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Morphodynamics of the Mont Blanc glaciers and their recent evolution

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Abstract. The surface velocity of glaciers is a key parameter that provides fundamental information on glacier dynamics and their adaptation to changes in climate; moreover, ice velocity measurements are a very important parameter for modelling glacier physics and their evolution. While a few decades ago ice velocity would rely on point measurements performed in the field, the processing of high temporal and spatial resolution information from satellites nowadays provides new insights and a vast quantity of data, on a global scale, for the measurement of ice velocity. As of today, few studies have been performed in Alpine regions, and rarely has the focus been on ice velocity evolution. In the present study, we analyse the average monthly velocities on Alpine glaciers in the Mont Blanc massif. Seven years of Sentinel-2 optical satellite imagery have been processed to obtain ice velocity data. The main objectives of the study are: (i) to characterise the variability of the velocity fields of such glaciers, referring both to their temporal (seasonal and interannual) and spatial variations; (ii) to find relationships between the morphology of glaciers and their kinematics. We measured the monthly velocities of thirty glaciers varying from 18.0 m yr^{-1} to 436.3 m yr^{-1}, highlighting a breakpoint in the trends in 2020. This led to the identification of 13 glaciers showing variation of more than 20.0 m yr^{-2} between 2020 and 2022 compared to the previous years. We identified five clusters of morpho-dynamic characteristics, thus describing five different glacier type classes.

1 Introduction

Glacier flow has been one of the early drivers of glaciological interest and research since it was first studied. Its understanding and modelling evolved via the observations and findings of Somigliana in the early 1900s, Glen's laboratory experiments (Glen, 1952), followed by the interpretations of Nye (Nye, 1952) during the 1950s, to cite just a few, and have explained that the two main mechanisms of glacier flow rely on ice deformation and basal sliding. However, the motion of Alpine glaciers is largely related to basal sliding (Willis, 1995). Continuous monitoring of sliding velocities is extremely difficult and rarely achieved (Vincent and Moreau, 2016), but also the continuous monitoring of surface velocities of Alpine glaciers is complex on specific study sites, and very rarely has it been performed on a spatially distributed scale.
The flow of glaciers generally depends on a variety of physical parameters: ice thickness, which is the main driver of ice flow (Jiskoot 2011), and is related indirectly to the glacier trend in mass balance as it determines an evolution towards increase or decrease in glacier thickness; the glacier surface slope which is the other fundamental driver of ice flow; other parameters that influence ice flow are: ice properties (temperature, density), bedrock conditions (hard, soft, frozen or thawed ice-bed contact), topography, the glacier's terminal area type (land, sea, ice shelf), but also air temperature and precipitation and their seasonality that influences subglacial hydrology (Jiskoot, 2011; Humbert et al., 2005; Cuffey and Paterson, 2010; Benn and Evans, 2014; Bindschadler, 1983).

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

The analysis of glacier surface displacements is often measured as a proxy of ice flow and has a wide array of applications: it is a powerful climate change indicator (Beniston et al., 2018). It is also an important input data for global ice thickness models (Millan et al., 2022; Samsonov et al., 2021) which estimate global freshwater resources and global mass balance models that can also approximate sea-level rise contribution by glaciers (Zekollari et al., 2019). In the field of glacial hazards, it is used as a proxy for the detection of glacier surges (Kamb, 1987; Kääb et al., 2021), and accelerations that can result in glacier-related hazards (Pralong and Funk, 2006; Giordan et al., 2020). Measurements of the surface velocity of glaciers can be achieved by terrestrial techniques (Dematteis et al., 2021) such as topographic measurements of stakes or fixed points on the glacier (Stocker-Waldhuber et al., 2019), GNSS repeated or continuous surveys (Einarsson et al., 2016), digital image correlation of oblique photographs (Evans, 2000; Ahn and Box, 2010) and terrestrial radar interferometry (Luzi et al., 2007; Allstadt et al., 2015).

Considering remote sensing solutions, glacier surface velocities can be measured by a variety of aerial and space borne sensors. In recent decades, public access to satellite optical and radar data (especially from Sentinel and Landsat constellation satellites), as well as the commercial availability of very high resolution (30 cm to 1 m ground resolution) optical imagery (Deilami and Hashim, 2011) and radar data (Rankl et al., 2014), have given great input to glaciological research. In particular, Sentinel-2 optical imagery is widely used in glaciological studies and has been tested in literature on various environments (Paul et al., 2016; Millan et al., 2019). Nowadays, the automated processing of ice velocity maps with global coverage from satellite imagery is freely available online from web-based platforms such as the Golive datasets (Fahnestock et al., 2016), the ITS Live dataportal (https://its-live.jpl.nasa.gov/) or the FAU-Glacier portal (RETREAT, 2021 Ice surface velocities derived from Sentinel-1, Version 1; http://retreat.geographie.uni-erlangen.de/search). The availability of such datasets is very relevant globally, but its application to Alpine glaciers is limited due to its relatively coarse spatial resolution - e.g., 300x300 m (GOlive), 120x120 m (ITS live) - which can provide data on just few of the largest Alpine glaciers. The adopted resolution is a trade-off between computational effort and best resolution of the output that must cope with the global availability of the analysis. Limiting the processing of images at a regional scale decreases the computational effort compared to global products and makes it easier to obtain higher resolution velocity maps that allows Alpine glaciers to be investigated (Berthier et al., 2005), even though very small glaciers (i.e., width <250 m) are still difficult to analyse (Millan et al., 2019).

Recent studies using different techniques have measured spatio-temporal variations of ice velocity on large valley glaciers in an Alpine environment (Argentière Glacier) (Vincent and Moreau, 2016) (Miage Glacier) (Fyffe, 2012) as well as on steep glacier snouts (Planpincieux Glacier) (Giordan et al., 2020) but a spatially distributed analysis, at a regional scale, of the variations of velocities over glaciers with different morphological characteristics is, as of today, still lacking in the Alpine environment.

The main purposes of this study are the production of seven year-long velocity time series of surface velocity of thirty glaciers at a massif scale, as well as an integrated analysis of morphological and kinematic features of such glaciers. The identification of possible trends in the velocity time series, and a classification based on kinematic and morphological features, are major objectives of the present study. We analysed seven years of Sentinel-2 optical imagery to retrieve monthly velocity data on thirty glaciers in the Mont Blanc massif. We describe different patterns and behaviours of surface; subsequently, a classification based on velocity and morphometric features is proposed.

2 Area of study

The study area is the Mont Blanc massif. It is located in the western part of the European Alps bordering France, Italy and Switzerland (Figure 1) and culminating at 4809 m with the Mont Blanc summit; the highest peak in Central Europe. Many

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

other peaks in the Mont Blanc massif reach well above 4000 m and the entire area is very highly frequented with famous tourist resorts such as Courmayeur and Chamonix attracting thousands of tourists every year.

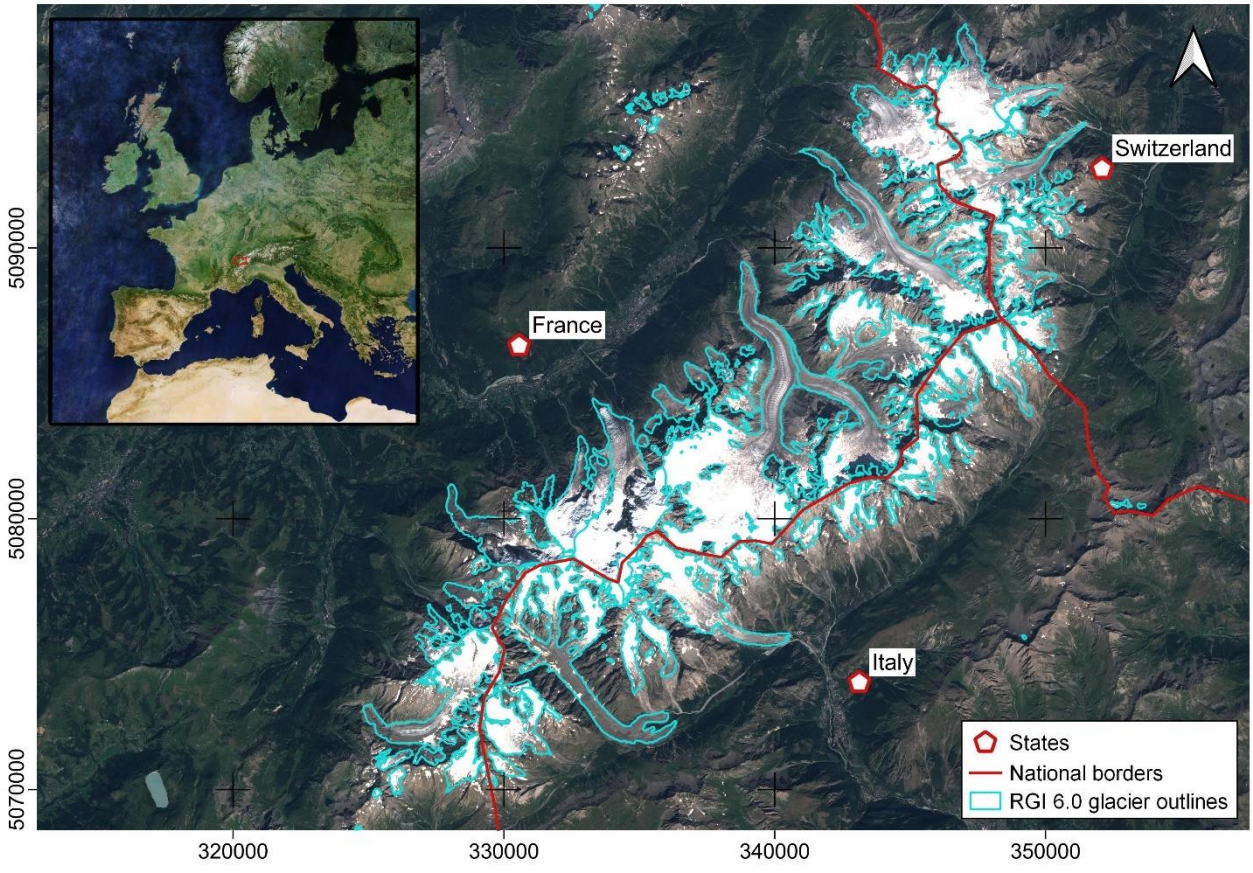


Figure 1. Study area of the Mont Blanc massif. Background: true colour image (cloud-free Europe mosaic in upper left panel), courtesy of the Copernicus Open Access Hub (https://scihub.copernicus.eu, last access: 10 September 2023).

