Response to reviews

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First of all, we would like to thank the editor and the reviewers for their careful reading of the manuscript and for their detailed and constructive comments, which helped to improve the manuscript.

In addition to the reviewers comments, we have carefully considered the editors' suggestions. In the revised manuscript, we focused more on the historical velocity dataset and expanded the discussion of ice-dynamic processes, as suggested.

In the following, we quote the reviewer´s comments followed by our replies, which are marked in orange. The figure numbers and line numbers refer to the original version of the manuscript (not the revised manuscript).

Author´s response to referee comment # 1

General comments

The manuscript reports on the temporal evolution of surface velocity of the glacier Vernagtferner in the Eastern Alps with focus on a period of major slowdown in recent years after the glacier broke up in several parts. The presented velocity data are based on in situ stake measurements and manual feature tracking in optical airborne images. The presented material and related discussion cover two main topics: (i) the presentation and description of the derived velocity field and of factors responsible for slow-down, including a review of the glacier behaviour since 1966; (ii) an overview on specific remote sensing products on glacier velocity, leading to the conclusion that these products are not suitable for application to slowly moving glaciers. Topic (i) is an interesting case study on a glacier in retreat, demonstrating the impact of long-term negative mass balance and related glacier thinning on a previously quite active Alpine glacier. Factors responsible for the decline are discussed, but an in depth assessment of the governing processes is missing. The presented material on topic (ii) does not contain any novel aspects. In summary, the paper presents an interesting case study on slow-down of an Alpine glacier in decay but has substantial shortcomings. Major revisions and shortening (in particular regarding topic ii) are required.

Topic (i): We have included a classification of the relevant processes for slowing down glacier velocity. Please see in the last comment of this response.

Topic (ii): We agree with the reviewer, that this topic does not provide any new aspects. However, the use of global data sets and standard remote sensing would be the most obvious choice, as these data also provide velocity maps for the area. We aimed to demonstrate that neither the existing global datasets nor our remote-sensing attempts specifically focussed on VF provide/are able to generate a reliable velocity field. We do not want to rule out the possibilities of semi-automated feature tracking. Rather, we would like to explain why we chose manual feature tracking and point out the problems caused by ablation in more detail (see comments). Based on this finding, we generate an interpolated velocity map based on in-situ measurements. The focus of the manuscript is more on the historical data sets, whereby we believe that an examination of current ice dynamics is relevant in order to provide a velocity map ready for other studies, e.g. ice flow modelling. We will try to better clarify this in an updated manuscript.

Specific Comments

Satellite remote sensing: Major parts of the manuscript refer to spaceborne remote sensing of glacier velocities (Introduction line 45 to 53, Sections 3.2, 3.3.1, 4.3.1, Section 5.2, Fig.2, Fig. 9). These sections refer to properties and suitability of particular products, but do not provide any novel information on methods, accuracy assessment and constraints regarding remote sensing techniques and products for mapping glacier surface motion. During more than three decades results of detailed performance analyses on glacier surface velocity methods and products have been reported in publications and product specification documents, both for so-called "standard satellite remote sensing products" as well as for products derived from data of different satellite missions. These publications show that the pixel size and errors of the "standard products" (based on offset tracking) do not match the accuracy and spatial detail required for mapping very slow velocities at comparatively small spatial scale as observed on Vernagtferner. Taking this into account, the sections on satellite remote sensing can be largely shortened and replaced by references on documents and publications specifying performance numbers for specific satellite-based velocity products. Furthermore, Figures 2 and 9 can be omitted because there is no need showing examples of deficient velocity maps using input data that are not matching the technical requirements needed for velocity retrievals of the study glacier.

Thank you very much for your feedback. You are absolutely right, further information on the accuracy assessments is missing, especially for the velocity products. We have added some information on this. We also agree that, due to the pixel size and errors, the "standard products" cannot provide any meaningful values for a slow-flowing glacier such as the VF. However, we would like to point out that this is the case for many slow flowing glaciers, which are contained in the datasets and are already used in regional-scale modeling studies (e.g. Cook et al 2023). We have now explicitly included this note.
We do not want to rule out the possibility that, in principle, no velocity data can be derived for the VF via remote sensing. Therefore, in Section 4.3.1 with Fig. 9, we would like to include an analysis of the significantly higher-resolution TerraSAR-X data with a spatial resolution of 2 m, which makes detection quite realistic, assuming a detection capability of 0.1 of the pixel size. On VF the challenge is not only in the slow flow, but also in the high ablation and therefore the change of features due to ablation. To explain this in more detail we added an Appendix.

We added in chapter "review of existing products":

The accuracy of the products can vary strongly locally and depends on the velocity level, coherence, existing features, etc., but can be estimated at 0.08 m per day for a temporal baseline of 12 days, for example (Gardner.2022,Friedl.2021,Millan.2022). The accuracy is insufficient for a slow-moving glacier such as the VF, as the speed is lower than the uncertainty of the measurement. This is the case for many slow flowing glaciers, which are contained in the datasets and are already used in 130 regional-scale modeling studies (e.g. Cook et al., 2023).

Appendix A:

The figures show the same situation at different points in time:

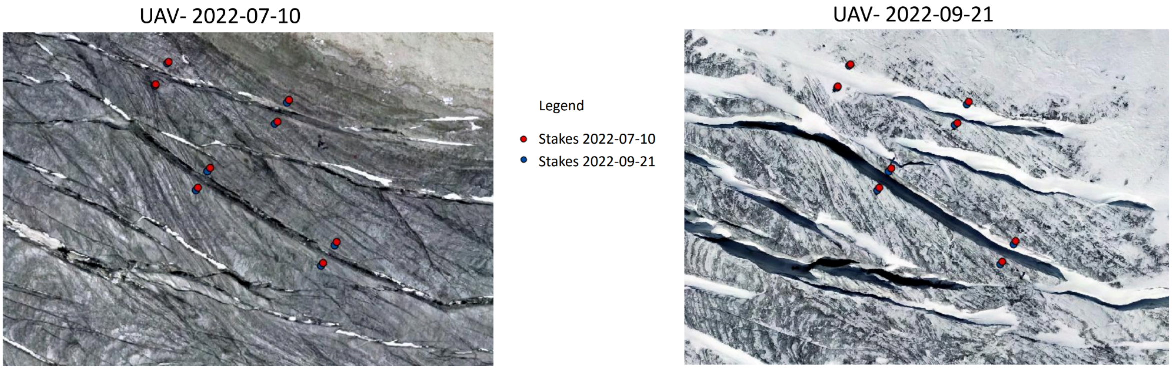


Fig. 2:. Melt-induced changes to crevasses. The example is taken from the upper part of the Taschach area at an altitude of approx. 3150 m. Maximum velocities occur in this area at the VF.

Figure 2 clearly shows a change in surface features, in particular a widening of the crevasses. We examined two of the crevasses in more detail using two stakes at the upper and lower edges of each crevasse. The average movement of the eight stakes (shown in Fig. 2) over the two months is approximately 0.73 m (change from the red to the blue points), with a standard deviation across the eight stakes of 0.12 m . The stakes rule out the possibility that a significant actual break-up of the crevasses has taken place. The stakes show an even shift of the upper and lower edges of the crevasses. Thus, the change in the surface is probably largely due to melting. Even if identical features (in this case, crevasse edges) could be identified during the period, the movement would be significantly overlaid by ablation due to the crevasse edges (and their varying melt rates), resulting in erroneous dynamics.

Even with larger temporal baselines, manual feature tracking can be used to exclude features that are likely to have changed due to ablation, as is often the case in 2022. Crevasse trace intersections are particularly well suited for this purpose, as can be seen in Fig. 3 Identifying identical features that have not been subject to high ablation is challenging even for the human eye, especially over longer baselines, such as the example in Figure 4 over a period of two years.

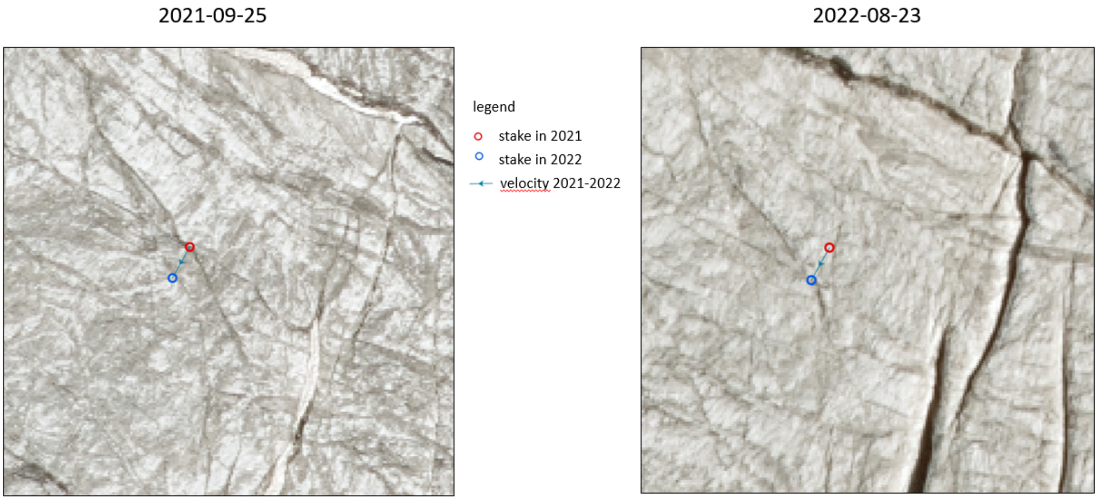


Fig. 3: Melt-induced changes to crevasses. Example from the upper part of the Brochkogel area at an altitude of about 3200m.

Fig. 4: Crevasse pattern in a period without significant melt. Crevasse pattern in a period without significant melt. Example from the highest part of the Brochkogel area at an altitude of about 3250 m.

Analysis and interpretation of surface velocities: The new velocity data, presented in the manuscript, refer to the period 2018 to 2023 when maximum velocities of Vernagtferner were below 5 m yr^{-1}. The presented velocities are horizontal displacements referring to individual points on a main branch of the glacier, based on manual feature tracking in optical airborne images and on stake measurements. Considering the average velocity of 1 m yr^{-1}, it is obvious that the magnitude of vertical surface lowering exceeds that of the horizontal displacements. Consequently, the vertical displacement of the surface (mass depletion due to surface/atmosphere exchange processes) is the dominating component for the glacier mass balance in the current state and ice dynamics plays a minor role. In this context, quantitative information on the annual mass balance (respectively the related topographic change) and its spatial pattern during the study period would be of interest.

We agree. We provided further analysis. Please see the last comment of the response to review 1.

Line 45 to 53: This is a one-sided introduction on space-borne remote sensing applications for ice velocity monitoring. The statement on the use of space-borne remote sensing “particularly in Antarctica” does not reflect the actual situation in which ice velocity products are generated routinely on behalf of various organizations, covering at large all global land ice areas. Several of these products exploit also radar repeat-pass interferometry in regions and seasons where coherence is preserved.

That´s true! The specialization in Antarctica should refer specifically to the cited literature. To avoid misunderstandings, we will rephrase this:

Space-borne remote sensing data can be utilized to estimate ice velocity of mountain glaciers and in particular of the large polar ice sheets (Dirscherl et al., 2020).

Line 56-57: Temporal decorrelation is not a particular problem for slowly flowing glaciers, but rather for fast movement, particularly in shear margins where interferometric fringes are often tightly spaced or aliased.

That is correct. It is the combination of high ablation (and the associated significant surface change) and low velocities that makes coherence formation difficult, as the very low velocity is barely measurable when coherence exists or the feature change is overlaid by ablation instead of actual ice dynamics. Therefore we changed the sentence to:

In addition, we aimed on providing a map representation of current ice flow, in order to demonstrate the low-flow character of the glacier, with its specific variability. We decided to use manual feature tracking, after highlighting the challenges associated with high ablation for retrieving glacier velocities on slow-moving glaciers with remote sensing techniques.

Regarding the high ablation, please see also the new Appendix, in the response to the first specific comment of this document.

Line 86: Horizontal displacement and surface velocity are not the same.
Thanks for mentioning that. We change it to:
This allows the calculation of the annual surface velocity.

Line 113-118: Whereas time spans of TerraSAR-X repeat-pass data are 11 days, there are other high resolution SAR constellations offering shorter repeat-pass sequences, well suitable for glacier velocity mapping based on the motion-related interferometric phase. For example, successful glacier monitoring applications have been reported for 1-day, 3-day and 4-day interferometric repeat pass pairs of the COSMO Sky-Med constellation, providing high accuracy velocity products. Coherence tracking applies cross-correlation matching of templates and thus has a spatial resolution and sensitivity similar to feature tracking.

You are absolutely right; in this paragraph, we describe the TerraSAR-X data in a very one-sided manner. We have added information about possible further (including shorter baseline) satellite missions, which have already been used to generate very good velocity information for faster-flowing glaciers. Since the average velocity on the VF is only about 1 m/year, which corresponds to an average movement of about 0.27 cm per day without taking possible seasonal fluctuations into account, baselines of 1-4 days for interferometric displacement mapping, might lead to some results. However, there are no acquisitions available for VF. Moreover, the considerable surface melt in summer will limit this application to winter months, where snowfall also leads to the loss of coherence.

We change the manuscript to:
In addition to user-ready products (which do not provide usable results), there are high-resolution SAR constellations that offer repeat-pass sequences beginning at 1-day. To name a few, ICEYE InSAR (Lukosz 2021), Capella Space SAR (Izzard 2025), COSMO Sky Med (Wang 2018), and TerraSAR-X (Schubert 2013) constellations have already been successfully used to generate velocity maps. As an example, we tested the suitability of TerraSAR-X stripmap imagery (≈2 m spatial resolution) for obtaining glacier surface velocity fields on VF. Therefore, we applied feature tracking using various tracking window sizes (32x32, 64x64, 128x128, 256x256) and temporal baselines ranging between 11 days and up to about 2 years to pairwise co-registered images. The SAR processing was carried out using GAMMA Remote Sensing Software. The dates and orbit information of the employed acquisitions are summarized in Appendix C. All possible image pair combinations were tested using an automated processing pipeline (e.g. Seehaus et al., 2015, 2018), including a filter algorithm based on a comparison of the magnitude and the alignment of the displacement vector with surrounding values to remove unreasonable displacement estimates (Burgess et al., 2012). Coherence tracking or InSAR-based displacement measurements were not feasible to carry out at VF, because the InSAR coherence was not maintained between subsequent acquisitions, which we attribute mainly to the pronounced surface-lowering rates in summer and snow accumulation in winter.

Figure 3: Please provide information on the time periods (years) to which the time sequences of the individual stakes refer.

