

Response to Reviewer #1

Dear Reviewer#1,

We sincerely thank you for your further positive and encouraging feedback. We have thoroughly addressed all the remaining 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. The paragraph numbers and line numbers mentioned in the responses refer to the clear version of the file. We hope that these revisions improve the clarity and overall quality of the manuscript.

I am pleased to see this much improved revised paper and I think the authors have done a really good job in addressing the comments. In particular I am pleased to see much improved figures. I now think the manuscript is close to being ready for publication subject to a few smaller considerations below:

Line 58: I think the 15 m panchromatic images are only available from Landsat 7 onwards, 30 m for Landsat 4/5 and 60 m for Landsat 1.

Response 1: Thank you for pointing this out. We have revised the relevant content in Section 2.1 to clearly specify the Landsat imagery used in this study and their corresponding spatial resolutions.

Section 2.1, revised paragraph 2&3:

“To characterize the overall changes in the ice-front position of the N-PIIS, we extracted ice-front positions from 1973 to 1998 using Landsat-1 MSS Collection 2 Level 1 imagery (60 m spatial resolution) and Landsat-4/5 TM Collection 2 Level 1 imagery (30 m spatial resolution) downloaded from USGS EarthExplorer platform. The imagery was first geometrically corrected, and the RGB bands were composited to generate true-color images for subsequent manual delineation of the ice-front. From 1999 to 2025, ice-front positions were extracted through manual visual interpretation using Landsat-7/8/9 Collection 2 TOA panchromatic imagery (15 m spatial resolution) and Sentinel-1 IW GRD imagery (10 m spatial resolution) on the Google Earth Engine platform.

The overall extraction uncertainty was estimated as ± 1 pixel. Ice-front positions from 1973 to 1998 were derived from Landsat-1/4/5 imagery, with uncertainties of ± 60 m for Landsat-1 and ± 30 m for Landsat-4/5, whereas positions from 1999 to October 2014 were derived from Landsat-7/8/9 imagery, with an uncertainty of ± 15 m. From October 2014 to 2025, Sentinel-1 IW GRD imagery was used to obtain ice-front positions during the polar night, with an uncertainty of ± 10 m. To ensure consistency between the ice-front positions derived from different sensors, Landsat and Sentinel-1 imagery acquired during their overlapping observation period were compared and cross-checked, with particular attention

paid to observations acquired at similar times.”

Section 2.1, paragraph 5:

“Landsat-1 optical imagery (60 m) and Landsat-4/5/7/8/9 optical imagery (30 m) from Google Earth Engine, Sentinel-2 optical imagery (10 m) and Sentinel-1 SAR imagery (10 m) from the Copernicus Browser, were used to manually identify 80 calving events during the 2025/2026 austral summer, rift propagation in 2022 and 2025, and manually identify polynya evolution from 1986 to 2026.”

Line 67: resolution for Landsat 4/5 is different

Response 2: Revised. See Response 1.

Line 95: Unclear to me why this only goes to 2023 – what is the reason for this, it’s not consistent with the dates in other datasets (e.g. velocity). The ICESat-2 data is available up to 2026?.

Response 3: Thank you for pointing this out. We downloaded data covering the period from 2018 to 2026. After removing data with elevation error larger than 2m, we found that there were data gaps before June 2019 and in 2026. Therefore, we only present the results from 2019 to 2025. We have also revised the relevant description in Section 2.4 accordingly.

Section 2.4:

“Surface elevation changes were assessed using ICESat-2 ATL06 land-ice height data (Smith et al., 2019, 2023) **from 2019 to 2025.**”

