

## Reviewer 1 comments:

### *General comments:*

*This is easily the most compelling, sophisticated and convincing manuscript I have encountered on the topic of ice-shelf/sea-swell interaction. The manuscript uses sophisticated, creative analytical methods and employs the state-of-the-art data sets. The manuscript is well written and well proof read. I have no significant questions or challenges to bring up in my review. I regard the manuscript as being very valuable and will be likely read, cited and used as inspiration going forward.*

**Many thanks for the kind comments.**

### *Specific comments:*

*Page 2, Line 34: “sea ice, in the form of both stationary consolidated face ice and moving pack ice, creates a barrier that” should face be “fast”?*

**Yes, it should be:**

... in the form of both stationary consolidated ~~face~~ fast ice and moving pack ice.

Page 2: somewhere in the introduction, it might be worth pointing out that there have been some studies supporting speculation that periodic ice-shelf features, like the “rolls” found on the Ward Hunt Ice Shelf in the Arctic, have an effect that prevents transmission of sea swell with certain frequencies into the wider ice-shelf region. There has been speculation that the only remaining elements of the Ellesmere Ice Shelf witnessed by European explorers in the mid 1800’s are the ones that have these rolls and are thus more robustly protected from sea swell associated with changing Arctic sea ice since the Little Ice Age and into the present day.

A reference to the above: Nekrasov P, MacAyeal DR. Ocean wave blocking by periodic surface rolls fortifies Arctic ice shelves. *Journal of Glaciology*. 2023;69(278):1740-1750. doi:10.1017/jog.2023.58

We now see that our original version of Fig. 2c could imply that our model ice shelf contains rolls, whereas we intended for it to show the swell-induced ice shelf flexure. We have modified Fig. 2c as shown below to avoid the confusion.

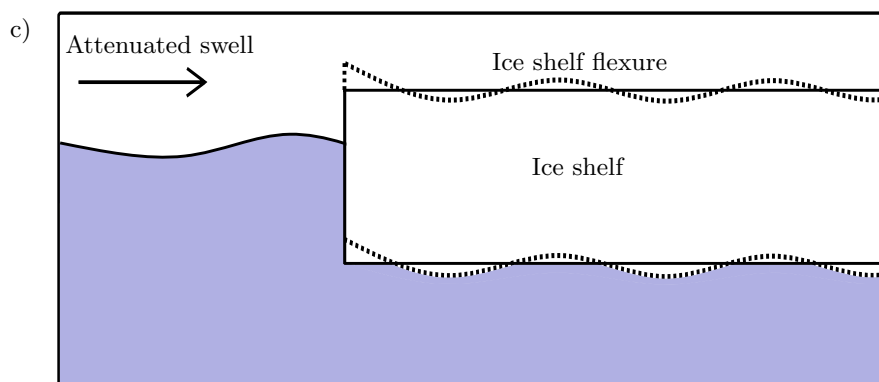


**Figure 1.** Revised version of figure 2c.

In addition, we will reference surface rolls in the Introduction regarding swell-induced ice shelf stress being greatest towards the shelf front, as shown below:

Swell that reaches an ice shelf is partially reflected by the shelf front and partially transmitted into the ice shelf and sub-shelf water cavity region (Meylan et al., 2021; Bennetts et al., 2024). The transmitted swell imparts flexural stress on the shelf front region (Banwell et al., 2017; Lipovsky, 2018), which models predict are generally largest towards the shelf front where the ice is thinner (Meylan et al., 2021; Liang et al., 2024), as well as at crevasses (Bennetts et al., 2022). Blocking of wave propagation along ice shelf has also been speculated to be caused by periodic “surface rolls” that induce Bragg scattering (Nekrasov and MacAyeal, 2023). ~~and~~ Sustained periods of sea ice loss and swell reaching ice shelves have been connected with observed large-scale calving and ice shelf disintegration events (Massom et al., 2018; Teder et al., 2025).

Page 5 Line 85: I'm not sure I understand what a "percentile" variable is... is it a single scalar number or is it a set or population of grid points satisfying some criterion. Perhaps an explanation is not needed due to my not being facile with this, but maybe a comment would help.

We propose re-writing the algorithm and section in § 2.2.1 as shown below.