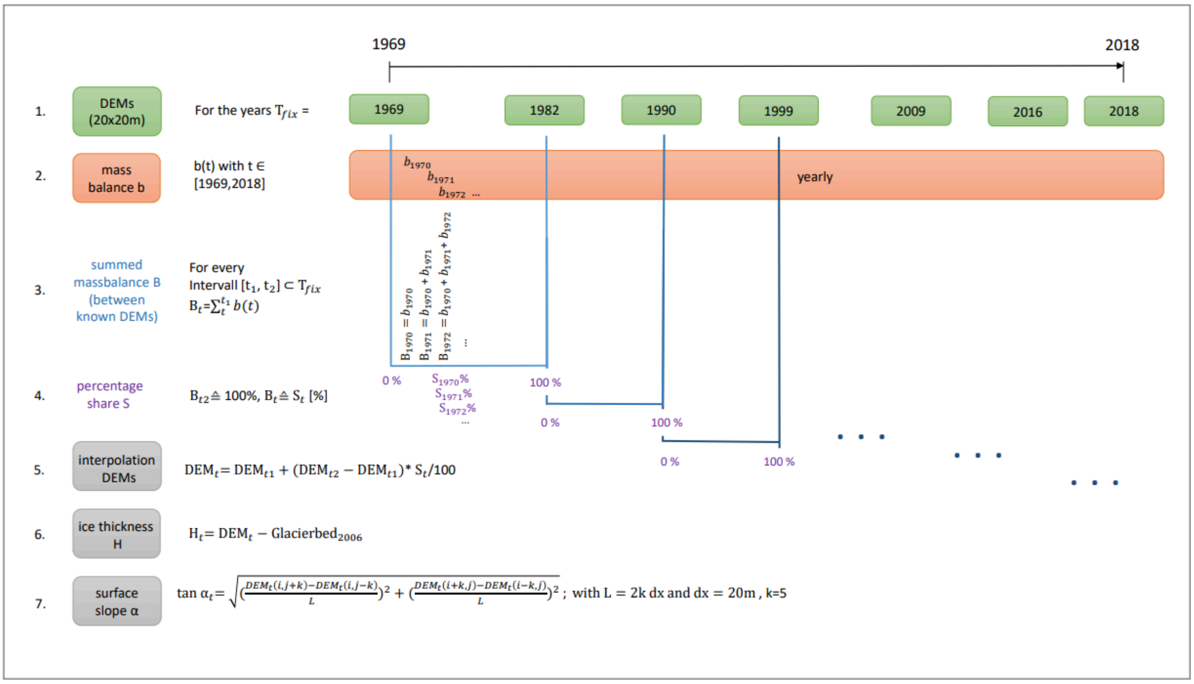
Due to limited display and space constraints, it is difficult to provide precise information on the exact period of time in this figure. The periods of the longer (more relevant) time series can be read from Figures 4 and 5, as the same color coding has been used here. We have added a note to the caption of Figure 3 to indicate the color correlation with the following figures:
The color coding correlates with Figures 4 and 5.

Figure 5 caption: Please provide reference for the source of the ice thickness data 1970.

Thank you for the hint. To explain the calculation of ice thickness in detail, a flow chart and a written explanation have been added to the method section:

In order to apply the SIA approach, annual ice thickness and surface slope are required. For this purpose, DEMs were generated by interpolation between available DEMs at known times (Finsterwalder, 1972; Rentsch, 1982 and more recent maps published by the group at BAdW) for workflow, see Fig. 3. All available datasets are listed in the Appendix A. Instead of assuming linear interpolation over time, the interpolation between two consecutive DEMs was scaled according to the cumulative SMB. The mass balance is described by a single glacier-wide value per year, as area distributed annual mass balances from the glaciological method are not available for all periods. For example, the DEM from 1969 and 1982 is available, the years in-between are interpolated. Therefore, we started to sum the SMB during this period of time and used as relative measure of surface elevation change. This means, that the elevation change between the DEMs from 1969–1982 corresponds to 100% of the cumulative SMB from 1969–1982 (in this example -596 mm w.e.). The yearly change in DEMs were generated according to the cumulative SMB reaching the respective year, for example cumulative SMB 1969–1976 with -520 mm w.e. corresponds to 87%, meaning that 87% of the elevation change from 1969–1982 would be applied to the DEM in 1976. In this way, elevation changes are distributed non-linearly in time and reflects periods of higher or lower loss/gain. The error of non-linear ice transport over time is neglected, as the velocities are relatively low.

The respective ice thickness is derived by subtracting the bed topography of 2006 (Mayer et al., 2013b) from the corresponding interpolated DEM. Surface slope was calculated from the annual DEM using five grid cells (k=5) in each horizontal direction, with a grid size (dx) of 20 m, the baseline length (L) is 200 m. The resulting ice thickness and surface slope were restricted to the last known glacier extent. To compare the calculated velocity to in-situ stake observations, we extract the calculated velocity from the 20 x 20 m grids using a nearest-neighbor approach.



Flowchart for calculating ice thickness and surface slope

Section 4.2, Seasonal variation: The summer velocities are based on measurements in summer 2022, the ablation period of the mass balance year 2021/22 with the largest mass deficit of the 2018 to 2023 period in the Eastern Alps. Consequently, it is unclear if the number for the seasonal velocity increase 2022 is representative for the whole period.

Thank you for pointing this out. We have added the reference to the extremely negative year.

Text:
However, we consider the derived seasonality to be representative for the entire VF for July-September and assume its applicability to other years, although 2021/22 was a year with an extremely negative mass balance.

Figure 8: The presentation of a few numbers (velocities, exact dates) in the form of a table would be more appropriate than the display within a diagram.

Precise data (not averaged) is certainly interesting at this point, which is why we have included a table now. However, to enable quick and easy reading of the 30% seasonal variation, the table has been added in addition to the figure.
The coordinates of the individual measurements are stored in the PANGAEA Database. The table only shows the resulting velocities, separated into the Taschach and Brochkogel areas, whereby the Brochkogel

area is only represented by 3 respectively 4 stakes within a few square meters, meaning that they all describe the same situation (one point could no longer be found in August 2023).

Table 3. Values of summer (v_{JA}, v_{AS}) and annual surface velocity (v_{a}) and the calculated seasonal variation ($v_{\mathrm{AS}}/v_{\mathrm{a}}$, $v_{\mathrm{JA}}/v_{\mathrm{a}}$) for Taschach (8 stakes) and Brochkogel area (4 stakes).

Area	Number	v_{JA} Juli 22–Aug 22 [m yr^{-1}]	v_{AS} Aug 22–Sep 22 [m yr^{-1}]	v_{a} Aug 22–Aug23 [m yr^{-1}]	$\frac{v_{\mathrm{JA}}}{v_{\mathrm{a}}}$ seas. var.	$\frac{v_{\mathrm{AS}}}{v_{\mathrm{a}}}$ seas. var.
Brochkogel	1	3.37	5.05	3.14	1.07	1.61
Brochkogel	2	3.44	4.74	3.03	1.14	1.56
Brochkogel	3	4.52	4.16	3.22	1.40	1.29
Brochkogel	4	4.62	3.00	no measurement		
Brochkogel	**mean**	**3.99**	**4.24**	**3.13**	**1.20**[a]	**1.49**[a]
Taschach	1	4.54	2.21	2.38	1.91	0.93
Taschach	2	3.78	2.39	2.27	1.67	1.05
Taschach	3	3.57	3.85	3.09	1.16	1.25
Taschach	4	4.12	3.97	2.17	1.90	1.83
Taschach	5	1.27	1.52	1.74	0.73	0.87
Taschach	6	1.82	3.84	2.11	0.86	1.82
Taschach	7	2.24	3.49	2.17	1.03	1.61
Taschach	8	2.08	1.95	1.77	1.18	1.10
Taschach	**mean**	**2.93**	**2.90**	**2.21**	**1.30**	**1.31**

[a] The mean ist without the measurement of Brochkogel 4.

Furthermore we determine the standard deviation. Therefore, we add to the manuscript:

in current line 221:
On average, seasonal variation is 1.30 (130%), with a standard deviation across all observations of 0.37 (37%).
and in current line 311:
At Vernagtferner, summer velocities are approximately 30% higher than the annual mean, with a standard deviation across all observations of 37%. The relatively high uncertainty results from the fact that the absolute measured values over a month (July-Aug or Aug-Sep) have maximum values of about 50 cm. However, these values have a relatively high measurement uncertainty of +/-14cm (see chapter Measurement Uncertainty).

Line 200: The statement that it is “not possible to (semi-) automatically produce a reliable surface velocity map from aerial or satellite imagery for slow-flowing Vernagtferner ….” is rather speculative, not taking into account capabilities of advanced airborne and spaceborne observation systems and analysis techniques. For example, several large satellite constellations with very high resolution SAR sensors are in space since several years. Some of these constellations provide repeat interferometric observations of excellent quality with repeat-pass intervals from one day onwards, as for example ICEYE InSAR products show.

Thank you for the helpful comment. We agree that the original wording “not possible” was too absolute and did not sufficiently take into account recent developments in high-resolution satellite and aerial remote sensing. We have therefore amended the passage and now refer to it as “challenging” to emphasize the difficulties, but not the fundamental impossibility.

In fact, there are now several satellite constellations with very high spatial resolution and short repeat intervals (e.g., ICEYE-InSAR products with daily repeats) that provide excellent data quality. Such systems open up new possibilities for detecting glacier movements. However, the specific problem of the Vernagt glacier remains: at maximum speeds of < 5 m a^{-1}, even with a repeat interval of one to several days, the displacement is only in the range of a few centimeters to millimeters, which is often within the signal noise in the currently available data. When using longer time periods, on the other hand, the melting process simply dominates the movement too much. We have added examples of other high-resolution satellite constellations to the text (see comment above).

Text:
Due to the combination of high ablation and slow velocity (for examples, see Appendix D) we decided to use manual feature tracking to produce a reliable surface velocity map from aerial or satellite imagery for the slow-flowing VF with maximum velocities of less than 5 m yr^{-1} . A sub-region with …

Line 223ff: Taking into account that the annual melt losses, amounting up to several meters, may cause significant changes of surface features, the estimates of feature position accuracy seem to be rather optimistic. For example, in line 53 it is stated that “surface features (e.g. crevasses) change considerably during this period”, a possible source for increased uncertainties in feature tracking. Furthermore, oblique views sideways of the central flowline may introduce errors, in particular if the surface elevation at the time of the survey is not exactly known. Please provide information on the procedures in which way these issues are taken into account.

Thank you for pointing this out. We have amended the description accordingly. In the new version, we now also take into account possible lateral oblique measurements, which we estimate to add approximately 5 cm of further uncertainty. We now state the positional uncertainty at ± 35 cm. As noted by the reviewer, this estimate is optimistic, but we ensure that only suitable features are included in the analysis through manual case-by-case decisions and the targeted selection of stable features (e.g., unchanged column intersections). We have added this note to the text.

The uncertainty of localizing these features depends on the image resolution (<= 20 cm pixel size), the feature size (>= 40 cm), possible sideways oblique views of the features (depending on the respective angle, in the order of around 5 cm) and the co-registration accuracy of the images. Considering these parameters, the feature position uncertainty can be estimated at 35 cm. Manual case-by-case verification and explicit searching for crevasse intersection points ensure that only features that do not change too much are selected, thus guaranteeing this very high quality.

Section 5.1, Ice dynamics: Basic mechanisms related to slow-down of glacier flow are addressed, as well as possible causes for seasonal variations. However, (1.) quantitative estimates on the impact and magnitude of the different processes at the study glacier and their (2) interactions during the observation period are missing. For contributing to the advancement of understanding of processes governing the slow-down of retreating glaciers, quantitative estimates would be essential. (3) Furthermore, hints on the significance of the study results in respect to the general glacier behaviour in this region would be of interest.

(1) Thank you for pointing this out. We have added a further analysis to quantify the ice dynamic process:

To quantify the ice dynamic process, we performed an analysis based on the observed geometry change, using surface elevation change derived from known DEMs (hereafter referred to as surface elevation change). Based on the ice thickness equation (Greve and Blatter, 2009), the dynamic contribution to ice thickness change can be computed by subtracting the local surface mass balance (SMB) from local changes in ice surface elevation. The residual component represent the local dynamic contribution to the vertical surface adjustment (assuming a stationary bedrock). The spatially distributed SMB for VF are available only from 1996 ongoing (earlier information as glacier-wide values). With a spatially distributed SMB and a surface elevation change map, the difference can be calculated as local dynamic contribution to elevation change. We apply this analysis to the period 2016–2018, for which data availability is particularly good. Although this is a very short period with regards to glacier response times, it is assumed to be representative of the current ice dynamics, as the glacier already has very low velocities during this period, similar to those observed in 2018–2023. The cumulative SMB for the years 2017 and 2018, is shown in Fig. E1a, while the surface elevation change between the years 2018 and 2016 can be seen in Fig. E1b. The difference between the two maps provide the local dynamic contribution to elevation change (Fig. E1c). In the accumulation areas (or former accumulation areas), negative values (red areas) indicate that the ice transport has a vertically downward component. In the ablation areas, on the other hand, positive values (green areas) indicate vertical mass compensation through ice transport. Figure E1c shows that the Taschach and Brochkogel areas exhibit hardly any vertical mass compensation (values very close to 0). In contrast, a local dynamic contribution to elevation change is still present in the former accumulation areas of these two sub-areas. The two green areas in the Taschach area provide good control. These are rock islands that were not excluded from the SMB map. However, the rock islands have remained stable during the period and have not moved, which is why they appear incorrectly as dynamic contribution to elevation change. A closer look at the Schwarzwand area reveals a stronger dynamic contribution to elevation change. In the northern accumulation area of the Schwarzwand area (as well as on the Hochvernagt plateau), positive values are observed that cannot be plausibly attributed to a dynamic contribution to elevation change. However, in the orthoimages, these areas are partially covered by snow and have hardly any features. It can therefore be assumed that the surface models in this area are uncertain. In addition, the SMB map is largely interpolated (in particular in the northern part of Schwarzwand area), further increasing the uncertainty of the estimated dynamic contribution to elevation change in this region. Pronounced negative error values are present in the northern part of the Hochvernagt plateau. These originate from the surface elevation models, where an error has likely occurred. In order to enable a numerical estimation of the processes, which excludes outliers as far as possible, the median of the absolute mass balance of 1.08 m yr^{-1} and a absolute dynamical contribution of 0.67 m yr^{-1} were calculated. Overall, further uncertainties must be taken into account, such as the compression and thus the change in altitude of possible firn areas due to a change in density, especially in the accumulation areas.

