Monthly velocity and seasonal variations of the Mont Blanc glaciers derived from Sentinel-2 between 2016-2024

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Supplementary materials

S1. Single glaciers description

In this supplementary chapter, we give a brief geographical and geomorphological description of every glacier on which the velocity time series analysis of our study was performed. The 30 glaciers are described in order of their increasing Randolph Glacier Inventory numbering.

A Neuve N Glacier: this (RGI60-11.02859) is a small (Area= 0.269km2) glacier located in the Swiss part of the Mont Blanc massif. It is the northernmost of different small glaciers formed by the retreat and fragmentation of the once unique A Neuve Glacier. Its aspect is mostly south-east and its accumulation area is overlooked by Grand-Luy Peak (3508m) by less than 100 vertical meters of cliffs. It drains in the Swiss Val Ferret in the Canton of Wallis.

A Neuve Central Glacier: this (RGI60-11.02864) is a medium-sized (Area: 0.889km2) glacier located in the Swiss part of the Mont Blanc massif. The analysed part of the A Neuve Glacier is the central section, one which is nowadays distinct from the northern (RGI60-11.02859) and southern parts (RGI60-11.02884); its aspect is mostly east and its accumulation area is overlooked by Tour Noir (3836m) from which the glacier originates with rock walls as high as 800m. It drains in the Swiss Val Ferret in the Canton of Wallis.

Pré de Bard Glacier: this (RGI60-11.02916) is a medium-sized (Area: 3.011km2) glacier located in the Italian part of the Mont Blanc massif. Its aspect is mostly south-east and its accumulation area is overlooked by rock faces from Mont Dolent (3823m), reaching a vertical drop as high as 600m. It drains in Val Ferret, in the Aosta valley region.

Greuvettaz E Glacier: this (RGI60-11.02978) is a small (Area: 0.196km2) glacier located in the Italian part of the Mont Blanc massif. Its aspect is mostly south-east and its accumulation area is overlooked by rock faces from Mont Greuvettaz (3684m), reaching a vertical drop as high as 400m. It drains in the Val Ferret, in the Aosta valley region.

Greuvettaz W Glacier: this (RGI60-11.02981) is a small (Area: 0.169km2) glacier located in the Italian part of the Mont Blanc massif. Its aspect is mostly south-east and its accumulation area is overlooked by rock faces from Mont Greuvettaz (3684m), reaching a vertical drop as high as 400m. It drains in the Val Ferret, in the Aosta valley region.

Planpincieux Glacier: this (RGI60-11.02991) is a medium-sized (Area: 1.013km2) glacier located in the Italian part of the Mont Blanc massif. Its aspect is mostly south and its accumulation area is overlooked by rock faces from Grandes Jorasses (4208m), reaching a vertical drop as high as 700m. It drains in Val Ferret, in the Aosta valley region.

Grandes Jorasses Glacier: this (part of RGI60-11.02991) is a small (Area: 0.482km2) glacier located in the Italian part of the Mont Blanc massif. It is mapped as a single glacier together with Planpincieux glacier in the Randolph Glacier inventory but it is classified as a single glacial complex in the Italian glacier inventory (Smiraglia, 2015). Its aspect is mostly south-east and its accumulation area is overlooked by Grandes Jorasses (4208m) from which the glacier originates with almost no cirque. It drains in Val Ferret, in the Aosta valley region.

Pra-Sec Glacier: this (RGI60-11.02996) is a small (Area: 0.119km2) glacier located in the Italian part of the Mont Blanc massif. Its aspect is mostly south-east and its accumulation area is overlooked by rock faces from Grandes Jorasses (4208m), reaching a vertical drop as high as 1000m. It drains in Val Ferret, in the Aosta valley region.

Rochefort Glacier: this (RGI60-11.03000) is a small (Area: 0.558km2) glacier located in the Italian part of the Mont Blanc massif. Its aspect is mostly south and its accumulation area is overlooked by rock faces from Dent du Géant (4014m), reaching a vertical drop as high as 900m. It drains in Val Ferret, in the Aosta valley region.

Brenva Glacier: this (RGI60-11.03001) is a large (Area: 6.579km2) glacier located in the Italian part of the Mont Blanc massif. Despite a unique glacial complex reaching as low as 1400m, as mapped in the Randolph glacier inventory, since 2005 it has separated into a lower stagnant tongue and a higher part. Its aspect is mostly south-east and its accumulation area is overlooked by the Mont Blanc summit (4809m). Huge cirque head rockwalls dominate the accumulation areas towards Mont Maudit (4465m) on the eastern part and towards Aiguille Blanche de Peuterey (4112m) on the western side. It drains in Val Veny, in the Aosta valley region.

