Response to Reviewer #1

This manuscript investigates the impact of enhanced meltwater associated with dynamic mass loss from the Antarctic ice sheet on Antarctic sea ice. The authors assess the response to a 0.1 Sv meltwater input applied uniformly at the ocean surface, using a new suite of simulations from 11 models comprising 43 ensemble members. The results show that, although the imposed freshwater forcing is substantially larger than the present-day observed increase in ice sheet and ice shelf meltwater, the simulated sea ice response exhibits a wide inter-model spread. This spread is influenced by differences in model mean-state sea ice area and volume, the prevalence of open-ocean deep convection, and the background ocean stratification. Overall, this is a well-written and interesting study that provides useful insights into the role of Antarctic meltwater in shaping sea ice variability. But several aspects need clarification before publication.

We thank the reviewer for their thoughtful and helpful comments on the manuscript. We provide a point-by-point response below. The reviewer comments are in black, our response is in blue, and quoted text is in italics.

Major:

Line 176-181. The reduction in sea ice concentration is primarily attributed to open-ocean deep convection. It may be helpful to further discuss whether the response of near-surface atmospheric circulation to the freshwater forcing could also contribute to the spatial pattern of sea ice concentration anomalies.

We thank the reviewer for this helpful suggestion. We agree that the sea-ice response will also be affected by atmospheric processes and feedbacks. In these Tier 1 antwater simulations there is no forcing due to anthropogenic GHG forcing, so any atmospheric influence can only be through feedbacks from meltwater-induced changes. While our analysis indicates that changes in upper-ocean stratification and open-ocean deep convection are a leading control on the magnitude and some aspects of the spatial pattern of the sea-ice concentration response, the associated changes in SST, sea ice, and air–sea fluxes can also drive a near-surface atmospheric circulation response. This atmospheric adjustment may in turn affect sea ice further through changes in surface winds, sea-ice drift, Ekman transport, heat and moisture advection, and turbulent heat exchange.

We have revised the discussion to make this point clearer and to cite the recent literature highlighted by the reviewer. In particular, Beadling et al. (2024) and Xu et al. (2025)—with the latter based on the same set of simulations used here—show that Antarctic freshwater forcing can produce a robust atmospheric response over the Southern Ocean, while Zhu et al. (2026) show that, when more realistic spatially distributed basal melt forcing is used, atmosphere–ocean–sea-ice interactions can make an important contribution to the sea-ice response. These results support the interpretation that atmospheric feedbacks may modulate the regional pattern of sea ice concentration anomalies in our simulations. However, because the SOFIA Tier 1 protocol uses an idealized, spatially uniform coastal surface freshwater perturbation and our experiments do not include atmosphere-fixed or wind-fixed sensitivity experiments, we cannot quantitatively separate the atmospheric contribution from the direct oceanic response in the present study. We therefore now state this as an important caveat and identify it as a motivation for future SOFIA experiments using spatially distributed and/or depth-dependent freshwater forcing.

We will add the following text to the discussion on this point:

"Although we interpret much of the sea-ice response as arising from the direct oceanic effect of freshwater forcing on upper-ocean stratification, and open-ocean deep convection, the fully coupled nature of these simulations means that atmospheric feedbacks may also contribute to the sea ice response. Freshwater input modifies SST and sea-ice cover, thereby altering the surface albedo of and turbulent heat fluxes over the Southern Ocean, and these surface changes can drive a near-surface atmospheric circulation response. Such circulation anomalies may influence sea ice dynamically, through changes in surface winds driving sea ice transport, and thermodynamically, through changes in near-surface temperature, moisture advection, and air–sea heat exchange. Recent analysis of the atmospheric response in the multi-model ensemble used here (Xu et al., 2025) and similar idealized freshwater-forcing experiments (Beadling et al., 2024) show that Antarctic meltwater can generate a large-scale atmospheric response over the Southern Ocean and beyond. Therefore, while changes in ocean deep convection and stratification provide a physically consistent explanation for much of the simulated response, atmospheric circulation changes may help shape the regional structure of the sea ice concentration anomalies, particularly near the ice edge and in sectors where the sea-ice response is less directly tied to regions of open-ocean convection.

