Reviewer #1

Comments on "Modeling ice shelf cavities in the unstructured-grid, Finite Volume Community Ocean Model: Implementation and effects of resolving small-scale topography" by Qin Zhou and colleagues.

This study proposes and evaluates a method to accelerate ocean–ice-sheet coupled simulations by considering that ocean simulations represent longer time periods than the mode time and by providing accelerated changes in ice geometry to the ocean model. Computational cost is a strong limitation of ocean–ice-sheet coupled models for sea level projections, so it is an important investigation. However, I am not convinced that "this approach could be applicable in modelling studies related to Antarctica's contribution to sea level rise projections" for the reasons below. This is a very important aspect that should be clarified before modelling groups start implementing this approach.

We thank the reviewer for his valuable feedback and the opportunity to clarify our study. We acknowledge the reviewer's concern about the applicability of our approach to modelling studies related to Antarctica's contribution to sea level rise projections. Our primary objective is to introduce and explore this novel approach rather than to claim its definitive success or applicability in all scenarios. To better reflect the exploratory nature of our research, we have substantially revised the discussion section of our manuscript. This revision aims to more comprehensively discuss the relevance and limitations of our approach in modeling studies concerning Antarctica's contribution to sea level rise projections. This update is intended to convey that while our approach shows promise, it is still in the developmental phase and requires further validation and refinement. Below, we will address the reviewer's concerns in detail by responding to each of his comments.

Major comments

I have two important concerns with the applicability to real world simulations, which should be discussed and probably reflected in the abstract:

***1-** Numerous studies have highlighted the significant impact of ice-shelf and iceberg meltwater on the ocean stratification, with important consequences for the evolution of sea ice (Bintanja et al, 2013; Swart and Fyfe 2013; Merino et al., 2018), Antarctic bottom water formation (Li et al., 2023), ocean currents around Antarctica (Moorman et al., 2020) and global climate (Bronselaer et al., 2018; Purich and England, 2023). If a global ocean model representing ice-shelf cavities is run with the accelerated approach over something like a (real) century, the total freshwater flux into the Southern Ocean won't be the same as in the regular simulation, which may significantly affect the climate system. Similarly, in some coupled ocean-ice sheet models like in Smith et al. (2021), the ice-sheet model sends its calving flux to the ocean model; how could this work with the accelerated approach? I guess that all these fluxes could be multiplied by alpha,* *but this would change the ocean dynamics. I am also unsure how it would work with an atmospheric forcing (which is absent from the idealised configurations presented here).*

We thank the reviewer for highlighting the critical aspect of meltwater flux when applying the accelerated forcing approach, which we did not address in our original manuscript. We agree that glacial meltwater (basal melting, calving flux, and subglacial discharge) significantly impacts many aspects of the ocean and global climate, as pointed out by the reviewer. We also agree these processes should be adequately represented when applying the accelerated forcing approach in real-world scenarios.

In our idealized simulations, we have only considered the ice draft change and far-field ocean conditions when investigating the sensitivity of basal melting response to the changes in the timescale of the boundary conditions, by assuming that these two factors predominantly control the cavity circulation and thus the basal melting. While this simplified approach has strengths, it presents challenges when applied to real-world scenarios where other influencing boundary conditions affecting the ocean are not considered, such as the glacial meltwater flux, wind, and radiation fluxes at the ocean-atmospheric interface.

Here, we take the glacial meltwater as an example, and the same applies to the precipitation/evaporation. Although accelerating the meltwater by multiplying it with the acceleration factor ensures the consistency of total freshwater input under the accelerated forcing, intense local freshwater input in a short period can disrupt local salinity gradients and stratification. This disruption can affect everything from mixing processes to ocean currents, potentially leading to unrealistic model behavior. Conversely, not accelerating the meltwater maintains realistic stratification for local processes but doesn't conserve total freshwater input, leading to inconsistencies over the long term.

To address this, we propose not accelerating the meltwater flux to maintain realistic local ocean dynamics. In stead, we suggest applying periodic restoration techniques to adjust the ocean's salinity and temperature field using observed or targeted values to mitigate the inconsistent freshwater input in the accelerated simulations. A similar technique has successfully been used in asynchronous coupling between ice sheets and climate models to reduce artificial drift in the ocean caused by inconsistent global freshwater input Lofverstrom et al. (2020).

