Reviewer #2

Summary

The study evaluates the applicability of an accelerated forcing methodology in the scope of high resolution ice-ocean coupling. The authors motivate their investigation by the typical time scale discrepancy between ice and ocean dynamics and the corresponding disparity in simulation time. First, the idea and methodology of an accelerated coupling approach is presented and the models used in the study are described.

Then, standalone setups of two ocean models are used to derive ice-shelf melt rates for warm, cold and mean far-field ocean forcing conditions, as well as oscillating profiles between the warm and cold case at different frequencies. The authors use the mean cavity response time (MCRT; for the mean forcing case) as a characteristic variable to evaluate the derived melt rates. They find that averaged cavity melt rates for oscillating far-field forcings that have significantly higher frequencies than the MCRT (periods ¡=10% of MCRT) are mostly in the range of 90-110% of melt rates from time averaged forcing. However, forcing frequencies that are in the same order of the MCRT or substantially lower do either under- or overestimate the mean melt rates. Based on these ocean standalone simulations the authors anticipate that the accelerating forcing approach would only work in the first case, which they subsequently test in coupled ice-ocean simulations.

The test scenarios for coupled ice-ocean simulations are structured in three categories: 1. constant cold-to-warm forcing as well as two periodic forcings with fast (2.) and slow (3.) varying time scales. For all categories different acceleration factors are tested (between 1.5 and 10) and evaluated to the baseline scenario (no acceleration) in terms of cavity averaged melt rates and total ocean volume changes (time series) as well as spatially fields of melt rates and ice draft changes. The authors find that acceleration works well for spun-up simulations in the constant forcing as well as the fast-varying ocean forcing case, but not in the slow-varying case.

Finally, the authors conclude, that their presented approach of accelerated forcing in high-resolution ocean-ice coupled models is also applicable in real-world applications for ocean to ice forcing that varies over century-long timescales.

We thank the reviewer for the detailed and accurate summary of our study.

General comments

The paper addresses a relevant and scientifically interesting topic which fits very well in the scope of GMD. It presents a novel investigation of testing the impact of asynchronous coupling in idealized setups and introduces a useful metric

(MCRT) to assess the applicability of the approach. The study has a sound methodology and follows a clear experimental design with valid, clear and justified assumptions. The manuscript is well written, with fluent and precise language. The title is appropriate and reflects the contents of the paper well. The abstract provides a concise and complete summary of the presented work.

We thank the reviewer for this positive assessment.

I have no major concerns, but a few remarks. More specific comments and suggestions for improvement are given in the attached pdf.

We thank the reviewer for his valuable and constructive comments on improving our manuscript. we agree with the overall comments and have addressed them in detail accordingly both in the response below and in the attached PDF.

The introduction motivates the following work well. However, more background on previous work about asynchronous ice-ocean coupling would be great to give the reader more context to the study like: What studies have used asynchronous coupling so far? Is there already some literature that compares synchronous vs asynchronous coupling?

We appreciate the reviewer pointing out the relevance of asynchronous coupling to our study. This technique is indeed useful for bridging timescale discrepancies between ice sheets and other model components in coupled ice sheet/climate models. In response to your suggestion, we have now expanded the introduction to include a discussion of previous work on asynchronous coupling in the revised manuscript, as

" A number of different climate related disciplines utilising coupled modelling have encountered these issues of optimising performance of a model system where individual components have varying response timescales, including atmosphere - ocean modelling (Sausen and Voss, 1996; Voss et al., 1998) and Paleoclimate modelling incorporating ice sheets (Roberts et al., 2014; Lofverstrom et al., 2020). Approaches have included "periodic synchronous coupling", where the outputs of the faster component are averaged over a short period of synchronous coupling and are then used to force the slower component(s) over a longer uncoupled period, and "asynchronous coupling", where the faster model is run for a shorter period during each coupling interval. In this context "synchronous coupling" simply means that the elapsed modelled time, measured at the time of any exchange of coupled variables, is the same for each component. This is a broader definition that has been recently used in the ice sheet - ocean community (Goldberg et al., 2018; Gladstone et al., 2021), where "synchronous coupling" has been taken to mean that both fast and slow components update the coupling variables every fast timestep. Coupling synchronicity is especially important in the regional marine ice sheet - ocean modelling community where ice shelf cavity circulation is fully resolved by the ocean model but where the

coupling region itself (the underside of the ice shelf) evolves with time."

