Response to Reviewer #2

Dear **Reviewer#2**,

We sincerely thank you for your careful and constructive review of our manuscript, as well as for your positive and encouraging feedback. We have thoroughly addressed all the comments and implemented the corresponding revisions. Below, we provide a detailed, point-by-point response. Reviewer comments are shown in black, and our responses are presented in blue, with newly added or revised text indicated in **bold**. Some key sentences are underlined to highlight content directly related to your comments. We hope that these revisions improve the clarity and overall quality of the manuscript.

This study seeks to investigate the stability of the Northern Pine Island Ice Shelf, particularly in the context of the drivers of stability changes, including loss of pinning points and polynyas. The study presents observations to suggest that these factors have been driving observed changes to N-PIIS (e.g. velocity increases, ice shelf thinning). The observations the authors show are quite interesting and the connections between ocean conditions, atmospheric conditions, and ice shelf weakening is a nice, comprehensive look at the system. However, I found the study to be missing some rigorous links between the factors that the authors seek to establish and I think some further analysis and figures may be needed to enhance the takeaways for the reader.

Structural Weakening

The paper (as evidenced by the title) seeks to make the argument that N-PIIS is experiencing structural weakening. While I certainly agree that this is the case, I think there is more evidence that needs to be shown here to make this case. When I hear “structural” weakening, I generally think this implies changes to the stress state and the load-bearing ability of the ice shelf. However, as far as I can tell, the only evidence the authors show to suggest there is weakening is ice front retreat (and even so, the retreat on the N-PIIS is fairly small; would maybe be useful to quantify or contextualize this to the rest of the ice shelf), calving events (but is this increasing?) and the formation of a new rift (what is the impact on the ice shelf, though?). I am intrigued by the estimates of buttressing shown in Fig 1 and wonder if this could be used to strengthen this argument – can you show how buttressing ability of N-PIIS changes in time? This would make a possibly clearer and more persuasive argument that there is real weakening happening. As it stands, I’m not sure what the calving events, loss of pinning points, and rift formation means for the overall ice shelf except that as those things are happening, there is also acceleration (which I’m sure is related, but there is no link established here).

Response 1: Thank you for this insightful and constructive comment. We agree that the original manuscript did not provide sufficient evidence to fully support the argument of “structural weakening”.

We also agree that quantifying changes in buttressing over time would provide a clearer and more compelling demonstration of weakening. However, robust estimation of buttressing typically requires numerical modeling, which is beyond the scope of this study. To avoid introducing additional complexity, we instead strengthened our argument by incorporating more comprehensive remote sensing observations that directly capture structural and dynamic changes in the N-PIIS.

Specifically, we revised the figures and manuscript to include:

(1) a more detailed record of ice-front evolution, including quantified retreat and area anomalies to better contextualize changes relative to the broader ice shelf (see revised Figure 1 and Figure 4)