For other atmospheric conditions, such as wind stress and heat fluxes, we also propose not accelerating the absolute values as it would lead to unrealistic and non-physical results. The same periodic restoration techniques can be used to mitigate the inconsistency of freshwater and energy input to the ocean due to not-accelerated atmospheric boundary conditions under the accelerating forcing. However, the full exploration of the impacts of these inconsistencies on the ocean and climate system extends beyond the scope of this study. Nevertheless, we have discussed these trade-offs and potential solutions in the discussion section of our revised manuscript, as

"*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.*"

2- *This work evaluates the accelerated forcing approach with two periods of vari-*

ability: 0.6 years and 30 years (in real years). It is clearly shown that the accelerated method does not well capture the changes in response to the 30-year forcing (Fig.11). How about periods of 2-7 years that correspond both to ENSO (which significantly influences regions like the Amundsen Sea) and is closer to the residence time? Isn't it an important issue that this range is poorly represented by the accelerated method.

We agree with the reviewer that another limitation of the accelerated approach lies in its poor representation of melting response to oceanic forcing of periodicity of sub-decades and decades in the accelerated forcing simulations because this range might be either close to the cavity residence time of the cold-water ice shelves or any acceleration of the timescale would be close to the mean cavity residence times. Given that forcing variability of these timescales significantly influences regions like the Amundsen Sea (Jenkins et al., 2018; Huguenin et al., 2024), we have added the discussion of this limitation in the revised version of the 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 variabil-

ity on sub-decadal to decadal timescales. ”

Specific Comments

-L. 22: this is not only a carbon emission scenario, there are other anthropogenic emissions.

We have removed ’carbon’ in the sentence to broaden the reference to emissions to include not just carbon but also other anthropogenic emissions that contribute to climate change.

-L. 24: a better or complementary reference on the uncertainty is Seroussi et al. (2023).

The reference has been added.

-L.30: “local” (instead of “regional”) would be more in line with the results cited here (the increase is relatively small at the scale of an ice shelf).

We have replaced ”regional” with ”local” in the sentence.

-L. 40: “primarily in testing phases or for sensitivity studies (Muntjewerf et al., 2021)” is not so relevant for UKESM which has been used for scenario-based projections by Siahaan et al.(2022) even if there are important model biases. Furthermore, I don’t understand the reference to Muntjewerf’s paper which is about the Greenland ice sheet.

We agree with the reviewer that “primarily in testing phases or for sensitivity studies (Muntjewerf et al., 2021)” is not so relevant in this context. We have removed it and instead cited Sianhaan et al’s work to support the preceding statement. The revised statement now reads: ” *More recently, coupled ice sheet-ocean model configurations on the circumpolar scale or beyond, with cavities explicitly resolved, have begun to emerge (Smith et al., 2021; Pelletier et al., 2022; Siahaan et al., 2022).*”

-L.57: replace “Specifically” with something like “In this case” or “Under this assumption”.

We have replaced ”Specifically” with ”Under this assumption”.

-L. 59-62: the formulations $\overline{\dot{z}_d(t)}$ *and* $\overline{\dot{z}_d(t/\alpha)}$ *are not clear to me as the bar indicates a time average. Would not* $\overline{\dot{z}_d}^{T}$ *and* $\overline{\dot{z}_d}^{T/\alpha}$ *be clearer?*

We have incorporated the reviewer’s suggestion to add subscripts indicating time averages. Furthermore, we have revised the notation for the oceanic effect on ice draft change to avoid confusion with the total ice draft change when introducing the data flow within the coupled system later in the text, as

" *Under this assumption, within the total ice draft change* Δz_d*, which includes contributions from ocean-driven change and ice-dynamics-driven change* Δz_{di}*, the ocean-driven draft change can be expressed as an integral of basal melt rate* M *over the coupling time interval* T*, as*

$$\Delta z_d = \int^T M dt + \Delta z_{di}. \tag{1}$$

The ocean-driven change can be further expressed as the time integral of a quasi-steady-state mean melt rate $\overline{M}^T$ *over the coupling interval* T*, as*

$$\int^T M dt = \overline{M}^T \cdot T. \tag{2}$$

By assuming that the mean melt rate $\overline{M}^T$ *during the coupling interval* T *can be approximated by a quasi-steady-state melt rate* $\overline{M}^{T/\alpha}$ *during a shortened coupling interval of* T/α*, the ocean model simulation duration can be reduced from* T *to* T/α*, hereby accelerating the timescale of the ocean model by a factor of* α*. Note that the superscripts* T *and* T/α *denote the coupling intervals, not the exponents or powers of a number. In addition, to maintain the model's integrity under the accelerated approach, the timescales of the ocean model's boundary conditions should be also accelerated accordingly to accommodate the timescale change from* T *to* T/α*.*"

-L.66-84: at this stage, the reader does not know that you are using the ISOMIP+/MISOMIP1 configurations, so "boundary conditions" may refer to the surface boundary conditions (especially for a global ocean model) as well as the ocean lateral boundary conditions. Similarly, "far field" is not so clear at this stage.

