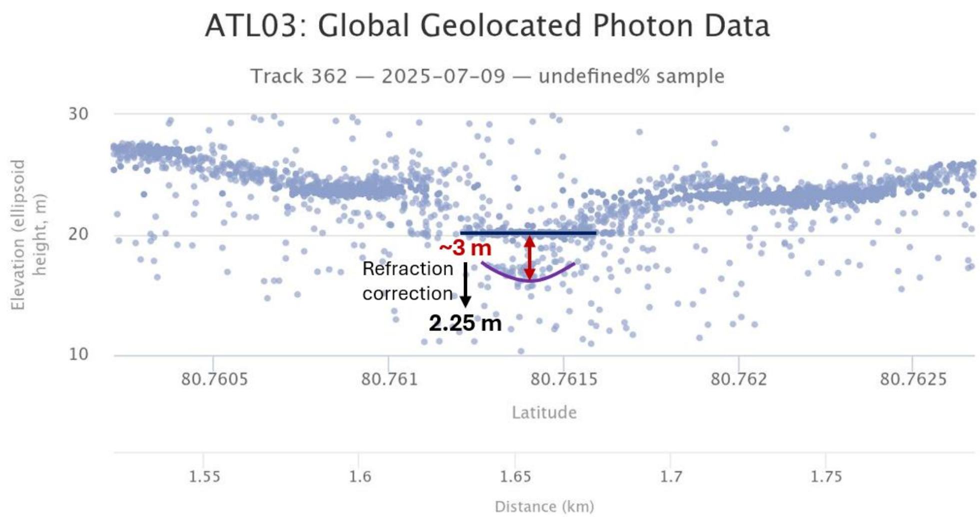
The manuscript describes an innovative remote sensing technique for exploring supraglacial channel incision rates in ice shelf settings. The authors calibrate an optical water depth retrieval method with IceSat-2 data in supraglacial lake settings, before applying the method to the Petermann Ice Shelf 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, 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.

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 will clarify 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). Due to the fact that 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 will add clarifying text into the Methods and Discussion to explain this.



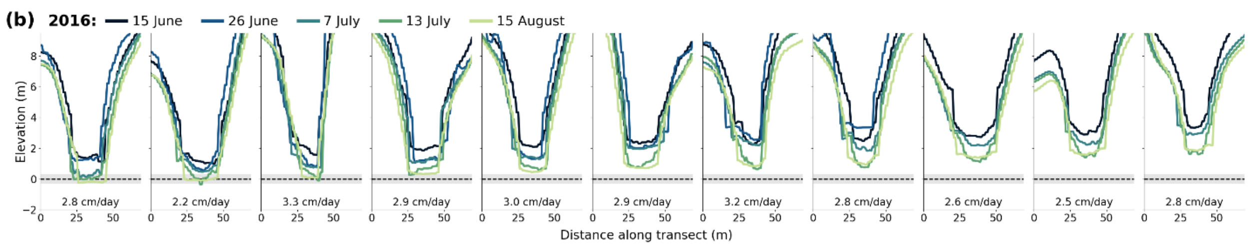
We agree that for the most downstream transects, the mixture of fresh and saline water could impact the optical imagery depth calculations; specifically due to sodium ions, which could increase light scattering, potentially resulting in an artificially higher depth estimate. However, we expect this impact 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 will elaborate on this in the Methods, as well as the limitations section of the Discussion.

Chen, J., Hodge, R. A., Jamieson, S. S. R., and Stokes, C. R.: Distribution and morphometry of large supraglacial channels on five Antarctic ice shelves, Journal of Glaciology, 71, e18, https://doi.org/10.1017/jog.2024.99, 2024.

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 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 a mean sea level that is calculated for each year (Li 239-242), which has a standard deviation of +/- 0.26 m for 2014 and +/- 0.31 m for 2016. We will edit 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 will clarify all of this in the text.

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 will edit Fig. 7 to instead show profiles all shifted 5 m away from the ocean (see below).



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 will ensure this is clearer in our revised paper. Additionally, we will add brief discussion of the potential implications of the estuary for Petermann's stability based on the findings from Boghosian et al. (2021).

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 we plan to elaborate on this in our revised paper, as well to the explain the role of basal channels in driving transverse fracture.

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 will change the sentence and add 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 (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)."

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 Antarctic ice shelves, which we will clarify.

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 1-2 of this letter). The text here will be changed to clarify as we have outlined above.

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 is only filled with 1-3 m of water, so the shoreline falls along the steeper parts of the riverbank. We will add text to our revised Methods explaining this reasoning for using the water-marginal pixels.

Dai, C., Durand, M., Howat, I. M., Altenau, E. H., and Pavelsky, T. M.: Estimating River Surface Elevation From ArcticDEM, Geophysical Research Letters, 45, 3107–3114, https://doi.org/10.1002/2018GL077379, 2018.

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 will be clarified in our revised paper.

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 will clarify this in our revised Methods.

Line 284: I'd avoid using the term 'downstream' and 'upstream' given the potential for flow reversal!
Great point, we will change the wording to either reference specific transects or distances along the centerline from the ice shelf front.

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 could thus be a step in the progression towards 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 will briefly mention this in our revised Discussion.

Line 324: See Main Comment 2.

Please see the more detailed response to Main Comment 2 (pages 2-3 of this letter). The text here will be changed to clarify as we have outlined above.

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 were intended to 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. We will clarify this in the figure caption. For the end of the melt season, yes, we are assuming that the conditions from the last cloud free image persist until the refreezing, which we will also clarify in the caption.

We will add a scale bar to the first WV image and specify in the figure caption that all image frames are at the same scale.

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 will change the phrasing of this to say something along the lines of "limits efficient meltwater export", as well as to explain this uncertainty more thoroughly in the text.

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 will rephrase to "We interpret this residual water as ocean water, indicating the presence of a persistent estuary at the start of September 2014, after the melt season has ended."

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 will add all the images used, but currently not shown in Fig. 8, to the Supplement.

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 will ensure we highlight this point in our revised Discussion.

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 if the ice shelf downstream of the rift calves. We will note this in our revised Discussion.

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 will add this as a limitation.

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?
Currently the ocean surface elevation is not accounted for in panel (a), but is in panel (c), which is relative to mean sea level. We will edit panel (a) to also make it relative to sea level, and explain this in the caption.