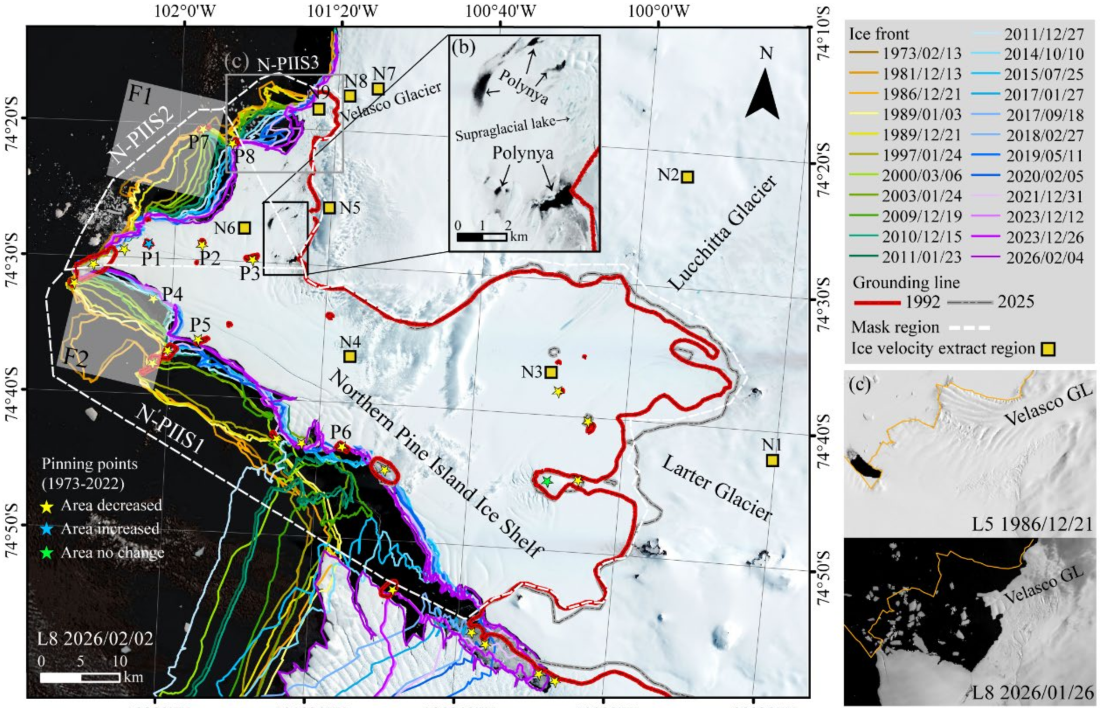

Figure 1. Location and geometry of the N-PIIS. (a) Overview map of the N-PIIS. The background is a Landsat-8 panchromatic image acquired on 2 February 2026, showing the extent of the northern ice shelf and its tributary glaciers. N-PIIS1, N-PIIS2, and N-PIIS3 denote ice-shelf masks used to calculate area anomalies. Points N1–N9 indicate locations of extracted ice velocity time series. Ice front positions were delineated from Landsat optical and Sentinel-1 SAR images, following Chien et al. (2025a, b). Grounding lines for 1992 (red) and 2025 (grey) are from Rignot et al. (2016) and Rignot et al. (2026), respectively. Changes in pinning points between 1973 and 2022 (stars) are from Miles and Bingham (2024). The black frame indicates the region shown in panel (b), while the grey frame outlines the region in panel (c). (b) Subregion highlighting polynya activity, with a Landsat-8 image acquired on 2 February 2026 as the background. (c) Ice-front changes at Velasco Glacier, comparing Landsat-5 imagery from 21 December 1986 and Landsat-8 imagery from 26 January 2026.

