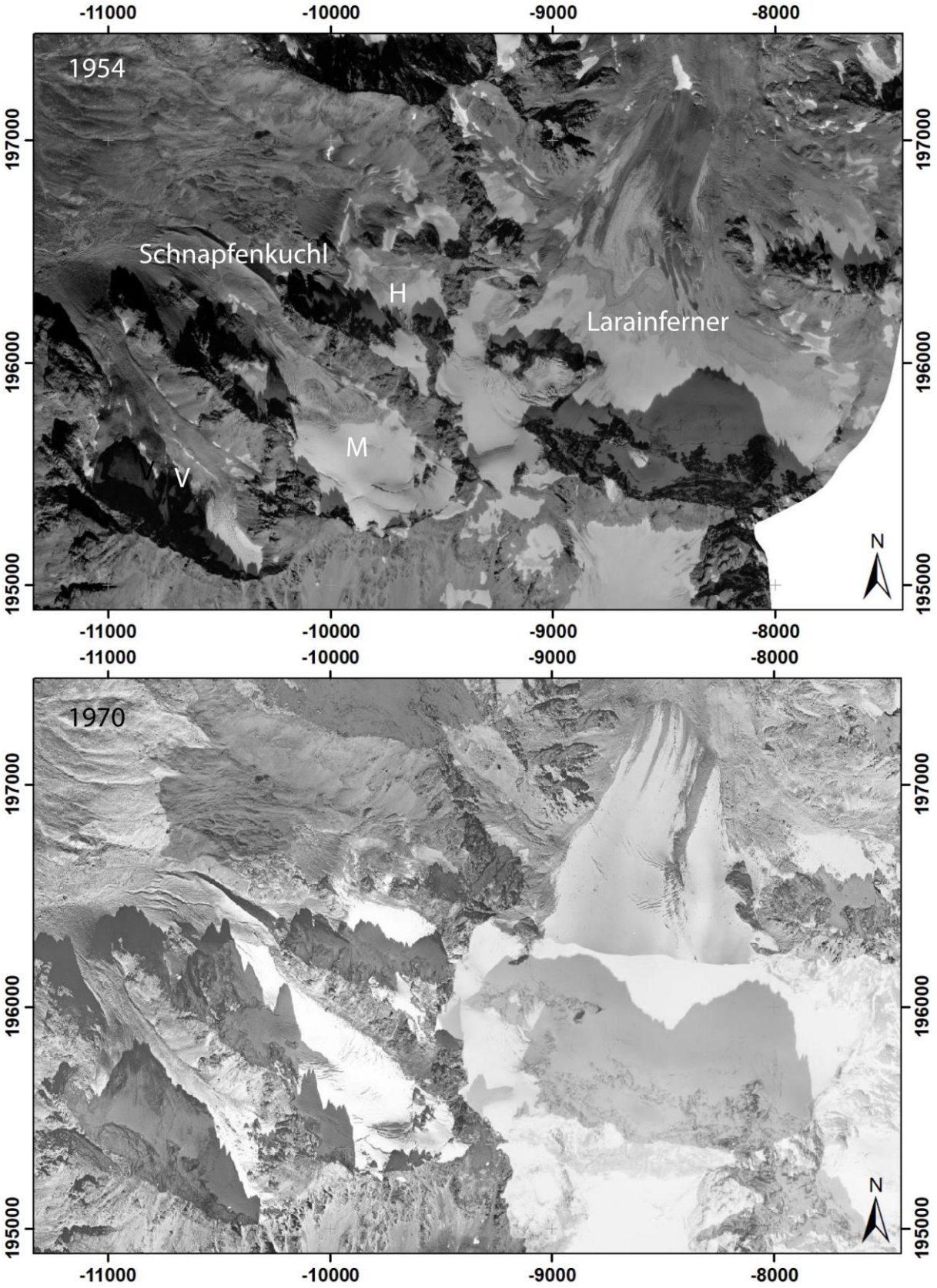

Figure S2A: The orthophotos of 1954 and 1970 of the Schnapfenkuchl glaciers/Larainferner show 'classical glaciers' with accumulation and ablation areas with bare ice exposed. Orthophotos: CC 4.0 https://www.data.gv.at/katalog/en/dataset/orthofoto.

