Response to Referee 2

We thank the referee for their careful and constructive review. Their comments have helped us improve the clarity and precision of the manuscript and strengthen the interpretation of our results. We have addressed each comment individually below.

Reviewer comments are shown in grey, author responses in black, additions to the manuscript are underlined in purple, and removed text is shown with strikethrough.

Short Summary: *This paper uses a standalone CICE6 configuration with a waves-in-ice module (CICE6-WIM) at 0.25° resolution to examine the synoptic-scale response of the Antarctic marginal ice zone (MIZ) to intense cyclones, analyzing hourly output for July–November of 2015–2018. The manuscript focuses on the evolution of sea ice properties in the MIZ and changes in MIZ width, presenting case studies of thermodynamic and dynamic processes related to sea ice drift and wave-induced ice breakup. They use an external cyclone-tracking algorithm to drive their modeling domain and to derive a statistical analysis. The study is a well-motivated extension of the 1° climatological configuration of Day et al. (2024) to the synoptic scale, and the focus on cyclone-driven ice processes is valuable. The configuration is clear, as well as the limitations of the model. My comments are about internal consistency with the Appendix and a few places where the wording could be tightened.*

Introduction: Well-structured and citations are up to date. Just ensure that the cited preprints are updated to their published format.

Thank you. We have updated the Massom et al. (2026) and Fraser et al. (2026) references, since those papers have now been published.

Major comments*:*

Methods:

1. The attenuation coefficients (c_1, c_2 in Eq. for α) and their values / SIC-scaling are not given, so the WIM cannot be reproduced from this paper alone. Please state the coefficients or reference the companion paper explicitly.

The coefficient values are now included along with the SIC-scaling. The manuscript now includes these details.

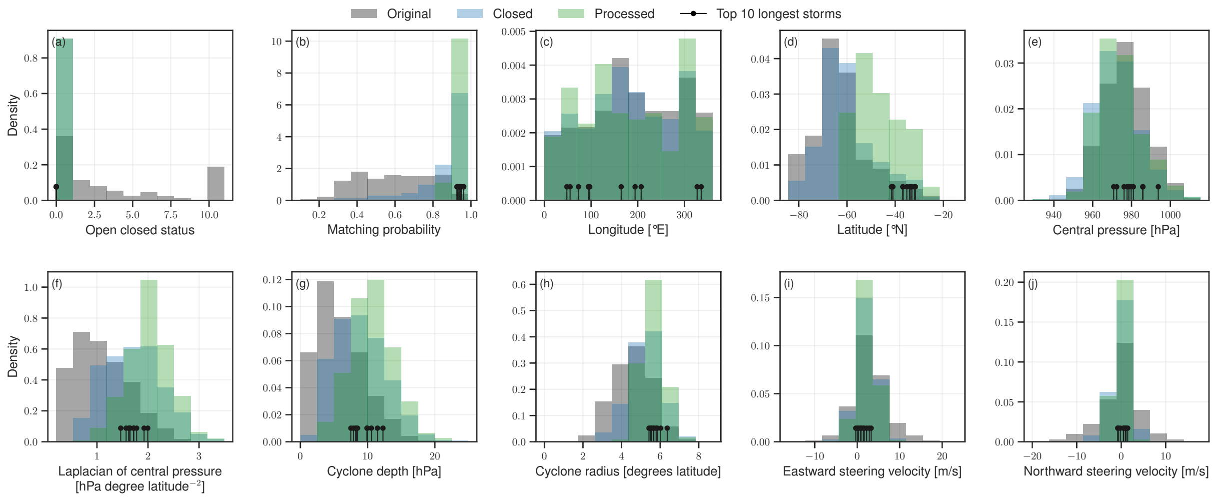
"...the attenuation coefficient $\alpha(\omega) = (c_1\omega^2 + c_2\omega^4)/a_{\text{ice}}^{\text{MBK}}$ is derived from the empirical model of Meylan et al. (2014), $c_1 = 5.38 \times 10^{-5}$, $c_2 = 2.95 \times 10^{-5}$, and $a_{\text{ice}}^{\text{MBK}} = 0.7$ corresponds to the sea-ice concentration at the observation location."

