Response to reviews for Hedetoft, Bang Brinck, Mottram et al.. Mélange or landfast ice: What controls seasonal calving at Greenland outlet glaciers?

Reviewer 1:

The authors combine in-situ tracking buoys, remote observations, CTD, and climate model data to explore the effects of melange and landfast sea ice on calving dynamics at three Greenland outlet glaciers: Tracy, Melville, and Farquhar glaciers. The data is novel and important for future investigations of Greenland calving dynamics. However, there are major concerns that need to be addressed before the manuscript to be considered for publication.

Thanks for your nice remarks, we're happy you see the importance of this study.

Major comments:

1) Melange is defined as "a granular mixture of calved icebergs and sea ice that forms in front of glaciers". Therefore, landfast sea ice is part of melange and directly modulates melange properties. For instance, in Robel 2017 Nat Commun paper, landfast sea ice is modeled as bonding material (cohesion) in between iceberg particles within the melange. In Meng 2025 Nat Commun paper, they stated that "On the other hand, cooler ocean and air temperatures in winter enhance mélange rigidity [*due to the formation of landfast sea ice*], making it easier to pile up thick mélange at the terminus to provide buttressing. How warmer oceans and atmospheric influence the mélange strength is the subject of future work." This manuscript could be a great contribution on quantifying how landfast sea ice modulates melange rigidity/thickness/buttressing force. But the current title/conclusion is confusing: landfast ice and melange should not be listed as two independent factors. With landfast sea ice, melange is easier to pile up to be thicker (due to the enhanced cohesion), which provides larger buttressing force. If melange does not affect calving dynamics, it's possible that it is just not thick enough. Theoretical derivation on how melange buttressing depends on melange thickness has been conducted in the following papers:

Amundson, Jason M., and J. C. Burton. "Quasi-static granular flow of ice mélange." *Journal of Geophysical Research: Earth Surface* 123, no. 9 (2018): 2243-2257.

Kavinda Nissanka, Nandish Vora, Joshua Méndez Harper, et al. Experimental Investigations of Ice Mélange and the Flow of Floating Granular Materials. *ESS Open Archive* . August 24, 2024.

Meng, Y., Lai, C. Y., Culberg, R., Shahin, M. G., Stearns, L. A., Burton, J. C., & Nissanka, K. (2025). Seasonal changes of mélange thickness coincide with Greenland calving dynamics. *Nature Communications*, *16*(1), 573.

Amundson, J. M., Robel, A. A., Burton, J. C., & Nissanka, K. (2025). A quasi-one-dimensional ice mélange flow model based on continuum descriptions of granular materials. *The Cryosphere*, *19*(1), 19-35.

Thanks for your comment, it is indeed conceptually challenging to separate out landfast sea ice from mélange, and as we note in the abstract we consider the calving front of outlet glaciers as part of a continuum that in fact starts before the glacier terminus and well into the landfast sea ice outside of the mélange zone. As landfast sea ice also extends well beyond the region of mélange we do think it helpful to distinguish between the two categories of land fast sea ice and unbonded mélange. Our observations show that the unfrozen or unbonded mélange at these outlet glaciers has very little influence on glacier velocity or calving rates and it is only when the separate ice blocks in the mélange zone are frozen into a matrix of landfast sea ice, losing the granular material properties that are characteristic of mélange and have the material properties more associated with rigid multi-year sea ice, that they start to exert any kind of (limited) influence on the calving rates. We have therefore clarified this in the definition of mélange and land fast sea ice in subsection 1.1 and added some additional sentences to the discussion where we focus also on the role of mélange and sea ice thickness on modulating calving processes.

We prefer to leave the title as it is as what we try to tease out here is the role of the sea ice as opposed to calved icebergs in the mélange.

2) Figure 5 implies that melange velocity is always faster than glacier, over the 1.5yr data aquisition period. This is surprising and not consistent with the finding in Amundson2018. Can the authors add some explanation of why this is the case for the 3 reported glaciers?

