Reviewer 2 comments:

This manuscript reports on the impact of the 2022/2023 sea ice lows on swell-induced flexure of a selection of ice shelves around Antarctica. The authors conclude that flexure has, for the most part, increased, but that at present most ice shelves are of sufficient thickness to avoid large-scale calving events. However, they show that based on hypothetical thinning rates, several ice shelves could become vulnerable towards the end of the century. The manuscript tackles an important and arguably understudied topic given the sea ice decline observed over the past decade (and expected future decline), and the results are novel. I believe it is suitable for publication in The Cryosphere, subject to addressing the comments below.

Thank you for the positive assessment.

General comments

I think some of the language and framing used to describe the increases in stress in 2022 and 2023 relative to the baseline does not match the results, e.g. 'far greater', 'substantial', 'major'. While this is true in relative percentage terms, most of the ice shelves appear to have experienced very little change in absolute terms. For example, is a 300% increase at Pine Island really meaningful when it represents an increase from 0 to 0.003 kPa? I think in 12 of the 14 ice shelves the increases in stress are less than 0.5 kPa. The manuscript suggests that 10 kPa is an important threshold for triggering greater calving, so in most cases could it be argued that the changes have been minimal in absolute terms?

In response to this comment, we propose moderating our language when describing relative changes and adding absolute changes where appropriate. Several of the changes are shown in response to the specific comments below.

How good is the wave model, and can we actually trust it? Some of the ice shelves included are quite small, with very complex coastlines. The resolution of the wave model is 0.4°: can this really do a good job for the smaller and more complex ice shelves (e.g. Sulzberger, which is fringed by islands, ice rises and other ice shelves)? Likewise, how confident are you in the way it treats sea ice? The 25% concentration threshold seems a little arbitrary. I appreciate that there may be no alternative, but I think some qualitative discussion is needed. Are there any field observations that validate it? Presumably there is a non-negligible chance that the true values are some way off.

We assume this comment refers to the CAWCR hindcast, which uses the WaveWatch III v4.18 wave model. We trust the hindcast within reason.

CAWCR significant wave heights have been assessed against altimeter data from 1993–2010 (Durrant et al., 2014) and ship observations from the Antarctic Circumnavigation Expedition (December 2018-March 2019; Derkani, 2021), finding generally strong agreement but also regions of biases up to 1 m. The Antarctic/Southern Ocean contains regions of positive bias up to 1 m, which is attributed to general issues with shallow-water regions and absence of wave–current interactions.

Moreover, the WaveWatch III model used in CAWCR operates up to sea ice concentrations of 75% and does not model wave attenuation caused by sea ice, instead treating sea ice between 25–75% as land and switching off for concentrations $> 75\%$. We choose to mask cells with $\geq 25\%$ sea ice cover to avoid the artificial treatment of the sea ice on wave propagation (although it does improve model performance for 25–75% concentrations; Durrant et al., 2014). We accept errors coming from the presence of sea ice $< 25\%$, favouring the ability to obtain wave data closer to the ice shelves.

Any cell containing an ice shelf is treated as land, such that CAWCR does not produce data where ice shelves exist and the complexity of the coastline for the wave model is not applicable.

We propose the following additions to the manuscript:

> Swell properties are extracted from the Collaboration for Australian Weather and Climate Research (CAWCR) Wave Hindcast - Aggregate Collection (Smith et al., 2020). The CAWCR hindcast starts on 1 January 1979, and provides hourly outputs on a 0.4° spatial grid of the ocean surface, where the operational range extends to 78° S. It is generated using the WaveWatch III v4.18 wave model and forced with hourly 10 m surface winds and daily sea ice concentration data from the National Center for Atmospheric Research Climate Forecasts System Version 2 reanalysis (since 2011). An assessment of the significant wave heights produced by an early release of the CAWCR wave hindcast (prior to the present study period) against satellite altimeter measurements found regions of positive bias up to 1 m around Antarctica (Durrant et al., 2014), which was attributed to challenges for models in shallow-water regions, neglect of wave–current interactions in the model and the crude treatment of wave attenuation due to sea ice. This assessment was verified by shipborne measurements as part of the Antarctic Circumnavigation Expedition (Derkani, 2021).
>
> The CAWCR implementation of WaveWatch III v4.18 neglects sea ice cover in each cell where the sea ice concentration is less than 25% (Tolman, 2003; Durrant et al., 2014; Smith et al., 2020). For cells in which the sea ice concentration is between 25–75%, an artificial sub-grid island correction is applied to attenuate wave energy. The wave model does not operate in cells with greater than 75% sea ice concentration. Thus, CAWCR data is only retained in the present study for cells with up to 25% sea ice concentrations, as a balance between increasing the incoming swell data available in the ice shelf regions and removing the data which is likely unreliable due to the presence of sea ice. Note that the wave model does not operate in cells that contain ice shelves or the coastline.

Line comments:

Line 8: I am not sure flexural stresses are far greater in absolute terms.

> Flexural stress levels have ~~are generally found to be far greater in 2022 and 2023 than~~ generally increased in 2022 and 2023 compared to the preceding eight years, and this is shown to be primarily driven by sea-ice loss

Figure 1: I think Nickerson and Sulzberger are labelled the wrong way around.

Thank you for spotting this error, which will be corrected, as shown below (and throughout the manuscript).

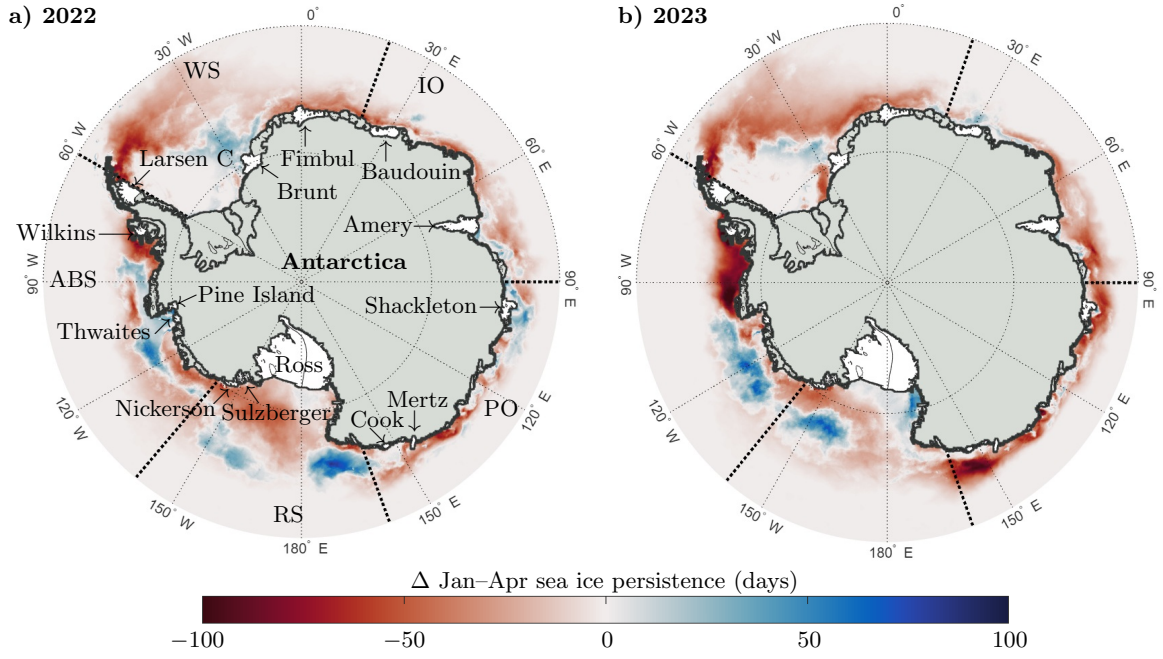

Figure 1. Figure 1 correction

Line 66: Arguably the most significant changes at any ice shelves over this time period have been at Pine Island and Thwaites, so it reads a little strangely when less significant changes at Larsen C and Sulzberger are discussed but Pine Island and Thwaites are not.

