Response to Reviewer 3:

Reviewer comments are red font. Replies are in black font.

"Datasets and protocols for including anomalous freshwater from melting ice sheets in climate simulations" By Schmidt et al. provides valuable transient forcing of ice sheets freshwater with protocol recommendations for modellers implementing the dataset consistently. This work certainly makes an important contribution to both the Earth system modelling and ice sheet modelling communities

Thank you very much for your support for this initiative and the constructive comments.

Please consider my suggested revisions below:

1. Missing figures showing the timeseries of each freshwater product listed in Section 3.3. These products are the key output of the paper. However, the features of some products are not presented and discussed. Figure 3-5 do this for Greenland ice discharge and iceberg maps, although Figure 5 is not cited in the main text. It would be good to include figures and discussions for the remaining products.

We have added additional figures for each data product..

2. Missing evaluations and discussions of how well this transient freshwater forcing and suggested modelling approaches improves the representation of ocean circulation, salinity, sea level, etc., in model simulations. The modelling approaches in the two runs are described in Section 4 (Pre-industrial control runs and historical simulations); however, evaluations of the methods and products are not provided. I appreciate the authors' time and effort, it would be good to include at least some preliminary modelled results using freshwater forcing from this work, along with comparisons to other studies.

Thanks. We are working on the implementation of these forcings in our own simulations but this takes time and would unnecessarily delay the publication of the forcing data if we were to wait until they were completed and analysed. We have made a conscious decision to only present the data inputs in this paper, in line with many other forcing input description papers for CMIP7. We have also added a section dealing specifically with sea level.

See specific comments below:

L5 – The abstract does not mention projections. Recommend clarifying that the proposed protocol relates solely to historical simulations but that freshwater forcing is likely to become very much more important in future projection scenarios.

We have clarified the abstract to be explicit about projections and have expanded Section 5.5 slightly to enhance that discussion. However, we aren't going to opine on the importance of the FW additions in the projections without having the projected fluxes ready to go - it may be that it

is a big deal for Greenland but relatively muted in the Southern Ocean (though Purich and England, Payne et al, Golledge et al have already looked at this). This is for a later paper in collaboration, for instance, with the ISMIP project.

L9 – Can the authors confirm that freshwater forcing will be included in the forcings for the CMIP7 historical experiments? CMIP7 is now very close to releasing this forcing, and it is unclear whether freshwater is actually included.

The goal is to provide an option for the CMIP7 simulations, but we are not in a position to mandate their use. We hope that a significant fraction of the historical simulations will employ these data.

L21 – Not convinced that computational expenses hamper the incorporation of ice sheets into ESM. They are by comparison to other elements of the climate system cheap.

This is true in the run-time sense, but the long time scales for ice sheets to equilibrate are prohibitive for CMIP-class models and so this has slowed the ability of such models to include ice sheets that are both accurate with respect to the present and with similar sensitivities to observed ice sheets, which could require multiple Holocene-length simulations.

Providing historical freshwater forcing is a step forward but it does introduce an issue around projections. What are ESMs supposed to do at the start of the projection period?

This is discussed in section 5.5.

L42 – There is no Appendix B.

Fixed.

L60 – Not convinced that these definitions are helpful. Are there not standardized definitions (CMIP or ISMIP6/7) that could be used? Runs the risk of making what is a fairly confused set of terms worse. Definitions could be improved by adding relevant units.

These definitions are for clarity within this paper, and are useful for that role. We have added discussion of the units and a definition for SMB.

L65 – This is confusing and does not match the definition of discharge immediately above (in which discharge sits between ice sheets and ice shelves, while here discharge is after ice shelves before calving).

Minor tweak to language for clarity.

L67 – Upstream of grounding line? What about ice floating on subglacial lakes? This is upstream but not grounded.

We have rewritten to be clearer that this means upstream of the final grounding line. Sub-glacial lake hydrology is significantly beyond the scope of this work!

L81 – Runoff is not purely a mass loss process if it includes rainfall (and melt of seasonal snow).

SMB is P-E-R, where R is the net runoff flux after any refreezing or retention, so we think that this can be considered a mass loss, just as precip is a mass gain. For a diagram of all mass flow terms, see https://github.com/mankoff/sankey (which is discussed in Mankoff (2025)).

