Response to the review of "Ephemeral grounding on the Pine Island Ice Shelf, West Antarctica, from 2014 to 2023," submitted to The Cryosphere.

Reviewer #2:

We sincerely thank reviewer 2 for the thoughtful review and constructive feedback, which has led to a significant improvement of the manuscript. We fully agree with the reviewer on the major concerns. Accordingly, we made the following major changes to the manuscript:

1. We critically re-examined our interpretations considering the results, making significant changes to the presentation of figures and our analytical conclusions.
2. We extensively rewrote the manuscript to enhance clarity and readability throughout.
3. We improved the visualization of all figures, added, and removed figures to improve the presentation.

In this document, we provide a detailed, point-by-point response to all comments. For clarity, the reviewer's comments are shown in black, and our responses are shown in blue, with proposed new text in **bold.** Some sentences were underlined to emphasize key content closely related to the comments.

Qian et al provide a detailed records of the ephemeral grounding events of a pining point on Pine Island Ice Shelf using Sentinel-1 SAR images and differential range offset tracking (DROT) method between 2014 and 2023. They claimed that ephemeral grounding is caused by basal melting, which is influenced by ice shelf calving and atmospheric forcing such as El Niño and La Niña. Although this is an interesting record, there is a lack of evidence to support the claims made by the authors, especially the results regarding basal melting are largely unconvincing and lacks care in overall logic and explanation.

The claim in the abstract that the ephemeral grounding site may evolve into a final pining point and may influence future ice shelf is rather speculative and has not been discussed anywhere in the paper. Overall I think this study requires substantial revision and its current form is not suitable for publication in the Cryosphere.

Response 1:

We agree that the original discussion lacks evidence supporting the claims about atmospheric forcing and basal melting in the long-term evolution of the ephemeral pinning point. We've removed speculative statements and the hypothesis of atmospheric drivers, while rephrasing our assessment of ocean activities' impact in the abstract, discussion, and conclusion.

Major Comments

The current results especially Figure 4 fail to establish the link between different tidal phases and intermittent grounding events of the Pine Island pinning point, because the double differential vertical displacement from DROT method and the double differential tidal heights do not provide information on tidal phases or tidal heights at specific timestamps. Therefore, it is not possible to identity whether a grounding event is associated with low tide or vice versa just based on these the current results.

Response 2: We agree with the reviewer. We have revised Figure 4 and the corresponding description in Section 3 to include a tidal height time series from the CATS2008_v2023 tidal model, overlaid with the acquisition times of the SAR image pairs used in the DROT analysis. This revision enables a direct comparison between tidal height and the observed differential vertical displacements. We have also updated the figure caption and the main text in Section 3.1 to more clearly explain how grounding status is inferred based on local tidal heights at specific timestamps.

- **The revised Section 3.1 is as follows:**

"Ephemeral grounding regions, characterized by double-differential vertical displacements close to zero, are influenced by oceanic tidal variations (Figures 6-7 and Movie S1). The tidal height difference was calculated from data extracted at a point near the ice rumple L (longitude 100.6149°W, latitude 75.1867°S), corresponding to the exact acquisition times of each Sentinel-1 image, which were at 4:35 AM on each date (Supplement Table S1). One or two near-zero vertical displacement signals were detected at ice rumple L from at least November 2016 through April 2020, followed by a reappearance in December 2020. These signals are highlighted by yellow arrows in Figure 6a and marked by red vertical lines in Figure 6b. The reduced number of signals before ~August 2016 and after ~December 2021 likely reflects data limitations during periods when Sentinel-1B was not operational. Near-zero vertical displacement signals also occurred in 2016, 2017, and after the 2018 calving event. In December 2020, a similar signal appeared upstream of ice rumple L and progressively migrated toward the rumple, indicating that ephemeral grounding occurred as a thicker section of the ice shelf moved across the southern side of the sea ridge."

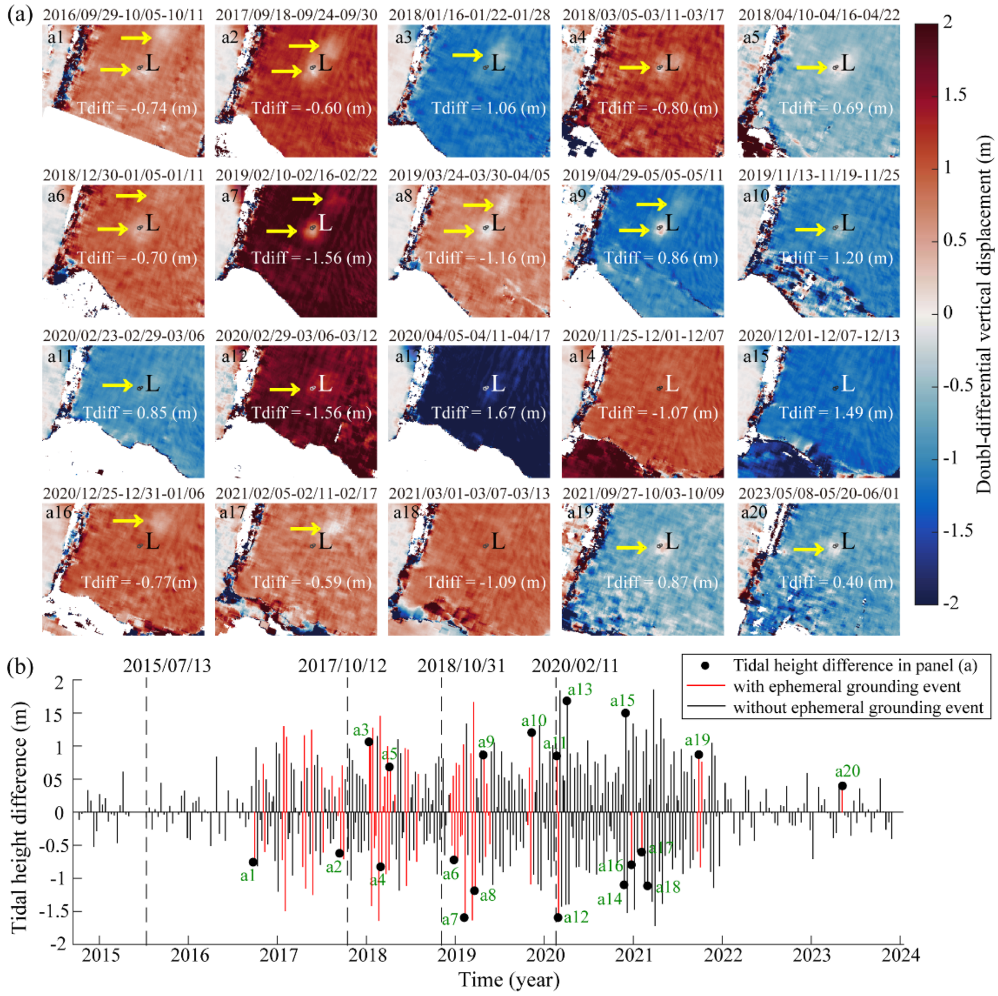

Figure 6. Two-dimensional double-differential vertical displacement changes and time series of double-differential tidal height differences. (a) Spatial distribution of double-differential vertical displacement changes between November 2016 and May 2023. Yellow arrows highlight inferred ephemeral grounding signals in each displacement map. The tidal height difference (Tdiff) is labelled in each frame. (b) Time series of double-differential tidal height differences (black vertical lines) and inferred ephemeral grounding events (red vertical lines). Dashed lines indicate the timing of four major calving events: 13 July 2015, 12 October 2017, 31 October 2018, and 11 February 2020.

