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, will improve the submitted manuscript. Below, please find your comments in black and our responses in blue; any new or edited text that will be added to the revised paper is shown in purple.

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 currently written, does not clearly explain this, nor the distinction that meltwater export is limited/slowed rather than fully inhibited. We will make adjustments to the text as described in detail below in response to your specific comments.

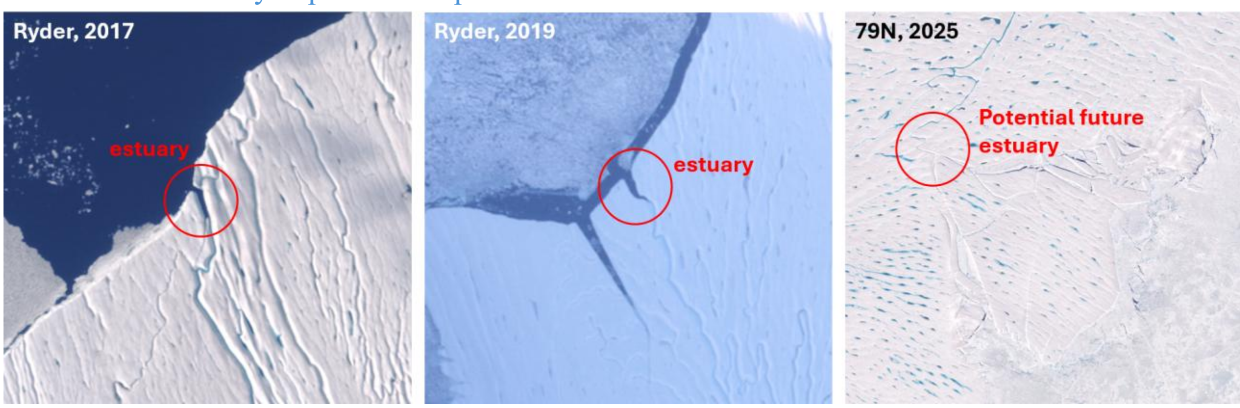
I do not understand why measurements of the surface channel geometry before and after the melt season would not suffice to investigate incision rate. It does not snow much on Petermann.

We agree that differencing of pre- and post- melt season DEMs could provide a decent estimate of a mean incision rate during the melt season, provided we are able to determine the number of melt days over which this incision would have occurred. However, due to the ice surface 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 determines 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 will add text to the introduction to clarify our goal of studying intraseasonal changes in estuary evolution and channel geometry.

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 will add a couple of sentences to the Discussion to briefly explain these possibilities.



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, 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 will mention in our revised Discussion.

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 will review 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 will change 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 will make the change to "channel geometry" throughout the paper.

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 will be shortened to 250 words maximum; an example is included below (although further changes to the exact wording may be made in to reflect any changes to the Results/Discussion as a result of reviewer comments):

"Ice shelf rivers may reduce ice shelf instability by exporting surface meltwater, limiting loading-induced stresses from ponded water. However, if a supraglacial river incises below sea level, forming an ice-shelf estuary, this mitigating effect may be negated. Water flow reversal in the estuary loads the ice shelf, inducing flexural stress, and prevents efficient meltwater export. This phenomenon has only been observed on the Petermann Ice Shelf in northern Greenland. A key factor in determining when and where ice-shelf estuaries form is river incision rate — the decrease in channel bed elevation over time. We present a novel method for calculating incision rate in supraglacial rivers from paired multispectral WorldView-2/3 imagery and corresponding ArcticDEM strips, applied over the Petermann Ice Shelf in 2014 and 2016. Incision patterns differ substantially between the two years: the highest rates occur near the supraglacial river/estuary mouth in 2014, compared to the lowest rates at the same location in 2016. Using high-resolution WorldView imagery from 2013–2018 and modelled runoff, we conclude that these contrasting patterns result from estuary formation and the resultant flow reversal, which limits meltwater export, reduces frictional melting of the channel bottom, and likely reduces water surface slope, causing the channel to cease deepening and widen instead. Although the estuary first forms in August 2014, it is absent early in the 2016 melt season before developing by early July. Subsequent melt seasons reveal a cyclical pattern whereby the estuary re-forms each season driven by meltwater and ocean water loading and unloading."

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 will address in the revised manuscript. This topic is addressed in more detail as part of the four major comments in the Discussion (pages 9-10 of this letter). We will amend the text in the abstract to reflect changes made to interpretation and estuary dynamics from the discussion.