I have a few general remarks for plots (more specific ones are given as annotations to the pdf):

- *for all spatial plots of ISOMIP+ domain (barotropic stream function, melt rates, ice draft changes): it would be helpful to either mark the grounding line as a line or to shade the grounded areas (e.g. light gray) to be able to distinguish regions with values close to zero and grounded areas.*

- *Do 2d plots show values out of the colorbar range (e.g. Fig 3c)? If so, please indicate this by adding out-of-range extensions to the colorbars and give maximum values in textcaption.*

- *If contour spacing can't be easily inferred from colorbar, please provide this information in the caption.*

- *Please make sure that all colorbars have meaningful ticks. Fig 3b & 10c have no tick for lower bound.*

We thank the reviewer for the detailed suggestions on improving the plots. We will update all the figures in the revised manuscript according to these recommendations, as well as those provided by other reviewers.

The simulation times (model & represented time) are all given in months. Personally I would find it more intuitive to speak of years, and where the precise number of months is important (e.g. start of spun-up simulations, etc), this information could be given in brackets in months. This remark also applies to time axis of the plots.

We will replace 'months' with 'years' when referring to the simulation time, both in the text and the plots of the revised manuscript.

I disagree with some statements that are made in the discussion and conclusion section:

The study shows that the accelerated forcing approach is not suitable when the time scale of periodical forcing is in the order of the MCRT. When the forcing period is significantly longer, mean melt rates are higher than in the mean-state (Fig. 6). I am wondering how Fig. 6 would look like if it would be extended to the right, with longer forcing periods. Would it stay constant at comparable levels like the longest tested time scales, or will it converge asymptotically to a higher value? How long would that tail be, and how big the differences? The *authors argue in the discussion that for a 30 year forcing period the cavity is assumed to be in equilibrium with the forcing at all times (can this be proven somehow?). But already the 20 year period deviates significantly, which is already a factor 5 higher than the MCRT of 4 years. So then the question arises, what is a minimum factor that is required to still yield realistic results? I understand that it is challenging to test much greater forcing periods due to long computation times and that this might not be feasible. However, I feel that there was little evidence given that 30 years is in equilibrium with the forcing and therefore would be same as 300 years, whereas in the same time it is shown that 20 years is already too short.*

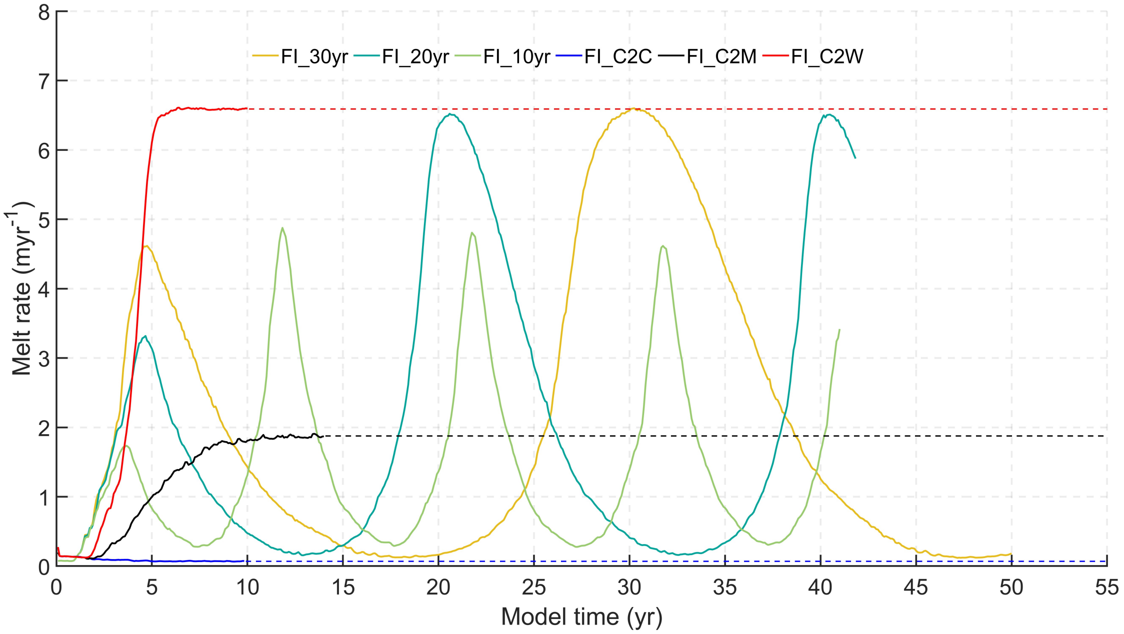

Figure 1: Time series of cavity-averaged melt rates from the selected FVCOM-ISOMIP+simulations. The dashed lines extend from their respective quasi-steady state values for interpretative purposes.

