Response to reviewers on: The Southern Ocean Freshwater release model experiments Initiative (SOFIA): Scientific objectives and experimental design
Neil Swart et al.

Review comments in black

Responses in red ; Text added/modified in manuscript in blue

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RC1: 'Comment on egusphere-2023-198', Anonymous Referee #1, 05 Apr 2023

The manuscript describes a new model intercomparison project devoted to the analysis of the impact of freshwater release in the Southern Ocean. Many studies have performed experiments imposing freshwater perturbations in this region but using different experimental designs, making an interpretation of the differences between the results of those experiments a complex task. This new initiative is thus timely. The protocol is clearly explained and several modelling groups have already agreed to participate in the exercise. It is thus very likely that the initiative will be a success.

1/ One of the stated main objectives is to have a protocol that is as simple as possible in order to ensure a wide participation. For instance, freshwater will be only added at surface, using simplified geographical distributions. The experimental design is consistent with this goal and this is well-adapted for an intercomparison exercise and to study why models have different responses to the same perturbations. However, it does not mean that the experiments will reproduce well the recent observations or the dynamics of the real system. It is perfectly fine to estimate the magnitude of the freshwater perturbation based on estimates of the mass balance of the Antarctic Ice sheet to have a reasonable order of magnitude but this can give the false impression that the intercomparison will give us a kind of measure of the uncertainty on the recent past and future impact of freshwater release in the Southern Ocean. The experiments will measure some elements of the uncertainty, related to model uncertainty, but not many others such as the impact of release at different depths or location, which could have a large impact too. This should be more clearly stated when the goals of SOFIA are described, starting for instance in the last sentence of the abstract which mentions ‘a consistent estimate of the climate system response to Antarctic meltwater, as well as the uncertainty of this response’ while it is only the uncertainty in the framework of the protocol related to the use of different models and different idealized scenario that will be estimated.

Thank you for pointing this out. We have modified the text to clarify that we do not address all sources of uncertainty equally and to guide readers on the interpretation of SOFIA results. In addition, we have added four new Tier 3 experiments to address this point (and also the community comment of Paul Holland). These new Tier 3 experiments test the impact of our simplified lateral distribution by confining freshwater forcing to the Amundsen and Bellingshausen seas, and test the impact of our surface addition by distributing freshwater over depth. Specific text changes are as follows:

The relevant remaining sentence in the abstract is now reads:

to quantify the climate system response to Antarctic meltwater input along with key aspects of the uncertainty.

The introduction (formerly line 64) has been modified to now read:

as well as some key uncertainties

In the Section "Forcing uncertainty" we have modified the text to note:

In the experimental design described below (Appendix A), we include multiple experiments over the historical period which aims to capture the uncertainty represented in the observational estimate. Similarly, for future projections, we use two scenarios - one with large increases anthropogenic forcing and meltwater, and another with smaller changes, to broadly bracket possible future combinations of forcing. There are also uncertainties in both the horizontal and vertical distribution of freshwater input to the ocean, as discussed for example in Pauling et al. (2016). We include multiple tier 3 experiments, which test the sensitivity to different vertical and horizontal distributions of freshwater forcing in an idealized way…We note that our experiments do not comprehensively test all the uncertainties in the meltwater forcing, but they are designed to span the largest known uncertainties at leading order.

We have also added a new section entitled "Interpreting SOFIA results", which explains the caveats in more detail (see also response to community comment by Paul Holland).

Finally in Appendix A, the new Tier 3 experiments are described.

2/ In the same line, the manuscript mainly mentions CMIP6 type of models (see Table 2). This focus is consistent with the goals of the project but the introduction should describe more extensively the limitations of those models, in particular through a comparison with the results of higher resolution models. For instance, it is mentioned that there is a consensus on the expansion of the sea ice cover in response to the freshwater input but some studies have shown on the contrary a reduction of the ice thickness in response to ice shelf melting (e.g., Merino et al. 2018, Mackie et al. 2020, already cited in the manuscript). Changes in the dynamics of the slope current that cannot be resolved at the typical resolution of CMIP6 models also have an impact on the response to the perturbation and specifically on the exchanges with the continental shelves that can have a large impact on deep water formation, a topic that is part of the objectives of this study (Moorman et al. 2020; Beadling et al. 2022, already cited). This does not reduce the interest of the proposed intercomparison but should be discussed clearly to avoid an over-interpretation of the results of the intercomparison (see for instance lines 220-221).