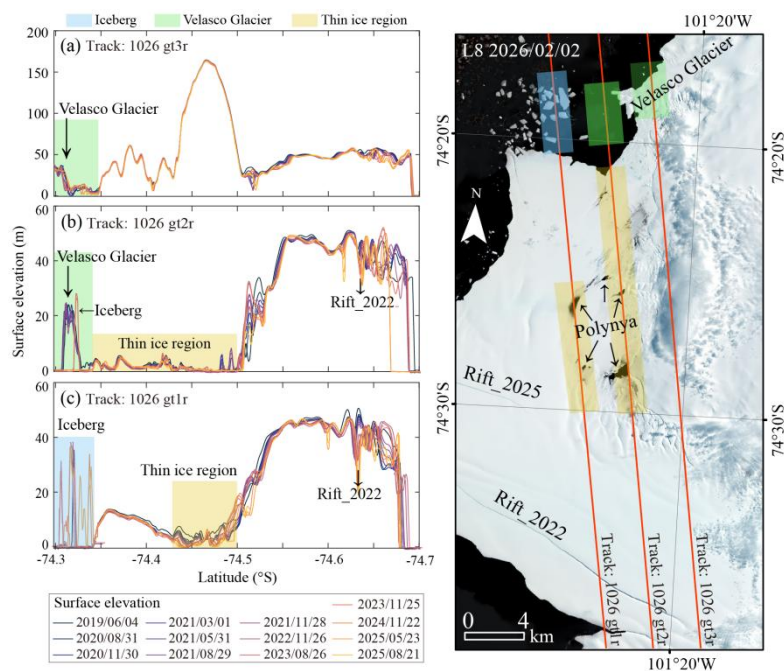


Figure 6. ICESat-2 ground tracks and surface elevation profiles at the N-PIIS. Panels (a–c) show surface elevation profiles along each beam over the latitude from 74.3°S to 74.7°S. Semi-transparent coloured bands highlight surface elevation over the Velasco Glacier (green), thin ice regions (yellow), and icebergs (blue). Panel (d) shows the

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).

Line 133 – figure number for N-PIIS2 and 3?

Response 4: Revised. The figure number for N-PIIS2 and 3 is Figure 4.

Section 3.1, line 146:

“The first occurred at the Velasco Glacier during 14–17 January 2022 (Fig. 3), and the second occurred at the N-PIIS2 and N-PIIS3 region after November 2025 ([Fig. 4](#)).”

Line 134- Surface melt pond or melting from below exposing a mix of sea-ice and ocean? Would be very odd to have a melt pond in September! If the polynya developed at the same location then more likely melting from below rather than surface melt.

Response 5: Thank you for pointing this out. We agree with your interpretation. The feature we previously labeled as a “melt pond” is located at the same location as the polynya. Therefore, we have revised the corresponding sentence as follows and removed the “melt pond” label from Figure 3.

Section 3.1, line 147:

“For the 2022 calving event at the Velasco Glacier, a rift was first observed in 14 September 2021, coinciding with the formation of ~~melt ponds on the fast ice, which later evolved into a polynya.~~”

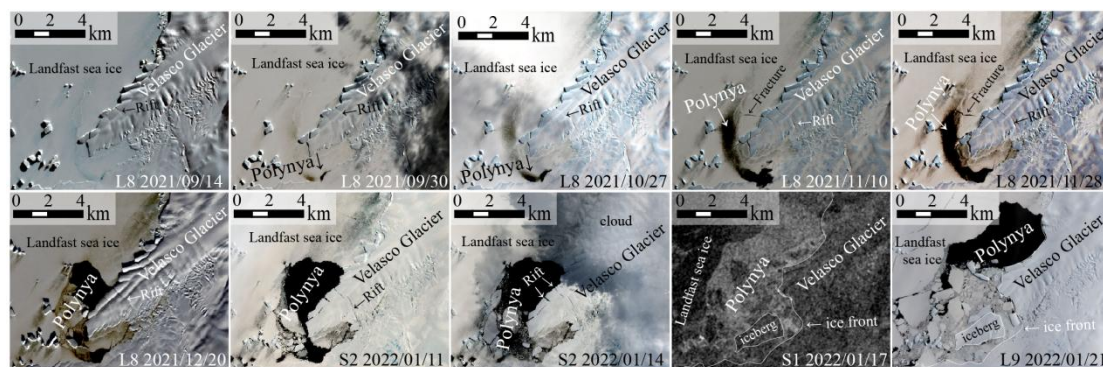


Figure 3. The 2022 calving event at the Velasco Glacier as documented by Landsat-8/9 and Sentinel-1/2 imagery from September 2021 to January 2022.

Figure 4 – where is panel B located?

Response 6: Thank you for pointing this out. We have revised the extent of Figure 4(a) to include Panel B.