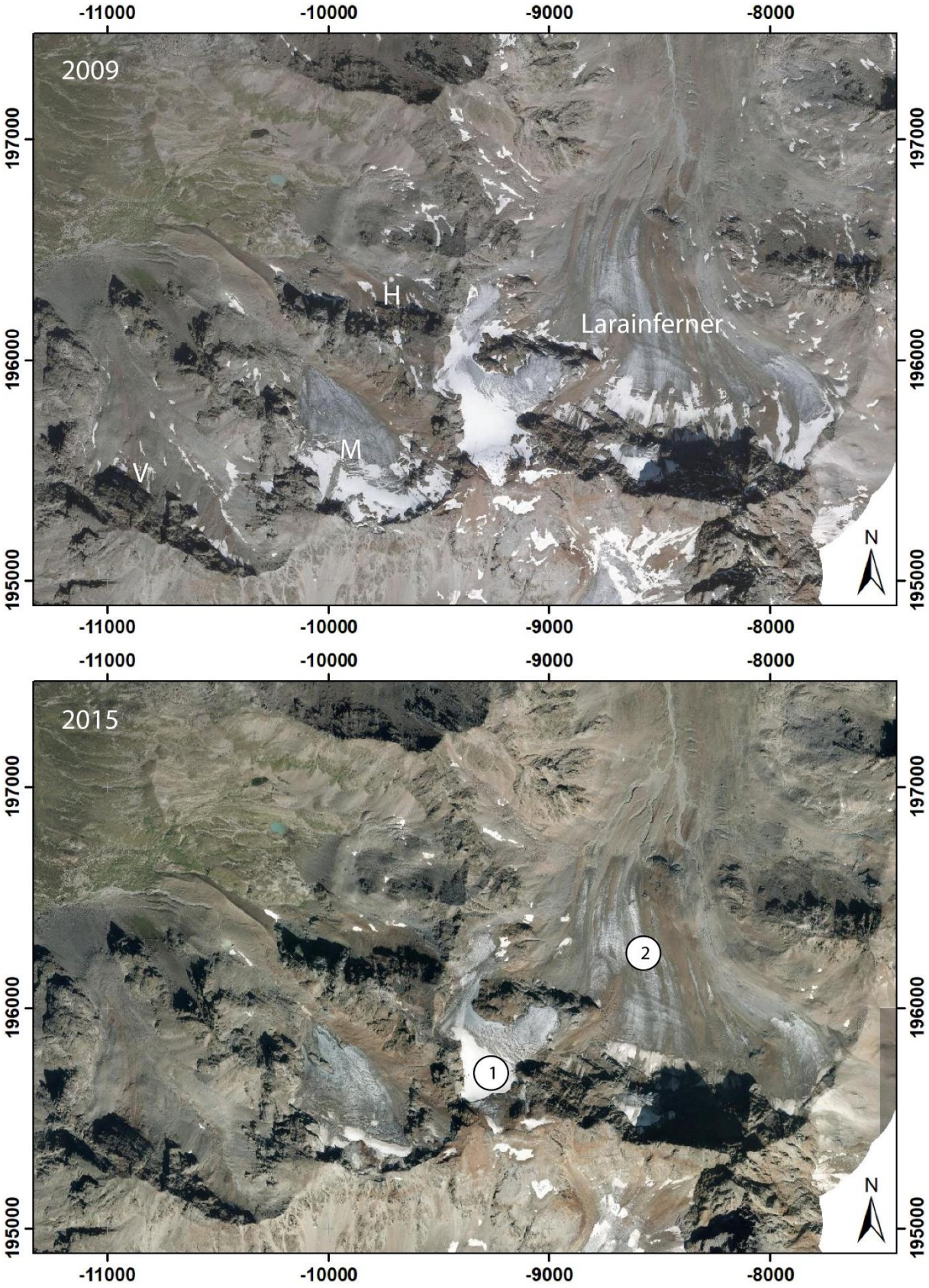

Figure S2B: The orthophotos of 2009 and 2015 of the Schnapfenkuchl glaciers/Larainferner show that the glacier changed quite rapidly within this time. The former main accumulation area (1) of Larainferner lost contact with the tongue (2) between 2002 and 2009, last remnants of permanently visible glacier ice at eastern Schnapfenkuchl glacier became covered with debris between 2009 and 2019. Orthophotos: CC 4.0 https://www.data.gv.at/katalog/en/dataset/orthofoto.