We added to the discussion section:

A quantitative analysis of recent geometry change (period 2016–2018) at VF indicates that SMB is the dominant control, while local dynamic contribution to elevation change remains secondary. The median absolute values for SMB (median = 1.08 m yr^{-1}) and the local dynamic contribution to elevation change (median = 0.67 m yr^{-1}) suggest that the ice dynamic is not able to fully compensate the losses due to melt, especially in the ablation area. There are indications that there may be slightly more compensation of elevation change through ice dynamics in the Schwarzwand area and that this area behaves fundamentally different from the rest of VF. This was already suggested by Reinwarth and Escher-vetter (1999) and can be confirmed here. Figure 8 also suggests a higher dynamic on the Schwarzwand tongue compared to the other tongues. Due to a lack of data (no spatially distributed SMB before 1996), it is not possible to quantitatively assess these processes for the early years of glacier observation. However, it can be assumed that the local ice dynamic contribution to elevation change was more pronounced during this time, as the measured velocities were significantly higher, particularly around 1980, with an absolute SMB being significantly smaller than it is today

Appendix E: Ice dynamics

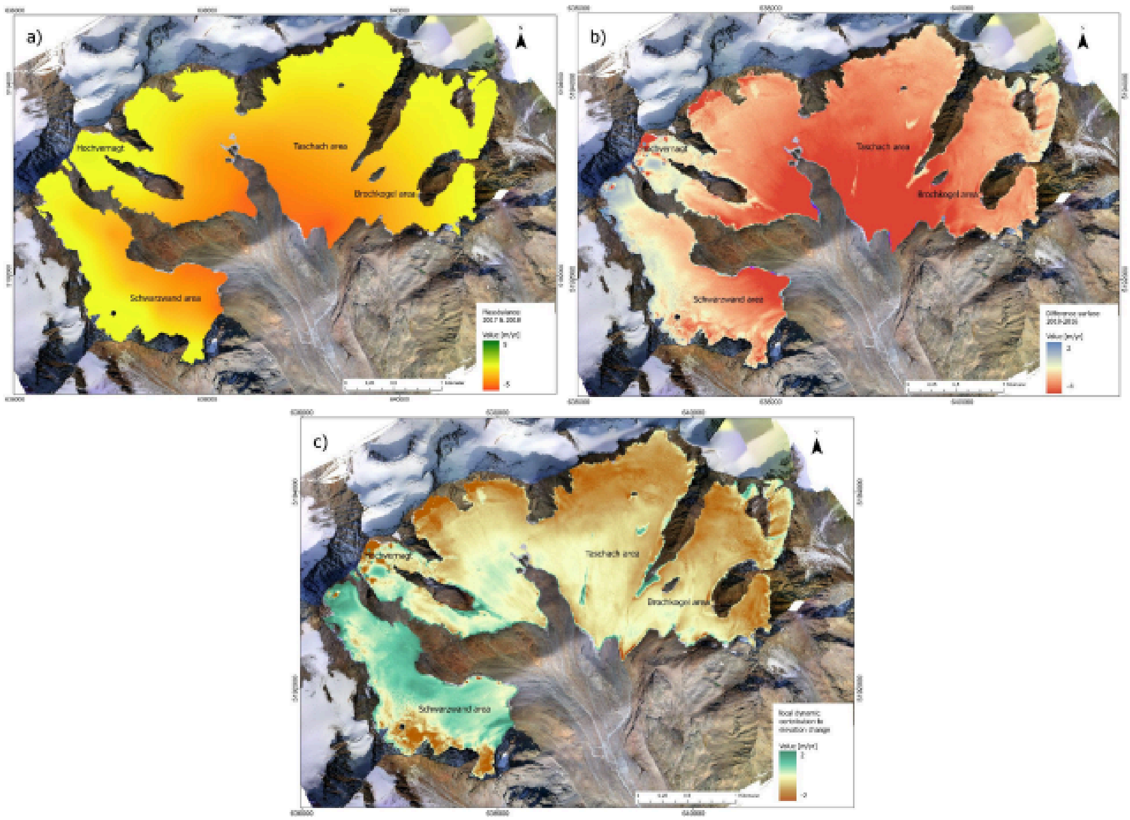


Figure E1. a) areal distributed surface mass balance summed for the years 2017 and 2018, b) surface elevation difference 2018-2016, c) Difference between a and b, which illustrates the local dynamic contribution to elevation change. Background image: Orthoimage 2016 © Bavarian Academy of Sciences and Humanities (BAdW), 2016.

(2) Thanks for the hint, we add an analysis of the temporal relationship between mass balance and velocity and compare it to other studies.

We add to the manuscript:

We have found evidence that the displacement of ablation stakes at VF react quickly to a change in the mass balance. An ongoing period of predominantly negative mass balance starting in the early 1980s marks the onset of a decrease in surface velocity in the ablation area. Ice thicknesses are rather small in the tongue areas of VF, where the stake measurements are carried out. Ice velocity is very sensitive to changes in ice thickness and the relative change of ice thickness due to strong ablation. With already reduced dynamic compensation leads to a fast reduction in ice velocity. In a year with a strongly negative mass balance, the strong melt in the ablation area directly decreases ice thickness, which represents the current status of the glacier. Stocker-Waldhuber et al 2019 have also found evidence that ablation stakes can be well suited to reflecting the current status of a glacier. They show that the Kesselwandferner (also in the Ötztal valley) shows relatively direct response of ablation area ice dynamics to changes in mass balance, regardless of the geometry of the glacier. On VF, there is insufficient data to substantiate this adequately. Further studies (including in other areas) are necessary to investigate this effect in more detail. Comparable behavior has been reported from long-term observations of the d'Argentière glacier, Mont Blanc area. Vincent et al. (2009) show an ongoing negative net mass balance since 1982, with a direct reflection (delayed by a maximum of 3 years) in the velocity. They describe that the change in velocities in the upper part of the glacier is smaller than in the lower part (ablation area). The velocity trend thus fits the VF timeline quite well.

(3) Unfortunately, apart from Vernagtferner, Hintereisferner and Kesselwandferner (we added information on that, see above) there are no other long-term measurements available for this region. Since they are two significant glaciers in the region with similar changes in ice dynamics, it can be assumed that the other glaciers in the region behave similarly, but we do not have any data on this. Instead, a comparison was made to a wider regional trend.

text:
Neighboring glaciers, such as Hintereisferner show a similar velocity peak around 1980, followed by a decrease (Stocker-Waldhuber et al., 2019). The peak aligns with a wider regional trend, as a significant proportion of glaciers in the European Alps experienced advances during this temporarily relatively cool phase (Patzelt, 1985; Wood, 1988).

Author´s response to referee comment # 2

Bevor responding to every comment, we would like to mention, that we adapted the manuscript in the following points to ensure a better readability:

- We followed the reviewers recommendation to restructure the current chapter 2 “Methods and Data”.
- We fully agree that, based on our tests, automated derivation of surface velocities cannot be ruled out (the manuscript is adapted accordingly). We would rather point out the high ablation, which overlays the ice dynamic feature change, and thus explain why we choose manual feature tracking.
- The reviewer suggested to skip parts of the manuscript by focusing either on historical data or on the interpolated present-day velocity map. As mentioned, we don't want to rule out automated derivation of surface velocities. The focus of the manuscript is more on the historical data sets, whereby we believe that an examination of current ice dynamics is relevant in order to provide a velocity map ready for other studies, e.g. ice flow modelling

In the following, we quote the reviewer´s comments followed by our replies, which are marked in orange. Since the reviewer posted many comments (i.e. general, major, specific with several subpoints), we tried to organize that with a kind of chapter structure to make cross-referencing easier. His/her general comments receive chapter index 1, while major comments chapter index 2, with every subpoint indexed accordingly. Sub-items within a comment are also numbered with numbers in brackets.
The figure numbers and line numbers refer to the original version of the manuscript (not the revised manuscript).

General comments
The manuscript by Dobler et al. analyzes the ice surface velocity of Vernagtferner, as an example of a well-monitored slow-flowing mountain glacier.
Leveraging 60 years of annual observations of stake positions, the manuscript draws a link between the glacier mass balance history and the patterns of ice speed-up and slowdown. After concluding that existing remote sensing products fail to resolve the slow flow field of Vernagtferner, the manuscript presents a map of present-day surface velocities over 2018-2023, compiled by interpolation of multi-source point measurements such as stakes and manually tracked features.
The topic of remote and in situ ice velocity measurements on slow-flowing glaciers is certainly of current interest, and a report on the long-term dynamics investigations at a data-rich site is definitely relevant and holds significant potential to advance knowledge of the ice dynamics of mountain glaciers.
However, the main direction of the manuscript is not fully clear in its current form - the two covered topics (re-analysis of long-term stake data and compilation of present-day velocity map) are only weakly linked. As such, the main message and achievements of the manuscript are somewhat hard to understand. Moreover, the manuscript stops short of advancing the current knowledge on the topic of ice dynamics. The glaciological conclusions from the analysis of such a rich historical dataset are somewhat qualitative and generic, and in some cases are not adequately supported by the collected evidence. Much of the data needed for interpretation of the ice dynamics (such as historical local mass balance, or changes of ice thickness and surface slope) are not adequately presented in the manuscript. Furthermore, the proposed method to compile a velocity map (in part) from manually tracked point measurements is affected by some significant flaws, raising questions about its suitability and advantages compared to state-of-the-art automated methods. Finally, the uncertainty analysis relies on several arbitrary estimations and

assumptions, rather than existing, well-established methods to quantify uncertainty in remotely sensed glacier dynamics.

1.1 Thank you for pointing this out. We will explain these points in detail below.

- Redefine research question see response to general comment 1.2.
- Strengthening glaciological interpretation and additional supporting evidence, see response to major comment 2.5.
- Add missing datasets, see response to major comment 2.1(4).
- Address methodological weakness in velocity map construction see response to major comments 2.3 and 2.4.
- regarding uncertainty analysis see response to major comment 2.6.

In light of this, I would suggest to repeat some key parts of the analysis, after reviewing the literature for the most appropriate methods to be applied to the high-quality datasets of Vernagtferner. I would suggest resubmitting the manuscript to reflect these major changes. In particular, I would suggest adjusting the scope to focus more on just one of the two topics - either (i) the compilation of the present-day velocity map, or (ii) the analysis of the historical dataset and its glaciological interpretation. The two topics are quite loosely related and the manuscript would really benefit from a clearer message, answering one or more well-defined research questions.

1.2 We define our research question more clearly. The aim of the manuscript is not to rule out the automated creation of a velocity map (we reworded the relevant sections of the manuscript accordingly), but rather to highlight the problems/challenges associated with high ablation for retrieving glacier velocities on slow-moving glaciers with remote sensing techniques. However, your raised points in this response convinced us to explain in more detail. We try to better explain what we mean by the problem of “high ablation” in the context of feature tracking (detailed information on this can be found in the response to major comments. Overall, the manuscript focuses more on (ii) the analysis of the historical data set, and we have also expanded the analyses to reflect this. However, we believe that detailed information on current ice dynamics is also highly relevant when analyzing historical data, especially since high-resolution data is available for the current period. Since the dynamics are now only minor, the maximum remaining velocities are particularly relevant. We think, generating a present-day velocity map is a logical consequence based on the data availability in order to provide a velocity map ready for other studies, e.g. ice flow modelling (either used as validation as target for an inversion).

For topic (i), I would specifically suggest application of digital image correlation on the UAV, aerial and/or satellite imagery, with an appropriate pipeline for pre-filtering, post-processing, and aggregation. Multiple studies (e.g., [1], [2]) have shown that data processing specifically optimized to a study site can resolve the ice dynamics of individual glaciers much better than global products. Given the high-quality available data (such as four years of end-of-season, whole-glacier airborne photogrammetry), I expect this processing to resolve very well the slow movement of Vernagtferner and automatically produce good-quality velocity maps, possibly even at annual intervals and on the whole glacier body, contrary to the current manuscript's conclusion that "It is obviously not possible to (semi-)automatically produce a reliable surface velocity map from aerial or satellite imagery for the slow-flowing Vernagtferner". The stake measurements (and possibly the manually tracked feature) would be a valuable reference for validation and uncertainty estimation. This kind of manuscript might be most suitable for a data-focused journal.

1.3 As mentioned, the focus should not be on excluding possible (semi-)automatic detection methods for the Vernagtferner. This statement is removed from the manuscript, as we don't test all possible methods. Instead, we would like to point out the special features of (automated) detection with high ablation. More detailed information on this can be found in the response to major comments 2.3.

For topic (ii), I would specifically suggest a more thorough re-analysis of the very interesting historical stake data, possibly including: (1) a more realistic model approach than the shallow ice approximation, for example an IGM inversion, given the high-quality data available over the entire glacier; (2) a better-processed ice thickness map, without the obvious major artifacts visible in Fig. 7; and (3) a more detailed analysis of the interplay of surface slope, glacier thickness, and stake velocity anomaly. The recent measurements shown in the manuscript could still be mentioned to compare spatial patterns over time and to investigate seasonality. This kind of manuscript would be most suitable for a glaciological journal.
1.4 Thank you very much for your valuable suggestions for further analysis. Regarding:

(1): You are right, a more sophisticated model would be appropriate for modelling the response of VF with the observed data for validation/tuning/inversion. However, our intention was to estimate whether the observed dynamic trends in the historical velocity data are connected to mass balance trends (i.e. ice thickness). We think for this rough estimation a simple model (i.e. SIA) is a fair approach, particularly, as our paper is not focusing on modeling. Using an IGM inversion would be a good approach but shifts the focus more to modelling rather than on the observations. The data on ice thickness and surface slope for the individual years are heavily interpolated (more on this under response to major comments 2.1 (1)), making realistic modeling difficult based on the initial data. However, the focus of the manuscript is on showing the velocities over time. Therefore, we only want to use SIA modeling to generate an uninterrupted timeline of the geometry in order to investigate the reproducibility of the velocity trends. This is therefore not an ice dynamics model in the true sense, but rather a first approximation. We added an explanation in the manuscript.

(2): The artefacts visible in Fig. 7 have been corrected (for result see the response to minor comment of Fig.7) . The calculation of ice thicknesses is explained in more detail under response to major comments 2.1 (1).