We appreciate the reviewer's observation regarding the potential ambiguity of 'boundary conditions' and 'far field' at this point in the manuscript. In response, we have revised our text, to begin with a general introduction to the various boundary conditions a coupled ice sheet-ocean model system is subject to, then specifically narrow down to the two boundary conditions central to our investigation. The revised text now reads:

"*In a coupled ice sheet-ocean model system, the ocean model is subject to a range of boundary conditions: changes in ice draft and meltwater flux at the ice sheet-ocean interface, momentum, freshwater, and radiation fluxes at the atmosphere-ocean interface, and lateral ocean conditions. In this study, we only focus on the lateral ocean conditions and the ice draft change at the ice sheet-ocean interface, as these two factors predominantly control the cavity circulation* *and, thus, the basal melting response.*"

In addition, we have also moved the term of "far field" at this point to avoid confusion.

-L. 99 & L. 104: these equations are not so clear to me. Why not using two variables for the model time (t_M) and the representated time (t_R).

We appreciate the reviewer's suggestion to use distinct variables for the model time and the represented time. However, we have opted to maintain our current notation of t and t/α for a couple of reasons. First, using t and t/α conveys the concept of compressed time, which is central to understanding the accelerated forcing approach. Secondly, introducing additional variables could potentially complicate the notation without adding significant clarity. We aim to keep the explanation as straightforward as possible while adequately conveying the necessary concepts.

Equations 3 and 4 are consistent with those used in Gladstone et al. (2021) because we employ the same coupling framework in our study, ensuring alignment and comparability of methodologies.

-Table 4: I am not sure that averaging the barotropic stream function is the most accurate way to calculate the residence time because this function is defined in a relative way (only its gradients are physical). Taking the maximum minus the minimum seems more relevant. I am also wondering whether the relevant time in the ISOMIP+ case is the residence time in the entire rectangular domain.

We appreciate the reviewer's concern regarding the method we employed to calculate the cavity residence time by averaging the barotropic stream function. Our choice to use this method was guided by its application in the study by Holland (2017), which inspired the design of our experiments. While we acknowledge that other methods might offer different insights into cavity dynamics, for the purposes of our current study, we believe this approach serves our study's objectives, providing a reliable measure of cavity residence time.

-L. 216: correct "Notably,Although".

Corrected.

-L. 219: another very good reference for this is Jenkins et al. (2018).

The reference is added.

-Fig. 6 is interesting. Do the authors have an explanation for the weaker melt at the frequency of the barotropic circulation? On the left of the plot, the ocean temperature does not have time to adjust in the water entering the cavity ends

up at a temperature of 0.5(TC+TW). Towards the right of the plot (and beyond), the temperatures tend to follow the oscillatory forcing (equation 7 of the manuscript). If you assume a melt dependency to the quadratic thermal forcing and average the melt rate over time, you can probably explain the left-right asymmetry. My guess for the low central value is that the melt-induced circulation starts to increase in response to thermal forcing just when the forcing switches back to cold condition, which quickly cools the cavity, while the return to a warm phase is slower due to the low melt-induced circulation in cold conditions. In this case, the mean temperature in the cavity is closer to TC, so melting is at its weakest value.

We thank the reviewer for the insightful interpretation of Fig.6. Your comments help deepen our understanding of the observed phenomena in the plot. In our manuscript, we discussed why the melting response tends to stabilize on the left side of the plot, explaining that " This is because multiple COLD and WARM waters coexist within the cavity in this regime, effectively canceling each other in the spatial mean, leading to a melting response close to that from the MEAN forcing simulation. ". However, We have not explained the weaker melt at the frequency of the barotropic circulation or the left-right asymmetry.