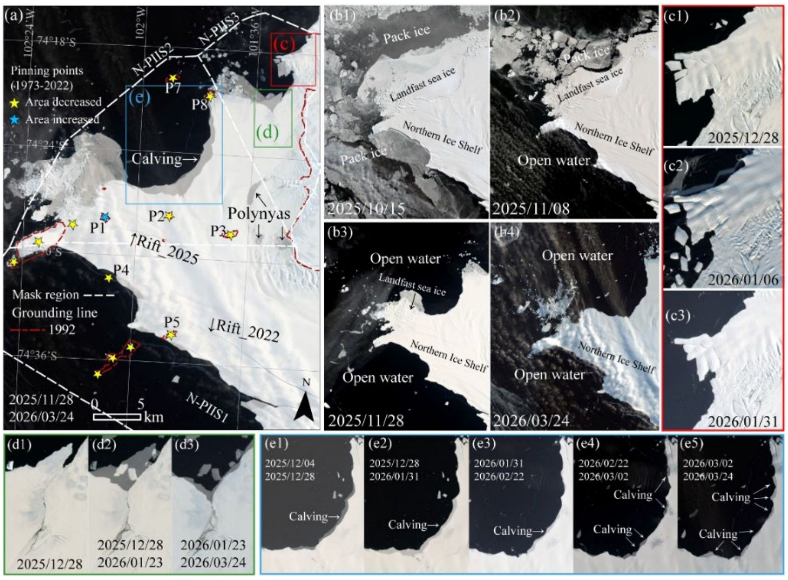

Figure 4. Overview of changes in the N-PIIS and its surrounding sea area from October 2025 to March 2026. (a) Changes in the area of the northern Pine Island Ice Shelf between 28 November 2025 and 24 March 2026. Pinning points (stars) are from Miles and Bingham (2024). The white dashed line indicates the ice-shelf mask. The 1992 grounding line is from Rignot et al. (2016). (b) Overview of fast-ice changes from 15 October 2025 to 24 March 2026. (c) Calving events at Velasco Glacier between 28 December 2025 and 31 January 2026. (d) Calving events at the N-PIIS between 28 December 2025 and 24 March 2026. (e) Calving events at the N-PIIS between 4 December 2025 and 24 March 2026. All optical satellite images used in this figure are from Sentinel-2.

(2) an expanded time series of DDInSAR interferograms (2017–2025) and ice bump changes in Landsat optical imagery (1997, 2003, 2007, and 2026) to document the progressive loss and modification of pinning points (see revised Figures 7, 8, 9, 12, and 13)

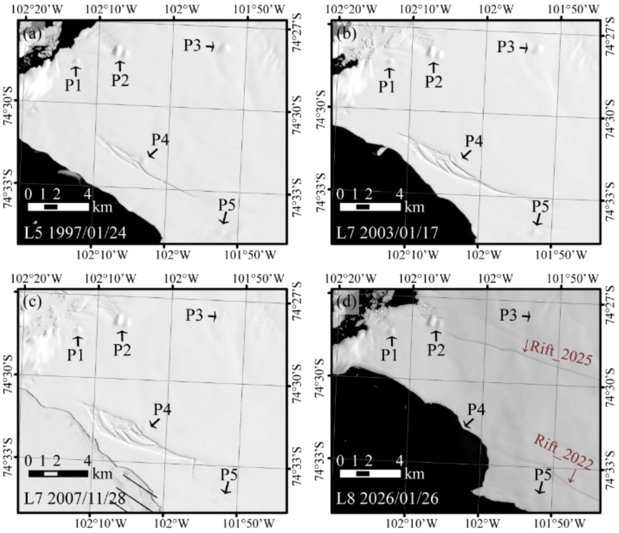

Figure 7. Changes in pinning points in Landsat imagery. Panels (a–d) show pinning-point conditions on 24 January 1997 (Landsat-5), 17 January 2003 (Landsat-7), 28 November 2007 (Landsat-7), and 26 January 2026 (Landsat-8), respectively.

Figure 8. Changes in pinning points P1–P5 derived from double-difference interferograms over the N-PIIS from 2017 to 2020. Panels (a–d) show results for 2017, 2018, 2019, and 2020, respectively.

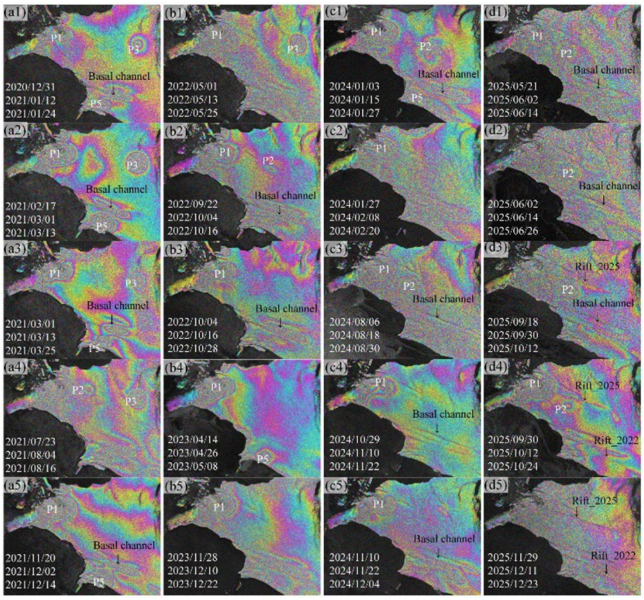

Figure 9. Changes in pinning points P1–P5 derived from double-difference interferograms over the N-PIIS from 2021 to 2025. Panels (a–d) show results for 2021, 2022, 2023, 2024, and 2025, respectively.