The role of atmospheric feedbacks is particularly relevant when comparing the present Tier 1 experiments with studies that use more realistic freshwater forcing. Zhu et al. (2026), for example, applied spatially distributed Antarctic ice-shelf basal melt forcing for 2006-2016 and found that the coupled atmospheric response can significantly affect the sea-ice response. Their results suggest that the spatial distribution and vertical placement of freshwater forcing can influence not only the local ocean stratification response, but also the atmospheric circulation anomalies that feed back onto sea ice. The idealized protocol used here is therefore best interpreted as a controlled multi-model test of the sensitivity of Antarctic sea ice to a consistent freshwater perturbation, rather than as a complete representation of the regional sea-ice response to realistic Antarctic ice-shelf basal melting. Quantifying the relative roles of ocean stratification, deep convection, and atmospheric feedbacks will require targeted diagnostics, and ideally sensitivity experiments with spatially distributed and depth-dependent freshwater forcing that will be conducted as part of Tier 3 of the SOFIA protocol, discussed further below."

Line 195-197. In CanESM5 and GFDL-ESM4, regions of increased salinity appear to coincide with regions of increased sea ice concentration. However, in EC-Earth3 and FOCI, sea ice decreases at the north and northeast of the Weddell Sea, while salinity increases in these regions. This suggests that the salinity increase may not directly linked to sea ice formation. It would be helpful to clarify this inconsistency by additional analysis or discussion of whether the sea ice reduction is driven by atmospheric or ocean dynamical processes.

We thank the reviewer for this comment. The regions of decreased sea ice (and increased surface salinity) in the Weddell Sea in EC-Earth3 and FOCI are associated with regions of open-ocean deep convection in that region in those models. The deep mixing in these regions brings relatively warm, salty water to the ocean surface from depth, resulting in the decreased sea ice and increased salinity. The increased sea surface salinity in CanESM5 and GFDL-ESM4, on the other hand, we attribute to increased sea ice formation and/or reduced sea ice melt in those regions resulting in increased salinity due to greater brine rejection and/or reduced input of relatively fresh sea ice meltwater. The text will be modified to read:

"There is general surface freshening overall, with some models showing regions of increased salinity due to regions of open-ocean deep convection bringing relatively warm, salty water to the surface (EC-Earth3 and FOCI), or increased brine rejection from sea ice formation or decreased freshening due to reduced sea ice melt (CanESM5 and GFDL-ESM4)."

Minor：
1. Line 93-94. Is the analysis for both the piControl and the antwater experiments based on the last 30 years of the simulations? Also, for the time series analyses of sea ice area and volume, are the changes in the antwater experiment calculated relative to the corresponding years of the piControl simulation, or relative to a 100-year mean? In general, it is more common to use a longer-term mean of the piControl simulation (e.g., Chen et al., 2023; Beadling et al., 2024; Xu et al., 2025), as this can help reduce the influence of inter-annual and decadal variability and improve the robustness of the response. While this choice is unlikely to substantially affect the main results, but it needs a proper explanation of the choice.

We thank the reviewer for this comment. The final 30 years of both the piControl and antwater simulations were used in the analysis, and this will be clarified in the Methods section as follows:

"The time averages of the response are always based on the last 30 years of monthly-mean output of the 100-year-long experiment and the overlapping period of the piControl run, if not stated otherwise. This averaging period was chosen to be long enough to reduce the influence of internal variability, while also allowing the models to equilibrate to the meltwater forcing as much as possible."

We deliberately chose to use overlapping periods from the piControl rather than a long-term average in order to make best use of the ensemble member branching method outlined in the SOFIA protocol (Swart et al., 2023). In the SOFIA protocol the ensemble members are branched from different years of the piControl run, rather than by using small perturbations from a single year, to sample across low-frequency ocean variability in the piControl. Using a long-term average as our baseline would reduce the impact of this branching choice. We will clarify this in the Methods section as follows:

"We choose to use overlapping periods from the piControl run for each ensemble member as the baseline, rather than a long-term average, to maintain the sampling across low-frequency ocean variability as outlined in the SOFIA protocol."

2. Line 131. It is difficult to identify the period used in this study (years 50–70) in Fig. 5 of Beadling et al.. Please clarify how the years analyzed here correspond to those shown in Fig. 5 of that study.

We thank the reviewer for noting this. The 100 years in the SOFIA simulation correspond to years 101-200 in Beadling et al. (2022). This will also be clarified in the text in the revised manuscript.