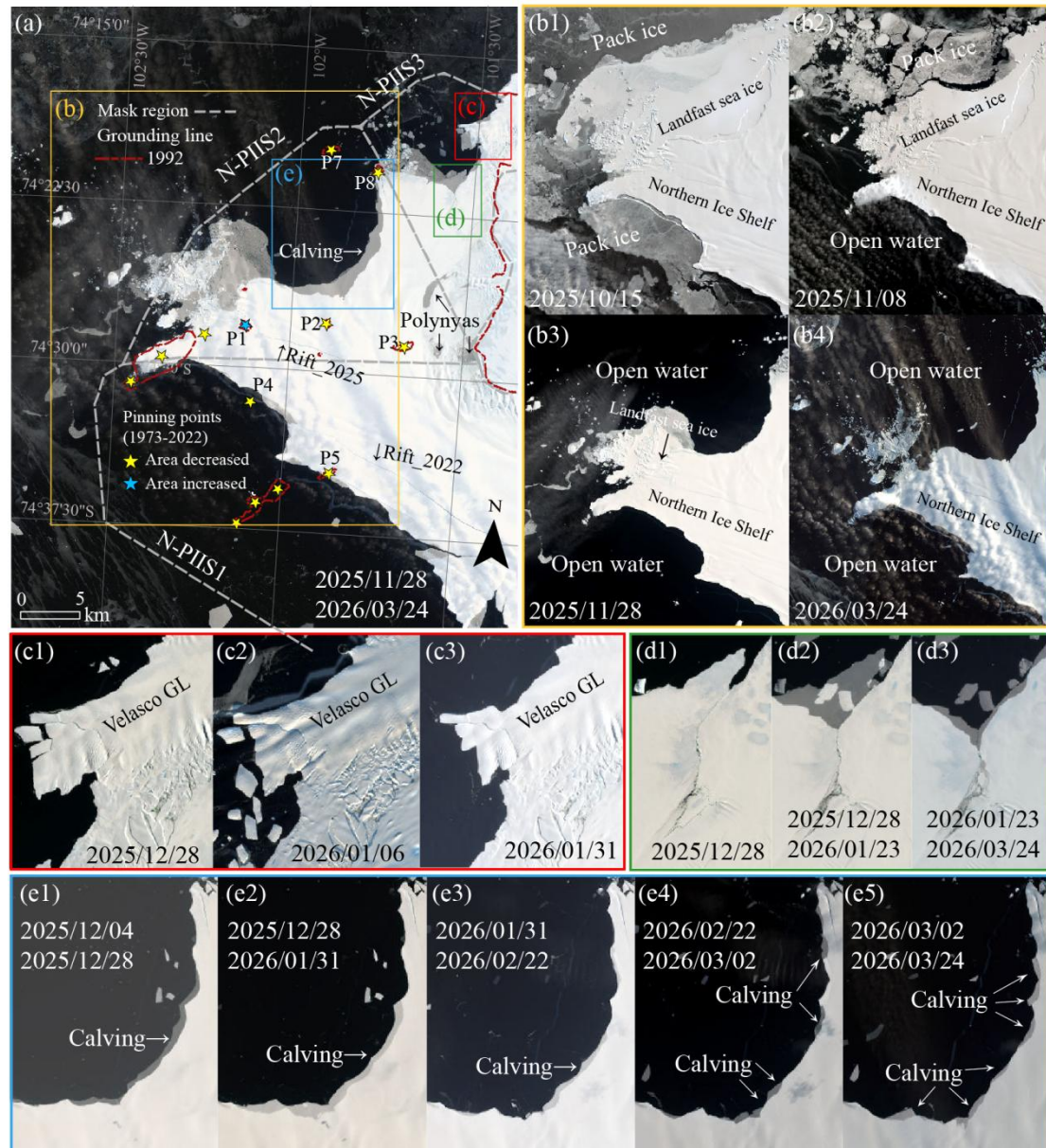


Figure 4. Overview of changes in the N-PIIS and its surrounding sea area from October 2025 to March 2026. (a) Changes in the area of the N-PIIS between 28 November 2025 and 24 March 2026. Pinning points (stars) are from Miles and Bingham (2024). The white dashed line indicates the ice-shelf mask. The 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 the 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.

Line 244-251: I think the link to fast ice is controversial, while plausible the argument it very one-sided and i think it needs to be restructured. There are also a load of other factors going on with changes in stresses at the pinning points, calving fronts, basal

melt. Simply linking this to fast ice is unsubstantiated. There have also been plenty of studies that show no link between fast ice extent and ice speed changes, so the evidence you provide to other regions is selective. See the below:

Surawy-Stepney, T., Hogg, A. E., Cornford, S. L., Wallis, B. J., Davison, B. J., Selley, H. L., Slater, R. A. W., Lie, E. K., Jakob, L., Ridout, A., Gourmelen, N., Freer, B. I. D., Wilson, S. F., and Shepherd, A.: The effect of landfast sea ice buttressing on ice dynamic speedup in the Larsen B embayment, Antarctica, *The Cryosphere*, 18, 977–993, <https://doi.org/10.5194/tc-18-977-2024>, 2024.