We agree that CMIP6-class models do not represent all of the relevant dynamics, and that responses could be resolution dependent. To address this, we have added text to clarify these points, and a new section on “Interpreting SOFIA results” including the following proposed text:

Beyond the simplifications in the SOFIA forcing protocol, users of the data should also remain aware of the limitations of the models used to run the experiments. For example, many of the models participating in SOFIA so far are CMIP6-class coupled climate models, that do not directly resolve mesoscale and submesoscale dynamics, the continental slope current, Dense Shelf Water overflows, etc. Nonetheless, such coupled models remain the best available tools for understanding future climate change, including the impact of meltwater that we examine here. Higher resolution models (particularly ocean only models), that participate in the future may better resolve these dynamics. Despite the simplification in the meltwater forcing protocol and the limitations of the models, we believe that the SOFIA results can be used to help inform the next generation of Earth System Models, as well as helping us to understand the possible impact of meltwater on the real climate system.

Our protocol also describes how ocean-only experiments might be conducted, which we hope will allow some higher resolution models to submit results and help to elucidate this resolution dependent response.

With respect to the sea-ice response in particular, we disagree with the reviewer that there is a reduction in sea-ice thickness in response to freshwater forcing only in the studies cited. Mackie et al 2020 (which we cite) clearly show an increase in sea-ice in response to freshwater forcing. A follow up study in Mackie et al. (2020b - not cited in our text), does show a decrease in sea-ice thickness, but this is a response to CO2 forcing and freshwater forcing, not freshwater forcing alone. Merino et al. 2018 use an ocean only model (not a coupled model), and their model is forced at the surface by an ERA-interim based forcing - and hence this historical forcing includes a CO2 effect too. As shown in their figures, the net response is an increase in sea-ice thickness, and by subtraction the response to freshwater only is a net increase in sea-ice (their fig 9b). Regardless of this point on sea-ice, we have clearly emphasised in the revised manuscript the limitations of the CMIP-class models, and resolution dependence of results.

3/ More and more ocean models include a representation of ice shelf cavities and we can expect that in the future several CMIP-type models will have such a representation. This is not discussed in the experimental design. Should these models be excluded from SOFIA and maybe be included in a future phase of the initiative as they will compute interactively some of the freshwater input that others will have to add at surface (for instance in the future scenario runs) or are they suggested adaptations to include them already at his stage?

Our current study is focused on the climate response (and hence CMIP-models) to freshwater forcing, and no CMIP6 models, or those currently participating in SOFIA, resolve ice-shelf cavities. We agree that future coupled models that explicitly resolve ocean ice-shelf interactions should not be included in SOFIA directly. Rather, we see SOFIA as providing some context and possible justification for moving to more complex ESMs, which include interactive ice-shelves. In future phases of the project we may include such models, but for now we choose to exclude them.

We note in the section "Model configurations and forcings" that models with interactive ice-shelf cavities should not be used for SOFIA experiments:

Models that already include interactive representations of ocean-ice shelf interactions should not be used for SOFIA experiments, as they already include the freshwater forcing that we represent with our protocol.

4/ Minor points.

Line 96, I would replace 'total' by 'additional' as the total freshwater input includes also the climatological mean fluxes, not just the recent increase as more explicitly stated line 99-100

Replaced "total" with "additional".

I would add in Table A1 that all the experiments are made with the Antarctic adjacent distribution, except 60Swater as currently the distribution is only clear for this experiment.

We have clarified in the table what the distribution of additional freshwater is for each experiment (including the four new tier 3 experiments)

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RC2: 'Comment on egusphere-2023-198', Nicholas Golledge, 19 Apr 2023

Swart et al: SOFIA

General comments

This paper outlines a new climate modelling initiative called SOFIA, that aims to assess the impact of including ice-sheet meltwater discharge on future projections of Southern Ocean and global climate evolution. This builds on the many studies that have done such experiments previously, but aims to formalise and standarise the procedures employed so that inter-model differences can be identified and quantified.

The paper is succinct and sets out the intentions and procedures clearly. I don't think it does a particularly objective job of summarising the previous literature, however, with overt reliance on some of the same few citations throughout (Bronselaer et al 2018 & Fyke et al 2018 for example are both cited repeatedly, yet Fyke was simply a review paper and not a modelling study). I realise that the authors are more familiar with the climate model literature than the ice sheet modelling literature, but I think some further work could be useful in this area, to avoid the current bias.