We appreciate the reviewer's concerns in the discussion section (lines 456-468). We will address these concerns/questions in detail below.

- **How would Figure 6 look like when extending the x-axis further to the right?** Time series of melt rates from the 30-year forcing period, as shown in Figure 1 and also Figure 4d in the manuscript, suggest that waters at each phase of the forcing cycle may have enough time to be flushed into the cavity, allowing the melting to reach a quasi-equilibrium state. Thus, we expect that the mean melting responses from longer-period forcing simulations would likely stay constant at comparable levels to that for the 30-year period, as it has more time to allow the waters at every phase to flush into the cavity. We have now explained this point explicitly in the discussion of the revised manuscript, as

"*When the timescale of the ocean forcing significantly exceeds the cavity residence time, the cavity is flushed several times during each cycle. Unlike with steady ocean forcing, the cavity can never fully achieve the equilibrium melting state under oscillating ocean forcing (Holland, 2017). Nevertheless, if the period is sufficiently long, waters at each phase of the forcing cycle may have enough time to be flushed into the cavity, allowing the melting to reach a quasi-equilibrium state. This state closely approximates equilibrium but includes slight fluctuations due to the continuous variation in forcing. For instance, a period of 30 years seems long enough for the FVCOM-ISOMIP+ configuration to this quasi-equilibrium melting state at each phase of the cycle. Figure 4d illustrates that the minimum mean melt rate in FI_30yr deviates slightly from that under the COLD forcing, indicating that even the coldest waters have enough time to fill the cavity and influence melting. This suggests that warmer water phases, especially the warmest, are also sufficiently flushed into the cavity to reach a quasi-equilibrium melting state, as evidenced by the maximum mean melt rate being nearly the same as that under the WARM forcing. Considering a hypothetical 300-year forcing period, waters in each phase of the cycle would have 10 times longer to influence the cavity compared to the 30-year cycle, allowing the quasi-equilibrium melting state in each phase to last about 10 times longer. Therefore, the melting response in any single phase of the 300-year cycle can be approximated by the response in the corresponding single phase of the 30-year cycle, supporting the fundamental assumptions of the accelerated forcing approach. While we have not tested forcings with periods longer than 30 years due to resource constraints, the constant forcing in the Constant experiment class essentially represents an infinitely slow varying force once the model reaches a quasi-steady state. This highlights the potential applicability of the accelerated forcing approach in century-long cavity-processes-oriented modelling studies, which could improve the accuracy of projections of Antarctica's contribution to sea level rise. In such projections, the slowly varying background forcing would not be periodic but instead steadily increasing at comparably slow rates in global warming scenarios. However, the linearly increasing trend from cold to warm can be considered as a warming phase of varying forcing over even longer timescales far exceeding the mean cavity residence time of any ice shelf, ensuring the applicability of the accelerated forcing approach.*"

- Figure 1 shows that the maximum melt rates from the 20-year period forcing (FI_20yr) slightly deviate from those observed under the steady

> WARM forcing (FI_C2W), unlike the 30-year period forcing (FI_30yr). This deviation suggests that even the warmest waters do not have sufficient time to fully circulate within the cavity during the 20-year cycle, and the colder waters have even less time to do so. Consequently, the normalized melt rate for the 20-year period is significantly different from that of the 30-year cycle. Our findings indicate that while the melting process can reach a quasi-equilibrium state during each phase of the 30-year cycle, it fails to do so within the 20-year cycle. We infer that the minimum period required to achieve realistic results would likely fall between 20 and 30 years.

That also relates to my second point in the discussion/conclusion: about the application for real-world scenarios. In global warming projections/scenarios the slowly-varying background forcing would not be periodically, but rather steadily increasing at comparable slow rates. When using this acceleration method for coupled simulations, the warming rate would be increased in the accelerated ocean compared to the unaccelerated case. Also in this case it is of great importance to know what would be still acceptable rates of changing forcing without impacting the results too much. Again, here it would help if testing of more than 30 years periodic forcing is possible, as a maximum change rate can be inferred from periodic forcing. However, as this seems not feasible for the given setup/resources, linear increasing forcing from a cold to a warm state at different rates could be an option? Especially for the ice-ocean coupled setup, this would be interesting.