"Figures 6a and 7a show that positive displacement anomalies are generally associated with negative tidal height differences, and vice versa—indicating a negative linear correlation between the two

variables. However, Figure 7b shows no clear relationship between tidal height and the area of the grounding region, suggesting that tidal forcing alone does not control the ephemeral grounding. In contrast, Figure 7c indicates that 64 ephemeral grounding events occurred between November 2016 and March 2021—35 during the neap tide period and 29 during the spring tide period. Notably, Figures 7c and 7d show that larger grounded areas are observed during spring tides, when tidal amplitudes are at their peak, while smaller grounded areas occur during neap tides, when tidal heights are at their lowest. These patterns suggest that the variation in grounded area is more closely linked to tidal period rather than tidal height alone. Together with Figure 6a, which shows the changes of the two near-zero vertical displacement signals, it suggests that thick ice advection from upstream may contribute to the grounding events. Consequently, ice dynamics likely play a significant role in the grounding process as well."

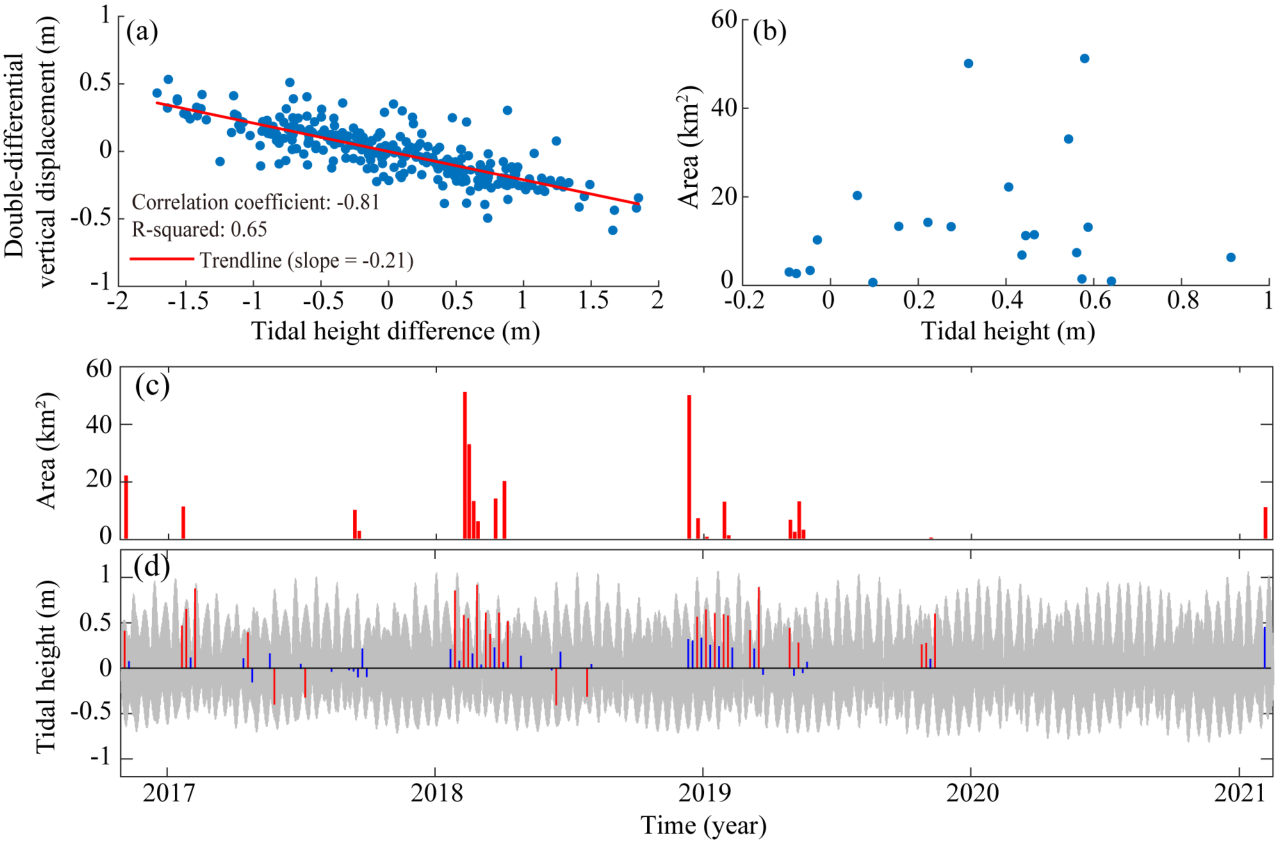

Figure 7. Comparison of tidal height differences with double-differential vertical displacement, comparison of tidal height differences and area of grounding region, including time series of area and tidal height variations. (a) Scatter plot of tidal height difference versus double-differential vertical displacement, showing a strong negative linear correlation between the two variables (Pearson's r = –0.81, R^2 = 0.65, slope = –0.21). (b) Scatter plot of tidal height versus area of zero vertical displacement region, indicating no clear relationship between the two datasets. (c) Time series of changes in ice rumple area. (d) Time series of tidal height changes, where 0 represents mean sea level. Blue vertical lines indicate ephemeral grounding events during the neap tide period, while red vertical lines represent those during the spring tide period.

Line 57-60: 'DROT-derived grounding line position were 2 km seaward of DInSAR and 2 km landward of H positions', is this 2 km bias applies to everywhere around Antarctica or just for specific locations? This statement also implies that DROT can only locate the middle location of the true grounding zone as a proxy grounding line, so if there is a 2 km bias, can we still trust DROT in identify the grounding line for Pine Island ice rumple? What if its maximum length is less than 4 km? There isn't any scale bar to measure this directly in the figures.

Response 3: We thank the reviewer for this valuable suggestion. The ~2 km offset between DROT-derived grounding lines and those obtained from DInSAR and hydrostatic methods, as noted in Friedl et al. (2020), specifically pertains to Petermann Glacier. This offset should not be interpreted as a systematic bias applicable across Antarctica, as the width of the grounding zone and local ice shelf geometry vary substantially between regions.

In response to this concern, we have revised the relevant discussion of the DROT method in the Introduction as follows:

"…Both DROT and InSAR methods in theory indicate the landward limit of tidal flexure. While InSAR is widely used to map grounding line migration, its effectiveness is limited in fast-flowing areas due to phase aliasing unless very short repeat intervals are available. For instance, Milillo et al. (2017) used 1-day repeat COSMO-SkyMed data to track grounding line changes at PIIS.

In contrast, DROT provides a complementary approach that does not rely on phase information, making it useful for observing vertical tidal displacements on fast-moving ice shelves, despite being less precise than InSAR in some contexts (Marsh et al., 2013; Hogg, 2015; Joughin et al., 2016; Christianson et al., 2016; Friedl et al., 2020; Wallis et al., 2024; Lowery et al., 2025; Zhu et al., 2025). Using TerraSAR-X data, Joughin et al. (2016) identified a vertical displacement anomaly near ice rumple L and estimated the grounding line position to within ~1.5 km. At Petermann Glacier, Friedl et al. (2020) found DROT-derived flexure limits ~2 km seaward of DInSAR results. More recently, DROT applied to Sentinel-1 IW data has proven effective for studying grounding line and pinning point dynamics on the Antarctic Peninsula (Wallis et al., 2024), Amery Ice Shelf (Zhu et al., 2025), and PIIS (Lowery et al., 2025). However, Lowery et al. (2025) focused only on the year 2017, leaving later changes unresolved. Thus, the evolution of grounding behaviour at ice rumple L following four subsequent calving events—in 2015, 2017, 2018, and 2020—remains poorly constrained."