3. Line 170-171. According to Fig. 1b–c and 3b–c, it is difficult to directly compare ensemble spread and model spread. It would be helpful to quantify these spread (e.g., using standard deviation) and present them in a table. In addition, I suggest adding the multi-model mean to Fig. B1 and B2 to facilitate comparison with Fig. 1 and 3.

We thank the reviewer for this comment, and note that we have quantified the spread in the sea ice area and volume responses for each model individually and the multi-model ensemble in Table 2. We will also add the multi-model mean to Figures B1 and B2 in the revised manuscript as suggested.

4. Line 241-242. The statement that "models with the thinnest mean-state sea ice in their piControl runs have the largest percentage changes" may not apply in all cases; for example, EC-Earth3 appears to be an exception. It may be helpful to either qualify this statement or briefly discuss such deviations.

We thank the reviewer for this comment, and agree that this statement is not true for all models. The sentence will be modified to read:

"Furthermore, models with low sea ice volume in their piControl runs typically have the largest changes in sea ice area (see Figure 10d, aside from CanESM5 and EC-Earth3). This indicates that models with lower mean-state sea ice volume are generally more sensitive to surface cooling driven by the addition of the meltwater and are able to grow a more extensive ice cover because of the reduced insulating effect of the existing sea ice. The fronts associated with the ACC form a natural barrier for northward sea ice expansion (Goosse et al., 2025) limiting the response amplitude in models with larger mean-state sea-ice cover."

5. Line 268-270.
"Furthermore, in the EC-Earth3, FOCI, and HadGEM3-GC31-LL
models, regions of deep convection form near the end of the antwater simulation, explaining the reduction in sea ice area observed in those models.
" However, based on

Fig. 1, there does not appear to be a clear decreasing trend in sea ice area during the final 30 years of the antwater simulation in these models. A clearer explanation of this point would be helpful. The correspondence between reduced sea ice and enhanced deep convection seems most evident in EC-Earth3 and FOCI, particularly in the northern and northeastern Weddell Sea.

We thank the reviewer for this comment, and agree that this summary does not reflect the results for these three models. The sentence will be modified to read:

"Furthermore, in the EC-Earth3, FOCI, and HadGEM3-GC31-LL models, open ocean deep convection forms near the end of the antwater simulation, explaining the regions of reduced sea ice area concentration in some ensemble members observed in those models."

6. Line 273-278. Based on aforementioned analysis, the relatively weak response in AWI-ESM-1-REcoM may be related to its use of a fixed freezing point and relatively strong stratification. It may be helpful to briefly conclude this interpretation.

We thank the reviewer for this note, after further investigation we have realised an error was made in identifying the freezing point equation in AWI-ESM-1-REcoM, and the relationship used is in fact non-linear. As such, the note about the constant freezing point will be removed from the revised manuscript.

7. Line 286-289. A recent study (Zhu et al., 2026) using spatially distributed freshwater forcing suggest that the atmospheric response associated with Southern Ocean air–sea interactions can also have a significant impact on sea ice. This aspect may deserve some discussion.

We thank the reviewer for this comment, and refer to our response to major comment #1 where we address this.

Reference:

Beadling, R. L., Lin, P ., Krasting, J., Ellinger, W., Coomans, A., Milward, J., et al. (2024). From the surface to the stratosphere: Large-scale atmospheric response to Antarctic meltwater. Geophysical Research Letters, 51, e2024GL110157. https://doi.org/10.1029/2024GL110157

Chen, J.-J., Swart, N. C., Beadling, R., Cheng, X., Hattermann, T., Jüling, A., et al. (2023). Reduced deep convection and bottom water formation due to Antarctic meltwater in a multi-model ensemble. Geophysical Research Letters, 50, e2023GL106492. https://doi.org/10.1029/2023GL106492

Xu, X., Martin, T., Beadling, R. L., Liu, J., Bischof, S., Hattermann, T., et al. (2025). Robustness and mechanisms of the atmospheric response over the Southern Ocean to idealized freshwater input around Antarctica. Geophysical Research Letters, 52, e2024GL113734. https://doi.org/10.1029/2024GL113734

Zhu, Z., Liu, J., Liu, Y ., Martin, T., Song, M., Yang, C.-Y ., et al. (2026). Implications of realistic Antarctic ice shelf basal melting during 2006–2016 on Southern Ocean climate. Geophysical Research Letters, 53, e2025GL119237. https://doi.org/10.1029/2025GL119237

Grammar:Line 68: Please delete one “evenly”

Corrected