This section may be helped by linking the definition to Figure 1 more tightly. At present, terms in Figure 1 do not match the definitions (eg basal melt) and vice versa (eg discharge).

We have improved the descriptions in the figure and expanded the definitions in the text to better align with one another.

L97 onwards – Defining symbols for these various quantities and how they relate to one another would be helpful here. There are a number of things going on in the section (baseline/anomaly, time period of baseline, separation of freshwater into various fluxes such as grounded, shelf melt and shelf calving) that need to be explained more clearly. There is also some danger in referring to 'ice mass anomalies' because terms such as this are often used in ice mass budget calculations (freshwater fluxes are related primarily to the loss terms where mass budget relates to the net of gain and loss).

We are now explicit in how we define 'anomaly' and are clearer in the definition of the baseline for any product (easy for Greenland, harder for Antarctica).

L100 – Needs to be made clear that GRACE does not directly measure freshwater flux.

This was not the intended implication, but the sentence has been adjusted to be clearer.

L104 – Figure 3 is cited before Figure 2.

Fixed.

L105 – This seems to be very detailed and relates to the way in which the forcing has been calculated. Would be better in Section 3 or 4 rather than Introduction.

We feel that the discussion of what we mean with 'anomalies' is fundamental to this paper and so we respectfully will leave this discussion where it is. We have nonetheless tried to make the discussion a little clearer.

L118 – Good to state that basal melt of grounded ice not included in the assessment however requires some justification to demonstrate, for instance, that this flux is much smaller than the other freshwater fluxes leaving the ice mass.

We now reference the summary paper of Manoff (2025) for that assessment (see https://github.com/mankoff/sankey)

L124 – quasi.

Fixed.

L153 – This is too vague – this assertion needs to be supported by references.

This assertion was summarised from the responses to our survey, and our own practices. We have put in some relevant citations.

L159 – Use of the term ‘Discharge’ here and in the next paragraph is confusing. Does this refer to the previous definition of ‘discharge’ or discharge of freshwater? If the latter, then it is not clear that the ESM calculations discussed here would explicitly calculate discharge (line 171).

This term refers to freshwater, and we have adjusted this paragraph. In the next paragraph, it is the discharge per the definition. They do not explicitly calculate discharge, but it is generally parameterized in order to account for non-dynamic ice sheets in GCMs.

L200 – Define what is meant by ‘regional flow’ here. Will this be done on the basis of sectors/basins as per IMBIE etc?

Edited to “we aim to provide data that represents the regional ice discharge, runoff, calving, and melting and their change over the historical period for…” And yes, per Fig. 2 we provide this at regional resolution based on the IMBIE etc. regions.

L203 – based on Rignot et al. (2013) and Mouginot and Rignot (2019).

Fixed.

L210 – Earlier grounded basal melt was explicitly disregarded.

We remove reference to basal sourced water here. There is water released throughout the year, but the bulk is released during the summer months.

L213 – Clarify differences between refreezing and retention. Retention on what timescales?

Removed retention - it was an unnecessary detail. Runoff is melt + rain - refreezing.

L223 – Why choose flux gates 5 km upstream from the grounding line?

We’ve added an explanation - but specifically it is because estimating ice thickness at the terminus is challenging, so flux gates are usually placed inland.

L242 – Clarification required here – grounding line retreat in itself is not a source of freshwater (increased freshwater flux and GL retreat are both consequences of increased melt for instance). Repeated confusion around inclusion of grounded ice melt.

Changed to “Additional sources of freshwater include frontal melt expressed as grounding line retreat…” and that basal melt is not included, “We neglect the basal melt of grounded ice because it is both one of the smallest terms (Mankoff, 2025) and it is mostly a steady state

processes, and therefore has no anomaly, which is the focus of many of the products presented here.

L245 – ‘Surface runoff’ Ideally all terms of this type should be defined in Section 1.1.

Removed most use of the word ‘surface’ as it was unnecessary.

L254 – Figures 3 and 4 are not cited in this section. The section does not include any discussion about the melt of ice bergs (i.e., Figure 4).