To evaluate the accuracy of our results, we compared the grounding lines derived from DROT with those obtained using the DDInSAR method (Rignot et al., 2014; Mohajerani et al., 2021). In the central part of the ice shelf, both methods identify similar ephemeral grounding regions, although the area delineated by DDInSAR is smaller than that outlined by DROT (Figure R1). Despite this difference, both approaches consistently detect the presence of ephemeral grounding signals. In other regions, while the DROT-derived grounding line is generally positioned slightly farther seaward compared to the DDInSAR result, the majority of the DROT grounding area still lies within the grounding zone identified by DDInSAR. Based on this consistency, we consider our results to be reliable.

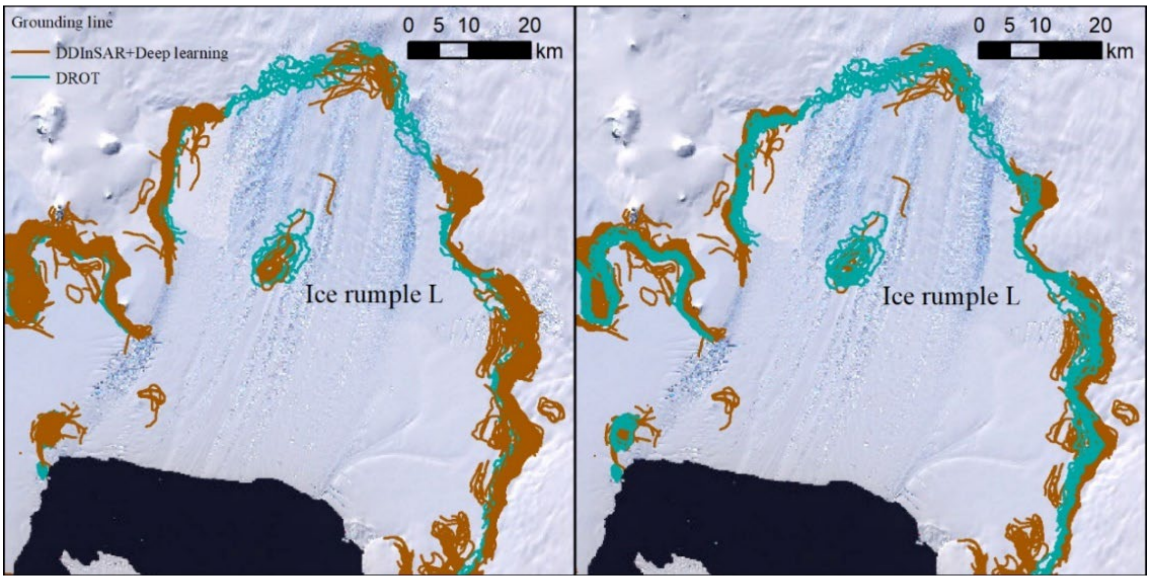

Figure R1. Comparison of grounding line positions derived from Sentinel-1 imagery using the DROT and DDInSAR methods in 2018.

Rignot, E., Mouginot J., Morlighem M., Seroussi H., and Scheuchl B. (2014), Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011, Geophys. Res. Lett., 41, 3502–3509, doi:10.1002/2014GL060140.

Mohajerani, Y., Jeong, S., Scheuchl, B. et al. (2021), Automatic delineation of glacier grounding lines in differential interferometric synthetic-aperture radar data using deep learning. Sci Rep 11, 4992, https://doi.org/10.1038/s41598-021-84309-3

Section 3.1:

- **Line 197-199** 'Our results are consistent with Friedl et al (2020)....', first there is no scale bar in the Figure 4 making it impossible to measure the distance between DROT-derived GL and the 2011 DInSAR GL; second, the thinning and thickening of the ice shelf can cause the shrinking and growing of the pining point, this will change grounding line extent of the ice rumple, how to rule out this possibility?

Response 4: We appreciate this observation and have revised Figure 4 and the associated text accordingly (see Response 2). Yellow arrows have been added to highlight the ephemeral grounding signals in Figure 4. We have also revised Figures 5 and 6 from the original submission and combined them into Figure 8 in the revised manuscript. A scale bar has been added to the updated Figure 8 to enable measurement of the distance between the DROT-derived grounding line and the 2011 DInSAR grounding line.

We agree with the reviewer that changes in ice shelf thickness can affect grounding at pinning points and may help explain the observed variability. Previous studies have suggested that ephemeral grounding may reflect temporal variations in ice shelf thickness (Rignot, 2002; Schmeltz et al., 2001). In our study, we not only examined the timing of grounding events but also analyzed concurrent changes in ice thickness. To achieve this, we used ICESat-2 data, which offer higher temporal resolution than REMA DEM strips, to investigate whether ephemeral grounding occurred between 2019 and 2022.

- **The revised discussion about the ice thickness changes in Section 3.2 is as follow:**

3.2 Changes in surface ridges and ice thickness

Figure 8 shows the evolution of surface ridges and their elevations from December 2010 to January 2021. Near ice rumple L (red point in Figure 8), surface elevations remained around ~65 m between 2012–2017 and again during 2019–2020 (Figures 8d–h and 8j–k). The highest elevation (~85 m) was recorded in 2018, while the lowest (~54 m) occurred in 2021. Between 2020 and 2021, surface elevation declined by ~10 m, equivalent to ~70 m of ice-equivalent freeboard thickness. The area enclosed by the grounding line, corresponding to the region of zero vertical displacement, was the largest in 2018 (Figure 8i).

