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Supplement of

Retreating glaciers and snow cover are amplifying summer droughts in the upper Adige River Basin (Italy)

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Supplementary material

S1. On the case study area

In Table S1 all the macro subbasins of the upper Adige River Basin are reported together with their geomorphological characteristics, their hydro-climatic variables and coverage of data availability.

Table S1 – Detailed information on the 16 macro catchments of the upper Adige River Basin and their characteristics

#	Area (km^2)	Elevation (m)	Precipitation (mm)	Temperature (°C)	Runoff(m^3/s)		Glacier (%)	Data availability
					Min	Max		
1	49	2387	1173	0.246	0.04	31.87	1.91	Oct 1997 - Sep 2023
2	76	2386	1081	0.251	0.14	55.06	8.96	Oct 2001 - Sep 2008
3	82	2026	1033	2.234	0.46	20.42	0.38	Oct 1997 - Sep 2023
4	93	1911	1061	2.868	0.53	11.17	0.00	Oct 2013 - Sep 2023
5	115	2278	1026	0.846	0.28	65.18	7.01	Oct 2008 - Sep 2023
6	117	1961	926	2.593	0.39	21.56	0.00	Oct 1997 - Sep 2023
7	125	2027	1059	2.229	0.58	26.53	0.00	Oct 2003 - May 2006; Sep 2006 - Sep 2010; Oct 2015 - Sep 2018; Oct 2019 - Jul 2021
8	150	2162	1054	1.485	0.36	109.32	4.13	Oct 1997 - Sep 2023
9	210	1933	1131	2.747	0.2	77.17	4.32	Oct 1997 - Jul 2021; Feb 2023 - Sep 2023
10	397	1855	955	3.176	2.04	57.36	0.00	Oct 1997 - Sep 2018; Oct 2019 - Sep 2023
11	414	1851	1131	3.199	1.85	213.35	0.88	Oct 2013 - Sep 2023
12	420	2117	1006	1.733	1.1	196.29	4.58	Oct 2001 - May 2018; Oct 2019 - Sep 2023
13	608	2036	992	2.179	1.82	251.48	3.80	Oct 1997 - Feb 2018; Jul 2018 - Sep 2023
14	1919	1859	969	3.154	8.8	416	1.22	Oct 1997 - Jan 2019; May 2019 - Sep 2023
15	2732	1895	871	2.956	17.13	506.18	2.72	Oct 1997 - Sep 2023
16	6924	1805	925	3.452	38.4	1184.87	1.64	Oct 1997 - Sep 2023



Figure S1 – Subbasins considered in the simulations and their associated ID number

Table S2 – Subbasin ID numbers and related macro-name. Subbasin macro-area names are indicative and intended to facilitate geographical interpretation; the mapped units correspond to hydrological subbasins and may not exactly coincide with valley boundaries.

Subbasin ID number	Subbasin macro-area name (Italian)	Subbasin macro-area name (German)
1	Vallelunga	Langtaufers
2	Val Monastero	Münstertal
3	Val di Mazia	Matschertal
4	Alta Val Venosta	Obervinschgau
5	Valle di Silandro	Schlandrauntal
6-7	Val Martello	Martelltal
8-53-54	Val Venosta	Vinschgau
9-10	Val Senales	Schnalstal
11	Bassa Val Venosta	Untervinschgau
12	Alta Val Passiria	Hinterpasseier
13-14	Val Passiria	Passeiertal
15-16-17	Val d'Ultimo	Ultental
18	Merano	Meran
19-58	Val d'Adige	Etschtal
20-21	Val Sarentino	Sarntal
22	Val d'Ega	Eggental
23	Val Gardena	Grödnertal
24	Val di Funes	Villnösstal
25	Valle di Racines	Ratschingstal
26	Val di Mezzo	Jaufental
27	Val Ridanna	Ridnauntal
28	Val di Fleres	Pflerschtal
29	Alta Valle Isarco	Oberes Eisacktal
30	Val di Vizze	Pfitschtal