We have now enhanced our explanation of Fig.6 in the revised version of the manuscript by incorporating your interpretation, as

"*Figure 6 not only reinforces the three distinct melting regimes observed in the time series and spatial distribution figures but also provides additional insights for predetermining suitable scenarios for the accelerated forcing approach. First, the normalized melt rates reach their minimum across all three model configurations when the oscillation periods approximate the MCRTs (Log2(Normalized timescale) $\simeq$ 0). In this regime, melt-induced circulation begins to increase with the warm phase of the oscillation just as the forcing shifts back to the cold phase, which rapidly cools the cavity. The return to the warm phase is slower due to diminished melt-induced circulation in cold conditions, resulting in a cavity temperature closer to the COLD forcing, thereby minimizing melting. This suggests that when the oscillation period of ocean forcing, either accelerated or not, approximates the MCRT, the melting response is likely to deviate significantly from the actual response, thus challenging the underlying assumption of the accelerated forcing approach. Secondly, when oscillation periods are shorter than the MCRT (Log2(Normalized timescale) ¡ 0), the melting rates tend to stabilize, as indicated by normalized melt rates clustering between 0.9 and 1.1. In this regime where the ocean conditions oscillate rapidly, the ocean temperature doesn't have time to adjust to that of the WARM or COLD profiles. This results in the water entering the cavity at a temperature close to that of the MEAN profiles, thereby leading to a melting response that is nearly equivalent to that observed under the MEAN forcing. Consequently, this response exhibits low sensitivity to rapidly varying ocean forcing. Given our earlier assertion that the accelerated forcing approach only remains valid when the basal melting response is* *not sensitive to corresponding accelerations in ocean boundary forcing, we deduce the approach is applicable in this regime. In contrast, when the oscillating forcing periods greatly exceed the MCRTs, melt rates increase significantly. In specific, the normalized melt rates increase from about 0.7 when the forcing period near the MCRT (Log2(Normalized timescale) $\simeq$ 0) to more than 1.1 when the period much longer than the MCRT (Log2(Normalized timescale) ¿ 2) for both ISOMIP+ domain configurations. In the FVCOM-ISOMIP+ configuration, the normalized melt rate further increases to about 1.3 when the forcing period (30 years) is seven times longer than the MCRT of 4 years. In addition, the FVCOM-Wedge simulations display a comparable increasing trend but at a slower rate, likely due to differences in cavity geometry. The increase in melt rates is attributed to the quadratic relationship between melt rates and ocean temperatures (Holland et al., 2008; Jenkins et al., 2018). In detail, as the ocean forcing oscillates slowly, ocean temperatures tend to follow the oscillatory forcing at every stage. When averaged over the oscillation period, the mean melt rate aligns more closely with that from the WARM forcing and thus is higher than that from the MEAN forcing. We expect that the melting response will stabilize when ocean temperatures fully adjust to the oscillatory forcing. However, due to the lack of simulations with longer periods, we are unable to determine the minimum period necessary for the melting response to reach equilibrium at every phase of the cycle. In scenarios where the forcing period exceeds the MCRT but does not allow a full equilibrium melting response, the accelerated forcing approach is likely not suitable, as it tends to underestimate the melting response."*

- Fig. 10, panel a: explain PFast1-mm in the caption.

We will explain it when updating the figure in the revised manuscript.

- Fig. 10, panel b: the yellow red curves seem to show the relative difference (in %), not the absolute difference as indicated in the caption. Showing δV for the three experiments as in Fig. 11 (not the relative difference) would probably be easier to read. I also don't understand the values: why donnot PFast3 and PFast10 start with 0 % difference at month zero.

We agree with the reviewer that presenting δV for the three simulations would likely enhance readability, and we will include these changes in the revised manuscript. Additionally, this update will avoid the issue of the unexpected non-zero values of 0% difference at month zero. These arise because δV, while close to zero in all three simulations, is not exactly zero. Small deviations among the simulations can therefore lead to significant relative differences when expressed in percentages.

- L. 392: "Here exists a few locations" , exist ?

Corrected.

- L. 401-404: I find this sentence hard to follow.

. We have rephrased this sentence in the revised version of the manuscript, as

" *In summary, our analyses show that the accelerated forcing simulations generally reproduce the time-averaged melting response, overall ocean volume changes, spatial distributions of melt rates, and integrated ice draft changes. The relative changes in these variables are kept under 10% across most locations. However, at a few locations near the grounding line, relative differences in melt rates and integrated ice draft changes exceed 10% when a higher acceleration factor of 10 is used. Thus, we consider the accelerated forcing approach to be suitable when the forcing timescale is significantly shorter than the cavity residence time, as suggested by our findings from the stand-alone experiments.*"

- L. 476: I do see reasons, see my main comments.

We have removed this over-selling sentence and responded to your main comments in this reply.