We were also surprised by this feature in our analysis. We also checked against the ITS_LIVE dataset and found a very similar result. In fact, careful examination of Figure 5 (which we have replotted to make it clearer) shows the inner mélange zone velocity is usually very close to the velocity of the lower glacier point, particularly on Melville and Tracy glaciers but with some large deviations over some periods which likely represent calving events. The buoy data shows that the average daily velocities in the mélange zone are generally low but with abrupt jumps which we interpret to be associated with calving events and the addition of these abrupt jumps likely explains the above average velocity when smoothed in the time series. It is one of the reasons that we suggest that the mélange does not exert much back stress on the glacier fronts even when held in place by land fast sea ice. Ocean measurements indicate substantial tidally driven mixing close to the mid point between Tracy and Farquhar which drives some of the movements we detect at these locations and the driving stress of the glaciers is clearly sufficient to keep the glaciers moving through the winter.

As the glacier front advances into the mélange zone the mélange is also pushed forward and has less resistance than grounded glacier ice. This also leads to the crumple zone of ice ridges, shown in figure 16 at a location around 4km in front of Melville Glacier. The landfast sea ice further out in the fjord is in general stationary, except for some tidally driven movement, so this velocity away from the glaciers does decay with distance. We have added some further sentences to the discussion of this result, to clarify this result and have also plotted up 2D velocity maps (see comment below).

3) Figure 9 could be a nice place to showcase landfast sea ice is important for interpreting calving dynamics. What will happen if the author superimpose air temperature profile (below 0C as blue, above 0C as red, as done in Fig10)? Will we see terminus advance coincide with below C (more sea ice, thicker melange, larger buttressing); terminus retreat with above C (less sea ice, thinner melange, less buttressing)?

This is a nice suggestion and we have modified Figure 9 with the blue/red colours suggested, but note that figures 6, 7 and 8 also show calving front position by month, in general all three glaciers have their maximum advanced position in April and then calve back through the spring and summer, even before the fast ice has broken up in June to reach their minimum frontal position in October.

4) Figure 11, can the authors provide summer CTD too? Are there any seasonal changes, and how do this correlate with landfast sea ice thickness? Also, any explanation on why mix layer is 100m at the mouth of the fjord (dotted red line, line 320 in text)? Can the author report more data on seasonal sea ice thickness (Line325 briefly mentions sea ice in between was consistently measured to be around 1m thick)?

Unfortunately, we do not have a year round programme of CTD observations in front of the glacier termini, though summer observations from other years in other parts of the fjord do not show a significant change compared to the profile shown here. The mixed layer depth of 100m at the mouth of the fjord is very consistent with other locations in NW Greenland and represents the Atlantic water entering the fjord. Closer to the glaciers, there is more turbulent mixing, probably driven by upwelling from the bed of the glaciers which changes the mixed layer depth. The sea ice thickness was measured systematically in a few locations during this study and was remarkably consistent both inside the mélange zone and in the fast ice area outside the mélange zone, as it has been in other years. Ongoing work in a data rescue project is compiling a large database of sea ice thickness and snow depth on sea ice observations from this region over at least the last 20 years and will be published as a dataset separately. We will add some sentences clarifying both these points in the results and discussion.

5) Figure 13, are there tidal/diurnal melange velocity signal in fall? Are the data presented here winter data, when melange is strong due to the cohesion induced by landfast sea ice, and thus less vulnerable to tidal forcing?

The buoy measurements are only possible when there is thick sea ice to travel on, and that we can use it as a platform to place the instruments. We therefore do not have any autumn or early winter measurements when the ice would be thinner. The fast ice reaches maximum thickness in March/April and starts to thin from May, so the observations we have include also very thin sea ice in June where we do not however see either a diurnal or tidal signal either. We note in addition that when the landfast sea ice breaks up, both the GNSS buoys and many of the icebergs are very quickly (within a few weeks) ejected from the fjord, indicating rapid circulation through the fjord system that may also be related to tidal circulation. The movement of icebergs and mélange out of the fjord is visualised in the short timelapse videos of Sentinel-2 satellite observations linked to in the Appendix. This is a good question though so we have clarified the field deployments in the methods section.

6) After drawing conclusion that "melange does not matter for these three glaciers", can the author look into melange thickness data (i.e., ArcticDEM) and check whether melange is just too thin to do anything? The 3 fjord here are all very short. If there is not enough lateral friction from the fjord, it will be very hard to pile up thick melange, which might explain the observation here.