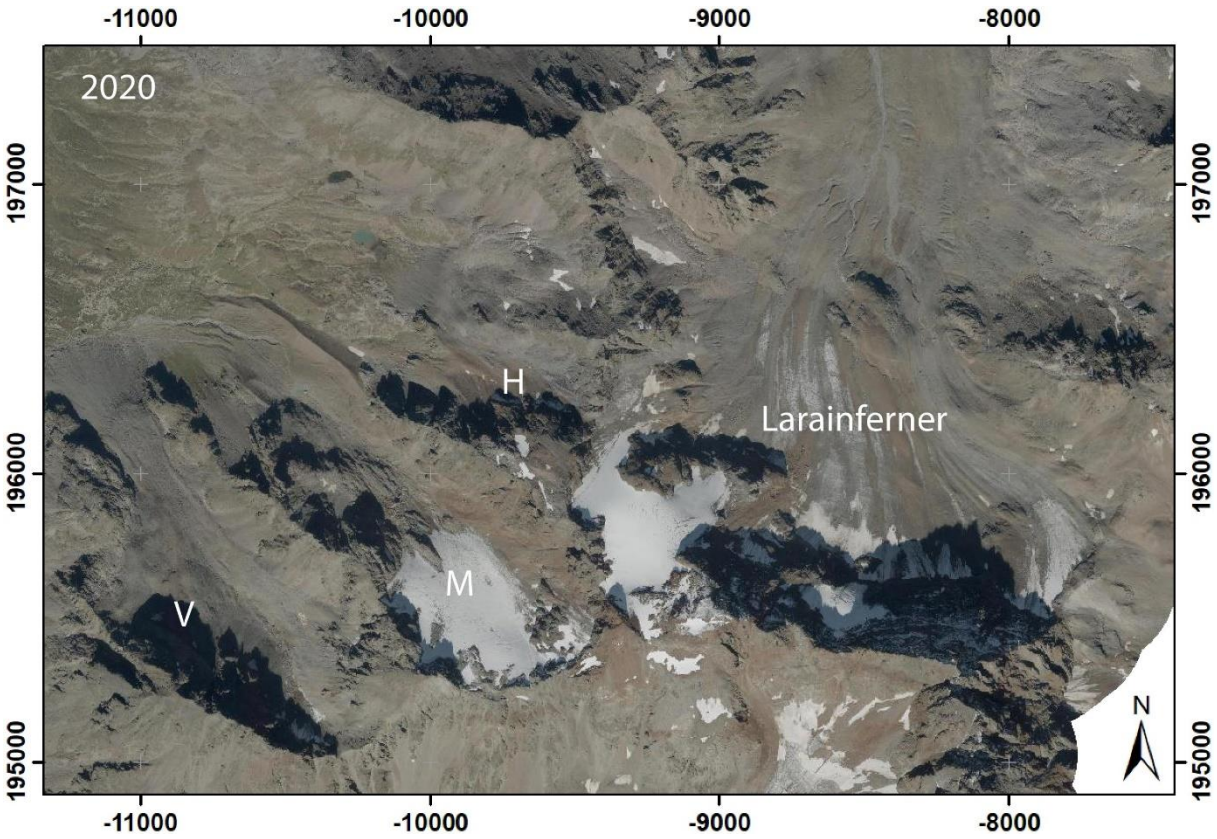

Figure S2C: The orthophoto of 2020 of the Schnapfenkuchl glaciers/Larainferner Orthophotos: CC 4.0 https://www.data.gv.at/katalog/en/dataset/orthofoto.