- L. 455-468: Ok but the real ocean has a lot of variability associated with periods between 1 year and 30 years (e.g., El Niño Southern Oscillation; Holland et al., 2019). For this reason, Fig. 11 is quite concerning for an application to a real ocean.

Your concern is valid. We have revised the paragraph substantially in the discussion section of the revised manuscript, also in response to the comments from the second reviewer, 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* **??***d 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, al-*

lowing 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."

The method should be compared to Lofverstrom et al. (2020) who present an approach for the atmosphere forcing of Greenland, but has some similarities with the method presented here.

We thank the reviewer for pointing out this important paper. We have now added a paragraph in the introduction of the manuscript that compares our acceleration approach with previous techniques used in climate models to bridge timescale discrepancies between various model components. This includes the technique from (Lofverstrom et al., 2020), 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.*"

References

Bintanja, R., van Oldenborgh, G.J., Drijfhout, S., Wouters, B., Katsman, C., 2013. Important role for ocean warming and increased ice-shelf melt in antarctic sea-ice expansion. Nature Geoscience 6, 376–379.

Bronselaer, B., Winton, M., Griffies, S.M., Hurlin, W.J., Rodgers, K.B., Sergienko, O.V., Stouffer, R.J., Russell, J.L., 2018. Change in future climate due to antarctic meltwater. Nature 564, 53–58.

Gladstone, R., Galton-Fenzi, B., Gwyther, D., , Q., Hattermann, T., Zhao, C., Jong, L., Xia, Y., Guo, X., Petrakopoulos, K., Zwinger, T., Shapero, D., Moore, J., 2021. The framework for ice sheet–ocean coupling (fisoc) v1.1. GMD 14, 889–905. URL: `https://gmd.copernicus.org/articles/14/889/2021/`, doi:10.5194/gmd-14-889-2021.

Goldberg, D., Snow, K., Holland, P., Jordan, J., Campin, J.M., Heimbach, P., Arthern, R., Jenkins, A., 2018. Representing grounding line migration in synchronous coupling between a marine ice sheet model and a z-coordinate ocean model. Ocean Modelling 125, 45–60.

Goldberg, D.N., Twelves, A.G., Holland, P.R., Wearing, M.G., 2023. The non-local impacts of antarctic subglacial runoff .

Griffies, S.M., Biastoch, A., Böning, C., Bryan, F., Danabasoglu, G., Chassignet, E.P., England, M.H., Gerdes, R., Haak, H., Hallberg, R.W., et al., 2009. Coordinated ocean-ice reference experiments (cores). Ocean modelling 26, 1–46.

Griffies, S.M., Danabasoglu, G., Durack, P.J., Adcroft, A.J., Balaji, V., Böning, C.W., Chassignet, E.P., Curchitser, E., Deshayes, J., Drange, H., et al., 2016. Omip contribution to cmip6: Experimental and diagnostic protocol for the physical component of the ocean model intercomparison project. Geoscientific Model Development , 3231.

Gwyther, D.E., Dow, C.F., Jendersie, S., Gourmelen, N., Galton-Fenzi, B.K., 2023. Subglacial freshwater drainage increases simulated basal melt of the totten ice shelf. Geophysical Research Letters 50, e2023GL103765.

Holland, D.M., Thomas, R.H., DeYoung, B., Ribergaard, M.H., Lyberth, B., 2008. Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters. Nat. Geosci. 1, 659–664. Doi:10.1038/NGEO316.

Holland, P.R., 2017. The transient response of ice shelf melting to ocean change. Journal of Physical Oceanography 47, 2101–2114. URL: `https://journals.ametsoc.org/view/journals/phoc/47/8/jpo-d-17-0071.1.xml`, doi:10.1175/JPO-D-17-0071.1.

Huguenin, M.F., Holmes, R.M., Spence, P., England, M.H., 2024. Subsurface warming of the west antarctic continental shelf linked to el niño-southern oscillation. Geophysical Research Letters 51, e2023GL104518.

Jenkins, A., Shoosmith, D., Dutrieux, P., Jacobs, S., Kim, T.W., Lee, S.H., Ha, H.K., Stammerjohn, S., 2018. West antarctic ice sheet retreat in the amundsen sea driven by decadal oceanic variability. Nature Geoscience 11, 733–738.

Li, D., DeConto, R.M., Pollard, D., Hu, Y., 2024. Competing climate feedbacks of ice sheet freshwater discharge in a warming world. Nature Communications 15, 5178.

