Seasonal biases induced by illumination changes and shadow casting in remote sensing derived glacier flow velocities

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Abstract.

Sub-annual glacier surface velocity time series are receiving increasing attention as they provide critical information on subglacial hydrology, glacier and ice-sheet instabilities, and responses to external forcing. Regional-to-global scale datasets of glacier surface velocities are based on optical and/or SAR remote sensing images. They are now available worldwide in open access or on demand. Meanwhile, systematic seasonal errors (i.e., biases) induced by illumination changes and shadow casting have been reported in displacement time series derived from optical imagery for various landforms, such as landslides or dunes. The extent to which such biases affect glacier velocity maps remains poorly investigated. These biases may lead to misinterpretations of sub-annual velocity variations, for example, by amplifying or attenuating real seasonal signals or, in the worst case, producing artificial seasonal signals. Here, we characterize the amplitude and spatial distribution of seasonal biases in velocity maps derived from Sentinel-2 and Landsat 8/9 images. First, we compare GNSS velocity data measured on Argentière Glacier (French Alps) with three glacier surface flow velocity datasets derived from remote sensing images and post-processed using different state-of-the-art methodologies. We highlight a systematic overestimation of the seasonal amplitude among the different datasets, regardless of the post-processing strategies employed. Then, we assess the characteristics of this seasonal bias by analyzing velocities estimated over static areas at the scale of the Mont-Blanc Massif. Clear seasonal biases are observed on north-facing slopes, particularly on the northwestern aspect. The amplitude of this bias differs between the existing glacier surface velocity products, depending on the satellite images used and filters applied to the raw data. Across the Mont-Blanc Massif, the median value of this bias ranges from 7 to 80 $\mathrm{m.yr^{-1}}$ on north-facing slopes, for high to low levels of filtering respectively. This seasonal bias reaches a maximal value at the spring and autumn equinoxes, except for the highly filtered dataset. We identify two main origins for this seasonal bias: the casting of shadows by the topography and the local relief, and changes in illumination. Indeed, we highlight that the amplitude of the seasonal bias is positively correlated with the number of days under shadows, and negatively correlated with variations in illumination. The dates at which the seasonal bias is maximal correspond to maxima in shadow cast expansion and shortening. To reduce the amplitude of the seasonal

bias, it appears crucial to filter the raw velocity data based on a wide range of filters, including spatial and directional filters. However, highly filtered velocities still reflect shadow tracking, rather than actual terrain motion, in areas affected by shadow casting. Therefore, we propose a strategy to identify the location and amplitude of expected seasonal biases in two steps: (1) the automatic mapping of areas affected by shadow casting; (2) the estimation of seasonal bias amplitudes in the remaining glacier covered areas based on an analysis of static areas with similar slopes and aspects. Finally, we show evidence of seasonal biases in other regions of the world, such as Yukon, Canada and Western Greenland. The code is published as a Python package called Seasonal Bias in Velocity measurement (SeBVel).

Copyright statement. TEXT

1 Introduction

Since the 2010s, the increasing number of optical and SAR satellites with a short repeat cycle ($\sim$ 5 days) and high spatial sampling ($\sim$ 10 m) has facilitated measurements of glacier surface flow velocities on sub-annual time scales (Joughin et al., 2018; Greene et al., 2020; Dirscherl et al., 2020; Wendleder et al., 2023; Wallis et al., 2023; Rabatel et al., 2023; Troilo et al., 2024; Gardner et al., 2025). These measurements have revolutionized our understanding of glacier dynamics, revealing changes in subglacial hydrological networks (Mouginot and Rignot, 2015; Armstrong et al., 2017; Nanni et al., 2023; Maier et al., 2023), providing information on the sensitivity of glacier dynamics to surface melt, terminus position, ocean temperature (Moon et al., 2014; Vijay et al., 2019; Wallis et al., 2023), surface temperature (Greene and Gardner, 2025), calving rate (Riel et al., 2021; Provost et al., 2024), lake drainage (Maier et al., 2023; Wendleder et al., 2023), icefalls (Armstrong et al., 2017; Baldacchino et al., 2025), changes in ice-stream regime (Zheng et al., 2019) or volcanic eruption (Martin et al., 2025). These measurements contribute to a better monitoring of glacier surges (Quincey et al., 2011; Round et al., 2017; Guo et al., 2020; Koch et al., 2023; Guo et al., 2025; Devaux–Chupin et al., 2025) and glacier detachments (Gilbert et al., 2018). They help validate glacier surge dynamics theories (Beaud et al., 2021; Guillet et al., 2025). Furthermore, recent modeling advances have highlighted the potential of sub-annual velocity time series to retrieve basal conditions (Jay-Allemand et al., 2011; Goldberg et al., 2015; Morin et al., 2023), and constrain near-future projections, for instance, through the use of transient inverse methods (Goldberg et al., 2015; Choi et al., 2023). This could also help better constrain the seasonal mass balance of mountain glaciers, which is essential for improving glacial runoff estimates (Ultee, 2025).

Meanwhile, displacement time series derived from optical images can be affected by systematic errors induced by seasonal illumination and shadow changes, as observed in the case of landslides (Lacroix et al., 2019) and dunes (Ding et al., 2020). However, the impact of such effects has been poorly studied on glacier and ice-sheet velocity retrievals. Derkacheva (2021) reported seasonal deviations in Sentinel-2 velocity maps in the Russell sector in Greenland, with a change in flow direction of +30° in spring and -30° in autumn compared to summer and winter. They also reported that the north/south components of Sentinel-2 velocities exhibit deviations of about +50 m yr^{-1} in early spring and -40 m yr^{-1} in late autumn, while the

same velocity component from Sentinel-1 remains around +10 m yr^{-1}. These results hint towards systematic errors caused by changes in illumination, which affect only optical images. Another potential source of systematic errors is the presence of shadows. Some studies mask shadow areas to mitigate their effects (Provost et al., 2022; Troilo et al., 2024). For example, Troilo et al. (2024) manually delineate regions impacted by shadow casting using optical images from autumn to spring and scene classification maps from Sentinel-2 L2A products.

To our knowledge, there is no systematic evaluation in the literature of seasonally correlated errors in glacier surface velocity estimates. Quantifying the amplitude and spatial distribution of such errors is highly challenging because glaciers and ice sheets naturally exhibit large seasonal variations in surface velocities. However, neglecting seasonal systematic errors, called seasonal biases in this study, may have significant implications, particularly where surface flow velocities are low to moderate (<500 m yr^{-1}), which encompasses the majority of mountain glaciers and the interiors of ice sheets. Seasonal biases could be misinterpreted as a real seasonality, or could amplify/weaken a real signal.

In this study, our objective is to evaluate the location and amplitude of seasonal biases in glacier surface flow velocity datasets. First, we compare GNSS data with three regional-to-global glacier surface flow velocity datasets, each post-processed using different strategies, over the Argentière Glacier (French Alps). Second, we analyze the spatial and temporal characteristics of seasonal biases. For that, we focus on static areas, where no displacement is expected, over the Mont-Blanc Massif (French Alps). Third, we investigate the potential sources of these biases, particularly illumination changes and shadow casting effects. Fourth, we explore a strategy to map areas likely affected by seasonal biases. Finally, we highlight examples of seasonal biases in other regions of the world.

2 Study sites and data

2.1 The Mont-Blanc Massif

We selected the Mont-Blanc Massif in the French Alps as our test site. The general orientation of the main ridge of this mountain range is southwest–northeast (Fig. 1). Most glaciers are steep and crevassed with low to moderate average surface flow velocities (tens to a few hundred meters per year). The valley floors surrounding the massif lie at low altitudes, ranging from approximately 1000 to 1500 m a.s.l., resulting in steep slopes with significant vertical elevation differences (up to $\sim$ 4000 m). Due to these characteristics, the Mont-Blanc Massif is often covered by shadows and is susceptible to significant illumination changes at the seasonal scale. In addition, several glaciers in the Mont-Blanc Massif have been monitored for half a century (Vincent et al., 2009; Six and Vincent, 2014; Vincent et al., 2022). In particular, continuous GNSS data have been acquired over the tongue of the Argentière Glacier for the period 2019-2021 (Vincent et al., 2022; Togaibekov et al., 2024, 2025). The Argentière Glacier extends from an altitude of 3,400 to 1,600 m a.s.l. at the glacier snout, and flows mainly towards the northwest (Fig. 1). This glacier, considered as the 19th largest glacier in the European Alps, has been widely studied using remote sensing and/or in-situ data (Roux et al., 2008; Fallourd et al., 2010; Vincent et al., 2022; Beraud et al., 2023; Rabatel et al., 2023; Roussel et al., 2025).

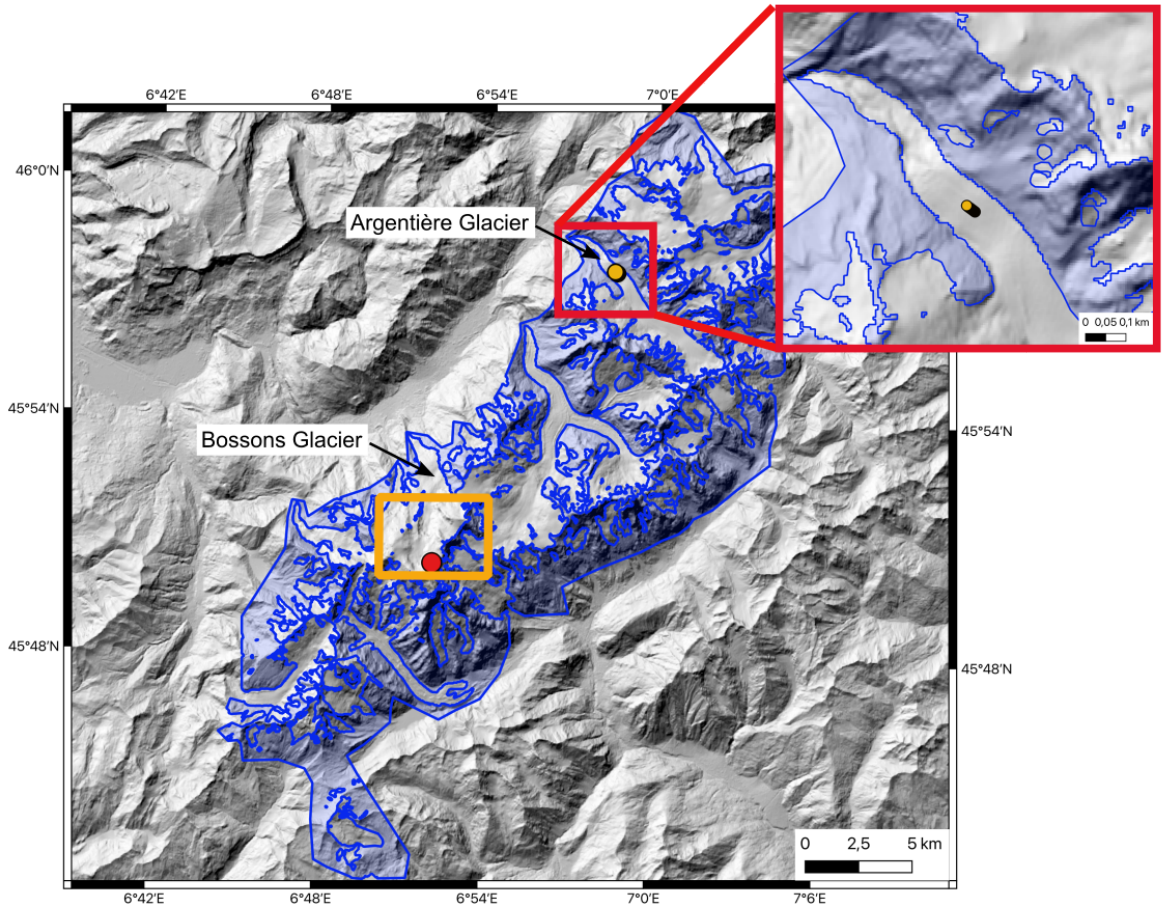


Figure 1. Study area of the Mont-Blanc Massif. The static areas used to estimate the seasonal bias are represented in transparent blue. The Arg1 GNSS station on the Argentière Glacier tongue is represented with yellow dots (the station moved ∼130 m over the 3-year period). The area covered by Fig. C4 is represented by a yellow rectangle. The point considered in Fig. 7 is represented in red. It is located at (6.86759°E, 45.83930°N) over the accumulation area of the Bossons Glacier. The projection of the map is EPSG:32632, and the displayed coordinates are in EPSG:4326.

2.2 Remote sensing datasets

We use the following remote sensing velocity datasets that cover the Mont-Blanc Massif:

- Monthly averaged velocity maps derived from Sentinel-2 images at a spatial sampling of 40 m by Troilo et al. (2024). Troilo et al. (2024) used the image correlation toolbox Glacier Image Velocimetry (GIV) (Van Wyk de Vries and Wickert, 2020). Monthly velocities are calculated as the weighted average of image-pair velocities (with temporal baselines ranging from 10 to 120 days) where the weights are proportional to the fraction of time included in a given month over the total time gap between the image-pairs. Previous filters are also applied: velocities higher than 1500 m yr^{-1} are discarded, and each image-pair velocity is smoothed using a 3×3 median filter. This dataset is later referred to as TRO.

- Image-pair velocities derived from Sentinel-2 images with a modified version of the Normalized Cross-Correlation (NCC) algorithm ampcor from ROI_PAC (Mouginot et al., 2017; Millan et al., 2019, 2022; Mouginot et al., 2023). Here, we use two products with different levels of filtering to assess the impact of the filtering process. In the first product, velocities were filtered using a 9×9 median spatial filter only (hereafter referred to as "IGE with a spatial filter"). Unlike the other datasets, this product does not have a threshold to remove outliers with abnormally high velocities, and is not intended for release in its current form. The second product from IGE has undergone more advanced filtering (hereafter referred to as "IGE with advanced filters"), based on the maximal expected velocity magnitude, a range of temporal baselines selected based on the glacier flow magnitude vs. the expected accuracy, the flow direction, and the distribution of surface flow velocities, as described in Rabatel et al. (2023). Spatial sampling is 50 m and temporal baselines range from 5 to 400 days. The IGE products therefore allow us to assess the impact of seasonal biases at different levels of filtering, which is not possible for the other datasets, which are either already filtered and/or averaged through time.

- Image-pair velocities from the NASA MEaSUREs project Inter-mission Time Series of Land Ice Velocity and Elevation (hereafter referred to as "ITS_LIVE with NDC filter") dataset (Gardner et al., 2018, 2025). We only considered in this study velocities derived from optical satellites, i.e., Sentinel-2, Landsat-8 and 9 images. The displacement was measured using the NCC algorithm named "autoRIFT". Outliers have been filtered out using the Normalized Displacement Coherence (NDC) (Gardner et al., 2018). This filter is applied to displacements divided by the NCC search distance. Displacements are accepted if seven or more of the values within a 5×5 pixel-centered window are within one-quarter of a search distance for both displacement components. Then, only displacements that agree within four times the centered mean absolute deviation are retained (Gardner et al., 2025). The spatial sampling of the velocity maps is 240 m resampled at a resolution of 120 m using a cubic spline approach. Temporal baselines range from 5 to 546 days.

A detailed comparison of these datasets is beyond the scope of this paper. Here, the objective is to investigate whether the seasonal biases are systematically present across different datasets.

Note that Sentinel-2 and Landsat-8/9 images are acquired at 10:30 AM and 10:00 AM Mean Local Solar Time (MLST), respectively, over the Mont-Blanc Massif (with a variation of ± 10 minutes for Landsat-8/9).