We agree with the reviewer that the slowly varying background forcing would not be periodic, but rather steadily increasing at comparable slow rates in global warming scenarios. However, the linearly increasing trend from cold to warm at different rates can be considered analogous to the warming phase of oscillating forcing with different timescales. This analogy allows us to apply the conclusions drawn from periodic forcing simulations in our study to scenarios involving linearly varying forcing. The applicability of the accelerated forcing approach in these scenarios depends on the ratio of the timescale of the varying forcing to the mean cavity residence time.

To clarify, we have explicitly addressed this comment in the discussion section of the revised manuscript, as presented in our response to your previous comment above.

Also important for the applicability of real world scenarios are the time scales of natural variability of ocean to ice forcing, e.g. at decadal timescales (Jenkins et al., 2018). I interpret the current result of the study that the MCRT for Filchner-Ronne/Ross (4-8 years) would conflict with oscillating forcing on decadal time scales. This could possibly impose major challenges for the applicability of the accelerated approach on real world scenarios. I am not certain whether this is a deal-breaker for later applications, but I would like to see much *more discussion about this. Stating that the ocean forcing in real world scenarios varies mostly over century-long time scales, seems a bit too simple in my view. Concerning this matter, also a discussion of mixed time scale forcing seems to be interesting, like seasonal forcing overlayed by decadal oscillations with a steady increase in the background signal.*

We agree with the reviewer that some important natural variability of the ocean forcing, such as those on sub-decadal timescales such as ENSO and decadal timescales, are expected to be poorly represented with the applied forcing approach. In response to this comment as well as the comment from the first reviewer, we have now addressed the limitation in the discussion section of the revised manuscript, as

"*The mean cavity residence time, mainly determined by the cavity geometry and barotropic transport, is an intrinsic timescale of the ocean model. It represents the time needed for the cavity to reach an equilibrium melting state, where the cavity is filled with water that is exactly in balance with the steady ocean forcing (Holland, 2017). When the timescale of unsteady ocean forcing approaches this intrinsic timescale, interactions occur between basal melting, cavity circulation, heat inertia within the cavity, and transient changes in boundary forcing. Consequently, the melting response becomes highly sensitive to any alterations in these factors. This scenario challenges the underlying assumption of the accelerated forcing approach that basal melting response is not sensitive to corresponding accelerations in ocean boundary forcing. Hence, the accelerated forcing approach loses applicability when the forcing timescale, whether under regular or accelerated forcing, is in the order of the mean cavity residence time. This finding limits the approach's applications in real-world scenarios. For example, the El Niño-Southern Oscillation (ENSO), which significantly influences regions like the Amundsen Sea (Paolo et al., 2018; Huguenin et al., 2024), may be poorly represented under accelerated forcing due to its typical 2-7 year cycle coinciding with the cavity residence time of certain ice shelves around Antarctica. Notably, cold-water shelves like the Fichner-Ronne Ice Shelf and the Ross Ice Shelf have a cavity residence time of 4-8 years (Nicholls and Østerhus, 2004; Loose et al., 2009), and warm-water shelves like those in the Amundsen Sea have even shorter cavity residence times given their smaller sizes and faster melting-driven cavity circulations. This alignment could lead to an overestimation of the melting response when ENSO's timescale is compressed under accelerated forcing. Moreover, even if the multi-decadal variation in forcing substantially exceeds the cavity residence time, applying the accelerated forcing approach may result in an underestimation of basal melting response once its compressed timescale is comparable to the cavity residence time. Therefore, caution should be used when applying the accelerated forcing approach to studies addressing climate variability on sub-decadal to decadal timescales.*"

We have also expanded the discussion section in the revised manuscript to address the reviewer's concern about the mixed timescale scenarios, as

” *For scenarios involving mixed timescales, such as seasonal forcing superimposed on decadal oscillations with a steady background increase, additional experiments are necessary to yield definitive answers. Addressing these complex interactions requires a broader range of studies to fully understand the dynamics at play. These studies would help clarify how various overlapping timescales influence each other, which is essential for more accurate climate modeling. Such investigations, however, fall beyond the scope of our current study and represent important directions for future research.*”

The authors provide a publicly accessible archive (similar as in Zhao et al. 2022, https://doi.org/10.5194/gmd-15-5421-2022) with detailed information about where to obtain the source code of ROMS, ElmerIce and the FISOC coupler (URLs + git commits) including configuration and restart files. As I've never worked with the described models, it is beyond my expertise to judge whether the given information and files are sufficient to reproduce the realized experiments. As far as I can tell the archive does not include information and restart files for the FVCOM model. I request the authors to check this, and update if necessary. Furthermore it would be helpful to include concrete information about the model versions and where to obtain the source code already in the manuscript, e.g. in the code availability section.
Also, please make sure, DOIs are provided for all references.