We thank the reviewer for this useful assessment, which also highlights that we need to better highlight the purpose of the proposed experiments. Our original paper cites over 100 references - which is a high citation density covering a wide range of the previous literature. It is true that there exists a large body of ice sheet modeling literature that explores the response and feedbacks of ice sheet dynamics to changing climate. However, a comprehensive review of that work and the mechanisms therein (e.g. quantifying the unfolding of a potential MISI) is outside the scope and mandate of the initiative that will be brought forward through SOFIA. Those aspects are already well captured and documented by community efforts, such as ISMIP, MISMIP, MISOMIP, while SOFIA really is about the response of “all other components” in the Earth System to ice sheet driven freshwater input from Antarctica (and feedbacks therein). To that end, we retain the review article of Fyke et al. because it provides a useful summary of previous modeling studies and hypotheses associated around interactions of the ice sheets in the Earth System. However, we have removed some of the original references to Fyke et al. and added additional references. We find that literature exploring the response of the climate system to potential future mass loss from Antarctica is generally more scattered and less comprehensive, which is part of the motivation for our initiative.

We have clarified our objective in the introduction:

A large body of ice sheet modeling literature exists that explores the response and feedbacks of ice sheet dynamics to changing climate, such as the Ice Sheet Model Intercomparision Project (Nowicki et al., 2016), or the Marine Ice Sheet-Ocean Model Intercomparison Project (Asay-Davis et al., 2016). However, there has not yet been a comprehensive effort to assess the response in other components of the climate system to ice sheet driven freshwater input from Antarctica (i.e. ocean, sea-ice and atmospheric changes), and particularly the role of model uncertainty in that response.

Further, in order to address the reviewer's concern of the overt reliance on few citations, we added several explicit modeling examples, three of which were first published after the first draft of the SOFIA description was submitted.:

Li et al. (2023). Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater (https://doi.org/10.1038/s41586-023-05762-w)

Hattermann and Levermann (2010). Response of Southern Ocean circulation to global warming may enhance basal ice shelf melting around Antarctica (https://doi.org/10.1007/s00382-009-0643-3)

Wang and Beckmann (2007). Investigation of the impact of Antarctic ice-shelf melting in a global ice–ocean model (ORCA2-LIM); https://doi.org/10.3189/172756407782871602

Park et al. (2023). Future sea-level projections with a coupled atmosphere-ocean-ice-sheet model (https://doi.org/10.1038/s41467-023-36051-9)

Jourdain et al. (2017). Ocean circulation and sea-ice thinning induced by melting ice shelves in the Amundsen Sea (https://doi.org/10.1002/2016JC012509)

Si et al. (2023). Heat transport across the Antarctic Slope Front controlled by cross-slope salinity gradients (https://doi.org/10.1126/sciadv.add7049)

Naughten, K.A., De Rydt, J., Rosier, S.H.R. et al. Two-timescale response of a large Antarctic ice shelf to climate change. Nat Commun 12, 1991 (2021). https://doi.org/10.1038/s41467-021-22259-0

We have added these references in various places where relevant.

The figures are fine and are useful, and with the modification suggested below I think Table 1 will be a very useful summary.

Specific comments

l2 - is 'injecting' the most appropriate verb to use here? The ice is melting slowly over a wide area, so maybe 'releasing' would be better?

Replaced “injecting” with “releasing”.

l2-3 - "This freshwater input could feed back onto climate change, particularly since the Southern Ocean is a key contributor to global heat and carbon uptake" - I find this sentence a bit vague. Why not lean on previous research and be more definite: "Previous studies have shown that this freshwater input could lead to xxx and yyy, exacerbating climatic changes already underway" or something like that.

The abstract has been modified. We now provide a more specific sentence on previous studies, as follows:

Previous modeling studies that have imposed additional Antarctic meltwater have demonstrated regional impacts on Southern Ocean stratification, circulation, and sea ice, as well as remote changes in atmospheric circulation, tropical precipitation, and global temperature.

l5-6 - "unaccounted for in current global climate change projections" - I would say 'typically unaccounted for', because some GCMs with interactive ice sheets do exist, and not all 'climate change projections' are just about temperature, some relate to SLR for example, for which several scenario-based simulations incorporating meltwater feedback now exist. I would suggest taking a look at AR6 Ch9 for some info on that.

Inserted "typically".

l11 - is it the 'team of scientists' that is important here, or the fact that different models are being used with standardised methods?

