Response to reviews

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 the following, we quote the reviewer´s comments followed by our replies, which are marked in orange, while changes in the text are marked in blue.

Author´s response to editor

From the reviews, minor revisions are needed. Following Referee 1, some further restructuring that links the recent and long-term measurements will help to further focus the message of the manuscript. In addition, the reviewer points to some interpretations of ice dynamics that should be addressed. Lastly, there are some adjustments in the text and figures that would improve the manuscript.

Thank you very much for your valuable comments. We have added the suggestions to the manuscript as described in more detail below.

Author´s response to referee comment # 1

The topic of ice velocity measurements for slowly moving glaciers takes up a disproportional share of the manuscript. The account on this topic does not contain novel information, neither on the methodological side, nor regarding the performance and constraints of remote sensing based products on glacier velocity. The related sections should be abbreviated. There is no need showing examples of velocity maps that do not meet the performance requirements. Limits regarding the performance and applicability of such products have been comprehensively reported in product specification documents and in the open literature. The related figures (Fig. 2, Fig. 10) may be shown in a Supplement. Under the given conditions the combination of stake measurements and manual feature tracking for velocity retrieval is an appropriate choice. The detailed documentation on the performance of the in situ and feature tracking velocities and of the compiled velocity map represents a comprehensive basis for the performance assessment.

Thank you for this comment. As recommended, we moved the entire chapter "Review of existing products," including Fig. 2, to the appendix.
We tested the suitability of TerraSAR-X imagery (in Fig. 10). We would like to keep Fig. 10 at this point, as the use of standard remote sensing techniques is the most obvious choice and has already been successfully used to generate velocity maps. Furthermore, this result supports our choice to use in situ measurements and manual feature tracking.

According to the statement in Section 1, the aim of the study is to investigate in detail the ice dynamics of the recent slow-flow period of Vernagtferner (line 62). A main basis for this task should be the ice velocity map of the recent slow-motion period. However, the links between the two items, ice dynamics and the observations of current ice velocities, are not conclusive and should be exemplified. A main parameter in this context is the dynamic contribution to local elevation change. Fig. E1c shows a map of this parameter, based on the difference between the observed surface elevation change and the surface mass balance for the period 2016 (2016-09-29) to 2018 (date to be specified), lacking reference to observed velocities. Independent estimates for dynamic contributions to observed glacier volume change can be obtained under the assumption of mass conservation by deriving the depth-integrated flux divergence from spatially detailed velocity fields and local ice thickness. Considering basic patterns of along-flow divergence and convergence in the velocity map, there seem to be some glacier sections in Fig. E1c that are not in accordance with mass conservation. For example, in Fig E1c the Schwarzwand area is dominated by positive dynamic contributions (flux convergence) but lacking a substantial accumulation area. The uppermost sections of the Taschach and Brochkogel areas have very low velocity bur show high dynamic contributions, probably an overestimation. On the other hand, the observed deceleration downstream of the velocity maxima is an indication for flux convergence, though also these dynamic contributions should be rather small due to the low velocity.

Thank you for pointing this out. We agree that, assuming mass conservation, the local dynamic contribution to elevation change (Fig. E1c) can in principle be generated using the flux divergence.
In the present case, this is hardly possible for two main reasons: firstly, the map of current velocity is only known for the Brochkogel area and parts of the Taschach area. Second, the errors in the ice thickness measurements are likely to be too large. Although relatively dense radar measurements were taken, we do not believe that they are dense enough to actually map the local divergence patterns. The quality of the ice thickness measurements is shown in the color code in Fig. 1 below (in this document). The quality of the Brochkogel measurement is insufficient for such an analysis and has to be excluded. The quality of the northern Taschach area has to be questioned at the very least (see Mayer 2013).

Nevertheless, we have determined a flux divergence map for the entire extent of the map of current velocity as an example (Fig. 2a in this document). For better comparability, this is contrasted with the local dynamic contribution to elevation change (Fig. 2b in this document or Fig. E1c of the previous manuscript version). However, as mentioned the eastern part (Brochkogel) would definitely have to be excluded.

Figure 2a shows positive divergence with relatively small magnitude in the Taschach tongue area and negative divergence in the northern part of the accumulation area. However, clearly negative divergences are shown in the transition (in the southern part of the accumulation area). These can be attributed to the strong gradients of the velocity field on the one hand and to the ice thickness information on the other. No ice thickness measurements could be taken around the rock island or in the crevassed areas there. It is likely that the ice thickness (especially around the rock island) is actually thinner than the interpolation shows.