Thoula Glacier: this (RGI60-11.03002) is a small (Area: 0.580km2) glacier located in the Italian part of the Mont Blanc massif. Its aspect is mostly south-east and its accumulation area is overlooked by rock faces from Aiguille d’Entrèves (3596m), reaching a vertical drop as high as 400m. It drains in Val Ferret, in the Aosta valley region.

Mont Blanc Glacier: this (part of RGI60-11.03005 - Miage Glacier complex) is a medium-sized (Area: 0.764km2) glacier located in the Italian part of the Mont Blanc massif. As mapped in the Randolph glacier inventory and other glacier inventories, it is a tributary of the large Miage Glacier complex. Even though it is part of the same glacier for inventory purposes, it has both a particular distinct behaviour in terms of cinematics and it has its own topographical designation in cartographies from all of the three bordering nations. Therefore, manual digitalisation of the glacier area was carried out based on Sentinel-2 Satellite Imagery. Its aspect is mostly south-east and its accumulation area is overlooked by the Mont Blanc summit (4809m). Huge cirque head rock walls dominate the accumulation areas towards Mont Maudit (4465m) on the eastern part and towards Aiguille Blanche de Peuterey (4112m) on the western side. It drains in Val Veny, in the Aosta valley region.

Dome Glacier: this (part of RGI60-11.03005 - Miage Glacier complex) is a medium-sized (Area: 1.973km2) glacier located in the Italian part of the Mont Blanc massif. As for the Mont Blanc Glacier, as a tributary of the large Miage Glacier complex, it has been remapped in order to obtain morphometrical information of the single glacial body. Its aspect is mostly south-west and its accumulation area is overlooked by the Dome du Gouter summit (4304m) in the western part and by the Mont Blanc summit (4809m) in the eastern part. It drains in Val Veny, in the Aosta valley region.

Bionassay Glacier (Italian – it has an homonymous in France): this (part of RGI60-11.03005 - Miage Glacier complex) is a medium-sized (Area: 1.354km2) glacier located in the Italian part of the Mont Blanc massif. The Mont Blanc and Dome Glaciers, as a tributary of the large Miage Glacier complex, was remapped in order to obtain morphometrical information of the single glacial body. Its aspect is mostly south-west and its accumulation area is overlooked by Dome du Gouter summit (4304m). It drains in Val Veny, in the Aosta valley region.

Tré-la-Tête N Glacier (Italian – it has a homonymous in France): this (part of RGI60-11.03005 - Miage Glacier complex) is a medium-sized (Area: 0.312km2) glacier is located in the Italian part of the Mont Blanc massif. The Mont Blanc, Bionassay and Dome Glaciers, as a tributary of the large Miage Glacier complex, was remapped in order to obtain morphometrical information of the single glacial body. Its aspect is mostly north-east and its accumulation area is overlooked by Aiguille de Tré-la-Tête (3920m). It drains in Val Veny, in the Aosta Valley region.

Freney Glacier: this (RGI60-11.03013) is a medium-sized (Area: 1,017km2) glacier located in the Italian part of the Mont Blanc massif. Its aspect is mostly south-east and its accumulation area is overlooked by the Mont Blanc summit (4809m). Huge cirque head rockwalls dominate the accumulation areas. It drains in Val Veny, in the Aosta valley region.

Brouillard Glacier: this (RGI60-11.03014) is a medium-sized (Area: 1.166km2) glacier located in the Italian part of the Mont Blanc massif. Its aspect is mostly south and its accumulation area is overlooked by the Mont Blanc summit (4809m). Huge cirque head rockwalls dominate the accumulation areas. It drains in Val Veny, in the Aosta valley region.

Lex Blanche Glacier: this (RGI60-11.03020) is a medium-sized (Area: 2.640km2) glacier located in the Italian part of the Mont Blanc massif. Its aspect is mostly south-east and its accumulation area is overlooked by Aiguilles de Tré-la-Tète (3923m). Cirque head rockwalls dominate the accumulation areas by as much as 600-700m. It drains in Val Veny, in the Aosta valley region.

Petit Mont Blanc Glacier: this (Part of RGI60-11.03020 – Lex Blanche Glacier) is a small (Area: 0.556km2) glacier located in the Italian part of the Mont Blanc massif. It is mapped in the RGI as a unique glacier complex together with the Lex Blanche Glacier (RGI60-11.03020). Its aspect is mostly south and its accumulation area originates at Aiguille de Tré-la-Tète (3920m). It drains in Val Veny, in the Aosta valley region.

Estelette Glacier: this (RGI60-11.03022) is a small (Area: 0.291km2) glacier located in the Italian part of the Mont Blanc massif. Its aspect is mostly south-east and its accumulation area is overlooked by Aiguille des Glaciers (3815m). Cirque head rockwalls dominate the accumulation areas by as much as 600m. It drains in Val Veny, in the Aosta valley region.

