Author response to Reviewer 1 for the manuscript entitled *Temporal evolution of the Petermann Ice-Shelf estuary constrained by satellite remote sensing observations*

The submitted manuscript outlines a creative study that looks at surface melting and the presence of an estuary at the edge of the Petermann Ice Shelf, Greenland. The manuscript is well-written and clearly present the necessary information for the reader to interpret their findings. However, there are some important gaps in the interpretation of the results that currently obscure the main takeaways of the text. I have no doubt that the information presented is of high value, but there needs to be some reinterpretation of the findings. I have included comments below on how the manuscript might to be altered to address these concerns - I believe that this will require a major revision. Ultimately, I think that with some more work this manuscript has high potential to be a significant contribution to the cryosphere discipline.
We thank you for your constructive comments and thoughtful review of our manuscript. We believe that the suggested edits, particularly regarding re-framing of the discussion, have improved the revised manuscript. Below, please find your comments in black and our responses in blue; any new or edited text that has been added to the revised paper is shown in purple. All line numbers mentioned in this letter refer to line numbers in the revised manuscript.

Larger Comments:

Seawater in theory flows underneath the freshwater in the estuary, resulting in a bidirectional flow that allow the freshwater still to flow out towards the top. Please demonstrate why you think this not to be the case for the Petermann estuary. See specific comments below.
Thank you for pointing this out. One of the challenges for this project has been the lack of field data, which was intended to include salinity measurements along the river/estuary to determine the degree of mixing and upstream reach of the estuary. Unfortunately, without this data, it is impossible for us to definitively say whether there is bidirectional flow or more homogeneous mixing within the estuary. However, we do agree that the manuscript, as previously written, did not clearly explain this, nor the distinction that meltwater export is limited/slowed rather than fully inhibited. We have made adjustments to the text as described in detail below in response to your specific comments.

I do not understand why measurements of the surface channel geometry before and after the melt season would not suffice to investigate incision rate. It does not snow much on Petermann.
Due to the ice shelf's vertical rebound in response to meltwater unloading at the end of the melt season, a post melt season DEM would likely not provide an accurate representation of channel bottom elevation relative to the ocean surface during the melt season, which is what is required to determine whether an estuary is present. Additionally, we are most interested in the timing of estuary formation and evolution *within the melt season*. By calculating channel geometry during the melt season, we are able to observe changes in incision rate throughout the melt season and

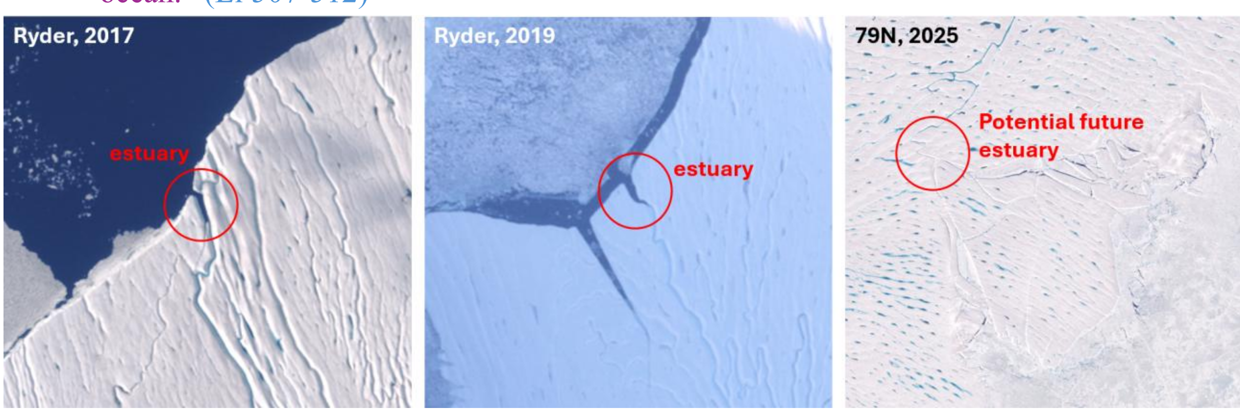
better constrain the timing of when the channel bottom first dips below sea level, as well as when it rises above sea level again. We have added text to the Introduction to clarify our goal of studying intraseasonal changes in estuary evolution and channel geometry:

- "Applying this method, we calculate channel bathymetry and incision rates in Petermann Ice Shelf's main supraglacial channel during the 2014 and 2016 melt seasons to investigate the role of river incision rate in ice-shelf estuary formation. Comparing these new calculated channel bathymetries and incision rates with modelled surface runoff from MARv3.11 (Fettweis, 2022; Fettweis and Grailet, 2024) and WorldView-2/3 imagery, we determine when the ice-shelf estuary first formed, constrain the timing of estuary formation within each subsequent melt season, and provide new insights into the dynamics of estuary formation." (Li 98-104)

Did you consider looking at 79N glacier also, just to comment on whether or not it has an estuary? It has an extensive supraglacial river network during the summer and is very thin at its front.

We did take a preliminary look at both Ryder and 79N. Although there is limited WorldView imagery available during melt seasons over these two ice shelves, there is plentiful Sentinel-2 imagery. On Ryder, there is evidence of potential estuary formation at two different locations on the ice shelf over the past 10 years (see images below). On 79N, the large supraglacial river has not reached the ice shelf front in recent years, and thus there is no evidence of estuary presence. However, there is potential for an ice shelf estuary to form on 79N if a calving event connects the surface river with the ocean (see image below). We have added the following text to the Discussion to briefly explain these possibilities:

- "For the Petermann Ice Shelf, freeboard is generally less than 10 m—similar to the freeboard of the Ryder and 79N ice shelves in Greenland. The large central river on Ryder reaches the ice shelf front, and there is some evidence of estuary formation within the past decade. The river on 79N does not yet reach the ocean, however, there is potential for an estuary to form if a calving event connects the surface river with the ocean." (Li 507-512)



Discussion lacks a commentary on how important this surface estuary is to Petermann Ice Shelf's stability. At present, the estuary only occupies the very outer portion of the ice shelf, which has been shown to exert no buttressing (Rückamp et al., 2019). However, if ice-ocean interactions continue to thin the ice shelf, then it will lower the freeboard to allow for further seawater ingress that will exert more of an impact on its stability.
We recognize that we have not discussed the implications of estuary formation for ice shelf stability in depth. However, as mentioned in our Introduction (Li 94-104), the primary goal of this paper is not to assess the impact of estuary formation on the stability of the Petermann ice shelf, but rather to assess the conditions on Petermann in the lead up to estuary formation. Despite this, we agree that the future stability of Petermann is an interesting discussion point, and one which we have now added a paragraph about in our revised Discussion (Li 486-501). This is elaborated on in our responses to the four major comments in the Discussion on pages 9-11 of this letter.