For each ice shelf, a 3 km<sup>2</sup> grid is calculated with the ice shelf coordinates imported from its boundary in the Making Earth System Data Records for Use in Research Environments (MEaSUREs) Antarctic Boundaries for International Polar Years 2007–2009 from Satellite Radar, Version 2 dataset (Mouginot et al., 2017). For ice shelf X in year yyyy:

1. All satellite elevations recorded over the grid for ice shelf X are assigned to the corresponding grid cell.
2. The shortest distance from the mid-point of each cell within the ice shelf to the front is calculated. Only the cells with distances  $\leq 50$  km and accompanying elevations are retained.
3. Elevations with  $\geq 30$  dB of backscatter (as provided in the satellite dataset) are removed (Siegfried et al., 2014). In each grid cell, outlier freeboard elevations ( $e$ ) are also removed to eliminate elevation tracks on the ice sheet. They are determined as  $e \notin (e_{25} - 1.5 \times IQR, e_{75} + 1.5 \times IQR)$ , where  $e_{25}$  and  $e_{75}$  are the 25th and 75th percentiles of freeboard elevation for each grid cell, and  $IQR = e_{75} - e_{25}$  is the associated interquartile range.
4. The remaining surface freeboard elevations are corrected for tides via the Circum-Antarctic Tidal Simulation (Padman et al., 2002), with ocean-tide loading from the Finite Element Solutions 2004 (FES2004) tidal atlas (Lyard et al., 2006). A dynamic atmospheric correction is applied from Mog2D (Carrère and Lyard, 2003) and the location of the geoid from the Earth Gravitational Models 1996 (EGM1996).
5. Following Chuter and Bamber (2015), the corrected freeboard elevations in each cell ( $e$ ) are converted to ice shelf thicknesses ( $h_{sh}$ ) via

$$h_{sh} = \frac{(e - \delta)\rho_w}{\rho_w - \rho_i} + \delta, \quad (1)$$

where  $\delta$  is the average yearly firn air content for the ice shelf (i.e., constant across ice shelf X) from the NASA GSFC Firn Densification Model version 1.2.1 (Ligtenberg et al., 2014; Medley et al., 2022),  $\rho_w = 1028 \text{ kg m}^{-3}$  is water density and  $\rho_i = 917 \text{ kg m}^{-3}$  is ice shelf density.

6. The 30th percentile of the generated set of 300–19,000 shelf thickness values across the retained grid cells (where the size of the set mainly depends on the ice shelf area) is used to represent the thickness of ice shelf X in year yyyy, and denoted  $h_{sh}^{X:yyyy}$ .

Actually many of the variables being described in the well written, but terse algorithm sections are subject to potential mis-interpretation by people trying to follow in the footsteps of this study. Perhaps a sentence or two (could be in supplemental material) on what constitutes each variable (is it a set, a population, a scalar, a vector, a parameter?) would help.

We propose the following changes to our algorithm sections § 2.2.2 and § 2.2.3, respectively.

The AMSR2 ASI dataset uses a 89 GHz channel to produce sea ice concentration, which gives a finer spatial resolution ( $3.125 \text{ km}^2$ ) than other sea ice datasets, although it is more susceptible than lower-frequency channels to uncertainties at low sea ice concentrations near the ice edge (Meier et al., 2017). To delineate locations of the ice shelf edge, the no land mask version of the AMSR2 ASI dataset is used, with a coastline mask created by converting the 2013 coastline boundary from Greene et al. (2022) to a  $3.125 \text{ km}^2$  grid. The mask flags the cells on the continent edge from which individual ice shelves can be extracted via coordinates from the MEaSURES dataset.

For each of the 14 ice shelves, the following algorithm (which is similar to that used for the Wilkins and Voyeykov ice shelves over 2002–2009 by Teder et al., 2025) is used to create an “effective” sea-ice-length dataset at a daily frequency from January–April in each of the ten years of the record. The algorithm is based on a set of straight line “transects” (on a polar stereographic projection is calculated) for each shelf. There is a transect for each grid cell along the shelf front, which runs from that cell to a corresponding cell  $10^\circ$  north of the mean shelf front latitude, and  $\pm 45^\circ$  east of the mean shelf front longitude. The increase to  $\pm 45^\circ$  (in contrast to Teder et al., 2025) facilitates analysis in the Weddell Sea, due to the dimensions of the embayment. Transects are discarded if they intersect any islands, or any other parts of the coastline. There are 20,000–200,000 transects, depending on ice shelf geometry.

For ice shelf X on day ddd of year yyyy:

1. For each transect,  $t$ , the sea-ice length,  $L^{(t)}$ , is calculated as the aggregate of the lengths of each cell along the transect with a sea ice concentration  $> 15\%$ , and the concentration along the transect,  $C^{(t)}$ , is calculated as the average sea ice concentration of these cells.

2. Effective sea-ice lengths ( $L_{\text{eff}}^{(t)}$ ) for each transect are calculated as

$$L_{\text{eff}}^{(t)} = L^{(t)} C^{(t)}. \quad (2)$$

3. The 10th percentile of the generated set of effective sea ice lengths is used to represent the effective sea-ice length for ice shelf X on day ddd in year yyyy, and is denoted as  $L_{\text{eff}}^{X:\text{ddd-yyyy}}$ .

1. Calculate the set of ocean cells (sea ice concentrations  $< 25\%$ ) along the straight-line transects (from § 2.2.2). There are between 1,400–7,700 cells, depending on the coastline length and coastal geometry.

2. For each hour during the day (h):

- (a) Extract the significant wave height and peak period in each ocean cell from the CAWCR dataset.
- (b) Take the maximum value of significant wave height and the maximum value of the peak period over the ocean cells,  $H_s^{h,\text{max}}$  and  $T_p^{h,\text{max}}$ , respectively.