Pierre Joseph Glacier: this (RGI60-11.03258) is a small (Area: 0.275km2) glacier located in the French part of the Mont Blanc massif. Its aspect is mostly south-west and it originates from Aiguille de Talèfre (3730m) with rockwalls as high as 400m. It drains in the Isère valley, in the Haute Savoie Département.

Nant Blanc Glacier: this (RGI60-11.03263) is a small (Area: 0.363km2) glacier located in the French part of the Mont Blanc massif. Its aspect is mostly west and it is overlooked by Aiguille Verte (4122m) with up to 800m of cirque headwalls. It drains in the Isère valley, in the Haute Savoie Département.

Charpoua Glacier: this (RGI60-11.03284) is a small (Area: 0.405km2) glacier located in the French part of the Mont Blanc massif. Its aspect is mostly south-west and its accumulation area is overlooked by high rock faces from Aiguille Verte (4122m), reaching a vertical drop as high as 700m. It drains in the Vallée de l'Arve, in the Haute Savoie Département.

Aiguille des Glaciers Glacier: this (RGI60-11.03339) is a small (Area: 1.091km2) glacier located in the French part of the Mont Blanc massif. Its aspect is mostly south and it originates straight from the very top of Aiguille des Glaciers (3815m). It drains in the Isère valley, in the Haute Savoie Département.

Talèfre Glacier N: this (RGI60-11.03466) is a medium-sized (Area: 2.037km2) glacier located in the French part of the Mont Blanc massif. We concentrated the study on the westernmost part of the glacier that we mapped accordingly, as it is now almost totally disconnected from the rest of the Talèfre Glacier. It originates from the foot of Aiguille Verte (4122m) with up to 600m of cirque headwalls. It drains in the Vallée de l'Arve, in the Haute Savoie Département.

Argentière Glacier: this (RGI60-11.03638) is a large (Area: 13.109km2) glacier located in the French part of the Mont Blanc massif. It originates from the ridges in between Aiguille de Triolet (3870m) and Mont Dolent (3823m). It drains in the Vallée de l'Arve, in the Haute Savoie Département.

Mer de Glace Glacier: this (RGI60-11.03646) is a large (Area: 23.556km2) glacier located in the French part of the Mont Blanc massif. It originates from a large accumulation area comprised in between Col du Midi (3522m), Mont Blanc du Tacul (4248m) and Dent du Géant (4014m). It drains in the Vallée de l'Arve, in the Haute Savoie Département.

Bossons Glacier: this (RGI60-11.03646) is a large (Area: 11.319km2) glacier located in the French part of the Mont Blanc massif. It originates straight from the very top of the Mont Blanc summit (4809m). It drains in the Vallée de l'Arve, in the Haute Savoie Département.

Taconnaz Glacier: this (RGI60-11.03647) is a medium-sized (Area: 4,898km2) glacier located in the French part of the Mont Blanc massif. Its aspect is mostly north and it originates straight from the very top of Dome du Gouter (4304m). It drains in the Vallée de l'Arve, in the Haute Savoie Département.

Bionassay Glacier (FR): this (RGI60-11.03648) is a small (Area: 4.774km2) glacier located in the French part of the Mont Blanc massif. Its aspect is mostly north-east and, like the Taconnaz Glacier, it originates straight from the very top of Dome du Gouter (4304m). It drains in the Vallée de l'Arve, in the Haute Savoie Département.

S2. Map of the sampling areas to extract the time series of velocity

In order to extract velocity time series, sampling areas were defined according to the procedure highlighted in the methods section of the manuscript. Sampling areas of all the selected glaciers in the study are highlighted in Fig. S1.