The total surface of glaciers in the Mont Blanc massif is equal to 169 km^2 and totals 116 glaciers, according to the Randolph glacier inventory (RGI) 6.0 data which refers to 2003 (Pfeffer et al., 2014; Arendt et al., 2017). Seventy-six glaciers are very small, covering an area of less than 0.1 km^2, twenty-eight glaciers fall in the range between 1 km^2 and 5 km^2, and twelve glaciers have surface areas of more than 5 km^2.

The geological setting and the geomorphology of the Mont Blanc massif forms a high mountain range with its main ridge line oriented in a south-west/north-east direction along the French-Italian border. The valley floors flanking the massif have low altitudes - in the range of 1000-1500 m - resulting in steep slopes originating from the highest peaks with large vertical altitudinal differences. The meteo-climatic local conditions on the massif are of a continental type, but orographic effects on the predominant incoming weather fronts mean larger amounts of local precipitation compared to nearby regions (Gottardi et al., 2012).

The Argentière Glacier is the only glacier with regular mass balance measurements included in the WGMS 'Reference Glaciers' dataset in the Mont Blanc massif (Zemp et al., 2009). The Argentière Glacier has shown a general negative mass

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

balance trend since the early 1990s, in line with mass balances of other Alpine glaciers and glaciers from other mountain ranges across the globe. Geodetic mass balance measurements of the Thoula Glacier, a small glacier on the border between France and Italy at altitudes between 2900 and 3300m, represent well the local meteo-climatic conditions that result in slightly less negative mass balance trends compared to other glaciers in the Alps (Zemp et al., 2021; Zemp et al., 2020; Mondardini et al., 2021).

A more spatially distributed analysis of mass balances in the Mont Blanc region has also been outlined in the literature by means of geodetic mass balances of the whole Mont Blanc massif using stereo satellite imagery from the Pléiades and Spot satellite constellations (Berthier et al., 2014; Beraud et al., 2023). The trend outlined by Berthier (2014) at the massif scale, reflects data trends comparable to the glaciological mass balances of WGMG reference glaciers in the Alps. Locally, glaciers at a very low altitude show large ice volume losses and subsequent substantial glacier front retreats (Paul et al., 2020), while glaciers at higher altitudes suffer less acute volume loss and shrinkage. Large differences in the glacier frontal position, especially for the lower altitude terminating glaciers, can be well assessed by the difference of the terminus position in recent satellite imagery compared to the position outlined on the Randolph Glacier Inventory (RGI).

3 Materials

In this paper, we analysed the Copernicus - ESA Sentinel-2 optical satellite imagery dataset available for the study area. In addition to the above-mentioned dataset, we used Airbus Pleiades Stereo derived digital elevation models (DEMs) for the morphometric analysis of glaciers, and publicly available modelled ice thickness data from Millan et al. (Millan et al., 2022).

3.1 Sentinel-2 optical satellite imagery

The Sentinel-2 mission is composed of twin satellites - Sentinel-2A and Sentinel-2B - orbiting on sun-synchronous orbits at an altitude of 786 km. Free availability of thirteen multispectral bands (443 nm-2190 nm central wavelengths) with ground resolutions ranging between 10 m and 60 m, and a revisit time as low as three days for some areas (five days for most areas), as well as global coverage, make this product a very important resource for glaciological studies. In particular, Sentinel-2 near infrared band B08 processing level L1C is used for the application of feature tracking on glacial surfaces, as suggested by previous studies (Kääb et al., 2016). Based on different publications (Kääb et al., 2016; Millan et al., 2019), the geometric error of Sentinel-2 can show up to 1.5 pixel offsets in the horizontal plane. Therefore, an image co-registration process is normally needed for multitemporal analyses.

In the present study, a set of 108 images between 5 February 2016 and 10 November 2022, covering the whole study area, was adopted (GRANULE T32TLR, relative orbit 108). Such images, named ‘tiles’, are ~110x110 km^2 ortho-images in UTM/WGS84 projection.

3.2 Morphometric analysis data

Morphometric analysis of sample glaciers was performed using altitudinal data from a 1m resolution DEM obtained by the processing of Pleaides stereo pairs from August 2018 (Berthier et al., 2014). Mean glacier thicknesses were extrapolated from globally modelled ice thickness data published by Millan et al. (Millan et al., 2022).

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

4 Methods

We used digital image correlation to produce monthly-averaged and multi-year averaged velocity maps to investigate variations of glacier surface velocity in time and in space over the selected glaciers. We can hereby summarize the workflow that was used (Figure 2):

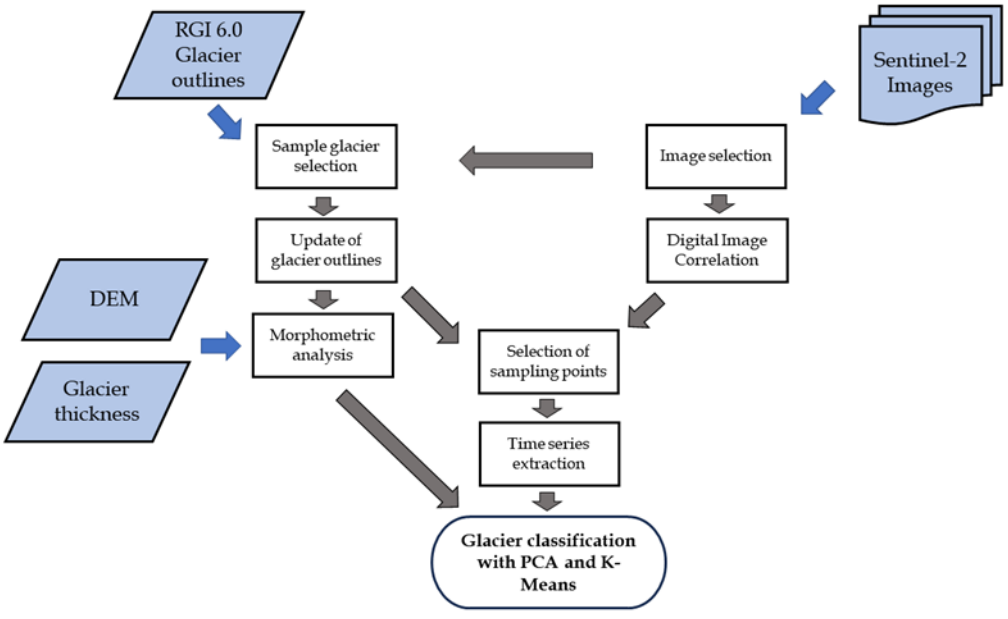


Figure 2. Workflow of the present study. The input datasets are evidenced in light blue while the processing steps are indicated in grey.

The input data are a DEM of the area of study, the RGI glacier outlines, the modelled glacier thickness and the stack of Sentinel-2 images in the reference period. The input DEM is used to obtain morphometric parameters of the glacier while the RGI glacier outlines are used, together with the selected satellite imagery, to choose suitable glaciers for surface glacier velocity analysis. After the glacier selection, we updated the RGI glacier outlines. Selected imagery is processed with digital image correlation to obtain glacier velocities. The glacier surface velocity maps are then used, together with the updated glacier outlines, to identify suitable areas and sampling points to extract velocity time series. Time series are analysed to identify general trends, seasonal patterns or particular kinematic behaviours. Finally, the velocity dataset and the morphometric parameters are analysed with a principal component analysis (PCA); subsequently, the principal components (PCs) are clustered using a K-means analysis to determine different classes of glacier based on their morpho-dynamic features.

4.1 Sentinel-2 image selection

To select the images, we considered two elements: (i) to maximize the geometric and geo-referencing precision, we adopted images acquired from the same orbit; (ii) to reduce the impact of clouds, we carried out a visual check of all images with a cloud cover percentage lower than 90% (as detected by the Copernicus cloud cover estimation algorithm) on the whole tile. We adopted this manual selection to maximize the number of available images; in the case of the Mont Blanc massif (like in

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

most mountainous areas worldwide), the local distribution of clouds can be extremely variable; in many cases, this can contribute to a considerable cloud percentage, even though high altitude areas may still be cloud-free.

4.2 Glacier selection

In the Mont Blanc massif, the presence of high-altitude accumulation areas, together with steep slopes, results in a significant number of very active glaciers with high average velocities in a relatively small region. In the present study, we selected a set of glaciers and investigated their surface velocity.
To minimize the presence of noisy and unreliable velocity data, we performed a selection of glaciers from the RGI 6.0 dataset. In particular, we did not include in our study:
A) glaciers with area < 0.1 km^2, as those glaciers would be too small for the reliable extraction of velocity maps with 10 m resolution optical satellite imagery (Millan et al., 2019).
B) glaciers showing strong variations of cast shadow.
C) glaciers that lack surface features to be tracked (e.g., ice caps).
Selection of point B) was made by creating a stack of images acquired between October and March, when cast shadows appear on satellite imagery, especially on north facing slopes. Subsequently, we manually individuated glaciers that are subject to large variations of shadow on their surface. We used the scene classification map (SCL) class 11 (cast shadows), available in processing level L2A of the Sentinel-2 images. However, since shadows on glaciers may often be misclassified in wintry conditions, we conducted a manual check to correct potential errors.
Selection of point C) is made manually by selecting glaciers that show very even surfaces on Sentinel-2 images. This is normally noted in ice caps at higher altitudes.

4.3 Glaciers' outline delineation

To analyse glacier areas and have an up-to-date mapping of glacier areas, we updated RGI 6.0 glacier outlines in order to fit with the glacier extensions that can be observed and manually outlined from Sentinel-2 imagery. We selected a cloud-free scene acquired on 28 August 2018 that represents well the conditions of the glaciers in the study period; True Color Image was used for this purpose. In some cases, a morphological indication that some parts of the glaciers could be considered independently from others in a division of kinematic domains was individuated (Paul et al., 2022; Zemp et al., 2021). As the kinematic analysis confirmed distinct behaviours of some glacier parts, those glaciers were mapped accordingly. The main examples of this are the tributary glaciers of the larger Miage Glacier complex, which all have distinct kinematic behaviour, well differentiated from the slow-moving, debris-covered main central valley tongue. Another example is present at Talèfre Glacier, where, over the past twenty years, the western part of the glacier has become totally independent from the eastern section so it made sense to consider it as a single glacier as of the RGI mapping of 2003. However, it should be considered independently in this study and consequently mapped.

4.4 Glaciers' morphometric analysis

The morphology that characterizes the glaciers selected in this study was analysed with the individuation of a series of key morphometric parameters:
1) the glacier planimetric surface (*Area*),
2) the glacier mean slope (*Slope*),
3) the glacier mean thickness (*Thickness*), obtained using the free dataset of Millan et al (Millan et al., 2022).

