Author response, “A Framework for Ice Sheet - Ocean Coupling (FISOC) V1.1”

Rupert Gladstone et al

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We repeat the reviewer’s text in black and provide our response in blue font.

1 Response to reviewer 1, anonymous

Gladstone et al. present a new coupling infrastructure (FISOC) that is designed to ac- commodate various types of ocean and ice-sheet models. The manuscript is well written, and FISOC, the verification protocol as well as the results are clearly presented. By implementing two ocean models (with distinct regridding methods) within the FISOC framework, the authors demonstrate the flexibility of their approach. The two simple verification experiments proposed here are convincing and could be used for the verification of other coupled models. Given the several references to synchronous vs asynchronous approaches in the paper, I would have found it useful to see a set of sensitivity experiments to estimate the influence of the coupling interval (e.g., from 1 day to a few months), which would also further demonstrate the flexibility of FISOC, but this is probably beyond the scope of the present paper. Therefore, besides a few elements that require clarifications (see below), I recommend the manuscript for publication in GMD.

We thank the reviewer for the positive review and for the comments that will improve clarity of the manuscript.
There are many interesting idealised studies to be carried out with FISOC and other ice sheet - ocean coupling tools, and we agree that impact of the coupling interval is one of these. In fact we are currently conducting such experiments and hope to be able to report on them in a future publication. We also agree that this is beyond the scope of the current paper.

Minor comments:

- L.7: “thesemechanisms”

Corrected, thanks.

- L.29: other anterior references for the ice geometry feedback onto melt rates in- clude De Rydt et al. (2014), Timmermann and Goeller (2017) and Donat-Magnin et al. (2017).

The Timmermann and De Rydt references are the most relevant mentioned by the reviewer, and we have incorporatd these into the introduction.

- L. 43-45: "offline coupling" and "partial restart" should be defined. I am not sure that "offline coupling" is very relevant as deciding what is "online" and "offline" can be some- what subjective and the synchronous/asynchronous distinction is probably enough.

Our intention was to refer to coupling in which one executable calls individual components as runtime libraries as "online" coupling and coupling in which models are restarted with variables being exchanged through files as "offline" coupling. However, we realise that this distinction is not essential to our paper, and have removed mention of online and offline coupling. Instead we mention runtime and libraries where needed.
We also remove "partial" to avoid confusion (see also later comment and response below).

- L.102: there is a subsection 2.1.1 but no subsection 2.1.2. I suggest putting every- thing under 2.1 with no 2.1.1 subsection.

There is now also a Section 2.1.2.

- L.113: indicate that the user manual is provided on github or as supplementary file.

We provide the FISOC manual as a supplement as this is requested by GMD. However, the version of the manual in the repository is evolving while the attachment will become more out of date over time. For this reason we only add mention of the repository version in response to the reviewer.

- L.135-138: in which circumstances is it necessary to extrapolate? Is the ocean grid extends beyond the ice grid, I would expect the ice geometry (seen by the ocean) to be taken from observational data, not extrapolated from the ice model.

Given that ice geometry evolution is one of the main purposes of coupling ice sheet and ocean models, we do not envisage a situation in which using observational data for a part of the domain would be beneficial. In particular, as the ice model geometry evolves, a non-physical discontinuity between modelled and observed geometry is likely to occur. We do not intend the coupled system to be used in such a way and do not feel that discussing it would benefit the current paper.
Extrapolation in the current paper is due to the ocean model using a staggered grid which also includes ghost cells. In this situation the ocean domain extends beyond the ice domain by one and a half ocean grid cells. We've re-ordered the sentence to make it clearer to the reader that this grid stagger and ghost cells are the cause of the need to extrapolate.

- L.151: ". Cavity geometry. . ." add "seen by the ocean".

We've added this clarification (albeit with slightly different wording).

- L.161: It is unclear what is meant by "partial restart" here. In Favier et al. (2019), the ocean is restarted every coupling interval by conserving its velocity field (and all infor- mation on the current and previous time steps that is usually used to restart the ocean model), not only temperature and salinity as in De Rydt et al. (2016), so shouldn't it be called a full ocean restart. The main difference between Favier et al. (2019) and ROMS/FVCOM here is that the ice geometry seen by the ocean evolves by step, i.e. every coupling interval rather than every ocean time step, and that there is an associated correction on barotropic velocities to cope with that.

Our use of the term "partial restart" was ambiguous, and it could also be that we were not up do date with how different groups are implementing their restarts. We've removed "partial".

- L.311-312 (or in section 2.6): please specify whether the 3-equation formulation is used with a constant exchange velocity. It could be worth mentioning that "rotation is disabled" to avoid asymmetric melt rates and seek a perfectly flat solution for the ice draft.

The exchange velocity is a function of friction velocity. We've now added this in the section on thermodynamics at the ice-ocean interface.
We have now stated in the experiment description section that rotation is disabled.

- L.320-323: if these details are given for FVCOM, I guess they should be provided for ROMS as well. Having said that, I am not sure these are useful in this paper, unless there are reasons to think that some schemes are less conservative than others.

We have added similar information for ROMS. We are not investigating the impact these schemes have on conservation, but they may have some relevance to melt rates. This is also not a focus for our study, but the information may be of some interest in this context.

- L.311 and 353-354: are these in-situ or potential temperatures?

This is potential temperature. We have clarified this in both places.

- section 4.1: it would be worth mentioning whether the ocean models make the Boussi- nesq approximation (which would probably mean that they are expected to conserve volume rather than mass). Is the ocean mass in Fig. 4 derived from the uniform sea water densities shown in Tab. 2 based on its volume?

Yes, the ocean models make the Boussinesq approximation.
Yes, the ocean mass in Figure 4 is derived from volume multiplied by the uniform density.
We now mention both of these things where Figure 4 is first referenced.

2 Response to reviewer 2, Xylar Asay-Davis

This paper describes a framework, FISOC, built on the Earth System Modeling Framework (ESMF), for coupling ice sheet and ocean components. Since ESMF is used for coupling in many Earth System Models (ESMs), the authors suggest that FISOC could provide an important stepping stone toward ice sheet-ocean coupling in an ESM. The paper describes the coupling infrastructure as well as the ice sheet and ocean components used for coupling verification. Then, the authors use two idealized test cases to demonstrate approximate conservation of mass and consistency between the grounding line as represented in each component.

The paper is well written and well organized. The figures do a good job at illustrating the design concept of the framework and its flexibility in addressing the unique requirements of the components it currently supports. For the most part, I find the description of FISOC and the verification experiments appropriately detailed and easy to follow. There are a few areas where I think more clarification or detail would be useful, as detailed below in the specific comments, before the paper is ready to publish in GMD.

The authors wish to thank Xylar Asay-Davis for his positive comments, thorough review and useful suggestions. We have added the requested clarification and information, making for a more complete paper.

First, the text mentions briefly that FISOC currently uses "sequential coupling" (but that "concurrent parallelization" would presumably require minimal effort). However, the text does not provide sufficient detail on how sequential coupling is performed, in particular what the conceptual start and end time of each component's coupling interval is. Nor is there any description of how this might be different for concurrent parallelization. I think these are needed to better understand the coupling strategy and, in particular, the inconsistencies between the geometry as represented in each component.