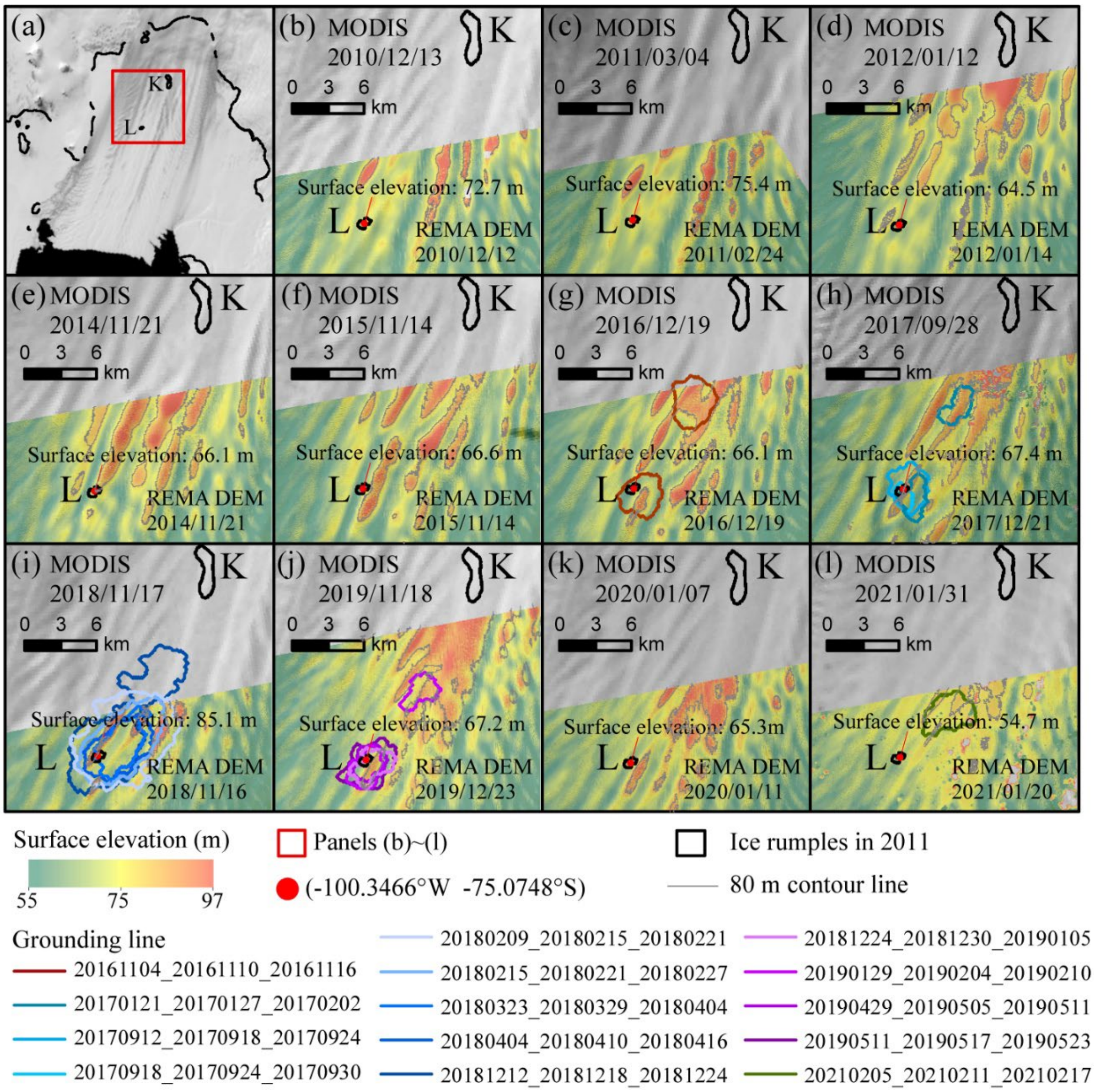

Figure 8. Changes in surface ridges at PIIS near ice rumple L. (a) Overview map showing the subregion outlined by the red frame, corresponding to panels (b)–(l). (b)–(l) Surface ridges and their elevation changes from 2010 to 2021, derived from corrected REMA DEMs. The two black circles indicate the positions of ice rumples. Grounding lines are delineated based on the zero-contour of the double-differential vertical displacement. Grey lines are the 80m contour line.

Profiles of ice-equivalent freeboard thickness derived from ICESat-2 (Figure 9) link surface elevation and grounding changes. Figure 7a shows mean thickness trends around the rumple along ICESat-2 tracks 965 and 1094 between 75.15°S and 75.05°S (Fig. 1b). Track 965 reveals increasing ice thickness from 2015 to 2021, while track 1094 shows a decrease from 2015 to 2017, a rebound in 2018, and a decline after 2020. Bottom elevation profiles derived from ICESat-2 (Figures 9b-e) further reveal changes in grounding status. The ice shelf was ungrounded on 27 August 2020, 5 March 2021, and 25 May 2022, but showed weak grounding on 6 June 2020. By integrating double-differential vertical displacement data with bottom elevation profiles, we find that ephemeral grounding signatures disappeared after March 2020 and reappeared in November 2020.

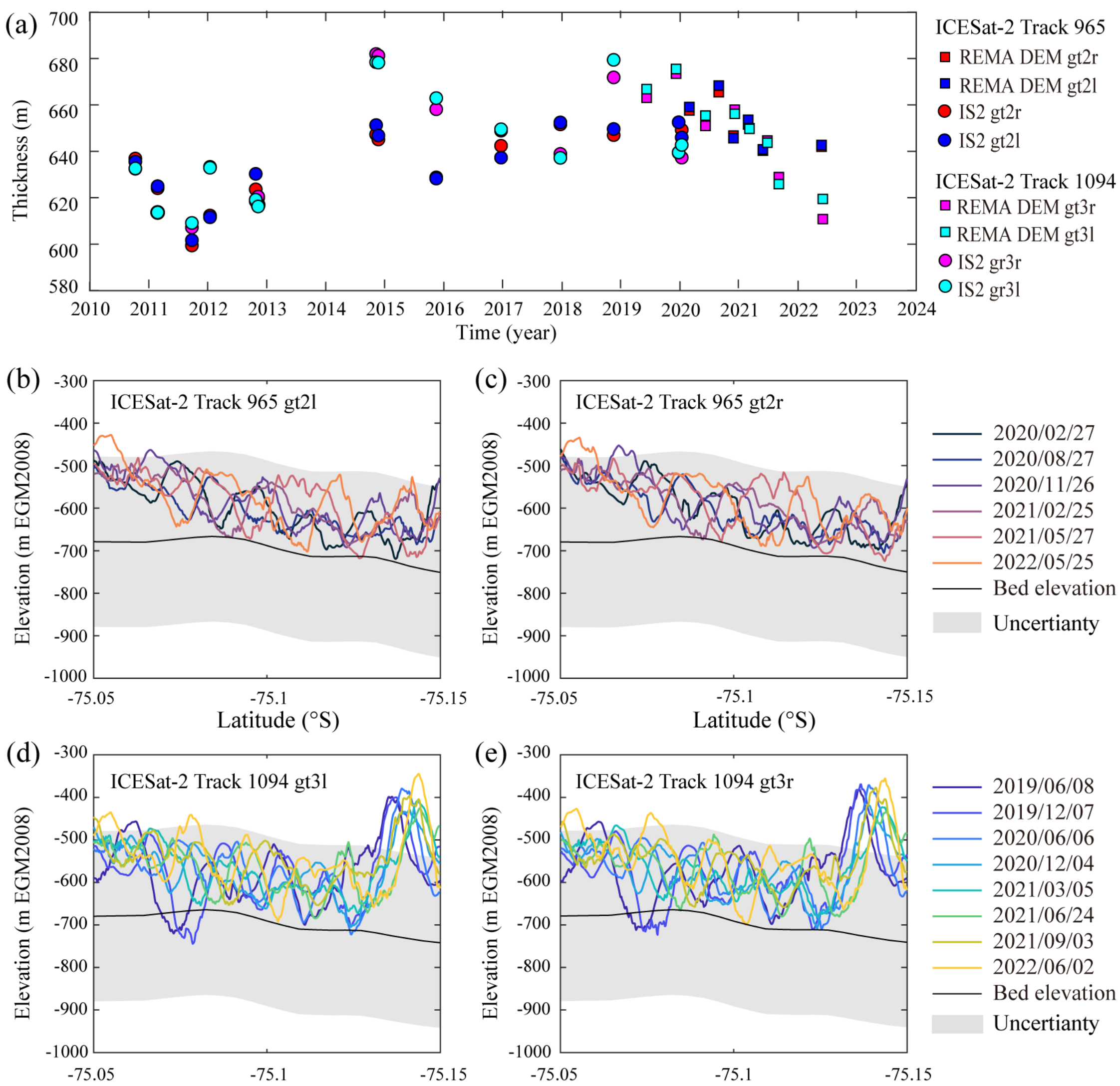

Figure 9. Time series of mean ice-equivalent freeboard thickness and ice shelf bottom elevation profiles along ICESat-2 tracks 965 and 1094. (a) Time series of mean ice-equivalent freeboard thickness (2010–2022). (b)–(c) Ice shelf bottom elevation profiles along ICESat-2 tracks 965 (gt2l and gt2r) between February 2020 and May 2022. (d)–(e) Ice shelf bottom elevation profiles along ICESat-2 tracks 1094 (gt3l and gt3r) between June 2019 and June 2022. Bed elevations are from the BedMachine v3 dataset (Morlighem et al., 2020; Morlighem, 2022), converted from EIGEN-6C4 to the EGM2008 geoid to match the vertical datum of REMA DSM strips. The estimated vertical uncertainty is ±200 m (shown as a grey transparent box).