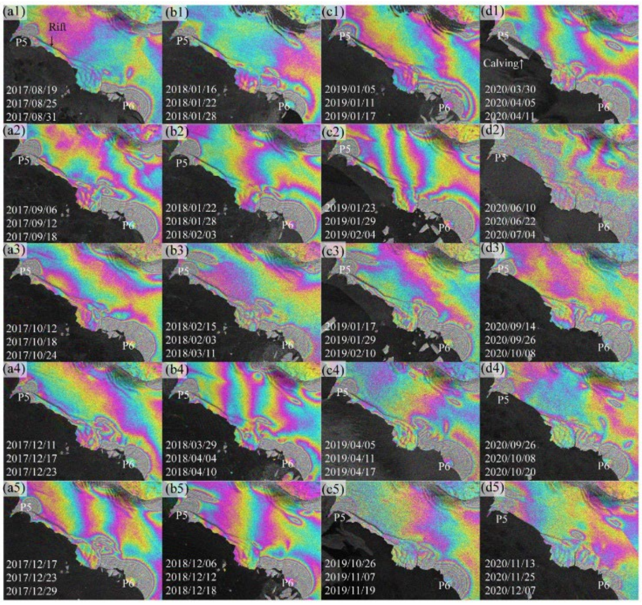

Figure 12. Changes in pinning points P5 and P6 derived from double-difference interferograms of the N-PIIS from 2017 to 2020. Panels (a–d) show results for 2017, 2018, 2019, and 2020, respectively.

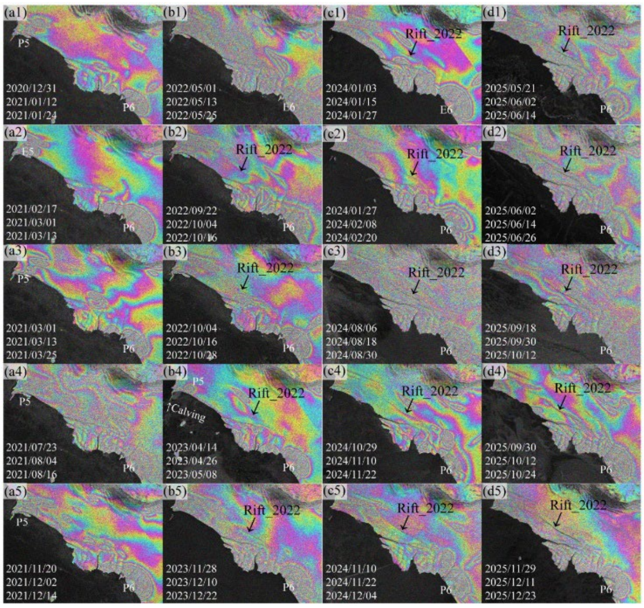

Figure 13. Changes in pinning points P5 and P6 derived from double-difference interferograms of the N-PIIS from 2021 to 2025. Panels (a–d) show results for 2021, 2022, 2023, 2024, and 2025, respectively.