2. The cyclone selection filter reduces 136,871 tracks to 396. Since all statistics rest on these 396 storms, the bias check described as "not shown" should be shown, at least in the supplement materials (spatial, central-pressure, and radius distributions of retained vs. discarded storms).

We have now added an additional figure to the Appendix (see below), which shows the mean cyclone statistics for the tracks before and after processing, as well as at the intermediate step where only cyclones with a "closed" status are retained. The latitude distribution shifts following the isolation of extratropical cyclones, while the central pressure distribution remains largely unchanged. The selected cyclones also show greater intensity, as indicated by their larger Laplacian of central pressure values and greater depths. Our selection criteria result in cyclones with moderately larger radii on average, with this difference arising primarily from the "closed" cyclone criterion. Steering velocities and longitude distributions are largely unaffected by the processing.

Case studies:

1. The first case study and the appendix (C1) describe the same event in opposite ways. Please clarify:



Distributions of key cyclone track variables before and after applying the selection procedure. (a) Open-closed status of the cyclone track; (b) matching probability; (c–d) longitude and latitude at the start of the cyclone track; (e) mean central pressure; (f) mean Laplacian of central pressure; (g) mean cyclone depth; (h) mean cyclone radius; (i) mean eastward steering velocity; (j) mean northward steering velocity. The ten longest tracks are shown as black stems to illustrate their characteristics relative to the full distribution.

- *The main text emphasizes melt and says average ice age increases, but C1 says the same event shows "substantial new ice formation" and a decrease in ice age. The appendix (new ice, age decrease) matches Fig. C1.*

We have clarified the text to distinguish the pre- and post-cyclone crossing changes as they were unclear. The revised section explicitly links the switch from sea ice melting to sea ice formation with changes in the latitude of the ice edge.

" ~~In this case, the sea ice remains thin, with thickness around 0.15 m throughout the event. Winds are dominated by the zonal (u) component (Fig. C1d), meaning the north–south changes of the ice edge are limited. These conditions suggest that thermodynamic processes were the dominant factor that influenced the sea ice response during this cyclone.~~ Throughout the event, the sea ice remained thin, with a thickness of approximately 0.15 m. The on-ice winds and associated sea-ice drift remained relatively consistent across the cyclone passage (Fig. C1d) and therefore could not explain the observed retreat of the ice edge before the crossing followed by its advance afterward. This reversal, despite relatively steady meridional drift conditions, indicates that thermodynamic processes were the dominant influence on the ice-edge response during this event."

- *The main text mentions that the warm air is "heating the ocean surface," but Fig. C1b shows sea surface temperature moving only from about -1.899 to -1.902 °C (0.003 °C change), at the freezing point, that then cools. There is effectively no ocean warming. Please remove or reword this.*

We have re-worded this section to distinguish changes at the ice edge (presented in the case study) versus the response averaged over the MIZ (shown in the Appendix).

"Warm surface air advects over the sea ice (Fig. 2a–c), raising its~~the~~ surface temperature ~~above the melting point~~ (Fig. 2d–f) ~~and heating the ocean surface~~."

- *The main text gives two different concentrations "at the time of crossing": 80% and 40% . Fig. C1d shows 0.82–0.85, supporting 80%. The heat-uptake mechanism relies on the 40%*

value, which the figure does not support. Please reconcile or clearly state that 40% applies only to the outermost cell.

The 40% corresponded with values at the ice edge (i.e., the northern most cell with at least 15% sea ice concentration), whereas the MIZ averages are presented in the Appendix. This has now been clarified in text:

"At this time, ice concentrations ~~near~~at the ice edge are relatively low (∼40%), allowing enhanced ocean heat uptake and driving melt from both above and below the ice."

- *The "basal melt" claim in the main text is stronger than the paper's own evidence. Fig. C1c shows ice thickness flat at 0.15 m through the event, so basal loss is not visible.*

We have ammended to text so make it clear that basal melt was impactful for sea ice at the ice edge, rather than claiming its importance over the whole MIZ.