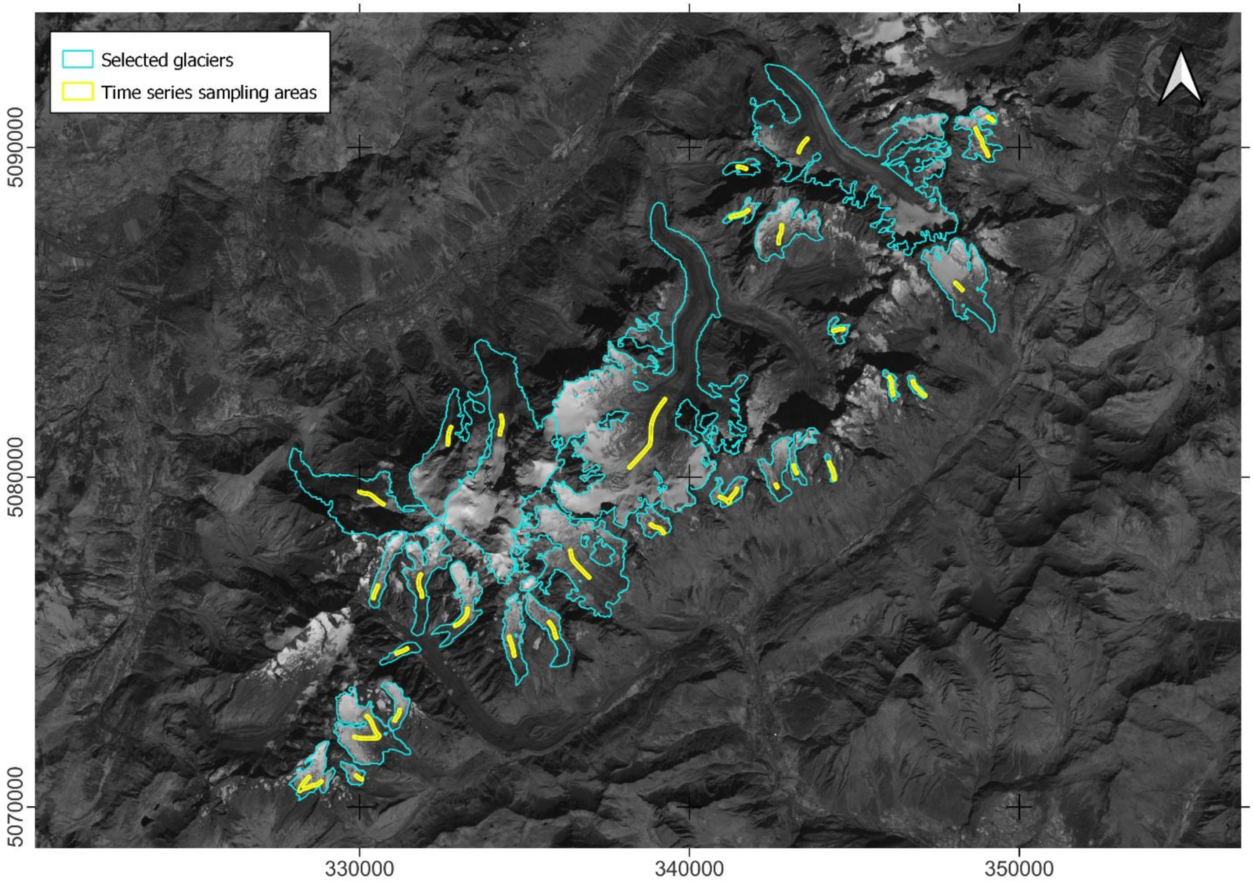

Fig S1. Sampling areas of all the selected glaciers in the study highlighted in yellow. Glacier outlines of single glacier are highlighted in cyan.

S3. Mean average velocity map of Mont Blanc 2016-2023 with velocity mapping of ice-free terrain.

To give a representation for the reader about data quality outside glaciated terrain, we hereby show in Fig. S2 a map with mean average velocity map of Mont Blanc 2016-2023 with velocity mapping of ice-free terrain.