Both are important and described in the abstract.

l19 - citation to support the first statement perhaps?

This sentence has been deleted in the revision.

l50-51 - "Since virtually

all existing Southern Ocean hosing experiments have involved only one model" - perhaps clarify that you mean 'have EACH USED only one model', because at the moment it reads as though all the experiments have used the same model, which is not the case, right?

Yes, many different models have been used across previous studies, but with each individual study using only a single model. We have amended the text as suggested to clarify this.

Table 1 - this is a very useful summary of the studies that have been undertaken. However, at the moment it only considers the climate model side of things. Since one of the key arguments being made to justify the SOFIA initiative is that few models

incorporate interactive ice sheets, how about having a column that shows the full suite of model components being employed? E.g. 'OA' could be a standard ocean-atmosphere setup, whereas 'IOA' could be ice-sheet/ocean/atmosphere. I feel like this could be very useful for identifying which studies have 'closed the loop' as it were. For example, the Bronselaer paper is repeatedly cited throughout this paper but they didn't include a ice sheet model, whereas Golledge et al & Sadai et al did. The groupings in the table could then be adjusted to reflect this.

The two primary intentions of this table are to highlight existing studies and the range of forcing magnitudes used (by which we organize the entries). For additional context we indicate in the "Function" field, whether the input is idealized (e.g. constant, linear or exponential), or more realistic and varying in time (V). The studies indicated as "V" are: Bronselaer et al. (2018), Sadai et al. (2020) and Golledge et al. (2019). The Bronselaer (2018) paper used a variable input of freshwater, derived from a previous study (De Conto and Pollard, 2016), which derived the input from an icesheet model (the same study cited for the forcing used in Sadai et al). Therefore, the "Function" field is an indicator of the freshwater forcing used, and we feel this provides a good indication of differences in forcing used at the level of detail appropriate for this table. None of the studies cited are truly coupled, so describing models as IOA does not seem appropriate. Describing the finer details of how forcing is derived/applied across the 30 studies listed is beyond our scope, but accessible to readers through the collected references and original papers.

l113-115 - I think it might be worth mentioning that these kind of coupled experiments using interactive ice sheets are more common for Greenland - see for example Vizcaino et al 2015, Muntjewerf et al 2021 and various others. Again, much of this literature was assessed in AR6 Ch9 so could be easily discovered and included, perhaps more in the intro part of the paper than in this particular section though.

We have modified these lines to include the references mentioned, and clarify that some fully coupled studies do exist, as follows:

In a limited number of dedicated studies, interactive ice-sheet components fully coupled to atmosphere-ocean climate models have been applied for Greenland (e.g. Vizcaino et al., 2015; Muntjewerf et al., 2020) and Antarctica (e.g. Siahaan et al., 2022). However, due to their large computational expense, long timescales, and sensitivity to background climate, fully interactive ice sheet and ice shelf components, or even ice shelf cavities for the surrounding ocean, have generally not been included in coupled climate models, particularly those participating in CMIP6 (Fox-Kemper et al., 2021).

l133-4 - I think this statement "using these to force stand-alone ice sheet models" with the citation to the four papers cited is misleading, because Edwards et al presented only emulated results, not direct model outputs, and Golledge et al used a two-way (albeit offline) coupling specifically to capture the ice-ocean feedback. Perhaps this sentence can be rewritten to clarify what each of these studies did.

We have modified these lines to clarify as follows:

Integrating ice sheet models directly into coupled climate simulations is challenging, and hence the primary approach to date has been to take ocean and atmospheric climate fields from climate models and using these to force stand-alone ice sheet models to produce future projections of ice mass (Seroussi et al., 2020; DeConto and Pollard, 2016), in some cases allowing for an offline, single step, coupling back to the ocean (Golledge et al., 2019) to explore feedback between the ice sheet and the climate system, or in some very recent studies using full inline coupling between the icesheet and climate models (Siahaan et al., 2022; Park et al., 2023)

l154-6 - "Furthermore, feedbacks have been hypothesized, where increased meltwater input further enhances on-shore ocean heat transport through different processes in different regions (Hellmer et al., 2017; Hattermann, 2018; Bronselaer et al., 2018)." Yes, true, but why not also mention that some models have actually TESTED this feedback and quantified the response?