2.3 GNSS data

We use data from the GNSS station ARG1 deployed along the glacier's central flowline between February 2019 and December 2021 (Togaibekov et al., 2024, 2025, 2026) (Fig. 1). The GNSS antenna was mounted on an aluminum mast anchored up to 6 m deep in the ice. GNSS data are processed in static mode using the high-precision geodetic software package GAMIT/GLOBK version 10.71 (Herring et al., 2018). The root-mean-square (RMS) scatter of the daily position estimates is about 2 mm in the horizontal directions (Fig. A1a-b), resulting in a horizontal velocity uncertainty of 2.3 mm d^{-1} (Fig. A1d). More details about the installation and processing can be found in Appendix A. We manually filtered out residual outliers and then computed a 30-day rolling mean for the antenna ARG1 to match the temporal sampling of remote sensing velocity time series extracted in

Section 3.1, and focus only on the seasonal variations in Section 4.1. This step also reduces the uncertainty of the GNSS time series.

3 Methods

Below, we describe the methodology used in each of the section of the manuscript.

3.1 Evidence of seasonal biases highlighted by a comparison between remote sensing and GNSS data

To carry on a comparison between remote sensing and GNSS data, we first extract velocity time series from the remote sensing data, because remote sensing image-pair velocities with different temporal baselines are not comparable (Altena et al., 2019; Charrier et al., 2022) as they correspond to the average of the instantaneous velocity over the temporal baseline. To evaluate the sensitivity of the seasonal bias retrieval to the post-processing approach, we apply three state-of-the-art algorithms (Fig. 2): 1) LOcally WEighted Scatterplot Smoothing (LOWESS) (Derkacheva et al., 2021); 2) an integrated Sinusoidal Regression (SR, Greene et al., 2020); and 3) the Temporal Inversion using linear Combinations of Observations, and Interpolation (TICOI) package (Charrier et al., 2025). LOWESS is a nonparametric local regression that fits a weighted linear regression model to the k nearest neighbors. The weights are defined according to the distance between the center point and each of its neighbors. Derkacheva et al. (2021) recommend fitting 20 points. However, our datasets are noisier, therefore, we selected 70 points. The SR approach (Greene et al., 2020; Greene and Gardner, 2025) aims to de-trend the time series using weighted polynomial regression. It then integrates a simple sinusoid and applies it to displacement rather than velocity measurements. In this study, we only use the integrated SR, without de-trending the time series, because the inter-annual variations appear to be roughly constant between 2017 and 2023. Lastly, the TICOI approach fuses velocity measurements with different temporal baselines using the temporal closure principle (Charrier et al., 2022, 2025). We chose a regularization coefficient of 500, which was estimated by finding the inflection point of the averaged Velocity Vector Coherence calculated at several places in the entire massif for different values of regularization, as described in (Charrier et al., 2025). Note that LOWESS must be applied to short temporal baseline velocities only (here, lower than 180 days), while the two other approaches can fuse velocities with different temporal baselines. However, we chose to exclude long temporal baselines (> 180 days) from the dataset "ITS_LIVE with NDC filter" due to the strong temporal decorrelation (Fig. A2b)).

3.2 Characteristics of seasonal biases inferred from static area analysis

In order to investigate the spatial and temporal characteristics of seasonal biases, we analyze the seasonal amplitudes and peak timings of image-pair velocities retrieved in static areas for different ranges of slopes and aspects.

3.2.1 Definition of static areas

Static areas are defined by excluding all areas within the glacier outlines from the Randolph Glacier Inventory v.7 (RGI Consortium, 2023), rock glacier inventories (Marcer et al., 2017) and active gravitational mass movements detected by InSAR as described in Appendix B1 (see blue polygons in Fig. 1).

3.2.2 Estimation of seasonal amplitudes and peak timings

Seasonal amplitudes and peak timings are estimated from time series smoothed using a weighted rolling circular median applied to the image-pair velocities stacked according to their respective day of the year. The window size of the rolling median is 30 days. The weights of the rolling median are defined using an exponential decay based on the temporal baselines: $exp(-\Delta_t/L)$, with Δ_t the temporal baseline and L an empirical value set to 90 to provide higher weights to shorter temporal baselines (which are closer to the instantaneous velocity). Then, the amplitude is defined as the difference between the maximum and minimum of this smoothed time series, while the seasonal peak timing corresponds to the date of the maximum velocity. We choose this approach to retrieve the seasonal amplitude and peak timings from the raw datasets, without risking the addition of artifacts due to advanced post-processing methods such as LOWESS, SR or TICOI. Examples of smoothed time series and corresponding seasonal amplitudes and peak timings are illustrated in Fig. D1).

Note that the seasonal amplitudes of velocity magnitude are not estimated by applying this approach directly on the velocity magnitude time series. The latest follows a Rice distribution which could lead to an overestimation of the seasonal bias (Dehecq et al., 2019). To mitigate this effect, we estimate the seasonal amplitude of the velocity magnitude as:

$$A_{magnitude} = \sqrt{A_{E/W}^2 + A_{N/S}^2} \quad (1)$$

with $A_{E/W}$ and $A_{N/S}$ the seasonal amplitudes estimated on the east/west and north/south velocity components, respectively. Seasonal peak timings are computed on the velocity magnitude because the sign of velocity components depends on the direction of the velocity vector.

3.2.3 Comparison with slopes and aspects

To characterize the spatial pattern of seasonal biases, we compute the median amplitudes and peak timings for every 10° bin of slopes and aspects. These parameters are derived from the Copernicus 30 m DEM (ESA, 2024) using the xdem library (xDEM contributors, 2024).

3.3 Potential origins of seasonal biases

3.3.1 Number of days under shadow extent and edges

To map areas affected by shadow casting, we simulate shadows projected by the Copernicus 30 m DEM (ESA, 2024) every day at 10:30 AM MLST, corresponding to the acquisition time of Sentinel-2 images (Copernicus Sentinels, 2015)), for one

arbitrary year (here 2024). For this, we use the package horayzon which takes hours in UTC as input (Steger et al., 2022). Therefore, we converted MLST to UTC using a longitude correction: 10:30 AM MLST corresponds to 10:02 AM UTC. Then, we compute for every pixel the number of days under shadow extent in 2024. In addition, we estimate the number of days under shadow edges. For that, we compute the difference between a dilation and an erosion, carried out using a disk of radius 160 m, for every daily shadow map. We chose 160 m to match the dimension of the correlation window used in the IGE dataset, which is 16 pixels, corresponding to 160 m on Sentinel-2 images.

3.3.2 Plane of array irradiance, a proxy of illumination changes

To estimate the changes in illumination, we derive the Plane Of Array (POA) irradiance. It corresponds to the total amount of light received by a square meter on a tilted panel. In addition to direct irradiance, the tilted panel receives diffuse and reflected irradiance. The POA irradiance depends on the sun azimuth and elevation, the panel angle, the soil reflectance factor, and other parameters. We simulated the POA irradiance using the pvlib package (Anderson et al., 2023). First, we compute the sun position at 10:00 AM UTC for every day in 2024. Then, we derive the clear-sky irradiance using the Ineichen and Perez clear-sky model, which is implemented by default. The geometry of the tilted panel is defined by the slope and aspect of each pixel, estimated from the Copernicus 30 m DEM (ESA, 2024) using the xdem library (xDEM contributors, 2024). Finally, we compute the average and Coefficient of Variation (CV) of POA irradiance for the year 2024. The CV corresponds to the ratio of the standard deviation to the mean.

3.4 Mapping of areas affected by seasonal biases

To mitigate the effect of seasonal biases, we implement a strategy to identify their location and amplitude.

First, we propose automatically mapping areas affected by shadow casting. We consider a given pixel to be significantly affected by shadow casting if it is under shadow edges more than 30 days, as simulated in Section 3.3.1.

Second, we estimate the expected seasonal biases over glacier areas. For this, we rely on the derived seasonal amplitude over static areas (Section 3.2). We compute the median of the distribution for each quadrant (northwest, northeast, southwest, southeast) for bins of 30° slope, to minimize the effect of an inaccurate DEM. The estimated amplitude is then interpolated for all glacier surfaces based on the corresponding slope and aspect of each pixel. Note that we could use the POA irradiance for this estimation, but this would take more computation time.

4 Results

4.1 Evidence of seasonal biases highlighted by a comparison between remote sensing and GNSS data

Remote sensing velocities are compared with GNSS data over the tongue of Argentière Glacier at the ARG1 location (Fig. 1), to investigate the accuracy of the seasonality recovered using remote sensing. GNSS data show a mean horizontal velocity of

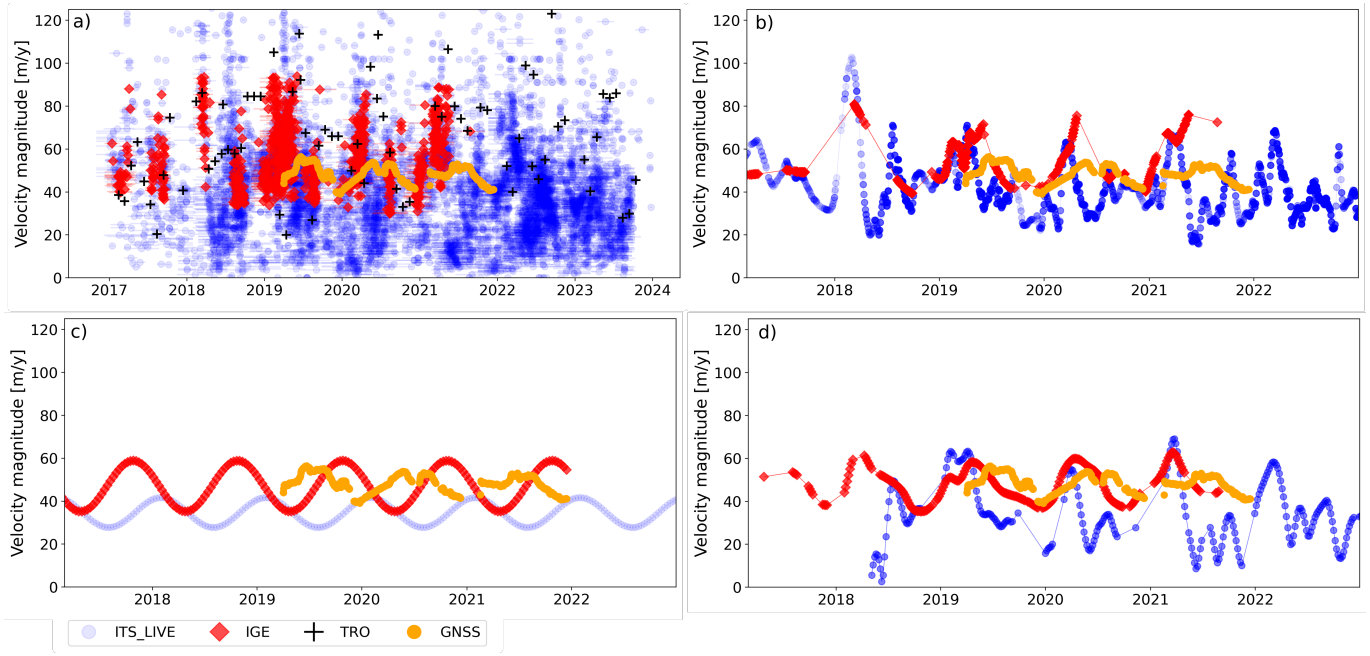


Figure 2. Velocity magnitude at the location of the GNSS antenna installed on the tongue of Argentière Glacier (yellow dots in Fig. 1), measured using a 30-day rolling mean of the GNSS data in orange; and remote sensing datasets from "ITS_LIVE with NDC filter" in blue, "IGE with advanced filters" in red and "TRO" in black. (a) Raw velocity estimates from small baseline velocities (< 180 days). Velocity post-processed using (b) LOWESS, (c) SR and (d) TICOI. Note that the maximum velocity magnitude of the ITS_LIVE and TRO datasets exceeds the limit of the axis in panel (a), reaching 400 m yr^{-1} and 500 m yr^{-1}, respectively (see Fig. A2).

48 m yr^{-1}, with a seasonal amplitude (defined as the difference between the yearly maximum and minimum) of 15 m yr^{-1} and a velocity peak timing in May/June.

The raw remote sensing datasets show a large dispersion (Fig. 2). The average velocity magnitudes between 2017 and 2024 are 45, 57 and 74 m yr^{-1} for the datasets "ITS_LIVE with NDC filter", "IGE with a spatial filter" and "TRO" respectively. The standard deviation is about 30, 10 and 54 m yr^{-1} respectively. Maximum values reach up to 400 m yr^{-1} and 500 m yr^{-1} for "ITS_LIVE with NDC filter" and "TRO" respectively (Fig. A2). This may be due to noise, and heterogeneous temporal baselines for the datasets "IGE with advanced filters" (Rabatel et al., 2023) and "ITS_LIVE with NDC filter" (Fig. 2a)). Therefore, it requires post-processing these two datasets to estimate velocity time series before investigating seasonal changes. To evaluate the sensitivity of the seasonality amplitude/phase retrieval to the post-processing approach, we applied three state-of-the-art strategies defined in Section 3.1. The TRO dataset (Troilo et al., 2024), available in open-access, already corresponds to monthly velocity time series.

The average amplitude during the 2019-2021 period measured using LOWESS, SR and TICOI post-processing is 29, 23 and 20 m yr^{-1} for the dataset "IGE with advanced filters"; 43, 14 and 40 m yr^{-1} for the dataset "ITS_LIVE with NDC filter", respectively. This highlights that remote sensing products overestimate the amplitude by up to a factor of three and by 90% on

average. Moreover, this underlines the dispersion of the retrieved amplitude, especially for the dataset "ITS_LIVE with NDC filter" which is less filtered and noisier over this area. The peaks in velocity observed after applying the LOWESS, SR and TICOI approaches are located in April-June (LOWESS), October (SR) and April (TICOI) for the dataset "IGE with advanced filters"; April (LOWESS), February (SR) and April (TICOI) for the dataset "ITS_LIVE with NDC filter". The peak timing variability observed when applying LOWESS to the dataset "IGE with advanced filters" is probably due to the scarcity of small baseline image-pair velocities. The combination of long and small baseline velocities alleviates this problem (Fig. 2d). We observe that SR provides the closest seasonal amplitude to the GNSS signal; however, the timing of the peaks is located four months later than the expected peak for the dataset "IGE with advanced filters", and four months earlier for the dataset "ITS_LIVE with NDC filter". We note that no clear seasonality appears in the TRO monthly velocity time series over this point.

It is worth mentioning that the SR approach differs from that used to produce ITS_LIVE seasonal maps (Greene et al., 2020): no previous filtering or detrending is applied in our case and the regression is carried out over a shorter time range. It is also worth noting that surface flow velocities on this part of the Argentière Glacier are difficult to map at a seasonal scale, due to a relatively low glacier surface velocity (<60 m yr^{-1}), which does not provide a favorable signal-to-noise ratio for short repeat cycles (Millan et al., 2019). This analysis is not representative of the performance of each dataset and method. A proper comparison would require a dedicated study involving several benchmarks and a sensitivity analysis. Nevertheless, this analysis highlights a systematic overestimation of the seasonal amplitude across different datasets regardless of the post-processing strategy used. We therefore extend the analysis to static areas over the Mont-Blanc Massif to assess whether our findings on Argentière Glacier are systematic.

4.2 Characteristics of seasonal biases inferred from static area analysis

To assess the characteristics seasonal biases, we examine the seasonality of velocity in areas assumed to be static, as defined in Section 3.2. We consider both the seasonal amplitudes and peak timings which are extracted as described in Section 3.2. Seasonal amplitudes correspond to the difference between the maximum and minimum velocity over one year while seasonal peak timings represent the day of the year when the maximum velocity occurs.