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

4) the glacier elongation evaluated as the ratio between glacier length and area (Shape).
5) the accumulation area ratio (*AAR*). The AAR is a common parameter used in glaciological studies to define the ratio between a snow-covered accumulation area and a bare ice ablation area of a specific glacier, at the end of the summer season. This gives an indication of the tendency of a glacier to tend towards stable or mass gain conditions or towards a mass loss condition (Cuffey and Paterson, 2010). AAR was obtained by mapping the snow accumulation areas on Sentinel-2 satellite images for every year between 2016 and 2022 at the end of the melting season. Subsequently, we calculated the average AAR for the study period.

4.5 Glaciers' surface velocity mapping

Digital image correlation is a common technique used to measure surface displacements using proximal (Evans, 2000; Ahn and Box, 2010; Schwalbe and Maas, 2017) and remotely sensed imagery (Scambos et al., 1992; Heid and Kääb, 2012b; Marsy et al., 2021; Dematteis and Giordan, 2021). The processing chain performed in the present study uses the open-source Glacier Image Velocimetry (GIV) toolbox (Van Wyk De Vries and Wickert, 2021). GIV uses frequency-based correlation, can process large datasets efficiently way and has been shown to perform well on glacier surface velocity measurements at different test sites (Van Wyk De Vries and Wickert, 2021). Co-registration of images is implemented in the GIV process chain using a stable area where potential shifts are estimated. To measure glacier surface velocities, we adopted the 'multi-pass' option which updates displacement estimates over multiple iterations, refining initial coarse chip size displacement calculations using progressively smaller chip sizes. The initial chip size is automatically defined by GIV and cannot be smaller than 32x32 px. Velocities higher than 1500 m yr^{-1} were considered as unrealistic and discarded. Grid spacing of the nodes in the displacement maps was set to 40 m. To produce the time series, given a specific image, we processed the first and second subsequent images (GIV order 2 time-oversampling). Then, the velocities of image pairs were averaged on a monthly basis. A temporal and spatial smoothing function was implemented in the processing algorithm and was used in the processing of data in this study.

4.6 Selection of sampling points

To analyse the time series that are representative of velocity variations of the selected glaciers, sampling points were identified on the velocity maps. The selection of sampling points for the time series extraction was carried out manually on the glacier surface, focusing on areas where velocity maps show high spatial coherence (Altena et al., 2019).
In some cases, the sampling points are not evenly distributed; when this occurred, the sampling points were located in areas that highlight velocity peaks (areas that show larger displacements than the surrounding areas) and high spatial coherence and that show no data voids (areas with unsuccessful image pair matching results in missing values). For each of the selected glaciers we analysed representative sectors: we extracted a variable number of sampling points ranging from 10 to 30 according to the glacier size and morphology.

4.7 Velocity time series extraction

Once we defined the sampling points for every selected glacier, we extracted the monthly time series of velocity by averaging the values of all the sampling points. Outliers' removal in the time series was performed via a manual check of the data.
We derived the velocity trend using an iteratively re-weighted least squares linear fit. To evaluate the significance of the fit coefficient, we consider the ratio between the coefficients and their standard errors; this equates to the t-statistics to test the null hypothesis that the corresponding coefficient is zero against the alternative that it is different from zero. That is, the lower the t-statics is, the lower the statistical significance of the obtained coefficient is.

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

Subsequently, we analysed a set of specific parameters:
A) GlobalAvg: the median global velocity during the whole considered period.
B) GlobalVar: the velocity min/max range (excluding the outliers $v < Q_1 - 1.5(Q_3 - Q_1)$ or $v > Q_3 + 1.5(Q_3 - Q_1)$, where Q1 are the first and third quartiles of monthly velocity)
C) SeasonalVar: the mean difference between the average velocities during the ablation season (i.e., from July to September) and the during the accumulation season (i.e., from December to April). The reference periods were chosen according to periods of acceleration and slow down measured at Planpincieux Glacier by Giordan et. Al (2020).
D) MaxAnom: the ratio between the maximum monthly velocity and GlobalAvg.

4.8 Glacier classification

We investigated the presence of distinct classes of glacier based on their morphodynamics using PCA and K-means clustering. PCA is a multivariate analysis technique that allows a reduction in the dimensionality of a given dataset, increasing interpretability but minimising information loss. This is achieved by creating new, uncorrelated variables that successively maximise the variance of the dataset (Jolliffe and Cadima, 2016). We applied PCA to the morphometric and kinematic features listed in Sections 4.3 and 4.7, respectively. Since PCA performs better with data of similar magnitude, we normalized the data by subtracting the mean and dividing it by the standard deviation (Figure S2).
The K-means clustering method is an unsupervised machine-learning technique used to identify clusters of data objects in a dataset. It is largely used in the analysis of remote-sensed data and earth observation data (Paradis, 2022). We applied the K-means algorithm to the two principal components (PCs), considering five classes.

5 Results

We obtained detailed kinematic data from thirty glaciers in the Mont Blanc massif. Different kinematic behaviours were analysed and compared to the morphometrics of the glaciers studied. Some particular seasonal kinematics were highlighted, and particularities in the average velocity trends observed. A brief description of all the glaciers we analysed is found in Appendix 1 to describe the location and geomorphological setting of the glaciers as well as highlight when a single glacier complex from the RGI inventory was divided into independent glacial bodies because of very distinct kinematic behaviour. We therefore detail all the results obtained in the present study in the following sections.

5.1 Sentinel-2 image selection

To select the Sentinel-2 images for glacier analysis, we discarded tiles with cloud cover, as detected by the Copernicus scene classification, of higher than 90% due to the low possibility of having cloud-free conditions in the study area. From 1 January 2016 to 31 December 2022, a total of 295 images with a could cover percentage lower than 90% was analysed. Of these images, 135 derive from Sentinel S2B and 160 from Sentinel S2A. From this dataset, we extracted a subset of 105 images that are cloud free on the selected glacier areas via the visual inspection of the individual images. The number of suitable images that are available per year varies from 10 to 21 with a yearly mean of 15 images in the following distribution: 2016: 10; 2017: 18; 2018: 10; 2019: 14; 2020: 11; 2021: 21; 2022: 21.
Year 2016, and partially 2017, is influenced by the lack of Sentinel 2B images. In fact, while Sentinel 2A was launched on 23 June 2015, Sentinel 2B was launched on 7 March 2017; image availability variations on the following years is influenced by

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

cloud cover at the time of scene acquisition. We chose to start the analysis from 2016 because it was the first full year of acquisition from the satellite.

5.2 Glacier velocity mapping and selection, outline delineation and morphometric analysis

The glacier selection process identified thirty glaciers with a total glacierised surface of 85.8 km^2. Compared to the total glacierised surface of the massif from RGI 6.0, this represents the covering of 50.8% of the total 169 km^2 and 25.9% in terms of number of glaciers; this rises to 39.5% if we consider the subset of seventy-six glaciers having a glacierised surface of more than 0.1 km^2. The selected glaciers are highlighted in Figure 3 and listed in Table 1, while a short description of each glacier is provided in the Supplementary. Two of the selected glaciers are located in Switzerland, ten are located in France and eighteen in Italy. This distribution is mainly due to a small portion of the massif being located in Switzerland and the presence of more fragmented glacierised bodies on the Italian side. Of the thirty glaciers, seven have been mapped as sub-areas in comparison to RGI individual glacier bodies.

In Figure 3 we present a velocity map with a resolution of 40 m (an masked over free-ice terrain in provided in Figure S1). This was obtained by averaging all the single monthly averaged velocity maps in the study period (2016-2022).

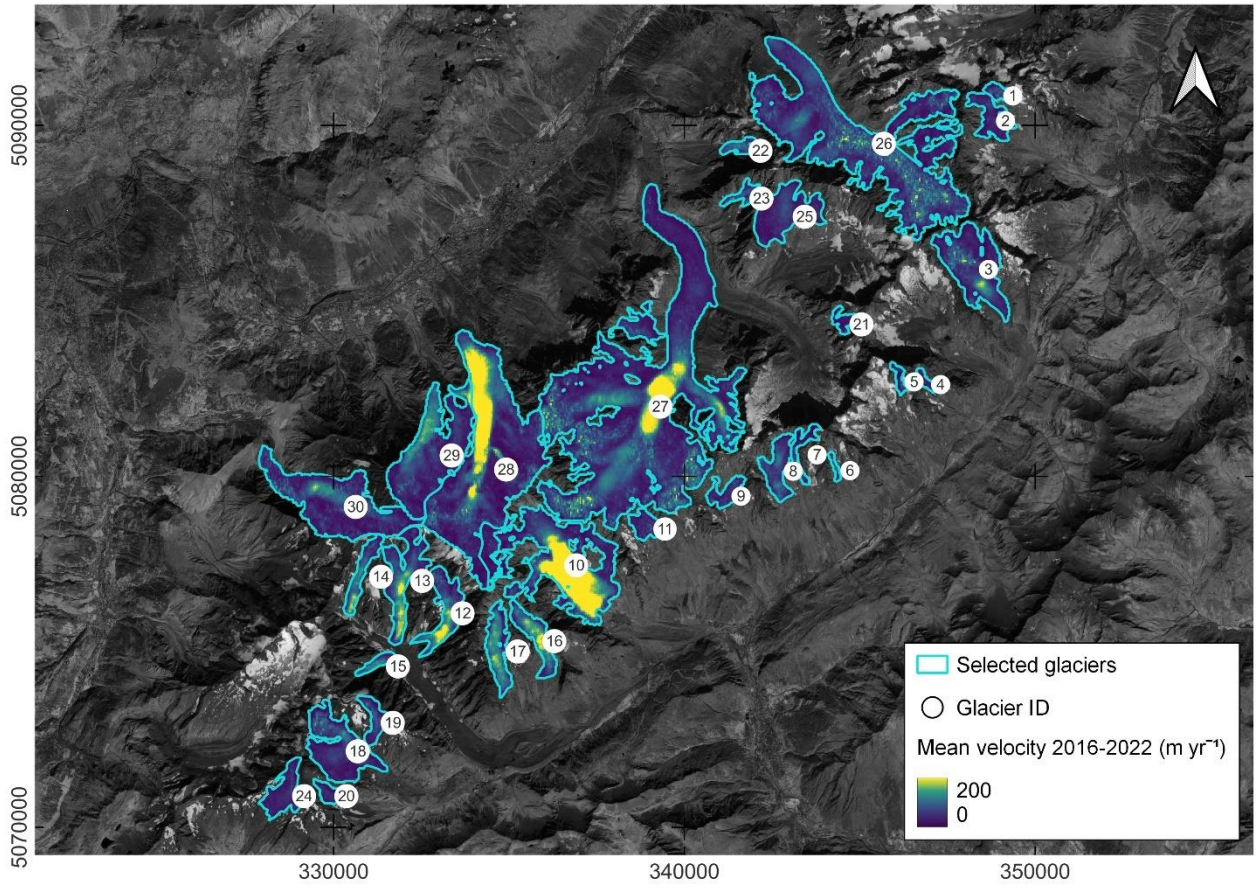


Figure 3. Surface glacier velocity map averaged in the 2016-2022 period. Selected glaciers for specific analyses are outlined in cyan. Background: Sentinel-2 image (B08 band), courtesy of the Copernicus Open Access Hub (https://scihub.copernicus.eu, last access: 10 September 2023).