Li, Q., England, M.H., Hogg, A.M., Rintoul, S.R., Morrison, A.K., 2023. Abyssal ocean overturning slowdown and warming driven by antarctic meltwater. Nature 615, 841–847.

Lofverstrom, M., Fyke, J.G., Thayer-Calder, K., Muntjewerf, L., Vizcaino, M., Sacks, W.J., Lipscomb, W.H., Otto-Bliesner, B.L., Bradley, S.L., 2020. An efficient ice sheet/earth system model spin-up procedure for cesm2-cism2: Description, evaluation, and broader applicability. Journal of Advances in Modeling Earth Systems 12, e2019MS001984.

Loose, B., Schlosser, P., Smethie, W.M., Jacobs, S., 2009. An optimized estimate of glacial melt from the ross ice shelf using noble gases, stable isotopes, and CFC transient tracers. J. Geophys. Res. 114, 15 PP. URL: `http://www.agu.org/journals/ABS/2009/2008JC005048.shtml`, doi:200910.1029/2008JC005048.

Merino, N., Jourdain, N.C., Le Sommer, J., Goosse, H., Mathiot, P., Durand, G., 2018. Impact of increasing antarctic glacial freshwater release on regional sea-ice cover in the southern ocean. Ocean Modelling 121, 76–89.

Moorman, R., Morrison, A.K., McC. Hogg, A., 2020. Thermal responses to antarctic ice shelf melt in an eddy-rich global ocean–sea ice model. Journal of Climate 33, 6599–6620.

Nakayama, Y., Cai, C., Seroussi, H., 2021. Impact of subglacial freshwater discharge on pine island ice shelf. Geophysical research letters 48, e2021GL093923.

Nicholls, K.W., Østerhus, S., 2004. Interannual variability and ventilation timescales in the ocean cavity beneath filchner-ronne ice shelf, antarctica. Journal of Geophysical Research: Oceans 109.

Paolo, F., Padman, L., Fricker, H., Adusumilli, S., Howard, S., Siegfried, M., 2018. Response of pacific-sector antarctic ice shelves to the el niño/southern oscillation. Nature geoscience 11, 121–126.

Pelletier, C., Fichefet, T., Goosse, H., Haubner, K., Helsen, S., Huot, P.V., Kittel, C., Klein, F., Le clec'h, S., van Lipzig, N.P.M., Marchi, S., Massonnet, F., Mathiot, P., Moravveji, E., Moreno-Chamarro, E., Ortega, P., Pattyn, F., Souverijns, N., Van Achter, G., Vanden Broucke, S., Vanhulle, A., Verfaillie, D., Zipf, L., 2022. Paraso, a circum-antarctic fully coupled ice-sheet–ocean–sea-ice–atmosphere–land model involving f.etish1.7, nemo3.6, lim3.6, cosmo5.0 and clm4.5. Geoscientific Model Development 15, 553–594. URL: `https://gmd.copernicus.org/articles/15/553/2022/`, doi:10.5194/gmd-15-553-2022.

Purich, A., England, M.H., 2023. Projected impacts of antarctic meltwater anomalies over the twenty-first century. Journal of Climate 36, 2703–2719.

Roberts, W.H., Valdes, P.J., Payne, A.J., 2014. Topography's crucial role in heinrich events. Proceedings of the National Academy of Sciences 111, 16688–16693.

Sausen, R., Voss, R., 1996. Techniques for asynchronous and periodically synchronous coupling of atmosphere and ocean models: Part 1: general strategy and application to the cyclo-stationary case. Climate Dynamics 12, 313–323.

Siahaan, A., Smith, R.S., Holland, P.R., Jenkins, A., Gregory, J.M., Lee, V., Mathiot, P., Payne, A.J., Ridley, J.K., Jones, C.G., 2022. The antarctic contribution to 21st-century sea-level rise predicted by the uk earth system model with an interactive ice sheet. The Cryosphere 16, 4053–4086.

Smith, R.S., Mathiot, P., Siahaan, A., Lee, V., Cornford, S.L., Gregory, J.M., Payne, A.J., Jenkins, A., Holland, P.R., Ridley, J.K., et al., 2021. Coupling the uk earth system model to dynamic models of the greenland and antarctic ice sheets. Journal of Advances in Modeling Earth Systems 13, e2021MS002520.

Voss, R., Sausen, R., Cubasch, U., 1998. Periodically synchronously coupled integrations with the atmosphere-ocean general circulation model echam3/lsg. Climate Dynamics 14, 249–266.