Response to reviewer comment #2

Pauling et al. present the results of the Tier 1 SOFIA experiment: a multi-model ensemble simulating how Antarctic sea ice responds to spatially uniform meltwater flux from ice discharge. They find that the models exhibit a wide spread in the sea ice response, which can be attributed to mean-state sea ice area and volume, deep ocean convection, and mean-state ocean stratification. Overall, this is a well-written and scientifically valuable manuscript that fills a notable methodological gap. The limitations in the methodology are also appropriately qualified. My comments are primarily minor, and mostly pertain to presentation as opposed to methodology.

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 any quoted text is in italics.

General comments:

The authors should discuss the influence of spatial resolution on their results. As shown in Table 1, the different models used in SOFIA have varying spatial resolutions. The authors allude to the influence of spatial resolution in lines 275-278, where they discuss the AWI-ESM-1-REcoM model and its high resolution near the coast. Since the antwater experiment is dependent on specifically the grid cells adjacent to the coastline being perturbed by meltwater flux, I would think that differences in coastal grid cell resolution could have a significant influence on the results (e.g. finer resolution of continental shelf bathymetry and mesoscale circulation). The authors can also utilize existing literature on this topic (e.g. Rackow et al., 2022 (https://doi.org/10.1038/s41467-022-28259-y), who find a delayed sea ice response in higher-resolution CMIP5 simulations).

We thank the reviewer for this comment, and will add the following discussion of model resolution to the revised manuscript:

"The models used in this study vary substantially in the horizontal resolution of the atmosphere, ocean and sea-ice model components (Table 1). Model resolution has previously been shown to impact both sea ice and the ocean response to Antarctic meltwater. Rackow et al. (2022) showed that the response of Antarctic sea ice to future warming projections is delayed in models with higher-resolution ocean and sea ice components. They attribute this to resolved ocean eddies that increase equatorward heat transport and moderates warming around Antarctica. The study of Beadling et al. (2022) employed the same GFDL-CM4 and GFDL-ESM4 models used in this study and showed

that the GFDL-CM4 model, with its higher horizontal resolution of ~0.25°, better resolves the Antarctic Slope Current which effectively traps the meltwater on the continental shelf, while in the lower-resolution GFDL-ESM4 (~0.5°) more meltwater is able to escape to the open ocean. The model with the highest resolution ocean-sea ice components used here are, in order, AWI-ESM-1-REcoM, GFDL-CM4, GFDL-ESM4, and FOCI, with the rest all at approximately 1° resolution. There is no clear resolution dependence of the overall sea ice area or volume response, with these four higher-resolution models spanning the full range of responses (Figures 1 and 3). Nevertheless, as shown in Beadling et al. (2022), model resolution is important for smaller-scale continental shelf processes."

The usage of "SI" to mean stratification index in a paper about sea ice (and where SIA and SIV are used as acronyms for sea ice-based metrics) is extremely confusing (e.g. in Fig. 10), I'd recommend changing that acronym to something more differentiated.

We thank the reviewer for noting this, and we will replace "SI" throughout the revised manuscript with I_{strat} to avoid the ambiguity.

Specific comments:

Table 1: The resolution column is confusingly formatted. When only one number is written, does this mean that the latitude and longitude spacing are on the same resolution? It would be better to explicitly write out all four numbers (both lat and lon for both ocean and atmosphere, even if they are the same), to avoid this confusion.

We thank the reviewer for this comment, and will make the suggested change in the revised manuscript.

77-86: The specifics detailing the experimental design of SOFIA seems better suited to the "Data and Methods" section, rather than the Introduction. Instead, the Introduction may benefit from some more general contextualization of the SOFIA initiative.