We have added a subsection on sequential parallelism in section 2. This clarifies the sequential workflow with new text and a new figure (Figure 2 in the revised manuscript). Further speculation on concurrent parallelism is also added in this new subsection.
The results section for experiment VE1 now also has some additional text near the end which includes mention of the sequential lag.

Second, there is no discussion in the paper about how the ocean components ensure ocean connectivity (if at all) and how this may need to be accounted for in the coupling. Would the ocean components allow melting in "subglacial lakes" (as emerge in the experiments of De Rydt and Gudmundsson, 2016) that meet the flotation criterion but are not connected to the ocean? If, so, this could drive unrealistic ice-sheet dynamics. Would these subglacial lakes be considered part of the floating area in the ocean component? If not, would this lead to a significant discrepancy in the geometric representation (or at least accounting) between the two components?

Neither of the ocean components make any attempt to ensure connectivity. "subglacial lakes" are allowed to occur. We now mention this at the end of the "grounding line evolution" section.
The ice component uses it's own grounded mask to avoid application of melt rates to grounded ice. This was applied to all simulations presented here but we were remiss in not explicitly stating this in the paper. The implication is that any geometry change due to melt occurring in locations the ocean component considers floating but the ice component considers grounded is effectively removed from the coupled system. This doesn't happen in the current simulations in which the ocean grounding line retreat slightly lags the ice grounding line retreat, but will be considered carefully in future studies. In particular, we will aim to incoroporate ESMF conservative masked regridding in the future.

We now mention the application of the ice component grounded mask to prevent applying melting under the section on "Thermodynamics at the ice-ocean interface".
One should also consider the possibility that allowing the ocean model to represent subglacial lakes could drive MORE realistic dynamics, and we hope to consider this in future studies, in which a subglacial hydrology model will be incorporated in the coupled system.

Third, while emphasis is placed on conservation, the interpolation methods used in the VE1 experiment are not conservative and therefore would not be appropriate for flux fields (like the melt rate) in ESMs. Relatedly, the results from VE1 demonstrate approximate, but not machine-precision, conservation of mass. Could this be improved by using conservative interpolation and also accounting for the mass accumulated in the coupler during a coupling interval?

We have added relevant content in two places.
1. We now discuss briefly the potential applicability of ESMF conservative regridding methods in the regridding subsection of section 2.
2. We discuss the sources of error in mass conservation at the end of the results section "VE1: Floating adjustment"
More generally, we aim to place emphasis on presenting the coupling rather than conservation. One experiment is set up in such a way that conservation can be assessed. It is clear that the reviewer would like to see more discussion and more detailed work generally on this topic. We agree that it is important, but our current setup is not aimed at providing close to machine precision and is not aimed at quantifying causes of mass drift. the reviewer's comments have helped us to consider the various factors contributing to non-conservation and we will investigate this in the future at the level of detail that the reviewer would like to see. We intend to do this once we have a setup in which the ESMF conservative regridding methods can be used within FISOC. For the current study, we have added relevant information and discussion in a number of places, though we recognise that this is not at the level of detail that the reviewer would ideally like to see.

Fourth, I found the geometry and design choices of the VE2 experiment hard to follow. It would be helpful to have a figure showing the initial side-view (x-z) geometry for the experiment as well as a cross-section of the geometry at 25 years shown in x-y in Fig. 5. It would also be helpful to have a velocity plot for the ice-sheet component similar to that for the ocean components in Fig. 6. The behavior of VE2 strikes me as quite dissimilar to realistic ice sheet/ice shelf dynamics in that the thickest part of the ice shelf is in an ungrounded region and (as near as I can tell) ice seems to be flowing out of the "inflow" boundary at x = 0. It seems like some acknowledgement of the rather significant limitations of this experiment are needed somewhere in the discussion.

The experiments were intended to be the simplest configurations in which a 3D coupled ice sheet - ocean modelling system could be demonstrated. They were never intended to provide a directly relevant abstraction of a real world set up like the MISOMIP experiments (which to some extent resenbles the Pine Island Glacier, or an embayed marine system more generally). FISOC is intended

to be applied to Antarctic systems in the first instance, and so the experimental design needed to feature large ice shelves. The only real requirement we had of VE2 is that it features a large ice shelf and has an evolving grounded region. We have added a sentence about the design at the start of the experiment description section for VE2.
We have replaced the previous Figure 5 with a double plot showing centerline profiles (Figure 6 in the revised manuscript). This shows the geometry at the start and also distribution of the ice flow speed along the domain. This aims to address the reviewer's requests for a geometry cross section and ice flow plots. The ice flow speed at the inflow boundary is close to zero for much of the simulation but is never actually negative. We've added clarification of this just after the new figure is referenced in the text (VE2 results section).

As long as the authors make an effort to address these comments or explain their reasoning for not addressing them, I do not need to see a revised manuscript before publication.

2.1 Specific Comments

l. 53: ESMF does not need to be redefined, since it was already defined on l. 47-48

Removed, thanks.

l. 69-70: I think this is an important point that should be explored in a new subsection of section 2. Presumably, both components start at t=0. Which component runs first? Let's say it's the ocean. Once the ocean has finished a coupling interval, it has computed a melt rate. Is this averaged over the coupling interval or is the instantaneous value at the end of the coupling interval used? (This has important implications for how precise conservation of mass will be computed.) Presumably, the dD/dt is initialized to zero in the ocean component, so this is clear for the first coupling interval, but I will come back to this. Then, let's say the ice-sheet component runs. It is able to apply the known melt rate for the coupling interval (10 days in VE1 and VE2), so there is no conceptual time lag here if the melt rate is a time average but there is one if it is an instantaneous value from t = 10 days. Based on the results of this coupling step, dD/dt can now be computed and interpolated to the ocean grid or mesh. This dD/dt is time-centered at t = 5 days, but will be applied over days 10 to 20 in the ocean component, so this is the source of a time lag that you discuss later.

If the components run in the opposite order, it is conceivable that the time lag could be placed on the melt rate instead of dD/dt. There is no explicit description of this, but I get the sense that this was not the choice that was made, since results from VE2 discuss a lag in D, not in melt rate.

If I am correct in assuming that the ice sheet component updates second, after the ocean, in a given coupling interval in the sequential scheme, this likely means you do not need to account for mass that conceptually accumulates in the coupler during a coupling interval. It seems important to me to discuss that "concurrent parallelization" will require a time lag in both dD/dt and in melt rate, since each component will be updated based on the state (or time average) at the end of the previous coupling interval. In this scenario, it would be important to keep track of the mass that conceptually accumulates in the coupler over a coupling interval over a time step. This is the approach used for fluxes between components in the Community Earth System Model (CESM) and Energy Exascal Earth System Model (E3SM), the ESMs I am most familiar with, and I think in other ESMs as well. Even in cases where components may run sequentially on the same processors, I do not think it is common to take advantage of this to remove the time lag in fluxes between components because of the conservation issues that could arise.

Again, I feel like some discussion of these nuances is missing from Sec. 2.

We have added a subsection on sequential parallelism in section 2 (subsection 2.1.1). This clarifies the sequential workflow with new text and a new figure (Figure 2 in the revised manuscript). It also mentions the lag related to our sequential coupling. We do not think that this lag imposes a mass conservation drift. Further speculation on concurrent parallelism is also added in this new subsection.

We have added a paragraph about time processing of variables to the section on "coupling timescales". This clarifies that ocean time averages are used in the current study.