We have pointed out in the discussion section that while we think these glaciers are very representative of many if not most Greenland glaciers, there are other very large outlet glaciers like Sermeq Kujalleq/Jakobshavn Isbræ and Helheim glacier, where large masses of mélange pile up within their long fjords and that this may have different properties and be able to exert more back stress, although modelling studies are not convincing on this point as the packing density is also not well observed. However, mélange thickness is a very difficult concept to apply because it is very clear when standing in the mélange zone that it is a highly heterogenous material and trying to reduce to a single number or even field of "thickness" is not very helpful, at least at these glaciers, given uncertainties in fjord bathymetry and iceberg sizes. Even high resolution datasets like ArcticDEM do not resolve this heterogeneity sufficiently at these glaciers. Future work will try to address the question of mélange thickness in more detail with photogrammetry based on UAV mapping that was carried out concurrently with the buoy deployments, from which we will derive a size distribution of icebergs and ice floes that can be applied in a modelling framework. We will be sure to make all data openly available for all groups to use when it becomes available. We have added some more text on this point to the discussion.

Minor comments:

1) Line 245 "there is a break point where the ... rather than the properties of the melange itself". If landfast sea ice modulates melange cohesion and in turn thickness, then it should affect the properties of the melange itself.

Hah yes, I see your point here, I have adjusted the sentence slightly to read:

"There is a break point where the ice in the mélange zone shifts between these two regimes in mid-June in both years, suggesting that the onset of enhanced calving is related to the break up of landfast sea ice in the melange zone."

2) Figure 3(b), is it better to use log scale for velocity so that we can see the baseline velocity more clearer? Also, the buoy data is very valuable. Can you archive some of the data with full temporal resolution (10~30mins, instead of the 1-day averaged shown here) in SI or repository? It's especially useful for future study on melange dynamics during calving, where iceberg velocity can vary by 3 order of magnitude (5~5000m/day).

We have replaced the figure 3b and 4b with log-scale plots as we agree it is clearer to see the baseline velocity.

And yes we are very much in favour of open data publishing whenever possible. We are currently preparing a full data paper which will include raw data as well as the processed analysis here as well as an additional two years of similar observations. We hope to keep adding data to it as part of a monitoring programme in the fjord. This will be published open access in 2026. We are happy to share the raw data before then with others who would like to use it and have added a line to this effect in the data availability section and in the future work section.

3) Line 270, extensional melange flow does not mean no buttressing. As long as the melange is thick enough, there can be enough buttressing. For instance, Meng2025 model and Amundson2018 remote observation data both show melange extensional flow during winter seasons;

We agree it does not mean no buttressing, we have slightly reformulated the sentence to read:

“Interestingly, our results confirm that the sea ice in the melange zone and the outer fast ice zone is moving away from the glacier fronts slightly faster than the outlet glaciers are advancing, even when the landfast ice is at its seasonal maximum thickness. This extensional flow has also been observed by Meng 25 and Amundson 2015 in remote sensing observations. We interpret this to indicate that the buttressing effect of mélange is limited in winter, though there it may still exert a resistive force on the glacier termini that suppresses, though does not entirely eliminate calving activity.”

4) Figure 5(b) legend of glacier position, "upper/lower" is confusing, how about "upstream/downstream"?

We have changed this to upstream and downstream in the figure.

5) Line490: "while several models incorporating iceberg melange exist, few of them have been tested against a range of datasets or for general application in Greenland". The author should double check the references here, at least Meng2025 looks into 32 Greenland termini with 108 ArcticDEMs.

Firstly, thank you for the reference to Meng 2025, we were not aware of this when writing our paper. We have added Meng et al 2025 and a couple of other references to the manuscript on this point. However, we are focused here on in situ datasets to resolve high time resolution calving events that satellite data cannot capture. We have updated the sentence to read:

While several models incorporating iceberg melange exist (Krug et al., 2015; Brough et al., 2023; Everett et al., 2021; Schlemm et al., 2022; Meng et al., 2024) few of them have been tested against a range of in situ observations. Satellite data has proved immensely useful for testing these models (e.g. Meng et al., 2025) but our results also show that for detailed process understanding, the time resolution of Earth Observation data is insufficient for resolving the rapid movements of the mélange, though Meng et al (2025) demonstrate how useful it can be for generalising across termini. In situ observations of ice melange are rare and difficult and expensive to obtain and we are therefore committed to open data access to datasets such as this one, we also urge the mélange community to use such in situ observations where available.

