Response to Reviewer #1

Dear Reviewer#1,

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.

Overview

The manuscript by Chien and others reports on remotely sensed observations on changes in the dynamics of the Northern Pine Island Ice Shelf and the glaciers that feed the ice shelf. The Northern Ice Shelf detached from the main ice shelf in 2015 and is now its own independent ice shelf. The Northern Ice Shelf is small and is fed by some very small glaciers in the context of the Antarctic Ice Sheet, thus the future of the ice shelf its self is rather inconsequential for sea level rise. That said, it is located in a very important region and observations of recent changes may help to improve regional understanding of ice-ocean interaction. While there are some nice observations, I feel substantial revisions are required before publication in The Cryosphere can be considered. At times this manuscript is difficult to follow because the dates don't match up i.e. the authors mention that an analysis is carried from x date, but then the results show a different date. I also found the section on the polynyas confusing and it is still a little unclear to me what you are trying to convey to the reader with these observations. I have included some more detailed comments below.

Major Comments

1. **Pinning points/structural weakening:** I am missing an overview figure showing the structural evolution of the northern ice shelf over time. Imagery exists since 1973 and I think it would be beneficial if you could show some snapshots through time. This way the reader can visualize these structural changes and pinning point changes that are sometimes visible in optical imagery. Part of the problem with this manuscript as the moment is that you conclude that the Northern Ice Shelf is undergoing progressive structural weakening, but don't actually show any evidence of this change through time. The DINSAR fringes are nice, but only show a small part of the ice shelf at one period in time. Also could the apparent ungrounding be linked to tides?

Response 1: Thank you for this insightful comment. We have revised the figures and added additional imagery to better illustrate structural changes in the N-PIIS. Specifically, we included the calving events in December 2025 to reveal the recent ice front changes (see revised Figure 4).

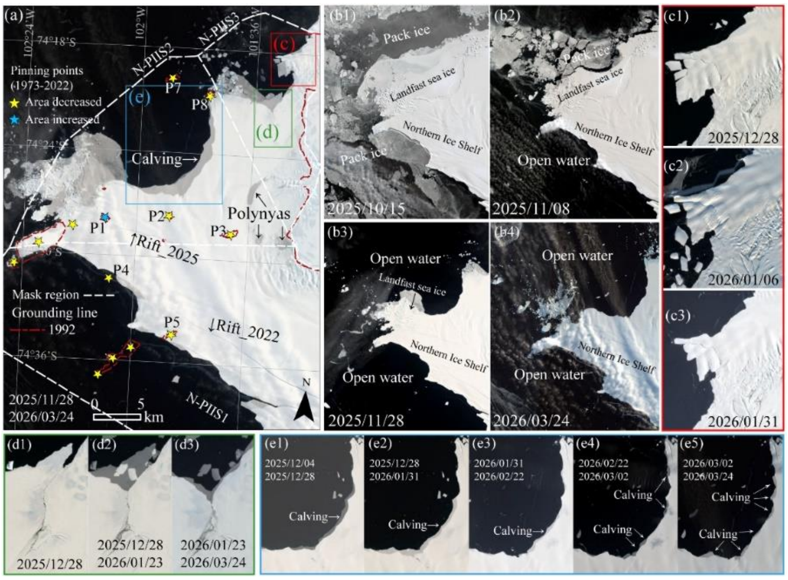

Figure 4. Overview of changes in the N-PIIS and its surrounding sea area from October 2025 to March 2026. (a) Changes in the area of the N-PIIS between 28 November 2025 and 24 March 2026. Pinning points (stars) are from Miles and Bingham (2024). The white dashed line indicates the ice-shelf mask. The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

We included Landsat optical images that reveal the ice bump changes which represent pinning point changes in 1997, 2003, 2007, and 2026(see revised Figure 7).