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

Table 1. Name and identification codes of glaciers selected for analysis in the present study. Codes from RGI and IDs used for simplicity in this study together with main morphometric parameters analysed in this study.

Glacier name	ID	RGI 6.0 ID	Area (km^2)	Length (m)	Min alt (m asl)	Max alt (m asl)	Avg slope (°)	Mean ice thickness (m)	Elongation ratio
A Neuve N	1	RGI60-11.02859	0.269	793	3084	3454	25.0	23.60	2.95
A Neuve Central	2	RGI60-11.02864	0.889	1800	2664	3554	26.3	26.29	2.02
Pre de Bard	3	RGI60-11.02916	3.011	3300	2360	3641	21.2	62.95	1.10
Greuvettaz E	4	RGI60-11.02978	0.196	985	2948	3582	32.8	11.88	5.03
Greuvettaz W	5	RGI60-11.02981	0.169	837	2704	3291	35.0	11.67	4.95
Planpincieux	6	RGI60-11.02991	1.013	2050	2627	3650	26.5	44.52	2.02
Grandes Jorasses	7	RGI60-11.02991	0.482	2110	2701	4206	35.5	15.27	4.38
Pra Sec	8	RGI60-11.02996	0.119	873	2536	3190	36.8	9.12	7.34
Rochefort	9	RGI60-11.03000	0.558	995	2720	3301	30.3	24.48	1.78
Brenva	10	RGI60-11.03001	6.579	4492	2374	4766	28.0	80.30	0.68
Thoula	11	RGI60-11.03002	0.58	1075	2880	3416	26.5	25.26	1.85
Mont Blanc	12	RGI60-11.03005	0.764	2486	2776	3773	21.9	46.85	3.25
Dome	13	RGI60-11.03005	1.973	3553	2453	4121	25.1	51.03	1.80
Bionassay (IT)	14	RGI60-11.03005	1.354	2926	2467	3816	24.8	52.69	2.16
Aiguille de Tre la tete N	15	RGI60-11.03005	0.312	1355	2408	3010	24.0	78.47	4.34
Freney	16	RGI60-11.03013	1.017	2623	2420	3698	26.0	60.74	2.58
Brouillard	17	RGI60-11.03014	1.166	2733	2499	3972	28.3	52.28	2.34
Lex Blanche	18	RGI60-11.03020	2.64	2450	2467	3757	27.8	41.40	0.93
Petit Mont Blanc	19	RGI60-11.03020	0.556	1767	2863	3580	22.1	26.31	3.18
Estelette	20	RGI60-11.03022	0.291	950	2716	3214	27.7	23.74	3.26
Pierre Joseph	21	RGI60-11.03258	0.275	710	2920	3409	34.6	14.77	2.58
Nant Blanc	22	RGI60-11.03263	0.363	1150	2600	3351	33.1	33.23	3.17
Charpoua	23	RGI60-11.03284	0.322	1211	2650	3479	34.4	25.41	3.76
Des Glaciers	24	RGI60-11.03339	1.091	2050	2735	3815	27.8	31.19	1.88
Talèfre N	25	RGI60-11.03466	2.037	1950	2700	3550	23.6	39.24	0.96
Argentière	26	RGI60-11.03638	13.109	7850	2178	3847	12.0	88.90	0.60
Mer de Glace	27	RGI60-11.03643	23.556	12090	1774	4025	10.5	103.75	0.51
Bossons	28	RGI60-11.03646	11.319	6795	1691	4776	24.4	59.66	0.60
Taconnaz	29	RGI60-11.03647	4.994	4291	2043	4286	27.6	40.15	0.86
Bionassay (FR)	30	RGI60-11.03648	4.774	5241	1835	4287	25.1	39.83	1.10

5.3 Spatial distribution of velocity patterns

Most glaciers can show seasonal velocity changes, as well as less markedly interannual velocity variations. Despite those variations, they maintain a constant spatial distribution of the velocity patterns on the velocity maps. To detect possible variations of the spatial distribution of velocities, we analysed single monthly maps on the selected glaciers for both winter

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

and summer months. This analysis led to the individuation of one glacier in particular - Charpoua Glacier (ID:23) - on which the spatial distribution of velocities can be significantly different (Figure 4). In fact, years that present surge-like behaviour show higher velocities towards the frontal part of the glacier while years that do not show surge-like activity show higher velocities in the higher part of the glacier (Figure 4).