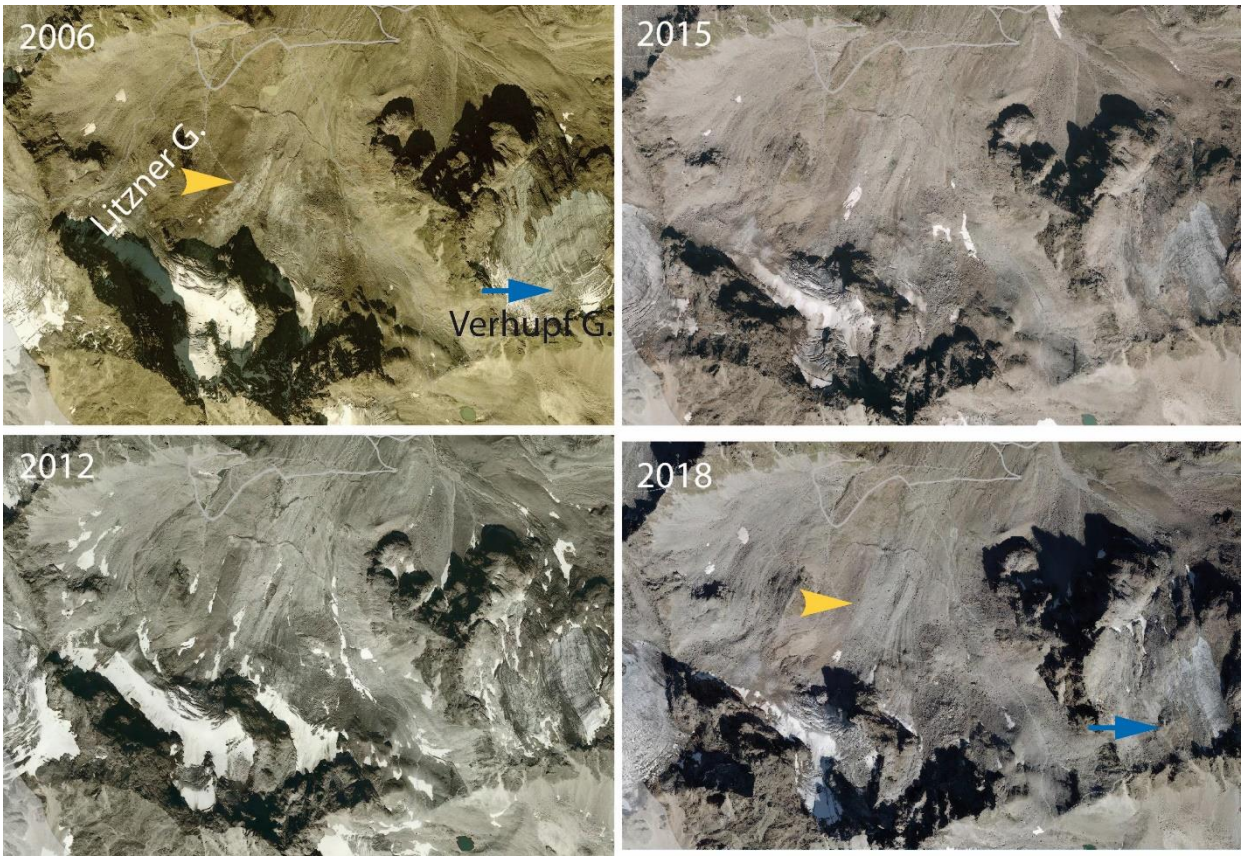

Figure S3: Time series of orthophotos of Litzner glacier. Between 2006 and 2018, we lose track of glacier ice at the tongue (yellow arrow). The flat summit glacier (blue arrow), intact in 2006, completely disintegrates as measured melt rates of 1.5 m (Fischer et al., 2016c) above 3000 m at Jamtalferner lead to a total loss of the shallow ice, leaving behind rock outcrops and debris-covered ice in small bedrock troughs. Orthophotos: CC 4.0 https://www.data.gv.at/katalog/en/dataset/orthofoto

Table S1: Glaciers of different classes (c), areas for the year (y) of the LiDAR survey, geodetic balance (total, specific and specific annual) in the Austrian part of the Silvretta between 2004/06 and 2017/18. For Vorarlberg, LiDAR flights were carried out in 2004 and 2017, for Tyrol in 2006 and 2018. Classes: d… widely debris covered, g…gone. For glaciers 13004 and 13005, no elevation data were available, so that the area was mapped with orthophotos.