We note that sequential and concurrent parallelism can both be run in such a way that the same lag is present in both components. Concurrent paralleism is a technical design choice affecting efficiency, but it does not offer any new options regarding variable lag (unless the coupling were to be implemented at a sub-timestep level, which is unlikely to occur between ice dynamic and ocean models). For this reason we do not discuss the lag in the context of sequential vs concurrent parallelism.

Given that, in the current study, the ice model timestep is equal to the coupling interval, and that the ocean model is also called for the same period (the ocean components themselves decide how many ocean timesteps are needed), the concept of mass (or any state property) "accumulating in the coupler" is not relevant to the current study. If, in the future, we call either component for a period shorter than the coupling interval then FISOC will need to handle cumulating variables. The code for this is in place but we do not feel that discussing in this paper is a useful direction. It will be introduced and discussed in the future as and when we need it.

l. 85-86: ESMF does not need to be reintroduced and the citations are not needed because the acronym is already defined on l. 47-48 and the citation are already covered on l. 69-70.

Removed, thanks.

l. 134: "All FISOC simulations to date have used a Cartesian coordinate system." Is Elmer/Ice capable of using a spherical coordinate system? The BISICLES and MALI models that I have worked with both work only on Cartesian (polar stereographic) meshes, which requires special care to ensure flux conservation but can be handled as long as the coupling infrastructure is aware of the discrepancy in areas between the component models.

Standard Elmer/Ice options include Cartesian and cylindrical coords. Regridding between components running on Cartesian coordinate systems is surely the least problematic option. Possibly the reviewer refers to difficulties regridding between components using different projections or coordinate systems? But here, as noted, all components use Cartesian coordinates.

l. 155: "FISOC assumes that time-step sizes are not adaptive." This seems quite restrictive to me and potentially unnecessary. It seems like this could use some discussion. I have worked with the BISICLES and Parallel Ocean Program coupled model called POPSIClLES. In that model, we had a different coupling strategy and we always ran with concurrent parallelism over a coupling interval. We found many cases doing more realistic simulations where it was highly beneficial that BISICLES (which can perform adaptive mesh refinement) could refine its time step to handle a particularly tricky geometric configuration that might emerge spontaneously. We simply required that BISICLES perform a time step that exactly reached the coupling end time as the last step in a coupling interval. It seems like this strategy would also be compatible with FISOC, and therefore the requirement that the coupling interval is equal to the ice-sheet time step is unnecessarily restrictive. If there are important reasons for the restriction, it would be helpful if they are clarified. If this is not a strict requirement but rather has been the convention in simulations to date, this should be discussed.

We've made modifications to this paragraph to clarify that these restrictions do not always need to be imposed.

Eq. (1): I think some more nuanced discussion is needed about the time-centering of dD/dt (which is at t - 1/2 Delta t) and when the dD/dt is actually applied in the ocean component (centered at t + 1/2 Delta t). You have dD/dt subscripted at time t but I do not think that is correct in either component.

This equation is correct if time t corresponds to the end of an ice component timestep. We have clarified this in the text. the reviewer's comments here essentially relate to the lag inherent in our approach to sequential coupling, which is now discussed in the new subsection 2.1.1 on "sequential parallelism".

l. 180: It is important to clarify that D is positive up. This might seem obvious from an ice-sheet modeling perspective, where D being positive down would not be an obvious choice since it can take either positive or negative values. But D in the ocean is often used for "depth" and is almost universally a positive quantity, so the choice of variable names and the sign convention are not intuitive for ocean modelers. There are also some later equations where I think the sign of D is not correct (as I will point out), leading to further confusion about the sign convention. A lot of confusion in the paper might be spared by renaming this variable "z_d" to go with "z_b" for the bedrock elevation/bathymetry.

Thanks for spotting this mistake. We assumed D to be positive down to start with though we didn't state this. Then later we state that D is positive upward.
We have replaced D with z_d as suggested, and this is positive up everywhere.

l. 183-184: "but has the potential for the ice and ocean representations to diverge over time as a result of regridding artefacts": Isn't some part of the divergence in time likely to come from the fact that there is a time lag between dD/dt from the ice component and as applied in the ocean component?

We are not convinced that a time lag can cause divergence in geometry over time. The integrated geometry change seen by the ocean after n + 1 ice timesteps would be (excluding regridding artefacts) the same as the integrated change given by the ice component after n timesteps. This is just a lag, not a source of divergence.

l. 213: "...FISOC can pass the temperature gradient from the ice component directly to the ocean component." I think this requires some discussion. The temperature at the ice-ocean interface is computed on the ocean time step and could potentially have significant temporal variability within a coupling interval (e.g. because of ocean eddies). Would the ice sheet get the time-average of this field as one of the coupling fields, and use this to compute the temperature gradient? If so, this would result in the temperature gradient going back to the ocean having a time lag of 2 coupling intervals in the temperature at the ice-ocean interface. Maybe this doesn't matter.

The temperature gradient in the ice should change pretty slowly compared to a coupling interval on the order of days. But this discussion is very speculative since we do not carry out thermodynamic coupling to the ice component in the current study. We prefer to focus discussion on the currently presented features of FISOC and leave detailed consideration of thermodynamic coupling to the future.

An alternative approach would be to pass the temperature in the bottom ice layer (and the ice thickness) and allow the ocean model to compute the temperature gradient on its time step. The differences between these approaches is likely only to matter for particularly long coupling intervals but it might still be worthy of some though and some discussion. The choice is not entirely obvious, at least not to me.

The temperature gradient is very unlikely to be linear through the ice shelf. The gradient is likely to be much steeper near the lower surface (except in significant freeze on zones where the opposite would occur). Again, this could be a lengthy discussion that doesn't need to occur here.

Eq. (3): I believe the RHS of this equation needs a negative sign if D is positive up. Otherwise, the pressure would be negative.

Eq. (4): There is a sign problem with this equation, too. I am pretty sure it is that the whole RHS needs a negative sign again. If drho_o/dz were 0, you expect a positive pressure for a negative D. Later, drho_o/dz is given as a positive number, which is not physically reasonable if z is positive up. Density should decrease toward the ocean surface. But if that term is positive, pressure should increase because of increasing density at depths, so the term -0.5 drho_o/dz D_[O] is positive for negative D_[O], as it should be. If drho_o/dz is changed to be negative (as I think it should be), the sign of this term would also need to be flipped. In any case, there's something to be fixed here. The confusion may arise from an ocean component that uses a positive-down definitely of z, but I think the paper needs to pick positive-up for everything and stick with it.

l. 245: "z_b is the bottom boundary depth (bathymetry, aka bedrock depth)": Most times the term "depth" is used in ocean modeling, there is an implication that it is positive-down. The fact that the variable is called "z_b" might tend to counteract that but I would state explicitly that it is positive-up.l.

In response to the last three reviewer comments: After changing ice draft from D to z_d we have corrected all instances of an incorrect sign.

246: "D_crit is a critical water column thickness (or depth)": This one is strictly positive, and is unrelated to D, which I find pretty confusing. Again, renaming D to z_d would do a lot to help with this. By the way, I don't see how the "or depth" bit applies at all in this context.

We removed "or depth".

Eqs. (6) and (7): I'm having trouble following these. An illustration would help a lot, but some text carefully defining the variables involved might do the trick.