4.2.1 Seasonal amplitudes

The highest seasonal amplitudes are observed on north-facing slopes, and especially on northwest-facing slopes with steep slope angles (Figs. 3 and 4). This is consistently observed for both the ITS_LIVE and IGE datasets, for different levels of filtering (Figs. B3 and B2). This highlights the systematic nature of seasonal biases. These results are consistent with Lacroix et al. (2019) and Mueting et al. (2026) who conducted a similar analysis on landslides in Peru and Argentina, respectively. Both studies reported the highest amplitudes on south-facing slopes, which are equivalent to the north-facing slopes in the Southern Hemisphere.

The median and 90th percentile of the amplitude in static areas for north-facing slopes are:

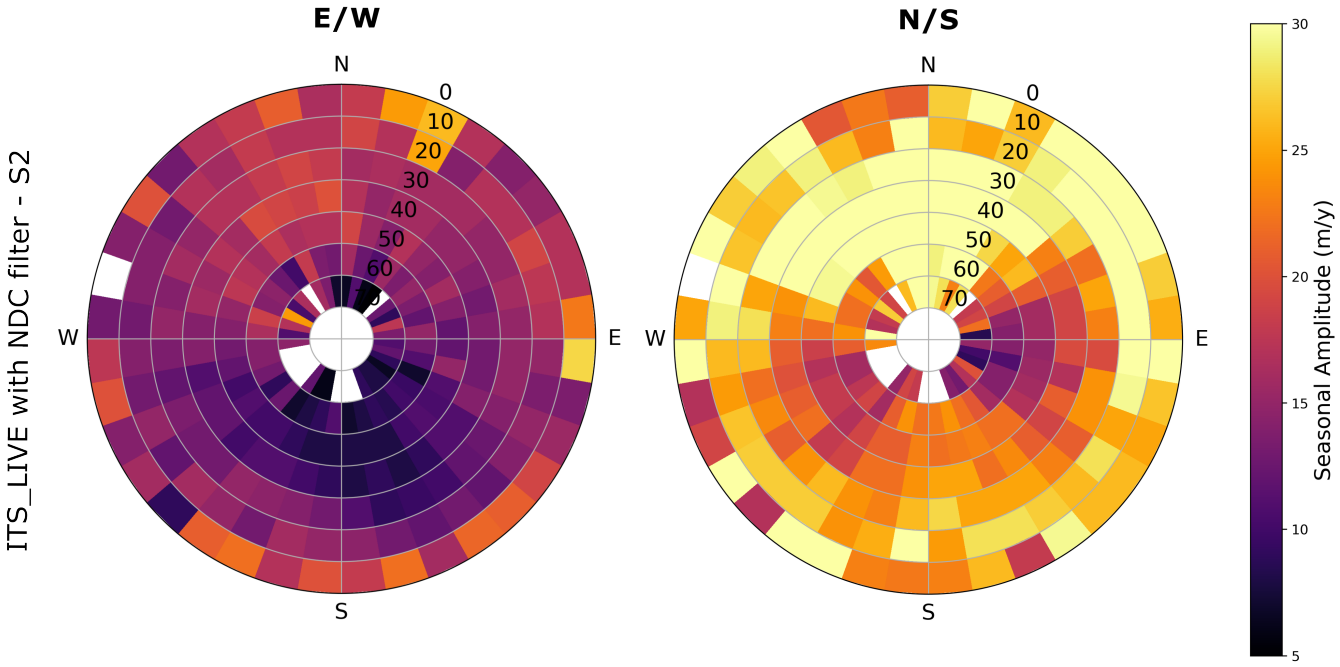


Figure 3. Polar diagram of the median seasonal amplitude of east/west (left) and north/south (right) velocity components of the dataset "ITS_LIVE with NDC filter" using Sentinel-2 images only, over static areas. The size of the bin is 10° for both slope and aspect. The slopes are shown along the radial axis, with the highest slopes in the center.

- 16 and 29 m yr^{-1} (east/west components) and 28 and 54 m yr^{-1} (north/south components) for the dataset "ITS_LIVE with NDC filter" based on Sentinel-2 images (Fig. B2)
- 29 and 55 m yr^{-1} (east/west components) and 47 and 88 m yr^{-1} (north/south components) for the dataset "ITS_LIVE with NDC filter" based on Landsat-8,9 images (Fig. B2)
- 71 and 308 m yr^{-1} (east/west components) and 93 and 428 m yr^{-1} (north/south component) for the dataset "IGE with a spatial filter only" (Fig B3). The high percentile values, compared to the other datasets, can notably be explained by the fact that this dataset has been filtered using a spatial filter only.
- 8 and 38 m yr^{-1} (east/west components) and 7 and 33 m yr^{-1} (north/south component) for the dataset "IGE with advanced filters" (Fig B3).

First, we notice that seasonal biases depend on the satellite missions used to derive the velocities. The amplitude tends to be higher with ITS_LIVE velocities based on Landsat-8,9 images than with those based on Sentinel-2 only. The median amplitude is multiplied by 1.6 and 1.8 for the east/west and north/south components, respectively, on north-facing slopes. This difference may be explained by different spatial and radiometric resolutions and slightly different acquisition times between Landsat-8,9 and Sentinel-2.

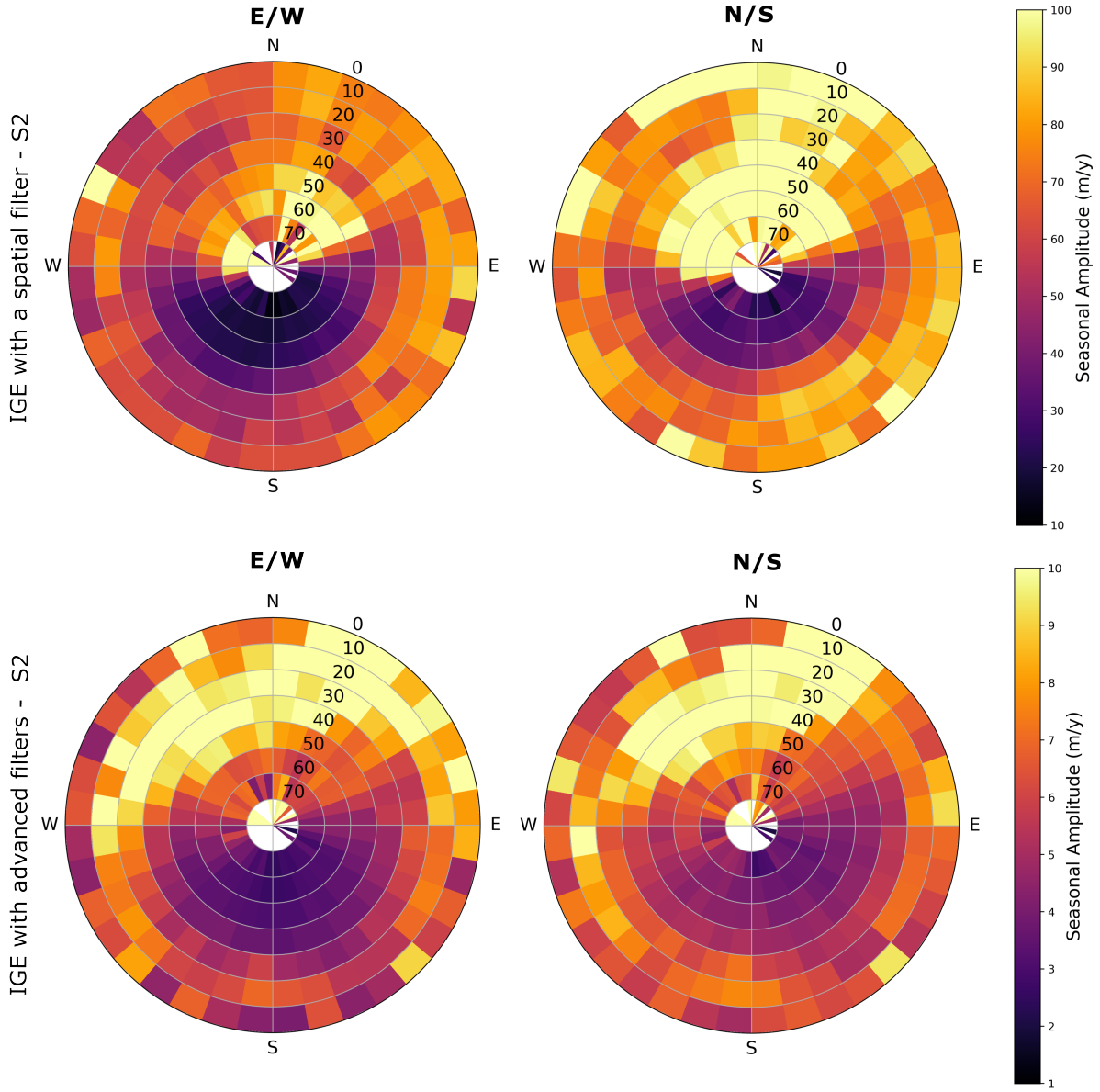


Figure 4. Polar diagram of the median seasonal amplitude of east/west (left) and north/south (right) velocity components of the datasets "IGE with advanced filters" and "IGE with a spatial filter only" (top and bottom rows) over static areas. The size of the bin is 10° for both slope and aspect. The slopes are shown along the radial axis, with the highest slopes in the center. Note that the color bars have different ranges.

Second, these results highlight the impact of the filters used to reject outliers. The amplitude of the seasonal bias drastically decreases with the use of advanced filters in the IGE dataset (which are based on the maximal velocity magnitude, the temporal baseline, the flow direction, and the distribution of surface flow velocities, as described in Section 2). We also note that the

differences between the east/west and north/south components are reduced. This underlines the importance of filtering surface velocity fields derived from optical image correlation, especially with direction-based criteria. However, even in a dataset where a wide range of filters has been applied, seasonal biases persist: for north-facing slopes, we observe a median of 7 m yr^{-1} and 90th percentile of 30 m yr^{-1} (Fig. B3).

4.2.2 Seasonal peak timings

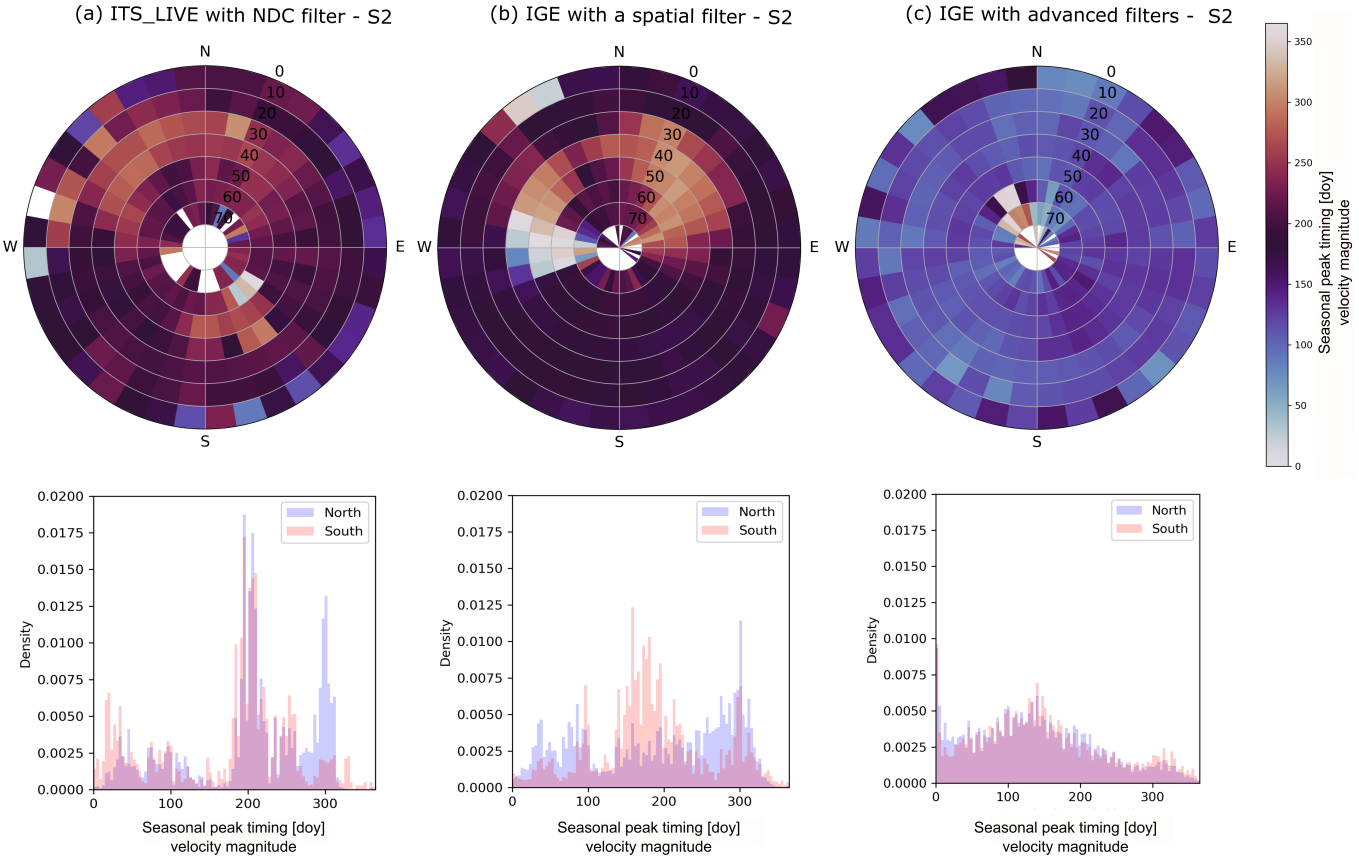


Figure 5. Polar diagram (top) and histogram (bottom) of the seasonal peak timings of velocity magnitude over static areas for the datasets: (a) "ITS_LIVE with NDC filter" using Sentinel-2 images (left column), (b) "IGE with a spatial filter", and (c) "IGE with advanced filters". In the polar diagram, the circular mean is computed for each 10° bin of slope and aspect, with slopes represented along the radial axis (highest slopes at the center).

Seasonal peak timings (i.e., the date of the maximum seasonal velocity; see Section 3.2) retrieved over static areas are also significantly different between south- and north-facing slopes (Fig. 5). We draw three key observations.

First, for both the datasets "ITS_LIVE with NDC filter" and "IGE with a spatial filter only", we observe that seasonal peak timings occur between days 260 and 330 of the year (i.e., between August and October) on north-facing slopes, especially for

the steepest slopes (Fig. 5 a) and b)). This peak timing is centered on the autumn equinox in the Northern Hemisphere. On south-facing slopes, the seasonal velocities reach a maximum mainly around days 180 and 240 of the year (i.e., between June and August).

Second, for the dataset "IGE with a spatial filter only", we also notice another high-density seasonal peak timing on north-facing slopes around day 90 of the year, corresponding to the spring equinox (Fig. 5b)). This is especially observed on northwest-facing slopes, for the steepest slopes.

Third, for the dataset "IGE with advanced filters" the seasonal peak timings show no significant differences between south- and north-facing slopes (Fig. 5 c)). This further highlights the ability of the filters to reject outliers.

The analysis of both seasonal amplitudes and peaks over static areas reveals a systematic seasonal bias over the Mont-Blanc Massif. To better characterize it, we examine potential sources of bias and the characteristic patterns they may produce in the following section.

4.3 Potential origins of seasonal biases

Seasonal biases exhibit strong spatial variations. These variations can result from several phenomena:

- The casting of shadows by the topography and the local relief (crevasses, seracs, etc.). Seasonal biases will especially arise when image correlation algorithms track the edges of the shadows.
- Changes in image contrast due to variations in illumination and surface properties.