name	c	ID (AT)	y	area	y	area	volume change	annual geodetic balance
				km²		km²	10^6m³	m w.e./yr
Jamtal F.		13019	06	3.65 ± 0.05	18	2.792 ± 0.042	-53.2 ± 4.46	-1.0 ± 0.2
Ochsentaler G.		12008	04	2.50 ± 0.04	17	2.135 ± 0.032	-33.9 ± 3.05	-0.9 ± 0.2
Vermunt G.		12007	04	1.79 ± 0.03	17	1.234 ± 0.019	-28.2 ± 2.19	-1.0 ± 0.2
Larain F.		13007	06	1.39 ± 0.02	18	0.989 ± 0.049	-15.4 ± 1.68	-0.8 ± 0.2
Schneeglocken G.		12009	04	0.67 ± 0.03	17	0.539 ± 0.027	-10.0 ± 0.95	-1.0 ± 0.2
Totenfeld		13021	06	0.66 ± 0.03	18	0.523 ± 0.026	-7.90 ± 0.89	-0.8 ± 0.2
Klostertaler G. N		12013	04	0.56 ± 0.03	17	0.369 ± 0.018	-7.04 ± 0.76	-0.8 ± 0.2
Futschöl F.		13014	06	0.47 ± 0.02	18	0.368 ± 0.018	-5.58 ± 0.63	-0.8 ± 0.2
Bieltal F.		13028	06	0.47 ± 0.02	18	0.280 ± 0.014	-5.81 ± 0.63	-0.9 ± 0.2
Schattenspitz G.		12011	04	0.46 ± 0.02	17	0.373 ± 0.019	-5.88 ± 0.63	-0.8 ± 0.2
Chalaus F.		13017	06	0.46 ± 0.02	18	0.358 ± 0.018	-4.83 ± 0.60	-0.7 ± 0.2
Litzner G.		12021	04	0.46 ± 0.02	17	0.228 ± 0.011	-4.96 ± 0.60	-0.7 ± 0.2
Klostertaler G. M		12014	04	0.40 ± 0.02	17	0.334 ± 0.017	-5.39 ± 0.55	-0.9 ± 0.2
Rauhkopf G.		12005	04	0.40 ± 0.02	17	0.257 ± 0.013	-5.79 ± 0.56	-0.9 ± 0.2
Fluchthorn F.		13011	06	0.38 ± 0.02	18	0.232 ± 0.012	-3.81 ± 0.50	-0.7 ± 0.2
Mittlere Schnapfenkuchl		13009	06	0.32 ± 0.02	18	0.242 ± 0.012	-3.68 ± 0.43	-0.8 ± 0.2
Kronen F.		13013	06	0.32 ± 0.02	18	0.146 ± 0.007	-3.86 ± 0.43	-0.9 ± 0.2
Jamtal F. W		13020	06	0.25 ± 0.01	18	0.184 ± 0.009	-3.55 ± 0.34	-1.0 ± 0.2
Im Glötter S		12016	04	0.25 ± 0.01	17	0.108 ± 0.005	-2.56 ± 0.32	-0.7 ± 0.1
Verhupf G.		12019	04	0.19 ± 0.01	17	0.073 ± 0.004	-2.03 ± 0.25	-0.7 ± 0.1
Rosstal F.		13024	06	0.19 ± 0.01	18	0.131 ± 0.007	-2.24 ± 0.26	-0.8 ± 0.2
Getschner F.		13023	06	0.19 ± 0.01	18	0.154 ± 0.008	-2.66 ± 0.26	-1.0 ± 0.2
Madlener F.		13026	06	0.18 ± 0.01	18	0.125 ± 0.006	-1.65 ± 0.23	-0.6 ± 0.1
Henneberg F.		13025	06	0.18 ± 0.01	18	0.113 ± 0.006	-2.40 ± 0.25	-1.0 ± 0.2
Tiroler G.		12006	04	0.18 ± 0.01	17	0.101 ± 0.005	-2.61 ± 0.25	-1.0 ± 0.2
Schweizer G.		12023	04	0.15 ± 0.01	17	0.068 ± 0.003	-1.76 ± 0.20	-0.8 ± 0.2
NN	d	12012	04	0.14 ± 0.01	17	0.091 ± 0.005	-1.71 ± 0.19	-0.8 ± 0.2
NN		13022	06	0.12 ± 0.01	18	0.083 ± 0.004	-0.97 ± 0.16	-0.6 ± 0.1
Kromer G.		12022	04	0.11 ± 0.01	17	0.062 ± 0.003	-1.09 ± 0.15	-0.6 ± 0.1