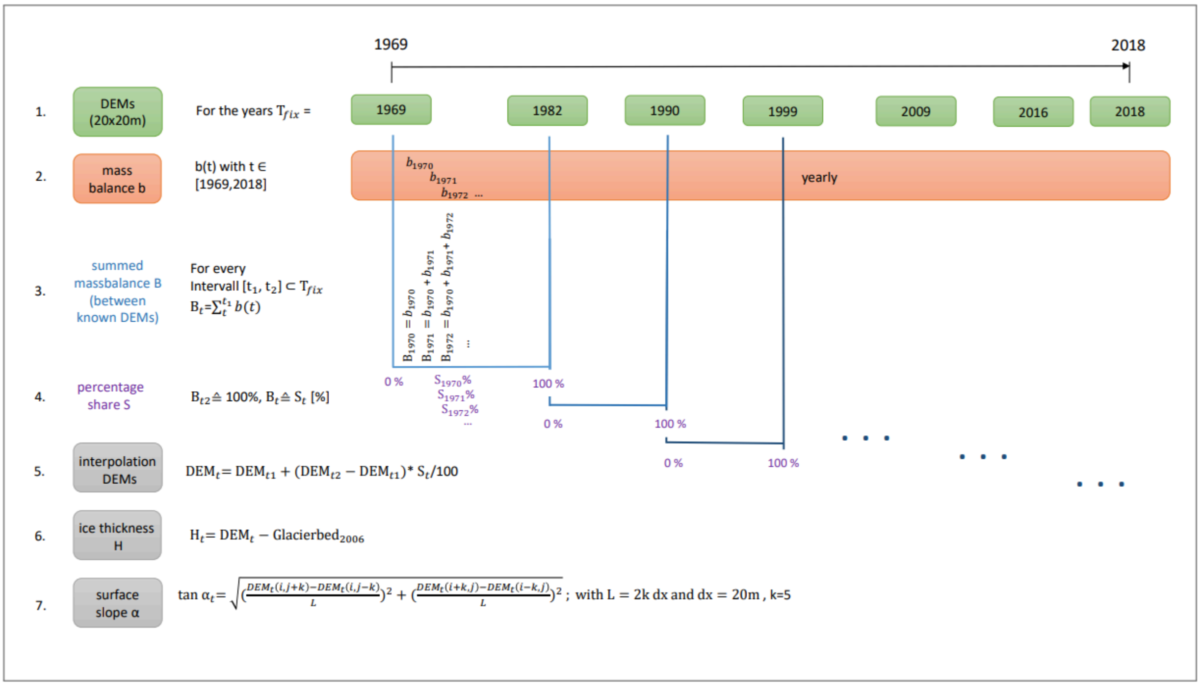
(3): Discussion of the analysis of the anomalies of various parameters such as ice thickness and surface slope can be found under response to major comments 2.5.

In both cases, it is important to perform a quantitative, data-driven uncertainty analysis, based on leave-one-out validation and rigorous error propagation, as described in the references provided below.

Detailed information under response to major comments 2.6 and specific comments.

Specific major comments:
- Presentation of the Data and Methods needs major restructuring in order to support the analysis. In the current form, it is really hard to understand where some important data come from or how they were processed. In particular, it is important to provide full information on: (1) the data sources used for glacier thickness, as well as all processing applied to (i) extrapolate it to the full glacier area, (ii) compute evolution over different time periods, and (iii) extract it at the stakes location; (2) all the stakes (at the very least, all the stakes whose data are plotted in the figures), with their identification numbers, observation period, and maximum/minimum altitude; (3) the actual calculation of modeled velocities according to the shallow ice equation, detailing the estimation and assumptions made for each variable; and (4) the processing of UAV and aerial data, including georeferencing, the used software pipelines, and the resulting spatial resolution and accuracy. Some relevant pieces of information are already mentioned in the manuscript, but in a rather scattered form across the sections, and should be rearranged.
2.1 Thank you for pointing this out. We reconstructed the Methods and Data section and added an extra chapter explaining the data and methodologies used .

(1): A flow chart as well as the following explanation for calculating ice thickness and surface slope for each year was added:



Flowchart for calculating ice thickness and surface slope

In order to apply the SIA approach, annual ice thickness and surface slope are required. For this purpose, DEMs were generated by interpolation between available DEMs at known times (Finsterwalder, 1972; Rentsch, 1982 and more recent maps published by the group at BAdW (for workflow, see Fig. 3. All available datasets are listed in the Appendix A. Instead of assuming linear interpolation over time, the interpolation between two consecutive DEMs was scaled according to the cumulative SMB. The mass balance is described by a single glacier-wide value per year, as area distributed annual mass balances from the glaciological method are not available for all periods. For example, the DEM from 1969 and 1982 is available, the years in-between are interpolated. Therefore, we started to sum the SMB during this period of time and used as relative measure of surface elevation change. This means, that the elevation change between the DEMs from 1969–1982 corresponds to 100% of the cumulative SMB from 1969–1982 (in this example -596 mm w.e.). The yearly change in DEMs were generated according to the cumulative SMB reaching the respective year, for example cumulative SMB 1969–1976 with -520 mm w.e. corresponds to 87%, meaning that 87% of the elevation change from 1969–1982 would be applied to the DEM in 1976. In this way, elevation changes are distributed non-linearly in time and reflects periods of higher or lower loss/gain. The error of non-linear ice transport over time is neglected, as the velocities are relatively low. The respective ice thickness is derived by subtracting the bed topography of 2006 (Mayer et al., 2013b) from the corresponding interpolated DEM. Surface slope was calculated from the annual DEM using five grid cells (k=5) in each horizontal direction, with a grid size (dx) of 20 m, the baseline length (L) is 200 m. The resulting ice thickness and surface slope were restricted to the last known glacier extent. To compare the calculated velocity to in-situ stake observations, we extract the calculated velocity from the 20 x 20 m grids using a nearest-neighbor approach.

(2): An overview of the measurement points that appear in the figures is added to the appendix.

3): A chapter on the shallow-ice approximation modeling, including formulas used and estimated parameters, is added:

We add a new paragraph to the data and methods section

Shallow-ice approximation method

The observed datasets of surface mass balance (SMB) and in-situ surface velocities motivate an investigation of the role of glacier geometry, as variations in SMB directly affect glacier geometry, which influences surface velocities. To assess whether 185 the observed velocity trends can be reproduced by geometric changes, we apply a simplified shallow-ice approximation (SIA) method. This approach requires only the geometry, consisting of the surface slope (α) and the ice thickness (H), to estimate the velocity (e.g. Hutter, 1983; Greve and Blatter, 2009). The SIA approach is also referred to as a 'zero-order' model, where only vertical shear stress gradients are taken into account. We therefore do not regard this as ice dynamic modeling in the strict sense, but rather a first approximation. The selected physical flow parameters are summarized in Tab. 2. The total surface 190 velocity (u_{total}) consists of the deformation velocity (u_{deform}) and the basal sliding velocity (u_{basal}):

$u_{total} = u_{deform} + u_{basal}$

For calculating the deformation velocity soft and temperate ice was assumed by choosing a rheology parameter A corresponding to a temperature of 0 ◦C (Paterson, 1994). The deformation velocity is given by:

u_{deform} = (2*A / n+2)) * τ^n * H)

, where τ is the shear stress, described as:

$\tau = -\rho * g * H * \sin(\alpha)$

The basal sliding velocity estimation requires a basal sliding coefficient C. As a priori determination is challenging, we tuned the coefficient so that the modeled velocity fall within the range of the measured velocities. The basal sliding velocity can be described as:

$u_{basal} = C * \tau$^n

The selected physical flow parameters are summarized in the following table:

parameter	value	unit
A	2.2e-16	Pa^-3 yr^-1
n	3	
ρ	900	kg/m³
g	9.81	m/s²
C	3e-14	m Pa^-3 yr^-1

(4): An overview of all available data is added as Appendix A.

Unfortunately, much of the information, such as the software pipelines used or the georeferencing of the source data, is unknown. Where possible, references to the respective source are provided, but particularly regarding the historical surface models there is no known information. As long as there are no legal reasons to the contrary, the data sets are now publicly available via the Zenodo platform. This information can also be found in the table of Appendix A.

- The discussion lacks almost any comparison of the findings of the present study with those of other investigations, in particular those about (1) long-term trends of ice velocities at reference glaciers in the European Alps, which are monitored at several key sites across the Alpine countries (a single publication on Hintereisferner is currently cited); (2) the derivation of velocity maps of slow-moving glaciers from remote sensing (e.g., [2], [5]); and (3) previous examinations of the dynamics of Vernagtferner (ll. 91-92). It is crucial to situate the findings of the current study in the context of published results, in order to highlight advancements and challenges.

2.2 (1): That´s true. We are expanding the discussion:

Comparable behavior has been reported from long-term observations of the d'Argentière glacier, Mont Blanc area. Vincent et al. (2009) show an ongoing negative net mass balance since 1982, with a direct reflection (delayed by a maximum of 3 years) in the velocity. They describe that the change in velocities in the upper part of the glacier is smaller than in the lower part (ablation area). The velocity trend thus fits the VF timeline quite well.

See also expansion due to discussion of possible “direct response”, and compare to studies in response to major comment 2.5.

2): Thank you for pointing that out. We are expanding our discussion regarding the derivation of velocity maps for slowly flowing glaciers, as follow:

For other relatively slow-flowing glaciers, such as the Griesglacier, surface velocities could be derived over short time periods using UAV-based imagery and software such as IDMatch, a tool for automated velocity derivation (Gindraux, 2019). Compared to the VF, the average velocities on Griesglacier with more than 1 m in just 1 month are significantly higher than the average velocities at the VF of about 1 m yr^{-1} . Furthermore, a short test of the IDMatch software using the UAV VF datasets from July 2022 and September 2022 results in no correlation between the images. Regardless of the software and the potential detection of identical features, surface changes caused by strong ablation at VF remain a dominant source of uncertainty, as illustrated in Appendix D. We do not want to rule out the possibility of automated derivation, but it would be essential to additionally correct for the false values caused by the ablation-induced change in features (a change not caused by ice flow). For this reason, we have chosen manual feature tracking.

Please also see response to major comment 2.3, for examples of the differentiation between ablation-induced feature changes and ice dynamics-induced feature changes.

(3): The two current studies show the changes in velocity up to the respective point in time, with basic analysis. Since this information is already contained in the manuscript, these studies will not be discussed in detail. However, since the data preparation up to the respective point in time and a rather rudimentary display were carried out here, we would like to mention their valuable work at this point. To avoid misunderstandings, we rewrite the sentence to: The derived velocities have been displayed in previous studies up to the respective point in time.

- The manuscript claims that "It is obviously not possible to (semi-)automatically produce a reliable surface velocity map from aerial or satellite imagery for the slow-flowing Vernagtferner", which is the main motivation to propose a manual tracking method (with the resulting downsides for spatial coverage, reproducibility, and labor effectiveness). However, this conclusion is based on observation of some global datasets of glacier velocity, as well as some very poorly detailed testing of automated methods on the available datasets, which are quickly dismissed as an option (ll. 113-119 and 189-199). However, several studies have thoroughly validated the derivation of glacier velocity fields on aerial and UAV imagery with automated methods, such as frequency-domain cross correlation ([3], [4]) and feature tracking ([5], [6]). These methods have been shown to resolve well the ice motion on optical imagery, typically with subpixel accuracy; in particular, the result of [5] (p. 58) clearly shows UAV-based feature tracking fully resolving ice displacements of the same magnitude and time interval as those of Vernagtferner. Thus, a claim of unsuitability of those well-established methods needs to be supported by much better evidence than a quick dismissal, especially given the high-quality available datasets at Vernagtferner (UAV and aerial imagery). The interest of manually pinpointed displacements of individual features is hard to justify without first testing and quantitatively reporting on these state-of-the-art methods.

2.3 You are absolutely right; we cannot rule out automatic methods at this point. We amend the manuscript accordingly. The aim of the manuscript is not to test all algorithms and rule out the possibility of automation. Instead, we would like to highlight the problems of overlapping due to ablation from a more glaciological point of view and explain why we chose manual detection. We would like to show that detection is not “rudimentary” and cannot simply be carried out using global data sets or standard remote sensing methods. Thank you very much for the reference [5] to a study on the detection of slow velocities. The study shows an average surface dynamics of more than 1 m over a period of about 1 month, with maximum values of up to 3 m. On Vernagtferner, the average velocity is only 1 m per year, with maximum values of 4 m per year. Over a period of one month, Vernagtferner will therefore only reach values of approx. 10 cm to maximum values of approx. 40 cm. This means that the dynamics of the Vernagtferner are once again slightly lower than those of the Griesglacier shown in the study. Furthermore, we only have high-resolution UAV data for the dates 2022-07-10 and 2022-09-21, i.e., for a temporal baseline of 2.5 months (the other datasets have significantly longer baselines). During this period, there was a significant change in surface structures, mainly due to high ablation. Nevertheless, we tested the IDMatch software for the UAV data. Unfortunately, no correlations could be found. This information is added to the manuscript, and we also mention further software options. (See also response to major comment 2.2 (2).)

The UAV measurements in 2022 relate to a year of extreme melting. This melting also causes significant changes to surface features. For this reason, we write in the manuscript that “high ablation means that the horizontal melt is even greater than the actual movement.” We did not go into further detail on this. The feedback has shown us that we need to clarify what exactly we mean by changes in features due to ablation. To this end, we include the following examples in the appendix:

The figures show the same situation at different points in time:

Fig. 2: Melt-induced changes to crevasses. The example is taken from the upper part of the Taschach area at an altitude of approx. 3150 m. Maximum velocities occur in this area at the VF.

Figure 2 clearly shows a change in surface features, in particular a widening of the crevasses. We examined two of the crevasses in more detail using two stakes at the upper and lower edges of each crevasse. The average movement of the eight stakes (shown in Fig. 2) over the two months is approximately 0.73 m (change from the red to the blue points), with a standard deviation across the eight stakes of 0.12 m . The stakes rule out the possibility that a significant actual break-up of the crevasses has taken place. The stakes show an even shift of the upper and lower edges of the crevasses. Thus, the change in the surface is probably largely due to melting. Even if identical features (in this case, crevasse edges) could be identified during the period, the movement would be significantly overlaid by ablation due to the crevasse edges (and their varying melt rates), resulting in erroneous dynamics.

Even with larger temporal baselines, manual feature tracking can be used to exclude features that are likely to have changed due to ablation, as is often the case in 2022. Crevasse trace intersections are particularly well suited for this purpose, as can be seen in Fig. 3. Identifying identical features that have not been subject to high ablation is challenging even for the human eye, especially over longer baselines, such as the example in Figure 4 over a period of two years.