Specific Revisions:

"Ice shelf" and "ice-shelf" are used interchangeably through the text. Please pick one expression and stick with it.
We use **"ice shelf"** when referring to the glaciological feature itself (e.g., "the ice shelf is melting"), and **"ice-shelf"** when the term precedes and modifies another word (e.g., "ice-shelf melt", "ice-shelf melting", "ice-shelf dynamics"), following standard English hyphenation conventions. We have reviewed the manuscript to ensure consistent usage in these two distinct situations.

Please use the phrase "seawater" instead of "ocean water" throughout the text and figures, as it is the more common expression. For example, compare "lake water" to "freshwater," or "ocean ice" to "sea ice."
Thank you for this clarification. We have changed the wording accordingly throughout the manuscript.

"Bathymetry" typically is reserved for surfaces that are persistently covered in water, which is not the case for this ephemeral feature. I think that "channel geometry" or "channel topography" or "the channel base" is more accurate here.
We appreciate the suggestion, however we have chosen to use the term 'bathymetry' here primarily because it can be used interchangeably for both ponds and rivers, which are both features we apply our methodology to in this study. Thus, the use of 'bathymetry' simplifies writing when we would otherwise have to specify both channel and basin geometry. Further, we feel justified in this use of the term 'bathymetry' as it is commonly used in other meltwater depth studies for both lakes and streams/rivers that we cite in the manuscript, such as Legletiter et al. (2014), Lv et al. (2024), and Datta and Wouters (2021).

Title:

Abstract:

The Abstract comes in a over 300 words, but online there is a word limit of 250 words. Please reduce the abstract length by 50 words. The coauthors should have addressed this before submission.
The abstract has been shortened to 250 words (Li 18-31).

Li 29-30: Seawater will most likely have a higher heat content than the freshwater, due to a higher temperature and greater density. Furthermore, the geometry of less-dense ice below more dense seawater should encourage melting. Thirdly, it is current shear that increases turbulent-driven melting, which means that times of flow reversal should actually drive the highest melting. For all of these reasons, the text in Li 29 and 30 does not seem to be accurate at face value.
This is an excellent point, which we have now addressed in the revised manuscript. We also reply in more detail to this point as part of the four major comments in the Discussion on pages 9-11 of this letter.

Introduction:

Li 37 – 38: The section of this sentence on the 25% of Greenland's glaciers that currently or once formed ice shelves does not benefit the text, as currently written. Please rewrite this section to provide a timeline over which the glaciers that lost their ice did, because without providing temporal constraints one could argue that almost 100% of Greenland's glaciers formed ice shelves at one time.
We have re-written this section as follows:

- "In Greenland, ice-shelf retreat has been ongoing since at least 1990, with three ice shelves collapsing completely over this period (Millan et al., 2023; Moon and Joughin, 2008). Today, there are only four major ice shelves remaining in Greenland: Petermann, Steensby, Ryder, and Nioghalvfjerdsbrae (79N; Millan et al., 2023). Of these, three have experienced grounding line retreat since 1992, and total ice shelf area in Greenland has decreased from 4,413 km^2 in 2000 to 3,513 km^2 in 2022 (Millan et al., 2023)." (Li 34-37)

Li 40: Rewrite "and is projected to increase.." to ",which is projected to increase"
We have made this change in the revised manuscript.

Li 36 – 47: I think it is important to link surface rivers to the basal channels that they often overlay (especially for Petermann). The following reference could be added to this paragraph and discussed some: Dow et al. (2018) https://www.science.org/doi/full/10.1126/sciadv.aao7212. This should be followed by a comment on the rift that shows up in Petermann's central channel in 2018 to point out how the ice surface and base are linked, and just because there is a surface river doesn't mean that the feature stabilizes the ice shelf.

This is an important point, and we have edited the text in the Introduction discussing the connection between surface and basal channels as follows:

- "Often, rivers on ice shelves form in the surface depressions over basal channels, and the presence of these basal channels has been shown to have a destabilizing effect on ice shelves by driving fracture formation perpendicular to ice flow (Dow et al., 2018)." (Li 44-46)

We have also elaborated on this in the Discussion:

- "However, as Boghosian et al. (2021) demonstrate, estuary formation on Petermann Ice Shelf has already been associated with the development of longitudinal fractures that propagate upstream from the calving front, promoting transverse fractures which sometimes lead to rectilinear calving events. For example, the formation of the 2018 rift was likely driven by the combined influence of estuarine weakening and concentrated ice-shelf thinning along the central basal channel (Dow et al., 2018)." (Li 487-491)

Li 58: Please rewrite to "when a supraglacial river incises the ice surface below sea level"

We have made this change in the revised manuscript.

Li 60 – 61: While I understand that this is not a paper dedicate to estuarine dynamics, if the estuary widens, then one could envision the fresher meltwater is still able to flow out at the surface while seawater flows in at depth, separated by a sharp pycnocline. Yes, there will be some mixing, but the seawater intrusion at Petermann may "partially slow down" more than "prevent" efficient meltwater export into the ocean. The amount of mixing and export in the estuary will also be influenced by the wind (and waves). I suggest adding several sentences to the end of this paragraph that discuss how estuarine dynamics may influence this setting.

We agree that meltwater export is more likely slowed than completely prevented, and we have clarified this in our revised paper. We have also added some detail about the potential dynamics at play within the estuary:

- "Driven by tides, river flow can also reverse, drawing warm seawater inward onto the ice shelf (Boghosian et al., 2021). This water flow reversal may act to load the ice shelf, which changes its stress field. This is due to both the inflow of seawater into the channel, as well as the decreased meltwater export from the ice shelf into the ocean. Mixing of freshwater and seawater in the channel, the extent to which remains unknown, is likely driven by wind and tidal fluctuations. Together, the enhanced loading and limited meltwater export may enhance ice-shelf instability." (Li 62-67)

Li 64: Please include a comment on this study, which revealed brine signatures on many Antarctic ice shelves with both radar and firn cores: Cook et al. (2018) https://tc.copernicus.org/articles/12/3853/2018/.
We thank the reviewer for the comment, however we do not think a reference on brine signatures on ice shelves is relevant here and are wondering if they may be referring to a different line/section of our paper. Observations suggest that brine signatures are common in the vicinity of ice shelf fronts Antarctic- and Greenland wide (e.g., Cook et al. 2018, which you refer too), so are not specific to estuaries.