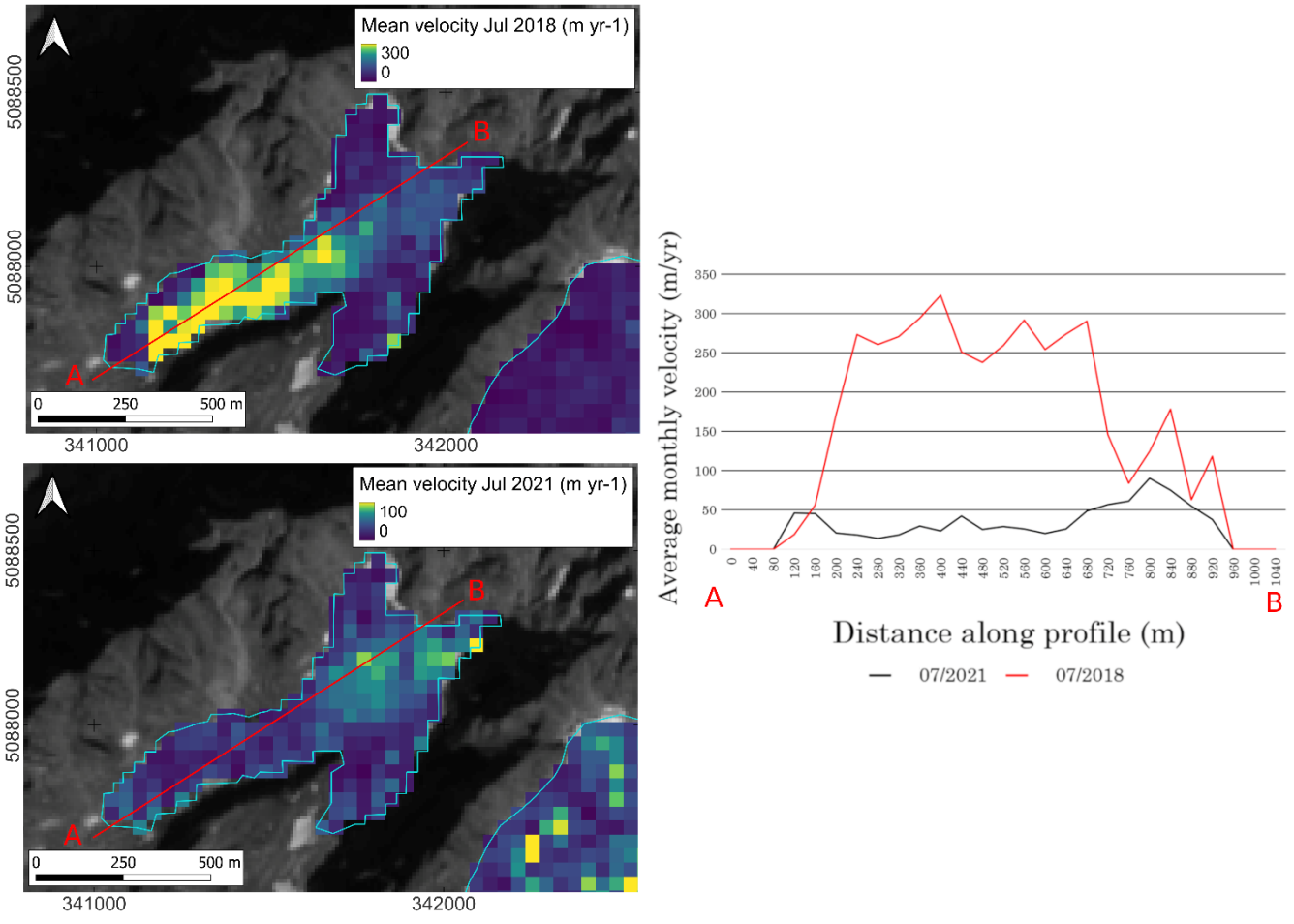


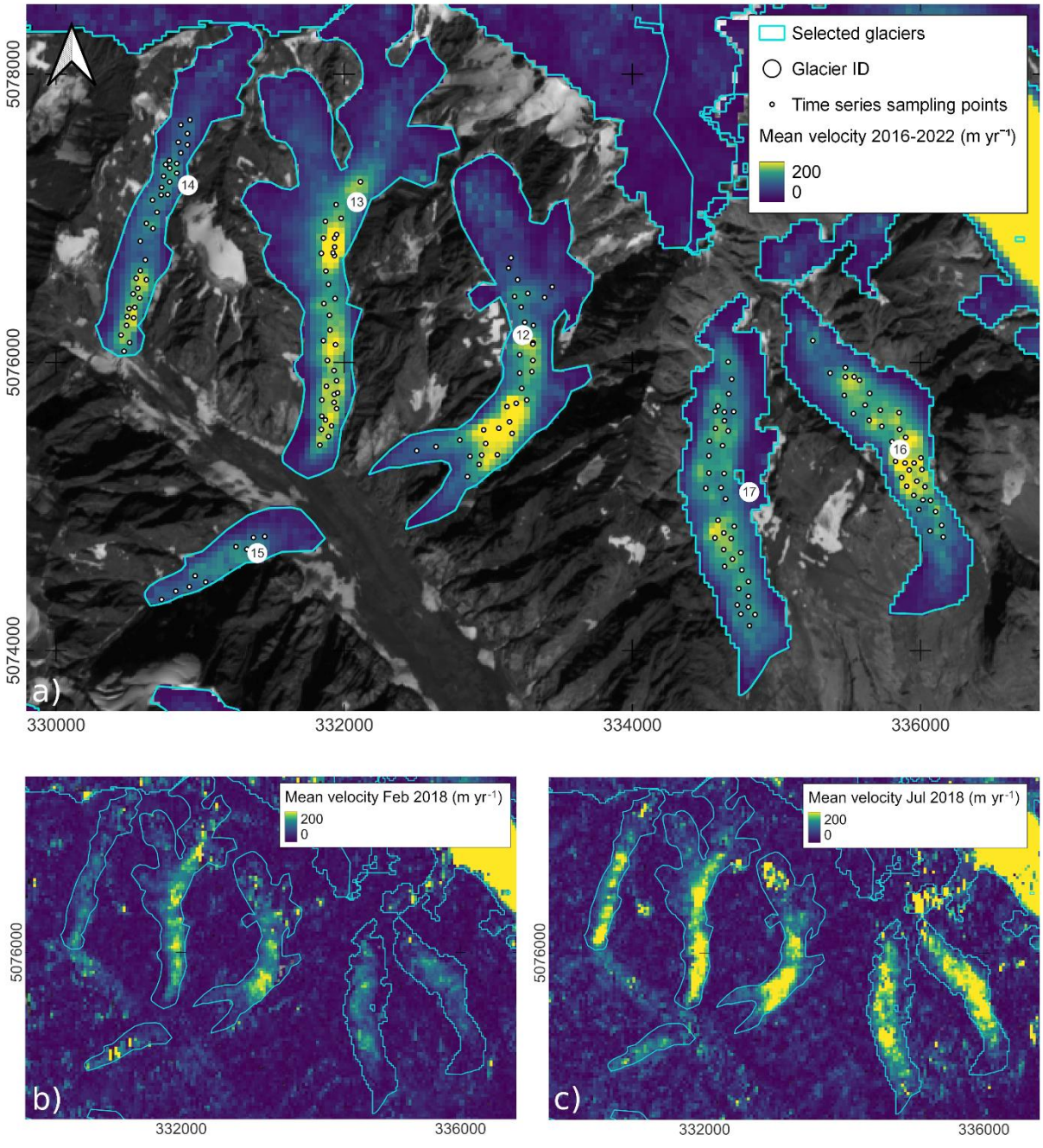
Figure 4. Charpoua Glacier (ID: 23) monthly surface velocity maps showing spatial variation of the velocity patterns in between July 2018 (upper left) and July 2021 (lower left); note the different colour scales to highlight spatial distribution of values. The right panel shows the average monthly velocity profile along a longitudinal west-east profile (in red on the maps, the profile start at A is altitudinally lower) with July 2018 values in red and July 2021 values in black. Sentinel-2 imagery base map (B08 band), courtesy of the Copernicus Open Access Hub (https://scihub.copernicus.eu, last access: 10 September 2023)

5.4 Selection of sampling points

Within every selected glacier, we manually identified ten to thirty points, depending on the glacier size, to extract velocity time series. The points were distributed on the glacier surface evenly when possible, or avoiding areas with low spatial coherence in the velocity maps which could be linked to local areas that suffered unsuccessful image matching. The presence of cloud or snow on the glacier surface made it impossible to extract reliable data in the following periods: i) January 2017 ii) December 2020, January and February 2021. However, the gaps represent only four months of no data out of the seven years

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

299 considered in the study (i.e., <5%). In Figure 5, we present an example of the obtained velocity map and the distribution of
300 sampling points over several chosen glaciers.



301
302 **Figure 5. a) Details of glacier surface velocity map averaged in the 2016-2022 period and sampling points of selected sample glaciers.**
303 **From left to right: Bionassay (IT) Glacier – ID 14; Tre la Tete N Glacier – ID 15; Dome Glacier – ID 13; Mont Blanc Glacier – ID**
304 **12, Brouillard Glacier - ID 17; Freney Glacier – ID 16. Note that on smaller glaciers there is a limited number of sampling points**
305 **because of their limited area; on medium glaciers there is a distribution of points over all areas that show velocity maps with high**

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

spatial coherence. Sentinel-2 imagery base map (B08 band), courtesy of the Copernicus Open Access Hub (https://scihub.copernicus.eu, last access: 10 September 2023). Lower left (b) and right panels (c) show single average monthly velocity maps of February and July 2018 respectively.

5.5 Velocity time series extraction

On the thirty glacial bodies we investigated in this study, the monthly velocity values range from 30-40 m yr^{-1}, typically reached during winter months, to 350 and 400 m yr^{-1}, typically reached in summer/late summer. Such high velocity values are attained by just a few of the largest glaciers in the dataset. In particular, monthly extreme values vary from 18.0 m yr^{-1} reached on January 2020 by the Greuvettaz E Glacier, to 436.3 m yr^{-1} reached by the Brenva Glacier in July 2016.
Figure 6 presents the distributions of the monthly velocity of the considered glaciers. The mean surface velocities averaged over the whole period range from 33.7 m yr^{-1} at the Pierre-Joseph Glacier to 309.7 m yr^{-1} at the Bossons Glacier. The standard deviation of the velocity time series of single glaciers varies from 8.9 m yr^{-1} at Pierre Joseph Glacier to 57.7 and 62.6 m yr^{-1} at the Pra Sec and Charpoua glaciers, respectively.

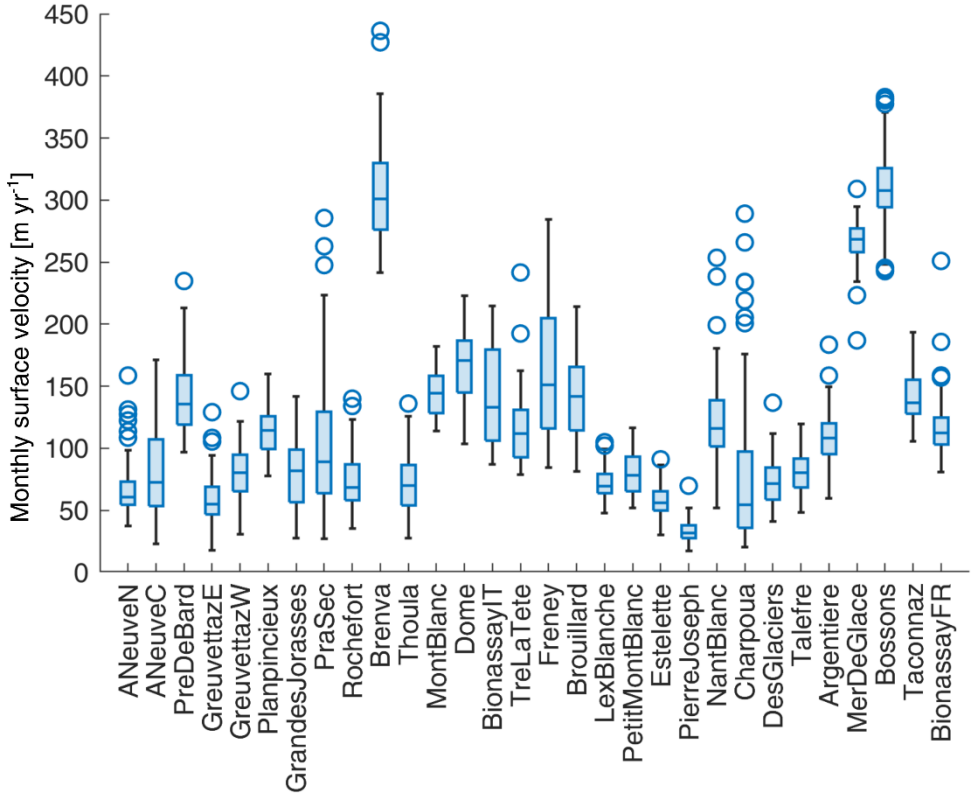


Figure 6. Boxplot of the glaciers monthly averaged surface velocity.

Velocity time series of the 30 analysed glaciers are represented in Figure 7. Glaciers such as the Freney, Brouillard, Dome, Mont Blanc and Bionassay (IT) show large seasonal variability while others, such as the Taconnaz, Mer de Glace, or smaller glaciers such as Pierre Joseph or Aiguille des Glaciers, show steadier values. Most glaciers with strong seasonality show distinct high velocity peaks that appear in summer/late summer (July to October) and minima that normally occur during mid-

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

winter (January to April). Some of the series show stronger interannual variations and this is particularly noticeable on Brenva Glacier and Charpoua Glacier.