4.3.1 Cast shadow effect

To investigate the cast shadow effect, we simulate the number of days under shadow extent and edges (see Section 3.3.1). We observe these numbers to be larger on northwest-facing slopes (Fig. C2) because shadows are elongated towards this direction in the Northern Hemisphere at the time of Sentinel-2 satellite acquisitions (the sun azimuth position is about 151° at the winter solstice over the Mont-Blanc Massif). Note that shadows would be elongated towards the southwest in the Southern Hemisphere. We observe a clear correlation between the velocity amplitude in static areas and the number of days under shadow extent or edges, except for the topographic ridges (Fig. 6).

A typical shadow casting example can be observed at the coordinate (6.86759°E, 45.83930°N), located in the accumulation part of the Bossons Glacier (Fig. C4). The flow direction deviates towards the west in autumn and towards the east in spring (Fig. 7). The velocity magnitude rises from the winter solstice to the spring equinox and decreases afterwards until the summer solstice (Fig. 7). The same cycle is repeated between the summer and winter solstices. This pattern corresponds to the casting of a shadow projected by the local relief, as illustrated by a drawing in Fig. C3, and on optical images in Fig. C4. This pattern is consistent with our observations over static areas: the seasonal bias induced by shadow casting tends to be maximal at the spring and autumn equinoxes. We note that filtering velocities, especially by removing velocities that deviate more than 45° from the average velocity, cuts the seasonal fluctuations and keeps only the lower part of the distribution (Fig. 7). However, these fluctuations may still reflect shadow casting and rather than real glacier displacements.

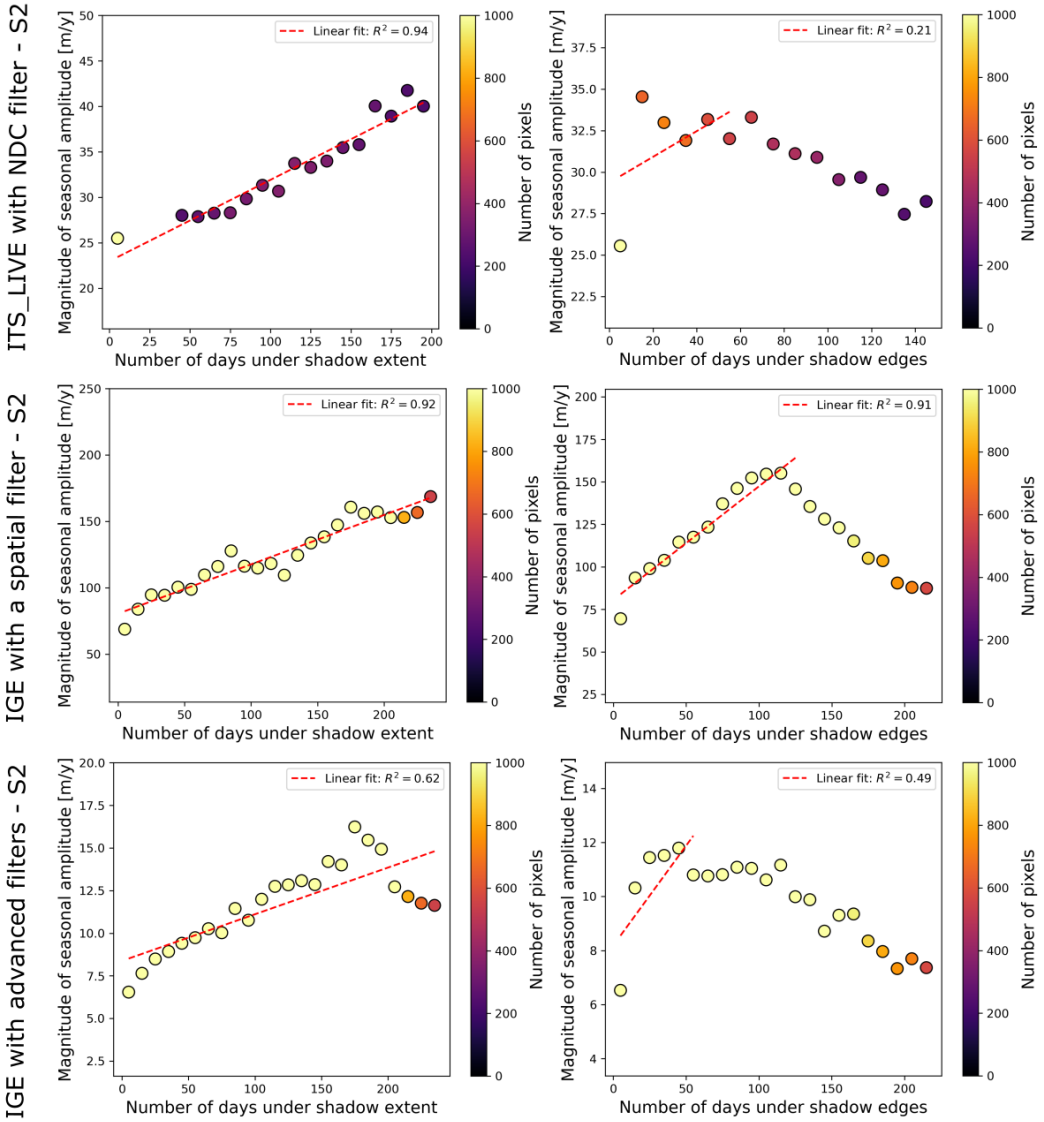


Figure 6. Magnitude of seasonal velocity amplitudes retrieved in static areas as a function of the number of days under shadow extent (left) and edges (right). Each dot corresponds to the median magnitude of seasonal velocity amplitudes binned by 10 days under shadow extent or edges. A linear trend (represented by a dashed red line) is observed when the number of pixels is sufficient. Bins where the number of days under shadow edges is higher than 120 days correspond to topographic ridges; the linear correlation does not hold in these areas. Note that bins where the number of pixels is not sufficient enougth are filtered out (corresponding to 500 pixels for the datasets "IGE with a spatial filter" and "IGE with advanced filters", and 200 for the dataset "ITS_LIVE with NDC filter"). The number of points is lower for the dataset "ITS_LIVE with NDC filter" than for the datasets "IGE with advanced filters" and "IGE with a spatial filter", because the spatial sampling is 120 m for the first dataset and 50 m for the other two datasets.

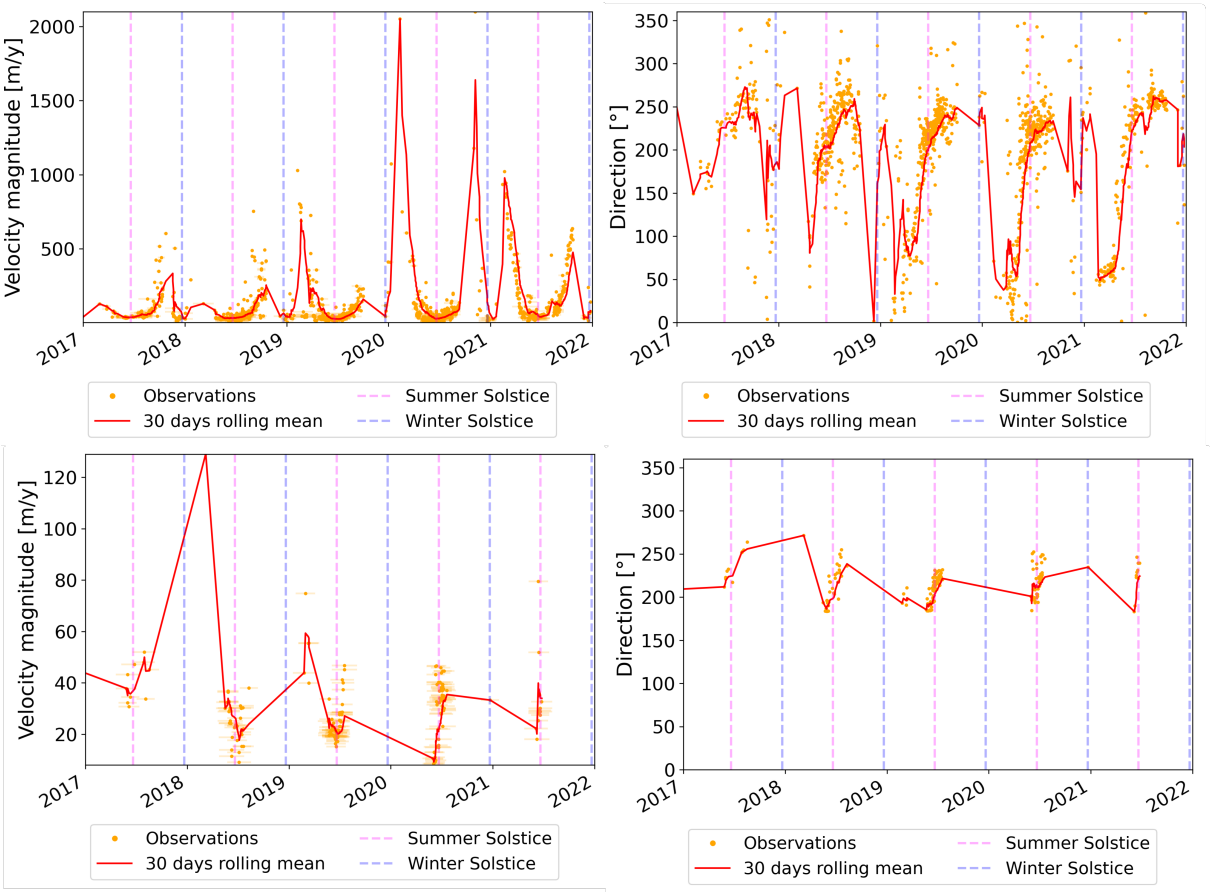


Figure 7. Example of velocities capturing shadow casting at the point located at (6.86759°E, 45.83930°N) (red dot in Figs. C1 and 1 and C4), over the accumulation area of Bossons Glacier. The upper panel corresponds to the dataset "IGE with a spatial filter" and the lower panel corresponds to the dataset "IGE with advanced filters". Velocity magnitudes are displayed in the left column, and directions in the right column. Shadow casting is illustrated on two Sentinel-2 images in Fig. C4.

4.3.2 Illumination changes effect

To estimate the effect of illumination changes, we derive the average and CV of the POA irradiance (see Section 3.3.2). The average and Coefficient of Variation (CV) of POA irradiance are, respectively, lower and higher for north- compared to south-facing slopes (Fig. C5). In addition, the CV is higher for north-facing slopes with angles between 20° and 60°. This is similar to the pattern observed in velocity amplitudes over static areas, especially for the datasets "ITS_LIVE with NDC filter" and "IGE with a spatial filter".

A linear correlation between the CV of POA and the amplitude of the velocity magnitude in static areas is observed for the three datasets in Fig. 8 (R2 score range between 0.88 and 0.96). Because the POA pattern follows the same pattern as shadows, we exclude areas with at least one day under shadow extent. The linear relationship remains (with a R2 score of 0.63 and 0.92).

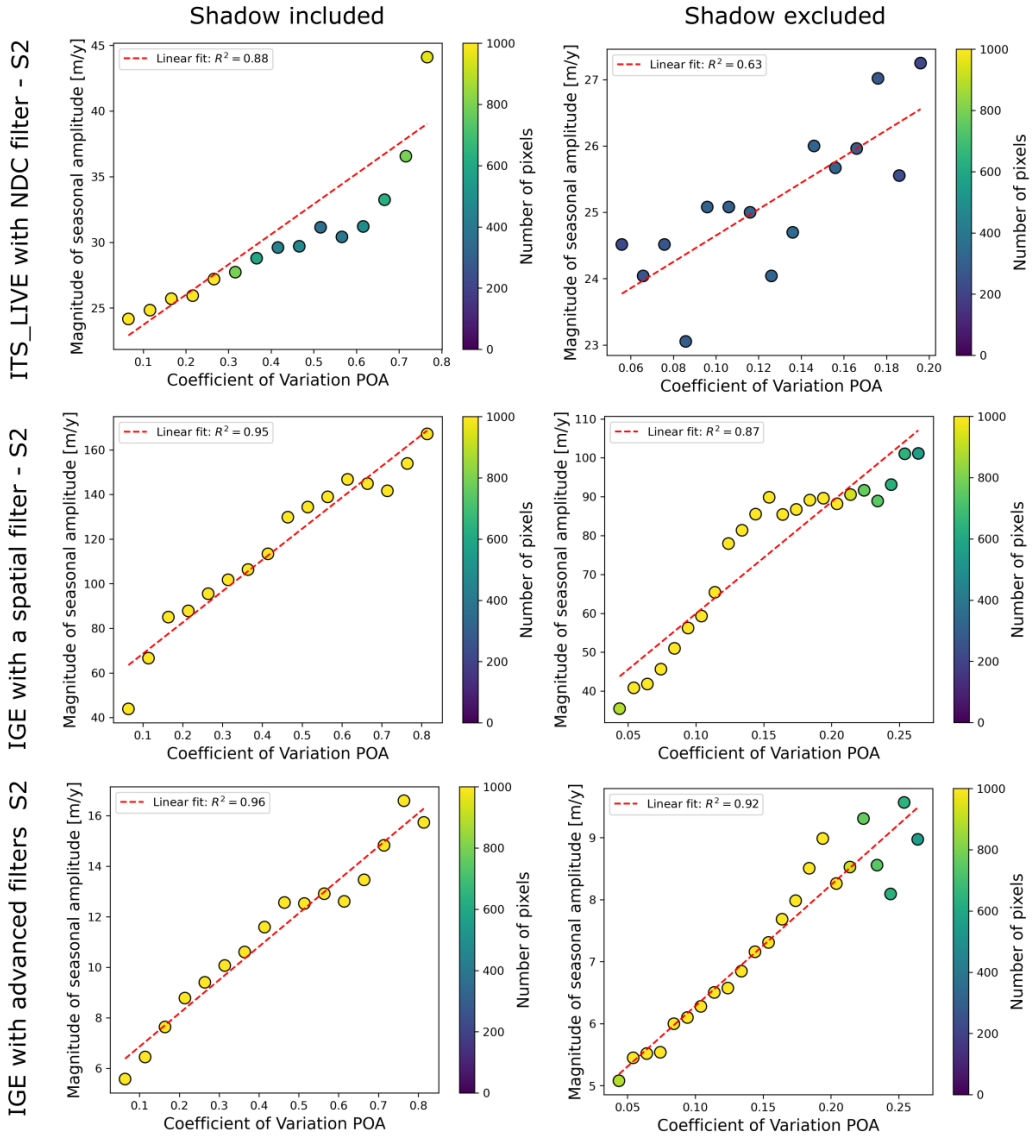


Figure 8. Magnitude of seasonal velocity amplitudes retrieved over static areas as a function of the Coefficient of Variation (CV) of POA irradiance when shadows are included (left) and excluded (right), for the datasets "ITS_LIVE with NDC filter" (top), "IGE with a spatial filter" (middle) and "IGE with advanced filters" (bottom). Each dot corresponds to the median magnitude of seasonal velocity amplitudes over a bin of 0.05. Bins where the number of pixels is unsufficient enougth are filtered out (corresponding to 500 pixels for the datasets "IGE with a spatial filter" and "IGE with advanced filters", and 200 for the dataset "ITS_LIVE with NDC filter").

325 Therefore, we conclude that both cast shadow and illumination changes control seasonal biases. They are related since shadow casting is likely to be observed on north-facing slope in the Northern Hemisphere, areas for which the illumination

changes are the strongest (Figs. C2 and C5). However, shadow casting does not only depend on the slope and aspect of the given pixel; it depends mainly on the topography above. Hence, both shadow casting and illumination changes should be considered.