(3) estimates of rift propagation rates to assess their development and potential impact (see revised Figures 10 and 11)

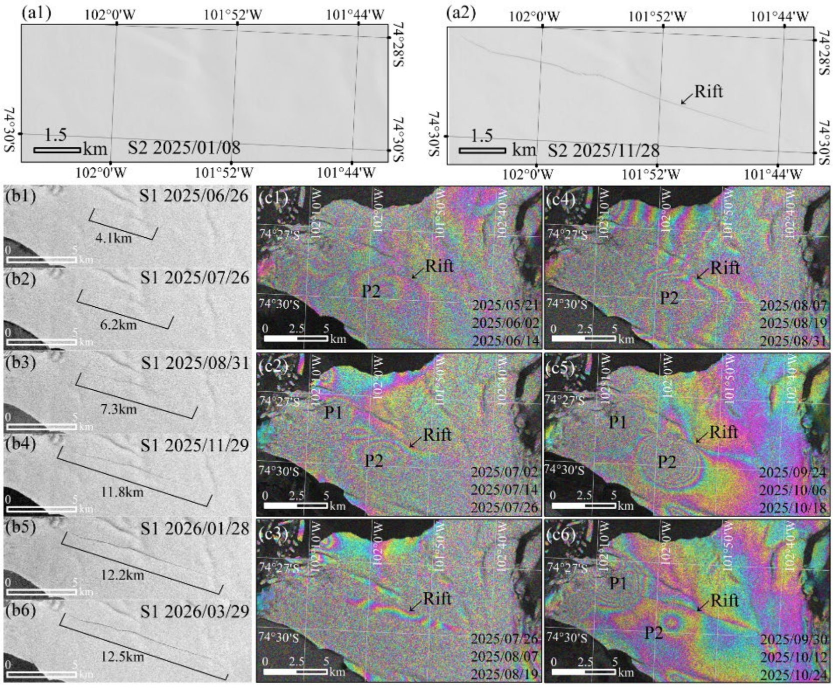

Figure 10. Development of the new rift in 2025 and corresponding double-difference interferograms. (a1) and (a2) Sentinel-2 images on 8 January 2025 and 28 November 2025, respectively. (b) Rift propagation from 26 June 2025 to 29 March 2026 derived from Sentinel-1 SAR imagery. (c) Double-difference interferograms from May to October 2025.

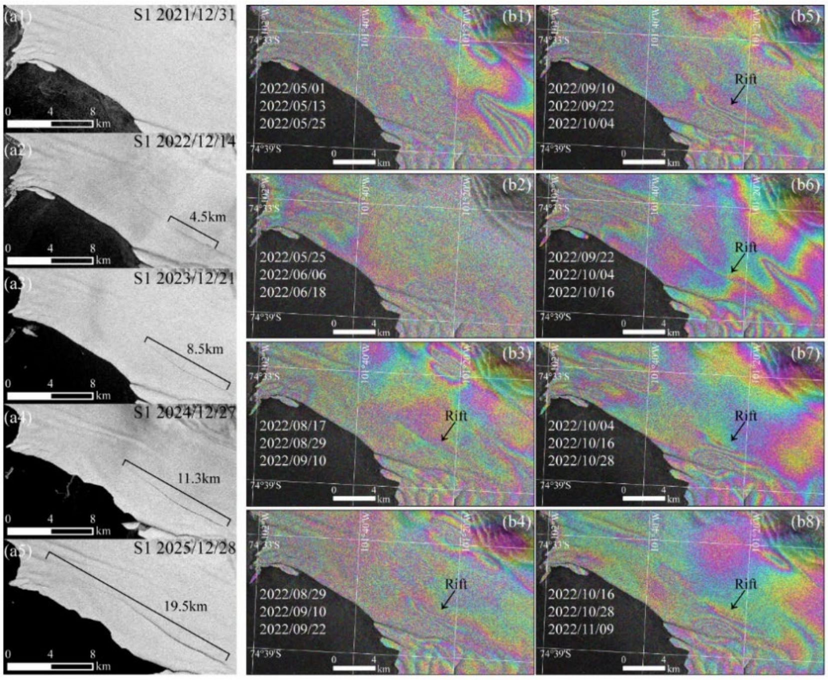

Figure 11. Development of the 2022 rift and corresponding double-difference interferograms. (a) Rift propagation from 31 December 2021 to 28 December 2025. (b) Double-difference interferograms from May to October 2022).