The original definition was "η is the free surface variable". In the new context, it's pretty hard to understand what η is. The best way I can understand it is that $\eta + D\_[O]$ is the ocean's representation of the location of the ice-ocean interface, which is allowed to move up and down because of changes in ocean dynamic pressure. Maybe some explanation along these lines would be helpful.

the reviewer is essentially correct in his interpretation of η (now renamed to ζ as it is usually termed in the ROMS community).
We've added some explanation along these lines about both the ice draft and ζ at the start of the section on "Handling cavity evolution".

As far as I can tell, Eq. (7) is equivalent to Eq. (6) except that D_crit is now a minimum ice-sheet thickness below flotation rather than a minimum ocean-column thickness? This is confusing and needs some explanation as to what exactly it means and why ROMS chose this definition instead of the simpler one from FVCOM. It is confusing to use the same name for variables with distinct meanings in the two models. Also, shouldn't a slightly different D_crit be used for ROMS to get the same ocean-column thickness (assuming this is desired)?

The definition of D_crit has not changed. It has the same meaning in both models.
We agree that interpreting the ROMS wet/dry equation is not intuitively obvious. We've added a couple of lines immediately after the equation to describe conceptually the ROMS wet/dry criterion.

l. 257: "as described in Section 2.8": The current section is 2.8, so this must be a mistake. Maybe the reference is supposed to be to Sec. 2.5?

Corrected, thanks.

l. 272-274: "The coupling is purely geometric in that the ocean component passes an ice shelf basal melt rate to the ice component and the ice component passes a rate of change of ice draft to the ocean component." This may be a nuance of interpretation but I do not think of the mass flux in the form of a melt rate as being a geometric quantity, so I would disagree that the coupling is purely geometric.

we modified this wording to “The coupling centers on the evolution of ice geometry”

l. 280-282: I think it would be helpful to have an explanation for why the FVCOM simulation required a domain of a slightly different size. It is not clear if the sizes given in Table 2 are for both components or just the ocean component (in which case a row is needed for the ice component).

We added a line later in the same paragraph to clarify that the ice domain matches whichever ocean component it is coupled to, and to explain why the FVCOM domain has slightly different size.

l. 295: “$\rho\_or = 1027 kgm^{-3}$”: You give a slightly different value for FVCOM in Table 2 but this difference is not addressed here or anywhere else. Why the difference?

Sorry, the FVCOM reference density is not actually used anywhere in the current study! We've removed it from the table.

l. 297-299 and Eq (9): You gave a definition of the pressure at the interface in Sec. 2.7 already, and it was different from this for FVCOM. Presumably this redundant definition is not needed.

The pressure is given here in the context of the ice sheet boundary condition. It matches the earlier equation for ROMS but has a small discrepancy when coupled to FVCOM. We have changed this text so that it now refers directly to the earlier equation instead of repeating it.

l. 303: I think “zero net accumulation” is a slightly confusing phrase here. I assume the idea is that ice sheet models typically have a field of net accumulation (called a) and that this is zero everywhere in this case. But it lends itself to the misunderstanding that there is accumulation but that the net effect is zero (e.g. averaged in time, space or both). Could this be simplified but just removing the word “net”?

Yes, we removed “net”.

l. 315 “ROMS specific details.” Nothing is given about vertical mixing or eddy parameterizations, whereas these details are given for FVCOM. No details are given about how the three-equation parameterization is handled in either ocean component. For example, where are “far-field” temperature and salinity sampled? What parameters are used? (Are they the same for both models?) Which equation of state and equation for the freezing point is used in each.

We have now added ROMS specific details that were previously given only for FVCOM.
We don't aim to reproduce the full description of the ocean component implementations of cavity physics as these are already described in existing papers. We have now given slightly more information, and also repeated the relevant references, in the section describing thermodynamics at the ocean interface.

l. 317: “FVCOM specific details.” In addition to the above, no details are given about time stepping for FVCOM as they are for ROMS.

We have added the time-step information under the FVCOM specific details.

Eqs. (10) and (11): As I stated in my general comments, I think a figure is needed to help better understand this experiment. A starting point would be a side-view (x-z) figure showing the initial ice-sheet, ice-shelf and ocean configuration as given by these equations. Also, since rho_or is slightly different for the 2 ocean components, is (11) accurate and H is therefore slightly different for the two but D is the same?

We have added a new Figure (Figure 6 in the revised manuscript) showing centreline geometry at the start and after 25 years.
ρ_{or} is not actually used in FVCOM, and so we have removed it from Table 2.

l. 338: "No restrictions to ice flow are imposed at the upstream and down stream boundaries". I have several difficulties here. First, some more explanation is needed about what "no restrictions" really means. Presumably, this means that ice is free to flow out of the boundaries. I do not see how ice can flow in through these boundaries if there is "no restriction". Is it necessary to calculate stresses at the boundaries and, if so, how is this handled (in particular driving stress)? Why was an open boundary condition like this chosen at x=0? A more typical setup would place a solid boundary here so it acts as something of an ice divide. This would also make the direction of ice flow a lot less ambiguous. That brings me to the second point, which I will discuss more below. The ice flow field is not discussed but I get the impression based on the thickness evolution that flow is happening out of both the x=0 and x=100 km (or 99 km) boundaries, so that the "upstream" and "downstream" directions aren't well defined in this problem.

The "no restrictions" was sloppy wording on our part. The inflow and outflow boundaries have appropriate external pressures prescribed. We have revised the experiment description to convey this.
In effect this means that ice is allowed to flow either out from or in through both the "inflow" and "outflow" boundaries. In practice ice only ever flows in through the "inflow" boundary and out through the "outflow" boundary, though the velocity is close to zero at the "inflow" boundary. We've added a new Figure (Figure 6 in the revised manuscript) showing profiles at the start and after 25 years as well as ice flow speed.
This experiment is not intended to represent an ice catchment extending to the ice divide. It simply aims to provide a large shelf and a grounded region that evolves. It would have been possible to impose a no-flow inland boundary, and we do not think this would significantly alter the applicability of the experiment to demonstrating coupling.

l. 364-366: I found this paragraph redundant to the paragraph on l. 268-270 and subsequent text. I realize it is nice to summarize things again from previous sections but this seems too repetitive to me.

Yes, this is redundant. We removed these lines.

l. 372-373: I don't think "along the domain" and "cross-domain" are well defined directions because they take the perspective of the ice flow in a context where ocean circulation is being discussed. I would just call these the x and y directions.l.

382-383: "The net mass change of the coupled system is more than an order of magnitude smaller than the mass change of the individual components for both experiments VE1_ER and VE1_EF." I think this needs considerably more discussion. For ESMs, anything less than machine-precision conservation is not considered acceptable and is one of the most important mechanisms for diagnosing model inconsistencies. To accomplish this, conservative regridding is always used for flux fields (the melt rate in the case of FISOC, and the heat flux in the future). Ice sheet-ocean modeling requires that special care must be taken to distribute that flux field to the ice-sheet component because melt should not get distributed to grounded cells by mistake but it also should not be lost in the regridding process because this would affect conservation. This issue is exacerbated by inconsistent representation of the grounding line between components. Is this taken into account in FISOC? If so, please discuss. If not, please discuss this as a potential issue for future consideration. Aside from interpolation, conservation of mass may be inexact in FISOC because of the lag between when melt rates are computed in the ocean component and when they are applied in the ice component. I convinced myself when I was discussing the staggered coupling approach above that this is likely not the case in the current approach but it would be in an approach with concurrent parallelism. Even so, it would be important to diagnose that total mass going into the coupler is exactly equal to total mass coming out of the coupler after each coupling interval (i.e. after both components have run) or that the difference between these two is computed and stored within the coupler to be distributed appropriately at the next coupling interval. Overall, I would like to see some discussion about why conservation of mass in FISOC is good but not machine-precision good.