4.3.3 Other potential sources of seasonal biases

It is worth mentioning that other effects may play a role:

- changes in the surface state between the two images of a pair (e.g., snow on one image and ice on the other, snow melt occurring between the two images). However, high surface changes usually result in completely incoherent velocities, which can be filtered out using the correlation score or spatio-temporal filters. In addition, seasonal biases caused by changes in illumination and shadow casting have also been observed in areas without any snow cover, such as in desert or semi-arid climates (Lacroix et al., 2019; Ding et al., 2020; Mueting et al., 2026).

- an imbalance in the temporal density of available images between summer and winter is also susceptible to resulting in an erroneous seasonality, but we did not observe such an effect in our study area.

- geometric refinement of the DEM used to co-register the optical images may also play a role, as described by Provost (2025). They noticed strong seasonal displacement over the Aletsch Glacier before summer 2021, and much smaller displacements afterwards for the same pixel. This may be due to a geometric refinement with the Copernicus DEM after summer 2021. Even though we did not see this effect for the ITS_LIVE and IGE datasets over the static areas of the Mont-Blanc Massif (Fig. C6), or as a general trend in the glacier covered areas, this effect could still impact some datasets and study areas and needs to be considered.

4.4 Towards a map of areas affected by seasonal biases

We propose a strategy to identify areas affected by shadows and illumination changes in two steps: (1) mapping of areas affected by shadow casting and (2) estimating seasonal biases over glacier areas (Section 3.4). The methodology is implemented in a Python package called SeBVel for Seasonal Biases in Velocity measurements.

First, SeBVel enables the user to automatically map shadows because this is not straightforward to do manually. For example, some areas affected by shadow casting, such as the upper part of the Bossons Glacier or the Combe Maudite in the accumulation zone of the Mer de Glace (red point and green rectangle, respectively, in Fig. C1) were not excluded from the study of Troilo et al. (2024), despite manual mapping of areas affected by shadow casting. Here, we propose a code to simulate the number of days under shadow extent and edges according to a given DEM (Section 3.4). Areas with a large number of days can be masked out before analyzing seasonal velocity time series to avoid artifacts (Fig. 9).

Second, we propose estimating the amplitude of the expected seasonal bias, based on an analysis of static areas with similar slopes and aspects (Section 3.4). For the dataset "IGE with advanced filters", the bias in velocity amplitude is estimated to be about 12 m yr^{-1} over the tongue of the Argentière Glacier, which is consistent with the error in velocity amplitude obtained while comparing this dataset with the GNSS data in Section 4.1. The average estimated seasonal bias for the entire

Mont-Blanc Massif is 10 m yr^{-1}. Such a map can ultimately be used to assess whether the retrieved seasonal variations are significant compared to the seasonal bias and if they could be attributed to actual ice velocity fluctuations. This approach could be employed for different datasets, post-processed with different strategies.

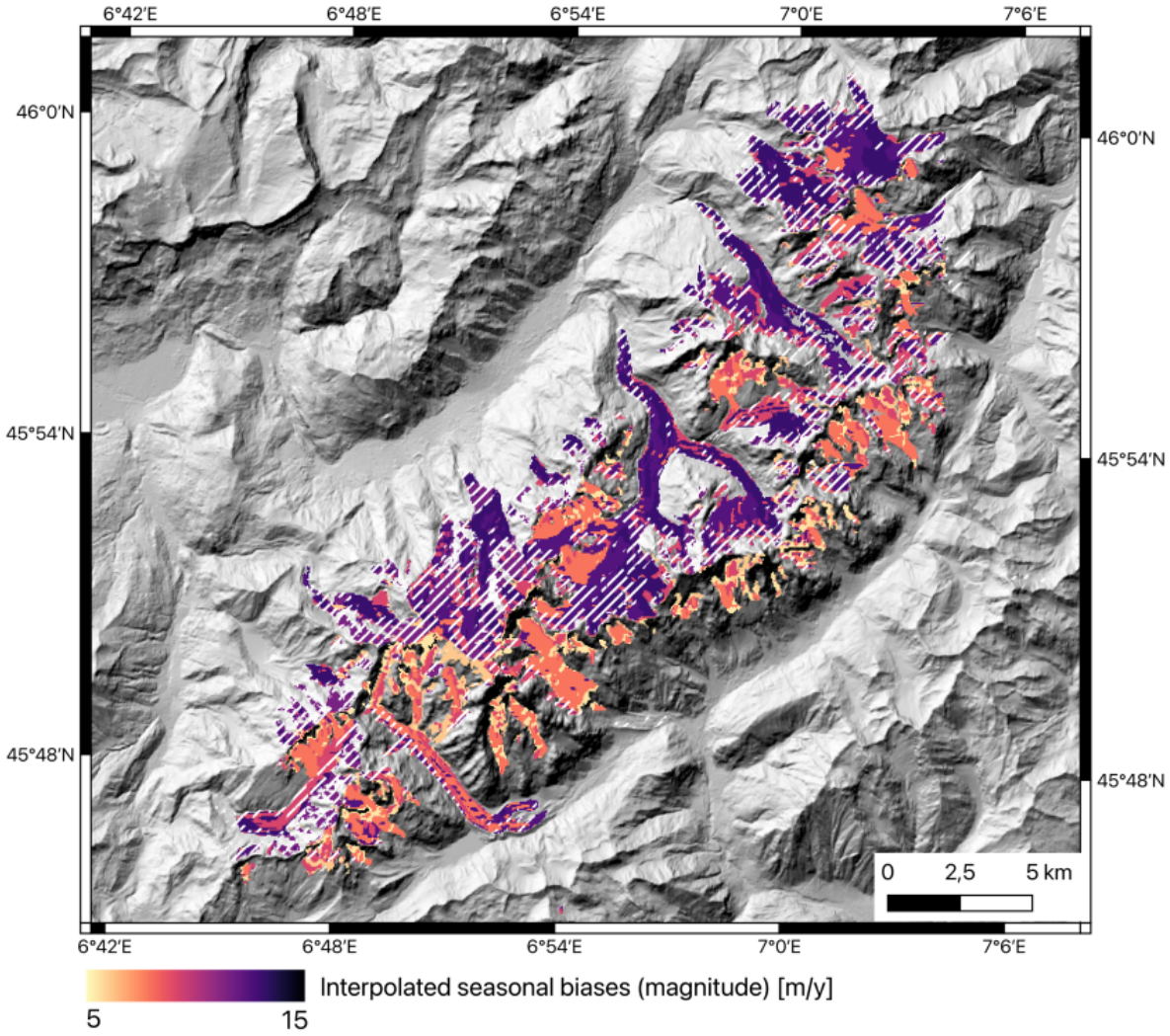


Figure 9. Estimated location and amplitude of seasonal biases over the Mont-Blanc Massif. Areas affected by shadow casting (number of days under shadow edges higher than 30), and assumed to be unreliable for seasonal analysis, are represented by hashed white lines. The amplitude of the expected seasonal bias based on an analysis of static areas for the "IGE with advanced filters" dataset is shown in color scale. The background corresponds to a hillshade from the Copernicus 30 m DEM (ESA, 2024). The projection of the map is EPSG:32632 and the displayed coordinates are in EPSG:4326.

5 Discussion

5.1 Evidence of seasonal biases in different regions worldwide

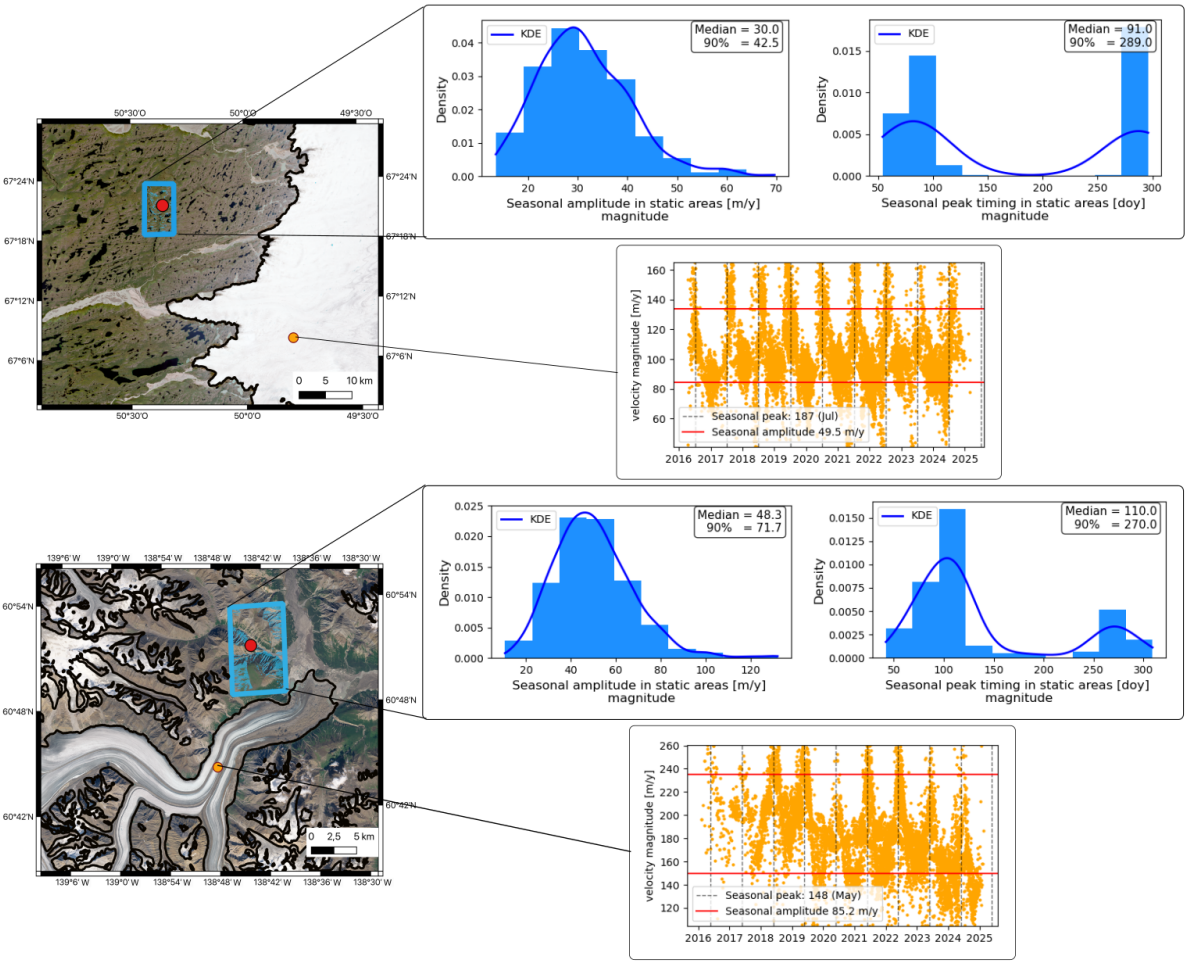


Figure 10. Example of seasonal biases identified by comparing seasonal velocity amplitudes and peak timings over static areas (blue histograms) and moving areas (orange dot) for the Issungata Sermia Glacier in Western Greenland (top) and Kaskawulsh Glacier in Yukon, Canada (bottom). The time series in moving areas correspond to raw ITS_LIVE image-pair velocity magnitude acquired at the location of the orange dots represented on the left. The histograms over static areas correspond to the seasonal amplitudes and peak timings derived as described in Section 3.2 over static areas with the same range of aspects and slopes as the moving point, i.e. a slope between 0° to 30° for both sites, an aspect between 180° and 270° for Issungata Sermia and 0° and 90° for Kaskawulsh. These areas are represented by blue polygons inside the blue rectangles. Black lines correspond to the ice-sheet or glacier contourlines defined in the PROMICE (Luetzenburg et al., 2025, 2026) or RGI (RGI Consortium, 2023) databases. Backgrounds are Sentinel-2 images in UTM projection. KDE stands for Kernel Density Estimation.

We chose the Mont-Blanc Massif to analyze seasonal biases because of the availability of GNSS data and different velocity products. However, seasonal biases are observed over glaciers and ice sheets worldwide. Seasonal biases mainly depend on the local topography and the sun incidence angle. We illustrate other examples of seasonal biases in Western Greenland, near the terminus of Issungata Sermia and in Yukon, Canada, near the tongue of the Kaskawulsh Glacier (Fig. 10). We apply the same methodology described in Section 3.3.1 to ITS_LIVE image-pair velocities to infer seasonal velocity amplitudes and peak timings over both static and glacier areas. Over the glaciers, velocity peaks in July and May with an amplitude of 50 m yr^{-1} and 85 m yr^{-1}, respectively, for Issungata Sermia and Kaskawulsh Glaciers. This has to be compared with the amplitude retrieved in static areas where clear seasonal patterns are observed (see the examples over two particular points in Fig. D1). To obtain a robust estimation of seasonal amplitudes and peak timings, we consider static areas with similar slopes and aspects to the moving point (blue polygons in Fig. 10). Over these areas, velocity peaks in spring and/or autumn for both sites, with a median amplitude between 30 and 48 m yr^{-1} for Issungata Sermia and Kaskawulsh Glaciers respectively. This is not negligible, as it represents 60% and 50% of the observed amplitude for Issungata Sermia and Kaskawulsh Glaciers, respectively.

This analysis is also consistent with the trend in velocity magnitude errors obtained by comparing ITS_LIVE image-pair velocities to GNSS velocities over the tongue of the Kaskawulsh Glacier (Lower GNSS station in Charrier et al. (2025); Van Wychen et al. (2023); Waechter et al. (2015)) (Fig. D2). The errors follow a seasonal pattern with two maxima. The first maximum is reached in spring, between days 120 and 160 of the year while the second maximum is reached in autumn, between days 250 and 300 of the year.

The amplitudes of seasonal biases reported here are not negligible, but could be reduced by post-processing the image-pair velocities before estimating seasonal amplitudes.

5.2 Possible other strategies to reduce seasonal biases

In this study, we propose a framework to estimate the location and amplitude of seasonal biases. We emphasize the importance of a drastic filtering of the image-pair velocities to reduce the amplitude of these biases. However, other strategies can also be considered to mitigate seasonal biases during the post-processing of image-pair velocities, particularly through a post-processing approach based on temporal closure inversion, as described in (Bontemps et al., 2018; Lacroix et al., 2019; Ding et al., 2020; Charrier et al., 2025). Recently, Mueting et al. (2026) compared different strategies proposed for studying dunes and landslides:

(1) removing a seasonal error, estimated on static areas through harmonic functions, from the displacement time series (Lacroix et al., 2019);

(2) restricting the image-pair velocities used as input of the temporal closure inversion to pairs with similar illumination (Ding et al., 2020);

(3) weighting the temporal closure inversion using a proxy of illumination changes (Bontemps et al., 2018);

(4) upsampling optical images (Antoine and Liu, 2025).

They found strategy (2) to be the most efficient. The study site of Mueting et al. (2026) is a slow-moving landslide in northwest Argentina. However, the same strategies could be used for glaciers because the effects of shadows and illumination changes are not object-dependent.

6 Conclusions

Despite the growing interest in quantifying sub-annual variability in glacier velocity, no study has systematically analyzed seasonally correlated biases, which can affect the interpretation of short-term ice flow variability. This is especially critical when investigating glacier velocities that have a seasonal cycle with an amplitude of a few to hundred m yr^{-1}.