Li 65 – 66: Please add to this sentence the a qualifying statement that for Greenland this requires that the ice shelves do not break up, which is a major concern.
The sentence has been edited to include a qualifier: "are expected to persist in Greenland for as long as ice shelves remain".

Li 72 – 72: What about ice penetrating radar for ice shelf thickness and basal channel depth.
We have added a mention of this in the revised manuscript:

- "…while ice shelf thickness and basal channel depth can be estimated from laser and radar altimetry (e.g., Chartrand and Howat, 2023; Griggs and Bamber, 2011), as well as ice penetrating radar (e.g., Washam et al., 2018; Whiteford et al., 2022)." (Li 77-79)

Li 72: Change to "the measure of change in surface channel bottom elevation"
We have made this change in the revised manuscript.

Data and methods:

Li 98: this is picky, but Petemann Ice Shelf spans a range in latitudes and longitudes. If you are going to provide only one coordinate, then please add something information like "located at approximately" or "centered at…"
The wording has been changed to "Petermann Ice Shelf in Northern Greenland, located at approximately 81º N, 60º W".

Li 98: Rewrite to ", which has an area of…"
We have made this change.

Li 100: Rewrite to "ice shelf's large central ice shelf supraglacial…," because there are in fact many streams and rivers on the ice shelf surface.
We have made this change.

Li 114: Presumably the lakes also experience diurnal cycles in water level if they have streams running into and out of them, but not as pronounced because of their larger area. Can you comment on this in the text?
This is a good point, and a few of the ponds that we have chosen do appear to be fed and/or drained by streams. As these streams are much smaller than the main Petermann channel (<5 m vs. 20-30 m across), we anticipate that the diurnal water level fluctuations will not be nearly as large. However, this is a potential source of error, and we have added the following text to the Methods to explain this:

- "While some of the ponds appear to be fed and/or drained by streams, which could also cause pond water levels to fluctuate diurnally, the streams are significantly smaller than the main channel on Petermann, and thus introduce less potential error between image acquisitions." (Li 125-127)

Li 155 – 169: How does this method compare to that used by Macdonald et al. (2018)?
Our method is similar to that used by Macdonald et al. (2018) in that it utilizes the same bands, blue and red, to identify water pixels based on a fixed threshold. However, Macdonald et al. (2018) use the ratio of blue/red directly, whereas we use the normalized difference between the two bands (blue-red)/(blue+red), also known as the $NDWI_{ice}$ (Yang and Smith, 2013). The threshold values are therefore also different between the two studies: 1.5 for Macdonald et al. (2018) and 0.23 for this study. As is mentioned in our paper (Li 175-179) we chose to use the $NDWI_{ice}$ because it has been successfully implemented with WorldView imagery in other studies (e.g., Yang and Smith, 2012; Moussavi et al., 2016) and provides a more intuitive output, with values ranging from -1 to 1 and higher values indicating that a pixel is more likely to be water.

Li 195 – 211: This is really cool.
Thank you!

Li 234 – 242: This is excellent.
Thank you!

Li 243 – 256: Maybe I missed this, but shouldn't ice advection be accounted for in this calculation? The river is incising on ice that is also flowing seaward.
Ice advection is certainly a complication to this method. The way that we have chosen to deal with it here is by aligning the ice front in all of the images and DEMs. This is done as part of the DEM pre-processing (Li 160-164). First, the DEMs are coregistered (x, y, and z dimensions) using the fjord walls as the common reference. Then, each DEM and corresponding image are shifted in the x and y dimensions to align the ice front for all acquisitions within a given melt season. The final step is the tidal correction and sea level elevation estimation (Li 262-270).

Results:

Li 280 – 310: This is really neat, but why does the time comparison stop in August before the end of the summer season, which should go until the beginning of September? Is it just because these are when there are available images around the same time? The near-surface air temperature from a weather station deployed on Petermann from 2015 to 2016 are published here: Washam et al. (2019)

Yes, this is a limitation of the optical data that we have available. The last images in the melt season with corresponding DEMs that contain water along the channel are in mid to late August for both 2014 and 2016, and we have added a sentence to the Results specifying this:

- "For both years, the last available images showing water along the full channel were acquired mid to late August, 1-2 weeks before the end of the melt season, meaning incision for each melt season is likely a slight underestimate." (Li 311-313)

As mentioned in an earlier response, we are unable to use empty post melt season DEMs to extend this analysis as we believe that the unloading of surface meltwater at the end of the melt season causes flexural rebound of the ice shelf, and thus the end-of-melt season channel bottom elevation relative to sea level would not be representative of its elevation during the melt season, when the estuary was present.

Li 334 – 339: The surface melt rates obtained here are similar to what was measured in 2016 by Washam et al. (2019) with an ApRES, which was 1.4 +- 0.2 m.

Thank you for pointing this out. We have added the following text to our Results to confirm that our remotely sensed estimates agree well with in situ observations, which lends further confidence to our employed methods:

- "It should be noted that these are likely overestimates as they do not account for hydrostatic adjustment due to basal melt; nevertheless, the 2016 estimate agrees well with in-situ observations of surface melt on Petermann Ice Shelf (1.4 ± 0.2 m) from Washam et al. (2019) over a similar time period." (Li 366-370)

Discussion:

Li 362 – 427: I think Section 4.1 lacks some critical elements of ice melting and estuarine hydrodynamics that result in a discussion of the formation mechanism of the Petermann estuary that is not completely accurate. The topics that need to be consider and integrated into the discussion are listed here below, please consider them and integrate them into this discussion.

The surface slopes more steeply in 2014 than 2016, which will drive a faster flow of water downstream. As melting is a function of current speed (by way of sheer between fastest flow and the ice), this could lead to a deeper incision in that year than in 2016.

Additionally, streams on steeper slope are generally narrower than on shallower slopes. This could contribute to the varying melt patterns between years.