Rignot, E.: Ice-shelf changes in pine island bay, Antarctica, 1947–2000, J. Glaciol., 48, 247–256, https://doi.org/10.3189/172756502781831386, 2002.

Schmeltz, M., Rignot, E., and MacAyeal, D. R.: Ephemeral grounding as a signal of ice-shelf change, J. Glaciol., 47, 71–77, https://doi.org/10.3189/172756501781832502, 2001.

- The authors claimed that pining point reappeared on 21 October 2021 in Line 199, but why this pining point locates upstream of the ice rumple L in Figure 4?

Response 5: We apologize for the lack of clarity in the originally submitted manuscript. The feature identified as a “reappeared” pinning point on 21 October 2021 is located slightly upstream of the previously grounded area, within a region where grounding was also observed in 2016 (Figure 4 a1), 2017 (Figure 4 a2), and multiple times in 2018 (Figure 4 a6–a9, a17).

- **We have revised the Section 3.1 to:**

"…**One or two near-zero vertical displacement signals were detected at ice rumple L from at least November 2016 through April 2020, followed by a reappearance in December 2020. These signals are highlighted by yellow arrows in Figure 6a and marked by red vertical lines in Figure 6b. The reduced number of signals before ~August 2016 and after ~December 2021 likely reflects data limitations during periods when Sentinel-1B was not operational. Near-zero vertical displacement signals also occurred in 2016, 2017, and after the 2018 calving event. In December 2020, a similar signal appeared upstream of ice rumple L and progressively migrated toward the rumple, indicating that ephemeral grounding occurred as a thicker section of the ice shelf moved across the southern side of the sea ridge.**"

The authors concluded that there are several possible factors causing this ephemeral grounding including atmospheric forcings such as La Nina and AO by including the analysis of ONI and AAO index. This conclusion is merely based on qualitative analysis just by roughly aligning the timeline of the ephemeral grounding with ONI and AAO phases, instead of providing a quantitative analysis or direct observation or modelling results of basal melting in Pine Island Ice Shelf. This makes the conclusion rather speculative and not convincing.

Response 6: We agree that our original conclusion overstated the influence of this climatic factor. We have removed the sections related to atmospheric forcing and discuss the part related to basal melting carefully in Section 4 and Appendix A.

- **The revised content in Section 4 is as follows:**

Section 4 (last paragraph):

"…De Rydt et al. (2014) demonstrated that both the height of the ridge and the gap between the ridge and the ice shelf strongly influence the inflow of warm bottom waters into the cavity, and consequently, the melt rate. The melt rate may influence the ice thickness near to the grounding line upstream of the ice rumples K and L. This process may have contributed to ice thickness changes upstream and indirectly influenced the disappearance of ephemeral grounding signals following the 2020 calving event. We have added further analysis on the basal melt rate and ocean temperature in the Appendix A. Although smaller-scale basal channels and keel geometries are primarily shaped by melt-driven processes (Bindschadler et al., 2011b; Dutrieux et al., 2013; Stanton et al., 2013; Dutrieux et al., 2014b; Joughin et al., 2016), the lack of direct, high-temporal-resolution basal melt rate measurements after 2020 limits our ability to capture short-lived grounding events and confirm the role of ocean-driven melting. Future work should prioritize the integration of dense time series from new SAR missions and in situ oceanic data to better resolve ephemeral grounding behaviour and its implications for ice shelf evolution and calving dynamics in a warming climate."

Appendix A. Oceanic condition changes and analysis

"To address the oceanic condition changes, we extracted time series data on mean basal melt rates from 2010 to 2017 using the MEaSUREs ITS_LIVE Antarctic Quarterly 1920 m Ice Shelf Height Change and Basal Melt Rates v1 dataset (Paolo et al., 2023; 2024). This dataset offers quarterly basal melt rate estimates, with uncertainties, from 17 March 1992 to 16 December 2017, at a 1920 m spatial resolution. However, these estimates are based on surface elevation changes from radar altimetry and ice fluxes from the Glacier Energy and Mass Balance model, not direct observations. Additionally, it does not cover our primary observation period from 2020 to 2023.

To further investigate oceanic influences, we examined ocean temperature time series from the PIG-N and PIG-S mooring locations using mooring data (Zhou et al., 2024; 2025). These records span from 2016 to 2024 and capture temperature variations at depths of 300–700 meters below mean sea level. This pan-Antarctic mooring compilation contains data on temperature, salinity, and current velocity in the Southern Ocean (90°S–60°S) since 1975, with contributions from data centres, research institutes, and individual data owners. This data compilation is available and regularly updated in NetCDF format via the SEANOE database at https://doi.org/10.17882/99922 (Zhou et al., 2024). However, the moorings located in Pine Island Bay and not directly beneath the ice shelf, which limits their applicability to sub-shelf melting processes.

Profiles of ice-equivalent freeboard thickness derived from ICESat-2 (Figure A) link surface elevation and grounding changes. Figure Aa shows mean thickness trends around the rumple along ICESat-2 tracks 965 and 1094 between 75.15°S and 75.05°S (Fig. 1b). Track 965 reveals increasing ice thickness from 2015 to 2021, while track 1094 shows a decrease from 2015 to 2017, a rebound in 2018, and a decline after 2020.