Review 2

Overview

This study makes use of a variety of datasets collected in the field and supplemented by satellite derived remote sensing data to investigate the role that landfast sea ice and melange may play in regulating iceberg calving at three outlet glaciers in Northwest Greenland.

Whilst the data collected and analysed in this study is novel and provides a fantastic opportunity to add nuance to the dynamic behaviour of the combined glacier, melange and fast ice regions over much shorter time intervals than is possible using satellite data, the evidence as currently presented is not a robust proof of the conclusions drawn from the study. Further use of remote sensing data could be used to investigate correlations between the extent and thickness of landfast sea ice and to gain further insight into the overall calving dynamics of the glaciers. The role of melange and fast ice in buttressing and suppression of calving is an important topic to address and with major revisions to the manuscript, this study could be very beneficial to furthering understanding in this area.

We thank the reviewer for recognising the contributions we hope to make with this study. We also appreciate the suggestions for widening the Earth Observation part of the study, but we do not intend to make this a remote sensing study but would rather allow the in situ observations to take centre stage. We have included the remote sensing analysis to help make sense of some of the in situ measurements and we think this allows a clean interpretation of the measurements. We are very happy to collaborate with remote sensing groups who would like to use our data for calibration, as well as for ice sheet/mélange modelling and have made this clear in the paper too.

Major Comments

• It is not explicitly stated in the methods how the roles of landfast sea ice and melange are distinguished in modulating the calving behaviours. This appears to be given by the extent of the fast ice? Further clarification could be given on this i.e. how the spatial coverage of the fast ice within the fjord changes throughout the assessed time period and how this correlates to calving and velocity changes. Satellite imagery could be used to quantify this.

R1 had a similar comment and we have clarified how we interpret landfast ice and mélange as a continuum in the abstract and in section 1.1. We did indeed use satellite imagery to identify the break up of the landfast ice in the fjord and we have added a few more details in the methods describing this. The animations of satellite images linked to in the supplement are also referred to on this point. The break up of the ice in the mélange zone is also clearly visible in the GPS buoy records, and very soon afterwards all are circulated out of the mélange zone, for which reason we stop the tracking when the buoys start to float.

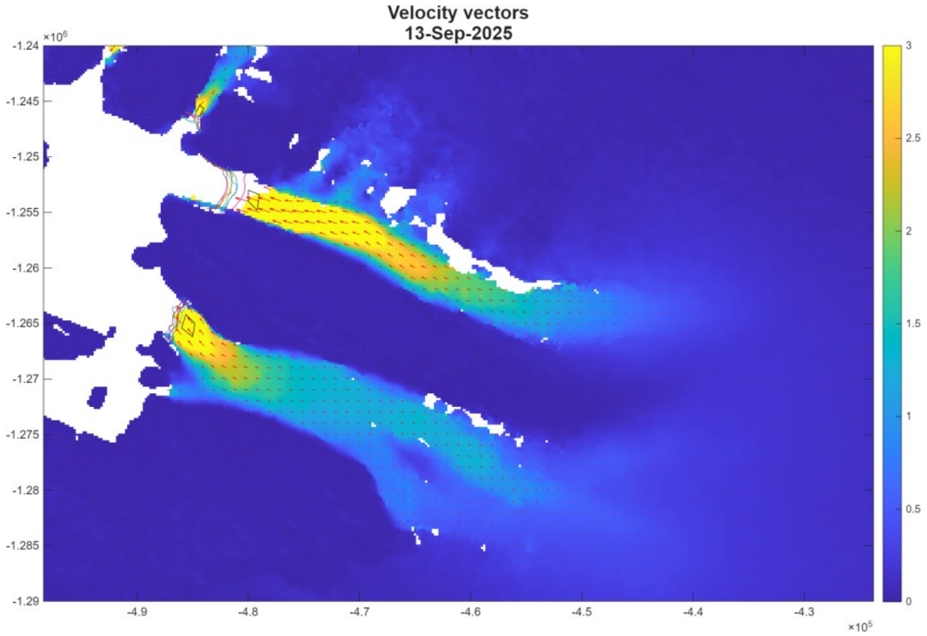
Similarly, the thickness of the fast ice could be an important factor – are any measurements available (either from the field or from altimetry) to quantify how the thickness changes over the time period? Note that times of maximum and minimum sea ice thickness are mentioned in the manuscript but it is not clear how these thicknesses were measured. Again, it would be interesting to see how thickness correlates to the velocities and calving dynamics.