Much of this overlaps with the reviewer's earlier comments and some requested discussion has been added (see above for details). It is true that component's mask discrepancies has the potential to impact on conservation, and a comment on this has been added to the section on "Thermodynamics at the ice-ocean interface" where we first talk about the ocean's basal melt rate which is passed to the ice component.

l. 386-387: "While the initial slope of the lower surface of the ice shelf is the same in both VE1 and VE2": I misunderstood this the first time I read it to be saying that the D's for VE1 and VE2 were the same. They differ by 20 m but the slope is the same. I guess it's fine as it is but I wanted to let you know about the confusion, in case you want to do anything about it.

We discussed this and are currently happy that the meaning is sufficiently clear.

l. 387: "the open inflow and outflow boundaries": I remain confused about the open "inflow" boundary at x = 0. Is it really inflow? If so, how does open inflow work?

Yes, it is inflow, though very slow. Pressures are prescribed. See our response above to where the reviewer's concern is first raised for a more complete response.

Fig. 5: First, as I stated in my general comments and as I think you are fully aware, this is an odd ice-shelf geometry. It is also not very intuitive to see thickness plotted as an x-y field, at least not for me. It would be more helpful in my opinion to have a more 3D plot similar to Fig. 3. It would also be really helpful to have a vector field for the ice like the one for the ocean velocity in

Fig 6, especially because I want to see how much the weird geometry is due to outflow (instead of inflow) at x = 0.

We've replaced this Figure with a Figure showing centerline profiles at t=0 and after 25 years. (FIgure 6 in the revised manuscript) This gives the reader a more direct visualisation of the initial and evolving ice geometry. We've now also included ice flow speed in the new Figure 6. We show this as a coloured field and not as suggested by a vector field because the flow direction is entirely dominated by the x component (the arrows all point the same way).

As mentioned in an earlier response, there isn't any flow out of the domain at x=0, though we appreciate that it would be confusing to the reader to think that this could be the case. The new Figure should make it clear that there is no outflow at x=0.

We would add the comment though that it is not necessary for this domain to resemble a real glacier. It would not be a problem for there to be outflow at x=0, so long as the grounding line evolves and can be analysed.

Fig. 6: Are these fields interpolated to a common, regular grid? They look like they might be and, if so, this should be mentioned.

Yes, FVCOM was regridded to the ROMS grid, then both subsampled at 2km. We've added this information to the figure caption.

l.415-421: It may be worth remarking that the difference in grounded area does not increase with time even with the Rate method, at least in this case.

We added one sentence about this.

2.2 Typographical and grammatical corrections

We have fixed all the typos listed below. Separate author responses to each are not needed here.

l. 7: "these mechanisms" missing a space

l. 8: a comma is needed between "this" and "ocean"

l. 22: "(MISI) (Mercer, 1978; Schoof, 2007; Robel et al., 2019)": I would combine these parentheses as you have done elsewhere: "(MISI; Mercer, 1978; Schoof, 2007; Robel et al., 2019)"

l. 38: Similar to above: "(ISOMIP+; Asay-Davis et al., 2016)"

l. 46: commas are needed: "Here, we present a new, flexible..."

l. 46: for consistency, a semicolon is needed instead of a comma: "(FISOC; Section 2)"

l. 47-48: "Earth System Modeling Framework" is a proper name so I think it needs to be spelled with the American version of "Modeling" that is used on their website: https://www.earthsystemcog.org/projects/esmf/

l. 53-54: "(Hill et al. (2004); Collins et al. (2005))" should be "(Hill et al. 2004; Collins et al. 2005)" without the nested parentheses.

l. 105: a comma is needed between "versa)" and "all"

l. 117: a comma is needed between "cases" and "a non-standard"

l. 120: "Regional Ocean Modeling System" is also spelled with the American spelling of "Modeling" in the documentation I could find: https://www.myroms.org/

l. 120: There should not be nested parentheses: "(ROMS; Shchepetkin and McWilliams 2005)"

l. 120-121: For consistency, this should be "terrain-following, sigma-coordinate" (with a comma and a second hyphen). In general hyphenation is used a lot more sparsely in this writing than I would use it but I fully acknowledge that that is a stylistic choice.

l. 123: Remove the nested parentheses: "(FVCOM, Chen et al. 2003)

l. 136: a comma is needed between "extrapolation" and "which"

l. 142: "time step" is not typically hyphenated but this may be a stylistic choice.

l. 174: a comma is needed between "used" and "this"

l. 176: a comma is needed between "large" and "occasional"

l. 194: a comma is needed between "case" and "the user"

l. 209: "ocean model ice shelf cavity shape" is quite a long compound noun...

l. 228: "kg m" needs a space or half-space

l. 247: a comma is needed between "Thus" and "cells"

Eq (7): Please remove the asterisk as a multiplication symbol. It is not needed and is not considered a valid multiplication symbol (outside of code).

l. 258: a comma is needed between "Study" and "dD/dt"

l. 275: I've left most of the hyphenation choices alone but I feel pretty strongly that "uniform-thickness" should be hyphenated.

l. 286: a comma is needed between "system" and "we"

l. 287: a comma is needed between "Therefore" and "the"

l. 288: a comma is needed between "corners" and "where"

Eq (9): should end in a comma, not a period.

l. 309: a comma is needed after "experiment" at the end of the line

l. 326-327: commas are needed after "VE1_ER" and "VE1_EF"

l. 338: "down stream" should be "downstream"

l. 360: a comma is needed between "interval" and "this"

l. 368-369: a comma is needed between "days)" and "the" and again between "years)" and "the"

l. 378: a comma is needed between "melting" and "the"

l. 380: a comma is needed between "system" and "the"

l. 388: commas should be removed from "...component and the relatively shallower ice in the grounded region both..."

l. 397: a comma is needed between "melting" and "as"

l. 400: a comma is needed between "2.8" and "the"

A Framework for Ice Sheet - Ocean Coupling (FISOC) V1.1

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Abstract.

A number of important questions concern processes at the margins of ice sheets where multiple components of the Earth System, most crucially ice sheets and oceans, interact. Such processes include thermodynamic interaction at the ice-ocean interface, the impact of melt water on ice shelf cavity circulation, the impact of basal melting of ice shelves on grounded ice dynamics, and ocean controls on iceberg calving. These include fundamentally coupled processes in which feedback mechanisms between ice and ocean play an important role. Some of these mechanisms have major implications for humanity, most notably the impact of retreating marine ice sheets on global sea level. In order to better quantify ~~thesemechanisms~~ these mechanisms using computer models, feedbacks need to be incorporated into the modelling system. To achieve this, ocean and ice dynamic models must be coupled, allowing run time information sharing between components. We have developed a flexible coupling framework based on existing Earth System coupling technologies. The open-source Framework for Ice Sheet – Ocean Coupling (FISOC) provides a modular approach to ~~online~~ coupling, facilitating switching between different ice dynamic and ocean components. FISOC allows fully synchronous coupling, in which both ice and ocean run on the same ~~time-step~~time step, or semi-synchronous coupling in which the ice dynamic model uses a longer time step. Multiple regridding options are available, and multiple methods for coupling the sub ice shelf cavity geometry. Thermodynamic coupling may also be activated. We present idealised simulations using FISOC with a Stokes flow ice dynamic model coupled to a regional ocean model. We demonstrate the modularity of FISOC by switching between two different regional ocean models and presenting outputs for both. We demonstrate conservation of mass and other verification steps during evolution of an idealised coupled ice - ocean system, both with and without grounding line movement.