We thank the reviewer for this suggestion and agree that the implementation details are better placed in the Data and Methods section. We will shorten the final paragraph of the introduction to read:

"In this study, we present results from the "Tier 1" antwater SOFIA experiment, where a constant meltwater perturbation is evenly distributed at the ocean surface across all grid cells immediately adjacent to the Antarctic coastline, under pre-industrial climate conditions. Comparing the response of Antarctic sea ice to this meltwater perturbation

across the 11 participating models allows us to investigate the factors contributing to the inter-model spread in the response of Antarctic sea ice and the Southern Ocean to meltwater from Antarctic ice sheet mass loss."

We will also move the SOFIA implementation details to the beginning of the Data and Methods section, which will read:

"The Tier 1 antwater experiment defined in the SOFIA protocol prescribes a meltwater flux of 0.1 Sv (3154 Gt yr^{-1}) evenly distributed at the ocean surface across all grid cells immediately adjacent to the Antarctic coast. Although this amount of meltwater is larger than contemporary observational estimates of ice shelf basal melt rates (0.035-0.050 Sv, Adusumilli et al., 2020; Davison et al., 2023) or Antarctica's current mass imbalance (0.006-0.016 Sv, Slater et al., 2021), the antwater experiment was designed to produce a robust signal for the purposes of model intercomparison, not to match observations over the historical period. This magnitude of meltwater input is comparable to the projected meltwater flux in the mid-to-late 21st century (e.g., Swart et al., 2023). The idealized nature of the antwater experiment allows us to examine the response to an increase in Antarctic meltwater without the additional interaction with anthropogenic greenhouse gas or aerosol forcing."

91: Specify that piControl is a pre-industrial control run, and briefly describe the experiment and why you choose it, for glaciology-oriented readers less familiar with the CMIP world.

We thank the reviewer for this suggestion, and in the revised manuscript this will now read:

"*For SOFIA, the antwater experiments were branched from each model's CMIP6 piControl (pre-industrial control simulation). The SOFIA protocol requested that the ensembles be generated by branching each member from a different year in the model's piControl run, where the years are chosen to have different phasing of low-frequency ocean variability."*

93: Is there a motivation behind the particular choice of the last 30 years? Is this selected because the model with the largest τ value has $\tau = 69.2$, and 70 is the smallest number greater than that—so are you trying to select the greatest number of years that have all models in an equilibrium state? Whether that's the reason or it's something different, you should specify why you choose 30 years.

We thank the reviewer for this comment, and will add the following text to the revised manuscript:

"This averaging period was chosen to be long enough to reduce the influence of the initial adjustment to the forcing and internal variability, yielding a quasi-equilibrated upper Southern Ocean."

157: "Changes in sea ice volume are important for ocean–atmosphere fluxes of heat, moisture, and carbon as well as biology in this region"; add some representative citations here.

We thank the reviewer for this suggestion. The revised sentence will read:

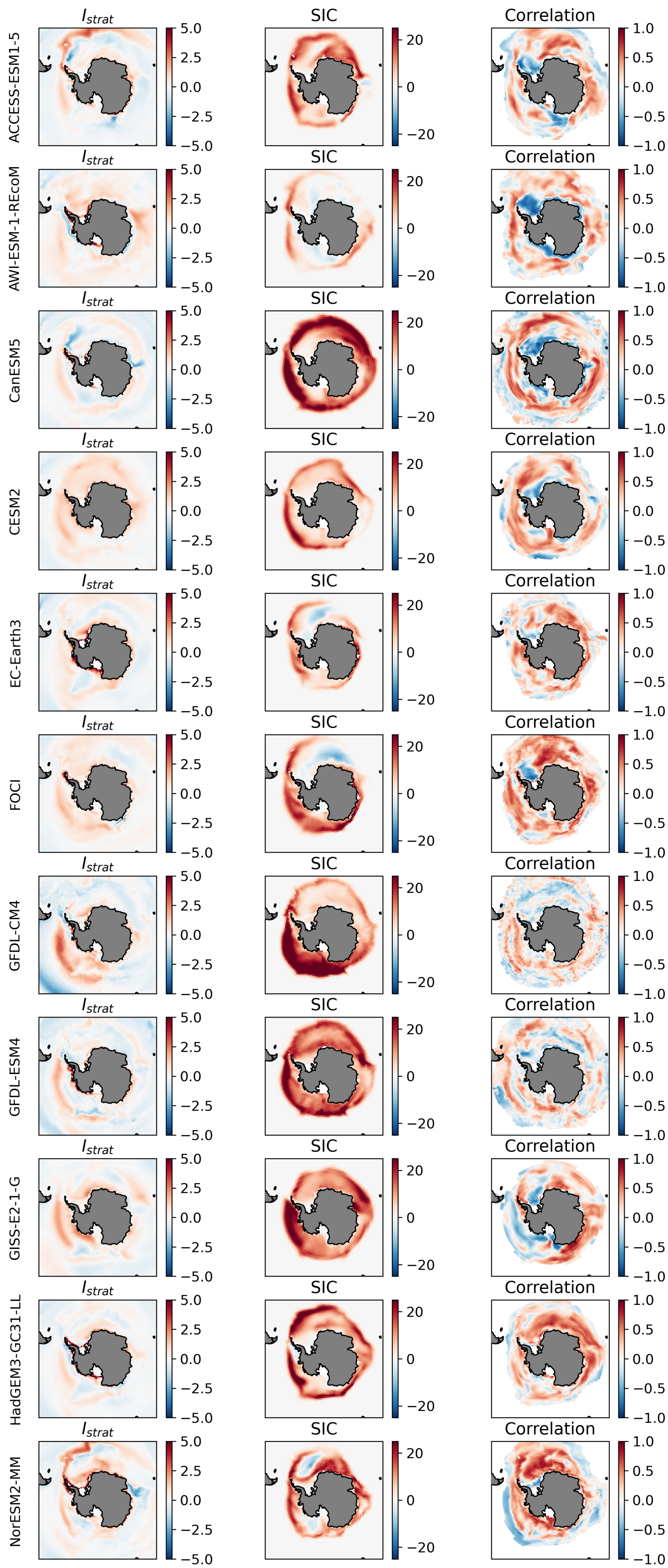
"Changes in sea ice volume are important for ocean–atmosphere fluxes of heat, moisture, and carbon as well as biology in this region (e.g., Massom and Stammerjohn, 2010; Gupta et al., 2020; Swadling et al., 2023)"

Fig. 10: In the caption, when you describe that the y-axis is "ensemble-mean Antarctic sea ice response," clarify that this is the area response and not the volume response. Also, the legend overlaps with a datapoint in Fig. 10d.

We thank the reviewer for catching this. In the revised manuscript we will update the figure caption to explicitly say sea ice area response, adjust the legend, and update the axis labels to use the new notation for the stratification index.

Fig. 10b: I'd be curious to see what this figure looks like as a correlation map, where you plot the correlation between ΔSIA and ΔSI for each grid cell. Are there geographic areas where this relationship better holds than others, and if so: does that provide you with any physical insight?

We thank the reviewer for this suggestion, and include the figure showing the change in stratification index, the change in sea ice concentration, and the correlation map between the two over the last 30 years of each simulation below. We see that the stratification index and sea ice concentration changes are in general positively correlated over most regions of sea ice, with little consistent spatial pattern between models. Since no consistent spatial pattern emerges from this analysis we do not include it in the revised manuscript.


I_{strat}
SIC
Correlation
ACCESS-ESM1-5
AWI-ESM-1-REcoM
CanESM5
CESM2
EC-Earth3
FOCI
GFDL-CM4
GFDL-ESM4
GISS-E2-1-G
HadGEM3-GC31-LL
NorESM2-MM
5.0
2.5
0.0
−2.5
−5.0
20
0
−20
1.0
0.5
0.0
−0.5
−1.0

241-242: I'm unsure where the support for this statement is coming from in the paper. Fig. 10d doesn't show any significant trend between piControl sea ice volume and the change in sea ice area. Is it that the trend becomes significant when it's reported in percentage units, as opposed to km2? If so, make that clear, and provide a plot and/or quantitative support in the text. Also, is this statement assuming that thinness is interchangeable with sea ice volume?