Miles, B. W. J., Stokes, C. R., Jenkins, A., Jordan, J. R., Jamieson, S. S. R., and Gudmundsson, G. H.: Slowdown of Shirase Glacier, East Antarctica, caused by strengthening alongshore winds, *The Cryosphere*, 17, 445–456, <https://doi.org/10.5194/tc-17-445-2023>, 2023.

Response 7: Thank you for this important comment. We agree that the relationship between landfast sea ice and ice-shelf change is complex, and that our original discussion placed too much emphasis on landfast sea ice without sufficiently considering other factors, including changes in stresses around pinning points, calving-front geometry, and basal melting. We also note that some studies have reported no clear relationship between landfast sea-ice extent and ice-shelf velocity. Therefore, we have restructured this part of the manuscript and substantially moderated our interpretation. The revised content is as follows:

Section 4.1, paragraph 3:

“At the Velasco Glacier, a polynya formed in October 2021, followed by a calving event at the glacier front in January 2022. However, no clear increase in ice velocity was observed following this event, suggesting that the associated loss of floating ice area did not substantially alter the buttressing of the grounded glacier at that time. In contrast, the area of N-PIIS3 decreased substantially after 2024, resulting in the loss of contact between the Velasco Glacier and N-PIIS3 (Movie S1). Ice velocity at the Velasco Glacier increased during the same period. This temporal correspondence suggests that the loss of the N-PIIS3 connection may have contributed to the observed velocity increase at the Velasco Glacier, although other factors may also have influenced its dynamic response. Further studies are needed to quantify the relative contributions of ice-shelf area loss, changes in pinning-point support, sea-ice conditions, and other factors to the observed changes in ice velocity.”

Line 258: It seems that the rift pattern and relation to pinning points has a strong resemblance to the processes occurring at Thwaites Eastern Ice Shelf, I think this could be worth a mention here. See the below for example:

Benn, D. I., Luckman, A., Åström, J. A., Crawford, A. J., Cornford, S. L., Bevan, S. L., Zwinger, T., Gladstone, R., Alley, K., Pettit, E., and Bassis, J.: Rapid fragmentation of Thwaites Eastern Ice Shelf, *The Cryosphere*, 16, 2545–2564, <https://doi.org/10.5194/tc-16-2545-2022>, 2022.

Response 8: Thank you for the suggestion. We have included this paper in our references and cited it in the revised manuscript.

Section 4.2, line 279:

“The loss of pinning points reduces local buttressing, alters internal stress distributions, and promotes rift propagation (Arndt et al., 2018; Benn et al., 2022). ”

Response to Reviewer #2

Dear Reviewer#2,

We sincerely thank you for your further positive and encouraging feedback. We have thoroughly addressed all the remaining 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**. Deleted words are shown in ~~bold-with-strikethrough~~. Some key sentences are underlined to highlight content directly related to your comments. The line numbers mentioned in the responses refer to the clear version of the file. We hope that these revisions improve the clarity and overall quality of the manuscript.

Thanks to the authors for addressing and replying to my earlier comments. Below I list some remaining comments but in general I think the revision addressed most of my concerns.

Structural Weakening

I appreciate the additions of the new observational figures, especially those focused on pinning point changes and rift propagation rates, which I do think help to make some links between observed changes and ice velocity changes (which point to more of the “structural changes” observation that the authors are making). That being said, my remaining comments are twofold.

First, I’m still not confident that the authors can make a “structural weakening” claim without a true stress-based analysis. In light of this, I would recommend altering the title to avoid the phrase “structural weakening” and instead point to acceleration/front retreat and the presentation of possible underlying mechanisms.

Response 1: Thank you for this thoughtful comment. We agree that the term “structural weakening” is not directly supported by our observations. To avoid the need for a stress-based analysis, we have therefore revised the title to **“Progressive Changes in Geometry and Dynamics of the Northern Pine Island Ice Shelf, West Antarctica,”** which more accurately reflects our observations and discussion of the possible underlying mechanisms.

I would also recommend avoiding language such as “Our results show an overall reduction in ice-shelf area...following the loss of buttressing from pinning points” (I don’t think the authors can make the claim that results show a loss of buttressing. Second, I would recommend the authors do a careful sweep of the paper to avoid a lot of causative language (e.g. line 181: “two representative calving events associated with sea-ice loss” – I don’t think just based on observations a casual link can be made; instead, the authors can point out that there were two calving events that occurred following sea-ice loss and this is a likely explanation).