All figures are now linked in the appropriate sections, and all data products now have a specific figure. The iceberg melt distribution maps are explicitly discussed in Section 3, and in more detail in Section 4.1.2.

The discussion on p5 about baselines and anomalies is not mentioned at all. It is unclear at this stage what form the freshwater forcing will be take.

The explicit statements about the form of the data products are in Section 3.3.

L262 – This is confusing Antarctic SMB has little to do with freshwater release from Antarctica and it is not clear what information on freshwater can be gleaned from trends in SMB.

The trends may not be relevant, but SMB is a key input to the mass balance of ice shelves. The method uses surface elevation and SMB inputs to estimate basal melting. We also use the input/output (IO) method to estimate grounded mass loss (most of which feeds into ice shelves), and the IO method uses MB = SMB - Discharge.

L266+271 – There are a few steps between the observations mentioned in the preceding paragraph and ‘good estimates of Antarctic freshwater fluxes’ that may be worth explaining.

Added: *We use the input/output method (mass balance = SMB - discharge) to estimate grounded mass loss (Rignot et al., 2019), a similar method to estimate ice shelf basal melt (SMB inputs minus elevation change, Davison et al. (2023); Paolo et al. (2024)), and remote sensing image time series of iceberg calving (Davison et al., 2023).*

L273 – Similar issue - sea level rise (ie net mass budget) is not directly linked to freshwater discharge (which is primarily to do with mass loss only).

We have added a specific section dealing with sea level in Section 3.

L289 – Is the ratio by each basin or the entire Antarctica?

Line removed for clarity since these calculations are independent. .

L297 – It would be helpful to have information on units here, as well as temporal resolution etc.

Added: *We provide the following data products. All time series are annual temporal resolution and units Gt yr^{-1}. All products have regional resolution per ice sheet (Fig.~\ref{fig:regions}). The iceberg melt maps 0.5 degree spatial resolution and monthly temporal resolution, but are steady state. Units for iceberg melt maps are m^{-2}, and when multiplied by cell area maps should sum to one.*

L297: Also it is unclear what the relationship is between the various products. For instance, were discharges and runoff used to calculate the freshwater anomalies for Greenland? Similarly, for Antarctica was calving and submarine melt used to find the freshwater anomaly? How? A conceptual figure may help here (also note use of products in protocol mentioned below).

We have expanded on the methodology in the text.

How is this related to the iceberg melt maps?

The iceberg melt maps are orthogonal to the calculations of the FW anomalies themselves.

These products are the key output of the paper. It would be useful to have some plots showing key features. Figures 4 and 5 do this for iceberg melt although they are not cited in this section.

Additional figures for each product have been added.

It would also be helpful to add some explanation of how each of the products is used in the protocols described in the rest of the paper and whether they are used as anomalies or absolute values. The two runs described in Section 4 are pre-industrial and historical: can the authors indicate which product is used when?

The piControl runs do not use any of our FW data - though they could use our maps, and protocols (for regional distributions and splits between forms of discharge). How the FW products are used in the historical runs is a function of the approach (as outlined in Section 4.3).

L351 – Tracer is not previously discussed.

Now mentioned earlier.

L353 – ‘Relaxation time constant’ seems to imply a specific way of incorporating freshwater into the pre-industrial but it is unclear what this method would actually be. More detail required.

The added flux (F) is defined as a weighted average of the discharge from the previous year (F0) and the previous year’s ice sheet imbalance (I). The weighting determines the relaxation time constant. I.e. a weighting of 0.9/0.1 would be equivalent to a 10 year timescale. Written another way, F = F0 - (I - F0)/tau where tau is the number of years over which a change is effectively spread. The language in the text has been clarified.

L396 onwards – This appears to be a discussion around the fine-scale physics governing local redistribution of freshwater in fjord and around glacier fronts. Not clear how it relates to the implementation of the products in ESMs. Perhaps this text should be moved to an early section?

It relates because ESMs will increasingly resolve the larger fjords even if they didn't in CMIP6 - and the distribution of the discharge components will need to change accordingly. We are trying to be forward looking.

L421 – It would be good to have more discussion on the differences/consequences of the injection depth (surface vs depth) of freshwater from icebergs and ice shelves melting in the Southern Ocean.