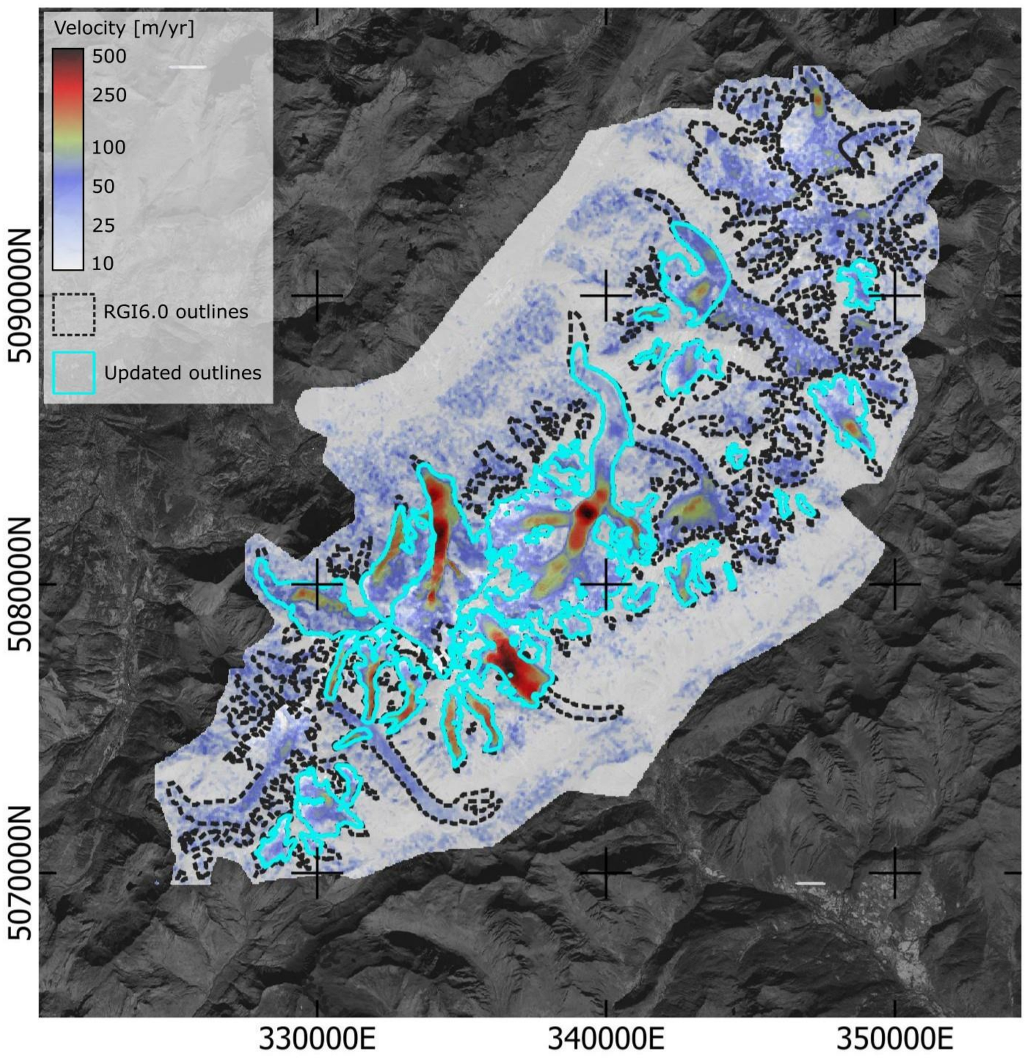

Fig S2. Surface glacier velocity map averaged in the 2016-2023 period. Selected glaciers for specific analyses are outlined in cyan.

S4. Comparison of velocity time series with data from Rabatel et al. (2023)

We performed a specific comparison with the data published by Rabatel et al. (2023). To do so, we chose four glaciers that could show well-defined seasonal variability and general trends. To compare the data, we considered the overlapping period 2016-2021. Plus, we discarded from the Rabatel dataset the velocities obtained from intervals lower than 10 days and larger than 120 days, as we did in our study. Moreover, we calculated the monthly velocities data. The comparison is shown in Fig. S3 and Table S1. The absolute values of the velocities find a good agreement between the two datasets, as well as the seasonal fluctuations that are of similar amplitude and have comparable timing of the velocity peaks, on Brenva glacier in particular. The accelerating trend noticed at Brenva and Brouillard glaciers is evident in both datasets.