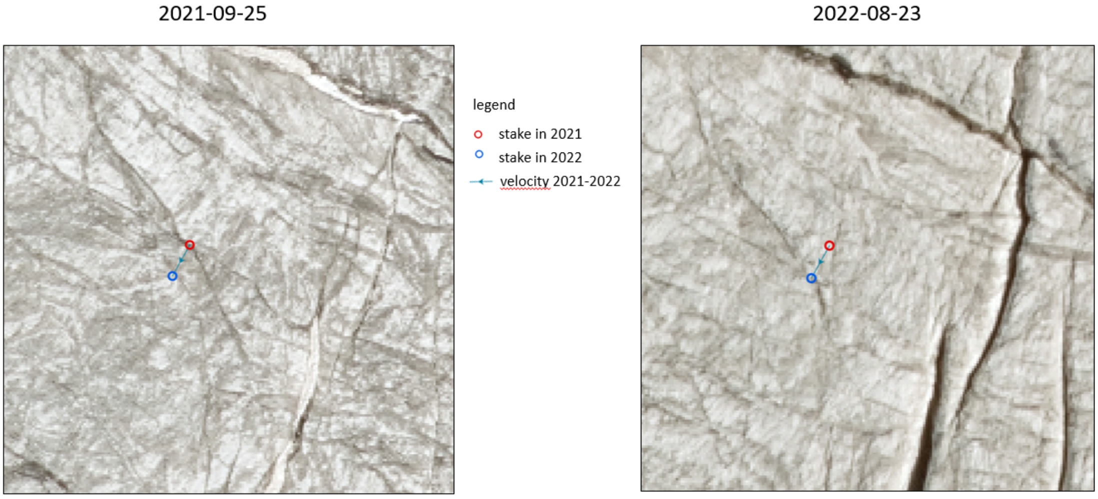


Fig. 3: Melt-induced changes to crevasses. Example from the upper part of the Brochkogel area at an altitude of about 3200m.

Fig. 4: Crevasse pattern in a period without significant melt. Example from the highest part of the Brochkogel area at an altitude of about 3250 m.

- The 2018-2023 velocity map is aggregated from data collected over 5 years, on the assumption that ice dynamics would "not change much" over that period. However, Fig. 4 and Fig. 5 show ice velocity changes by more than 50 % taking place over 5 year periods at several stakes. Such a change is larger than (for example) the 30 % correction factor applied to convert summer to annual stake velocities in the data used within the velocity map. As such, the validity of the aggregation of such heterogeneous data is questionable and should at least be discussed in the uncertainty budget. Moreover, the assumption of zero velocity at the glacier edges is questionable - a contribution from transverse stress coupling could potentially be significant on such a slow-flowing glacier. See for example [7]. A rigorous analysis and discussion of these uncertainties is required to support the presented results, especially when the manuscript claims that other existing methods and results are not suitable for the study site.

2.4 Thank you for pointing that out. The assumption of an “unchanged” velocity for the period 2018-2023 needs to be explained in more detail and substantiated with data. We used the stake series (measured over at least three epochs in the period 2018-2023) to calculate whether there was a significant average slowdown in velocity from one epoch to the next, taking into account the measurement uncertainty. As explained in the manuscript, the measurement uncertainty of the stakes is +/-10 cm or, taking into account the law of error propagation, +/- 14 cm for the calculated velocity.

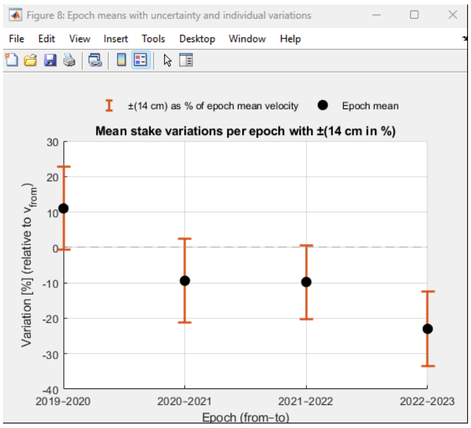


Fig. 5: Average variation in velocity between the periods 2018–2023, for stakes with at least three measured values during this period.

There are no measured values for the period 2018-2019. The variation from 2019 to 2022 is within the measurement uncertainty. Only the period 2022-2023 shows a decrease of approximately 10% (excluding the measurement uncertainty), but there are only three relatively widely scattered measurements for this period. Therefore, it cannot be assumed that there is a significant decrease. However, this uncertainty should be taken into account in the uncertainty budget by including the maximum variation of 10% in the measurement period 2019-2023. We added the maximum variation in the uncertainty chapter of the manuscript.

We agree that transverse stress couplings are not taken into account when assuming a velocity of 0 m/yr at the glacier margin. Nevertheless, the dynamics at the margin of the glacier are significantly slower than in the center. Since the VF itself flows relatively slowly even in the center, the velocities at the margin will be close to 0 m/yr. The reference to transverse stress couplings will be included in the manuscript.

- The manuscript mentions a "strong sensitivity of velocity to mass balance", claiming that "even the small effect of slightly positive mass balance years on the glacier geometry, results in very pronounced changes of ice flow". While this "effect [...] on the glacier geometry" is not further described, this conclusion suggests that changes of glacier geometry due to positive glacier-wide mass balance would be reflected as faster ice flow in the ablation area already during the same mass balance year, with little to no lag. Such a conclusion is somewhat at odds with the notion of glacier response time and would need to be backed up by some evidence (such as an actual analysis of the mentioned "effect on glacier geometry"). As such, a more thorough analysis of the interplay between glacier mass balance, geometry changes (especially thickness and slope), stake location within the glacier, and stake velocity, is needed.

2.5 We agree that a more detailed analysis of anomalies in, for example, glacier geometry and stake velocities could reveal the sensitivity to the mass balance more accurately. The parameters surface slope and ice thickness for each year are derived from an interpolation, whereby a surface model is only available approximately every 10 years. The scaling of the change in surface area between years is performed using the mass balance (as described in more detail under response to major comment 2.1(1)). However, a continuous stake series extends over a maximum of two of these known surface models before the stake melted out. The remaining surface models and ice thicknesses are derived from interpolation. Accordingly, an investigation of the anomalies is strongly influenced by the interpolation, and this in turn is influenced by the mass balance, among other factors. In order to avoid generating a false dependence of the mass balance on the glacier geometry (slope and ice thickness), we focused on the mass balance parameter and did not carry out any investigations into the glacier geometry.

Furthermore, we fully agree that the effect we describe as “strong sensitivity of velocity to mass balance” suggests the conclusion that changes in glacier geometry due to mass balance are reflected in the ablation area with little or no delay. As already mentioned, we are unable to perform more detailed analyses due to the rough interpolation of the geometry data. The effect can be seen particularly clearly in Figure 4 of the manuscript for the year 1983. Already in the year following a strongly negative mass balance, the velocity appears to decrease significantly. Unfortunately, very little stake information is available for the years 1983-1985, which are particularly relevant here. However, this information suggests that the stakes in the ablation area react relatively directly to changes in mass balance. We will now describe this effect in more detail and discuss it with the help of further literature:

We have found evidence that the displacement of ablation stakes at VF react quickly to a change in the mass balance. An ongoing period of predominantly negative mass balance starting in the early 1980s marks the onset of a decrease in surface velocity in the ablation area. Ice thicknesses are rather small in the tongue areas of VF, where the stake measurements are carried out. Ice velocity is very sensitive to changes in ice thickness and the relative change of ice thickness due to strong ablation. With already reduced dynamic compensation leads to a fast reduction in ice velocity. In a year with a strongly negative mass balance, the strong melt in the ablation area directly decreases ice thickness, which represents the current status of the glacier. Stocker-Waldhuber et al 2019 have also found evidence that ablation stakes can be well suited to reflecting the current status of a glacier. They show that the Kesselwandferner (also in the Ötztal valley) shows relatively direct response of ablation area ice dynamics to changes in mass balance, regardless of the geometry of the glacier. On VF, there is insufficient data to substantiate this adequately. Further studies (including in other areas) are necessary to investigate this effect in more detail. Comparable behavior has been reported from long-term observations of the d’Argentière glacier, Mont Blanc area. Vincent et al. (2009) show an ongoing negative net mass balance since 1982, with a direct reflection (delayed by a maximum of 3 years) in the velocity. They describe that the change in velocities in the upper part of the glacier is smaller than in the lower part (ablation area). The velocity trend thus fits the VF timeline quite well.

Furthermore, we have added a further analysis to quantify the ice dynamic process:

To quantify the ice dynamic process, we performed an analysis based on the observed geometry change, using surface elevation change derived from known DEMs (hereafter referred to as surface elevation change). Based on the ice thickness equation (Greve and Blatter, 2009), the dynamic contribution to ice thickness change can be computed by subtracting the local surface mass balance (SMB) from local changes in ice surface elevation. The residual component represent the local dynamic contribution to the vertical surface adjustment (assuming a stationary bedrock). The spatially distributed SMB for VF are available only from 1996 ongoing (earlier information as glacier-wide values). With a spatially distributed SMB and a surface elevation change map, the difference can be calculated as local dynamic contribution to elevation change. We apply this analysis to the period 2016–2018, for which data availability is particularly good. Although this is a very short period with regards to glacier response times, it is assumed to be representative of the current ice dynamics, as the glacier already has very low velocities during this period, similar to those observed in 2018–2023. The cumulative SMB for the years 2017 and 2018, is shown in Fig. E1a, while the surface elevation change between the years 2018 and 2016 can be seen in Fig. E1b. The difference between the two maps provide the local dynamic contribution to elevation change (Fig. E1c). In the accumulation areas (or former accumulation areas), negative values (red areas) indicate that the ice transport has a vertically downward component. In the ablation areas, on the other hand, positive values (green areas) indicate vertical mass compensation through ice transport. Figure E1c shows that the Taschach and Brochkogel areas exhibit hardly any vertical mass compensation (values very close to 0). In contrast, a local dynamic contribution to elevation change is still present in the former accumulation areas of these two sub-areas. The two green areas in the Taschach area provide good control. These are rock islands that were not excluded from the SMB map. However, the rock islands have remained stable during the period and have not moved, which is why they appear incorrectly as dynamic contribution to elevation change. A closer look at the Schwarzwand area reveals a stronger dynamic contribution to elevation change. In the northern accumulation area of the Schwarzwand area (as well as on the Hochvernagt plateau), positive values are observed that cannot be plausibly attributed to a dynamic contribution to elevation change. However, in the orthoimages, these areas are partially covered by snow and have hardly any features. It can therefore be assumed that the surface models in this area are uncertain. In addition, the SMB map is largely interpolated (in particular in the northern part of Schwarzwand area), further increasing the uncertainty of the estimated dynamic contribution to elevation change in this region. Pronounced negative error values are present in the northern part of the Hochvernagt plateau. These originate from the surface elevation models, where an error has likely occurred. In order to enable a numerical estimation of the processes, which excludes outliers as far as possible, the median of the absolute mass balance of 1.08 m yr^{-1} and a absolute dynamical contribution of 0.67 m yr^{-1} were calculated. Overall, further uncertainties must be taken into account, such as the compression and thus the change in altitude of possible firn areas due to a change in density, especially in the accumulation areas.

We added to the discussion section:

A quantitative analysis of recent geometry change (period 2016–2018) at VF indicates that SMB is the dominant control, while local dynamic contribution to elevation change remains secondary. The median absolute values for SMB (median = 1.08 m yr^{-1}) and the local dynamic contribution to elevation change (median = 0.67 m yr^{-1}) suggest that the ice dynamic is not able to fully compensate the losses due to melt, especially in the ablation area. There are indications that there may be slightly more compensation of elevation change through ice dynamics in the Schwarzwand area and that this area behaves fundamentally different from the rest of VF. This was already suggested by Reinwarth and Escher-vetter (1999) and can be confirmed here. Figure 8 also suggests a higher dynamic on the Schwarzwand tongue compared to the other tongues. Due to a lack of data (no spatially distributed SMB before 1996), it is not possible to quantitatively assess these processes for the early years of glacier observation. However, it can be assumed that the local ice dynamic contribution to elevation change was more pronounced during this time, as the measured velocities were significantly higher, particularly around 1980, with an absolute SMB being significantly smaller than it is today

Appendix E: Ice dynamics

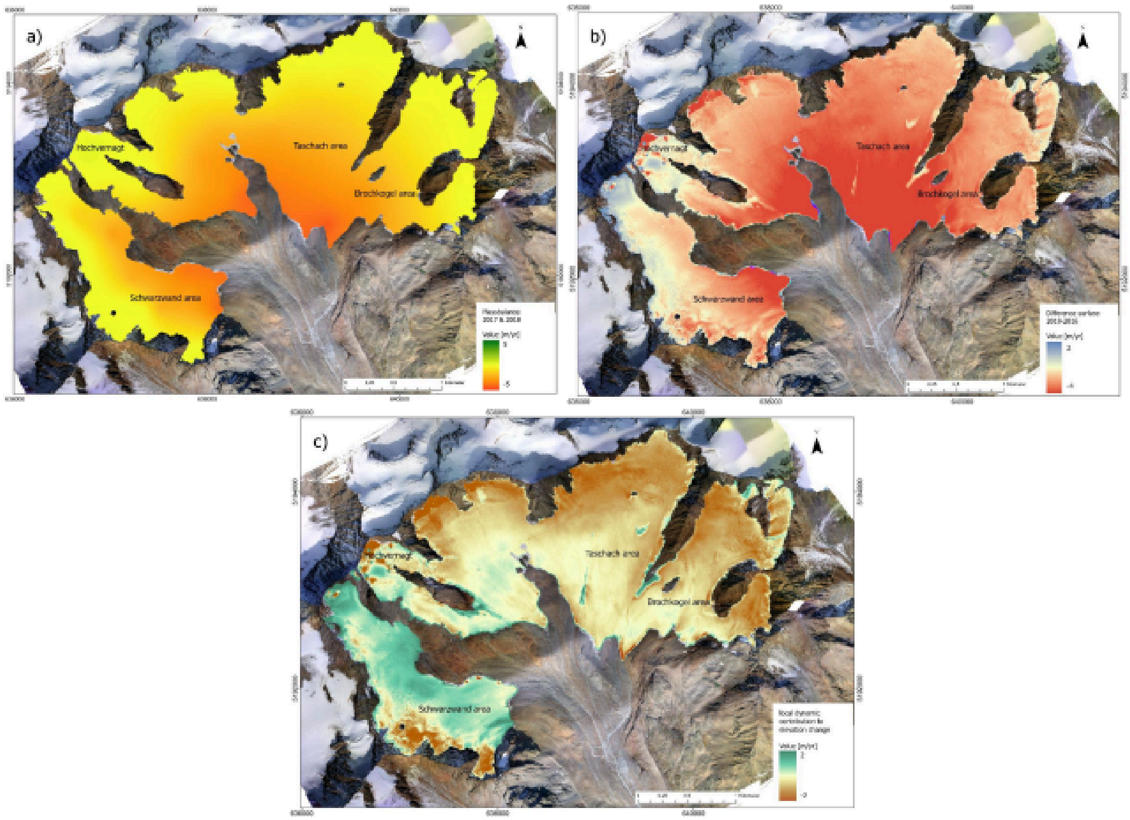


Figure E1. a) areal distributed surface mass balance summed for the years 2017 and 2018, b) surface elevation difference 2018-2016, c) Difference between a and b, which illustrates the local dynamic contribution to elevation change. Background image: Orthoimage 2016 © Bavarian Academy of Sciences and Humanities (BAdW), 2016.