name	c	ID (AT)	y	area		y	area		volume change		annual geodetic balance	
				km²	km²		km²	km²	$10^6 m^3$	$10^6 m^3$	m w.e./yr	
Klostertaler G. S	d	12015	04	0.11	± 0.01	17	0.040	± 0.002	-0.95	± 0.14	-0.6	± 0.1
Oberer Augsten F.		13016	06	0.10	± 0.01	18	0.089	± 0.004	-1.02	± 0.13	-0.7	± 0.2
Hintere Schnapfenkuchl	d	13008	06	0.082	± 0.004	18	0.025	± 0.001	-0.42	± 0.10	-0.4	± 0.1
Unterer Augsten F.	d	13015	06	0.078	± 0.004	18	0.036	± 0.002	-0.33	± 0.10	-0.3	± 0.1
Im Glötter N		12017	04	0.078	± 0.004	17	0.049	± 0.002	-1.14	± 0.11	-1.0	± 0.2
NN	d	12018	04	0.073	± 0.004	17	0.021	± 0.001	-0.38	± 0.09	-0.3	± 0.1
Bieltal F. E		13027	06	0.068	± 0.003	18	0.019	± 0.001	-0.51	± 0.09	-0.5	± 0.1
NN		13004	06	0.064	± 0.003	18	0.043	± 0.002				
NN	d	13005	06	0.052	± 0.003	18	0.033	± 0.002				
NN		13018	06	0.050	± 0.003	18	0.030	± 0.001	-0.35	± 0.06	-0.5	± 0.1
Fluchthorn F. S	g	13012	06	0.046	± 0.002	18	0.000	± 0.000	-0.06	± 0.05	-0.1	± 0.1
Vordere Schnapfenkuchl	d	13010	06	0.043	± 0.002	18	0.028	± 0.001	-0.30	± 0.05	-0.5	± 0.1
NN	g	13006	06	0.039	± 0.002	18	0.000	± 0.000	-0.12	± 0.05	-0.2	± 0.1
Schattenspitz G. E	d	12010	04	0.033	± 0.002	17	0.006	± 0.000	-0.24	± 0.04	-0.5	± 0.1
Garnera G.	d	12026	04	0.030	± 0.002	17	0.011	± 0.001	-0.14	± 0.04	-0.3	± 0.1
Platten G.	d	12025	04	0.026	± 0.001	17	0.012	± 0.001	-0.17	± 0.03	-0.4	± 0.1
Litzner G. E	g	12020	04	0.0038	± 0.0002	17	0.000	± 0.001	-0.01	± 0.00	-0.1	± 0.1

Table S2: Glaciers of different classes (c), average areas, and geodetic balance based on the average area in the Austrian part of the Silvretta between 2004/2006 and 2017/2018 with the difference in geodetic mass balance based on using either the area at the beginning the period or the average area. For Vorarlberg, LiDAR flights were carried out in 2004 and 2017, for Tyrol in 2006 and 2018. Classes: d… widely debris covered, g…gone. For glaciers 13004 and 13005, no elevation data were available, so that the area was mapped with orthophotos.

name	c	ID (AT)	avergae area	annual geodetic balance average area	difference geodetic balance	
			km²	m w.e./yr	m w.e./yr	%
Jamtal F.		13019	3.22 ± 0.05	-1.2 ± 0.2	0.1	13
Ochsentaler G.		12008	2.32 ± 0.03	-1.0 ± 0.2	0.1	8
Vermunt G.		12007	1.51 ± 0.02	-1.2 ± 0.2	0.2	18
Larain F.		13007	1.19 ± 0.02	-0.9 ± 0.2	0.1	17
Schneeglocken G.		12009	0.61 ± 0.03	-1.1 ± 0.2	0.1	11
Totenfeld		13021	0.59 ± 0.03	-0.9 ± 0.2	0.1	12
Klostertaler G. N		12013	0.46 ± 0.02	-1.0 ± 0.2	0.2	20
Futschöl F.		13014	0.42 ± 0.02	-0.9 ± 0.2	0.1	12
Bieltal F.		13028	0.37 ± 0.02	-1.1 ± 0.2	0.2	25
Schattenspitz G.		12011	0.42 ± 0.02	-0.9 ± 0.2	0.1	11
Chalaus F.		13017	0.41 ± 0.02	-0.8 ± 0.2	0.1	13
Litzner G.		12021	0.34 ± 0.02	-0.9 ± 0.2	0.2	33
Klostertaler G. M		12014	0.37 ± 0.02	-1.0 ± 0.2	0.1	9
Rauhkopf G.		12005	0.33 ± 0.02	-1.2 ± 0.2	0.2	22
Fluchthorn F.		13011	0.31 ± 0.02	-0.9 ± 0.2	0.2	25
Mittlere Schnapfenkuchl		13009	0.28 ± 0.01	-0.9 ± 0.2	0.1	14
Kronen F.		13013	0.23 ± 0.01	-1.2 ± 0.2	0.3	37
Jamtal F. W		13020	0.21 ± 0.01	-1.2 ± 0.2	0.1	14
Im Glötter S		12016	0.18 ± 0.01	-0.9 ± 0.2	0.3	39
Verhupf G.		12019	0.13 ± 0.01	-1.0 ± 0.2	0.3	46
Rosstal F.		13024	0.16 ± 0.01	-1.0 ± 0.2	0.2	19
Getschner F.		13023	0.17 ± 0.01	-1.1 ± 0.2	0.1	9
Madlener F.		13026	0.15 ± 0.01	-0.8 ± 0.1	0.1	18
Henneberg F.		13025	0.15 ± 0.01	-1.2 ± 0.2	0.2	23
Tiroler G.		12006	0.14 ± 0.01	-1.2 ± 0.2	0.3	27
Schweizer G.		12023	0.11 ± 0.01	-1.0 ± 0.2	0.3	38
NN	d	12012	0.11 ± 0.01	-1.0 ± 0.2	0.2	21
NN		13022	0.10 ± 0.01	-0.7 ± 0.1	0.1	20
Kromer G.		12022	0.09 ± 0.00	-0.8 ± 0.1	0.2	30
Klostertaler G. S	d	12015	0.08 ± 0.00	-0.8 ± 0.1	0.3	47