These additions allow us to better link observed processes (ice-front retreat, calving activity, pinning point degradation, and rift propagation) to changes in ice dynamics, including the observed acceleration. Our results show that the N-PIIS has undergone sustained retreat without recovery to its historical extent, alongside progressive weakening of pinning-point control. Although some pinning points remain, continued thinning and their potential loss are likely to further reduce buttressing, increasing the susceptibility of the ice shelf to enhanced retreat and possibly large calving events.

We have revised the manuscript to clarify these connections, thereby strengthening the overall argument for ongoing weakening of the N-PIIS.

Connection to Atmosphere/Ocean Conditions

This is a nice addition that makes this paper stand out from other PIIS-focused papers. However, I do think more needs to be done to convince readers of the link between these external conditions and the weakening of the ice shelf. I believe the authors seek to argue that the existence/persistence of the polynyas allows basal melt to more directly impact the ice shelf, thus driving some of the weakening. Can the authors actually mark on Fig. 5 and 6c where the polynyas are open, so we can see the link between the winds and the polynya existence? I see that surface elevations reduced near the polynyas but is there evidence that this had implications for the rest of the ice shelf? The link between the polynya existence and the ice shelf stability could be made more clearly and persuasively. Some more clarity on the polynya tracking would also be useful – the methods say that they are tracked in 2021, 2024, 2025 but the manuscript later discusses polynya evolution from 2003 (line 143).

Response 2:

Thank you for this thoughtful and constructive comment. We agree that the link between polynya activity and ice-shelf weakening was not sufficiently clear in the original manuscript and required stronger supporting evidence and clearer presentation.

We have revised Figures 5 and 6c to mark the timing of polynya openings, as also illustrated in the new Figure R1. Prior to the formation of polynyas in November 2021, several foehn wind events were observed (Fig. R1a). However, fewer such events occurred during the austral summer of 2021/2022, when the polynyas expanded (Fig. R1a). Although additional foehn wind events were detected during the austral winter of 2024, Sentinel-1 backscatter shows a gradual decrease during this period, suggesting that these wind events may have had a limited influence on the observed changes (Fig. R1b).

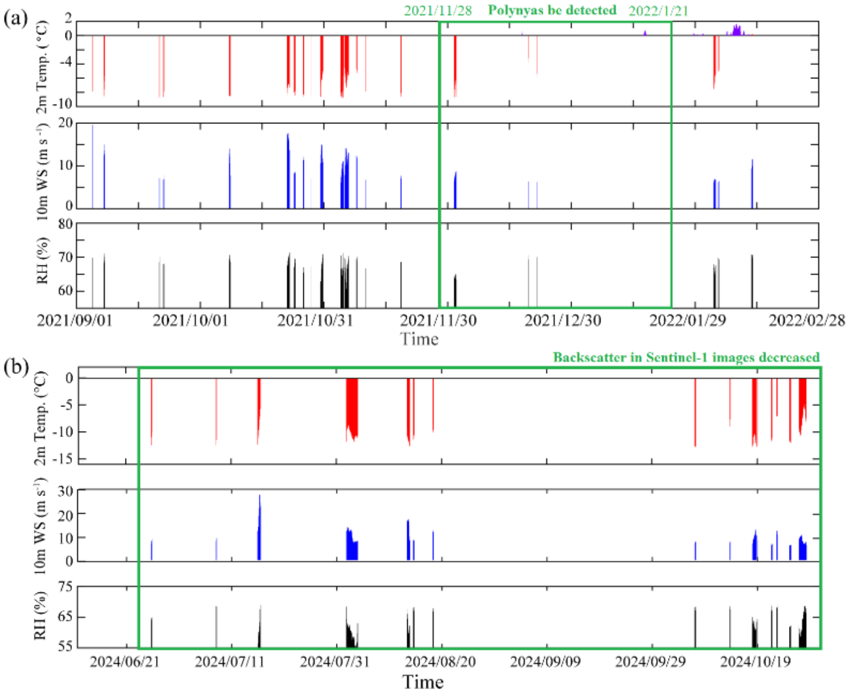

Figure R1. 2m temperature, 10 m wind speed (WS), and relative humidity (RH) time series in (a) 2021/2022 austral summer and (b) 2024 austral winter.