31	Vipiteno / Val di Vizze	Sterzing / Pfitschtal
32	Alta Valle Aurina	Oberes Ahrntal
33-34	Valle di Tures	Tauferer Tal
35	Bassa Valle Aurina	Unteres Ahrntal
36	Valle di Braies	Pragser Tal
37	Val di Landro / Alta Val Pusteria	Höhlensteintal / Hochpustertal
38	Val Casies	Gsiesertal
39	Val di Anterselva	Antholzertal
40-42	Val Badia	Gadertal
41	Valle di Marebbe	Enneberger Tal
43	Val di Fundres / Val Pusteria	Pfunderer Tal / Pustertal
44	Valle di Valles	Valler Tal
45	Alta Val Passiria	Hinterpasseier
46	Alta Valle dei Molini	Oberes Mühlwalder Tal
47	Valle di Tures / Valle dei Molini	Tauferer Tal / Mühlwalder Tal
48	Val Pusteria / Val Casies	Pustertal / Gsiesertal
49	Val Pusteria	Pustertal
50-51-55-56	Valle Isarco	Eisacktal
52	Val di Solda	Suldenertal
57	Bolzano	Bozen
59-60-61	Bassa Atesina	Unterland

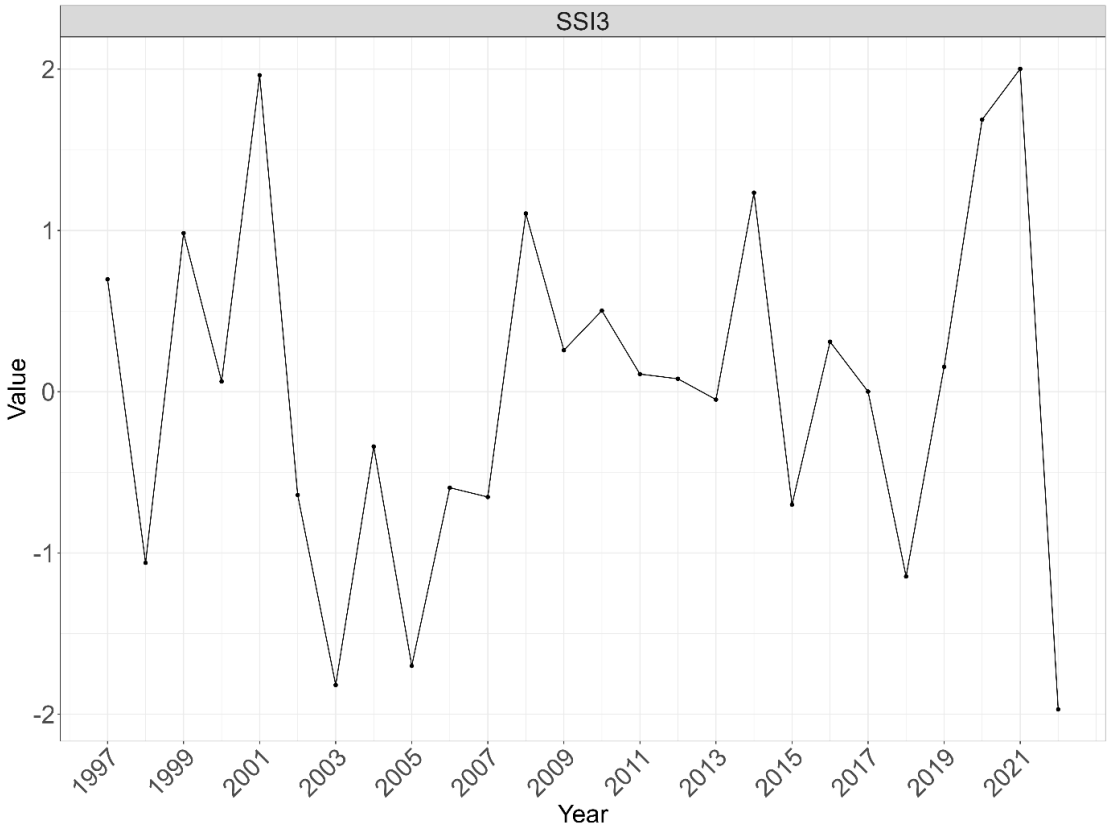


Figure S2 - Standardized Streamflow Index calculated over 3 months of time window for the Bronzolo streamflow station from 1997 until 2022