We have revised this sentence to include a larger body of literature and differentiate more carefully the nuances of the individual contributions.:

Furthermore, feedbacks have been hypothesized, where increased meltwater input further enhances on-shore ocean heat transport through different processes in different regions (Hellmer et al.,2017; Hattermann, 2018; Bronselaer et al., 2018) and with impacts on the ice sheet mass loss (Park et al., 2023; Golledge et al.,2019; Timmermann and Goeller, 2017; Naughten et al., 2021). Some of these feedbacks have been assessed more carefully in regional (Jourdain et al., 2017) or process-oriented (Si et al., 2023) context, while other studies delineate larger-scale effects (Li et al., 2023b; Hattermann and Levermann, 2010; Wang and Beckmann, 2007). However, a systematic assessment of the response of on-shore heat transport to increased freshwater input from Antarctica across state-of-the-art climate models is still lacking, and is subject to resolution and other uncertainties in the models.

l176 - see note earlier regarding 'only one model'

Have added “each” to clarify, as above.

Secion A4.3 - might be worth mentioning somewhere that Bakker et al 2017 used hosing experiments to explain some of the centennial-scale variability in climate during the Holocene - the timescale is different to the Historical experiments planned here, but the rationale and mechanics are the same.

We thank the reviewer for this suggestion, but we do not believe this citation will improve the clarity of the Appendix.

Section A4.4 & 4.5, 4.6 - using ISMIP6 for basal melting is ok, but why then use an approximation for the calving flux? This assumes that the calving to basal melt ratio stays constant in time, which might not be true. It would be more physically robust to use calving fluxes directly from the ISMIP model outputs.

We have discussed this issue with the ISMIP project leads (and some of us are also participants in ISMIP). To summarise, ISMIP was not designed to accurately quantify the calving flux, although it is a by-product of many of the models. However, there is a massive spread in the calving flux across models, and its physical robustness has not been assessed. The advice we were therefore given is that the calving flux would be unreliable to use. Hence, we stick with the fixed ratio of basal melt to calving flux, which has also been employed in previous studies. To clarify this aspect, we have explained this reasoning in the revised version of the manuscript in section A4.4, as follows:

Basal melt rates for ISMIP6 were obtained from projected ocean temperatures and time-varying ice geometry, intended to provide boundary conditions for the ice sheet simulations to quantify the mass flux across the grounding line (Jourdain et al., 2020), which is relevant for assessing sea level contributions from Antarctica. Although iceberg calving is a by-product of many of the ISMIP6 models, its reliability was not systematically assessed, and the intercomparison does not make any statements about the partitioning of the total freshwater flux between basal melting and iceberg calving in future scenarios. Hence, to account for additional iceberg calving, we divide the ISMIP6 basal melting rate by a factor of 0.55, following the fraction of basal melt to calving given in Rignot et al. (2013).

N R Golledge, 20th April 2023

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Community comment 1:
CC1: 'Comment on egusphere-2023-198', Katherine Turner, 24 Mar 2023

Review of *The Southern Ocean Freshwater release model experiments Initiative (SOFIA): Scientific objectives and experimental design* by Swart et al.

The Southern Ocean Freshwater release model experiments InitiAtive (SOFIA) provides a set of climate model experimental protocols for quantifying the response to Antarctic meltwater. The protocols are general, which allows them to be applied to both high- and intermediate-complexity climate models.

The manuscript reviews the theory behind ice mass budgets, current representation of meltwater forcing in climate models, and historical trends and projections for ice sheet mass. Additionally, the manuscript covers how uncertainties in model architecture, internal variability, and the location of meltwater addition may impact the climate response. A thorough description of the experimental setup is located in the appendix.

The manuscript presents an interesting set of experiments to explore the role of freshwater forcing in the Southern Ocean, which is both highly uncertain and poorly represented in current climate model setups. The experimental setup includes three broad experiment types within tiers 1 and 2:

> (tier 1) Pre-industrial climate conditions forced with constant freshwater forcing,
> (tier 2) Historical climate conditions forced with linear freshwater forcing near the end of the historical runs, and
> (tier 2) Future projections with transient freshwater forcing calculated from ice models forced with RCP climate forcing (although I am unsure whether the ice models are forced with surface temperature changes or radiative forcing from GHGs + land use + aerosols)

There is a third tier of experiments that tests the sensitivity to the horizontal distribution of meltwater addition and to the heat fluxes involved in the phase change.