We thank the reviewer for noting this. While there is no significant trend in figure 10d, if the outliers of CanESM5 and EC-Earth3 are removed there is a general relationship between mean-state sea ice volume and sea ice area response. We agree that we should say “smallest sea ice volume” rather than “thinnest” here. The revised sentence reads:

“Furthermore, models with small 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 smaller mean-state sea ice volume are generally more sensitive to surface cooling driven by the addition of the meltwater and are able to grow more ice because of the reduced insulating effect of the existing sea ice.”

248: Fig. 4 does appear to show that there is a varying response between different models. Some models show a much more spatially homogeneous response (as a function of longitude) than others. You should mention this wide spread between the models. Which of these models are “consistent” with the simulations of Ashley et al. 2021? And are you able to attribute the differing behavior to different model representations of ocean circulation?

252: You refer to “sea ice volume changes shown here” but you are referencing Fig. 4, which is a figure of sea ice concentration. Shouldn't you be referencing figure 5?

We thank the reviewer for noting this and respond to both of the above two comments here. The comparison with Ashley et al. (2021) was indeed intended to refer to the sea ice volume response and so we will update this paragraph to read:

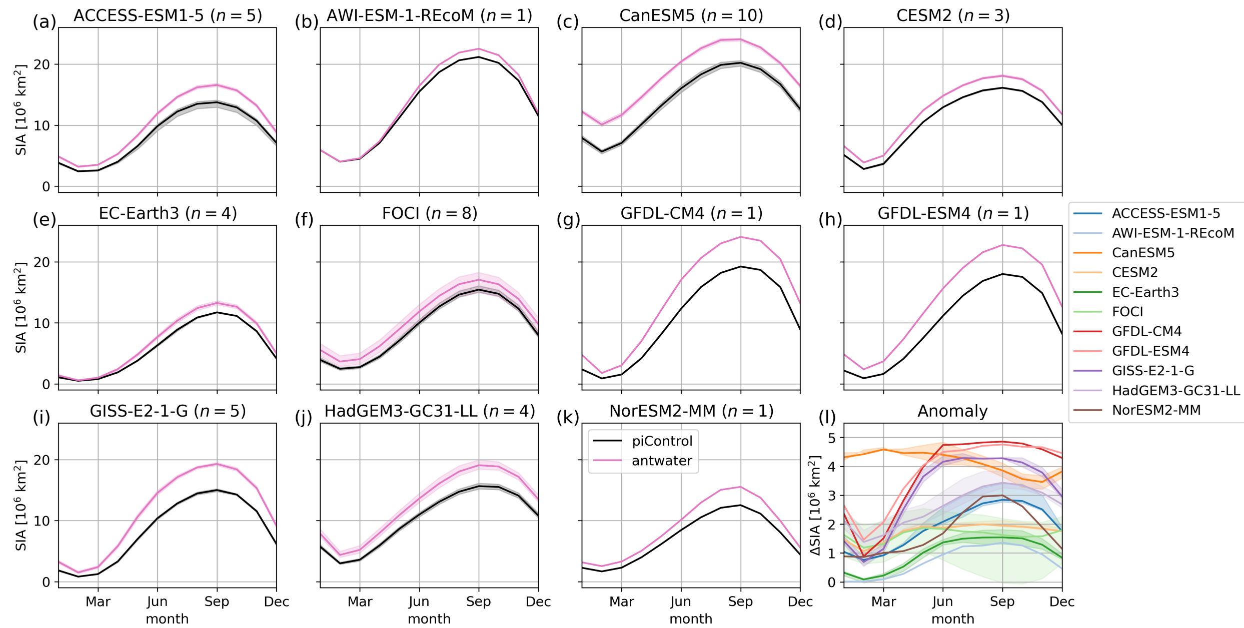
“While the spatial response of sea ice concentration and volume (Figures 4 and 5) varies widely across models, some features are consistent with ocean model simulations of meltwater release (see supporting information of Ashley et al. 2021) showing that

meltwater released as far away from the Peninsula as the Ross Ice Shelf front follows the Antarctic coastal and slope currents anticlockwise around the continent, before separating at the tip of the Antarctic Peninsula. Some of the meltwater continues around the Antarctic coast, with the remainder flowing into the Weddell Gyre and out into the Atlantic Ocean, in a pattern similar to the sea ice volume changes in several models shown here."