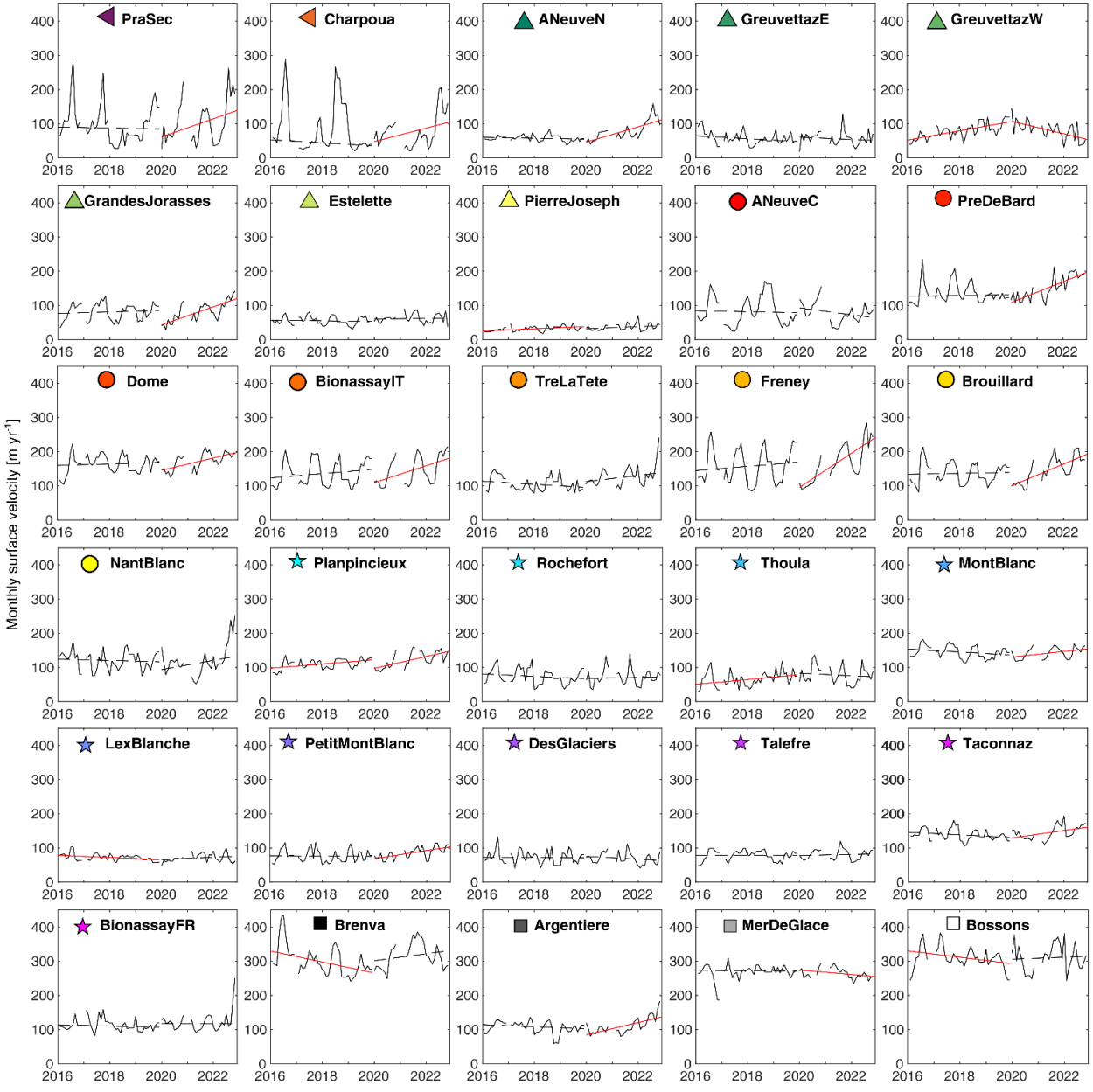


Figure 7. Time series of monthly glacier surface velocities over the 2016-2022 period. Robust linear trends calculated on each full period (i.e.: 2016-2019 and 2020-2022) are highlighted in solid red (*t*-statistics > 2) and dashed black (*t*-statistics < 2) lines. Coloured markers refer to the glacier classification.

Pra Sec and Charpoua, in particular, show very low minimum velocities (in the range of 25 m yr^{-1} to 50 m yr^{-1}) but very high peaks with a max/min ratio that can reach a 7:1 value. These velocity peaks seem to appear in summer/late summer and extreme velocity changes from winter to summer velocities can be noticed (Pra Sec 2022, Charpoua 2018). Charpoua Glacier shows

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

seasons with high summer peaks (2016, 2018) and other summer seasons that maintain particularly low displacements throughout the entire summer (2017, 2019, 2021). Pra Sec Glacier seems to display more regular annual summer speed ups: in the period analysed, every summer had a strong velocity peak only, except 2018.

The analysis of the time series shows that many glaciers had a positive trend of velocity starting from 2020, which is particularly evident in some glaciers like Argentière, Biossanay (IT), Brouillard, Freney, Pré de Bard. To statistically and quantitatively estimate this behaviour, we divided the full timespan into two periods: a first period between 2016 and 2019, and a second one between 2020 and 2022 (Figure 7). Subsequently, we applied a robust linear regression to each full period (i.e., considering all the monthly data) and only to winter (i.e., from December to April) and summer (i.e., from July to September) months. Figure 8 shows the linear trends of the first vs second period in the three cases. Considering the winter months, a well-defined general behaviour is not clearly noticeable. In the first period, most velocity trends are included in the range $\pm$10 m yr^{-2}, 11 have negative trends and 19 positives; the trends in the second period are in general similar to those of the first, with exception of six glaciers that show an increase compared to the first period (i.e., Trend in 2019–2022 minus Trend in 2016–2019, t_2-t_1), of t_2-t_1>10 m yr^{-2}, and three with a decrease t_2-t_1<10 m yr^{-2} (Figure 8a). Considering the full year, in the first period, the velocity trends are basically the same as those of the winter case; while in the second period, 17 glaciers showed a velocity increase of >10 m yr^{-2} and seven glaciers an increase of >20 m yr^{-2}. Overall, 24 glaciers showed an acceleration (or a decrease of deceleration, i.e., t_2-t_1>0) between the first and second periods, of which 17 glacier t_2-t_1>10 m yr^{-2} and 9 glacier t_2-t_1>20 m yr^{-2} (Figure 8b). Considering the summer months, in the first period, most glaciers (26 of 30) have negative velocity trends, while in the second period, 23 glaciers show positive acceleration of which 17 glaciers have trends >10 m yr^{-2} and 12 glaciers >20 m yr^{-2}. Overall, 27 glaciers have a velocity trend in the second period greater than in the first period, in 20 glaciers, the difference between second and first period is at least t_2-t_1>10 m yr^{-2}, and in 13 cases the difference is t_2-t_1>20 m yr^{-2} (Figure 8c). Overall, we observed that the trends included in the range $\pm$10 m yr^{-2} had *t*-statistics (i.e., linear slope divided by its standard error) <2, thus they were less statistically significative.

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

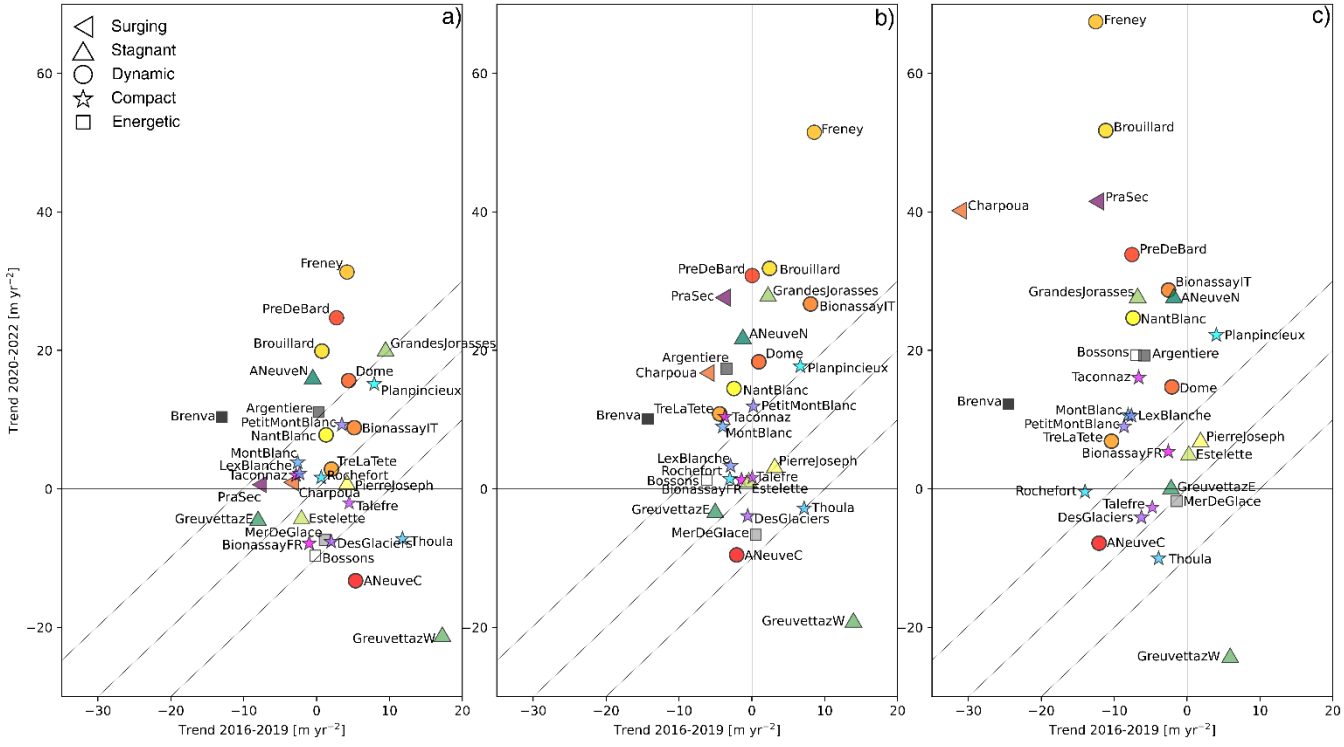


Figure 8. Annual velocity variations of the glaciers during the period 2016-2019 (x-axis) and 2020-2022 (y-axis). Trends have been calculated using: in a) cold months (from November to April); in b) every month (i.e., From January to December), while in c) warm months (from June to September). The oblique lines indicate the boundary where the difference between the trends of the two periods (second minus first period) is +10 m yr^{-2}, 0 m yr^{-2} and -10 m yr^{-2}, respectively from the upper to the lower line. Markers indicate the glacier class.

5.6 Glacier classification

The investigation of the possible presence of distinct classes of glacier based on their morphodynamics using PCA and K-means clustering is hereby presented. Figure 9 shows the biplot of the two principal components (PCs). The first PC (PC1) accounts for 42% of the explained variance of the dataset. It is principally composed of the morphological features - Area and Thickness contribute positively; Shape and Slope negatively - and glacier flow velocity (GlobalAvg). Accordingly, wide, compact (i.e., non-elongated), gentle and fast glaciers have PC1 high positive values. On the other hand, PC2 explains 26% of the dataset variance and is mainly formed of kinematic features and AAR, which contributes negatively. In this case, glaciers with high velocity variability and small accumulation areas assume PC2 high positive values. Based on the two first PCs, an unsupervised K-mean clustering identified five classes of glacier.

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

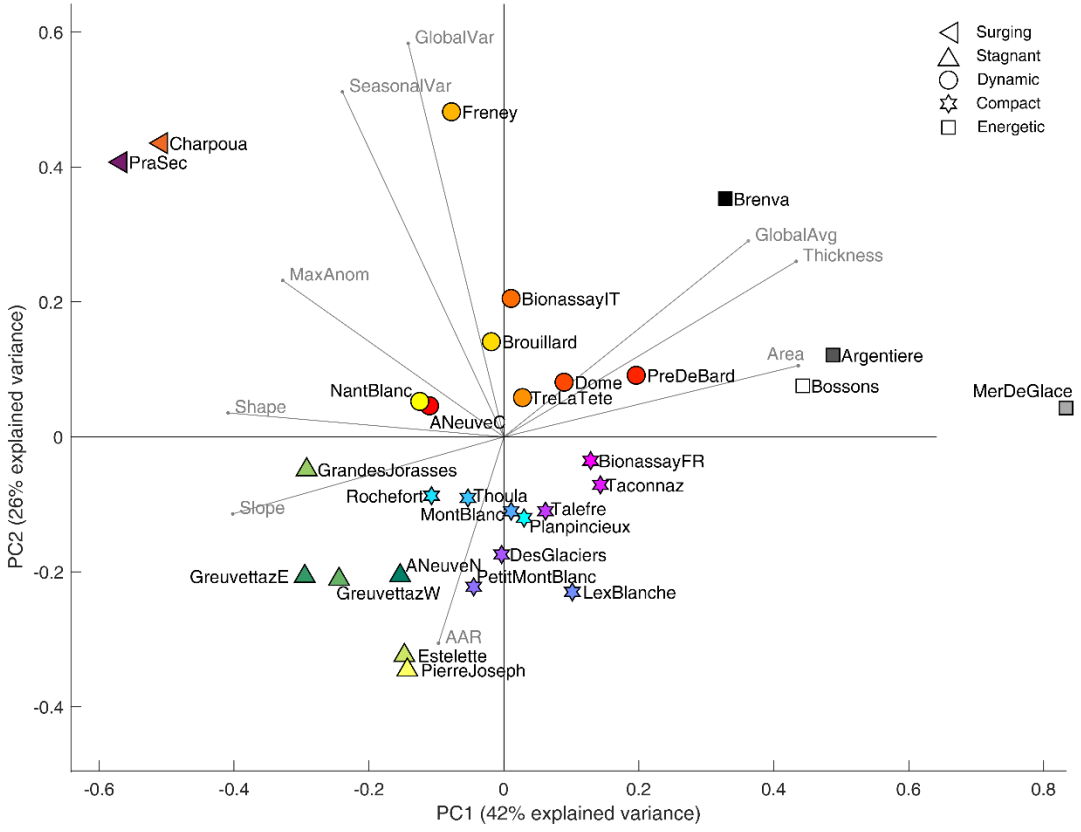


Figure 9. Biplot of the two principal components describing the variance of the dataset. Five clusters of glaciers are identified and highlighted by different markers.