Overall, the Taschach area supports the basic principle of the analysis, but for further analysis it would be necessary to measure ice thicknesses in greater detail and generate velocity maps for the entire VF in order to obtain the necessary level of detail. For this reason, we are not including this initial analysis in the manuscript.

Regardless of the lack of current velocity data for the Schwarzwand area, we agree that there appears to be a significant accumulation area missing in the Schwarzwand tongue area. It seems as if this was previously a more significant accumulation area and is currently no longer as pronounced. However, this can certainly be attributed in part to the interpolation of the surface mass balance, which is particularly extrapolated in this area, leading to increased uncertainty in this area. It is therefore possible that there is still some accumulation area present, even if it can not be seen in Fig. 2b. We will mention these points in more detail in the manuscript and add the following to our text (blue):

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.It seems that a substantial accumulation area is missing. 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. It is also possible that these are formerly significant accumulation areas that are no longer very pronounced.

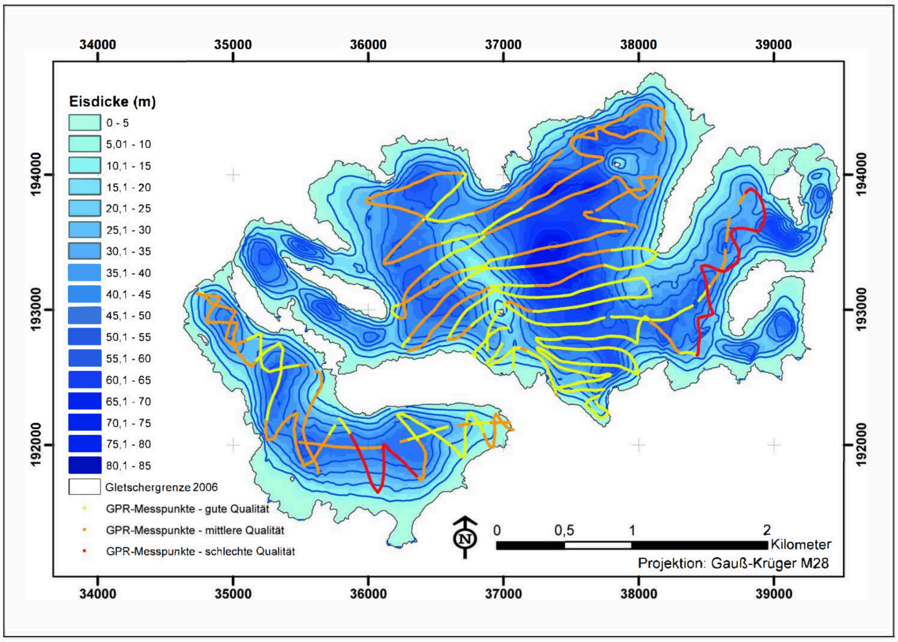

Fig.1: Ice thickness of the VF based on the radar survey of April 2007 and in the glacier boundaries of 2006. The quality of the surveys is color coded. (from Mayer 2013)