Here, we demonstrate that sub-annual velocity measurements derived from optical satellite images are influenced by seasonally correlated biases. Remote sensing velocities systematically overestimate seasonal amplitudes in comparison to GNSS data, regardless of the filtering and regression approach used to post-process the image-pair velocities. Based on an analysis over static areas, we estimate that these biases are primarily concentrated on north-facing slopes in the Northern Hemisphere (and south-facing slopes in Southern Hemisphere) and are driven by shadow casting and irradiance variations. The magnitude of this bias depends on the satellites used to derive glacier surface velocities and the filters applied to remove outliers. For our study area of the Mont-Blanc Massif, the median value of these seasonal biases for north-facing slopes are about 10, 20 and 80 m yr^{-1} (for strong to low levels of filtering). The 90th percentile is about 30, 40 and 400 m yr^{-1} (for strong to low levels of filtering). Theses biases are maximal around the spring and autumn equinoxes. Our results highlight that the use of a wide range of filters, based on the maximal velocity amplitude, the flow direction, the temporal baselines, or the velocity distribution, drastically reduces the amplitude of seasonal biases. However, the measured velocities could still reflect shadow tracking, rather than actual terrain motion, in areas affected by shadow casting.

This effect is not specific to the Mont-Blanc Massif and can be observed worldwide. We illustrate seasonal biases over two other sites: Kaskawulsh Glacier in Yukon, Canada and Issungata Sermia in Western Greenland. Therefore, it appears crucial to interpret sub-annual velocity variability after a careful post-processing of the raw image-pair velocities and an estimation of the seasonal biases, regardless of the region of interest. Otherwise, erroneous conclusions about seasonal variations in velocities can be drawn.

In this context, we propose a strategy to identify the location and amplitudes of seasonal biases by (1) automatically mapping areas affected by shadow casting and (2) estimating the amplitude of the bias in the remaining areas. First, we compute the number of days affected by shadow casting for each pixel of the velocity field, according to a simulation of shadow cast over a given DEM. We propose masking out areas where the number of days in cast shadows is too large (e.g., 30). Second, based on an analysis of static areas with similar slopes and aspects, we estimate the amplitude of the expected seasonal bias. The amplitude of the seasonal velocity retrieved over glaciers can be compared to this bias to assess the significance of the estimated seasonality. This approach can be easily applied to any area and dataset and is transferable to other displacement estimation applications, such as landslides or dunes.

This study provides a first guideline for accounting for seasonal biases in the interpretation of glacier sub-annual velocity time series. The code is released as a Python package called SeBVel for Seasonal Bias in Velocity measurement.

Code and data availability. The code is available on https://github.com/LauraneC/SeBVel.git. The simulated number of days under shadow extent and edges, and the estimated error in the amplitude of velocity magnitude is available on https://cloud.univ-grenoble-alpes.fr/s/SooSoYPQH7FGKiZ, and will be shared on a zenodo link upon acceptance of the paper.

Author contributions. LC, FB, AR and AD designed the study. LC and NL worked on the python package with advice from AD, AR and FB. LC generated and analyzed the results with feedbacks from AD, FB, AR and RM. RM and AR derived the velocity field from IGE. AW and AT provided the GNSS data. DC provided an inventory of active moving areas detected from InSAR. LC led the writing, and all authors contributed to it.

Competing interests. The authors declare no competing interest.

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Appendix A: GNSS data

Daily GPS phase processing is performed using the GAMIT module of the GAMIT/GLOBK software. The GAMIT module employs the ionosphere-free linear combination of GNSS phase observables and applies a double-difference technique to eliminate phase biases caused by drifts in the satellite and receiver clock oscillators (Bock et al., 1986). The GLOBK (Global Kalman filter) module then performs a network adjustment of the bias-fixed, loosely constrained solution using a Kalman filter estimation algorithm (Herring et al., 2018). Survey sites on the glacier are processed with respect to a network of 13 IGS (International GNSS Service) stations located at distances ranging from 110 km to 1080 km from Argentière Glacier. We define the reference frame using the well-determined IGS stations, with a priori coordinates in the Eurasian-fixed plate EURA14, by estimating a seven-parameter transformation (Altamimi et al., 2017).

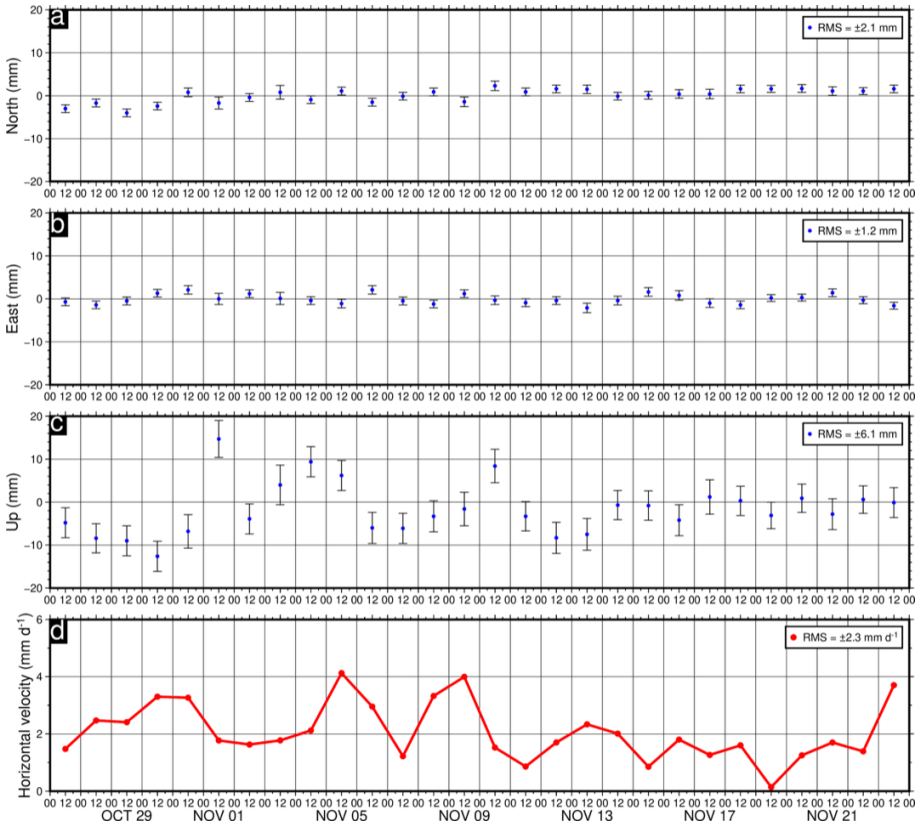


Figure A1. (a-c) Daily position estimates with one standard deviation error bar for the site ARGB in November 2022. (d) Noise level in horizontal velocity determined at the stationary site ARGB for static solutions.

We empirically assess the quality of position estimates using a stationary site ARGB which was intentionally installed on bedrock in November 2022 close to the survey sites on the glacier with a similar multi-path scattering environment. This site serves as a control point because the formal errors generated by the software for a static position estimate are only applicable

to “true” stationary sites. Since Argentière Glacier moves faster than 10 cm per day, GAMIT considers this motion as a formal error in position estimates. Applying these formal errors would violate the least-squares requirement, resulting in overestimated and biased residuals (King, 2004). The position time series of the stationary site ARGB yields an average root-mean-square (RMS) of ±2.1 mm and ±6.1 mm for horizontal and vertical position estimates, respectively (Fig. A1a–c), and the RMS of "speed" is about 2.3 mm d^{-1} (Fig. A1d).

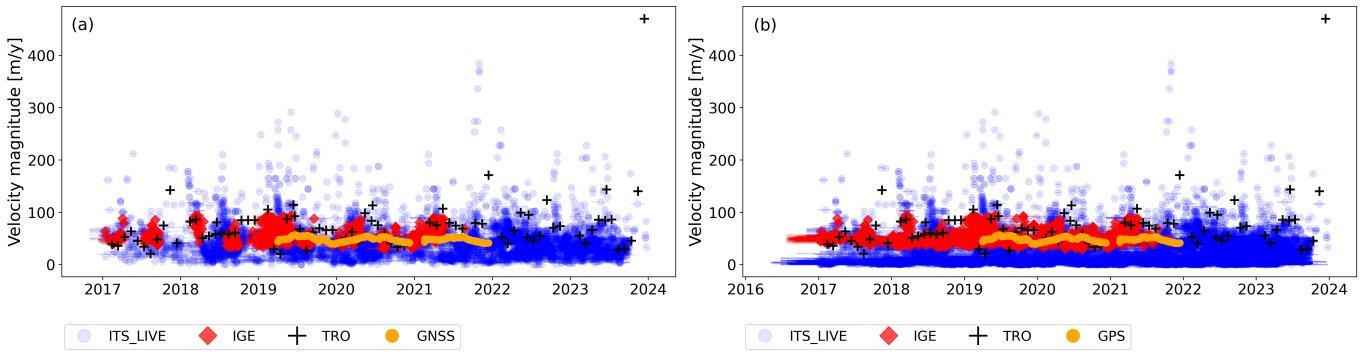


Figure A2. Velocity magnitude at the location of the GNSS antenna installed on the tongue of Argentière Glacier (yellow dots in Fig. 1), measured using a 30-day rolling mean of the GNSS data in orange; and remote sensing datasets "ITS_LIVE with NDC filter" in blue, "IGE with advanced filters" in red and "TRO" in black. (a) Raw velocity estimates from small baseline velocities (< 180 days). (b) Raw velocity estimates from all baseline velocities.

Appendix B: Insight from static areas analysis

B1 Active moving areas detected using InSAR

With regard to the InSAR catalog, active moving areas were obtained by visually inspecting 134 Sentinel-1 interferograms (75 and 59 on ascending and descending orbits, respectively) across the entire French Alps. Interferograms were processed using the ForM@Ter LArge-scale multi-Temporal Sentinel-1 InterferoMetry processing chain —FLATSIM— service (Thollard et al.) at different temporal baselines (6, 12, 60 and 360 days).

Appendix C: Origin of seasonal biases

Appendix D: Evidence of seasonal bias in different regions

We compare each of the ITS_LIVE image-pair velocity magnitudes to the GNSS velocity magnitude from (Charrier et al., 2025) on the Lower GNSS station of Kaskawulsh Glacier (Fig. D2). For simplicity, we neglect the temporal baseline and assign each image-pair velocity measurement to the central date of the pair. We stack the difference between the image-pair velocities and the GNSS, i.e., the errors, by day of the year (red dots in Fig. D2). Then, we apply a 30-day rolling median to

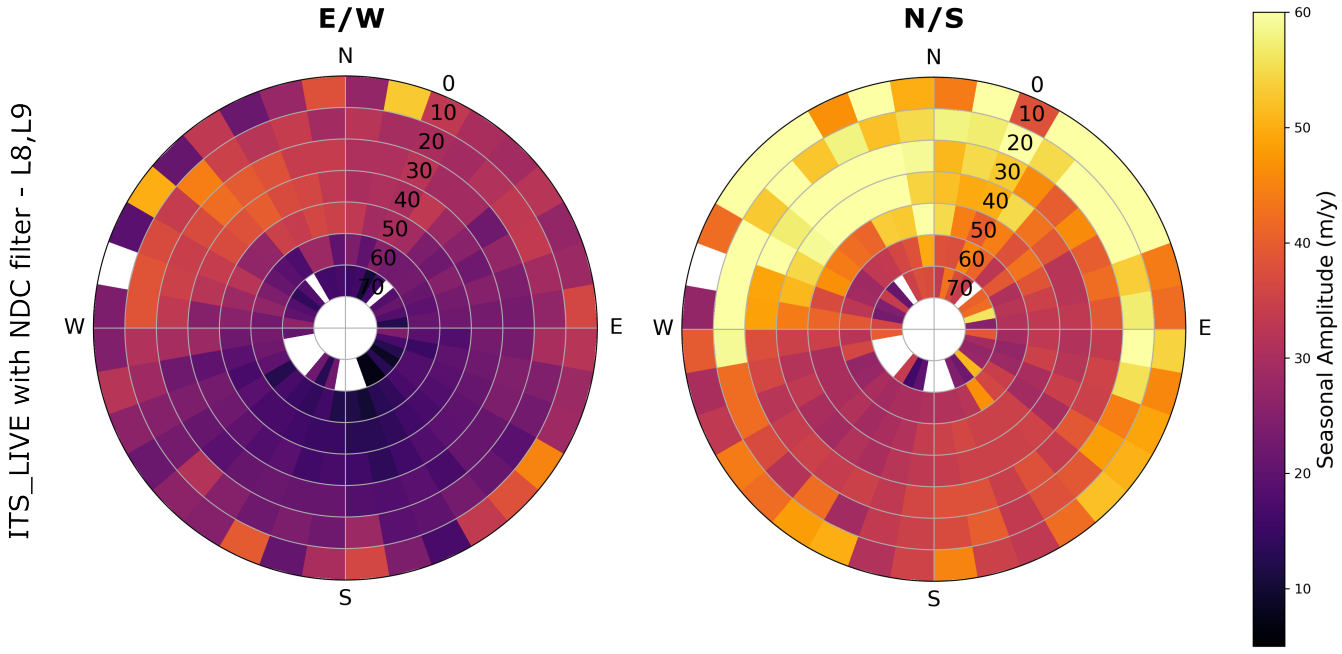


Figure B1. Polar diagram of the median seasonal amplitude of east/west (left) and north/south (right) components of the dataset "ITS_LIVE with NDC filter" using Landsat-8/9 images over static areas. The size of the bin is 10° for both slope and aspect. The slopes are shown along the radial axis, with the highest slopes in the center.

these stacked data (black line in Fig. D2). The errors seem to follow a seasonal pattern with two maxima. This first maximum is reached in spring, around days 120 to 150 of the year while the other is reached in autumn, around days 250 to 300 of the year. This is consistent with the pattern of seasonal bias identified in Section 4.2 and Fig. 5.