6 Discussion

6.1 Velocity trends and comparison with other regional studies

Concerning the time series analysis, we compared our observations with similar existing studies in this region considering two long-term glacier velocity records in the Argentière Glacier (Vincent and Moreau, 2016) and Miage Glacier (Smiraglia et al., 2000; Fyffe, 2012). At Argentière Glacier, a unique series of continuous basal sliding measurements exist from 1997 and was still active as of 2022 (Vincent et al., 2022; Nanni et al., 2020). The whole series indicates a general decrease in basal sliding velocities (Vincent and Moreau, 2016) since the end of the 1990s. This general decrease has shown a strong correlation with the negative mass balance of the glacier, which agrees with the conceptual model from Span and Kuhn (Span and Kuhn, 2003), in which the glacier flow variation is primarily driven by the mass balance of the accumulation area in the previous year (as it determines glacier thickness variations). Seasonal field surveys conducted at Argentière Glacier from the 1950s document a longer data series than the basal sliding measurements started in 1997, and an increase of surface velocities was clearly measured during a period of positive mass balances in the early 1980s (Vincent and Moreau, 2016). The same trend was highlighted by Span and Kuhn (Span and Kuhn, 2003) for at least six other glaciers: Saint Sorlin in France, Gietro and Corbassiere in Switzerland, and Pasterze, Vernagtferner and Odenwinkelkees in Austria. At Miage Glacier, surface velocities

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

have been measured historically by different authors (Diolaiuti et al., 2005; Smiraglia et al., 2000; Fyffe, 2012; Lesca, 1974; Pelfini et al., 2007; Deline, 2002) and also show a general velocity decrease in recent decades. (Smiraglia et al., 2000; Fyffe, 2012). Globally, glacier slowdown linked to negative mass balance trend was also shown for six different regions around the globe and dates spanning from 1953 to 2009 by Heid and Kaab in 2012 (Heid and Kääb, 2012a) by an analysis of remotely-sensed optical images. Specific analysis of velocity trends and glacier mass loss showed generalized decreasing velocity trends over different regions of High Mountain Asia between 2000 and 2017 and a strong correlation with the negative mass balance trend (Dehecq et al., 2019).

According to the observations at the Argentière and Miage glaciers, the signal of velocity decrease from the early 2000s can be linked to continuous negative mass balances (Vincent and Moreau, 2016) of most Alpine glacier since the 2000s (Zemp et al., 2021). The results of our study agree with this negative trend in the first part of the considered period (i.e., 2016–2019), but we detected an inverse trend and a velocity rise from 2020 occurring in most glaciers under study. Notably, the velocity trend inversion in the recent years is most visible during the warm season, while there is not a clear signal in winter. An accelerating trend (+5 m yr^{-2} between 2015-2021) has recently been shown for the Brenva Glacier by an analysis of remotely-sensed optical images (Rabatel et al., 2023). Besides, (Rabatel et al., 2023) observed a slight ice thickening (~1 m between 2000 and 2019) in an upper sector of the Brenva Glacier. They proposed three hypotheses to explain the acceleration of the Brenva: a) a glacier thickening; b) a change in thermal regime; and c) a change in subglacial hydrology, possibly related to an increased ablation in the upper reaches of the glacier (Rabatel et al., 2023). Even though the hypothesis of glacier thickening could explain the specific case of Brenva, the glacier surface elevation change across the Mont Blanc massif has been generally negative in the last years, as evidenced by the negative mass balance of the reference glaciers in the area (Zemp et al., 2021; Zemp et al., 2009). Local anomalies of positive mass balance could explain an increase of velocity but the lack of measurements at higher altitudes does not allow us to confirm this behaviour at present. However, the meteorological conditions in the recent years have remained approximately constant, with slight trends of increasing temperature and decreasing precipitation between 2020-2022 that make unlikely a general glacier thickening in the region (Figure S3). Localized high rates of accumulation due to increased avalanche activity and wind accumulation should also contribute to the ice thickening (thus yielding an acceleration), but cannot be investigated at this stage. In any case, these hypotheses can be valid for specific sectors of glaciers, while we observed a generalised acceleration across the region; thus, glacier thickening seems not to be the most relevant forcing of velocity increase. A variation of the hydrology of groups of glaciers could be more reasonable, especially if they lie in neighbouring basins, but is unlikely to occur contemporary over the whole region. On the other hand, the distribution of the acceleration trend over different areas of the massif and regarding different classes of glaciers suggest the existence of a climatic driver of the phenomenon. Therefore, a thermal regime change could explain the velocity rise. The fact that the acceleration is most evident during the warm season seems to corroborate this hypothesis, even though the mean summer temperature was slightly lower (-0.2°C) in 2020-2022 than in 2016-2019 (Table S1). In the end, a definitive answer cannot be formulated so far and further research is necessary to understand the processes involved in this trend.

The general acceleration detected in the study should be monitored in the future. In fact, if this trend continues, it should be also considered that an acceleration trend over few years (2012-2016) has been measured before the large destabilization of Aru 1 Glacier (Gilbert, 2018). However, the trend highlighted in our study is detected over a short period (2020-2022) and could be a fluctuation onset on a generally decreasing trend at a decadal scale. In any case, the causes of such an anomaly should be a matter of further research.

6.2 Glacier classification

In regard to glacier classification, we individuated five groups:

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

'*Surging glaciers'*: only two glaciers belong to this group: Charpoua and Pra Sec. They are thin small steep elongated glaciers. Their average velocity is rather low but they feature a much stronger annual cycle with periods of surge-like dynamics during which they occasionally show accelerations of almost one order of magnitude. Possible glacier advances are prevented by the steep bedrock cliff at the snout, which causes the disintegration of the glacier by repeated ice falls from the glacier front (Giordan et al., 2020; Pralong and Funk, 2006). Both glaciers have had documented ice avalanche activity from their frontal areas (Buisson et al., 1999; Mourey and Ravanel, 2017; Ravanel, 2009; Deline et al., 2010). Ice avalanches from the Pra Sec Glacier occurred in the 1930s, in August 1981 (Deline et al., 2010), and repeatedly in 2020 and 2021 (Forestry Service of Aosta Valley, personal communication). Ice avalanches from the Charpoua snout between 40000 and 60000 m^3 occurred in 1997 (Deline et al., 2010; Deline et al., 2012) and 2018 (Lehmann, 2018 - https://news.unil.ch/display/1536777918113, accessed online 11 October 2023). During 2018, a strong summer acceleration was highlighted in the present study at Charpoua Glacier. The precursory acceleration before a failure has been investigated and measured in landslides and rockfalls (Fukuzono, 1985), cold-based glaciers (Faillettaz et al., 2016) and, in a few cases, temperate or polythermal glaciers (Giordan et al., 2020; Faillettaz et al., 2012).

Elevation changes typical of surging glaciers should be investigated to better describe such processes but, presently, such data is not available. As far as we know, to date, such surge-like behaviour on small steep temperate Alpine glaciers have not been documented.

'*Stagnant glaciers'*: they are morphologically similar to *surging glaciers* (i.e., small, steep and elongated). *Stagnant glaciers* lie, in general, at high altitudes, thus they have a larger AAR compared to other glaciers (in particular *surging glaciers*). The velocity seasonal cycle is modest or even non-detectable since the velocity in winter is close to the measurement uncertainty (besides the Grandes Jorasses, which has a relatively pronounced seasonal cycle). It is worth highlighting that signals of potential velocity fluctuations could exist but remotely-sensed data are not currently suited for the analysis of such small glaciers.

'*Dynamic glaciers'*: the morphology of these glaciers is less homogeneous, even though most are generally gentler and thicker than average. They all feature strong kinematic activity, their velocity is higher than average with marked variability and they often show a pronounced regular annual cycle, as in the case of the Bionassay (IT) and Freney glaciers. A large ice avalanche event was documented in 1956 at Freney Glacier (Chiarle et al., 2023), which is one of the glaciers displaying some of the largest velocity variations in this group. A possible correlation between summer accelerations and glacier destabilisations that can lead to ice avalanche processes would need further research; in any case, this would be more site-specific research and goes beyond the scope of the present study.

'*Compact glaciers'*: gentle, medium-sized glaciers that are not very elongated. Morphologically similar to *dynamic glaciers* but generally thinner, they are markedly less active. In particular, even though some display a regular seasonal cycle (e.g., Planpincieux, Mont Blanc, Rochefort), their velocity variability and average thickness are much lower, comparable to the *stagnant glaciers*. Since their extension is limited, the areas suitable for the analysis presented in this study can also be small and influence the quality of the output. This group of glaciers would probably be better analysed using higher resolution imagery and higher frequency image acquisition.

'*Energetic glaciers'*: this group includes large and thick glaciers which are not very elongated. *Energetic glaciers* have accumulation areas located at high altitudes; they show high surface velocities across the whole year and seldom display seasonal variations (except Brenva, which follows an evident seasonal cycle). Their morphology is complex - e.g., the slope varies considerably. In the present study, we concentrated the analyses on the middle sectors of the glaciers where the quality of the velocity data was higher. Since they are large, reach a low altitude and have flat and little crevassed valley tongues, they have often been historically chosen for glaciological field surveys (Span and Kuhn, 2003). Therefore, the knowledge of Alpine

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

glaciers kinematics is generally mostly related to this type of glacier, which can be significantly different compared to the other glacier groups analysed in this study.