Oberer Augsten F.		13016	0.10	±	0.00	-0.8	±	0.1	0.1	8
Hintere Schnapfenkuchl	d	13008	0.05	±	0.003	-0.6	±	0.1	0.2	53
Unterer Augsten F.	d	13015	0.06	±	0.003	-0.4	±	0.1	0.1	37
Im Glötter N		12017	0.06	±	0.003	-1.2	±	0.2	0.2	23
NN	d	12018	0.05	±	0.002	-0.5	±	0.1	0.2	56
Bieltal F. E		13027	0.04	±	0.002	-0.8	±	0.2	0.3	55
NN		13004	0.05	±	0.003	0.0			0.0	0
NN	d	13005	0.04	±	0.002	0.0			0.0	0
NN		13018	0.04	±	0.002	-0.6	±	0.1	0.1	26
Fluchthorn F. S	g	13012	0.02	±	0.001	-0.2	±	0.0	0.0	0
Vordere Schnapfenkuchl	d	13010	0.04	±	0.002	-0.6	±	0.1	0.1	21
NN	g	13006	0.02	±	0.001	-0.4	±	0.1	0.0	0
Schattenspitz G. E	d	12010	0.02	±	0.001	-0.8	±	0.1	0.3	70
Garnera G.	d	12026	0.02	±	0.001	-0.4	±	0.1	0.1	48
Platten G.	d	12025	0.02	±	0.001	-0.6	±	0.1	0.2	37
Litzner G. E	g	12020	0.00	±	0.0001	-0.2	±	0.0	0.1	