As I understand it, this paper aims to 1. provide experimental context for future papers which are already in the pipeline, and 2. advertise the SOFIA experiments to other climate modeling groups and encourage them to provide additional runs. Regarding aim 1, I think the paper is successful. Appendix A provides useful suggestions for creating ensembles, detailed descriptions for how forcings were calculated (particularly for the future projections), and a discussion of how ocean-ice models can contribute if SSS restoring is included. The standardization of experiments through SOFIA will help increase the transparency of future model-based studies and bring new, much-needed knowledge on Southern Ocean dynamics.

Regarding aim 2, I think the manuscript would benefit from some restructuring before submission. Signposted argumentation across the introduction, review, and ending discussion would be helpful in guiding the reader along the manuscript. I had difficulties understanding exactly how specific experimental setups would be used to reduce the various uncertainties and goals described in Sections 2 and 3. As a non-expert, I think the manuscript would benefit from a (sub)section in which the experiment aims are explicitly stated, rather than requiring the reader to infer some of these aims. I also think that connections to other model intercomparison projects (e.g., FAFMIP) should be emphasized, as these connections could attract modeling groups that already participate in these other projects.

Ultimately, I think the manuscript is a useful and timely work that merits submission. My suggestions below are to help readers from other fields within climate modeling appreciate the need to understand meltwater impacts and, in the long term, work towards creating coupled climate models that include interactive land and sea ice.

Thank you for the detailed comments. We address specific suggestions below.

Signposting suggestions:

As it stands, each main section jumps directly into a subsection. A few sentences at the beginning of each section could provide extra motivation and emphasize the connections between the review material and the proposed experiments.

We have added short sentences of the goals of each section, and used this to link the sections together.

While the experimental descriptions are in the appendix, it would be useful to the reader to have a brief outline of the experiments and overarching themes of the project in the introduction. Perhaps in the introduction, the aims/motivating questions can even be listed with bullet points. That way, the reader can reference either the introduction or the appendix as they read the rest of the manuscript, depending on their level of involvement.

In the introduction, we include a brief summary of the major aims of the initiative. We have added content to the main “Scientific Objectives” sections to further elaborate on the key questions.

References to the SOFIA experiments are sparse and general (see line 128 for an example), which hinders readability. I recommend that the references to the experiments be more specific if the authors decide against adding an “experimental setup” section to the main text.

We have added content to the main “Scientific Objectives” sections to more explicitly link the experiments to specific scientific questions.

It would be nice to see more discussion, both within the main text and in the descriptions of the experiments in Appendix A, about why these specific experiments were chosen. For instance, regarding the preindustrial *antwater* experiment, how will the results be used in coordination with the other experiments (if at all), considering the differences in magnitudes? Will the authors test the linearity of the response using the idealized historical experiments? What are the advantages of using SSP-style forcings for future projections over the 1% CO_2 experiments commonly used in other model intercomparison projects such as FAFMIP?

For each experiment, we state our main intended aim within the experiment description in Appendix A. We have added content to the main “Scientific Objectives” sections to discuss the link between scientific questions and the experiments in more detail. While we have made an effort to expand this, without doubt there will be other uses and questions we have not foreseen.

Regarding comparison of the experiments, yes this is anticipated. The meltwater forcing magnitude in *antwater* is comparable to our ssp585-ismip-water experiment in about year 2070. We choose to use SSP style forcings over idealized forcings for several reasons. Firstly, the basal melt terms from ISMIP are available for the SSPs, but not for idealized scenarios. Secondly, we are interested in exploring the future impact of meltwater under the range of plausible future rates, which we bracket with ssp585-ismip-water and ssp126-ismip-water. We have added some text to help to clarify these objectives.

I would be interested to know if there are additional benefits to these runs outside quantifying uncertainty from the Southern Ocean. For instance, is there the potential to use some of these results to improve global or regional projections of sea level rise? The connection to biogeochemistry is mentioned briefly, but I would also be interested to read more about any (even speculative) impacts.

A major aim of SOFIA is to explore how meltwater from Antarctica influences the global climate system, beyond the Southern Ocean - as described in the section Scientific Objectives. However, for sea-level rise, although meltwater input to the ocean (from grounded ice) is important, the SOFIA experiments and models are not designed to provide an accurate quantification of eustatic sea-level rise (for example, the experiments do not differentiate between the melt of grounded vs floating ice, and the models may make fixed volume assumptions). What could be diagnosed from the models is the impact on steric sea-level rise. We have added text to clarify these points into a new section entitled: *Interpreting SOFIA results.* We anticipate a future analysis paper will expand on the biogeochemical impacts of adding meltwater, which we have noted as an area of interest, but do not expand on as we are not aware of any existing literature on this topic.