We agree that if the slope in 2014 was significantly steeper than 2016, it would drive faster river flow and enhanced melting on average. However, the mean slope for both melt seasons is 0.03º. We have added this point to our Discussion:

- "The slightly steeper slope of the channel bottom at the end of the 2014 melt season (Fig. 6a) compared to the 2016 melt season (Fig. 6b) could contribute to faster river flow and thus increased vertical incision (Holland and Jenkins, 1999). However, the mean slope over the 5 km river segment for both melt seasons is 0.03˚ (Fig. 6a-b), therefore it is unlikely that this is a major driver of the overall slightly higher mean incision rates observed in 2014 compared to 2016." (Li 404-408)

Additionally, within each year, surface slope is relatively consistent over the entire 5 km transect (Fig. 6). Therefore, we do not believe that these varying incision patterns are the result of differences in surface slope and flow velocity; instead, we state they are due to the formation of the estuary and associated flow reversal in the most downstream 1.5 km. This, however, is an important point to make, which we have added to our revised Discussion:

- "Furthermore, surface slope varies gradually and consistently over the full 5 km study reach on all observed dates in in both years (Fig. 6a-b) and therefore cannot explain why the most pronounced differences in incision rate between 2014 and 2016 are confined to the 1.5 km nearest the ice-shelf front (Fig. 6c)." (Li 408-410)

The melting that occurs in this channel is a function of temperature relative to freezing and current sheer, as stated in point 1. Seawater will likely have a higher temperature relative to freezing than freshwater, because of its salt content. Also, the current will be most sheered as two flows merge, because delta U will be greater than if one flow was simply sheered to zero at the ice surface. For both of these reasons, it seems that the seawater should drive higher melting than the freshwater in the channel, unless the freshwater is much warmer or is flowing much faster than the seawater.

We agree that the warmer temperature of the seawater relative to freezing, as well as the turbulent mixing of the two waterbodies should drive higher melt rates within the channel. This is mentioned in the Introduction (Li 61-63), but we have reiterated it in the Discussion as well.

- "First, channel melting is controlled by turbulent heat exchange at the ice-water boundary, driven by both the heat content of the water and the flow speed (Holland and Jenkins, 1999)." (Li 422-423)
- "Second, the intrusion of warm, saline seawater increases thermally driven melt, and the shear between the two converging water masses drives melting more broadly across the channel walls rather than concentrating it at the channel bed (Boghosian et al., 2021; Holland and Jenkins, 1999)." (Li 426-428)

However, our observations indicate that the channel does not become deeper, but rather wider and flatter as a result of this enhanced melting (Fig. 7). This could be due to changes in flow speed due to mixing and/or shear of the two waterbodies along the sides of the channel. In both scenarios, melt would be less concentrated at the bottom of the channel than during river export alone, thus leading to more dispersed melting across the entire channel profile, causing the channel to become wider and flatter. We have added text to the Discussion explaining these potential drivers of changes to melt patterns within the channel following estuary formation:

- "During the river phase, fast unidirectional flow concentrates melt at the bottom of the channel, favoring vertical incision (Pitcher and Smith, 2019). Once the estuary forms and tidal flow reversal begins, the net seaward flow speed is reduced, lowering the turbulent exchange velocity and thus the rate of vertical incision." (Li 423-426)
- "Additionally, as in terrestrial estuaries, the two water masses may not mix instantaneously but instead form a stratified system, with less dense freshwater flowing seaward above denser inflowing seawater, further distributing melt across the channel profile rather than concentrating it along the centre of the bed (Geyer and MacCready, 2014). Although the relative melt contributions of seawater and supraglacial meltwater depend on their respective temperatures and flow speeds, which are not known here, we hypothesize that the net effect of estuary formation is to shift the dominant melt pattern from vertical incision to lateral erosion, causing the channel to become broader and flatter rather than narrower and deeper. This is consistent with our cross-sectional observations of the channel, which show widening and flattening of the channel that is most pronounced in the 1.5 km nearest the ice-shelf front (Fig. 7b)." (Li 428-435)

Frictional heating is not really the right expression for what is happening in the channel. Review Holland & Jenkins (1999) and incorporate their results into the discussion of how the ice shelf channel melts.

Thank you for pointing us to Holland and Jenkins (1999). We agree that "frictional heating" is not the best way to describe this process and have revised our Discussion to instead reference turbulent heat transfer at the ice-water boundary, which is driven by both flow speed and how much warmer the water is than the local freezing point. Please see our responses to the previous two major comments in the Discussion (pages 9-10 of this letter) for a more detailed explanation of the role of these processes in estuary formation, as well as the newly edited text.

This discussion ignores the possibility that freshwater could be flowing above seawater in the estuary, as well as that seawater can continually flow into the channel once ice has formed on the surface after the melt season.

This is a good point, and we have added text to the Discussion explaining the possible stratification within the estuary and its impacts on melting/incision and estuary formation:

- "Additionally, as in terrestrial estuaries, the two water masses may not mix instantaneously but instead form a stratified system, with less dense freshwater flowing seaward above denser inflowing seawater, further distributing melt across the channel profile rather than concentrating it along the centre of the bed (Geyer and MacCready, 2014)." (Li 428-431)

Further, in the original paper, we attributed the removal of the estuary at the end of the melt season to the unloading of water from the ice shelf surface, and the ice shelf's resultant flexural rebound, causing the channel bottom to rise above sea level. However, we do not know what the timescale of this rebound is, so we do not how long the seawater is able to remain in the channel at the end of the melt season. It is also possible that some of this seawater freezes in the channel at the end of the melt season, contributing to the raised elevation of the channel bottom. We have edited the Discussion to include these possibilities:

- "The timescale of this flexural rebound is not well constrained, and it is likely that seawater continues to flow into the channel with the tide for some period after surface melting ceases before eventually freezing in-situ, with this refreezing potentially contributing an additional, though unquantified, rise of the channel bottom elevation above sea level." (Li 448-451)
- "we suggest that the estuary forms repeatedly with the channel becoming seasonally disconnected from the ocean (Fig. 9) by ice-shelf uplift, refreezing of seawater in the channel, and/or sea ice blockage." (Li 474-475)
- "The rebound phase (c) occurs towards the end of the melt season as surface melting ceases and meltwater is offloaded from the ice-shelf surface, causing the most downstream part of the ice shelf to hydrostatically flex upwards, thereby raising the channel bottom above sea level; refreezing of seawater in the river channel likely also contributes to elevating the channel bottom above sea level." (Li 468-471)