Response 2: Thank you for the careful review and insightful comment. We have

revised the causative language throughout the manuscript, as detailed below.

Line 13-14: Our results show an overall reduction in ice-shelf area, with increased calving following the loss of ~~buttressing from~~ pinning points and reduced protection by landfast sea ice against ocean swell.

Line 18-19: ~~These changes suggest a progressive reduction in structural stability.~~

Line 35-39: “These observations raise the question of whether processes similar to those identified for the Conger–Glenzer, Wilkins, and Voyeykov ice shelves are also active at the N-PIIS, where ice-shelf thinning, loss of pinning points, and enhanced fracturing driven by ocean swell following regional sea-ice decline preceded rapid structural weakening and eventual collapse (Walker et al., 2024; Teder et al., 2025).” revised as **“The observations raise the question of whether processes similar to the changes reported by Walker et al. (2024) and Teder et al. (2025) are also active at the N-PIIS. Walker et al. (2024) and Teder et al. (2025) documented ice-shelf thinning, loss of pinning points, and enhanced fracturing at the Conger-Glenzer, Wilkins, and Voyeykov ice shelves, accompanied by regional sea-ice decline and increased exposure to ocean swell before rapid rift propagation and ice-shelf collapse. Whether a similar sequence of changes is occurring at the N-PIIS remains unclear.”**

Line 50-54: To address this, we present an observation-based analysis of recent ~~structural and~~ dynamic changes of the N-PIIS. Rather than attributing changes to a single forcing mechanism, we document co-evolving ice-front retreat, grounding conditions, thinning signals, and polynya occurrence. We focus on the key phenomena that related to rapid collapse event, including the ice front retreat, the evolution of rifting and pinning points, and the changes of landfast sea ice. Together, these observations provide new insights into the evolving **changes stability** of the N-PIIS-~~and its susceptibility to future structural weakening.~~

Line 145: Here we present two representative calving events ~~associated with that occurred following~~ sea-ice loss (particularly landfast sea-ice loss).

Line 245-248: This relationship is further supported by the 2021 calving event at the Velasco Glacier, ~~associated with which occurred following~~ polynya formation and landfast sea-ice breakup (Fig. 3), as well as ~~by~~ calving events between November 2025 and March 2026 ~~link to that followed~~ the loss of landfast ice in the N-PIIS2 and N-PIIS3 regions (Fig. 4).

Line 260-268: At the Velasco Glacier, a polynya formed in October 2021, followed by a calving event at the glacier front in January 2022. However, no clear increase in ice velocity was observed following this event, suggesting that the associated loss of floating ice area did not substantially alter the buttressing of the grounded glacier at that time. In contrast, the area of N-PIIS3 decreased substantially after 2024, resulting in the loss of contact between N-PIIS3 and the Velasco Glacier (Movie S1). Ice velocity at the Velasco Glacier increased during the same period. This temporal correspondence suggests that the loss of the

N-PIIS3 connection may have contributed to the observed velocity increase at the Velasco Glacier, although other factors may also have influenced its dynamic response. Further studies are needed to quantify the relative contributions of ice-shelf area loss, changes in pinning-point support, sea-ice conditions, and other factors to the observed changes in ice velocity.

Line 271-276: The loss of pinning points and the formation of a polynya within the ice shelf are consistent with regional thinning and may have facilitated the progressive disconnection of the ice shelf from the grounded ice sheet. The formation of a polynya may alter local air-ocean heat exchange and indicate enhanced oceanic heat reaching the surface, potentially contributing to ice-shelf basal melt and fracture (Savidge et al., 2023). The presence and distribution of pinning points near both ends of the rifts that developed in 2022 and 2025 may indicate changes in the interaction between the ice-shelf base and the underlying bedrock (Figs. 7-13).

Savidge, E., Snow, T., & Siegfried, M. R. Multi-decadal record of sensible-heat polynya variability from satellite optical and thermal imagery at Pine Island Glacier, West Antarctica. *Geophys. Res. Lett.*, 50, e2023GL106178. <https://doi.org/10.1029/2023GL106178>, 2023.

Line 282-288: The observed ice thinning, loss of pinning points, and propagation of new rifts suggest that the N-PIIS may be undergoing changes that could decrease its stability to further dynamic evolution. Although large-scale collapse has not yet occurred, continued thinning and the loss of pinning points may influence ice-shelf stability, while changes in sea-ice conditions may alter the exposure of the ice-shelf front to ocean swell and associated flexural stresses, potentially affecting further rift propagation and ice-shelf calving. Sustained satellite observations, together with in situ measurements and numerical modelling, are therefore needed to better constrain the relative contributions of these processes and assess the potential for further rift propagation and large-scale ice-shelf change.