Fast ice thickness was measured at all sites during deployment as well as at CTD deployment sites and as part of observations of opportunity and was found to be remarkably consistent in thickness all through the fjord, but we do not have continuous measurements near the glacier termini following deployment. Altimetry is unfortunately not an easy proposition so close to the coasts and in the narrow fjords and we found that even high resolution datasets such as ArcticDEM do not represent the mélange zone at sufficient resolution. We are in the process of compiling a detailed sea ice thickness database from direct measurements in the region in a data rescue project, to be published in 2026, which will hopefully also be a useful dataset for future studies. We have noted this in the discussion section.

• The distinction between velocities at different points within the glacier compared to velocities within the fast ice may be misleading. We may expect the velocities to increase as the ice approaches the terminus (or flotation – are they grounded at the time of these measurements as they are mentioned to transiently float in the introduction?). A 2D velocity map would show the spatial change in velocity better and could still be used to illustrate the temporal changes in velocity as Figure 5b attempts.

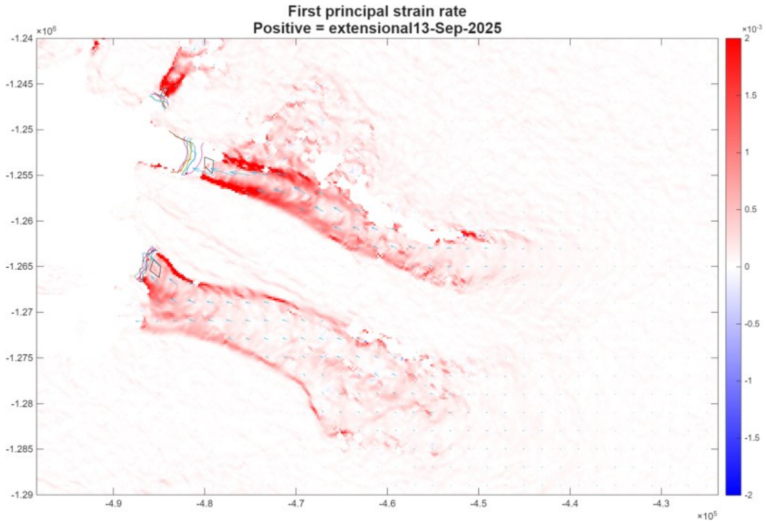
We have plotted the 2D velocities (see below) and will add them as an appendix to the paper with some additional explanation in the results section as a supplement to the current point velocities in the main manuscript to illustrate our point about the mélange velocities. They show very much the expected pattern with slower margins along the fjord side and a faster centre line and also increasing velocity close to the calving front.

It is unclear how much of each glacier termini is floating or when, but we interpret the occurrence of tabular icebergs as a marker of at least partial transient flotation close to the terminus. We have added some additional text to the paper on this point as well as including the following additional figure.



• The differences in velocities as presented in Figure 5b are used to infer that the fast ice does not significantly buttress the glaciers (Section 4.2). The velocities can be used to calculate strain rates and with knowledge of the thickness of the fast ice the backstress can be quantified, so we don't need to speculate on this.

We have calculated the first principal strain rate based on the satellite derived velocities (see below), and we will also add this to the supplementary materials. Unfortunately, the satellite data is rather noisy at the calving front and in the mélange zone, and this makes it complex to interpret beyond the glacier front. In addition, the thickness of the fast ice and mélange is also difficult to reduce to a single number or even grid of numbers as it is a very heterogenous material depending on how large the icebergs are in between the fast ice which also becomes ridged and crumpled through the winter as the glaciers advance into it. A full stress and strain analysis of the region is beyond the scope of this study but is the focus of a follow-on project where a UAV was used to map the surface of parts of the mélange area during buoy deployment. This is being processed to derive a particle size distribution of icebergs and ice floes and could be incorporated into a mélange model.