We will add details on the retreat of the Pine Island and Thwaites shelf fronts, as well as the PIGlet split on Pine Island.

> The Pine Island shelf front has retreated by 26 km from 2015–2024, and, moreover, the shelf front has broken into multiple outlets (Chien et al., 2025). Meanwhile, the Thwaites shelf front retreated by 17 km from 2016–2023, with the retreat being predominantly on the Western Ice Tongue (Zhu et al., 2024).

Line 80: Presumably you did this manually for Thwaites, given the mélange and icebergs in front of it? In many ways it is a strange choice for inclusion among the 14 ice shelves, because it is hardly an ice shelf any more.

No, it was automated using the same algorithm as used for the other ice shelves.

We will add details to §2.1.1 to justify why we chose Thwaites.

> Whilst Thwaites Ice Shelf has lost $\approx 70\%$ of its mass since 1997, it was included as it had retained $> 1000\,\mathrm{km}^2$ of ice shelf area, alongside evidence that it is rapidly preconditioning for further break-up events (Greene et al., 2022; Benn et al., 2022; Davison et al., 2023; Wild et al., 2024; Wang et al., 2025).

Line 100: It is perhaps worth noting that in complex ice shelves with multiple outlets of differing thickness (e.g. Sulzberger, Shackleton) this might bias the results towards outlets with lower discharge.
+
Line 338: Presumably Denman — which is responsible for the vast majority of discharge from Shackleton — is substantially thicker than the surrounding ice shelf and thus not as vulnerable? see comment reference line 100

We agree on both points. We will add a sentence that highlights the bias towards thinner glacial outlets and that these thinner regions will be more vulnerable to changes in swell-induced flexural stress, alongside ice shelves where this is relevant.

> The 30th percentile is chosen somewhat arbitrarily but noting that thinner sections of the shelf fronts will experience the greatest flexure in response to swell forcing (Liang et al., 2024). For ice shelves with multiple outlet glaciers, such as Shackleton, Sulzberger, Fimbul and Baudouin, the choice will bias the assessment towards the thinner/lower discharge shelf fronts.

Line 176: What is the justification for using E = 9 GPa?

We will add text to justify why we used $E = 9\,\mathrm{GPa}$.

> The ice shelf is modelled as a floating Kirchoff plate of semi-infinite length, with thickness h_{sh}, Poisson's ratio $\nu = 0.3$, and Young's modulus $E = 9\,\mathrm{GPa}$ ~~(Liang et al, 2024)~~. A range of Young modulus values have been used in previous studies. As in Liang et al. (2024), a value towards the upper end of the range is used here, discounting the much smaller values based on Sayag and Worster (2013), and similar to value values used in multiple other studies.

Figures 7, 8 and 9: I find it a little difficult to pick out the 2014–2021 boxes because they are so thin. Please make them the same size as the 2022 and 2023 boxes, and perhaps use a different colour.

We will make the suggested changes. For example:

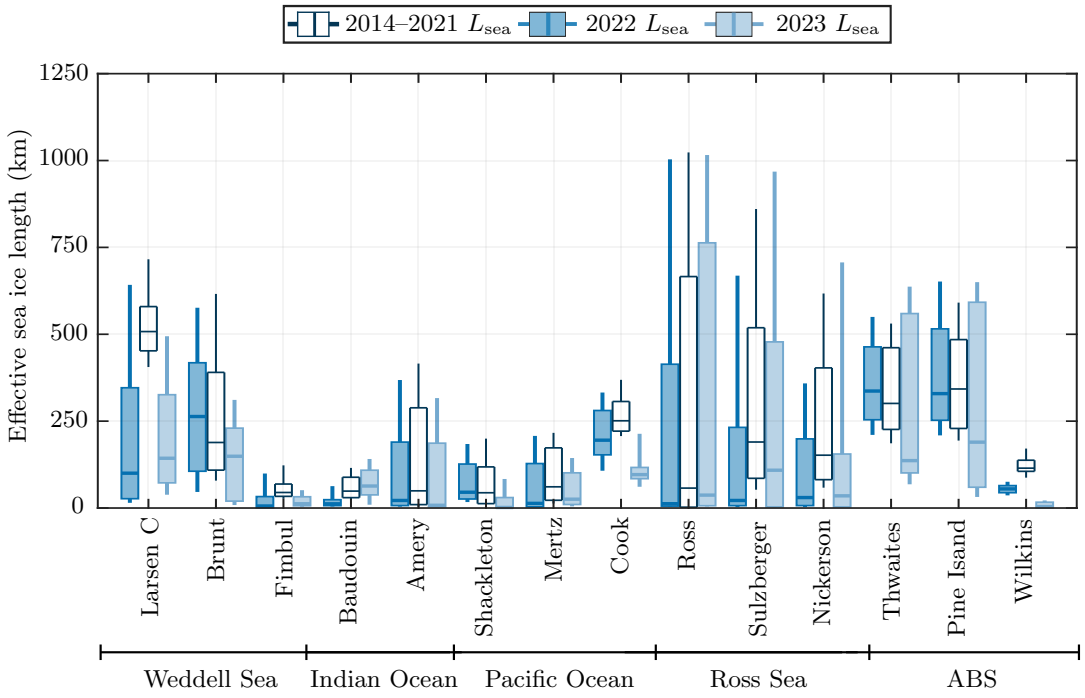

Figure 2. Figure 6 changes.

Line 215: This compares ice shelf thickness change with ice shelf frontal thickness change, and is therefore not like for like. As an ice shelf front advances, it will typically become thinner; in contrast, most of the thickness change usually occurs near the grounding line.

We will change the labelling to "Δ Shelf front thickness (%)" to make this clearer.