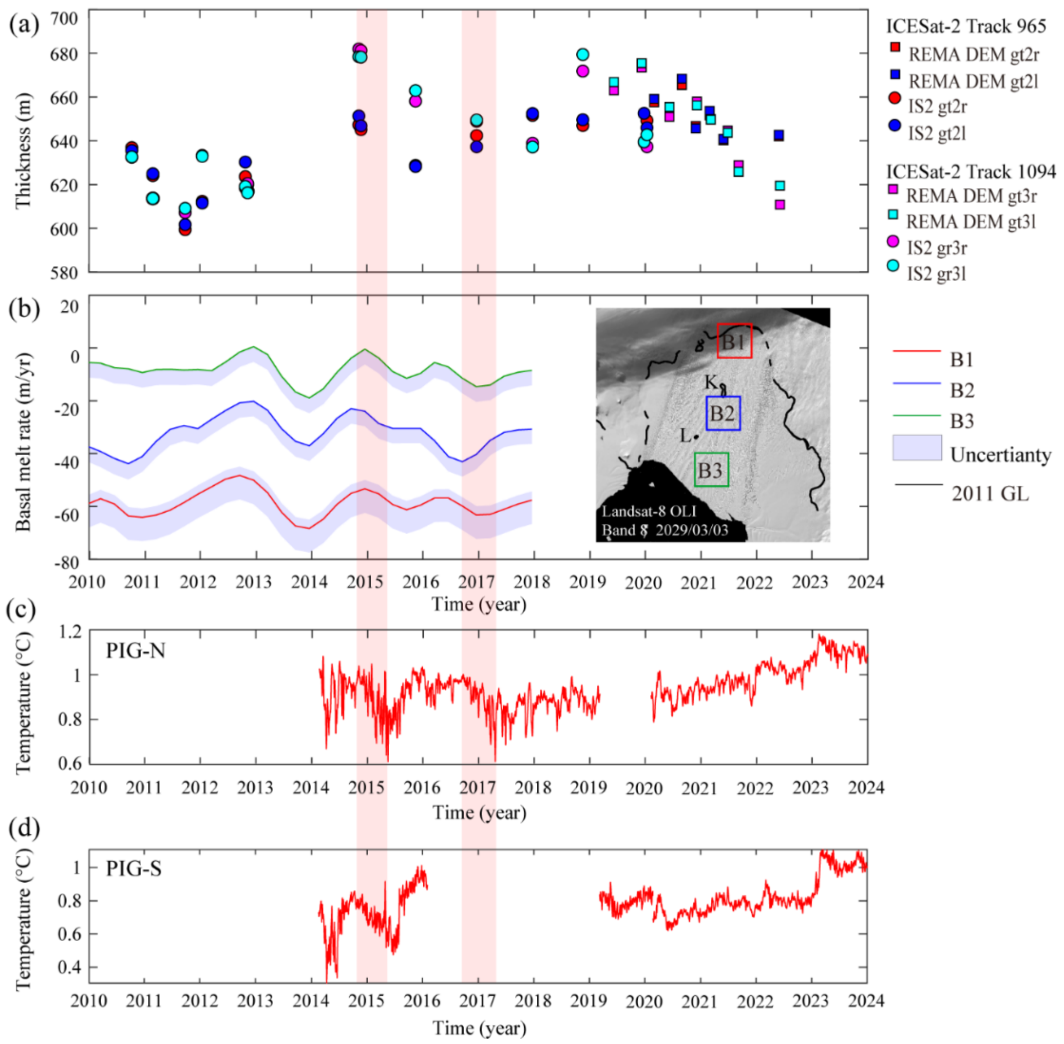

Figure A. Time series of mean ice-equivalent freeboard thickness, basal melt rate, and ocean temperature. (a) Time series of mean ice-equivalent freeboard thickness (2010–2022). (b) Time series of mean basal melt rate (2010–2017), averaged across blocks B1, B2, and B3, extracted from the MEaSUREs ITS_LIVE Antarctic Quarterly 1920 m Ice Shelf Height Change and Basal Melt Rates v1 dataset (Paolo et al., 2024). (c)-(d) reveal time series of ocean temperature at the PIG-N and PIG-S mooring stations from 2014 to 2024.

The basal melt rate time series show a decrease in melting around 2015, coinciding with a peak in ice-equivalent freeboard thickness at all three locations (B1–B3; Figure Ab). During the same period, ocean temperatures near 600 meters depth decreased at both the PIG-N and PIG-S mooring stations (Figures Ac and Ad). At B2, located between ice rumples L and K, the basal melt rate increased after 2015 but declined again after 2017 (Figures Aa and Ab). This decline corresponds with a drop in ocean temperature recorded at PIG-S (Figure Ad). However, from 2020 to 2023, ocean temperatures near 600 m depth at PIB showed a continuous increase, which could have contributed to enhanced basal melting of the ice shelf during that time (Figures Ac and Ad).

Smaller-scale basal channel and keel geometries are primarily shaped by melt-driven processes (Bindschadler et al., 2011b; Dutrieux et al., 2013; Stanton et al., 2013; Dutrieux et al., 2014b; Joughin et al., 2016). Mooring observations from 2014 to 2024 reveal two distinct periods of ocean temperature decline around 2015 and 2017 (Figure Ac, d), during which basal melting near ice rumple L also decreased (Figure Ab). Following 2020, however, ocean temperatures began to rise again. Correspondingly, ice thickness time series (Figures Aa) show a substantial thinning of approximately 70 meters. Although direct basal melt rate measurements are unavailable for this period, the observed warming at 600 m depth near PIB suggests that the ice shelf base may have reached this depth, potentially enhancing basal melting. This increased melting would have further thinned the ice shelf, thereby widening the thickness gap between the ice base and the submarine ridge.

In summary, these data show periods of temperature decline around 2015 and 2017, which were accompanied by reduced ice thickness near ice rumple L, followed by warming after 2020 and a corresponding ice shelf thinning of approximately 70 meters. However, direct basal melt rate measurements are unavailable for the post-2020 period (Figure R1). While the observed warming at 600 m depth near PIB suggests increased basal melting that likely contributed to the thinning, variations in ocean temperature and basal melt rates alone cannot fully explain the observed changes in ice shelf thickness or influence the small-scale keels."

Section 3.2

- The selected ice ridge is difficult to identify in Figure 5 given the small figure size, it is actually more visible from the elevation map in Figure 6, I suggest putting Figure 6 before Figure 5 to explain the choice of this ice ridge.

Response 7: We agree that the ice ridge is more clearly visible in the elevation map shown in Figure 6. We have reorganized Figure 5 and Figure 6 by combining the MODIS imagery with the surface elevation data (see revised Figure 8 in response 2). The ice rumples detected each year are also plotted to highlight changes in the ephemeral grounding locations. Additionally, we have added the 80m contour line and labeled the elevation values near ice rumple L to facilitate identification of elevation changes.

- Without labeling ice rumple L in Figure 5 and ice ridge in Figure 6, it is difficult to link the movement of ice ridge passing through the pining point, making it hard to follow the logic.

Response 8: We appreciate this suggestion and have figures to include clear labels marking the location of ice rumple L in each panel (see revised Figure 6 in response 2 and revised Figure 8 in response 2 and 7).

Discussion

- **Line 249,** the authors claimed that deep keels no long contacted the submarine ridge in 2020, this does not seem to be the case from Figure 7b where the orange line (2020) is in contact with the bedmachine bed topography.

Response 9: We thank the reviewer for this careful observation. Upon closer examination of the double-differential vertical displacement and ICESat-2 ice shelf bottom elevation profiles, we found ephemeral grounding signals both before April 2020 and after December 2020. We have corrected it in the manuscript as follows:

Discussion (paragraph 3)

"Changes in surface elevation and ice-equivalent freeboard thickness indicate that the ice shelf underwent thickening prior to grounding events and thinning prior to ungrounding. Notably, the surface elevation peaked in 2018 and declined significantly between 2020 and 2021, coinciding with changes in grounding behavior. <u>Near-zero vertical displacement signals—indicative of ephemeral grounding—were detected at ice rumple L from at least November 2016 through April 2020, then disappeared during the 2020–2021 thinning period before reappearing in December 2020.</u> In that instance, a similar signal emerged upstream of the rumple and gradually migrated toward it, suggesting that a thicker section of the ice shelf had moved over the sea ridge, re-establishing ephemeral contact with the bed."

- **Line 259:** can you label the basal channels in Figure 4?

Response 10: Thank you for the suggestion. We have reviewed Figure 4 and considered labeling the basal channels. However, to maintain clarity and avoid overcrowding, we did not add explicit labels for basal channels in revised Figure 8 (see Response 2 and 7). Instead, we enhanced the figure with combined surface elevation data and MODIS imagery in revised Figure 8, where the surface ridges and troughs are more clearly visible.

- **Line 263-264:** yes, the W shaped troughs can allow thicker ice to be advected downstream and form surface ridge, but this depends on the bed topography, and again does this matter to ice rumple L discussed in this paper?

Response 11: The W-shaped troughs do play a role in the formation and maintenance of ice rumple L by allowing thicker ice to be advected downstream, contributing to the development of surface ridges in that area. We agree with Reviewer 1 that distinguishing between the formation processes of large-scale and small-scale keels helps clarify the discussion. Accordingly, we have revised the text in Section 4 to explicitly link the general mechanism of W-shaped troughs to the specific case of ice rumple L, making this connection clearer for readers.