256: I'm not sure this is immediately obvious from visual inspection of Fig. 2. Why not make a plot showing the derivative of this plot (i.e. the change in SIA with respect to time)? In lines 152-154, you should also quantify the difference between the magnitudes of the September and February increase, which can support this assertion.

We thank the reviewer for this suggestion and have added a panel with the difference between antwater and the piControl for each model to Figure 2 for each model (see below). For all models except CanESM5, the smallest change is in February, and the largest is around September. The average difference between the minimum and maximum monthly anomaly is 2.06 million km^2. We will also add a sentence to the results section so that the relevant section reads:

"In most models, the increase in sea ice area is largest around the time of the annual sea ice area maximum in September, with a much smaller increase around the time of the annual minimum in February (Figure 2l). The multi-model mean difference between the minimum and maximum monthly anomaly is 2.06×10^6 km^2. However, in CanESM5 and FOCI the increase in the sea ice area is approximately the same year-round. Particularly the FOCI ensemble (green shading in Figure 2l) demonstrates the limiting effect of open ocean deep convection, which is present in some of its members, on the winter sea ice response."



Revised Figure 2

280-283: Can you provide numbers quantifying these statements? E.g. what is the spatial variability in meltwater flux, and how much of the meltwater flux actually enters at depth instead of the surface?

We will add the following sentence to the revised manuscript to quantify the contribution of the Amundsen/Bellingshausen sea sector:

"For example Kim et al. (2024) showed that over the period 2003-2020, the Amundsen/Bellingshausen sea sector lost 173.9 ± 6.9 Gt yr^{-1}, while the Antarctic continent overall lost 122 ± 22 Gt yr^{-1} (the overall loss is smaller than the Amundsen/Bellingshausen Sea loss due to compensating regions of mass gain)."

For the partitioning between meltwater input at the surface vs at depth we will modify this section to read:

"Meltwater also only enters the ocean surface in antwater, whereas in reality it enters the ocean through a combination of basal melting of ice shelves, where the meltwater enters the ocean at depth, and calving and subsequent melting of icebergs, where the meltwater enters the ocean far from the coastline. For example, Davison et al. (2023) found that, of the Antarctic ice shelves that lost mass over the period 1997-2021, 68% of that melt entered the ocean at depth through basal melting, with the remainder entering at the surface through melting of calved icebergs."

290-291: This would benefit from some more context about the SOFIA protocol. Particularly as it pertains to future work building on this paper, you should briefly describe the design of the Tier 2 and Tier 3 SOFIA experiments.

We thank the reviewer for this suggestion, and we will add additional discussion of the SOFIA protocol and the additional experiment tiers to the revised manuscript as follows:

"Future SOFIA experiments will provide an opportunity to further understand the mechanisms linking Antarctic meltwater and sea ice. The SOFIA protocol outlines additional "tiers" of meltwater experiments designed to improve our understanding of the impact of Antarctic mass imbalance in climate models (Swart et al., 2023). Tier 2 consists of experiments with estimates of historical meltwater forcing, and projections of future meltwater input under different emissions scenarios. Tier 3 consists of sensitivity tests to factors such as the spatial distribution and the inclusion of the latent heat effect. At the time of writing, the running and analysis of these additional tiers by multiple modeling groups is ongoing. The results presented here are an important first step in understanding the inter-model spread in the response of Antarctic sea ice to meltwater from the ice sheet, and can be built on by this future work."