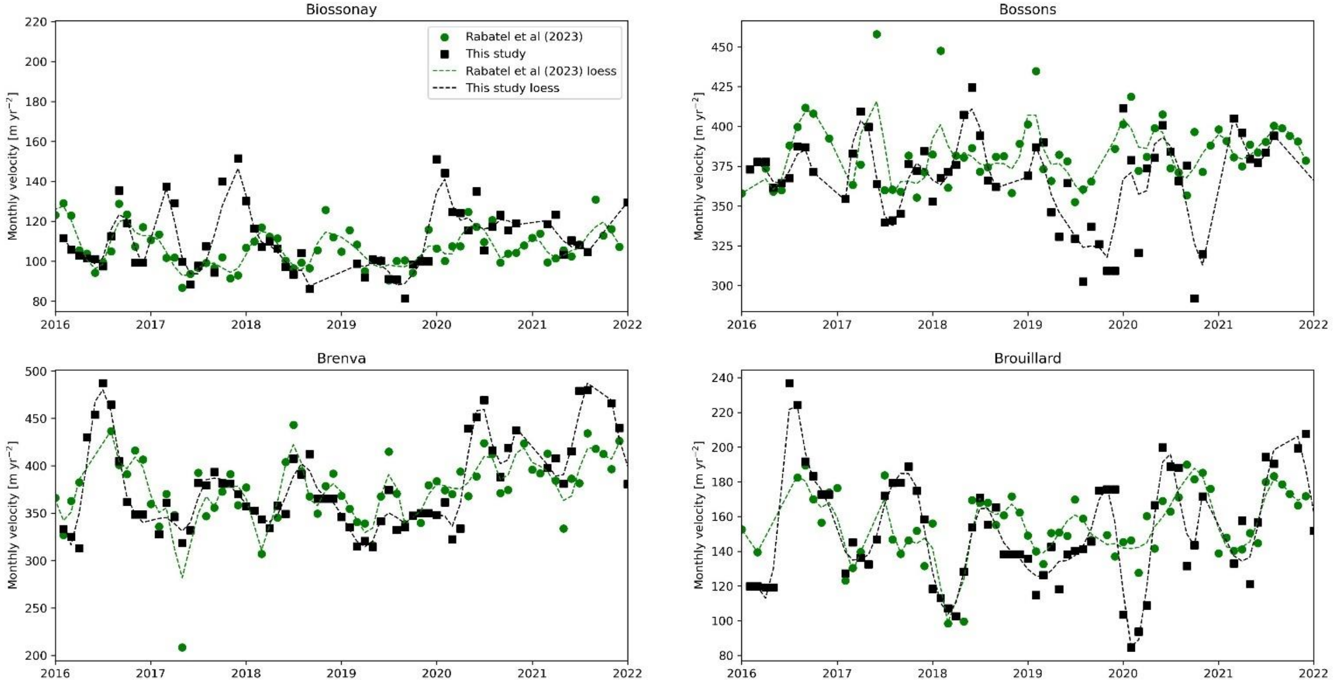

Fig S3. Surface glacier velocity time series comparison between data from this study and data from Rabatel et al. (2023) over the 2016-2021 period.

Table S1 reports the root mean squared deviation (RMSD), median absolute deviation (MAD), Pearson correlation coefficient (CORR) with the p-value CORR in brackets between the dataset of Rabatel et al (2023) and the present study, and the linear trend of annual velocity variation of this study (trend Troilo) and that of Rabatel et al (2023) (Trend Rabatel) considering raw and smoothed values.

	Bionassay (FR)	Bossons	Brenva	Brouillard
RMSD raw	17.3 m	34.6 m	39.0 m	27.0 m
MAD raw	8.0 m	19.4 m	26.2 m	22.4 m
CORR raw	0.26 (0.06)	0.24 (0.08)	0.57 ($<10^{-4}$)	0.51 (0.0001)
RMSD loess	15.1 m	30.9 m	37.6 m	24.2 m
MAD loess	5.9 m	18.4 m	27.3 m	18.2 m
CORR loess	0.28 (0.04)	0.26 (0.06)	0.56 ($<10^{-4}$)	0.56 ($<10^{-4}$)
Trend Troilo	0.19 m yr^{-2}	-0.04 m yr^{-2}	0.85 m yr^{-2}	0.25 m yr^{-2}
Trend Rabatel	0.05 m yr^{-2}	0.18 m yr^{-2}	0.68 m yr^{-2}	0.26 m yr^{-2}

S5. GIV parameters set-up used in the processing

isgeotiff	'Yes'
minlat	-50.9640
maxlat	-50.8920
minlon	-73.7460
maxlon	-73.4730
temporaloversam...	2
parralelize	'Yes'
name	'Glacier Velocities 1'
numpass	'Multi'
snr	5
pkr	1.3000
windowoverlap	0.5000
idealresolution	40
searchwindowsize	30
minsearcharea	50
minyear	1900
maxyear	2050
minmonth	1
maxmonth	12
minday	1
maxday	31
mininterval	0.0190
maxinterval	0.7500
CLAHE	0
hipass	0
intenscap	0
NAOF	1
CLAHEsize	10
hipasssize	10
sobel	0
laplacian	0
savearrays	'Yes'
savekeyvel	'Yes'
savegeotiff	'Yes'
imageformat	'png'
maxvel	1500
excudedangle1	*1x1 struct*
excudedangle2	*1x1 struct*
stable	'Yes'
excludeangle	'No'
finalsmooth	'Time and Space'
nummonthiter	0
geotifflocationdata	*1x1 struct*
geotiffreference	*[ ]*
numimages	11
cropmask	*2822x2719 double*
realresolution	40
sizeraw	[2822,2719]
sizevel	[564,543]

S6. Meteorological conditions

To estimate the meteorological conditions during the period of study, we analysed the data of ERA5-Land monthly averaged data of temperature and precipitation. We calculated the mean monthly air temperature and precipitation and the robust linear trends over the period of study, considering the annual data (i.e., using all the months), the winter data (i.e., months from November to April) and summer months (i.e., from June to September). We averaged the data over the area 45.71°N–46.01°N and 6.60°E–7.10°E. We observed a slight increment in the temperature, more marked for summer months and a decrease in precipitation, especially in summer (Fig. S4).