3. Take the median and 90th percentile of the 24 maximum hourly values of (i) significant wave height and (ii) peak period,  $H_s^{X:\text{ddd-yyyy}}$  and  $T_p^{X:\text{ddd-yyyy}}$ , respectively.

The median and 90th percentile of maximum hourly values of significant wave height and peak period are chosen to capture a range of the potentially most damaging swells in range of the relevant ice shelf.

*Figure 2: it is worth pointing out that some attenuation by the arrangement of ice out in front of the ice shelf front may be also due to Bragg scattering, a la the same process as “rolls” on the Ellesmere Ice Shelf.*

The periodic form of the sea ice floes shown in Figs. 2(a,b) cartoon representations is not representative of the swell attenuation by sea ice model used. The model uses randomly distributed ice floes to avoid the bands of strong attenuation that would result from periodic arrangements and Bragg scattering, which is not observed in the field.

We will explain this aspect of the model in § 2.3.1.

By including disorder in the distribution of ice floes to avoid Bragg scattering effects (Bennetts et al., 2009), ~~Consistent with observations,~~ models of this form ~~typically~~ predict exponential attenuation rates (Bennetts, 2025), ~~consistent with observations,~~ such that ...

We will also modify the Fig. 2 caption.

**Figure 2.** a) Model schematic, indicating incoming swell from the open ocean being attenuated by sea ice before reaching an ice shelf and forcing the ice shelf to flex (§ 2.3.3). The full model combines two sub-models: b) swell attenuation over distance through a sea ice cover, where the sea ice cover consists of a marginal ice zone and an inner ice pack (§ 2.3.1); and c) swell-induced flexure of an ice shelf (§ 2.3.2). ~~The periodic distribution of the sea ice floes in the MIZ and inner ice pack is for simplicity of presentation and is not representative of the swell attenuation model.~~

*Page 11: It may be worth indicating why thin ice shelves can get >100 kPa vs. thicker ice shelves being more like 10 kPa. Why does flexure stress increase with decreasing thickness. . . just a basic principle or idea can be mentioned for the curiosity of the reader who may not have experience with this.*

We propose adding to the text accompanying Fig. 4, as shown below, to explain the decrease in flexural stress with increasing ice shelf thickness.

The spatial maximum flexural stress due to swell forcing,  $\max_x |\sigma|$  (which occurs in the shelf front region **even with uniform ice shelf thickness**; Massom et al., 2018), increases with wave period and decreases with ice shelf thickness (Fig. 4). The latter is may appear to contradict the  $h$ -factor in Eq. 6, but is due to thicker ice shelves (i) reflecting a greater proportion of the incoming swell (Fox and Squire, 1991), and (ii) elongating waves in the shelf–cavity region (Meylan et al., 2021).

*Page 20: sometimes p-values and sometimes rho-values appears. Are these different?*

Yes, rho-values quantify the strength and direction of the correlation, whereas p-values quantify whether the correlation is statistically significant.

We will clarify this in § 3.3 as shown below.

The strength and direction of these correlations between variables is quantified by  $\rho$ -values, alongside the statistical significance being quantified by  $p$ -values (Lane et al., 2017). There are statistically significant correlations ( $p$ -values  $\approx 0$ ) between stress anomalies and anomalies in effective sea-ice length (negative correlation,  $\rho < 0$ ; Fig.10a) and peak period (positive correlation,  $\rho > 0$ ; Fig.10b).

*Conclusion: It might be worth mentioning that seismological methods might be able to assess damage that is associated with increasing flexural fatigue of the various ice shelves, and give a simple citation that interested readers could follow. It may be that seismological monitoring of ice shelves could assess the damage of increasing sea swell effects in the Antarctic ice shelves.*

We propose adding the below to the Conclusions to recommend further seismic measurements to assess increases in swell-induced ice shelf displacements since Antarctic sea ice has dramatically retreated.

Over the past two decades, experiments have been conducted to measure Antarctic ice shelf displacements, by deploying seismometers, including towards the shelf fronts (MacAyeal et al., 2006; Bassis et al., 2007; Bromirski et al., 2017; Aster et al., 2021). The measurements have shown increases in ice shelf displacements in the swell frequency band during Austral summer when the Antarctic sea ice barrier is relatively low (Baker et al., 2019; Aster et al., 2021). Although some experiments cover multiple years, the most recent measurements were made between 2015-2017, i.e., long before the sea ice lows of 2022 and 2023, and the measurements have been restricted to a handful of ice shelves, such as Ross (MacAyeal et al., 2006; Bromirski et al., 2017), Amery (Bassis et al., 2007), Nansen (Dziak et al., 2019) and Pine Island (Olinger et al., 2022). We recommend more experiments of this kind and targetted to potentially vulnerable ice shelves, as identified in the present study.

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