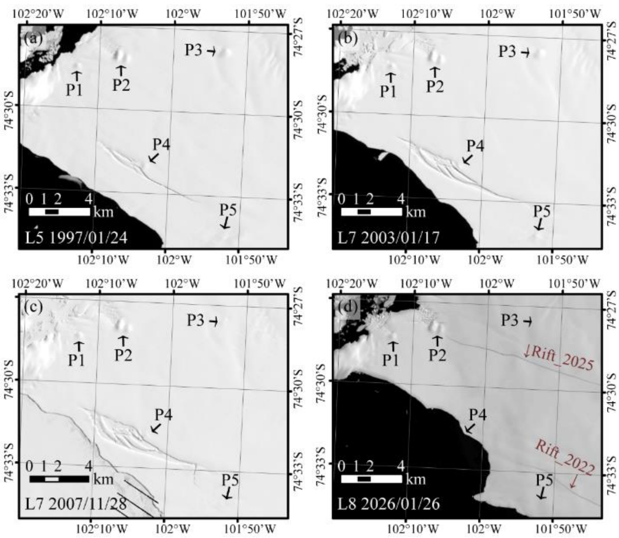

Figure 7. Changes in pinning points in Landsat imagery. Panels (a–d) show pinning-point conditions on 24 January 1997 (Landsat-5), 17 January 2003 (Landsat-7), 28 November 2007 (Landsat-7), and 26 January 2026 (Landsat-8), respectively.

We also included a time series of double-difference interferograms from 2017 to 2025 to highlight changes in pinning points (see revised Figures 8, 9, 12, and 13). We agree that double-difference interferograms are influenced by tidal effects, and that incorporating a time series helps distinguish long-term changes from tidal variability and ice-shelf thinning.

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.

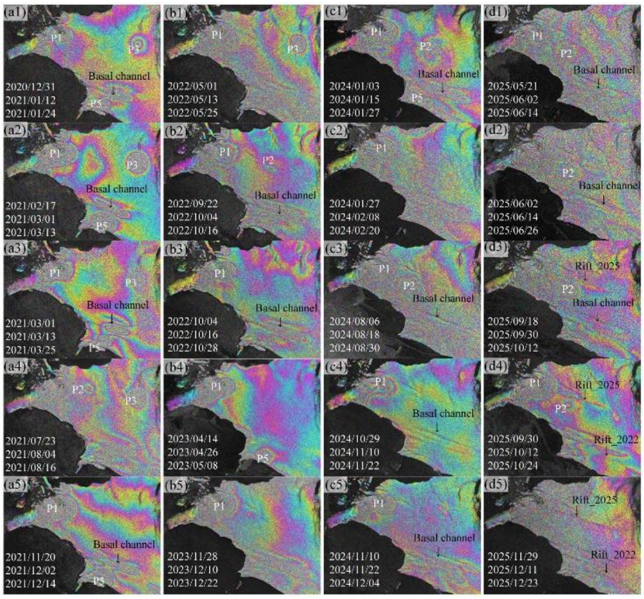

Figure 9. Changes in pinning points P1–P5 derived from double-difference interferograms over the N-PIIS from 2021 to 2025. Panels (a–d) show results for 2021, 2022, 2023, 2024, and 2025, respectively.

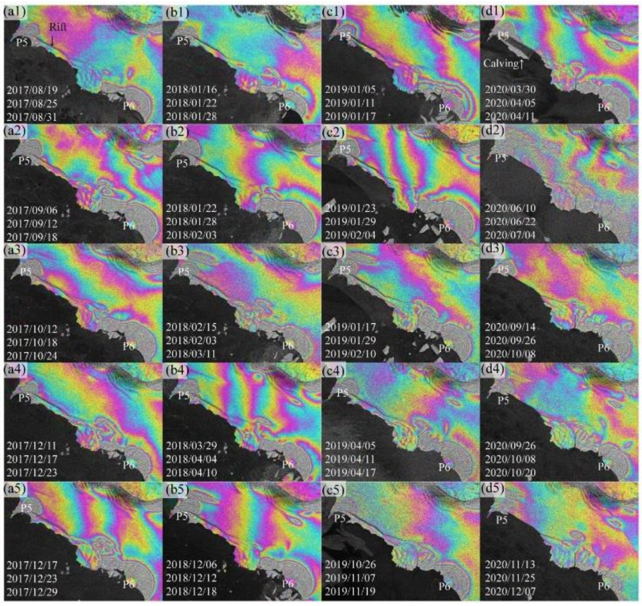

Figure 12. Changes in pinning points P5 and P6 derived from double-difference interferograms of the N-PIIS from 2017 to 2020. Panels (a–d) show results for 2017, 2018, 2019, and 2020, respectively.