- **The revised Section 4 in the manuscript is as follows:**

"Changes in surface elevation and ice-equivalent freeboard thickness indicate that the ice shelf underwent thickening prior to grounding events and thinning prior to ungrounding. <u>Notably, the surface elevation peaked in 2018 and declined significantly between 2020 and 2021, coinciding with changes in grounding behavior. Near-zero vertical displacement signals—indicative of ephemeral grounding—were detected at ice rumple L from at least November 2016 through April 2020, then disappeared during the 2020–2021 thinning period before reappearing in December 2020</u>. In that instance, <u>a similar signal emerged upstream of the rumple and gradually migrated toward it, suggesting that a thicker section of the ice shelf had moved over the sea ridge, re-establishing ephemeral contact with the bed.</u>

Evidence of corrugations with periodic spacing on the submarine ridge supports the idea that this seafloor landscape was formed by sub-ice-shelf keels modulated by tidal motion (Graham et al., 2013; Davies et al., 2017). <u>Surface elevation data (Figure 8(b)-(l)) show that the center of the ice shelf is higher</u>

than the flanks, suggesting the presence of a central basal keel beneath the shelf. This large-scale geometry is primarily shaped by bed topography upstream of the grounding line. Specifically, the bed exhibits a W-shaped profile, with two troughs flanking a central topographic high (Lowery et al., 2025). These troughs may channel thicker ice toward the downstream ridge, promoting the formation of surface ridges aligned with basal keels. As ice flows downstream from the grounding line, local surface elevation adjusts toward hydrostatic equilibrium (Shean, 2016). The consistent positioning of basal channels and keels reflects this inherited bed structure. Therefore, the large-scale development of basal keels and channels is strongly controlled by upstream bed topography (Lowery et al., 2025).”

- The discussions on possible factors influencing basal melt rates are mainly build on qualitative analysis of El Niño and La Niña events and iceberg calving events, without providing detailed records on ocean temperature and time evolving basal melt rates, making the arguments largely unconvincing.

Response 12: We thank the reviewer for this insightful comment. We agree that our initial discussion relied too heavily on qualitative correlations with ENSO and calving events, which limited the strength of our arguments. We have removed those interpretations.

Specific Comments

Abstract:

1) The entire abstract needs to be rewritten. The first sentence ‘Ephemeral grounding sites form when ice shelves thin or relative sea level rises...’ is difficult to understand, need rephrase. I suggest first explaining on what condition ice rumple can be formed – for example the bottom of the ice shelf gets grounded on a bathymetric high, then mentioning that the thinning of ice shelf or vertical movements of ice shelf caused by tides can cause ‘ephemeral grounding’.

Response 13:

We agree with the reviewer. We have re-written the abstract and carefully revised relevant statements throughout the manuscript.

- **The revised abstract was as follows:**

“**…Recurring ice keels beneath the ice shelf cause ephemeral grounding events that remain poorly understood but may significantly influence ice shelf stress fields and flow dynamics.**”

2) Please remove line numbers from the abstract

Response 14: Done.

Line 31: ‘Over time, some pinning points have disappeared entirely, particularly since 1973’ this statement is unexpected here and doesn’t seem to be linked to the following statement on ephemeral grounding, I suggest rephrasing or deleting it.

Response 15: Deleted.

Line 32: should be (Miles and Bingham, 2024), not ‘Milles’. Please change this reference throughout the manuscript.

Response 16: We corrected this error throughout the manuscript.

Line 38: what do you mean by ‘it is believed’? How reliable was this ungrounding event in 1973-1989?

Response 17: Thank you for requesting clarification. The ungrounding event during 1973–1989, reported by Miles and Bingham (2024), is supported by indirect evidence such as changes in ice flow speed and satellite imagery. However, due to limited data availability, the exact timing and location remain uncertain. The phrase "it is believed" reflects this uncertainty and the reliance on the best available, albeit indirect, observations. We have revised the sentence to:

"This oceanic forcing initially caused transient grounding of the central ice shelf on a submarine ridge from the 1940s through the 1970s, followed by complete ungrounding between 1973 and 1989 (Jenkins et al., 2010; Smith et al., 2017; Miles and Bingham, 2024)."

Line 43: rephrase 'is now understood to result'

Response 18: The revised sentence is as follows:
"Despite the grounding line retreat, the Pine Island Ice Shelf (PIIS) was observed to maintain intermittent contact with the bathymetric high when thick ice column being advected from the upstream deep trough (Joughin et al., 2016; Lowery et al., 2025). This ephemeral grounding is now attributed to interactions between sub-ice keels and a submarine ridge (Graham et al., 2013; Joughin et al., 2016; Shean, 2016; Davies et al., 2017)."

Lie 44-46: 'After four calving events...remain unclear' I am not sure why mentioning calving events here, why does calving have anything to do with ephemeral grounding and the changes of ice rumple L?

Response 19: We thank the reviewer for this insightful comment. We believe the ephemeral grounding could have facilitated rift propagation, and the development of calving events in the past. As such, we have revised the abstract and the introduction to emphasize this point and have added further analysis on the rift propagation process in Sections 2.4, 3.3, and 4.

- **The revised sections are as follow:**

Abstract

"The evolution of ephemeral grounding sites offers valuable insights into changes in ice shelf thickness, which can affect buttressing, alter ice flow dynamics, and influence ice shelf stability. Long-term observations of these sites are crucial for understanding how thickness, basal conditions, and tidal interactions evolve over time."

"Landsat-8 images reveal that the rifts that cause the 2020 calving event formed after the region passed through the ephemeral grounded area suggesting that ephemeral grounding events may contribute to the formation of rifts. These findings provide new insights into the mechanisms driving ephemeral grounding behaviour and highlight its potential role in modulating ice shelf stability."

1. Introduction (paragraphs 4)

"… The grounding of ice shelf on high bathymetry features could impact ice dynamics as an obstacle against ice flow: <u>1) enhance the buttressing effect by providing back stress against upstream ice; 2) facilitate fracturing and ice shelf weakening in response to stress associated with grounding (Rignot, 2002; Christianson et al., 2016; Jeong et al., 2016; Shean, 2016; Benn et al., 2022; Wang et al., 2025)</u>."

1. Introduction (paragraphs 6)

"…More recently, DROT applied to Sentinel-1 IW data has proven effective for studying grounding line and pinning point dynamics on the Antarctic Peninsula (Wallis et al., 2024), Amery Ice Shelf (Zhu

et al., 2025), and PIIS (Lowery et al., 2025). However, Lowery et al. (2025) focused only on the year 2017, leaving later changes unresolved. Thus, the evolution of grounding behaviour at ice rumple L following four subsequent calving events—in 2015, 2017, 2018, and 2020—remains poorly constrained."

2.4 Rift propagation observation

Previous studies have suggested that such grounding may be linked to the formation of transverse rifts south of ice rumple L (Joughin et al., 2021), potentially contributing to calving events between 2015 and 2020. However, limitations in the spatial resolution and clarity of SAR imagery hinder a definitive assessment of the connection between ephemeral grounding and rift formation. We used Landsat-8 optical images, specifically the panchromatic band with a 15m spatial resolution, to track the rift propagation history. We then compared these results with our grounding line data to better understand the interaction between ephemeral grounding and rift propagation.

3.3 Rift propagation observation

Using Landsat images, we tracked the propagation history of the rifts from 2013 to 2019 (Figure 10). Rift R1 first appeared in the image from December 15, 2017 (Figure 10d), after the region passed through the ephemeral grounding zone, as seen in Figure 10c. Similarly, Rift R2 appeared in the December 11, 2018 image (Figure 10f), following its passage through the same grounding region. These two rifts ultimately led to the 2020 calving event. Therefore, our results suggest that ephemeral grounding events are linked to rift propagation, indirectly influencing the ice shelf calving process.