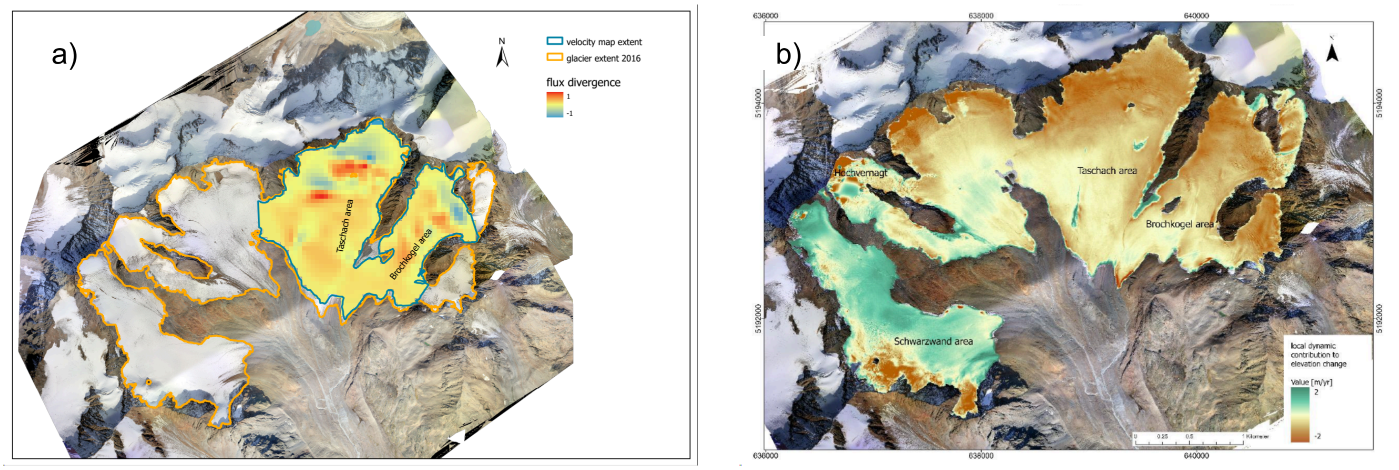

Fig.2: a) flux divergence b) local dynamic contribution to elevation change

Further issues:

- In the abstract a note on results of the ice dynamic investigations, a key point of the presented work, is missing. A short note on main findings would be meaningful.

That's true, we extend the abstract to:

…With the onset of the negative mass balances, the velocity has decreased steadily until today. Our results suggest that the displacement of ablation stakes response relatively direct to changes in surface mass balance. The surface mass balance is currently the dominant control for geometry change, while local dynamic contributions to elevation change remain secondary.Based on recent in-situ measurements, a seasonal variation of surface…

- Mass balance is one of the key parameters for the study. Please provide numerical values for the annual mass balance of the years 2016/2017 to 2022/2023, if available separately for the focus areas Brochkogel and Taschach area.

Thanks for the hint. The SMB values across the entire glacier are shown in Fig. 5, numerical values separately for Brochkogel, Taschach and Schwarzwand area are provided by the BadW.

We add to the text:

Overall, for the period 2016-2023, the SMB at Brochkogel is approximately 20% less negative than in the Schwarzwand and Taschach area (BadW 2025).

- Line 25: “Understanding these velocity pattern and their temporal changes on a resolution considerably higher than the spatial variability is increasingly important …. “ The message of this sentence is unclear, mixing up temporal and spatial scales.

Thanks we changed the sentence to:

Understanding these velocity pattern and their temporal evolution requires observations at sufficiently high spatial and temporal resolution.

- Line 79: Here it is stated that the Vernagtferner can be divide in three areas, but Fig. 1 shows 4 separate sections of the glacier: Schwarzwandzunge, Taschach area, Brochkogel area and an additional section between Schwarzwandzunge and the Taschach area.
Historically, there have been three glacier tongues (Schwarzwand, Brochkogel, Taschach). Among others, the SMB was divided into these sectors. For this reason, we would like to use these sectors here as well. The reference to Hochvernagt (Fig. 1) is just another description of a location that will be referred to later in the text, but it belongs to the Taschach area, as it is still connected to it.

- Fig. 1: According to the figure caption glacier extents from 1969 to 2016 are shown, but the inset shows symbols for velocity maps up to 2018. Please clarify. Furthermore, elevation contour lines (in this figure or elsewhere) might be useful as references to elevations, quoted in various other figures and in the text.
Thanks for the hint. We correct the figure caption to glacier extent from 1969 to 2018. Furthermore, we added contour lines in Figure 1.

- Section 3.4.1: Here reference is made to offset tracking as tool for glacier velocity retrievals. However, many successful applications have also been reported on the use of short-term repeat-pass high resolution InSAR for glacier velocity retrievals, e.g. for COSMO Skymed. The sensitivity to surface displacement is much higher than for offset tracking. The method is applicable for time spans without surface melt and snowfall.
We are not sure whether this comment refers to Section 4.3.1 or Section 3.4.1. In Section 3.4.1 we describe the methodology (with reference to other short-term InSAR constellations). Section 4.3.1 presents the results of the TerrSAR-X experiment (without reference to other short-term InSAR constellations).
We show examples of the results from a TerraSAR-X constellation. It is likely that other InSAR constellations will also encounter problems due to the issue of high ablation, as they are only suitable for periods without surface melt.

- Line 205: Please specify the methods used for determining the annual mass balance for the focus period of the study (2016 to 2023).
We added the information:
Instead of assuming linear interpolation over time, the interpolation between two consecutive DEMs was scaled according to the cumulative SMB. The annual mass balance is determined through the glaciological method and 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 (WGMS, 2024).