- Most uncertainty estimations (Sect. 4.4) appear to be qualitative, arbitrary or statistically inaccurate. A more rigorous uncertainty analysis is needed, since an extensive literature exists on relevant methods, specifically concerning glacier dynamics (e.g., [8], [9], [10]). The availability of a large number of data points suggests application of a leave-one-out method for robust uncertainty estimation. Finally, the formulas used to calculate and transform uncertainties should be shown.

2.6 Thank you for pointing that out. In this section, we also address your minor comments on line 229 and 235.

As suggested in reference [14] (minor comment on line 235), the interpolation uncertainty can be calculated using a bootstrap technique. We tried this technique on our interpolated velocity field consisting of 177 measurement points. To do this, we selected 10 random datasets from 20, 50, and 80% of the points and interpolated each of them. At the skipped points, the misfit to the measured velocity was plotted (separately for velocity in the X and Y directions). The relative misfit (the absolute misfit (Δ v) in relation to the measured velocity ($v_{x\ meas}$)) in percentage is shown as gray points in Figure 90. The median is shown in red, as well as the 2σ-confidence interval, grouped for distance intervals. Sufficient measurements are only available for the range up to approx. 50 m distance to the closest observation. A significant trend, as could be described by a linear regression, for example, cannot be found.

This is most likely due to the inhomogeneous distribution of the points and the fact that there is a high point density with a high variation in magnitude in the crevassed areas, whereas there is a low variation with a low point density on the glacier tongue. Due to the structure of these data, no statement can be made about a possible dependence of the interpolation uncertainty on the distance to the nearest observation point.

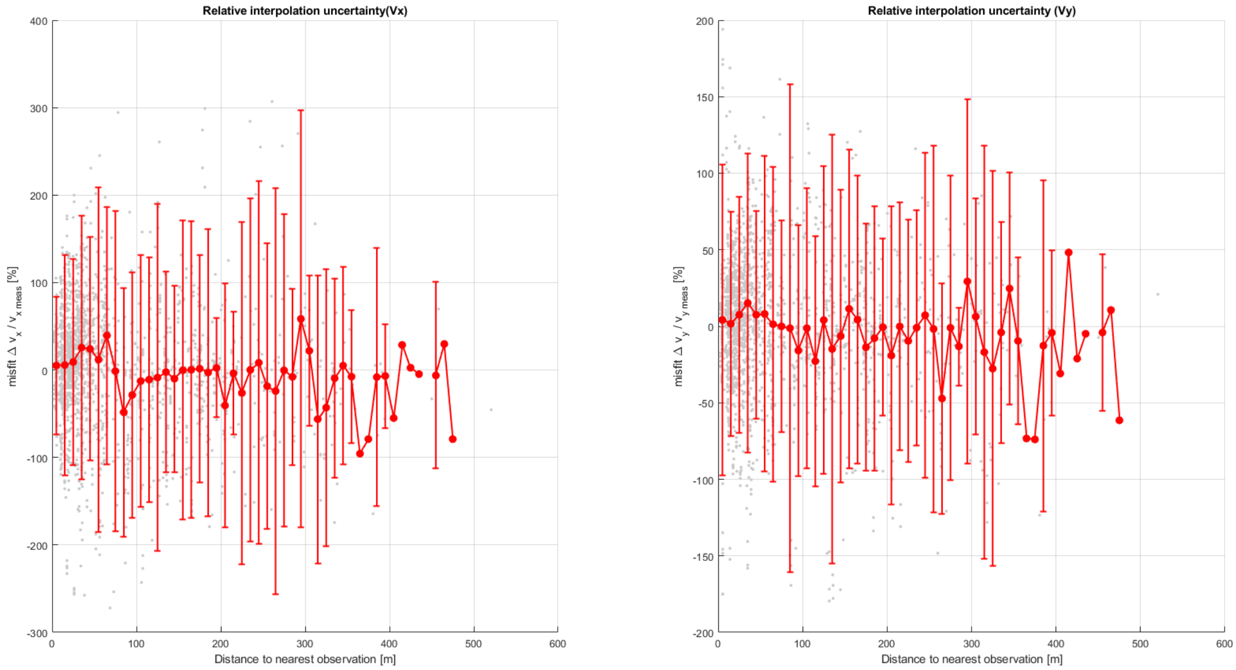


Figure 90: Misfit between interpolated and measured velocity (Δ v) in relation to the measured velocity (v_{meas}) versus distance to the nearest observation as grey points. Red points indicate the median for a distance interval with its 2σ-confidence interval.

Furthermore, we performed a leave-one-out method. The results (Figs. 91, 92, and 93) and a description, is added to the manuscript as Appendix F as follows:

A further uncertainty analysis can be performed using a leave-one-out method. For this purpose, an interpolation was performed for each point without using this point and the misfit of the interpolated velocity to the measured velocity was determined. The generated misfits are shown as relative and absolute errors with respect to the distance to the closest observation in Figures F2 and F1. The figures show that there is no significant correlation between the misfit and the distance to the nearest observation. This is most likely due to the inhomogeneous distribution of points and the fact that there is a high point density with a high variation in magnitude in the crevassed areas, whereas there is a low variation with a low point density on the glacier tongue. This can be seen in Figure F3. The individual misfits for each point are shown, with the mean average being formed in case of an overlay. The percentage uncertainty does not appear to be significant in specific areas. Due to the structure of the data, no statement can be made about a possible dependence of the interpolation uncertainty on the distance to the nearest observation point. Instead, as can be seen in Figures F2 and F1, there is a normal distribution around the value 0, so a 1σ-confidence interval can be derived as the mean uncertainty of the interpolation (in x- and y-direction). The relative error is estimated at 50.4% in x-direction and 28.3% in y-direction, while the absolute error is 0.6 m/yr in each direction.

The interpolation uncertainty ($u_{interpolation}$) for the velocity magnitude can be calculated from the 1σ-confidence interval in x- and y-direction as follow:

$$u_{interpolation} = \sqrt{u_{interpolation\,x}^{2} + u_{interpolation\,y}^{2}}$$

resulting in an interpolation uncertainty of 57%, respectively 0.8 m/yr.

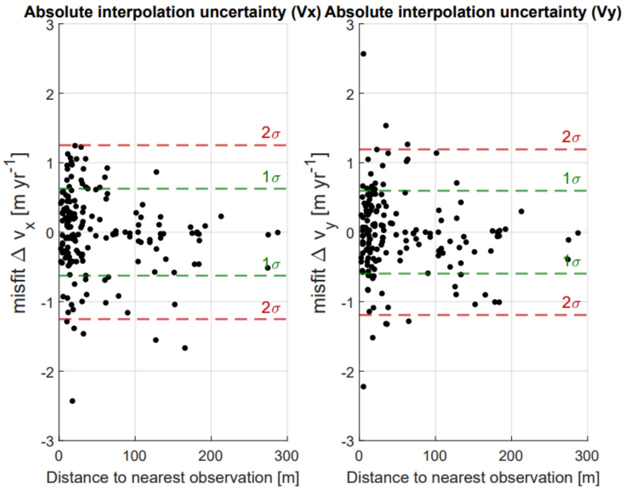


Figure F1: Misfit between interpolated and measured velocity (Δ v) in relation to the measured velocity (v_{meas}) versus distance to the nearest observation according to a leave-one-out-method, referred to as $u_{interpolation\_x}$ and $u_{interpolation\_y}$.

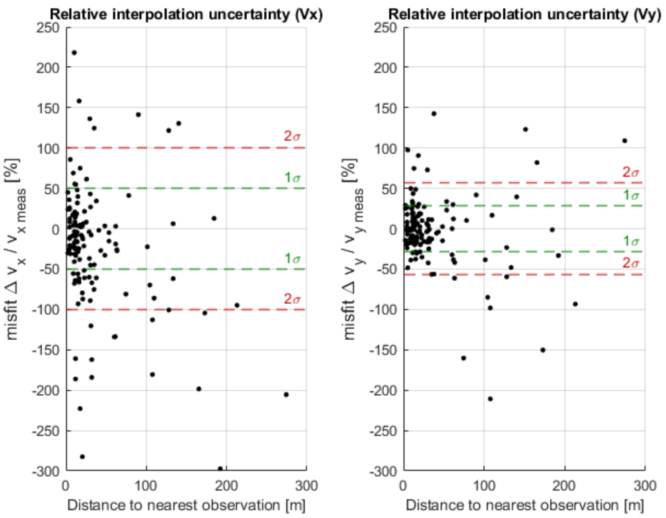


Figure F2: Misfit between interpolated and measured velocity (Δ v) in relation to the measured velocity (v_{meas}) versus distance to the nearest observation according to a leave-one-out-method, referred to as $u_{interpolation\_x}$ and $u_{interpolation\_y}$.

a) b)

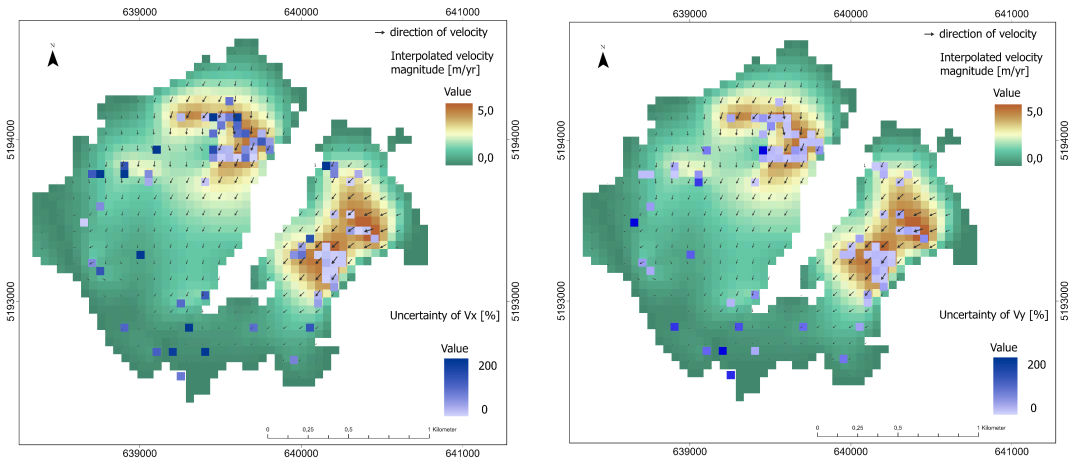


Fig. F3: Interpolation uncertainty ($u_{interpolation\_x}$, $u_{interpolation\_y}$) as misfit of a leave-one-out-method, with the misfit between interpolated and measured velocity (Δ v) in relation to the measured velocity (v_{meas}) for measuring point, averaged in case of overlaps. a) for velocity in x-direction, b) for velocity in y-direction .

Furthermore, a position uncertainty (referred to as $u_{measured}$) of the measured points can be calculated for the velocity, by following the covariance propagation law. Where t is the temporal resolution in years and $u_{startdate}$ the position uncertainty of the startdata, as well as $u_{enddate}$ for the position uncertainty of the enddata, from whom the velocity of each point is calculated. The start and end date, the temporal resolution as well as the resulting velocity uncertainty for each set of data is reported in Tab.5.

$$u_{measured} = \sqrt{(u_{startdate}^{2} + u_{enddate}^{2}) / t}$$

Regarding the utilized datasets, different measurement uncertainties arise. An approximate total measurement uncertainty $u_{measured\ total}$ across all observations can be estimated:

$$u_{measured\ total} = \sqrt{\sum_{i=1-5} (n_i * u_{measured\ i}^{2}) \ / \ n_g}$$

with i indicates a row in Tab. 5, n_i being the respective number of points, and n_g the total amount of points. This leads to an approximate total measurement uncertainty of 0.31cm.

For clarification in the main manuscript we:

-deleted line 228-230, as the mean uncertainty is not the mean of individual uncertainties.

- change the column name of column 5 (Table 5) to: position uncertainty $u_{measured}$

- add in line 226: The resulting velocity uncertainties represent one standard deviation (1σ) and are listed in Tab. 5, a detailed description to the calculation is in Appendix F. It is also demonstrated that an approximate total measurement uncertainty of 0.31 m/yr can be estimated.

- add in line 233: To examine the uncertainty of the interpolation more closely, a leave-on-out method was performed (e.g. Grab et al. (2021). This shows that there is no significant dependence of the misfit (between interpolated velocity and measured velocity) and the distance to the next observation. However, a relative interpolation uncertainty of 57% and an absolute interpolation uncertainty of 0.8 m/yr can be estimated from the standard deviation. Detailed calculations and explanations can be found in Appendix F.

Specific minor comments:

- The Introduction needs to provide more focused context on the specific topic of the manuscript, citing more literature on the monitoring of slow-flowing mountain glaciers, on long time series of ice velocities, and on the creation of glacier velocity maps for single glaciers; at present, it is somewhat meandering over broad topics of ice dynamics (basics of glacier flow, glacier hydrology, global ice velocity products).

That´s true. We provide further specific context in the introduction:
to line 27:
Therefore, long-term measurements of the ice velocity are essential for detailed analyzes. A long time series of measurements makes it possible to investigate the flow processes of a glacier and their response to climate change. For example, Vincent and Moreau (2016) found no correlation between changes in surface velocity and subglacial water runoff for the Argentière glacier in the Mont Blanc area. On the other hand, mass balance influences the flow behavior, where Vincent et al. (2009) found a reaction of glacier velocities within a maximum time span of three years. However, ice geometry variations and surface velocity evolution are not always directly correlated. For example at glacier de Saint Sorlin, Grandes Rousses area, velocities around the year 2000 are still larger than in 1960, despite a negative cumulative net mass balance since 1957 (Vincent et al., 2000). This shows the complexity of the processes involved. Spatial high-resolution velocity information as well as long-term monitoring allow a reliable analysis of glacier behavior.

We add in line 50:
For individual glaciers, better results can be achieved with specific optimized data processing than with global data sets (Mattea et al., 2025). Even relatively low ice velocities can be detected, as Gindraux (2019) shows for Griesglacier. However, slow-flowing glaciers need specific temporal baselines between image pairs to capture recognizable flow. This implies a potential loss of coherence, as surface features (e.g. crevasses) can change considerably during this period (van Wyk de Vries and Wickert, 2021).

- l. 29, Nye (1959) was most definitely not the first rigorous investigator of ice velocities; see e.g. [11]

That´s true. We change it to “A method established by Nye(1959)...”.