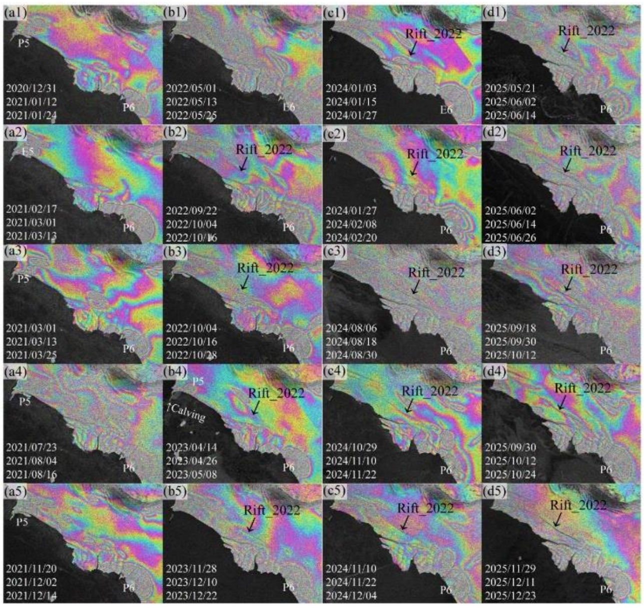

Figure 13. Changes in pinning points P5 and P6 derived from double-difference interferograms of the N-PIIS from 2021 to 2025. Panels (a–d) show results for 2021, 2022, 2023, 2024, and 2025, respectively.

2. **Ice velocity:** what are the large spikes on the ice velocity record. Are these erroneous results or do they reflect something more geophysical? This needs to be addressed?

Response 2: Thank you for pointing this out. These anomalies are erroneous. Due to the low ice velocity in the N-PIIS, uncertainties are relatively large in this region in our Sentinel-1 derived ice velocity product. To clearly reveal the velocity change, we replaced the dataset with the ITS_LIVE annual composite ice velocity product (see revised Figure 2). Annual composite ice-velocity data (2014–2026) were obtained from the ITS_LIVE web map interface (https://its-live.jpl.nasa.gov/app/index.html; last access: April 2026), which enables interactive exploration of glacier velocity time series at any location on earth (Fahnestock and Dow, 2023; Gardner et al., 2025). Users can query geographic coordinates or select points on a map to retrieve full velocity records at specified locations. Annual composite velocities were extracted following the method of Gardner et al. (2025), in which all input velocity data are first smoothed using a 15-point moving window filter. A coefficient matrix is then constructed to represent the fractional contribution of each image pair to individual years, allowing least-squares estimation of annual mean velocities. Weighting is defined as the inverse square of displacement uncertainty (velocity error × time interval), and annual velocities are derived from an error-weighted least-squares fit of all valid observations.

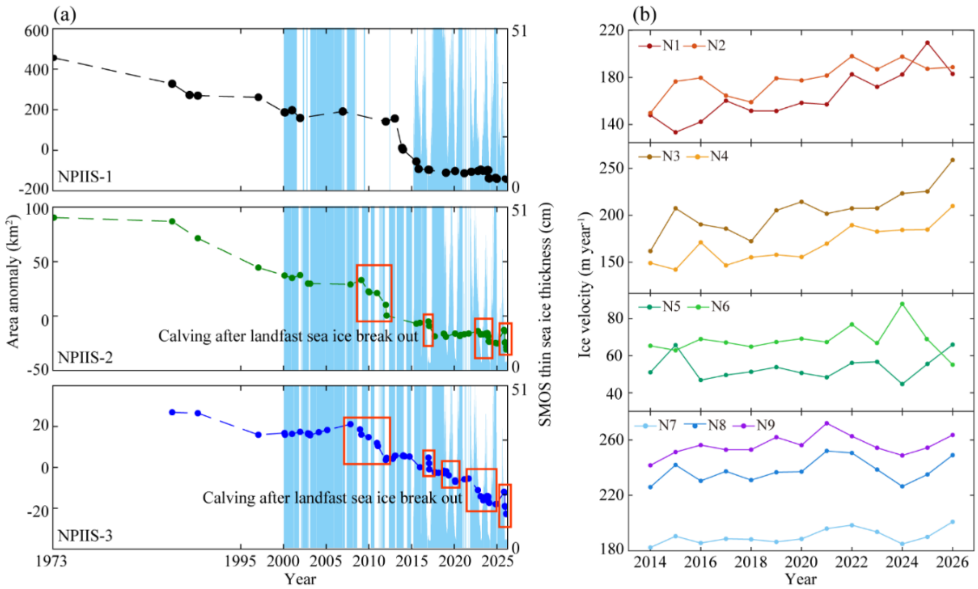

Figure 2. Time series of area anomalies, SMOS thin sea-ice thickness, and ice velocity. (a) Area anomaly time series for the N-PIIS from 1973 to 2026, together with SMOS thin sea-ice thickness from 2000 to 2026. Blue bars represent SMOS thin sea-ice thickness, and red frames denote calving events that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

3. **Ice front:** You mention since 1973 in some parts of the manuscript, but you do not provide any observations since 1973? The methods says 1997-2025, but figure 1 goes from 1989-2023? Please sort out these inconsistencies.