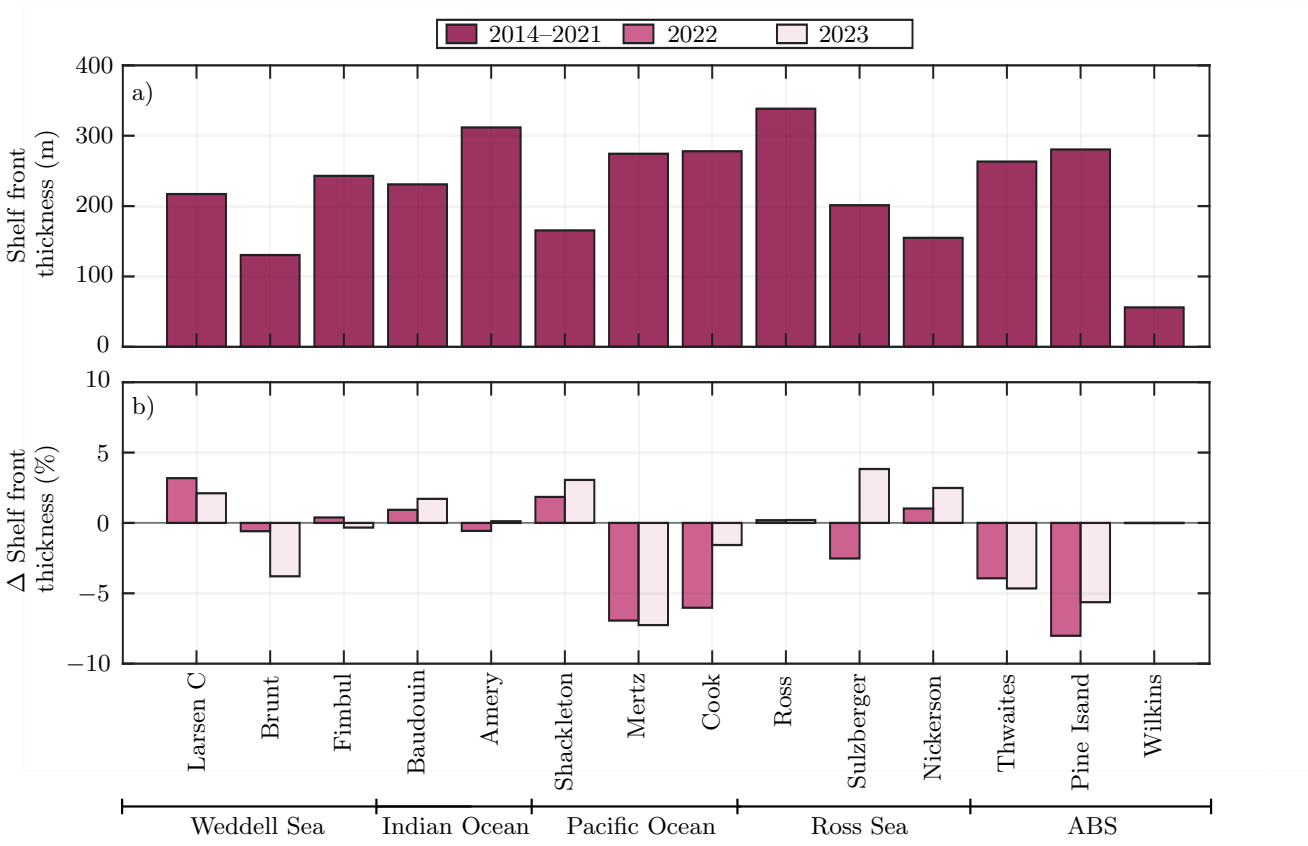

Figure 3. Figure 5 labelling correction. Also note the Sulzberger and Nickerson have switched positions

Line 292: A reader picking out this line may think there has been a dramatic and meaningful increase in stress at Pine Island and Thwaites, when in fact the changes are negligible.

We will change the line as shown below.

> Further, the relative flexural stress levels of Thwaites and Pine Island increase by 100–300% for 90th percentile (Thwaites: 0.637 kPa to 1.537 kPa, Pine Island: 0.406 kPa to 1.880 kPa) and >300% for median (Thwaites: 0.004 kPa to 0.016 kPa, Pine Island: 0.000 kPa to 0.008 kPa), highlighting that their severe thinning (Fig. 6b) alongside a retreating effective sea-ice length made them particularly ~~susceptible~~responsive to wave period increases (cf. Fig. 4).

Figure 11 caption: 20921 $\longrightarrow$ 2021.

We will make the correction.

Line 324: Consider rewriting: arguably there have not been large increases in flexural stress at most ice shelves in absolute terms.

> ~~Most~~ In relative terms, most of the studied ice shelves experience large increases in ~~relative~~ flexural stress in 2022 and/or 2023 (Table 2).

Line 355: 'much greater': arguably they were not, in relative terms.

> Results showed that flexural stress levels were generally ~~much~~ greater in 2022 and 2023 than the prior eight years (2014–2021) in terms of relative changes.

Line 372: 'major amplification' — again, consider rephrasing?

> We used data and models to quantify the ~~major~~ amplifications in flexural stress that Antarctic ice shelves experienced in the pronounced sea ice loss years of 2022 and 2023.

Line 375: If they thin by around 20–30% of present thickness (i.e. thinning at 1% per year)?

> If sea ice loss ~~and ice shelf thinning continue~~ is combined with a shelf front thinning rate comparable to Pine Island/Thwaites ($\approx$ 1% per year), we predicted that many of the ice shelves will reach damaging flexural stress levels within the next century, and certain ice shelves, most notably Shackleton and Nickerson, are susceptible within a few decades.

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