- l. 48, what are "sensors such as Sentinel-2" compared to "other optical sensors"? Define the groups or reword for clarity.

We reword for clarity: “Millan et al (2019) showed that Sentinel-2 data can produce more precise results than Landsat-8.”

- l. 69, "continuous monitoring" is unclear given the present-day availability of automated, sub-hourly monitoring sensors. Consider using "systematic" or similar

Thanks for the hint, we use "systematic" instead of "continuous".

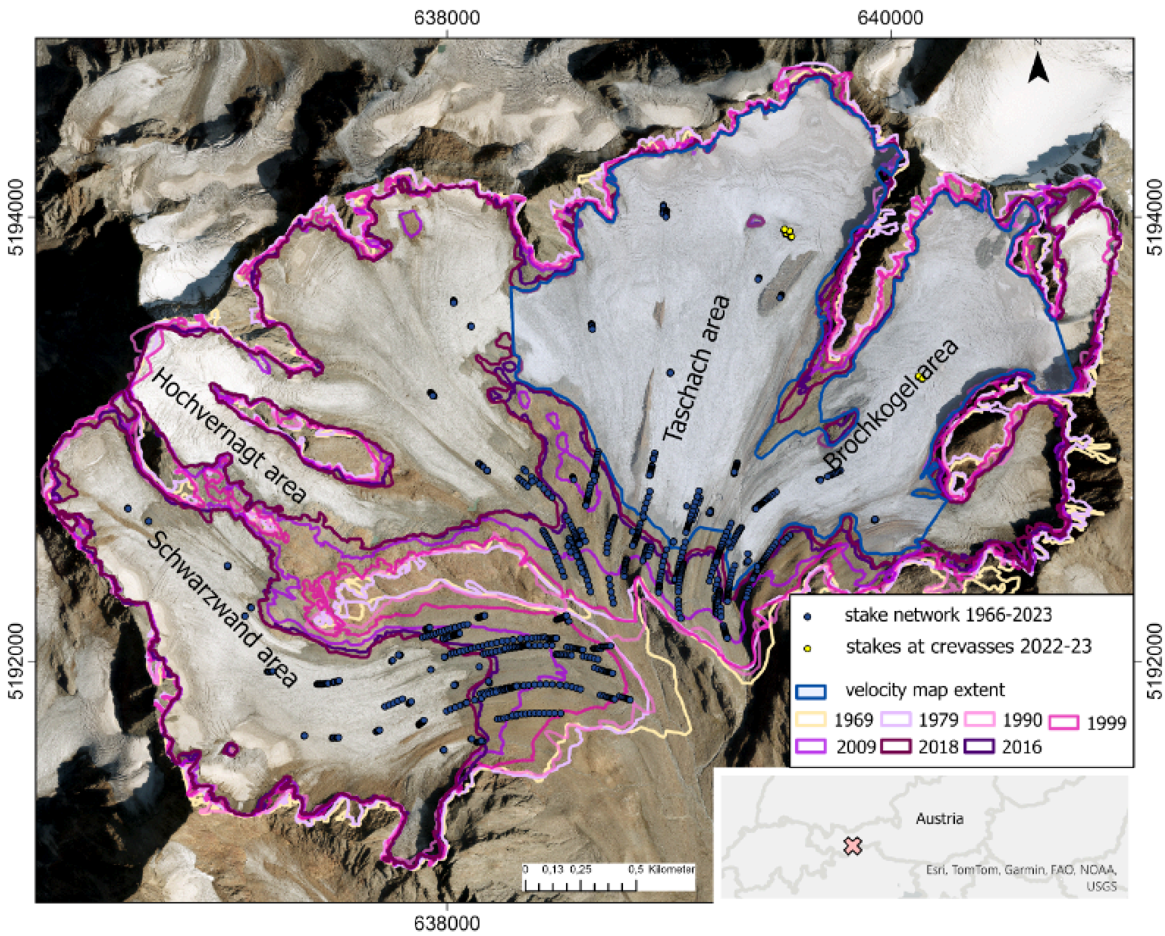
- l. 72, what makes the site "unique"? Explain concrete reasons for uniqueness if possible, otherwise consider rephrasing.

We rephrase it to: "Together, VF, Kesselwandferner, and Hintereisferner forming a well-monitored site of glacier-related variables."

- Fig. 1, why show the glacier extent from 2016 and not the present-day? Especially since high-quality whole-glacier imagery is available (Table 1). Also, the 2022/2023 stakes installed and surveyed specifically for the present study should be clearly marked as such and distinguished from the historical archived stakes.

We update Fig. 1, showing the glacier orthoimage from 2022 (newest available). Regarding the glacier extent we now show all available glacier extents, showing the change in the glacier extent, since we also have historical data here. The available extents are listed in the Appendix (see response to major comment 2.1(4)) (1969,1979,1990,1999,2009,2016).

Furthermore, we mark the stakes installed especially for the survey 2022/2023 with a different colour, to distinguish the data from the historical stakes.
updated Fig.1:



- l. 82, maybe it should be mentioned that the stakes were never repositioned at a fixed location, rather they were re-drilled at or close to their last location?

Thanks for the hint. We add in Line 86: “The measurement series are usually interrupted due to melt out of the stakes. However, the stakes are then re-drilled very close to the melt out location, so that the flow can be monitored.

- l. 90, "terrestrial polar connection" yields zero results on Google Search - is the method also known by different names? Please check and possibly rephrase or provide a reference

True, change to: “Polar coordinate methods”.

- ll. 91-92, the two "previous studies" analyzing velocity at the site appear to be unpublished and unaccessible diploma theses. However, their findings should probably be (1) quickly presented and (2) discussed and compared with the ones of the present study.

As mentioned in response to major comment 2.2 (3), information contained in these diploma theses are already included in the data. These studies focused on data preparation up to the respective point in time, which is why we would like to mention their valuable work here.

- l. 102, "image pair velocity fields" - I think ITS_LIVE and possibly Millan rather provide annual or biennial velocity composites?

That´s true. We change to: “ Figure 2 exemplarily shows the ITS_LIVE (for the period 2017-2018) and the Millan mosaic (for 2018) for VF.

- l. 113, please provide more details about the TerraSAR-X data and methods used - at least the following: (1) acquisition dates and pairs tested, (2) software used for feature tracking, (3) tracking window sizes used, (4) any post-processing and filtering steps

We provide more information and therefore change line 113-118 to:

In addition to user-ready products (which do not provide reliable results in our study region), there are high-resolution SAR constellations that offer repeat-pass sequences beginning at 1-day. To name a few, ICEYE InSAR (Łukosz et al., 2021), Capella Space SAR (Izzard et al., 2025), COSMO Sky Med (Wang et al., 2019), and TerraSAR-X (Schubert et al., 2013) constellations have already been successfully used to generate velocity maps. As an example, we tested the suitability of TerraSAR-X stripmap imagery (≈2 m spatial resolution) for obtaining glacier surface velocity fields on VF. Therefore, we applied feature tracking using various tracking window sizes (32x32, 64x64, 128x128, 256x256) and temporal baselines ranging between 11 days and up to about 2 years to pairwise co-registered images. The SAR processing was carried out using GAMMA Remote Sensing Software. The dates and orbit information of the employed acquisitions are summarized in Appendix C. All possible image pair combinations were tested using an automated processing pipeline (e.g. Seehaus et al., 2015, 2018), including a filter algorithm based on a comparison of the magnitude and the alignment of the displacement vector with surrounding values to remove unreasonable displacement estimates (Burgess et al., 2012). Coherence tracking or InSAR-based displacement measurements were not feasible to carry out at VF, because the InSAR coherence was not maintained between subsequent acquisitions, which we attribute mainly to the pronounced surface-lowering rates in summer and snow accumulation in winter.

Appendix C:

date	orbit dir. (decending/accending)	rel. orbit number	strip number
2011-07-03	D	78	6
2011-07-14	D	78	6
2011-08-08	A	131	10
2013-07-01	A	131	10
2014-06-07	A	131	10
2017-07-11	D	78	6
2017-08-13	D	78	6
2017-08-24	D	78	6
2018-07-31	D	78	6
2018-08-22	D	78	6
2019-07-29	D	78	6
2019-08-31	D	78	6
2020-01-02	A	131	7
2020-01-30	A	55	1
2020-01-30	A	55	1
2020-02-21	A	55	1
2020-02-21	A	55	1
2020-02-26	A	131	7
2020-05-02	A	131	7
2020-05-08	A	55	1
2020-05-08	A	55	1
2020-07-04	D	78	6
2020-07-26	D	78	6
2020-09-11	A	131	7
2020-09-17	A	55	1
2020-09-17	A	55	1
2020-11-11	A	55	1
2020-11-11	A	55	1
2020-12-25	A	55	1
2020-12-25	A	55	1

date	orbit dir. (decending/accendi	rel. orbit number	strip number
2021-01-27	A	55	1
2021-01-27	A	55	1
2021-02-01	A	131	7
2021-02-07	A	55	1
2021-02-07	A	55	1
2021-02-23	A	131	7
2021-03-25	D	78	5
2021-03-28	A	131	7
2021-04-08	A	131	7
2021-04-30	A	131	7
2021-05-11	A	131	7
2021-06-13	A	131	7
2021-06-24	A	131	7
2021-07-05	A	131	7
2021-08-18	A	131	7
2021-08-26	D	78	6
2021-09-09	A	131	7
2021-09-17	D	78	6
2021-10-12	A	131	7
2021-11-14	A	131	7
2021-11-25	A	131	7
2022-03-04	A	131	7
2022-03-26	A	131	7
2022-04-06	A	131	7
2022-05-09	A	131	7
2022-05-20	A	131	7
2022-05-31	A	131	7
2022-06-11	A	131	7
2022-07-03	A	131	7
2022-07-25	A	131	7
2022-08-02	D	78	6
2022-09-18	A	131	7
2022-09-29	A	131	7
2022-10-21	A	131	7

- Table 1, please provide details about the "UAV" and the "Optical airborne photogrammetry" - which platform, camera, flight altitude, spatial resolution?

Information on spatial resolution is added. Details on the platform, camera and flight altitude used in optical aerial photogrammetry are only partially known. Where available, the relevant literature is cited for more information. The UAV data was obtained through manual flights, meaning that no uniform flight altitude was used, as it varies.

updated Table 1:

Name of dataset	Sensor/Instrument	Date	Res. [m]	Covered area	Data provider
Airborne 2020	Optical airborne photogrammetry	2020-09-08	0.2	Entire glacier	© Land Tirol tiris Tirol (2025)
Airborne 2018	Optical airborne photogrammetry	2018-09-16	0.2	Entire glacier	Geissler et al. (2021), Withheld for legal reasons
Airborne 2021	Optical airborne photogrammetry	2021-09-25	0.2	Entire glacier	Withheld for legal reasons
Airborne 2022	Optical airborne photogrammetry	2022-08-23	0.2	Entire glacier	Withheld for legal reasons
UAV 07/2022	DJI UAV with optical RGB camera	2022-07-10	0.04	Parts of Taschach and Brochkogel	10.5281/zenodo.17590496
UAV 09/2022	DJI UAV with optical RGB camera	2022-09-21	0.04	Parts of Taschach and Brochkogel	10.5281/zenodo.17590496
Stake network (since 1966)	Polar coordinate method / GNSS (annual surveys in Sept)	1966–present (annual)	—	Entire glacier, mainly ablation area	10.1594/PANGAEA.982940
Stakes at crevasses 07/2022	GNSS	2022-07-10	—	Parts of Taschach and Brochkogel	10.1594/PANGAEA.982940
Stakes at crevasses 08/2022	GNSS	2022-08-04	—	Parts of Taschach and Brochkogel	10.1594/PANGAEA.982940
Stakes at crevasses 09/2022	GNSS	2022-09-21	—	Parts of Taschach and Brochkogel	10.1594/PANGAEA.982940
Stakes at crevasses 08/2023	GNSS	2023-08-08	—	Parts of Taschach and Brochkogel	10.1594/PANGAEA.982940

- l. 130, please provide more details here already about this seasonal correction - is it a single multiplication factor? How is it calculated? This information cannot be postponed to the second half of the manuscript.

We add to the manuscript (as later also suggested): “By comparing measured summer velocities at a few locations in the Brochkogel and Taschach area with the corresponding annual average, the seasonal variation is estimated to be approximately 30% (detailed information see chapter 4.2). Although the seasonal variation shows some differences between the Brochkogel and Taschach area and was only estimated for 2022/23, we consider the mean derived seasonality to be representative for the entire VF and assume its applicability to other years. Therefore, the seasonality observed in 2022/23 is applied to data covering the period from 2018 to 2023 where required.”

- l. 150, first introduce Fig. 3 and what is displayed there, then add specification such as which stakes are included
Done, changed to: “For this purpose, the stake network data, which has been measured annually at VF since 1966, is analyzed. Figure 4 displays the stake positions during the years. The focus lies on evaluating the temporal evolution of the ice movement, only time series of at least six consecutive years are considered. The data clearly demonstrate …”
- l. 157, the modeling of velocities should be described in detail in the Data and Methods, not just passingly in the Results. In particular, it should be explained (including formulas): (1) Where do the values for local ice thickness come from? (2) How are thickness and surface slope calculated for each stake to evolve for each year? The resulting ice velocity is a high power of both variables, thus it is highly sensitive to their precise values and variations.
Information has been added, for a more detailed description see response to major comment 2.1.

- l. 163, strictly speaking, in the modeled values, we see the sensitivity of velocity to ice thickness, not directly to mass balance.
That´s true, changed to: “ To evaluate a possible reproduction of the velocity trends using only geometry, we compared the measured velocities with modeled velocities (from the SIA approximation) in Fig. 6. While the modeled values provide the same dynamic trends as the measured, offsets occur, which can be attributed to uncertainties in the input data (especially the ice thickness) and the temporally fixed choice of flow parameters.”
- l. 165, what is "the temporally fixed choice of flow parameters"? This has not been described before, it has to be fully explained in the Methods subsection about the modeling.
Thanks for the hint. See response to major comment 2.1 (3).
- Fig. 4, this figure is very interesting. However, the "average elevation" of each stake is possibly not the most informative value here, since all elevations are clustered within less than 100 m altitude. If possible, provide also the maximum and minimum elevation of each stake (supposedly corresponding to the earliest and most recent observation dates)
Done.
- Fig. 5, to better highlight interannual changes of ice velocity, it would likely be more informative to display stake velocities not all together as absolute values, but rather as anomalies (additive or multiplicative) compared to the long-term mean at each stake
That's true, we add a subfigure to Fig. 5, showing the anomalies.