"~~In the MIZ~~For sea ice at the ice edge and near the cyclone, basal melt is the primary mode of ice loss, occurring when sea ice surface temperatures ~~exceed the melting point~~are heightened prior to the cyclone's arrival at the ice edge (red shading in panel g)."

- *The word "controlling" overstates the case-1 result. §3.1 says thermodynamics is "controlling ice edge location," but Fig. 2h shows only that edge position and net melt/growth move together in time.*

Agreed. We have now edited this sentence accordingly.

The new section reads as:

"A cyclone crossing the sea ice in the Bellingshausen Sea between 2 and 8 August 2015 is illustrated in Figure 2. The cyclone intensifies as it approaches the ice-covered region, with central pressure dropping from 960 to 930 hPa over 24 hours. The cyclone reaches its minimum pressure at the time of the crossing, which is accompanied by a steepening pressure gradient, as indicated by the compacted isobars. Sea ice in the MIZ is thin (∼0.15 m), with concentrations averaged over the MIZ being around 80% at the time of the cyclone crossing (see Appendix C, Fig. C1). Warm surface air advects over the sea ice (Fig. 2a–c), raising its~~the~~ surface temperature ~~above the melting point~~ (Fig. 2d–f)~~ and heating the ocean surface~~. At this time, ice concentrations ~~near~~at the ice edge are relatively low (∼40%), allowing enhanced ocean heat uptake and driving melt from both above and below the ice. The warming contributes to the retreat of recently formed ice (less than three weeks old), evidenced by an increase in average ice age ~~of about one week~~ over a two-day period (Fig. C1i). Following the cyclone crossing, surface temperatures cool, leading to substantial new ice formation and an increase in ice concentration near the ice edge~~from 40% to 70%~~(Fig. C1e), and a decrease in sea ice age over the MIZ (Fig. C1i).

In the MIZ near the cyclone, basal melt is the primary mode of ice loss at the ice edge, occurring ~~when~~where sea ice surface temperatures ~~exceed the melting point~~are heightened prior to the cyclone's arrival at the ice edge (red shading in panel g). Basal melt exhibits periodic peaks that coincide with solar insolation, highlighting a diurnal signal in the MIZ's thermodynamic response. After the cyclone crosses the ice edge, surface temperatures decline, promoting new ice formation~~ through both frazil and congelation processes at comparable rates~~, with a spike in frazil growth immediately after crossing followed by a combination of frazil and congelation growth. During the cyclone passage, the ice edge retreats from 60.4° S to 61.1° S, while the inner MIZ boundary moves southward by only 0.4° (panel h). The retreat and subsequent rebound of the ice edge closely track periods of net ice melt and growth, respectively (red and blue shading in panel g), ~~underscoring the role of thermodynamics in controlling ice edge location~~illustrating the relationship between thermodynamic changes and ice edge location."

2. Edge-motion attribution: make case 1 consistent with case 2.

- *Case 2 (§3.2, Appendix C2) correctly ties edge motion to the meridional (v) wind. Case 1 instead argues the edge motion is thermodynamic because winds are "u-dominated" (C1). But Fig. C1 shows the v-wind still reaches ∼-10 m s^{-1}, which is enough to move a thin (0.15 m), low-concentration edge. "u is larger" does not mean "v is negligible," since it is v that moves the edge north–south. Since the authors already apply the edge-velocity-vs-wind check in case 2, they should apply it to case 1 as well. It will either confirm a genuinely melt-dominated case or reveal a contribution from drift.*

We agree and have now applied the same edge-velocity-versus-drift analysis used in Case 2 to the cyclone examined in Case 1 (see Fig. 2). During this event, the meridional wind remained consistently on-ice. The corresponding sea-ice drift was also relatively steady at approximately between −0.1 and $-0.2 \mathrm{m\,s^{-1}}$ (northerly winds), whereas the ice edge retreated at as the cyclone approached the ice edge and advanced afterwards. Thus, the meridional winds do not correlate with the reversal in ice edge location. To clarify for the statistical analysis, a particular cyclone track can contain both thermodynamic and wind events (they are not exclusive), allowing periods of significant on- and off-ice winds to be identified consistently even if thermodynamic processes are dominant.