• The conclusions of the study are based on calving events identified through satellite imagery (shown in Figure 10). Whilst larger calving events may be discernible from satellite imagery, smaller events cannot be identified, as is discussed in the manuscript. Assessing calving through this methodology may therefore not tell the whole story. The 'overall' calving rate could be analysed from remote sensing data as the difference between the glacier's flow velocity and the change in the calving front position over time. Considering averaged calving rates in this way rather than as discreet events may shed more light, in particular if they can be plotted against changes in fast ice thickness / extent.

In the manuscript we present the calving dynamics at the three glaciers in several different ways, including the overall frontal advance and retreat through time in Figure 9 as well as the monthly terminus position in Figures 6,7 and 8 and 10. The suggestion to calculate an overall "calving rate" is a good one but we feel it is already covered by the analysis we show here given the adjustments we have made to Figure 9 with some additional modifications showing the breakup of fast ice and the days with positive temperatures. The analysis in the table in the appendix, which Figure 10 is based on, is an attempt to identify large calving events which may have an external cause such as for example the break up of sea ice or onset of high surface melt. Changes in fast ice thickness are hard to identify as we do not have a continuous observation of this and the extent in the fjord typically follows a rather abrupt pattern. As we observe in the discussion section, many different processes that may affect calving occur at around the same time, so deriving causation from correlation is very difficult and several processes are likely co-causal (see also below). We have added emphasis on this point in the discussion section which has also been restructured somewhat.

• It is difficult to conclude from the results as currently presented where correlation and causation between the factors discussed in the study lie. Restructuring the results could therefore be beneficial in comparing the relationship between all of the variables discussed. For example could a single plot show a time series of velocities, calving rates, sea/air temperatures, smb/melt rates etc. would make a nice visual comparison of correlated events.

We agree that it is difficult to disentangle causation and correlation as many of the factors are deeply entwined and in fact are also co-causal. We have therefore restructured the discussion section as requested to draw out the different processes and we will also clarify this point further, including drawing on the following changes to the figures, as also requested by R1; a) we will add the sea ice break up date lines to Figures 9 and 15; b) we have added positive and negative colours shown in Figure 10 to Figure 9.

We believe this gives a greater clarity to all figures rather than trying to compress all processes into one single figure.

• The glaciers assessed in this study are discussed as being widely representative of Greenland's outlet glaciers due to the different calving styles observed however further information on the flow speeds / widths / thicknesses etc of the glaciers may help the reader to determine how representative these glaciers are in the wider context. Adding this information in a table may help. We also need to understand the thickness and the extent of the fast ice and melange regions as these may vary in different regions around Greenland. Similarly, the topography/confinement of the fjord may also impact how readily backstresses from fast ice may be transmitted to the glaciers. It is therefore not clear whether the results presented here can be considered representative across Greenland.

We will add the details of glacier and fjord geometry to the description of the study sites, though note that we are unsure how reliable the standard outlet glacier thickness data for this region is. The style of calving discussed in the manuscript and summarised in the table in the supplement is very much aligned with the analysis of Bezu and Bartholomeus, 2024 as we point out in the manuscript. The seasonal cycles in velocity also align with those analysed using K-means clustering by Solgaard et al 2023 and we therefore consider these outlet glaciers very representative of the small to medium-sized glaciers but likely not the very large outlets like Jakobshavn and Helheim Glaciers.

Specific Comments

Figure 2 – It is later discussed that the start points of the buoys were influenced by accessibility / patterns of melange then a basemap from around the time of deployment would be useful.

Were certain spatial coverages of the buoys targeted?

It is hard to get a good basemap of the dates of deployment as the relatively early date of deployment means optical images suffer from shadows and or cloud cover that obscure the mélange. In fact, while we do use satellite imagery to plan deployment, actual conditions are verydifficult to interpret from the pictures and often different than imagined on the ice. It is rarely as easy to access particular locations as the imagery can suggest. This is difficult to see on satellite images as the size of the icebergs and ice floes is not easily captured at relevant spatial scales. We therefore prefer to use a single standard basemap for both seasons.