Minor points:

> Some sentences are difficult to read and have slight grammatical mistakes – for instance lines 19-21 has a misplaced modifier, and the clauses in 156-157 do not share the same subject. Overall, the manuscript has quite complicated sentence structures where the meaning can be unclear (e.g., line 163-164). I would recommend the longer sentences throughout the manuscript be broken up to improve clarity.

We agree that improvements could be made on clarity and sentence structure throughout and have made many modifications to address this. Thank you for pointing this out.

Line 45: is there a contrasting study to Beadling et al., 2022 missing?
Beadling et al., (2022) showed a disagreement (contrast) in the thermal response on the Antarctic shelf in two different climate models (GFDL-CM4 and GFDL-ESM4). However, yes there are a few other studies who also show disagreement in the sign and magnitude of the thermal response on the shelf. We have added those studies to the list.

Lines 97-98: What are the estimates from the Shepard et al. and Green et al. papers?

Line 195: Behrens et al., 2015 (doi: 10.1002/2015JC011286) investigates this with the CMIP5 models – perhaps good to include

Added, thank you.

Lines 288-289: A reference to FAFMIP in the main paper would also be a useful comparison as it is an established model intercomparison that includes freshwater forcing.

We agree and have added this to the introduction.

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CC2: 'Comment on egusphere-2023-198', Karen J. Heywood, 28 Apr 2023

This is a fantastic initiative and a most interesting paper. I wondered if you were aware of the paper by Richardson et al. In 2005, which was, I believe, the first to undertake an experiment using a coupled climate model (HadCM3) to investigate the impact of a meltwater addition around Antarctica, demonstrating an increase in Antarctic sea ice and subsurface ocean warming.

Short-term climate response to a freshwater pulse in the Southern Ocean

Glen Richardson, Martin R. Wadley, Karen J. Heywood, David P. Stevens, Helene T. Banks

Geophysical Research Letters

First published: 01 February 2005

https://doi.org/10.1029/2004GL021586

Of course, the models and experiments are much better nowadays, and longer model results are possible. I look forward to further results from Sofia!

Thank you for the comment. Richardson et al. is an interesting early study. After some consideration, we choose not to include it in table 1, as that study applied an instantaneous pulse of freshening, while all the other studies in Table 1 applied an ongoing forcing over time. One issue is that it is not clear how best to report the pulse input since, instantaneously, the Richardon et al. forcing (given as 1.677 × 10^{14}m3 of freshwater) is 1.7e8 Sv - so 8 orders of magnitude larger than the next study (but averaged over time it is more comparable at 0.5 Sv). As we note in the caption, table 1 is not a comprehensive list of all previous studies.

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CC3: 'Comment on egusphere-2023-198', Paul Holland, 10 May 2023

Hi Folks

Many congratulations on this initiative, which is very timely and will be a very important addition to this field. The range of experiments out there at present does complicate matters, and SOFIA should clear that up very nicely. I have a few comments on the experimental design. Apologies for the unsolicited review!

We appreciate the input!

Clearly the over-riding goal of SOFIA is to provide a consistent set of experiments that are practically achievable to the modelling centres, and that will necessitate some compromise on the physics. I am fully sympathetic to that. Therefore I am really expressing the below in order to raise a few possible caveats to the results that emerge, and to prompt future discussion, rather than to suggest any change in experimental design.

> The climate models will still have their ‘runoff’ (as shown in Figure 1b) from Antarctica during these experiments, but that will provide an uncontrolled additional Antarctic freshwater source to the ocean that may complicate the intercomparison of models. For example, there is a large increase in precipitation onto Antarctica during SSP5, which varies between models, and that will flow straight into the ocean. This precipitation increase can be the same size as changes in ice discharge during the 21st century so I think it is important (e.g. Seroussi et al 2020). The best solution could be to turn off runoff during these experiments and just implicitly accumulate the mass on Antarctica.

Next best could be requesting further control experiments where needed (e.g. SSP585 without added FW) so that the effect of adding FW can be isolated from the model runoff changes. Simplest would be just analysing the runoff alongside the other results.
We agree that runoff is an important term in the budget. Our data request includes terms for precipitation, evaporation and runoff. We will encourage analysis of changes in runoff (and E-P more generally), in upcoming analysis studies (but we do not conduct analysis in this paper).