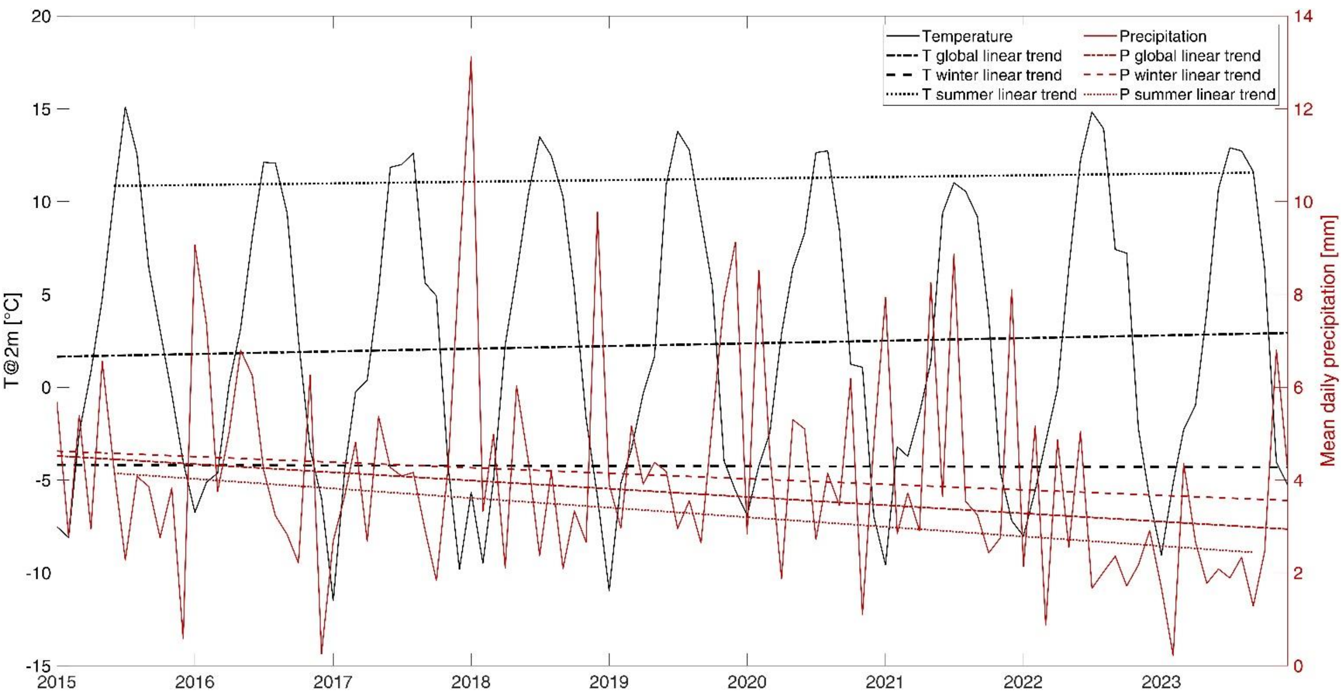

Fig. S4. Mean monthly temperature (black) and daily precipitation (red).

S7. Normalised time series of velocity

Fig. S5 presents the monthly velocities normalized by the median velocity of each glacier evaluated over the whole period. Glaciers such as Freney, Brouillard, and Bionassay (IT) show evident and regular seasonal behaviour and large winter/summer differences; in these cases, summer velocities (occurring between July and October) are 50% to 100% higher than winter ones (occurring between January and April). Another group of glaciers has smaller winter/summer differences or pronounced but irregular variability (e.g., Planpincieux, Pre de Bard, Talefre). A third group does not display evident or regular seasonal behaviour (e.g., Taconnaz, Mer de Glace, Pierre Joseph), with winter/summer differences below 10%.