1 Introduction

The Antarctic and Greenland ice sheets have the potential to provide the greatest contributions to global sea level rise on century timescales (Church et al., 2013; Moore et al., 2013), with the greatest uncertainty in projections being due to the Marine Ice Sheet Instability (MISI) (Mercer, 1978; Schoof, 2007; Robel et al., 2019)MISI; Mercer, 1978; Schoof, 2007; Robel et al., 2019). Ice dynamic behaviour is strongly sensitive to ocean currents, in particular the transport of warmer waters across the continental shelf causing high basal melt rates under ice shelves (Hellmer et al., 2012; Thoma et al., 2015). For Antarctica's Pine Island Glacier, which is likely undergoing unstable retreat due to MISI, ocean induced basal melting has been established as a trigger for MISI through both observational evidence (Christianson et al., 2016) and model studies (Favier et al., 2014; Gladstone et al., 2012) (Gladstone et al., 2012; De Rydt et al., 2014; Favier et al., 2014). While MISI is fundamentally fundamenatally a geometrically controlled phenomenon, its onset and the resulting rate of ice mass loss are strongly dependent on tight coupling between ice dynamic behaviour and ocean processes. Importantly, ocean-driven basal melt rates respond to the evolving geometry of ice shelf cavities (Mueller et al., 2018)(Timmermann and Goeller, 2017; Mueller et al., 2018), and the grounded-ice dynamic behaviour responds to the evolving basal melt rates through their impact on the buttressing force provided by ice shelves to the grounded ice. While most ice sheet model based studies use relatively simple parameterisations for calculating basal melt rates beneath ice shelves, a recent comparison has recent studies have highlighted limitations of this approach (Favier et al., 2019) (De Rydt and Gudmundsson, 2016; Favier et al., 2019). In particular, melt parameterisations as a function of depth or thermal driving do not impose conservation of heat in the system, and none of the parameterisations fully capture the impact of evolving ice geometry on cavity circulation.

Several projects to couple ice sheet and ocean models are underway, and most (including the current study) will contribute to the Marine Ice Sheet – Ocean Model Intercomparison Project first phase (MISOMIP1) and its child projects: the Marine Ice Sheet Model Intercomparison Project third phase (MISMIP+); and the Ice Shelf Ocean Model Intercomparison Project second phase (ISOMIP+) (Asay-Davis et al., 2016); Asay-Davis et al. (2016)).

Coupling projects take different approaches to handling the different timescales of ice and ocean processes. An ice sheet flowline model coupled to a five box ocean model allows large ensemble simulations to be carried out, but is limited in terms of implementation of physical processes (Gladstone et al., 2012). A temporally synchronous approach allows the cavity geometry to evolve on the ocean time-step time step as a function of the melt rates calculated by the ocean model and the ice dynamics calculated by the ice model (Goldberg et al., 2018). Asynchronous approaches incorporate a longer time-step time step for ice than ocean, and sometimes involve offline coupling with partial coupling through file exchange and with restarts for the ocean model (Seroussi et al., 2017; De Rydt and Gudmundsson, 2016; Thoma et al., 2015).

Here, we present a new, flexible Framework for Ice Sheet – Ocean Coupling (FISOC, ; Section 2). FISOC allows runtime coupling between in which ice and ocean components with a are compiled as runtime libraries and run through one executable. FISOC provides the user choice of synchronicity options. Adopting Earth System Modelling Modeling Framework terminology (ESMF; Section 2), we refer to an ocean model coupled through FISOC as an "ocean component" and an ice sheet or ice dynamic model coupled through FISOC as an "ice component". We use FISOC to couple two different 3D ocean models to an ice dynamic model and present idealised simulations demonstrating mass conservation and consistent grounding line behaviour (Section 3). FISOC is also currently being used to contribute to ISOMIP+ and MISOMIP1.

2 Methodology

FISOC is an open source coupling framework built using the ~~Earth System Modelling Framework (ESMF, Hill et al. (2004); Collins et al. (2~~ ~~)~~ESMF (Hill et al., 2004; Collins et al., 2005). FISOC aims to provide seamless runtime coupling between an existing ice sheet model and an existing ocean model for application to Antarctic ice sheet - ocean systems. In its current form, FISOC assumes that the important ice sheet - ocean interactions occur at the underside of a floating ice shelf, and that the lower surface of the ice shelf can be projected on to the horizontal plane.

FISOC aims to provide flexibility and computational efficiency through the following key features:

- Flexible modular architecture (Section 2.1) facilitates swapping between different ice components or between different ocean components according to purpose (Section 2.2).
- Access to ESMF tools allows multiple regridding and interpolation options, including between regular grids and unstructured meshes (Section 2.3).
- Multiple options for handling differing ice and ocean time scales include fully synchronous coupling, passing rates of change, time averaging of variables (Sections 2.4 and 2.5).
- Flexible run-time control over the exchange of variables allows specific coupling modes to be (de)activated as required, e.g. geometric coupling, thermodynamic coupling.
- Grounding line movement (Section 2.8) is implemented using geometry change rates and a modified wet/dry scheme in the ocean component, with multiple options available for updating cavity geometry (Section 2.5).
- Flexibility for parallelisation options. Currently sequential coupling is implemented, but any combination of sequential and concurrent parallelisation is possible with minimal coding effort ~~.~~ (see also Section 2.1.1).
- ESMF compatibility means that FISOC can be embedded within any ESMF-based modelling system, e.g. as a regional model within a global model.
- ESMF compatibility also means that additional ESMF components (e.g. an atmosphere model) could easily be added to the coupled system.

These features are described further in the following sections and in the FISOC manual, which can be found in the FISOC repository (see “code availability” at the end of this paper).

2.1 Software design

While coupled models in Earth System science have been in existence for decades, and such coupled models are often viewed as single entities (ocean - atmosphere general circulation models for example), the field of coupled ice sheet - ocean modelling