6.3 Uncertainty analysis

To estimate the quality of our data, we performed two investigations. First, following the method proposed by (Millan et al., 2019), we calculated the standard deviation of the monthly time series during the whole period 2016–2022 on a set of 155 points selected on stable terrain; subsequently, we consider the median of these standard deviations, obtaining an uncertainty of 10.9 m yr^{-1}. In their study, (Millan et al., 2019) estimated the nominal precision according to the temporal baseline between the correlated images, which they found being between 6–16 m yr^{-1} for baselines respectively of 40 and 20 days, which is the typical range of temporal gaps between images used in our study. Moreover, the value of 10.9 m yr^{-1} is in close agreement with the uncertainty found by (Mouginot et al., 2023), which obtained a root mean squared error of 10.5 m yr^{-1} between glacier velocities measured over the Mer de Glace and Argèntiere glaciers using image correlation of Sentinel2 images and GNSS in situ data (https://glacioclim.osug.fr/).
Second, we considered the glacier velocity from (Millan et al., 2019), who published mean annual velocity in the period 2017–2018 on a 50x50 m regular grid. They adopted normalised cross-correlation and chip size refinement (initial size of 16x16 px). They estimated an overall uncertainty of glacier surface velocity time series of ~12 m yr^{-1} over the Mont Blanc glaciers, and, specifically at Brenva and Bosson glacier, an uncertainty of 15–20 m yr^{-1}. We compared these data and ours along four glacier longitudinal central lines (i.e., in Bossons, Brenva, Freney and Taconnaz), obtaining good agreement (Figure 10). The largest differences (>50 m yr^{-1}) where found in a specific sector of the Taconnaz Glacier (Figure 10d), where the flux is highly channelized in a narrow passage. There, the data of (Millan et al., 2019) show a velocity decrease that seems unlikely considering the geometry of the site. However, the velocity profiles are similar elsewhere. On average, the surface velocities that we obtained are slightly higher, with difference mean +6.6 m yr^{-1} and root mean squared deviation (RMSD) of 28.2 m yr^{-1} (Table 2). The slightly higher RMSD compared to the expected uncertainty can be due to the fact that the precision in glacierized areas is probably larger (less precise) than in ice-free zones because the surface texture is different and changes (e.g., snow precipitation, surface melt, glacier movement) occur more rapidly, therefore causing more decorrelation (Millan et al., 2019).

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

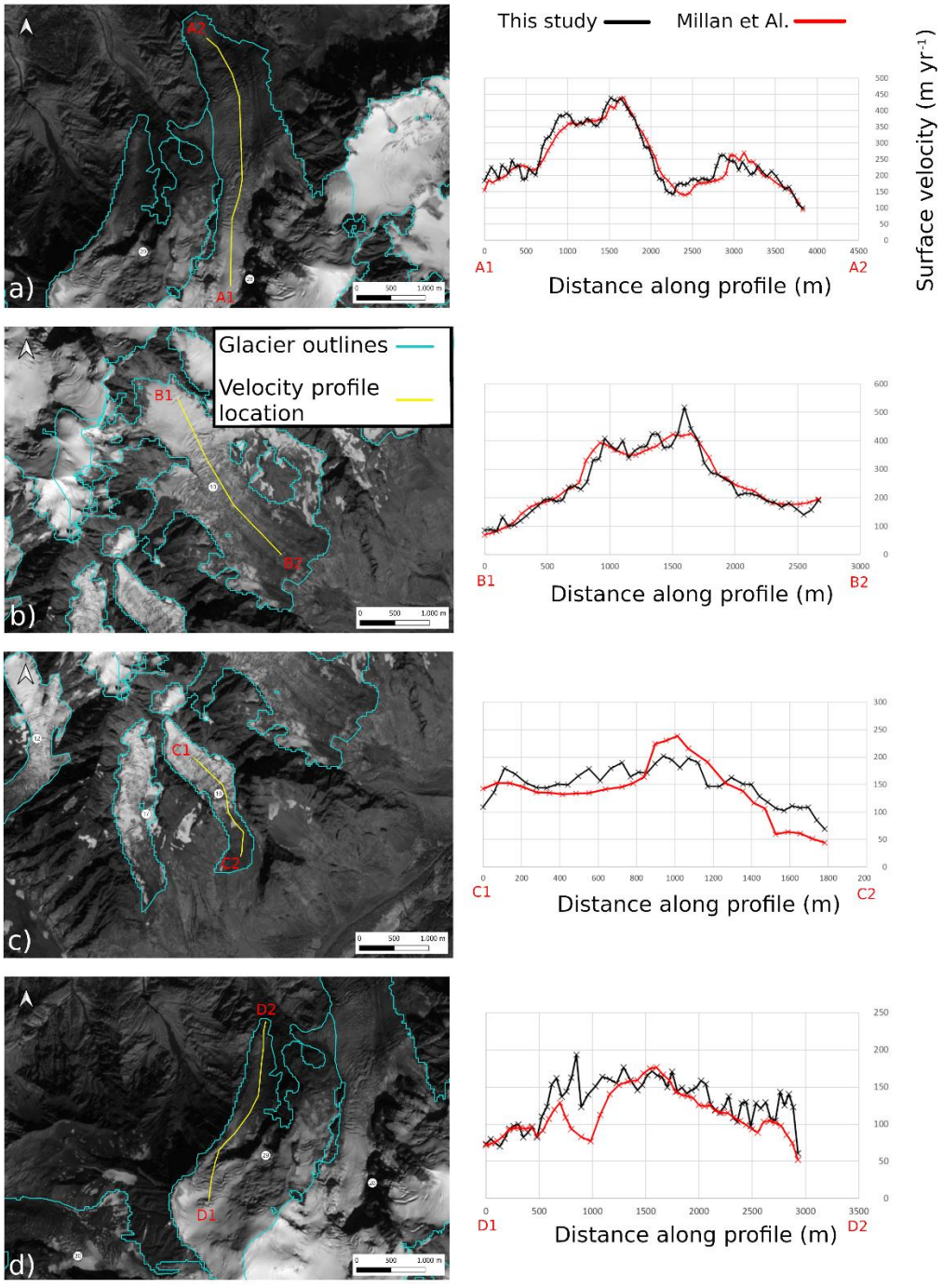


Figure 10. Comparison of velocity profiles from Millan et al. (2022) (red) and from this study (black) at: (a) Bossons Glacier, (b) Brenva Glacier, (c) Freney Glacier and (d) Taconnaz Glacier. Higher altitude to the left, lower altitude to the right, traced along profiles in yellow on the corresponding maps. Sentinel-2 image base map (B08 band), courtesy of the Copernicus Open Access Hub (https://scihub.copernicus.eu, last access: 10 September 2023).

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

Table 2. Mean difference and root mean squared deviation (RMSD) between this study and Millan et al. (2022) along velocity longitudinal profiles.

	Bossons	Brenva	Freney	Taconnaz	Mean all profiles
Mean [m yr^{-1}]	3.2	5.9	6.7	10.7	6.6
RMSD [m yr^{-1}]	28.9	33.3	30.2	20.6	28.2

6.4 Limits of the proposed methodology

The methodology presented in this study allow the detection of anomalous accelerations of glaciers, which can be precursors of ice avalanches (Pralong et al., 2005; Faillettaz et al., 2008; Giordan et al., 2020). In this frame, it would be very relevant to measure and know typical velocity fluctuations of specific glaciers in stable conditions. This could allow an assessment and to what extent a suspect acceleration may be anomalous and potentially destabilising, bearing in mind that high-rate monitoring is essential to detect glacial instabilities, since the expected sharp increase in velocity in the weeks before the failure (Pralong and Funk, 2006) could be hardly detectable from remote sensing (e.g., due to scarce visibility, image decorrelation, low resolution).

Limits of the methodology presented in this study should also be considered: considering the estimated precision of ~11 m yr^{-1} and the usual revisiting time between available images (i.e., with sufficient visibility), which typically ranged between 20 to 40 days, the minimum measurable velocity is approximatively 40 m yr^{-1}. Glacier moving at slower rates can be surveyed using larger temporal baselines (Millan et al., 2019; Mouginot et al., 2023), but this implies reducing the ability to catch short-term velocity fluctuations, like those observed at Charpoua and Pra Sec glaciers. Another known issue pertains to the lack of features of the glacier surface that makes it impossible to track movements using optical imagery. Satellite optical imagery is limited and can be strongly influenced by the presence of clouds that could yield extensive periods without data acquisition, even though, in the present study, few limiting conditions have occurred (four months with no data out of eighty processed months of available imagery). Anomalies due to image decorrelation for the presence of shadows, snow or morphological surface modifications can occur and an expert-based visual check may be required to discriminate anomalous velocities.

7 Conclusions

In the present study, we produced ice velocity maps and time series of thirty glaciers of the Mont Blanc massif during the period 2016–2022. The existing publicly available automatically processed velocity datasets, normally have coarse velocity maps (i.e., >100 m), which cannot detect correctly the kinematics of most Alpine glaciers, due to their small size. Therefore, specific processing and studies are needed to characterize the surface kinematics of Alpine glaciers. We used Sentinel-2 imagery due to its free availability, ground resolution and revisit time in the study area. Using PCA and unsupervised K-means clustering, we proposed a classification of five groups of glaciers based on their morpho-kinematic features. Plus, we observed a significative acceleration trend in most of the studied glaciers in the last years (2020–2022), but the causes are still not well understood.

Processing and analysis of such datasets around other massifs in the Alps, and globally, should be a base for stimulating research on high resolution spatiotemporal variations of velocities on Alpine glaciers and, especially, on understanding the variations in the motion of mountain glaciers. A large research question remains open and deals in understanding and

https://doi.org/10.5194/egusphere-2023-2771
Preprint. Discussion started: 4 December 2023

measuring the drivers of change in motion of alpine glaciers. This implicates the complex acquisition of data related to the possible drivers of the variations such as mass balances, water inputs and the temporal variations in subglacial hydrology of single glaciers. However, in order to delve further into these investigations, more complete and widespread glacier surface velocity databases such as that presented in this study, are needed to build future research on the topic.

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Data availability

Glacier outlines shapefiles can be requested by contacting the lead author. Sentinel-2 imagery is available from the Copernicus Open Access Hub (https://scihub.copernicus.eu, Copernicus, 2022). The GIV toolbox is freely available online (https://github.com/MaxVWDV/glacier-image-velocimetry). The original glacier surface velocity dataset is available for download as a supplement.

Competing interests. The authors declare that they have no conflict of interest.

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