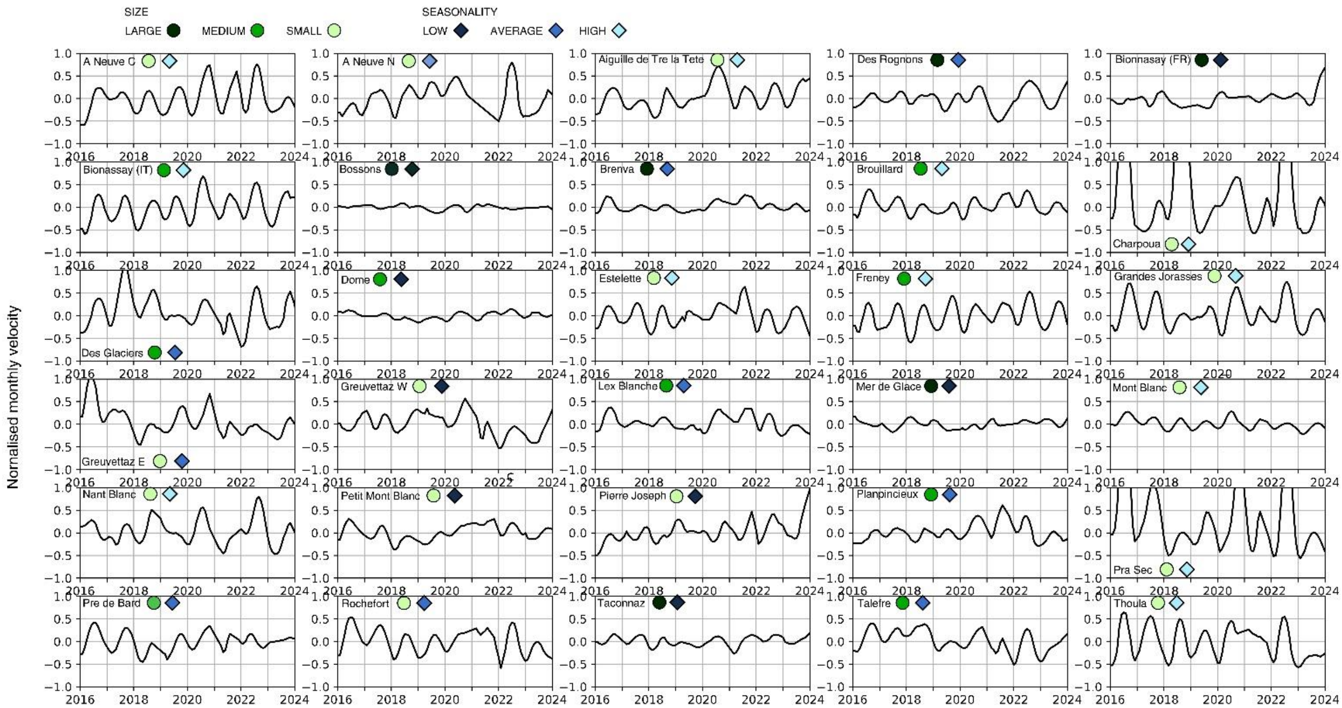

Fig S5. Normalised time series of velocity. The coloured markers indicate the size (green circles) and seasonal kinematics (blue diamonds).

S8. Repeat cycles of the image pairs used to calculate the monthly velocity

Image date	t1-t2 cycle	t1-t3 cycle
05/02/2016	50	90
26/03/2016	40	120
05/05/2016	80	90
24/07/2016	10	20
03/08/2016	10	20
13/08/2016	10	40
23/08/2016	30	70
22/09/2016	40	100
01/11/2016	60	
31/12/2016		
19/02/2017	20	30
11/03/2017	10	30
21/03/2017	20	30

10/04/2017	10	30
20/04/2017	20	60
10/05/2017	40	80
19/06/2017	40	60
29/07/2017	20	40
18/08/2017	20	50
07/09/2017	30	40
07/10/2017	10	25
17/10/2017	15	30
01/11/2017	15	20
16/11/2017		10
21/11/2017		15
26/11/2017	10	35
06/12/2017	25	
31/12/2017		
30/01/2018	20	50
19/02/2018	30	65
21/03/2018	35	85
25/04/2018	50	70
14/06/2018	20	35
04/07/2018	15	25
19/07/2018	10	40
29/07/2018	30	45
28/08/2018	15	25
12/09/2018	10	125
22/09/2018	115	125
15/01/2019	10	30
25/01/2019	20	30
14/02/2019	10	30
24/02/2019	20	40
16/03/2019	20	45
05/04/2019	25	60
30/04/2019	35	60
04/06/2019	25	40
29/06/2019	15	75
14/07/2019	60	75
12/09/2019	15	25
27/09/2019	10	70
07/10/2019	60	

06/12/2019		
05/01/2020	25	35
30/01/2020	10	25
09/02/2020	15	65
24/02/2020	50	70
14/04/2020	20	70
04/05/2020	50	100
23/06/2020	50	85
12/08/2020	35	85
16/09/2020	50	70
05/11/2020	20	
25/11/2020		
28/02/2021	25	30
25/03/2021		15
30/03/2021	10	25
09/04/2021	15	65
24/04/2021	50	85
13/06/2021	35	40
18/07/2021		30
23/07/2021	25	35
17/08/2021	10	15
27/08/2021		15
01/09/2021	10	20
11/09/2021	10	35
21/09/2021	25	45
16/10/2021	20	60
05/11/2021	40	70
15/12/2021	30	60
14/01/2022	30	50
13/02/2022	20	50
05/03/2022	30	55
04/04/2022	25	40
29/04/2022	15	50
14/05/2022	35	50
18/06/2022	15	20
03/07/2022		15
08/07/2022	10	25
18/07/2022	15	25
02/08/2022	10	30

12/08/2022	20	40
01/09/2022	20	35
21/09/2022	15	20
06/10/2022		20
11/10/2022	15	30
26/10/2022	15	
10/11/2022		
19/01/2023	15	30
03/02/2023	15	30
18/02/2023	15	30
05/03/2023	15	35
20/03/2023	20	30
09/04/2023	10	25
19/04/2023	15	70
04/05/2023	55	60
28/06/2023		40
03/07/2023	35	50
07/08/2023	15	30
22/08/2023	15	35
06/09/2023	20	25
26/09/2023		15
01/10/2023	10	75
11/10/2023	65	75
15/12/2023	10	15
25/12/2023		40
30/12/2023	35	45
03/02/2024	10	
13/02/2024		

1)