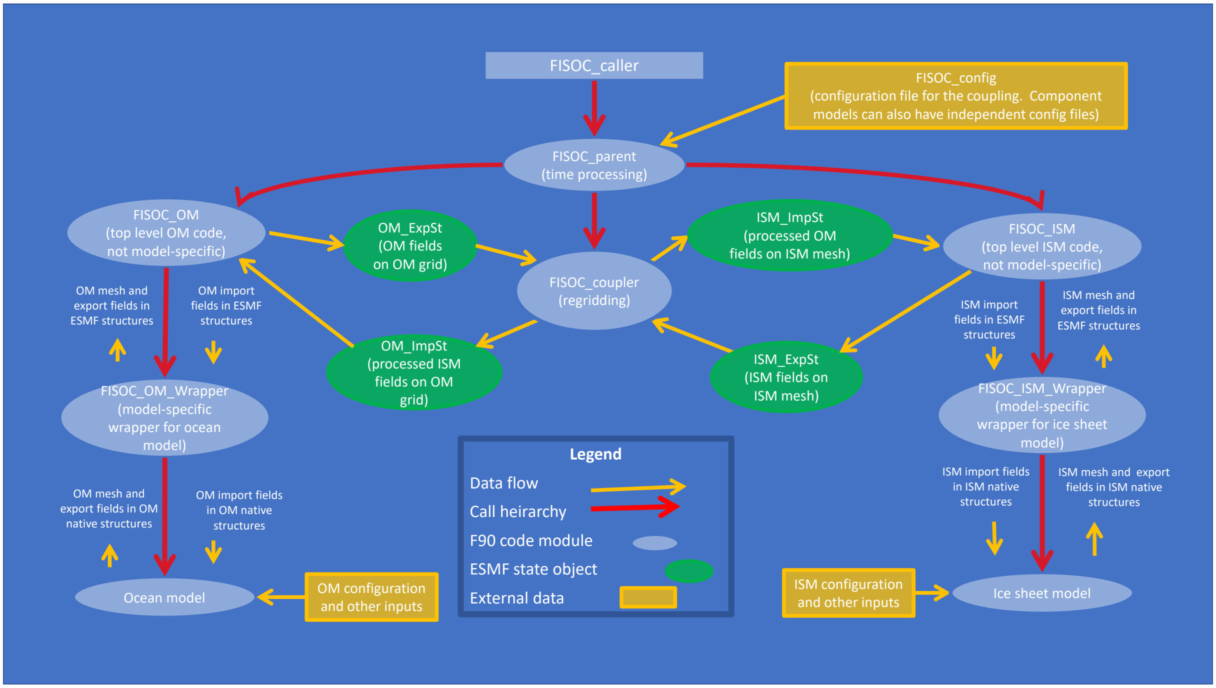

Figure 1. Overview of FISOC code structures. "OM" and "ISM" are short for Ocean and Ice Sheet Model (or component) respectively. "ImpSt" and "ExpSt" are short for Import and Export State respectively.

is relatively young. FISOC is intended as a framework for coupling independent models rather than as a coupled model in itself. Building and running a coupled ice sheet - ocean model is currently more complex than building and running both an ice and an ocean model independently. FISOC aims to minimise the additional complexity.

The ice and ocean components may use their standard run time input files, and their paths are set in a FISOC run time configuration file, along with information about ~~time-stepping~~ time stepping and variables to be exchanged.

FISOC adopts the hierarchical modular structure of the Earth System Modelling Framework~~(ESMF, Hill et al. (2004); Collins et al. (2005~~ ~~).~~. The FISOC code structures are summarised in Figure 1. A top level executable calls a FISOC parent module (this could in principal also be embedded within a larger coupled model framework). The parent module coordinates calling of the ice, ocean and regridding components. Regridding is one of the reasons to make use of ESMF, described further in Section 2.3. The ice and ocean components are independent models, not included in the FISOC code repository, compiled as libraries to be called by FISOC at run time. On each side (ice and ocean) of the coupling is a model-specific wrapper, whose main run time functions are:

– Call the component's initialise, run and finalise routines as required.

– Convert the component's grid or mesh to ESMF format, using ESMF data structures.

– Read from, or write to, the component's required state variables, converting between the component's native data structures and ESMF data structures.

Further processing of variables (such as calculating rates of change) is implemented by the ice and ocean generic code modules.

Incorporating a new ice or ocean component into FISOC can be straightforward, depending on the existing level of ESMF compatibility of the new component. Models able to provide mesh information and variables in ESMF data structures can be very easily built in to FISOC. The only coding required for a new component is a new model-specific wrapper in the FISOC repository. Copying an existing wrapper can be a viable starting point.

2.1.1 Sequential parallelism

FISOC currently adopts a sequential parallelism paradigm. Each component runs on the full set of available Persistent Execution Threads (PETs). PET is an ESMF abstraction catering for multiple parallelism options. FISOC has so far used only the Message Passing Interface (MPI), in which one PET wraps one MPI process.

The sequential workflow is illustrated in Figure 2. The order of events during time stepping is as follows: The ocean component is called for the full number of ocean time steps required to complete one coupling interval. Ocean outputs are then regridded and passed to the ice component, which also runs for as many time steps as are required to complete one coupling interval. The ice component outputs are then regridded and passed to the ocean component. The ice component time step size is equal to the coupling interval for all simulations in the current study.

The initialisation is not shown in Figure 2, but we note that this is similar to the run time event order: the ocean component is initialised first, followed by regridding and then the ice component. There are two initialisation phases for each component, allowing for the possibility that variables may be needed to be passed from ice to ocean component in order to finalise initialisation.

This ordering of events imposes a lag in the sytem: While the ice component receives ocean variables for the current coupling interval, the ocean component only recieves ice variables for the previous coupling interval. This could be reversed (running the ice component before the ocean component) or could be modified such that both components receive variables from the other component for the previous coupling interval.

While FISOC implements sequential parallelism, ESMF also supports concurrent parallelism. Concurrent parallelism allows different components to run at the same time on different subsets of the available PETs. This approach is beneficial when different components have very different computational costs and parallel scaling: a cheap component that scales poorly is more effectively run on a subset of the available PETs, and concurrent parallelism allows this to be implemented more computationally efficiently than sequential. This could easily be implemented in FISOC if it becomes necessary, as the components, which utilise MPI, are assigned a distinct MPI communicator during initialisation. This communicator could be made to represent a subset of the available PETs. In principal concurrent parallelism also offers sub-time step coupling: it is possible to exchange variables between components during convergence of numerical schemes. Such coupling is unlikely