While these observations suggest a potential link between atmospheric and oceanic processes and polynya evolution, we recognize that a rigorous investigation of the underlying mechanisms is beyond the scope of this study, which focuses primarily on ice dynamic changes. To avoid overinterpretation and maintain a clear narrative, we have removed detailed discussions of foehn wind effects and ocean temperature variability. Instead, we strengthened the discussion by more explicitly linking polynya evolution with observed structural and dynamic changes of the ice shelf.

We have clarified the methodology for polynya tracking. Polynya extents (i.e., their spatial distribution and area) were manually delineated from optical satellite imagery, where they are clearly visible. While the Methods section previously emphasized observations from 2021, 2024, and 2025 due to data availability and image quality, the analysis has now been expanded to include polynya evolution since 2003, as well as surface conditions in 1986, 1989, and 1997. The manuscript has been revised to ensure consistency between the Methods and Results sections.

We revised the surface elevation analysis to show that localized thinning derived from ICESat-2 is most pronounced near polynya regions, while also extending beyond these areas, indicating a broader-scale thinning response across the ice shelf.

Other Comments

I think you can remove the second sentence, as it doesn't have much impact on the rest of the introduction.

Response 3: Revised. The second sentence in the Introduction has been removed.

Line 23: what does “change in ice-shelf grounding” mean?

Response 4: Thank you for pointing this out. The term “grounding” was ambiguous in this context. We have revised the sentence to explicitly refer to changes in the **grounding line position**.

Methods section – what specifically about the polynyas was tracked? Existence, size, shape, etc.? Why just consider rift propagation in 2025 and thinning in 2024?

Response 5: Thank you for this important comment. Polynya extents (i.e., their spatial distribution and area) were manually delineated from optical satellite imagery, where they are clearly identifiable.

In the original manuscript, we highlighted rift propagation in 2025 and thinning in 2024 because these represent the most recent and visually prominent changes in the N-PIIS. However, as also suggested by Reviewer #1, a more comprehensive temporal perspective is necessary.

Accordingly, we have expanded the analysis to include a longer observational record. We incorporated Landsat imagery dating back to 1986 to document changes in surface features (e.g., “ice bumps”) indicative of pinning-point evolution and ice thinning. In addition, we included a time series of DDInSAR interferograms from 2017 to 2025 to capture progressive changes in pinning points and rift development (see Response 1, Figures 7,8,9,12, and 13).

We also identified an additional rift that formed in 2022 and have included its evolution in the revised manuscript. Rift propagation rates are now quantified for both the 2022 and 2025 rifts (see Response 1, Figures 10 and 11).

Regarding the 2024 thinning event, this appears to be an anomalous signal observed during the austral winter of 2024. Based on our examination of seasonal data from 2016 to 2026, this feature is not present in other years, making it a unique event. We therefore retain and report it as a notable short-term thinning signal.

Line 239: “The observed combination…more vulnerable structural state” – what evidence is there for this?

Response 6: Thank you for highlighting the need for stronger supporting evidence. We have revised the manuscript to provide clearer and more comprehensive evidence for this statement.

1. Ice thinning: We incorporated surface elevation change data derived from ICESat-2 over a broader region (see revised Figure 6). These results show that thinning is not limited to areas near polynyas but occurs across a larger portion of the ice shelf. Changes in pinning points and surface features (e.g., ice bumps) further support ongoing thinning.