Conclusions:

Li 65: here the authors point out that the seawater may be warm. Please consider the points raised above about how seawater will melt the ice, versus the fresh meltwater.
Please see the response to point 2 in the Discussion (pages 9-10 of this response letter). We have edited the wording of our revised Conclusion accordingly:

- "However, the evolution of a river into an ice-shelf estuary may counteract this effect by limiting efficient meltwater export and allowing up-ice intrusion of warmer, saline seawater (Boghosian et al., 2021), thereby shifting the dominant melt pattern in the channel from vertical incision to lateral erosion, and loading the ice shelf with both meltwater and seawater." (Li 563-566)

Figures and Tables:

Figure 1c is too small to convey useful information. Please either increase the size of this image or trace the outline of the river so that the reader can better identify it. I also suggest to add the glacier's grounding line, so that the reader can appreciate the area of the Petermann ice shelf that buttresses the upstream glacier.
Thank you for this suggestion. We have traced the outline of the river to make it more visible in the figure as well as added in the grounding zone.

Figure 2 should have the glacier grounding line plotted on the main panel.
We have edited the figure to include the grounding zone.

Author response to Reviewer 2 for the manuscript entitled *Temporal evolution of the Petermann Ice-Shelf estuary constrained by satellite remote sensing observations*

The manuscript describes an innovative remote sensing technique for exploring supraglacial channel incision rates in ice shelf settings. The authors calibrate an optical water depth retrieval method with IceSat-2 data in supraglacial lake settings, before applying the method to the Petermann Ice Shelf estuary to calculate bathymetry and incision rates of the river channel in 2014 and 2016. They use their incision dataset, combined with manual interpretation of optical satellite imagery and modelled runoff data, to discuss the timing, evolution and persistence of the estuary between 2013 – 2018. The manuscript is well-written and has a clear and logistical structure. The data is excellently presented, and the figures are clear and easy to interpret. However, I have some methodological and data interpretation concerns which require addressing before publication. I would also encourage the authors to provide more discussion on the wider relevance of their findings.

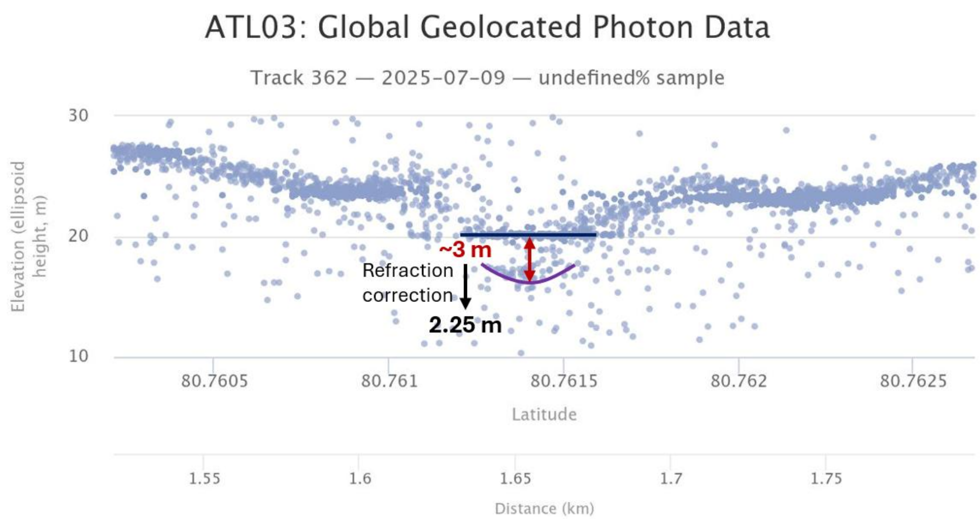
We thank you for your constructive comments and thoughtful review of our manuscript. We believe that the suggested edits, particularly regarding the interpretation of results, have improved the revised manuscript. Below, please find your comments in black and our responses in blue; any new or edited text that has been added to the revised paper is shown in purple. All line numbers mentioned in this letter refer to line numbers in the revised manuscript.

Main comments

My main methodological concern is whether a relationship derived for supraglacial lakes is suitable for application in a river channel setting, where the water is much deeper, and contains a mixture of freshwater and seawater. Optical depth-reflection methods for deriving supraglacial lake depths have been shown to work reasonably well for shallow lakes, but typically lose accuracy with deeper water. Supplementary Figure 3 shows that out of the 12 supraglacial lakes used to derive the IceSat-2 optimized formula, nine lakes have a maximum depth of one metre or less. None of the lakes have a maximum depth greater than ~2.5m. By comparison, Figure 7 shows that the channel depth is often greater than 8 metres deep. This raises the question of how accurately the method works for deeper water. I would like the authors to provide some reassurances relating to this, justifying why they deem the transferability of the method to be appropriate.

Thank you for this comment. The important distinction here, which we have clarified in the revised manuscript, is that while the channel is often 8-10 m deep (e.g., Fig. 7), it only fills with 1-3 m water depth. We have verified this water depth range with ICESat-2 data over the river (see example below), as well as with other commonly used optical imagery meltwater depth algorithms (e.g., Williamson et al., 2018). As water depths within the channel are a similar order of magnitude to the water depths in the lakes we calibrate our depth algorithm on, we consider our approach to be reasonable. We have add clarifying text into the Methods:

- “Although the river channel itself can incise depths of 8-10 m, melt season water depths observed by ICESat-2 and calculated using established optical depth algorithms (e.g., Williamson et al., 2018) are typically much shallower, ranging from 1-3 m. The water depths within the channel are therefore of a similar order of magnitude to those of the ponds used to calibrate our depth algorithm, thus we conclude that the transfer of the method from ponds to the river channel is appropriate here.” (Li 127-131)



We agree that for the most downstream transects, the mixture of fresh and saline water could impact the optical imagery depth calculations; specifically due to sodium ions, which could increase light scattering, potentially resulting in an artificially higher depth estimate. However, we expect this impact to be small given the fairly shallow depth of the water and the limited impact of salinity-driven scattering in the visible bands (Chen et al., 2024). We have elaborated on this in the Methods:

- “In the portion of the channel closest to the ice front, where the estuary is sometimes present, we acknowledge that the mixture of fresh and saline water may influence optical depth retrievals. However, given the relatively shallow water depths in the channel (1-3 m) and the knowledge that the influence of salinity-driven scattering in the visible wavelength bands used here is limited, we expect this effect to be small (Zhang and Hu, 2021).” (Li 249-252)

as well as the limitations section of the Discussion:

- “For ice-shelf estuaries, higher salinity closer to the ice front may reduce depth retrieval accuracy. However, the shallow water depths (1-3 m) and the limited sensitivity of visible-band reflectance to salinity-driven scattering (Zhang and Hu, 2021), means that this effect is likely to be a minor source of uncertainty..” (Li 553-556)

The incision dataset does not appear to support some of the interpretation made relating to estuary formation timeline (Section 3.2). The authors state that the estuary was *'present for the majority of the 2016 melt season'* (Line 368). This conclusion is based on visual interpretation of Worldview images, where it is stated that all images after 7th July confirm the existence of an estuary (Line 324). However, Figure 7b shows that the channel didn't incise below sea level until 15^{h} August at Transect 0, which is almost at the ice-shelf/ocean boundary (hence presumably key for determining the timing of estuary establishment). On 7th and 13th July the channel is shown to still be above sea level. Is there a reason for this inconsistency? Presumably once channel incision becomes close enough to sea level, diurnal tidal range causes sea level to fluctuate between above/below the channel lip? I think more clarification and explanation on this is required, as the relative timings of estuary formation and persistence are central to most of the discussion. I also suggest adding the Worldview images for 2016 to the Supplement.

Thank you for pointing this out. There are a few contributing factors to why we see some of these inconsistencies between the channel transects (Fig. 7) and visual interpretations (Fig 8). First, as you mention, the diurnal tidal range, as well as wind and waves can cause ocean water to enter the channel once the lip of the channel is close to sea level—we cannot say for certain what the elevation threshold above sea level is for this. Second, the sea level shown in the transect plots is just a mean sea level that is calculated for each year. We have edited figs 6 and 7 to include a shaded standard deviation around sea level to make it clearer that the sea level has some uncertainty. We have clarified all of this in the Results:

- "We note that there may not always be perfect agreement between the channel bottom elevation relative to mean sea level (Figs. 6,7) and the visual indicators of estuary presence in the WorldView imagery (Fig. 8). This is because diurnal tidal fluctuations, wind, and waves can cause seawater to enter the channel once the channel bottom elevation is close to, but not necessarily below, mean sea level, and because our mean sea level estimate carries some uncertainty (Figs. 6,7). Therefore, the elevation threshold above mean sea-level at which seawater can first enter the channel is not precisely known, and visual indicators of estuary presence in WorldView imagery may precede the date when the channel bottom drops definitively below mean sea-level in our elevation profiles (Figs. 6,7)." (Li 383-389)

The third contributing factor is that the transects are point measurements along the channel rather than mean cross-sections for an aggregated area, so they should not be viewed as entirely representative of the surrounding region. For example, T0 is likely situated on an anomalous topographic high as it has a slightly higher elevation than T1 for some of the dates in 2016. We have since tested shifting all of the 2016 transects ±5 m and ±10 m along the river while maintaining the 500 m spacing between transects. All of these tests yielded more representative bathymetric profiles at T0 and similar profiles at all other transects, confirming the original T0 is likely an anomalous bathymetric high point. We have edited Fig. 7 to instead show profiles all shifted 5 m away from the ocean.

The main stated motivation for the work is that the formation of ice shelf estuaries via supraglacial channel incision might inhibit meltwater export and reduce ice shelf stability. However, there is no discussion of the wider implications of the work presented – it is only really mentioned in a line or two in the conclusion. Given you have constrained the timings and evolution style of the estuary over several years (thus extending the work of Boghosian et al., 2021), can should discuss how important you think the estuary is for ice shelf stability. For example, how much seawater is actually getting into the channel? Is seawater intrusion necessarily preventing simultaneous meltwater export, or could both be happening at the same time? Is the estuary currently having any effect on ice shelf stability given how spatially and temporally limited (Fig 6 & 7) the seawater intrusion is? I realise in-situ or modelling would be required to answer some of these questions, which is likely outside the scope of the study, but I think there should at least be more discussion of these sort of ideas.
Thank you for raising this point. The primary goal of this paper is not to assess the impact of estuary formation on the stability of the Petermann ice shelf, but rather to assess the conditions on Petermann in the lead up to estuary formation. We have ensured that this is clearer in our revised Introduction (Li 100-104).

That said, we believe that the Petermann estuary, as well as its corresponding basal channel, contributed to the formation of a large fracture perpendicular to ice flow which bisected the river channel in 2018 and led to a recent calving event, and we have elaborated on this in our revised Discussion, along with a brief discussion of the potential implications of the estuary for Petermann's stability:

- "For 2014 to 2018, the Petermann estuary likely occupies only the final few kilometres of the ice shelf, a region that has been shown to contribute little to buttressing of upstream glacier flow (Rückamp et al., 2019). However, as Boghosian et al. (2021) demonstrate, estuary formation on Petermann Ice Shelf has already been associated with the development of longitudinal fractures that propagate upstream from the calving front, promoting transverse fractures which sometimes lead to rectilinear calving events. For example, the formation of the 2018 rift was likely driven by the combined influence of estuarine weakening and concentrated ice-shelf thinning along the central basal channel (Dow et al., 2018). Further, these processes likely contributed to a large rectilinear calving event (~75 km^2) along this rift on 4 August 2026, as observed in Sentinel-1 radar imagery, suggesting that even the spatially and temporally limited seawater intrusion documented here prior to 2018 may have been sufficient to weaken the ice shelf and contribute to fracturing. If continued channel melting driven by warm seawater intrusion thins the ice shelf and lowers the freeboard in the channel, seawater may penetrate further upstream towards the grounding line, allowing estuarine-induced flexural weakening to influence ice that plays a more significant buttressing role." (Li 485-495)

Line-by-line comments

Line 37: This is an odd sentence as it gives no timescales for former ice shelf extent – I'd just state the present day percentage or area that is buttressed by an ice shelf.