- Figure 6: Fig 6a includes a stippled line with very high velocity (150m/yr) in 1985 (the computed velocity for stake 231). Please explain the cause for the large deviation from the measurement.
Due to the highly simplified modeling, only the trends of the stakes can be evaluated. The temporally fixed choice of flow parameters and basal sliding can lead to higher values. Furthermore, the ice thickness interpolation does not allow for the mapping of small-scale topographical conditions. This can also lead to high calculated velocities. Due to data uncertainty, such variations are quite possible, which is why we would like to evaluate only the trends.

This information can be found in chapter Results 4.1 Long-term ice dynamics:

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.

- Line 273: Uncertainty numbers for the mass balance and dynamic contribution should provided, if possible in dependence of altitude or at least for the different sections of the glacier.

Thanks for the hint. We are expanding out explanations:

In order to enable a numerical estimation of the processes, which excludes outliers as far as possible, the median of the absolute mass balance and the absolute dynamical contribution were calculated separately for the three glacier parts. The median of the absolute mass balance amounts to 1.48 m/yr , 1.32 m/yr and 1.06 m/yr for the Taschach, Schwarzwand and Brochkogel area, respectively. The corresponding median of the absolute dynamical contribution to elevation change are 0.54 m/yr, 0.43 m/yr and 0.74 m/yr.
For the mass balance determined by the glaciological method, a total uncertainty of less than 0.40 m/yr can be assumed (Zemp et al 2013). For the period 2016-2018, an uncertainty of approximately 0.28 m/yr can therefore be calculated, taking into account the law of error propagation.
The mean errors of the DEMs can be estimated at approximately 20 cm for 2016 and 10 cm for 2018 (TIRIS 2018). Taking into account the law of error propagation, this results in an uncertainty of 0.11 m/yr for the surface difference from 2018 to 2016. For the dynamic contribution to elevation change, calculated as the difference between SMB and surface difference, a total uncertainty of approximately 0.30 m/yr can be assumed. 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 also change the part in the Discussion chapter:

The median absolute values for SMB (Taschach:1.48 m/yr , Schwarzwand: 1.32 m/yr and Brochkogel area 1.06 m/yr) and the local dynamic contribution to elevation change (Taschach:0.54 m/yr , Schwarzwand: 0.43 m/yr and Brochkogel area 0.74 m/yr) suggest that the ice dynamic is not able to fully compensate the losses due to melt, especially in the ablation area.

- Seasonal variation and Table3: Estimates regarding uncertainty for seasonality should be provided. The uncertainties of the velocity numbers for the summer periods (July-Aug and August-Sept 22) are certainly higher than for the annual time span. For example, some of the stakes show a switch for acceleration to deceleration (or vice versa) for the two summer periods. This would imply switching between flow divergence and convergence within comparatively small sections of the glacier, rather unlikely.

We fully agree. The general position uncertainty can be estimated at +/- 10cm. Taking into account the law of error propagation, an annual velocity uncertainty of +/-0.14cm/yr can be estimated for a yearly period, for example Aug 2022- Aug 2023, as already mentioned in the uncertainty chapter. The period July 2022- Aug 2022 and Aug 2022 - Sep 2022 have significantly higher uncertainties due to the shorter measurement periods. The period July 2022 - Aug 2022 (25 days) leads to an uncertainty of 2.06 m/yr, while the period Aug 2022-Sep 2022 (48 days) has an uncertainty of 1.08 m/yr. We add this information to the table caption of table 3.

- Line 459 to 461: In the text there is a switchover from long term observations to the estimation of seasonal variations based on in situ measurements. It should be made clear that the statement in the second sentence refers to the recent period.

Thanks, we add to the text:
Long-term observations at Vernagtferner indicate that glacier flow responds to changes in surface mass balance on short timescales, with velocity changes in the ablation area occurring within at most a few years. Recent ground-truth measurements enable the estimation of current seasonal variations in ice flow, with summer velocities being up to 30% higher than the annual average.

- Fig. E1a and E1b: The same numerical range of the color scale for the two parameters would facilitate the visual comparison.

Done.

Additional Literature used in this document:

Mayer, Lambrecht, Blumthaler, Eisen: Vermessung und Eisdynamik des Vernagtferners, Ötztaler Alpen, in: Zeitschrift für Gletscherkunde und Glazialgeologie, 2013