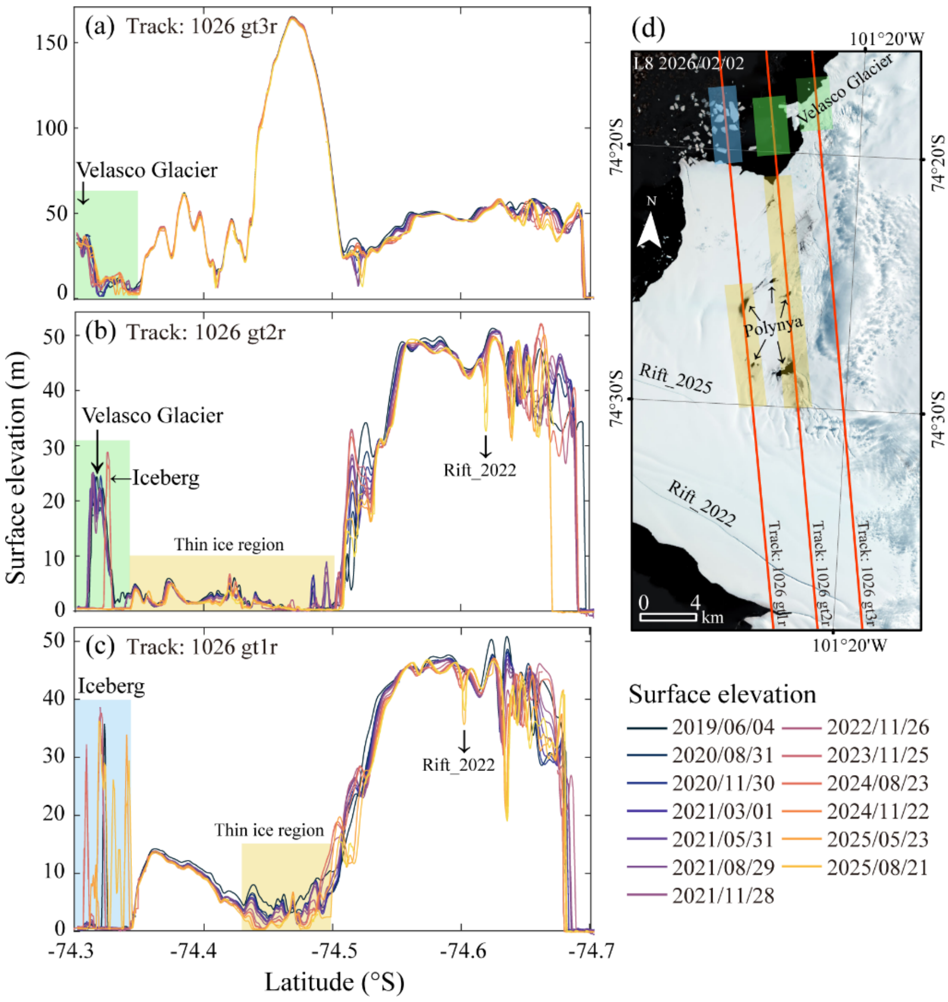

Figure 6. ICESat-2 ground tracks and surface elevation profiles at the N-PIIS. Panels (a–c) show surface elevation profiles along each beam over the latitude from 74.3°S to 74.7°S. Semi-transparent coloured bands highlight surface elevation over Velasco Glacier (green), thin-ice regions (yellow), and icebergs (blue). (d) Locations of the three strong beams (gt1r, gt2r, gt3r) from ICESat-2 track 1026. Coloured bands in (a–c) correspond to the same regions indicated in (d).

2. Pinning-point loss: We combined optical satellite imagery with DDInSAR interferograms (2017–2025) to document the progressive weakening and loss of pinning points (see Response 1, Figures 7,8,9,12 and 13).

3. Rift development: Both the 2022 and 2025 rifts formed in proximity to pinning points. We quantified rift lengths and found that the 2022 rift experienced accelerated propagation during 2025–2026, while the 2025 rift also exhibits rapid growth. These rifts are likely precursors to future calving events (see Response 1, Figures 10 and 11).

Together, these observations provide consistent and multi-source evidence that the ice shelf is undergoing structural degradation, supporting the interpretation of an increasingly vulnerable state.