Response 3: Thank you for your suggestion. We have revised Figure 1 to include additional observations prior to 1997, providing a clearer depiction of historical ice front changes in the N-PIIS (see revised Figure 1).

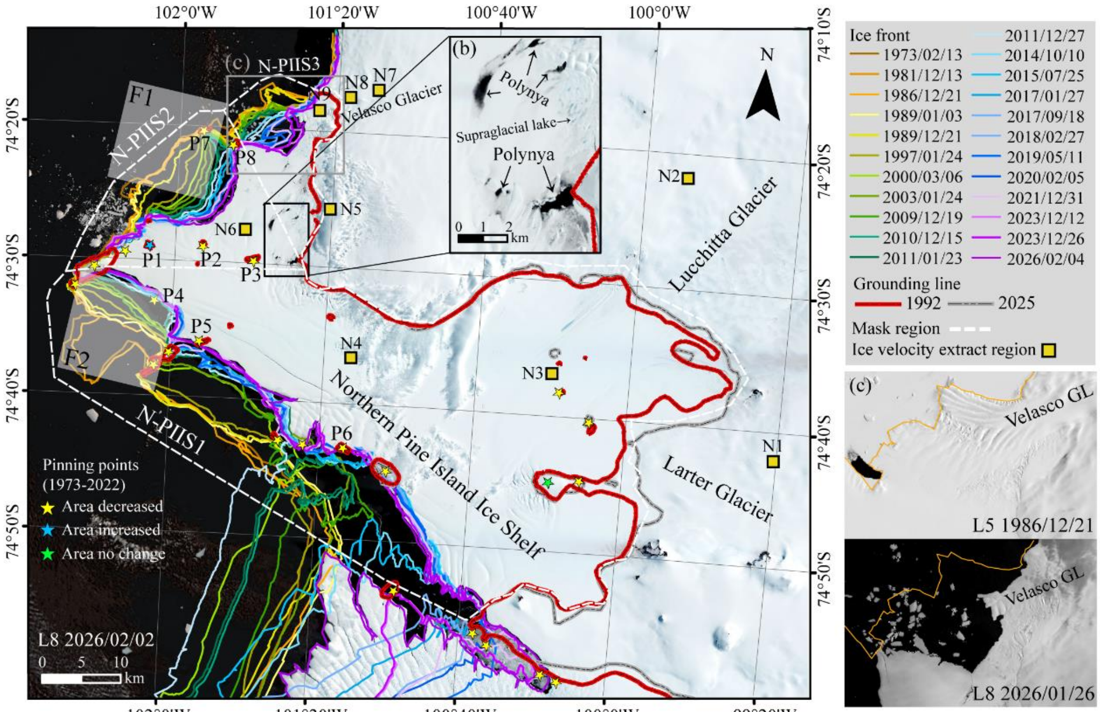

Figure 1. Location and geometry of the N-PIIS. (a) Overview map of the N-PIIS. The background is a Landsat-8 panchromatic image acquired on 2 February 2026, showing the extent of the northern ice shelf and its tributary glaciers. N-PIIS1, N-PIIS2, and N-PIIS3 denote ice-shelf masks used to calculate 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.

4. **Polynyas:** Overall I found this analysis confusing and difficult to follow. This section is written as if the authors are arguing that the occurrence of polynya means that something has changed and there is now more basal melt. I agree that the polynyas could be formed by channels of basal melt, this is a well known process and has been studied in detail – see Alley et al 2016 – an important paper in the context of this analysis. However, I do not understand how any temporal changes can be reliably linked to any type of forcing with the observations the authors present. Firstly, it is not clear how you are actually measuring the size/occurrence of these polynyas. You mention in the methods you only track polynya development in 2021, but then highlight some going back to 2003 – presumably there are other occurrences you simply have not been able to observe, for example in the winter? You also mention that there are more polynya activity when there is strong fast ice, this makes sense, by nature sea-ice is required for polynya formation.

Presumably the underlying cause of the polynya formation (basal melt) is still happening when the sea ice is not present.