We thank the reviewer point out this issue. We are now updated the code availability section, as

”*Code availability. The coupled model used the ice sheet model Elmer/Ice Version 9.0 (https://github.com/ElmerCSC/elmerfem. git;Gagliardini et al. (2013)), the ocean model FVCOM (https://dx.doi.org/10.17632/m6g4c3hm9m.1], Zhou and Hattermann (2020)), the ocean model ROMSIceShelf Version:1.0 with code (https://doi.org/10.5281/zenodo.3526801; Galton-Fenzi (2009)), and the coupled framework FISOC Version 1.1 (https://doi.org/10.5281/zenodo.4507182; Gladstone et al. (2021)). The FISOC-ROMSIceShelf-Elmer/Ice source code and input files needed to run the ROMS-based coupled experiments in this study are all publicly available (https://doi.org/10.5281/zenodo.5908713, Zhao et al. (2022)). The FISOC-FVCOM-Elmer/Ice model shares the same ice sheet model input files as ROMS. The FVCOM-based simulations use the same ice sheet model input files as the ROMS-based simulations. The input and output files for these FVCOM-based simulations are preserved at the Norwegian national research data archive and can be downloaded anonymously by anyone via a web-based interface. A DOI will be assigned upon acceptance of the manuscript.*”

Furthermore, I share the concern by Nicolas Jourdain (RC1) about how to deal with calving fluxes in more realistic/non-local applications.

We have addressed the concern raised by Nicolas Jourdain regarding calving fluxes and glacial meltwater input in more realistic applications. This discussion is now included in the revised manuscript, as follows:

"*It is important to acknowledge the limitations of our idealized study. When investigating the sensitivity of melting responses to changes in the timescale of the boundary conditions, we have only considered the lateral ocean conditions and changes in the ice draft, assuming these factors predominantly control the cavity circulation and, thus, the basal melting. This simplification presents challenges when applied to real-world scenarios where other boundary conditions affecting the cavity properties, as well as the open ocean, can not be ignored. One of them is the total glacial meltwater input to the ocean, comprising melt due to iceberg calving, basal melting, and subglacial discharge (from the subglacial hydrologic system). Numerous studies have highlighted the significant impact of glacial meltwater on ocean stratification, with important consequences for the evolution of sea ice(Bintanja et al., 2013; Merino et al., 2018; Goldberg et al., 2023), Antarctic bottom water formation (Li et al., 2023), ocean currents around Antarctica (Nakayama et al., 2021; Gwyther et al., 2023; Moorman et al., 2020), (Bronselaer et al., 2018; Purich and England, 2023; Li et al., 2024). The current study, which focuses on fine-resolution ice sheet-ocean interactions at the Antarctic margins, specifically the ice shelf cavity, includes only the ocean-driven melt component of glacial meltwater. This is because basal meltwater has the largest impact on cavity circulation, mainly through buoyancy forcing. Larger-scale studies would also need to quantify the impact of other components of glacial meltwater, especially the calving flux, under accelerated forcing.* "

"*Furthermore, adjustments in glacial meltwater input are necessary to realistically represent its impacts on ocean and climate under the accelerated forcing. Without such adjustments, the total freshwater flux into the Southern Ocean would not be consistent with that under the regular forcing, potentially distorting climate simulations. However, accelerating the meltwater flux introduces its own challenges. A significant increase in local freshwater input over a short period can drastically alter local salinity gradients and stratification. This disruption can affect everything from mixing processes to ocean currents, potentially leading to unrealistic model behavior. Following Lofverstrom et al. (2020), we propose not accelerating the meltwater flux in order to maintain realistic local ocean dynamics. Instead, to mitigate the inconsistent freshwater input in the accelerated simulations, we suggest applying periodic restoration techniques to adjust the ocean's salinity and temperature fields using observed or targeted values (Griffies et al., 2009, 2016; Lofverstrom et al., 2020). Moreover, we expect similar inconsistencies in atmospheric boundary conditions—such as precipitation (freshwater input), and wind and radiation fluxes (energy input)-under the accelerated forcing. The aforementioned periodic restoration techniques can also help reduce the effects of these inconsistencies, thereby ensuring more representative freshwater and energy inputs in the ocean model.*"

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