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 will re-write 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 (Moon and Joughin, 2008; Millan et al., 2023). Today, there are only four major ice shelves remaining in Greenland: Petermann, Steensby, Ryder, and Nioghalvfjerdsbrae (79N; Millan et al., 2023). Three of these remaining ice shelves 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 40: Rewrite "and is projected to increase.." to ",which is projected to increase"
We will make 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 will add/rewrite the following text discussing the connection between surface and basal channels:

"Often, these rivers form in the surface depressions over ice shelf basal channels (e.g., Dow et al., 2018) and can export large volumes of surface meltwater from the ice shelf into the ocean, limiting loading-induced stresses from ponded meltwater (Banwell et al., 2013) and thus mitigating ice shelf breakup (Banwell 2017; Bell et al., 2017). However, if a supraglacial river incises to below sea level, forming an ice-shelf estuary (Fig. 1), this mitigating effect may be negated, and further, additional instability may be introduced by the resultant tidal loading (Boghosian et al., 2021). The presence of large basal channels has also been shown to have a destabilizing effect on ice shelves by driving fracture formation perpendicular to ice flow (Dow et al., 2018). The combination of these effects likely drove the formation of a large rift perpendicular to the river and basal channels on Petermann, which bisected the central river channel 13 km upstream of the ice front in 2018."

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

We will make 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 will clarify this in our revised paper. We will also add some detail about the potential dynamics at play within the estuary:

"This water flow reversal acts 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, and is likely driven by winds and tidal fluctuations. Together, the enhanced loading and limited meltwater export may enhance ice shelf instability."

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, 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 will be edited to read as follows:
"As atmospheric temperatures rise and melt seasons continue to lengthen on the Greenland and Antarctic ice sheets, driving increased surface melt (Hanna et al., 2024; Jourdain et al., 2025), ice-shelf estuaries are expected to persist in Greenland for as long as ice shelves remain, and begin forming around Antarctica within 30 years (Boghosian et al., 2021)."

Li 72 – 72: What about ice penetrating radar for ice shelf thickness and basal channel depth.
We will add a mention of these 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 72: Change to "the measure of change in surface channel bottom elevation"
We will make 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 will be 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 will make 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 will make 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 will edit the text to explain this: "Focussing on ponds minimizes the need to account for large diurnal cycles in supraglacial river water levels (e.g., Smith et al., 2021; Yang et al., 2022) between WorldView-2 and ICESat-2 acquisition times and increases the number of overlaps between the two satellites over waterbodies. While some of the ponds appear to be fed and/or drained by streams, which could cause water levels to fluctuate diurnally as well, the streams are significantly smaller than the main channel on Petermann, and thus introduce much less potential error between image acquisitions."

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. 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. We will add a sentence to briefly summarize the difference between our and Macdonald et al.'s methods in our revised paper.

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 139-144). 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 234-242).

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 will add a sentence to the Methods specifying this. 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, 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 will add the following text to confirm that our remotely sensed estimates agree well with in situ observations, which lends further confidence to our employed methods:
"When we estimate ice shelf surface ablation by differencing our tidally-corrected DEMs along a surface transect to the west of the river, we also find close similarity between the two years; 1.4 ± 0.4 m in 2014 (0.25 ± 0.07 mm d-1) and 1.4 ± 0.3 m in 2016 (0.24 ± 0.05 mm d-1). 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."

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 the steeper surface slope in 2014 relative to 2016 likely drives faster river flow and enhanced melting on average, and we will add this point to our Discussion. However, within each year, surface slope is relatively consistent over the entire 5 km transect; if slope were the primary driver of differences in incision rate between the two years, we would expect incision rate to vary along the entire transect rather than just in the 1.5 km nearest to the ice shelf front (current 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 will add to our revised Discussion.

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 58-61), but we will reiterate it in the discussion as well. 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 will add text to the discussion explaining these potential drivers of changes to melt patterns within the channel following estuary formation.

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 this comment and for pointing us to Holland and Jenkins (1999). We agree that "frictional heating" is not the best way to describe this process and will revise our discussion accordingly. Following Holland and Jenkins (1999), channel melting is better understood as turbulent heat transfer at the ice-water boundary, driven by both flow speed and how much

warmer the water is than the local freezing point. In the river phase, fast flow and warm meltwater both promote efficient melting and favor vertical incision (Fig 9a); once tidal flow reversal begins, slower net flow and mixing with saltier ocean water reduce this heat transfer and shift melting from vertical to lateral, consistent with the channel widening and flattening we observe following estuary formation (Fig 7 and 9b). We will revise Section 4.1 to better describe this process, citing Holland and Jenkins (1999).

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. In the current paper, we have 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

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 (page 9 of this response letter). We will edit the wording of our revised Conclusion accordingly.

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 will trace the outline of the river to make it more visible in the figure as well as add in the grounding line.

Figure 2 should have the glacier grounding line plotted on the main panel.
We will edit this figure to include the grounding line.

References:

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