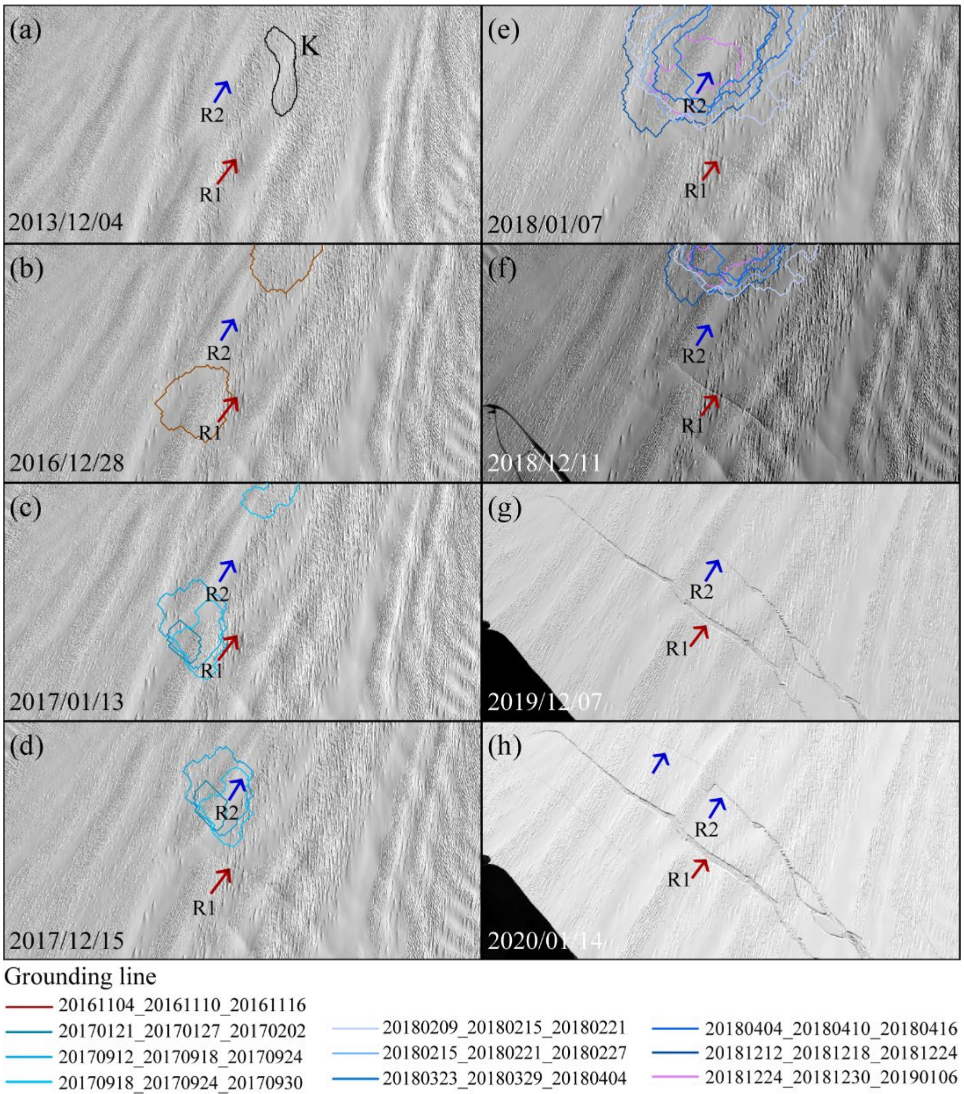

Figure 10. Rift propagation history from 2013 to 2019. (a)-(h) show the propagation history of the rifts R1 (red arrow) and R2 (blue arrow), which led to the 2020 calving event. The black circles indicate the positions of ice rumple K. Grounding lines are delineated based on the near-zero value of the double-differential vertical displacement.

4 Discussion (paragraph 5)

"In summary, our study demonstrates that ephemeral grounding at ice rumple L is modulated by the interaction between tidal forcing, ice shelf thickness, and evolving sub-ice geometry. These results provide new insights into the mechanisms driving ephemeral grounding behaviour. Notably, we find that the rift that caused the 2020 calving event appeared after pass through the ephemeral grounding region. Though we did not have enough images that could capture the whole process in 2017 and 2018, our results indicate that the ephemeral grounding events could cause the formation of the rifts. Arndt et al. (2018) further emphasized the importance of final pinning points in controlling calving line orientation, raising the possibility that ice rumple L may have acted as a final pinning point after the 2015 calving event, thereby influencing rift propagation and subsequent calving. These findings underscore the need for high-resolution ice shelf modelling to evaluate how ephemeral grounding affects stress redistribution and overall ice shelf stability."

5 Conclusion (paragraph 2 and 3)

"… We also show that the rifts responsible for the 2020 calving event appeared after the region passed through the ephemeral grounded area, suggesting that these ephemeral grounding events may have contributed to the formation of the rifts.

Our findings highlight the critical role of combining remote sensing and in situ ocean measurements to monitor grounding processes. The grounding lines derived from our DROT results provide valuable input for modelling work. We also underscore the need for high-resolution ice shelf modelling to assess how ephemeral grounding influences stress redistribution, calving dynamics, and the long-term stability of vulnerable ice shelves. In future, improved satellite coverage, denser SAR time series, and in situ ocean measurements will be essential to constrain short-lived grounding behaviours and their response to a changing climate."

Line 88: what is NCC?

Response 20: NCC is "normal cross-correlation coefficient". Th revised sentence is as follows:

"First, we retained only pixels with a normalized cross-correlation value greater than 0.05, which also used by Solgaard et al. (2021) to ensure reliable displacement measurements."

Line 168-175: this part reads repetitive and needs rewriting, no need to repeat everything listed in the table

Response 21: Thank you for this helpful suggestion. We have revised the section to provide a more concise summary of the key observations, eliminating repetitive details already covered in the table. The updated content is as follows:

"As shown in Table 2, the corrected REMA strips exhibited lower standard deviations compared to the uncorrected data, indicating reduced uncertainty. However, a consistent negative mean bias remained, with the corrected REMA elevations appearing systematically lower than those from ICESat-2.

This bias likely results from the differing measurement principles of the two satellite systems: CryoSat-2 (used for REMA correction) operates in the Ku-band and can penetrate the upper snowpack, whereas

ICESat-2 uses green laser altimetry, which reflects off the snow surface. As a result, CryoSat-2—and by extension, the corrected REMA strips—tend to report slightly lower surface elevations than ICESat-2, especially over snow-covered areas. Additional factors such as residual temporal offsets, snow accumulation variability, and surface roughness may also contribute. <u>Based on this comparison, we estimate the uncertainty of the corrected REMA strips as −1.93 ± 2.54 m, equivalent to 15.44 ± 20.32 m in floating ice thickness.</u>"

Line 174: how is this 3 m uncertainty derived?

Response 22: The ±3 m vertical displacement uncertainty was initially estimated from the mean difference between ICESat-2 elevations and the corrected REMA DSM. However, we have now revised this estimate to −1.93 ± 2.54 m, based on the total difference between the two datasets (see Response 21).

Figure 5:

1) Please label the location of ice rumple L in all subplots

Response 23: Revised (see response 2, 4, and 7).

2) Please provide a large zoomed-in map of the ice ridge, the current figure size makes it very difficult to distinguish this surface feature from neighboring surface undulations

Response 24: The zoom-in map is increased in revised Figure 8 (see Response 4 and 7).