We have changed the sentence and added additional context as follows:

- "In Greenland, ice-shelf retreat has been ongoing since at least 1990, with three ice shelves collapsing completely over this period (Millan et al., 2023; Moon and Joughin, 2008). Today, there are only four major ice shelves remaining in Greenland: Petermann, Steensby, Ryder, and Nioghalvfjerdsbrae (79N; Millan et al., 2023). Of these, three have experienced grounding line retreat since 1992, and total ice shelf area in Greenland has decreased from 4,413 km^2 in 2000 to 3,513 km^2 in 2022 (Millan et al., 2023)." (Li 34-38)

Line 39: Be clear if you are talking about Antarctica, Greenland, or both in relation to projected melt increases.

Thank you for pointing this out. This is meant to be referencing both Greenland and Antarctica, which we have clarified in the revised text.

Line 122: The maximum depths of Ponds 2 and 8 are 2.5 m and 2 m respectively (Supplementary Fig 3). Unless I have misunderstood what is being shown, Figure 7 shows that water depth within the river channel typically ranges between 6-9 m. They therefore do not have '*very similar depth*', which you go on to say is important for calibrating the depth model. See Main Comment 1 for more details.

Please see the more detailed response to Main Comment 1 (pages 13-14 of this letter). The text in the Methods has been changed to clarify as we have outlined above (Li 127-131).

Line 162: I'm confused by the need for identifying water-marginal pixels. Is this not just your lake outline? Is two-pixel width to allow for error in the lake outline mapping? Please clarify.

The two pixel buffer is to allow for some error in shoreline mapping. As Petermann's main channel has fairly steep banks, a one pixel error in shoreline location could lead to a significant difference in elevation (e.g., Dai et al., 2018). This is particularly relevant as the channel has a bell curve shape and is only filled with 1-3 m of water, so the shoreline falls along the steeper parts of the riverbank. We have added text to our revised Methods explaining this reasoning for using the water-marginal pixels:

- "A buffer with a two-pixel width is required to account for potential errors in shoreline mapping; as the channel banks are relatively steep, a one-pixel error in shoreline location could lead to a significant error in the water surface elevation estimate, which in turn would propagate into the bathymetry calculation (Dai et al., 2018)." (Li 182-184)

Line 228: In the example shown in Figure 5, the original DEM (dashed line) shows the same elevation either side of the lake. In this example, it is therefore obvious what elevation to take as the smoothed lake surface. Did you have some lakes where the two sides of your lake outline didn't match in DEM elevation? If so, how did you select what elevation to take as the lake surface?

Fortunately, we did not encounter this problem as the range of surface elevations around the lakes we considered were fairly small, attributable to the relatively low surface slope of the ice shelf, and thus lakes did not span a large elevation gradient on the ice shelf. That said, we mitigated this potential problem by using the mean marginal pixel elevation for the entire lake shoreline, rather than just the transect endpoints, to calculate the water surface elevation. This has been clarified in our revised Methods:

- "The use of the mean elevation of all water-marginal pixels around the entire lake shoreline, rather than just the elevations at the endpoints of the ICESat-2 transect, is intended to mitigate any potential error introduced by elevation differences around the lake perimeter." (Li 243-245)

Line 255: Do you remove sea ice pixels from within the channel that fall along either the crosssectional or longitudinal transects? The presence of blocks of sea ice within the channel would presumably impact bathymetry results if not identified and removed prior to data extraction.

There is only sea ice in the channel in three of the images that we used for the bathymetry calculations, so we were able to draw the transect and river centerline shapefiles to avoid any sea ice pixels. We have clarified this in our revised Methods:

- "If necessary, these transects are manually shifted 1-2 pixels along the river centreline to minimize overlap with shaded pixels and floating sea ice." (Li 273-274)
- "As with the transects, this profile deviates 1-2 pixels from the centre of the river in some locations to minimize overlap with shaded pixels and floating sea ice." (Li 280-282)

Line 284: I'd avoid using the term 'downstream' and 'upstream' given the potential for flow reversal!

Great point, we have changed the wording to ensure that when these terms are used, it is in reference to location relative to the ice shelf rather than the flow direction of the water in the channel, e.g.:

- "the estuary extended 0.5-2 km upstream from the ice-shelf front"
- "a large rift bisected the central river channel 13 km upstream of the ice front"
- "from at least 26 km downstream of the grounding zone"

Figure 6: This figure shows that even by mid-August, only the very end of the channel (~100200m) gets incised enough to drop below sea level, and even then only by a few

centimetres. Do you think the amount of seawater that is currently getting in actually enough to do anything to the ice shelf? I'd bring this into the discussion.
This is a good question, and it is really challenging to know how much seawater is entering the channel in a given year, and what effect that has on the ice shelf's stability, which is beyond the scope of the current study. However, Peterman has a history of rectilinear calving events which occur when rifts transverse to flow intersect the river/estuary channel, and Boghosian et al. (2021) have proposed that this form of calving is characteristic of estuary formation. The 2018 rift was likely a step in the progression towards the recent calving of a rectilinear iceberg, which would imply that the amount of seawater entering the estuary prior to 2018 was sufficient to have an impact. We have briefly mentioned this in our revised Discussion (Li 485-495), and the relevant text is included in our response to Main Comment 3 (pages 16-17 of this letter).

Line 324: See Main Comment 2.
Please see the more detailed response to Main Comment 2 (pages 15-16 of this letter), which includes the relevant text that was added to the Results to address this (Li 383-389).

Figure 8: This is a really nice figure! I'm a bit confused by some of the time bar colourings though – for example, in 2017 and 2018, why does the coloured line turn red (indicating confirmed estuary presence) before you have a red circle indicating a cloud-free image? How do you know there was an estuary before this? Similarly, what marks the end of the timeline for each year – do you just assume that the same conditions persistent until mid-September as observed in the last cloud free image? Can you please also add a scale for the Worldview images.
Thank you for pointing this out. The gradient colors between images indicate that a given change would have happened at some point between the image dates but that we cannot determine exactly when due to image availability. For the end of the melt season, yes, we are assuming that the conditions from the last cloud free image persist until the refreezing. We have clarified all of this in the revised figure caption. We have also added a scale bar to the first WV image and specified in the figure caption that all image frames are at the same scale. Please see the updated figure caption below:

- **"Figure 8: Timeline of Petermann ice-shelf estuary formation showing surface runoff and WorldView imagery from 2013 to 2018 (copyright Vantor 2025). Summer (1 June to 15 September) runoff over Petermann Ice Shelf from MAR is shown in black with a dashed line indicating peak runoff. A corresponding timeline coloured by likelihood of estuary presence (blue for no estuary, purple for ambiguous, and red for estuary) is shown below each of the runoff plots with coloured circles on the timeline representing availability of cloud-free WorldView-2/3 images; 12 example images (a-l; all at the same spatial scale) are shown below their respective coloured circles on the timeline and are labelled with relevant estuary formation criteria information. Gradients between two solid colours on the timeline indicate that a change in estuary likelihood occurred between two dates, but that the exact timing cannot be determined. At the end of each melt season, it is assumed that the conditions from the last cloud free image persist until refreezing."**

Line 371: When you say that estuary formation '*inhibits efficient meltwater export to the ocean',* do you mean it stops it entirely? Or is it possible that lots of meltwater continues to flow out into the ocean, even if ocean water is also getting in?