Line 227 – 'the melange velocities when bounded by landfast sea ice' - when exactly were these not bound by the fast ice? Can a figure be referenced in relation to this statement?

Apologies, this is a little ambiguous, all of the position data we show here is when the mélange is locked up by landfast ice as the buoys circulate out of the mélange zone very quickly after the sea ice breaks up. We will add this to the methods sections.

Line 236 – 'a more spatially dispersed dataset is necessary to fully determine this' – can satellite data be used in this sense?

While satellite data could certainly help, the point about our method is to capture the very brief high time resolution movements, which satellite data cannot capture. However, we hope to continue these deployments in future years to get a longer time series of data. We have clarified this statement as we intended to mean more deployments at different locations in front of the glaciers.

General – the results sections tend to contain some interpretation which may be better placed in the discussion sections - and in some cases is repeated/contradicted later in the discussion.

For example line 241 – 'these large abrupt movements likely represent large calving events' and line 408/409 'it is difficult to judge therefore if the abrupt movements reflect stress relief in the melange that then leads to calving, or if the iceberg calving leads to the abrupt jump..'

Thankyou for this feedback, we have edited and slightly restructured both results and discussion sections to avoid mixing the two and make the interpretation more clear.

Figure 3 – the plot scale on panel b) could be changed so we can better see the velocities for the majority of the data – which are mostly <50 m d-1 (note units don't need the 'x' in m x d-1). In panel a) it is not clear why a base map from 2024 is used? Could large iceberg fragments influence the lateral deviation in movement (particularly seen in red / blue / orange / yellow buoys? There may be a better visual representation of this. The grey outline of the start point is not clear. Same comments apply to Figure 4.

Thank you for the suggestion we have updated the figures 3b and 4b to show a log scale and also enlarged the dots to make the figures clearer, see also our reply to the basemap request above. We discuss the role of the larger icebergs in the discussion too.

Line 263/264 – 'The Sentinel-1 data has a 12 day repeat orbit which means it cannot be used to assess the abrupt events identified in the GNSS buoy data' . Do the calving front time series in Figure 9 not correlate? Plotting the calving front time series under fig 3b / 4b may allow correlation to be identified?

The table in the supplement are intended to try and correlate calving activity with the buoy movements shown in figures 3b and 4b, based on visual identification of calving front changes. We have clarified this in the text.

Line 268/269 – the melange zone and outer fast ice zones are mentioned a few times – can you mark on a figure what you mean by these zones?

Yes we will add these labels to Figure 2.

Figure 5 – Flow speeds are shown, not velocities. Can 2D velocity maps be used to better illustrate the spatial changes in velocity?

We have plotted up a 2D velocity map and will put it into the supplementary material as it does not substantially change our conclusions.

Figure 6 / 7/ 8 – The colour scheme makes it quite difficult to follow the difference between sequential months. Are the spatial scales different? If so why?

Figures 6-8 are a continuous dataset and the colours are chosen to be sequential from white through light to dark blue showing how the front varies through time. We will update this in the caption. However, we also discovered a slightly offset map frame, which made the scales appear different. We have corrected this so they all appear the same.

Figure 7 /8 – is it necessary to plot the calving fronts which are clearly wrong and can be discounted from the datasets? Are any higher resolution basemaps available?

There are no higher resolution basemaps unfortunately as these are rather small glaciers, and we feel that while some of the calving fronts are very likely wrong in the plot it's a nice illustration of the point we make in the discussion that while automated tracking algorithms based on machine learning methods are really useful, they still require some work and need to be checked by a human user. We have made this point clear in the caption too.

Figure 9 – can the central flow lines that these refer to be marked on Figures 6 -8 for reference? More subdivisions on the x axis would make it easier to see how this correlates to the displacements shown in figs 3 and 4. Even better to combine with figs 3 and 4.

This is a nice suggestion which we tried out, but unfortunately, as the scaling is different between the two plots, it made them rather hard to interpret. We have therefore removed it again. We prefer to keep both plots as they are since it illustrates the difficulty in representing a three dimensional object through time in a simple figure.

Figure 10 – title not required – this is covered in the caption.