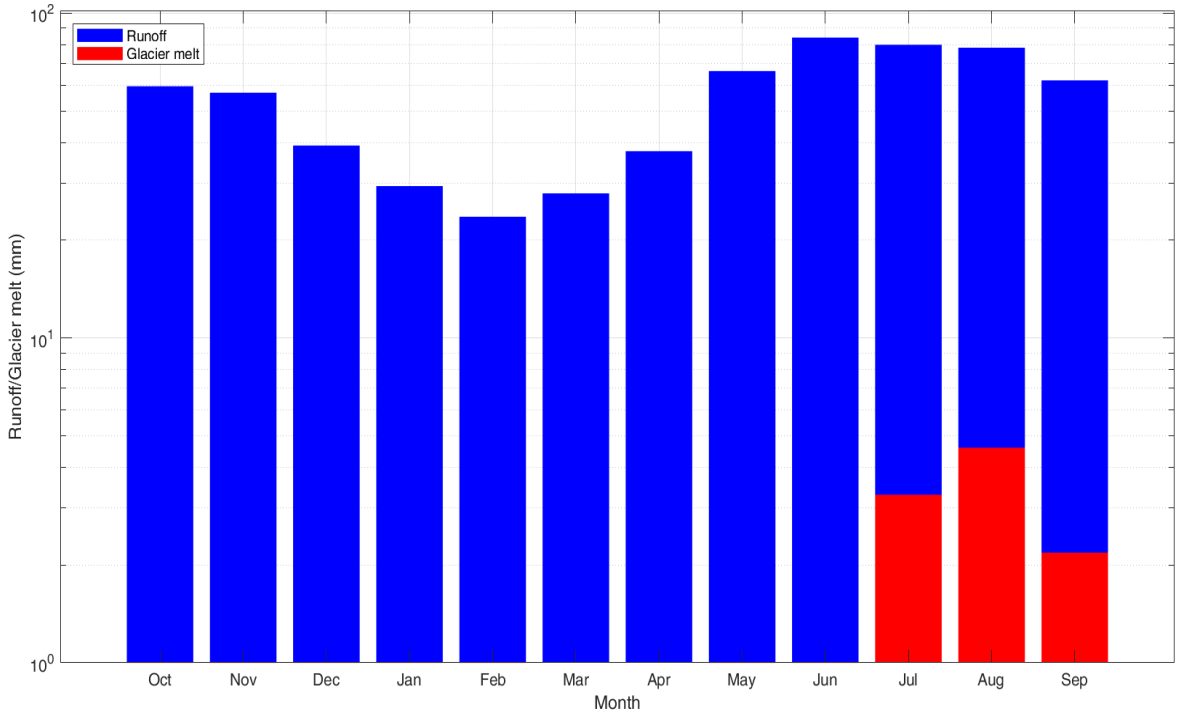


Figure S3 –The monthly average runoff along with the glacier melt contribution for the Adige River at Bronzolo. The Y-axis is in log scale.

S2. On the integrated hydrological model

Table S3 – Kling-Gupta Efficiency (KGE) and Mean Bias Ratio (MBR) for the runoff simulations of the upper Adige River Basin during the 2003, 2005 and 2022 summers

		Dynamic glaciers		Static glaciers	
#	**Subbasins**	**KGE**	**MBR**	**KGE**	**MBR**
1	Rio Plan	0.547	1.318	0.514	1.356
2	Rio Riva a Seghe	0.653	0.768	0.660	0.783
3	Rio Anterselva Bagni	0.811	0.968	0.808	0.994
4	Braies	0.401	0.931	0.401	0.931
5	Rio Riva a Caminata	0.638	1.131	0.547	1.294
6	Rio Casies Colle	0.719	0.988	0.719	0.988
7	Gadera a Pedraces	0.628	1.105	0.628	1.105
8	Aurino a Cadipietra	0.749	0.913	0.756	0.972
9	Ridanna a Vipiteno	0.784	1.042	0.784	1.042
10	Gadera Mantana	0.797	1.089	0.797	1.089
11	Passirio	0.482	1.477	0.396	1.564
12	Aurino a Caminata	0.728	1.091	0.685	1.173
13	Aurino a S.Giorgio	0.730	1.198	0.665	1.273
14	Rienza Vandoies	0.819	1.107	0.789	1.147
15	Ponte Adige	0.780	0.992	0.777	1.030
16	Adige a Bronzolo	0.863	1.070	0.839	1.102