The wording in the appendix was imprecise, we have revised the Appendix to say:

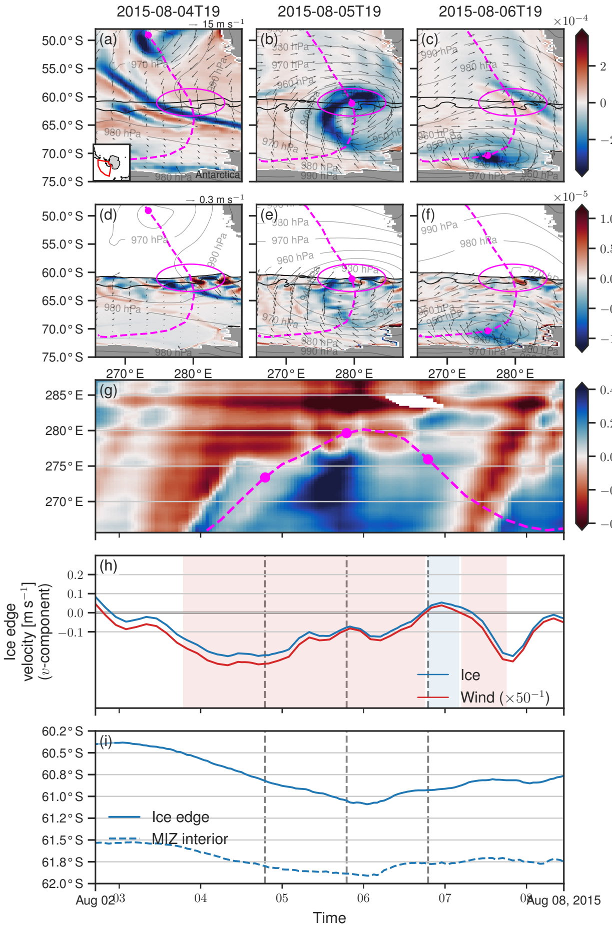
"Throughout the event, the sea ice remained thin, with a thickness of approximately 0.15 m. The on-ice winds and associated sea-ice drift remained relatively consistent across the cyclone passage (Fig. C1d) and therefore could not explain the observed retreat of the ice edge before the crossing followed by its advance afterward. This reversal, despite relatively steady meridional drift conditions, indicates that thermodynamic processes were the dominant influence on the ice-edge response during this event."

Statistical results:

- *The "melting/freezing" event labels are defined by a freezing point, which is misleading. T_{ice} > -1.8 °C defines "melting events," but Fig. D1b confirms -1.8 °C is the ocean freezing point, not the ice-surface melting point (∼0 °C). So a "melting event" does not indicate surface melt, it indicates the ice surface sitting at or above the freezing point. Moreover, since the dominant melt mode is basal, a threshold on surface temperature does not track the process which is also why melt occurs during "freezing" events. Please rename these events or state explicitly that the threshold marks a surface thermal state, not surface melting or a growth/no-growth boundary.*

We thank the referee for this clarification and agree that the −1.8 °C threshold does not represent the ice-surface melting point or a direct boundary between melting and freezing. We use ice-surface temperature, rather than sea-surface temperature, because it is more sensitive to the atmospheric changes associated with cyclone passage. The threshold of −1.8 °C was selected because it effectively isolates the peak in ice-surface temperature associated with close cyclone proximity (e.g., Fig. 5), and therefore distinguishes contrasting surface thermal states rather than melting and freezing processes directly. We have removed references to the threshold as a melting point.

In addition, in line 289: "Melt during freezing events exceeds July–August melt during melting events" is confusing and mainly reflects season, not the events. By November, basal melt is high regardless of the surface-temperature label. This actually shows the surface label does not capture basal melt,



Dynamics case study of the cyclone used in the thermodynamic case study (§3.1).

worth stating plainly, and rewording "heightened ice vulnerability" to name what is increasing. We have revised the sentence as follows: "By November, the seasonal shift is evident even during *freezing events*, when the average melt rate exceeds that modelled during July–August *melt events*."