This has been fixed

Figure 12 – Refer to panels a and b (rather than left and right) for consistency. Titles are not needed and they reference Qaanaaq – should this be a specific outlet glacier? Can a colour scale or legend be added to show what times the dots refer to?

This has been fixed. The title was indeed unnecessary and we prefer not to refer to a specific glacier as the position of the buoys was between two of the three. The colours refer to specific times in the day, but not to specific days. We have updated the caption to reflect this and will add a colour scale too.

Figure 13 - What are the intervals that are referred to in the caption? The caption could be a bit more detailed to ensure that the figure can be interpreted without needing to refer back to the main text. Refer to panels a and b (rather than top and bottom) for consistency.

Thanks for this feedback we have updated the caption to give more detailed information on interpreting the spectral analysis. The intervals referred to are simply the first half of the record and the second, to assess if there is any change over the period. We have also added a and b to the panels

Line 439 – 'given the importance of melt and glacier sliding on velocities, it is likely that these processes are also moderating calving activity'. It was discussed in Section 3.3.4 that a significant increase in glacier / melange velocities were not observed in correlation with runoff, please can you clarify this? Plotting the panels in Fig 15 against velocities and calving rates could better display correlation or lack of.

Our point here is that many different processes are acting on glaciers and on the fast ice and mélange at the same time. We have updated Figure 9 to show the break up of the fast ice and above/below 0 mean daily air temperatures. Fig. 15 now also marks the point where the land fast sea ice breaks up as identified from the satellite record as a continuous marker point through the plots. We have added a section in the discussion around how we interpret these different factors and clarified in section 3.3.4 that while we don't see an increase in average velocity in the mélange, during this period, we do see an increase in the number of abrupt movements in the mélange record.

Line 449/450 – 'we do detect a small increase in the glacier velocity in 4 out of 10 calving events detected in 2022' – can this be shown by plotting calving vs velocity? Line 450/451 goes on to say 'we can conclude that the presence or absence of melange … seems rather unimportant for calving dynamics'. This conclusion does not seem robust to me. It could be that these are large tabular style caving events in which a large amount of energy is released – in which case we may not expect backstresses from fast ice / melange to be of a magnitude large enough to suppress this. The melange may have more impact on suppressing smaller calving events (which could be analysed by assessing overall averaged calving rates), which in turn could moderate the glacier velocities – in which case it could be argued that the melange does play an important role. Neither conclusion is clear to me on the evidence provided so far, but a plot of melange / fast ice thickness and extent against velocities and calving rates could go a long way to showing this. I wonder also if discreet calving events could be looked at separately to overall calving rates – i.e. does the calving type matter and does melange / fast ice inhibit the smaller calving events but have little impact on the larger scale events?

We have restructured the discussion section fully to a more logical structure following the different processes important for calving processes and frontal position as well as the mélange cycle. Figure 10 together with Table A1 show the relative size of individual calving events identified from satellite imagery and in the GNSS record and we refer to this in this section again. Calving activity occurs all through the winter period (as also shown in the satellite data animation) including small and large events. The presence of land fast sea ice suppresses the removal of calved icebergs and allows the mélange to build up further, but while it may exert some back pressure on the calving fronts (see also the additional figures showing the principal strain rates), this is not large compared to the forward motion of the outlet glacier. We do also note that this may not be the case at the very large outlets like Sermeq Kujalleq/Jakobshavn Isbræ. As noted before, we do not unfortunately have a good dataset for fast ice/melange thickness at these glaciers yet. However, as we also try to make clear, we focus very much on seasonal calving dynamics in this study. The position of the calving front does have a clear seasonal cycle at all fronts, likely related to a complex combination of changes in ice velocity, runoff and air temperature and the presence or absence of land fast sea ice as well as to the general stability of the position of the calving front and the dominant calving styles of the glacier, which is also related to bed topography and fjord geometry as well as mass budget and hydrology. We highlight these factors in the restructured discussion section.

Typos –

Thank you for catching these. The following have all now been fixed in the manuscript.

Line 44 – 'spring and early summer' ?

Line 99 – '… all outlet glaciers ins not well constrained'

Line 312 – 'observations of ocean processes'

Figure 12 caption – 'dispersionsm'