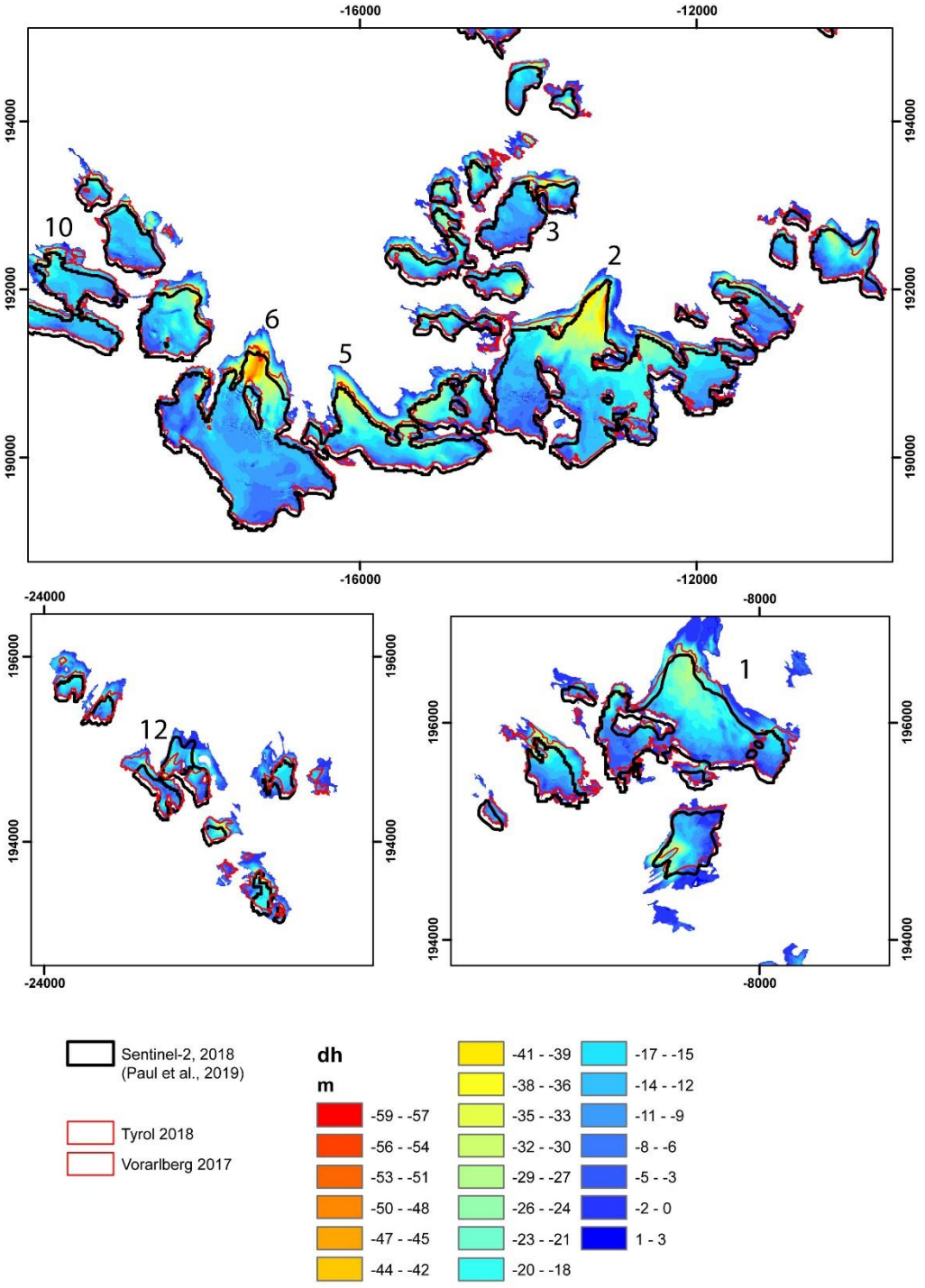

Figure S4: Volume differences 2004-2017 for Silvretta glacier in Vorarlberg, 2006-2018 for the Tyrolean part with glacier outlines derived from LiDAR for 2017/2018 and from Sentinel-2 for 2018 (Paul et al., 2019). Glacier numbers refer to the overview map in Figure 1.

Definitions of glaciers

"Diese Eisberge werden Ferner genennet, welches Wort… das Eis bedeutet welches mit Schnee vermenget gesammelt hat" (Walcher, 1773) [These mountains of ice are called „Ferner", a word …that denotes ice mixed with snow which has accumulated]

"At its origin then a glacier is snow — at its lower extremity it is ice." (Tyndall, 1860)

***Gletscher sind Massen körnigen Firns und Eises**, die aus Schneeansammlungen hervorgehen und sich dahin bewegen, wo sie abschmelzen oder verdunsten können….scheinbarer oder auch wirklicher Mangel an Bewegung schliesst aber doch die Bezeichnung Gletscher nicht aus, übergeordnetes Merkmal ist die Körnerstruktur."*

(Klebelsberg 1948)

[Glaciers are masses of granulated firn and ice that have evolved out of accumulations of snow and which move towards where they can melt or evaporate… however, an apparent or actual lack of movement does not preclude it being labelled a glacier, the predominant characteristic is the granular structure.]

***"**A glacier is a mass of relatively slow moving ice created by the accumulation of snow"* (Dexter, 2013)

"A perennial mass of ice, and possibly firn and snow, originating on the land surface by the recrystallization of snow or other forms of solid precipitation and showing evidence of past or present flow… In contrast to what is natural in dynamic glaciology and glacial geomorphology, for mass-balance purposes the glacier consists only of frozen water. Sediment carried by the glacier is deemed to be outside the glacier."

(Cogley et al., 2011)

"*A glacier or perennial snow mass, identified by a single GLIMSglacier ID, consists of a body of ice and snow that is observed at the end of the melt season, or, in the case of tropical glaciers, after transient snow melts. This includes, at a minimum, all tributaries and connected feeders that contribute ice to the main glacier, plus all debris-covered parts of it. Excluded is all exposed ground, including nunataks. …. A stagnant ice mass still in contact with a glacier is part of the glacier, even if it supports an old-growth forest…All debris-covered parts of the glacier must be included…. Rock glaciers and heavily debris-covered glaciers tend to look similar, but their geneses are different. GLIMS does not currently deal with the former, but does include the latter."*

(Raup and Khalsa, 2010*)*