While we can't say for certain, it is more likely that some water is still being exported, and we have changed the phrasing of this to say "limits efficient meltwater export", as well as explained this uncertainty more thoroughly in the revised Discussion:

- "Additionally, as in terrestrial estuaries, the two water masses may not mix instantaneously but instead form a stratified system, with less dense freshwater flowing seaward above denser inflowing seawater, further distributing melt across the channel profile rather than concentrating it along the centre of the bed (Geyer and MacCready, 2014)." (Li 428-431)
- "Furthermore, as the volume of seawater intruding into the channel, its reach within the river/estuary, and the magnitude to which it limits meltwater export remain poorly constrained, direct measurements of water temperature, salinity, and flow velocity would help to fully assess the impact of the estuary on ice-shelf stability." (Li 558-560)

Line 382: The image you show in Figure 8e is taken on 1st September 2014. So how do you know that the estuary persisted for the rest of the month if you don't have a later image?
This is good point; we do not know this for sure. We have rephrased to:

- "Following Boghosian et al. (2021), we interpret this residual water as seawater, indicating the presence of a persistent estuary at the start of September 2014, after the melt season has ended." (Li 442-444)

Line 389: It would be useful to see these images in the Supplement, given they seem to contradict the timing of channel incision dropping below sea level (see main comment 2).
We have added all the images used, but currently not shown in Fig. 8, to the Supplement (Fig. S9).

Figure 9: This is another really nice figure!
Thank you!

Line 415: This is a really interesting point, which I feel needs more discussion. Estuaries are only likely to form on thin ice shelves where the freeboard is relatively low, and where supraglacial melt is high (i.e. turbulent melt channels that can incise). At the point at which the freeboard is low enough that supraglacial channels can incise to below sea level, it's likely that the whole ice shelf area has already been weakened substantially by surface meltwater ponding and hydrofracture, and could already be near to collapse. Could this potentially limit the importance and impact of these estuaries? i.e. By the time an estuary forms, the ice shelf may be near to collapse already.
This is an excellent point, we agree that in order for an estuary to form, it is likely that an ice shelf will have been thinned by basal and/or surface melting. So yes, while estuary formation can weaken ice shelves and drive major calving events (Boghosian et a., 2021), a thin, and

potentially weak ice shelf may be near to collapse regardless of an estuary forming. We have highlighted this point in our revised Discussion:

- "It is worth noting, however, that the conditions required for estuary formation—low freeboard and high surface melt—also promote ice-shelf instability through surface meltwater ponding and hydrofracture (e.g., Banwell et al., 2013), meaning that by the time an estuary forms, the ice shelf may already be significantly weakened. Estuary formation may therefore represent one of several concurrent destabilizing processes on an already-vulnerable ice shelf, rather than a singular potential trigger for collapse." (Li 496-500)

Does the fracture that appeared in 2018 mean the river no longer reaches the ocean? If so, could large supraglacial channels elsewhere also be impacted by ice shelf fracturing, precluding the potential for estuary formation?

The rift on Petermann bisected the river in 2018 such that the original estuary drains only the portion of the ice shelf downstream of this rift. The upstream portion of the river now drains into the rift, so no, this river does not reach the open ocean. However, this upstream portion of the river could potentially form a new estuary at the location of this 2018 rift in the coming years, particularly as the ice shelf downstream of the rift has recently calved. Furthermore, there is potential for estuaries to form on other ice shelves with supraglacial rivers in Greenland. We have noted this in our revised Methods:

- "We end our analysis with the 2018 melt season as a large rift bisected the central river channel 13 km upstream of the ice front prior to the start of the 2019 melt season. As a result, the upstream portion of the river no longer reaches the open ocean, instead draining into the rift, while only the downstream portion maintains a connection to the ocean through the original estuary." (Li 143-146)

And Discussion:

- "For the Petermann Ice Shelf, freeboard is generally less than 10 m—similar to the freeboard of the Ryder and 79N ice shelves in Greenland, both of which are also known to have large basal channels (e.g., Song et al., 2022). The large central river on Ryder reaches the ice-shelf front, and there is some evidence of estuary formation within the past decade (Boghosian et al., 2021). The river on 79N does not yet reach the ocean, however, due to the low freeboard and presence of basal channels, there is potential for an estuary to form if a calving event connects the surface river with the ocean. On Petermann, the upstream portion of the river could itself form a new estuary at the 2018 rift location in the coming years, particularly as the ice shelf downstream of the rift calved rectilinearly on 3 August 2026, as seen in Sentinel-1 radar imagery, connecting the river to the ocean." (Li 506-513)

Line 451: Data availability is mentioned as a limitation in terms of image acquisition, but I think you need to also mention that WorldView data is not open source. This is likely to be a major limitation on who else within the research community can implement this method.
Thank you for pointing this out; we have added this as a limitation in the revised Discussion:

- "A further limitation is that WorldView imagery is not openly available, with access requiring either a commercial license or provision via a federally funded grant and organizations such as the Polar Geospatial Center. This represents a practical constraint on the wider adoption of the methods presented here; future work could explore whether similar approaches could be developed using freely available satellite data, such as Sentinel-2 or Landsat 8/9 imagery, albeit at coarser spatial resolution." (Li 544-548)

Supplementary Figure 6 & 7: Why does the tidal correction change the elevation y-axis from 2030m down to 0-10m, given the tide only changes water level by a maximum of ~2m?
Originally, the ocean surface elevation was not accounted for in panel (a), but was in panel (c), which is relative to mean sea level. We have edited panel (a) to also make it relative to sea level and explained this in the caption.