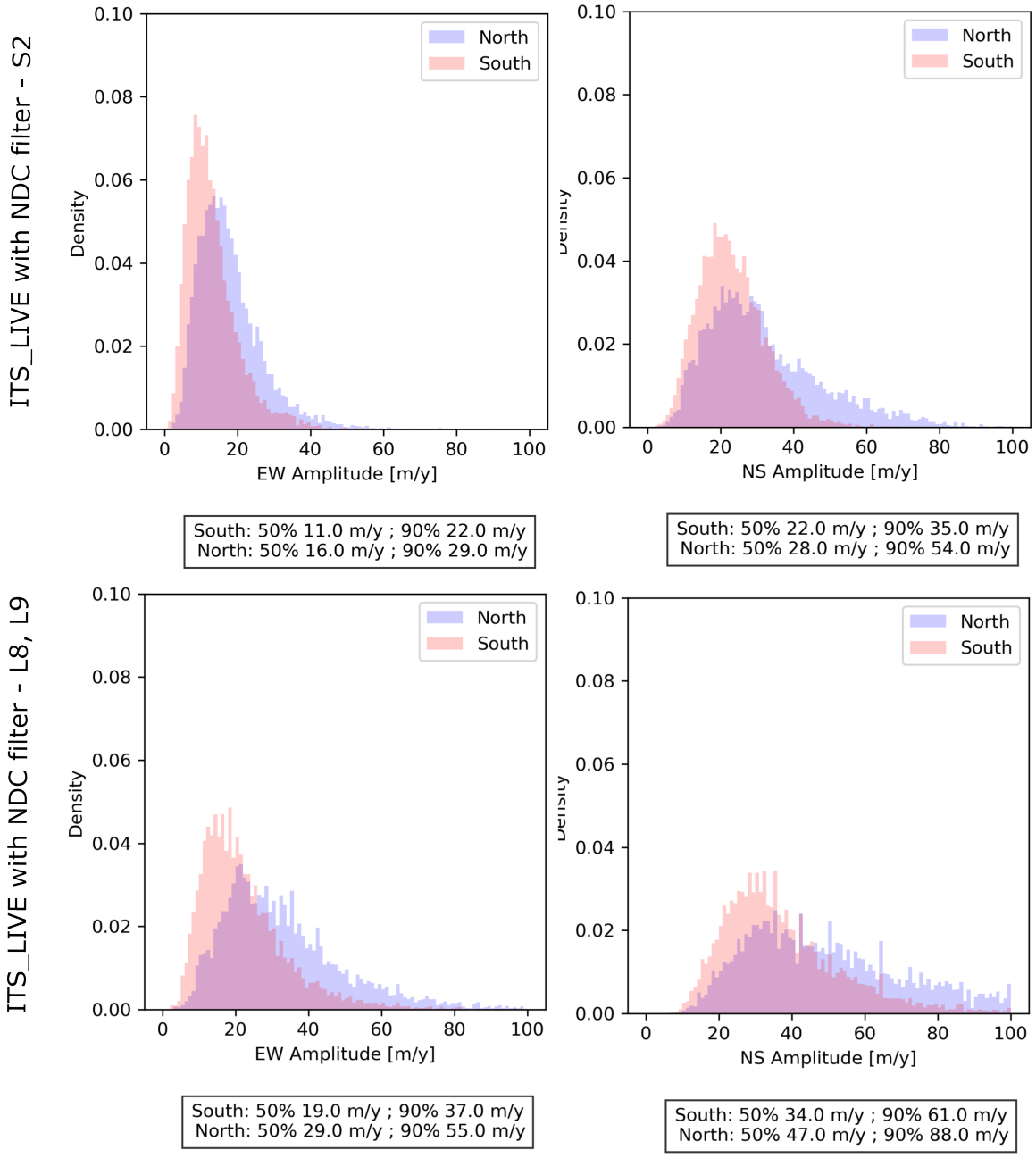


Figure B2. Histograms of the amplitude in static areas of a sinusoidal regression applied to the east/west (left) and north/south (right) components of the datasets "ITS_LIVE with NDC filter" based on Sentinel-2 images (top row) and based on Landsat-8 and 9 images (bottom row). Red bins correspond to south-facing slopes while blue bins represent north-facing slopes. Note the different ranges of the x-axes.

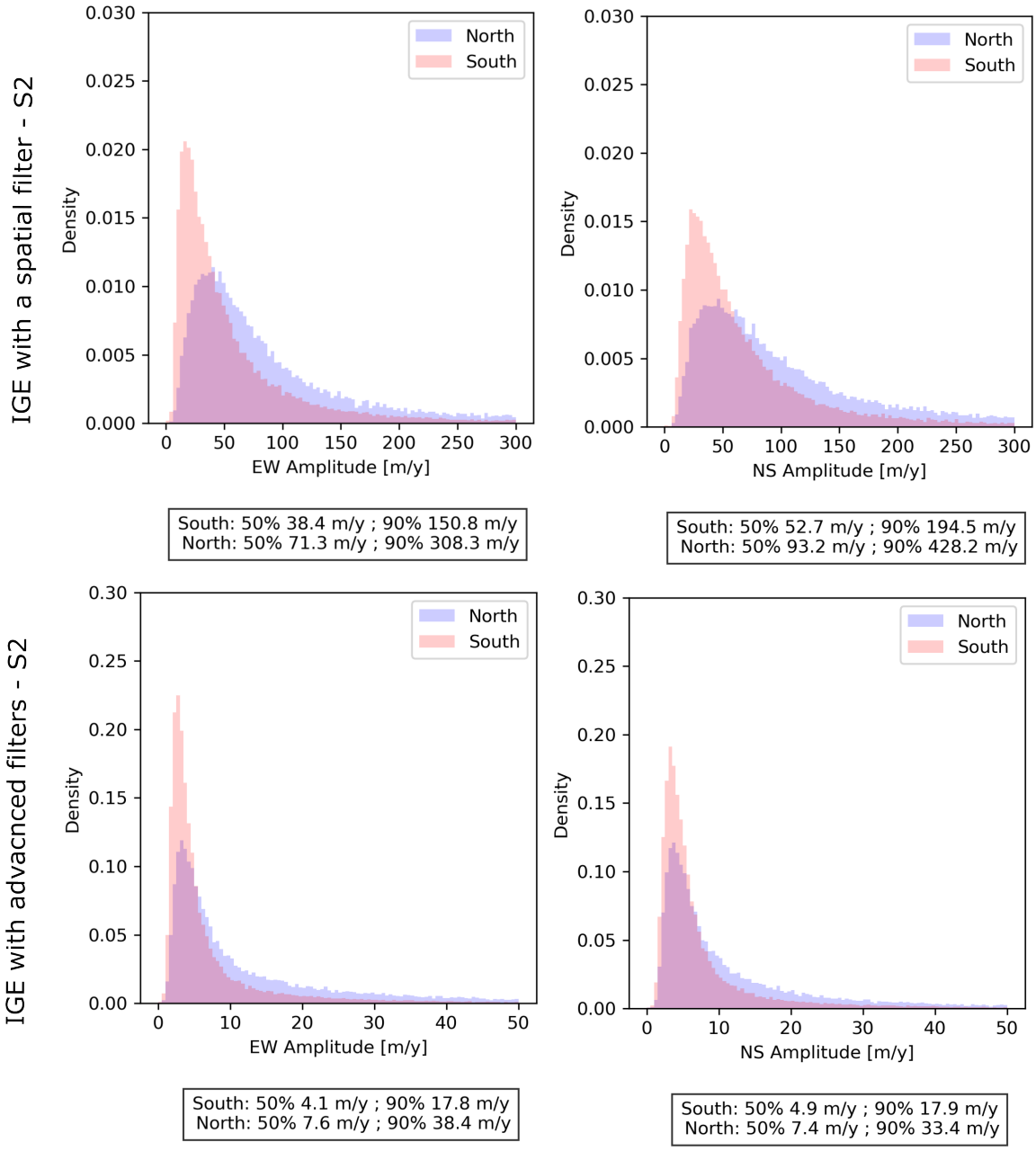


Figure B3. Histograms of the amplitude of a sinusoidal regression applied to the east/west (left) and north/south (right) components of the datasets "IGE with a spatial filter" (top row) and "IGE with advanced filters" (bottom row). Red bins correspond to south-facing slopes while blue bins represent north-facing slopes. Note the different ranges of the x-axes.

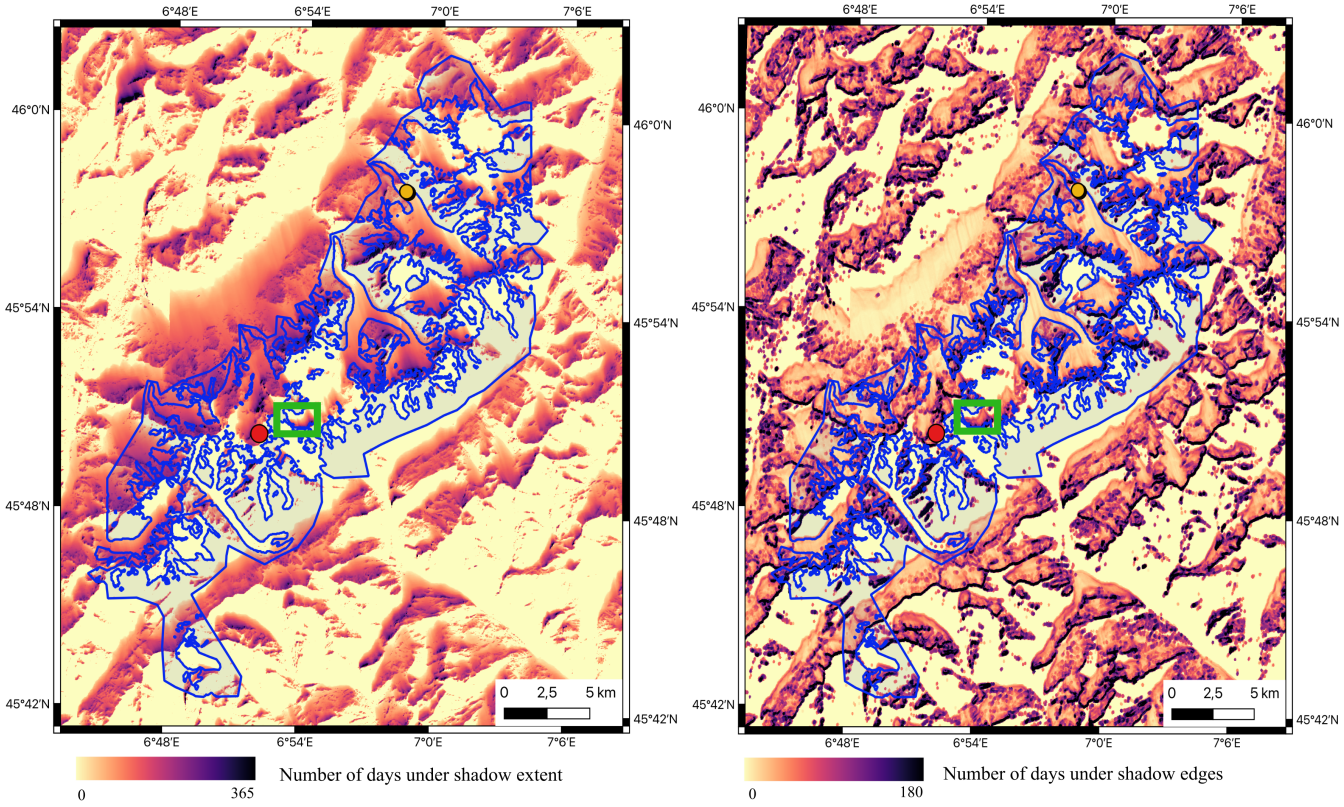


Figure C1. Simulation of the number of days covered by shadow extent (left) and shadow edges (right). The red dot represents the point of coordinate (6.86759°E, 45.83930°N) over the Bossons Glacier given as an example in Fig. 7. The yellow dots correspond to the Arg1 GNSS station. The green rectangle corresponds to Combe Maudite, an area highly affected by shadow casting. The projection of the map is EPSG:32632 and the displayed coordinates are in EPSG:4326.

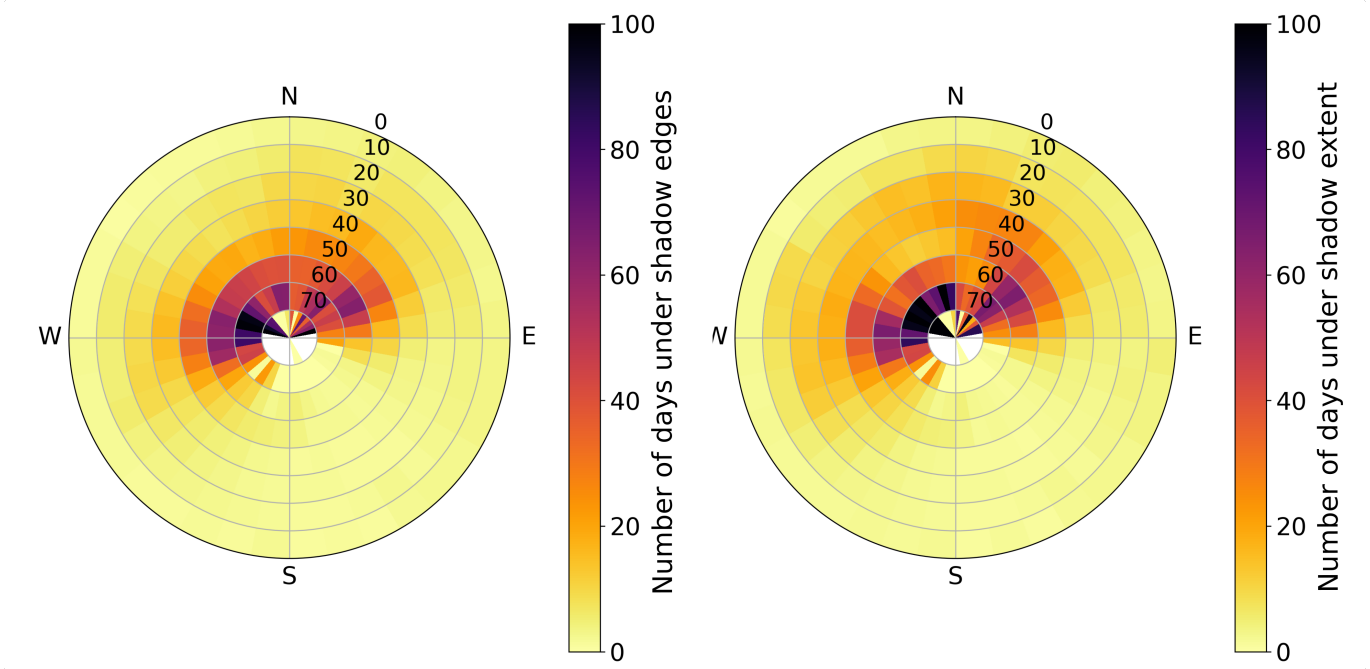


Figure C2. Polar diagram of the number of days under shadow edges (left) and extent (right) over one year for different ranges of aspects and slopes. The simulation has been run over the entire Mont-Blanc Massif.

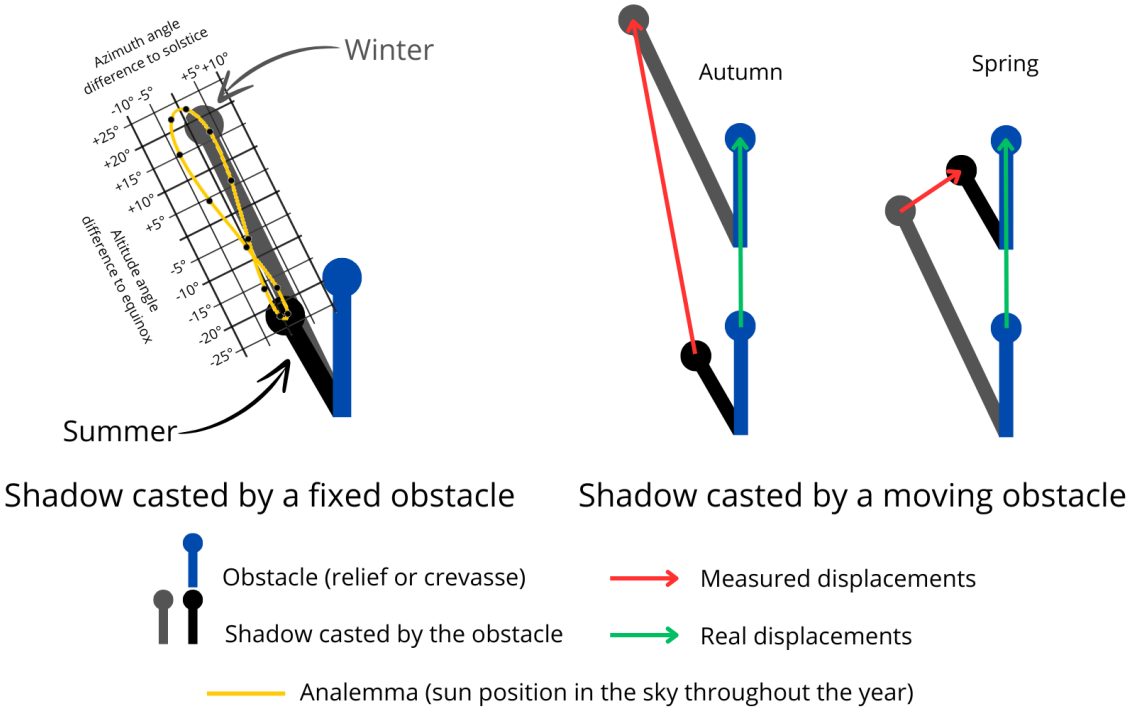


Figure C3. Theoretical illustration of the cast shadow effect. A shadow can be either projected by the topography or the local relief (crevasses, seracs, etc.), here, moving towards the north. We note that the direction will deviate from the real glacier flow direction depending on the angle between the shadow elongation and the glacier flow direction. The expected movement of a shadow cast through the year is represented by the analemma (in yellow). The shadow cast extends from the winter to the summer solstice and shortens from the summer to the winter solstice. The velocity at which the shadow extends or shortens increases from the summer solstice to the autumn equinox (and from the winter solstice to the spring equinox), and then decreases.