Line 290-291: Using satellite imagery and datasets, we investigated recent changes in the N-PIIS and ~~identified documented~~ ongoing ~~structural weakening, as well as the processes linking~~ calving, thinning, and ungrounding ~~conditions~~.

Line 292-293: Polynya formed within the ice shelf may promote disconnection from the ice sheet ~~and reduce lateral buttressing~~.

Line 295: ~~These findings suggest that the structural integrity of the N-PIIS is weakening.~~

Connection to Atmosphere/Ocean Conditions

The revisions to this side of the paper addressed all of my concerns.

Figures:

Figure 2:

- Please define “area anomaly” (anomaly from what?)
- In plot (b), the y axes are different for each location, which makes comparison hard. I would standardize.

Response 3: Thank you for these constructive comments. We previously described the calculation of area anomalies in the second paragraph of Section 2.1 as follows: “Ice-shelf area anomalies were calculated by subtracting the mean area of the full time series from each individual observation.” Based on your comment regarding panel (b), we revised the method for calculating **the percentage area loss**. Accordingly, the sentence in Section 2.1 has been revised as follows: “**Percentage area loss for each observation was calculated relative to the maximum area in the full time series.**”

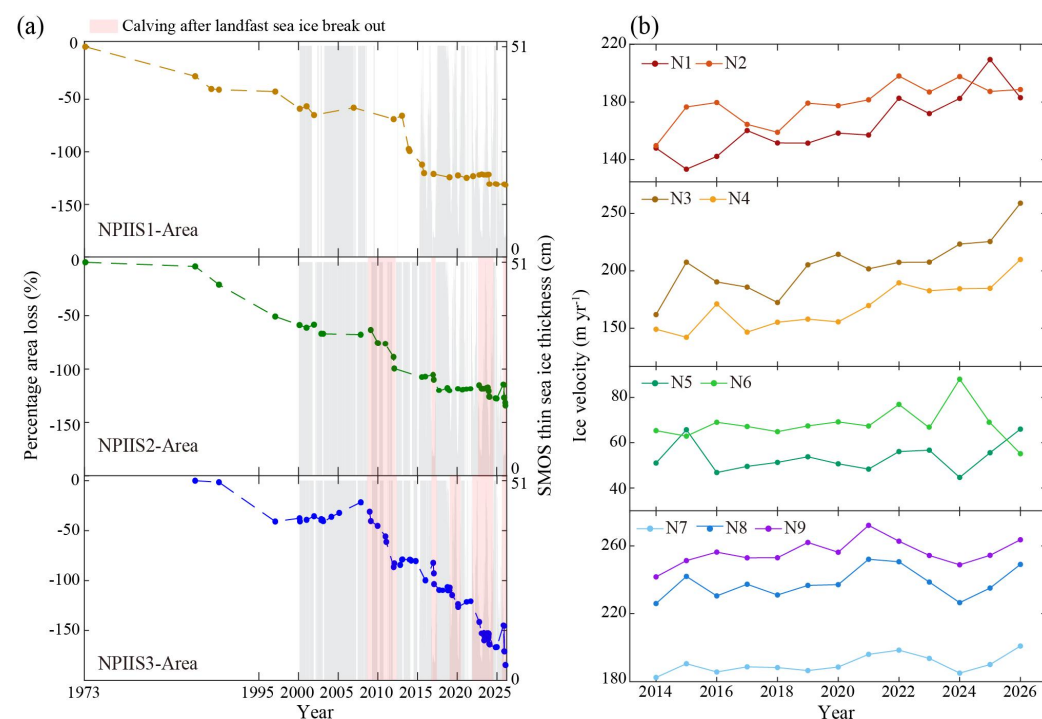


Figure 2. Time series of percentage area loss, SMOS thin sea-ice thickness, and ice velocity. (a) **Percentage area loss** time series for the N-PIIS from 1973 to 2026, together with SMOS thin sea-ice thickness from 2000 to 2026. Blue bars represent SMOS thin sea-ice thickness, and red frames denote calving events that occurred following landfast sea-ice breakup. (b) Ice velocity time series at locations N1–N9.

- The blue bars are a bit distracting; can sea ice thickness be plotted as a line plot on top of this figure?

Response 3: We changed the color of the blue bars and increased their transparency to reduce visual distraction. Please see the revised Figure 2 in Response 2.