Table S4 - KGE values for the whole simulation period for the dynamic and static glacier module

#	Subbasins	KGE dynamic module	KGE static module	Delta KGE
1	Rio Plan	0.820	0.820	0.033
2	Rio Riva a Seghe	0.757	0.761	-0.007
3	Rio Anterselva Bagni	0.829	0.830	0.004
4	Braies	0.658	0.658	0.000
5	Rio Riva a Caminata	0.775	0.778	0.090
6	Rio Casies Colle	0.780	0.780	0.000
7	Gadera a Pedraces	0.804	0.804	0.000
8	Aurino a Cadipietra	0.828	0.832	-0.007
9	Ridanna a Vipiteno	0.870	0.870	0.000
10	Gadera Mantana	0.795	0.795	0.000
11	Passirio	0.741	0.738	0.086
12	Aurino a Caminata	0.823	0.828	0.043
13	Aurino a S.Giorgio	0.885	0.878	0.065
14	Rienza Vandoies	0.896	0.894	0.031
15	Ponte Adige	0.848	0.849	0.003
16	Adige a Bronzolo	0.888	0.889	0.024

S3. On the hydro-climatic drivers of droughts

Table S5 - Z-score values for the summers months JAS from 1998 until 2022 for precipitation, temperature, snow water equivalent, glacier melt and runoff

Year	Precipitation	Temperature	SWE	Glacier melt	Runoff
1998	0.017	-0.503	-0.716	0.898	0.175
1999	1.120	-0.079	-0.228	0.195	0.340
2000	1.026	-0.810	-0.508	-0.067	0.043
2001	-0.133	-1.226	2.611	-1.405	1.405
2002	-1.151	-1.358	-0.520	0.319	-1.208
2003	-2.252	1.186	-0.982	2.509	-1.788
2004	-1.517	-0.570	0.289	-1.006	-0.977
2005	-0.278	-1.275	-0.698	-0.758	-1.622
2006	-0.437	0.112	-0.881	1.020	-0.443
2007	0.108	-1.563	-0.483	-0.785	-0.725
2008	0.425	-1.241	-0.531	-0.232	1.025
2009	-0.285	0.676	0.374	-0.287	0.299
2010	0.856	-0.489	-0.182	-0.882	0.225
2011	0.516	0.376	0.327	-0.281	0.304
2012	1.558	0.511	-0.600	0.625	0.368
2013	-0.991	0.614	1.080	-0.954	-0.178
2014	0.155	-1.430	3.238	-2.367	1.704
2015	0.285	1.196	0.234	0.573	-0.446
2016	-0.622	1.074	-0.249	0.703	0.470
2017	1.391	-0.302	-0.311	0.280	0.454
2018	-0.469	1.664	-0.444	0.922	-0.810
2019	-1.163	0.600	-0.085	-0.669	-0.356
2020	1.410	1.035	0.237	0.204	1.575
2021	1.201	0.474	-0.369	0.298	1.607
2022	-0.770	1.328	-0.604	1.145	-1.444

S4. On the counterfactual analysis

Table S6 – Values of glacier melt and runoff for the three selected drought years of 2003, 2005 and 2022 at the Bronzolo gauge station and the percentage decrease of glacier melt contribution for the dynamic glacier module compared to the static module with 1997 levels.

Average summer flow (mm)							Glacier melt % of runoff		Δ [%]
Years	Glacier melt			Runoff			Dynamic module	1997 glaciers	
	Dynamic module	1997 glaciers	Δ [%]	Dynamic module	1997 glaciers	Δ [%]			
2003	5.80	6.29	**-7.81**	49.68	50.17	**-0.99**	11.67	12.54	**-6.89**
2005	2.52	2.96	**-15.03**	51.86	52.32	**-0.87**	4.85	5.66	**-14.29**
2022	4.43	8.00	**-44.69**	54.19	57.79	**-6.23**	8.17	13.85	**-41.01**