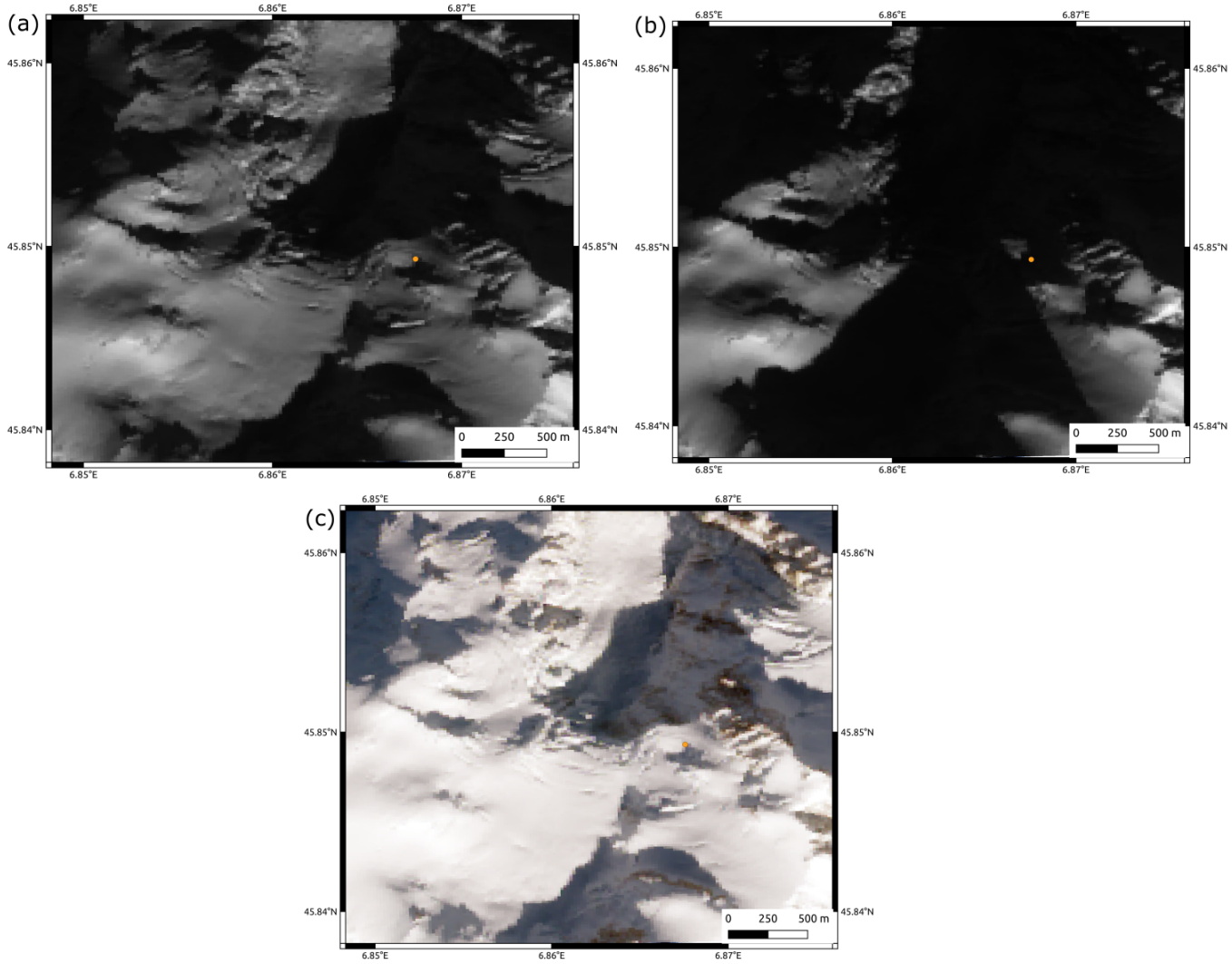


Figure C4. Shadow casting example at the point (6.86759°E, 45.83930°N) over the Bossons Glacier. Sentinel-2 Band 8 images from 10 October 2024 (a) and (b) 04 November 2024. (c) Sentinel-2 True color from 10 October 2024. The location of the area is represented by a yellow rectangle in Fig. A1.

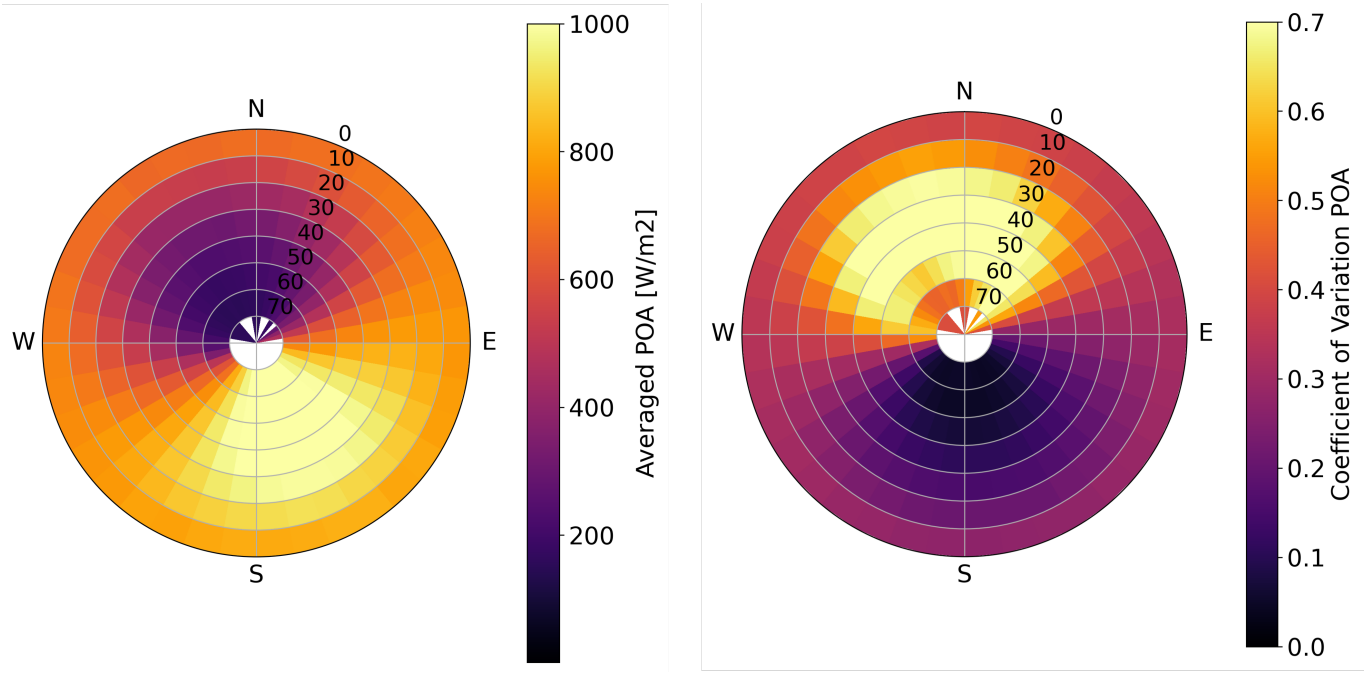


Figure C5. Polar diagram of the average (left) and coefficient of variation (right) of the POA irradiance over the Mont-Blanc Massif for different ranges of aspects and slopes.

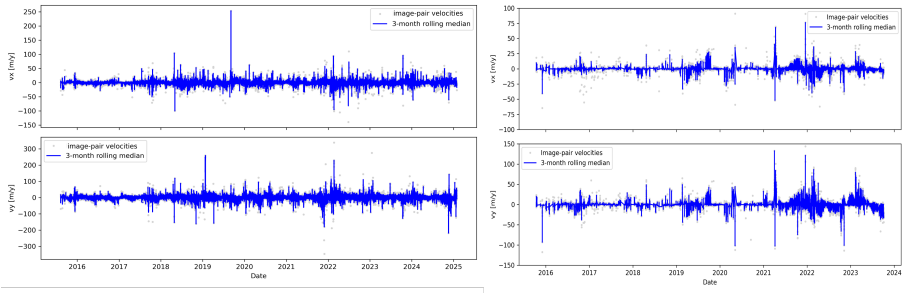


Figure C6. Raw data (light gray) and three-month rolling mean (blue) of velocity over the static areas of the Mont-Blanc Massif for the datasets "ITS_LIVE with NDC filter" (left) and "IGE with a spatial filter" (right). Note the different limits of the y-axis between the left and right figures. Note that we observe no changes in the velocity time series after summer 2021 that could be related to the geometric refinement of the Copernicus DEM used to co-register Sentinel-2 images.

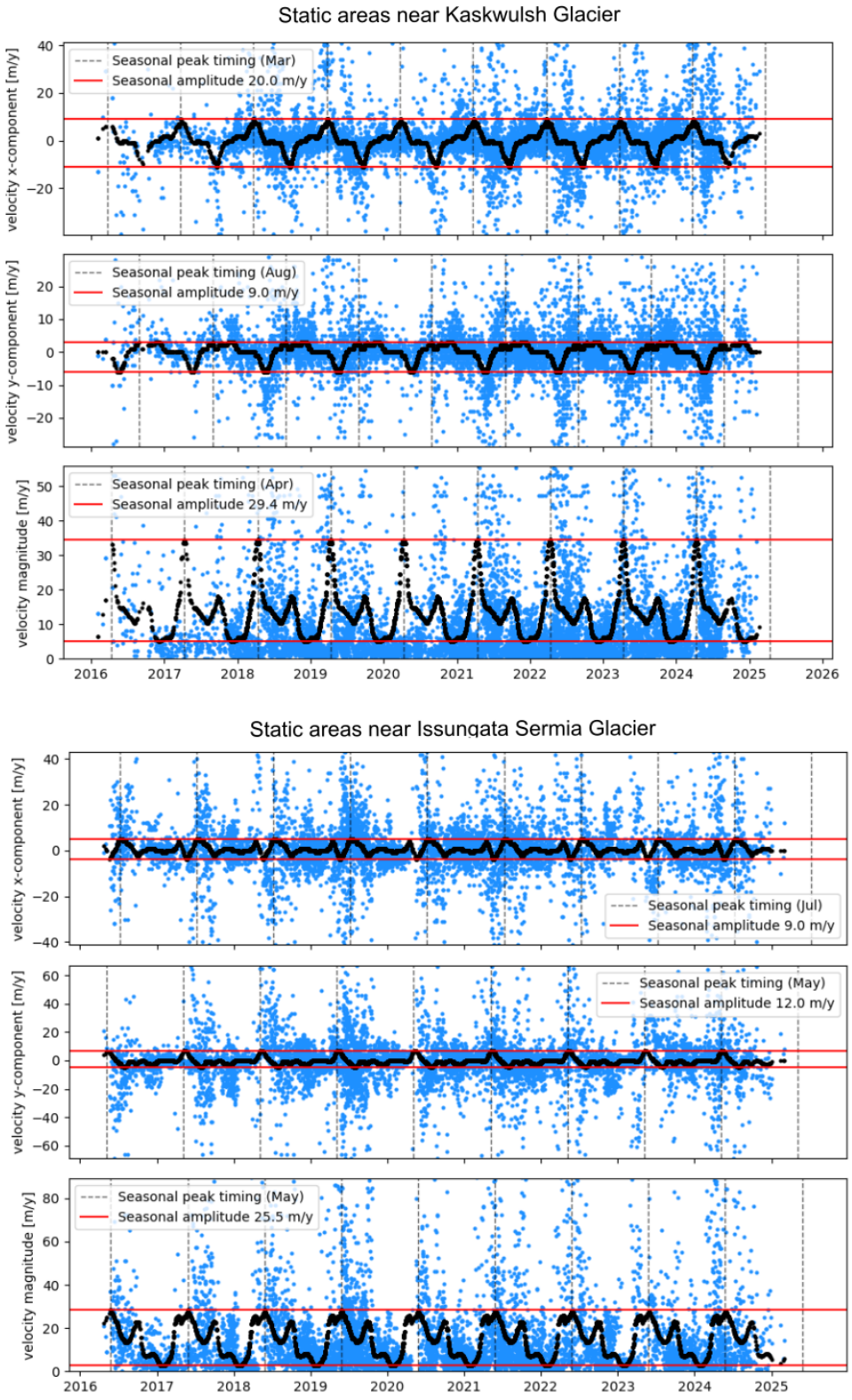


Figure D1. Example of velocity time series over static areas, represented by the two red points in Fig. 10. The coordinates of the points located near Kaskawulsh Glacier and Issungata Sermia are (-138.7238°E, 60.8552°N) and (-50.348547°E,67.339909°N) respectively. Blue dots correspond to ITS_LIVE v2 image-pair velocities. Black dots represent the smoothed velocity time series used to infer seasonal peak timing and amplitude. This time series is computed using a weighted rolling median applied to the image-pair velocities stacked according to their respective day of the year (see Section. 3.2).

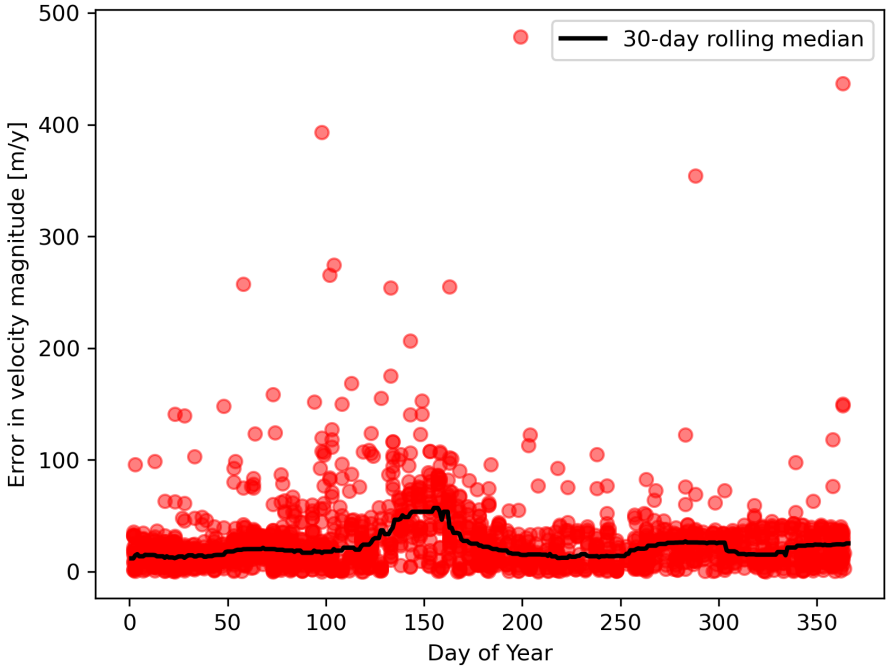


Figure D2. Difference between the velocity magnitude of GNSS and ITS_LIVE image-pair velocities over the the Lower GNSS station of Kaskawulsh Glacier (Charrier et al., 2025).