Response 4: Thank you for this important comment. We agree that the previous description of polynyas lacked clarity. Polynya extents were manually delineated from optical satellite imagery, where they are clearly visible. Our observations indicate that polynya areas expanded notably during 2021–2022 and 2025–2026. We also identified a backscatter reduction event in austral winter 2024 in the same region, which may be associated with ice-shelf thinning.

However, we recognize that a comprehensive analysis of polynya formation and evolution would require a dedicated investigation. Therefore, we have removed discussions related to atmospheric and oceanic forcing and retained only the analysis directly relevant to polynya evolution and its potential impact on ice-shelf stability.

5. **Methods:** Please make the methods section consistent with what you actually show. There are numerous instances of the dates not matching up which creates some confusion.

Response 5: Thank you for pointing this out. We have carefully revised the Methods section to ensure that all reported dates are consistent with the results.

Line comments

Line 12: There are no data from 1973 in this manuscript???

Response 6: Revised. We have added the 1973 ice front position to the updated Figure 1 (see Response 3).

Line 15: 'three polynyas have developed around the ice shelf, suggesting enhanced ocean-ice interaction' – the manuscript shows some polynya developing sporadically since 2021. But this is not enough to say 'enhanced ocean-ice interaction' those polynyas could have been there for decades.

Response 7: Thank you for your suggestion. The abstract has been revised accordingly.

Line 18: it is unclear how the ice shelf can have an increased sensitivity to ocean and atmospheric forcing

Response 8: Thank you for pointing this out. We have removed the sentence in question and revised the abstract.

Line 30 – could you show the basal melt rates, is there are dataset available for this ice shelf?

Response 9: Several basal melt rate datasets are available for the Pine Island Ice Shelf. We compared products from Paolo et al. (2023) and Adusumilli et al. (2020), as shown in Figure R1. Both datasets indicate that basal melt rates in the northern ice shelf are generally less than 1 m yr^{-1}, compared to values exceeding 20 m yr^{-1} in the central region. However, no datasets cover the full period from 2018 to 2026, which is required for this study. Therefore, we have removed this discussion from the Introduction.

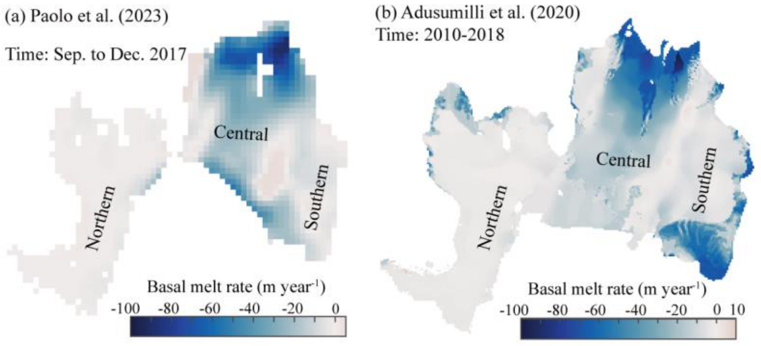

Figure R1. Basal melt rate at the Pine Island Ice Shelf. (a) Basal melt rate from Paolo et al. (2023). (b) Basal melt rate from Adusumilli et al. (2020).

Adusumilli, S., Fricker, H.A., Medley, B. et al. Interannual variations in meltwater input to the Southern Ocean from Antarctic ice shelves. Nature Geoscience, 13, 616–620 (2020). https://doi.org/10.1038/s41561-020-0616-z

Paolo, F. S., Gardner, A. S., Greene, C. A., Nilsson, J., Schodlok, M. P., Schlegel, N.-J., and Fricker, H. A.: Widespread slowdown in thinning rates of West Antarctic ice shelves, The Cryosphere, 17, 3409–3433, https://doi.org/10.5194/tc-17-3409-2023, 2023.

Line 31 – the ice shelf lost 25% of its area? An Ice shelf can only retreat by distance, not a percentage.

Response 10: Thank you for pointing this out. The sentence has been revised for clarity.

“Over recent decades, the region has experienced substantial frontal retreat. The ice-shelf area decreased by 13.3% in 1992 (relative to 1966), 16.7% in 1996, and 27.2% in 2000, with the 1996–2000 reduction being three times that of 1992–1996, indicating an accelerating retreat rate (Rignot, 2002).”

Line 50: if they are increasingly recognized then you need to provide citations to show this.

Response 11: Thank you for your comment. We have removed sections related to polynyas and basal melting where they focused on thermodynamic processes. As this study emphasizes ice dynamic changes, we now focus on observations derived from remote sensing and exclude discussions of atmospheric and oceanic forcing.