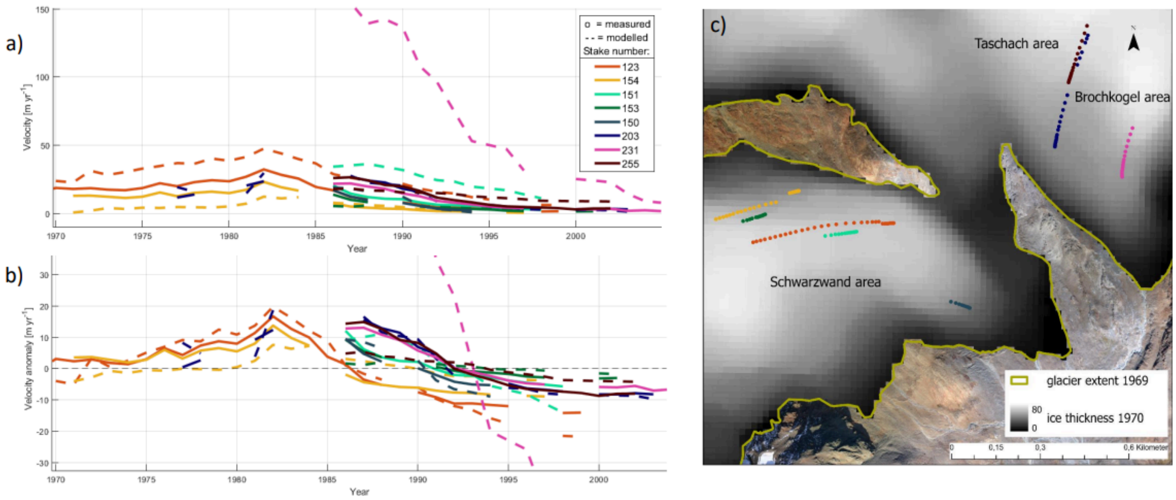


Figure: Measured and modeled stake velocity according to a shallow-ice approximation for selected stakes a) as absolute values and b) as anomalies from the long-term mean of each stake. c) Position of the selected stakes with the glacier extent from 1969 and the ice thickness from 1970 (details on the calculation see chapter 3.6). Background image: Orthoimage 2016 © Bavarian Academy of Sciences and Humanities (BAdW), 2016.

- l. 168, no data above 3000 m a.s.l. has been introduced in the text before Fig. 6 - please give a quick introduction to those stakes, are they all stakes with < 6 consecutive years of data? Are they stakes in the accumulation area?

We do not understand this point of the reviewer. Figure 6 shows the whole dataset of measured velocities; no differentiation was made e.g. on length of time series. We updated the Figure caption accordingly: "Glacier velocities of all observations in m yr−1 in dependence of altitude and time (color code)"

Regarding the point "no data above 3000m": We basically have velocity measurements in the ablation zone, since the stake network was designed to measure ablation rather than the velocity pattern of VF (see lines 82-84 of original manuscript version). To clarify, we added in line 84 of the manuscript: "Note that the stake network was adapted over the years to capture the ablation area which changed over the years due to the propagation of ablation to higher elevation in response to global warming. For this reason, the elevation range captured by the stake network varies.

- l. 172, these are all methodological details that belong to the Methods section, as they are necessary to understand most of the results presented so far. Also, more details are needed on the calculation of ice thickness change: was it computed only from local mass balance, fully neglecting ice advection? This would introduce a major, systematic, elevation-dependent bias in the ablation area (too fast thinning)

We agree and move these methodological details to the Methods section. Details on the calculation of ice thickness are explained in response to major comment 2.1. Both, mass balance and mass transport are taken into account in the surface models. We interpolate between two surface models. The mass balance is only used to scale the geometric change. The geodetic height change includes ice advection, so at least the average ice transport is taken into account.

- Fig. 6, this interesting plot is hard to read, especially since all point measurements from all stakes are shown without distinction. At this stage, the reader does not know how many stakes are visualized on this plot, and how many stakes exist at each given point in time. Thus, it is not clear what is the time evolution here, apart from a general trend of "slowdown at all altitudes". It could make more sense to connect the

points of single stakes, possibly aggregating in multi-annual intervals (even decadal aggregation) and/or excluding stakes with very few years of observation, in order to reduce the complexity of the data shown.
We are not sure whether we have correctly understood the suggestion regarding Fig. 6. Representing stakes with a long observation period and connecting the points of single stakes would lead to a Figure close to Fig. 4 of the original manuscript. We agree that it is not possible to distinguish between the individual stakes in Fig. 6 in the current way, but we intent to show that the glacier velocity slow down occurs in all height levels. Therefore, we keep this Figure in the manuscript.

- Fig. 7, the thickness maps exhibit obvious major interpolation/processing artifacts, which would be strongly reflected in any calculated ice velocity. The thickness data need to be made available and/or re-examined in the light of these artifacts, if any conclusion about changes in glacier geometry is to be drawn. Also, if possible, please show simultaneous extent and thickness of the glacier rather than inconsistent dates; the 2016 extent is already in Fig. 1. Finally, the arrows indicate the flow direction, how was it determined? Please provide methodological details in the relevant section.
That is true, thanks for the hint. We re-examined these artifacts (see new figure 7 in this comment).
In addition, the publication of the DEMs (see response to major comment 2.1(4)) allows the calculation of ice thickness data to be traced.

In Figure 7, we show the average stake velocities for three different periods (1970–1980, 1990–2000, and 2010–2020). In order to represent the average ice thickness for each epoch, we decided to show the ice thickness for the respective average year (1975, 1995, 2015). Unfortunately, we do not have glacier extent data for these exact years, therefore the ice thickness is clipped to the last known glacier extent, as it is described in more detail in the response to major comment 2.1(1). To avoid misunderstandings, and since the clipping is already described, the glacier extent is removed from Fig. 7.
The arrows indicate the average direction of movement of the respective stake. This information is added to the figure caption.
updated Fig.7:

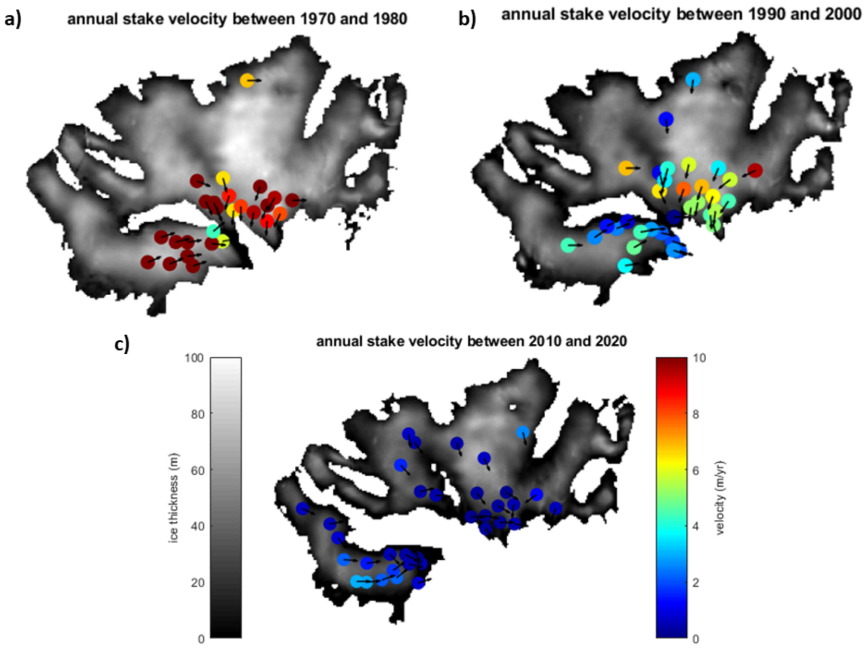


Figure 7. Mean annual stake velocities during the indicated period a) between 1970–1980 with 1975 ice thickness b) between 1990–2000 with 1995 ice thickness c) between 2010–2020 with 2015 ice thickness. Details on the ice thickness calculation can be found in chapter 3.6). The arrows indicate the determined flow direction, which is calculated from the mean angle of movement of the respective stake.

- l. 184, here is a description of a methodological choice and would fit very well around l. 130 if it is the same seasonality correction that is described here.

Done, thanks.

- Fig. 8, what is the standard deviation of this 30 % summer speed-up? If I understand correctly, the monthly (in summer) and annual velocities are available for each of the 8 + 4 stakes mentioned here, thus it would be quite important to show how much these stakes deviate from the 30 % estimate (and thus, how uncertain the estimate is) - especially if the correction factor is to be considered "representative and applicable" anywhere.

Velocity data used to calculate seasonal variations is available at PANGAEA. An additional table is added to explicitly show the individual vales and the calculated seasonal variation:

Area	Number	v_{JA} Juli 22–Aug 22 [m yr^{-1}]	v_{AS} Aug 22–Sep 22 [m yr^{-1}]	v_a Aug 22–Aug23 [m yr^{-1}]	$\frac{v_{JA}}{v_a}$ seas. var.	$\frac{v_{AS}}{v_a}$ seas. var.
Brochkogel	1	3.37	5.05	3.14	1.07	1.61
Brochkogel	2	3.44	4.74	3.03	1.14	1.56
Brochkogel	3	4.52	4.16	3.22	1.40	1.29
Brochkogel	4	4.62	3.00	no measurement		
Brochkogel	**mean**	**3.99**	**4.24**	**3.13**	**1.20**[a]	**1.49**[a]
Taschach	1	4.54	2.21	2.38	1.91	0.93
Taschach	2	3.78	2.39	2.27	1.67	1.05
Taschach	3	3.57	3.85	3.09	1.16	1.25
Taschach	4	4.12	3.97	2.17	1.90	1.83
Taschach	5	1.27	1.52	1.74	0.73	0.87
Taschach	6	1.82	3.84	2.11	0.86	1.82
Taschach	7	2.24	3.49	2.17	1.03	1.61
Taschach	8	2.08	1.95	1.77	1.18	1.10
Taschach	**mean**	**2.93**	**2.90**	**2.21**	**1.30**	**1.31**

[a] The mean ist without the measurement of Brochkogel 4.

We add to the manuscript:
in line 221:
On average, seasonal variation is 1.30 (130%), with a standard deviation across all observations of 0.37 (37%).
and in line 259: At Vernagtferner, summer velocities are approximately 30% higher than the annual mean, with a standard deviation across all observations of 37%. The relatively high uncertainty results from the fact that the absolute measured values over a month (July-Aug or Aug-Sep) have maximum values of about 50 cm. However, these values have a relatively high measurement uncertainty of +/-14cm.

- l. 218, a claimed 3 cm measurement error corresponds to a good-quality dGNSS / RTK survey, whose method (instruments and protocol) should be described in the Methods section.

We now name the method in the data description in Appendix 1. In our opinion, GNSS measurement is a state-of-the-art method. Therefore, we do not describe this method explicitly in the “Methods” section and do not submit any protocols.
This was a classic static GNSS measurement using a multi-frequency GNSS receiver, with our own base station in operation. The post-processing evaluation, which we had to rely on due to a lack of data connection for RTK processing, consistently delivered solutions with fixed ambiguities. This resulted in an accuracy of approximately 3 cm. We are adding this information to the data description in Appendix 1 as:
sensor: multi-frequency GNSS receiver; processing: post-processing with fixed ambiguities

- l. 222, the data resolution should be introduced in the presentation of the UAV / aerial data.

Done, see response to major comment 2.1 (4).

- l. 229, the statistical basis of this calculation of overall uncertainty is unclear: the mean uncertainty is most definitely not the average of individual uncertainties. See e.g. [12], [13]. Another possibility would be to use leave-one-out validation of each available measurement.

That´s true. We change the uncertainty analysis, a new version can be found in the response to major comment 2.6

- l. 233, the dataset contains maps of ice velocity and of surface slope, it should be easy to calculate proper metrics (such as a correlation coefficient) of the agreement between surface aspect and flow direction, rather than a qualitative "overall alignment of the calculated flow directions with the glacier topography".

That´s true. We calculated the angle deviation of the flow direction of the topography to the flow direction of the velocity in the median at 43 degrees. Larger angular deviations may occur, especially at lower magnitudes. This information is added to line 233.

- l. 235, there exist published methods to estimate interpolation error in areas of heterogeneous point data coverage. See for example [14].
This must be a misunderstanding; we don't interpret here the quality of the interpolation. We just say the ice flow map is most trustworthy in areas of high data density. We slightly rewrite the sentence for clarity: "Despite the estimated interpolation error, the velocity map becomes less reliable in regions with limited data availability. In zones where observational data is lacking, there is insufficient information, making the reliability of the velocity map for understanding ice flow dynamics in these areas questionable."
However, we think the reviewer comment also belongs to lines 231-234 where we estimate the interpolation error. More information, including testing of the method described in the literature suggestion [14], can be found in the response to major comment 2.6.
- l. 253, is this "wide range of notable differences between the summer and winter seasons" shown anywhere? So far the Authors have presented only three spatially-aggregated, monthly data points from a single summer season (Fig. 8).
As shown in Table 2 (of this document) above, the datapoints are represented now. We agree, the description as "wide range of notable differences between summer and winter seasons" is not sufficiently justified based on the initial data, we change it to: "with a notable difference between summer and winter seasons".
Information on the restrictions regarding the summer year and the spatial extent can already be found in lines 256-267.
- l. 315, this conclusion can only be taken if proper state-of-the-art methods are tested and the results are shown, the well-established methods validated by several studies (including on slow glaciers) cannot be so quickly dismissed.
We agree. We don´t want to rule out the possibility that there could be a successful tracking of the features. At this point, we would like to draw more attention to the overlap caused by ablation. Even if a modern method enables feature tracking, the challenges associated with high ablation remain. We would like to clarify this statement as follows:
"With the general tendency of strong negative mass balances and the associated high ablation, changes in surface features may be caused predominantly by ablation rather than ice dynamics.
- l. 323, I would caution against using a map with manually tracked features as benchmark for validating other datasets, since the computed quality of such datasets would then inherit the reproducibility issues of the manually-compiled map.
We agree and rewrite: …. allow a detailed modeling of glaciological processes as well as plausibility assessments of future remote-sensing results."
- l. 329, data availability: most of the datasets mentioned and used within the study are actually missing, including the ice thickness data, any digital elevation models, and the UAV and airborne data. Only the historical stake data are provided, the other assets are rather results from the study such as the manually tracked displacements and the five-year velocity map. Unless there are legal restrictions, for both review and reproducibility purposes it is important to provide access to the actual data (not just the results) used in the study.
We publish all data (via zenodo) that is not subject to legal restrictions. An overview can be found in the new created table, see response to major comment 2.1 (4).
DOi: https://doi.org/10.5281/zenodo.17590496

Additional Literature used in the response:

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