- *The seasonal reversal in ice-edge change (advance in Jul–Aug retreat by Nov, Fig. 8c) is a clear trend in the medians, but the interquartile ranges include zero every month, so it is not yet shown to be significant. Since the claim is a sign change across the season, a bootstrap testing whether the July and November medians differ from each other and from zero would substantiate it.*

Following this advice, we performed a bootstrap analysis to estimate the 95% confidence interval for the median response. We found that there was a significant difference from zero in August (5.2 km) and November (−9.1 km), indicating that the seasonality does produce a sign change. We have added "Bootstrapping of the median net change (9,999 resamples per month) confirms that, despite this spread, the net shift is statistically significant at the 95% level in August (median +5.2 km, 95% CI [1.5, 10.0] km) and November (median −9.1 km, 95% CI [−18.2, −4.4] km), while July, September, and October are not distinguishable from zero. This indicates that the seasonality does produce a genuine sign change between August and November, rather than one attributable to sampling noise." to the manuscript.

- *10b shows major-breakup widening and minor-breakup narrowing largely cancel, so the net cyclone effect on MIZ width is near zero each month. Could this be stated more clearly in the results? This would also right-size case study 3: major breakup is common but case-3-scale widening is a tail event (Fig. 10a), not the typical response.*

We have added:

"Although major and minor breakup events are associated with opposing tendencies (MIZ widening and narrowing, respectively), these tendencies largely balance across all cyclones, with the monthly median net change remaining close to zero throughout the season. During early winter, minor breakup events have a greater influence on the MIZ response, whereas from September to November, when the circumpolar MIZ is relatively narrow, major breakup events become more influential and the variability increases. This aggregate balance does not preclude substantial changes during individual cyclones. The event examined in Section 3.3 illustrates this variability, showing pronounced breakup and MIZ widening during the cyclone, followed by sea-ice reconsolidation after the cyclone crossed the ice edge."

- *With only two predictors, a random forest is a heavy choice, and its smooth background surface can give an impression of confidence not supported by the underlying data density, particularly the narrow-MIZ hotspot, which rests on few points. Additionally, the two predictors are not independent, since a wider MIZ attenuates more wave energy before it reaches breakable ice, so edge Hs and MIZ width jointly control breakup. This collinearity is likely why the relative contributions are challenging to quantify and is worth stating explicitly. If the random forest is retained, please report its validation (train/test error, per-region sample sizes) so the result is not overread.*

The random forest was intended to be a visual guide for the relationship between wave heights and MIZ widths. We agree that it is probably excessive for this figure, so we have reverted to a simpler binned median approach.

- *The authors note that the CICE6 welding rate is orders of magnitude below the Roach et al. (2018b) estimate, which adds uncertainty to MIZ-narrowing timescales. Could you go one step further? Since the low rate means the model under-welds, the modelled reconsolidation (e.g., case study 3) is plausibly biased slow or incomplete. Conversely, if reconsolidation is in practice dominated by new-floe formation, the welding error may not affect the result. A one-line statement of which process dominates the narrowing, and in which direction the low welding rate biases it, would resolve this.*

We explored increasing the welding rate to the values reported in Roach et al. (2018), but found this to be infeasible in CICE: at these rates, the associated timescales become so short that numerical stability requires prohibitively small time steps, making the simulations computationally prohibitive. We believe that future work (observations and modelling) is required to delineate the contributions of new floe formation versus welding on predicted floe sizes.