Line 51: ocean circulation – please delete. The ocean circulates everywhere to some degree!

Response 12: Revised.

Line 66-67: Elsewhere in the manuscript 1973 is mentioned. In Figure 1 there is an ice front position from 1989. This is confusing. If the imagery in 1973 is available, which I think it is, then I think you should present it.

Response 13: Revised. Revised Figure 1 has been updated to include the ice front position from 13 February 1973. Because the 1973 imagery does not cover the Velasco Glacier, we supplemented it with imagery from 1986 (see Response 1 and 3).

Line 73-75: You present other observations of polynyas later in the manuscript going back to 2004

Response 14: Thank you for pointing this out. Polynya prior to 2004 were also manually delineated.

Line 81: Please use ±0.25

Response 15: Thank you for this valuable comment. We have replaced the ice velocity dataset with the ITS_LIVE annual composite product. Due to the low velocities in the N-PIIS, offset tracking using 6- or 12-day Sentinel-1 data introduced significant uncertainties, resulting in spurious spikes. The annual composite dataset provides a more reliable representation of long-term changes from 2014 to 2026.

Line 90: were they corrected for firn content?

Response 16: Due to the coarse spatial resolution of the NASA GSFC-FDM v1.2.1 firn air content product (27 km × 27 km; Medley et al., 2022), we estimated firn air content over the N-PIIS rather than directly removing it from the surface elevation results.

Medley, B., Neumann, T. A., Zwally, H. J., Smith, B. E., and Stevens, C. M.: Simulations of firn processes over the Greenland and Antarctic ice sheets: 1980–2021, The Cryosphere, 16, 3971–4011, https://doi.org/10.5194/tc-16-3971-2022, 2022.

Line 110: again 1973 mentioned?

Response 17: Revised. See Response 3.

Line 143: How are you observing these polynyas in 2003, 2005 etc?

Response 18: Polynyas prior to 2021 were identified manually from optical imagery.

Line 201: I do not think the maximum buttressing values in Figure 1 are valid given that the system has changed so much since it was computed.

Response 19: Revised. Figure 1 has been updated, and the discussion of buttressing values has been removed.

Line 203: How do you get a delayed dynamic response? What is the physical reasoning behind this?

Response 20: Revised. In the original manuscript, we attempted to describe a delayed dynamic response associated with buttressing effects from the central ice shelf to the N-PIIS. However, after updating the ice velocity dataset, the revised results indicate that ice velocity increased prior to the 2015 calving event in the central ice shelf, rather than showing a delayed response. Therefore, this interpretation is no longer supported, and the corresponding sentence has been removed from the manuscript.

Line 252: 1973 mentioned again…

Response 21: Revised. See Response 13.

Line 256: I am not sure what the term 'fully stable' means. It is either stable or not stable, there is no in-between. Perhaps you mean 'weakening'

Response 22: Thank you for pointing this out. We intended to use the term "weakening," and the sentence has been corrected accordingly.

Line 257: 'Episodic atmospheric forcing' – what does this mean? Do you mean anonymously warm summers? (is there any evidence surface melt is doing anything in this region?) Snowfall drought?

Response 23: Thank you for your comment. We initially considered discussing the potential influence of foehn winds; however, to maintain focus on ice dynamic processes and avoid ambiguity, this discussion has been removed.

Figure 1: I do not think the maximum buttressing values add anything to this figure. They were computed under a very different set of geometries to the current state, you can see this in the image where there is ocean along the shear margins of the ice shelf. Aside from this, the overlay make it very difficult to see the pinning points and structure of the northern ice shelf. I would suggest removing the maximum buttressing.

Response 24: Revised. See revised Figure 1 in Response 3.

Figure 2: The ice speed estimates look very noisy with all the spikes. Are they seasonal in origin? What is causing this?

Response 25: No. Due to the low ice velocities in the N-PIIS, the original velocity estimates contained substantial uncertainties. Although we attempted to filter high-error values, residual noise remained. Therefore, we replaced the dataset with the ITS_LIVE annual composite product, which is sufficient for capturing annual-scale changes

Figure 4: Looks like E3 is still there. Nice observation of a new rift following grounding of E9 – this is an interesting observation.

Response 26: Thank you for pointing this out. Based on our analysis of DDInSAR interferograms, we confirm that the E3 region is present. Its spatial extent reached a maximum in 2020, including its current configuration. We have revised the figures and included additional DDInSAR results to better illustrate changes in pinning points (see Response 1).