It is a very uncertain choice taking the future parameterised melt from ISMIP6 models and multiplying by ~2 to account for calving. Calving could not change at all (larger, thinner ice shelves are implicit in the ISMIP6 melt rates) or could increase massively (ice shelves collapse as the grounding line retreats). Even if calving did increase, melting should be reduced accordingly, so it is not clear whether x2 is needed. One solution could be to take the change in ice sheet discharge across the grounding line from the ISMIP6 models, because that circumvents this point.
We agree that this is an uncertainty. Reviewer 2 raised a similar issue, and our response to that comment explains that calving flux from ISMIP shows a massive inter-model spread, and thus is not reliable enough to be used here. In the text we add additional explanation of our choice, and a caveat on this uncertainty. We note that if we took the change in grounding line discharge, we would be introducing the assumption that the ice shelf volume was remaining constant, which is in itself not justified. We acknowledge that the currently available choices are imperfect and contain assumptions - however we believe they are reasonable for our goal of quantifying the first-order impact of including meltwater into climate simulations.

Inputting freshwater into the surface, uniformly around Antarctica, with no latent heat extraction, produces a clear, tractable experiment but it is an unrealistic choice. In reality almost all of the additional mass flux has appeared in the Amundsen Sea, at depth, with a latent heat extraction. (Admittedly some ice shelf collapses have occurred on the peninsula - though those bergs were quickly exported - and the Ross and FRIS cavities could melt by 2100 under SSP5.) As with all of my points, I am not concerned about the model experimental design, just its interpretation. For me the stated design creates three issues: 1) Hosing the ocean with freshwater at the surface and no strong cooling produces a strong stabilising effect, which is not representative of real glacial melting. I assume this will cause excessive shutdown of dense water formation in 'cold' shelf regions, and excessive warm-water feedbacks in 'warm' shelf regions; 2) The uniform near-coastal distribution hoses the ocean directly in the 'cold' regions that form dense AABW, unlike in reality, thus over-stating the potential effects on AABW; 3) the 60S distribution hoses the ocean beneath the sea ice, over-stating the potential effects on sea ice and Southern Ocean SSTs. Issue 1 is compounded in issues 2 and 3, of course. So I think the current experiments are all extreme in over-stating the role of FW. For me the best solution would be to add the opposite extreme experiment with the all FW added in the Amundsen Sea only, distributed over depth, and with corresponding latent heat removed.

Thank you for pointing out these limitations. In the revision we have added three new tier 3 experiments to test the sensitivity to freshwater inputs at depth and that are focused in the Amundsen and Bellingshausen Seas. We agree that users of the SOFIA data must interpret the results with these limitations in mind. To assist readers and users of the experiments to understand the limitations described above we have added a section called Interpreting SOFIA results, as follows:

Our experiments are best interpreted as tests of the impact of adding meltwater into coupled atmosphere-ocean or ocean only models, and for understanding how excluding this meltwater has influenced existing climate change projections, such as those from CMIP6. When interpreting results from SOFIA, and in particular the tier 2 historical and future scenario simulations, users should bear in mind the idealized nature of the horizontal and vertical distributions of meltwater input, and the absence of latent heat of melt associated with this water. While the tier 2 experiments aim to use realistic meltwater inputs, there are large uncertainties in these historical and future meltwater input rates. We encourage users to make use of the various tier 2 and tier 3 experiments that have different magnitudes and distributions of forcing, and the inclusion or not of latent heat of melt, in order to understand the sensitivity of their results to these choices.

Beyond the simplifications in the SOFIA forcing protocol, users of the data should also remain aware of the limitations of the models used to run the experiments. For example, many of the models participating in SOFIA so far are CMIP6-class coupled climate models, that do not directly resolve mesoscale and submesoscale dynamics, the continental slope current, Dense Shelf Water overflows, etc. Nonetheless, such coupled models remain the best available tools for understanding future climate change, including the impact of meltwater that we examine here. Higher resolution models (particularly ocean only models), that participate in the future may better resolve these dynamics. Despite the simplification in the meltwater forcing protocol and the limitations of the models, we believe that the SOFIA results can be used to help inform the next generation of Earth System Models, as well as helping us to understand the possible impact of meltwater on the real climate system.

As I said above, all of these are just thoughts for discussion. SOFIA is fine as-is, and the authors should feel free to ignore these comments or take whatever action they feel sensible. I hope these thoughts help more than they hinder. Best of luck with SOFIA.

Cheers, Paul