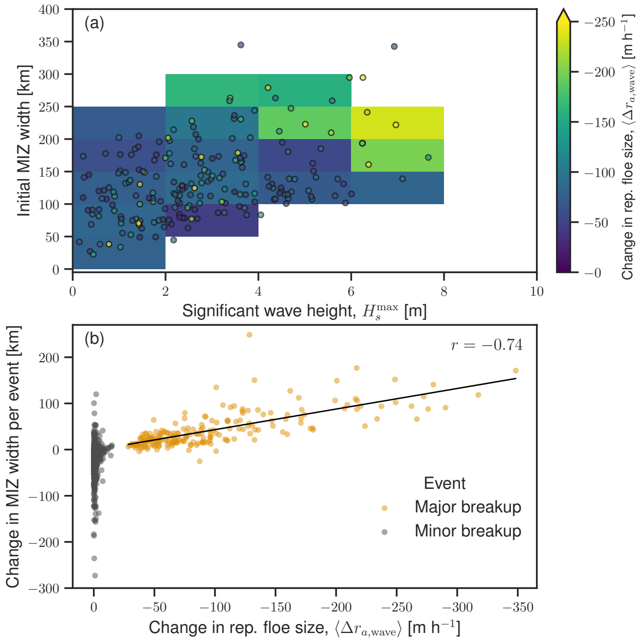
To the main text we have added:

"Notably, the default welding rate in CICE6 (and in CICE6-WIM) is several orders of magnitude lower than the rate estimated by Roach et al. (2018), which could introduce uncertainty in the timescales associated with MIZ narrowing through re-consolidation. Despite the lower welding rate, the model still represents rapid re-consolidation of the ice cover driven by the floe formation process."

Minor comments:

- *Line 84: Please correct to: elastic-viscous-plastic rheology*

Corrected. "...with an elastic-viscous-~~plate~~plastic rheology"



The relationships between MIZ widths and wave heights to wave-induced breakup during major breakup events. (a) Relationship between Antarctic initial MIZ width (taken just before a major breakup event) and the maximum significant wave height during each major breakup event, $H_s^{\max}$. The average wave-induced breakup over the event is shown as coloured dots with the heatmap corresponding to the binned median values. (b) Change in MIZ width per event versus average wave-induced breakup, grouped by breakup event type. The correlation coefficient for major breakup events is displayed in the top-right corner. Note that the horizontal axis is inverted.

- *Line 176: "During the cyclone passage, the ice edge from 60.4° S to 61.1° S" is missing a verb*

It now reads "During the cyclone passage, the ice edge retreats from 60.4° S to 61.1° S, while the inner MIZ boundary moves southward by only 0.4° (panel h)."

- *Lines 209–211: the wave-fracturing sentence is duplicated.*

Line removed.

- *Line 249: "Melting events occurs" → "occur."*

Corrected. "*Melting events* occur~~s~~ when ice surface temperature..."

- *Line 359: "leave the the MIZ" →typo*

Removed. "...but once cyclones leave the ~~the~~ MIZ off-ice winds drive rapid cooling and ice-edge advance"

- *Line 373: "a the mixed-layer" →typos*

Removed. "...rather than ~~a~~ the mixed-layer parameterisation used in this study"

- *Line 450: Probably means decreases in mean sea ice thickness and age.*

Corrected.

- *"Frazil and congelation at comparable rates" (§3.1) overstates Fig. 2g, where frazil is initially ∼3× congelation.*

Sentence has been changed to: "After the cyclone crosses the ice edge, surface temperatures decline, promoting new ice formation ~~through both frazil and congelation processes at comparable rates~~, with a spike in frazil growth immediately after crossing followed by a combination of frazil and congelation growth."

- *Report the actual correlation ($r = -0.74$, already in Fig. 11b) in the text rather than "moderate to strong."*

This has now been corrected (note that we found a minor bug in the code used to process the figure, resulting in the correlation changing from −0.75 to −0.74). "Major breakup events are almost always associated with MIZ widening, with a ~~moderate to strong negative relationship~~correlation of −0.74 between wave-induced breakup and changes in MIZ width."

Kind regards,
Noah Day

References

Fraser, A. D., Day, N., Wang, Z., Bennetts, L. G., Liu, Q., O'Farrell, S., Coleman, R., Voermans, J., Xu, S., Zhu, W., et al. (2026). Revealing the Antarctic marginal ice zone with a decade-long wave-in-ice climatology. *Nature Communications*, 17(6648).

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