Agreed. But we don't really know the answers yet, though the SOFIA project will make some progress related to whether it matters. We leave this for a future paper.

L429 – Not clear why the depth range of 130-230 m is suggested? '130 m is the mean depth of current ice shelf fronts in Antarctica.', but where does the number '230 m' come from?

We have expanded this section and now provide a rationale.

L434 – Please clarify if it is the configuration for the Greenland iceberg model? I don't think it is what was used in Mathiot and Jourdain (2023).

The Greenland iceberg modeling comes from Rackow et al (2017), updated by Marson et al (2024), which is a separate effort from that in Mathiot and Jourdain (2023) for the Southern Ocean, even though they are using the same base ocean model (NEMO).

L436 – The translation of iceberg fluxes to spatially variable melt rates is a key component of this paper and is lost here in the middle of a very detailed section. This important material would be better in its own subsection positioned to accompany Figures 4 and 5 perhaps between 3.2 and 3.3. Note that this text does not cite Figure 5. Currently, this text is located in the pre-industrial subsection although it would appear to be more generic than this and would be relevant to all time periods?

We have reorganised this into a section talking about general implementation and the specifics of a pre-industrial control.

L456 – Again, this subsection appears to contain a generic discussion around freshwater and energy. It is not clear why it appears under the pre-industrial.

As above.

L481 – Although this subsection is about the historical, the approach described (and shown in Figure 6) would appear to be applicable to projections as well (assuming suitable freshwater forcing was available).

Added.

L487 – May be mixing papers on historical and projection scenarios here.

Fixed.

L493 – It is more consistent to use 'Antarctica and Greenland' rather than 'SH and NH', as mountain glaciers are also included in SH and NH. Moreover, SH or NH acronym is not defined.

Fixed. But in the model results described the diagnostics were for each hemisphere, not the ice sheets specifically.

L508 – It is not clear how this discussion relates to the specific products that have been created. Which of the products are used and which are not? For instance, do the iceberg melt maps play a role?

This section has been reworked, with the sea level discussion moved to a separate section.

L589 – Worth pointing out that using this protocol for the historical implies that some extension of the freshwater forcing is required for projection experiments. Otherwise, there would be an abrupt change in forcing at the start of the projection period. An alternative might be to maintain the historical freshwater forcing into the projection period which would avoid a hiatus but become increasing unrealistic as (presumably) freshwater fluxes from the ice sheets increase into the future.

Yes. We have explicitly discussed this in Section 5.

L590 – Would it be possible to use this protocol with the variables supplied by ISMIP6? What additional work would be required? Presumably, as a minimum the iceberg melt patterns would need to be calculated for time in the future.

Yes. We are working (separately) to produce the relevant timeseries, but for the near term (say to 2100), we don't anticipate needing to change the iceberg melt patterns. But clearly, one could envisage extreme warming situations where the patterns will shift, but these will need to be calculated using appropriate models (that include Lagrangian icebergs, suitable melt parameterizations, and relevant projections).

L667 – This is a bit misleading. The products for Antarctica do not cover the period before 1991.

Fixed. New text: *We provide regionally disaggregated time-series of freshwater forcing estimates for all major basins in Greenland for 1850 through 2024 and Antarctica for 1990 through 2024.*

Figures

Figure 1. Indication of scale required for all panels.

We have improved the clarity and correctness of the figure, but note it's a schematic.

Depiction of runoff across and through the ice sheet on the Antarctica side of the diagram is misleading and should be on the Greenland side. If the diagram is meant to represent the contemporary ice sheets then the presence of a substantial ablation zone in Antarctica is also extremely misleading.

Agreed. Fixed in the updated figure.

Figure 4 – Please clarify how the iceberg melt rates are weighted in the caption and the main context. The same as Figure 5.

Fixed. New text: *Each map multiplied by cell area and summed equals one, so that these can be used for distributing freshwater inputs computed elsewhere.*

Figure 5 – What are the white lines in front of the Ross Ice Shelf in the subpanels [11] and [12]? Are they NaNs, or are they due to the grid mesh? If the latter, why are there no white lines in, for example, the panel [9], [10] and All?

Fixed.