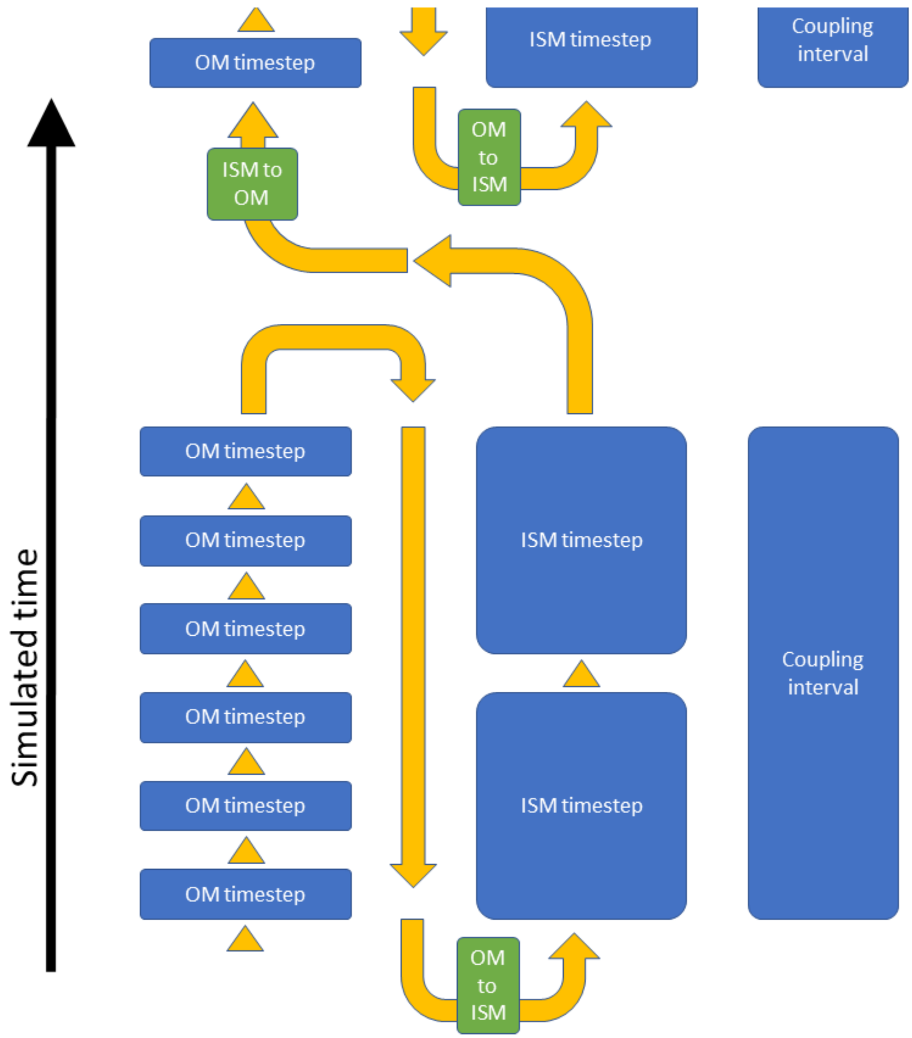

Figure 2. FISOC workflow. "OM" and "ISM" are short for Ocean and Ice Sheet Model respectively. The black arrow indicates the direction of simulated time. The yellow arrows indicate the order of events during a FISOC simulation. The green boxes indicate when regridding and passing of variables between components occurs. The length of the blue boxes in the vertical indicates example relative size of time steps and coupling interval (this is illustrative; in practice there will be many more OM time steps per ISM time step and the ISM time step size will usually equal the coupling interval).

to be implemented within FISOC as the timescales for ice and ocean components are so different. While sequential coupling imposes a lag between components (described above), concurrent coupling implemented in FISOC would impose a lag in both components: exchange of variables in both directions would occur at the end of the coupling interval.

Table 1. Ice and ocean components currently coupled through FISOC.

Type	Name	Notes
OM	ROMS	3D, gridded, sigma coord
OM	FVCOM	3D, unstructured mesh, sigma coord
ISM	Elmer/Ice	3D, full Stokes and shallow models

2.1.2 Error handling

The ESMF adopts a defensive strategy to error handling: All errors are logged and passed back up the call stack. The calling routine has the option of attempting to continue running in the event of errors occurring. As the call structure between FISOC and ESMF is one-way (FISOC routines may call ESMF routines but not vice versa), all such errors are eventually returned to FISOC.

FISOC adopts a fail-fast approach. Errors are generally considered to be fatal, in which case FISOC will log error information and finalise both ice and ocean components and ESMF. FISOC also aims to provide consistency checks, most of which are considered fatal if not passed. For example, ice and ocean input files might both contain time-stepping time stepping information, potentially duplicating information in the FISOC run-time configuration file, and these can be checked for consistency in the model-specific wrappers. The general intention is to stop running if something unexpected happens and provide a meaningful message to the user about why.

There are a few cases where ESMF errors can be handled at run time. Details can be found in the FISOC manual., which can be accessed from the FISOC repository (see “code availability” at the end of this paper).

2.2 Components

FISOC is designed to facilitate swapping between different ocean or ice components. Currently two different ocean components and one ice component are available through FISOC. Table 1 summarises components currently coupled into FISOC. In some cases, a non-standard build of the component is required for FISOC compatibility, and these are described in the FISOC manual, which can be obtained through the FISOC repository (Section 2.1).

The ice component Elmer/Ice (Gagliardini et al., 2013) is a powerful, flexible, state-of-the-art ice dynamic model.

The Regional Ocean Modelling System (ROMS; Shchepetkin and McWilliams (2005)Modeling System (ROMS; Shchepetkin and McW) is a 3D terrain-followingsigma coordinate , sigma-coordinate ocean model that has already been adapted to use in ice shelf cavities (Galton-Fenzi et al., 2012). The module for ice shelf cavities implemented in the Finite Volume Community Ocean Model (FVCOM, Chen et al. (2003)(FVCOM; Chen et al., 2003) provides non-hydrostatic options, a horizontally unstructured mesh that lends itself to refinement, and may be more suited to small scale processes such as ice shelf channels (Zhou and Hattermann, 2020).

2.3 Regridding

As stated above, FISOC provides coupling on a horizontal plane onto which the lower surface of an ice shelf can be projected. It is this plane on which ice and ocean properties are exchanged through the FISOC framework. Adapting the FISOC code to handle a vertical ice cliff is expected to be straightforward, and would be desirable for application to the Greenland ice sheet. More complex 3D ice-ocean interface geometries are challenging not only for FISOC but also for the current generation of ice sheet and ocean models.

FISOC has access to all the run-time regridding options provided by ESMF. These include nearest neighbour options, conservative options, patch recovery and bilinear regridding. These options are available for structured grids and unstructured meshes. FISOC requires that both ice and ocean components define their grid or mesh on the same coordinate system, and that both components use the same projection. All FISOC simulations to date have used a Cartesian coordinate system ~~.~~ (i.e. all components have so far used Cartesian coordinates).

Our current FISOC setup does not meet the requirements for all forms of ESMF regridding. Specifically, the conservative methods, when an unstructured mesh is involved, require that field values are defined on elements and not on nodes. Elmer, by default, provides field values on nodes, but can also provide element-wide values or values on integration points within elements. We will need to either map nodal values to element values or utilise element-type variables in order to use conservative regridding, and this is intended as a future development.

When using FISOC to couple Elmer/Ice to ROMS, the ROMS ~~staggered grid , including ghost cells,~~ grid extends beyond the ~~domain of the~~ Elmer/Ice mesh. This is due to ROMS using a staggered grid (Arakawa C-grid) and ghost cells extending beyond the active domain. This necessitates the use of extrapolation. ESMF regridding methods ~~also~~ provide options for extrapolation, which are used here. Simulations in the current study use either nearest "Source TO Destination" (STOD, a form of nearest neighbour~~regridding)~~) regridding or use bilinear interpolation ~~with nearest STOD to extrapolate to points outside the domain~~(in which case nearest STOD is used only for destination points that lie outside the source domain).

We use subscripts with square brackets, $_{[X]}$, where X is either O (ocean component) or I (ice component), to denote a variable that exists in both ice and ocean components with the same physical meaning, but potentially different values due to being represented on different grids/meshes.

2.4 Coupling timescales

The timescales for sub-shelf cavity circulation behaviour are in general much shorter than the timescales for ice flow and geometry evolution (typically minutes to days instead of years to centuries). Typical ~~time-step~~ time step sizes are correspondingly smaller for ocean models (seconds to minutes) than for ice sheet models (days to months). A single ice sheet model ~~time-step~~time step, if the Stokes equations are solved in full, will typically require orders of magnitude more computational time than a single ocean ~~time-step~~time step. Due to the combination of these two reasons the ice and ocean components of FISOC will in general use different ~~time-steps~~time steps, with the ice ~~time-step~~ time step size being much larger. We define relevant terminology for coupling timescales:

- **Fully synchronous coupling.** The ice and ocean components have the same time-step time step size, and exchange variables every time-steptime step.
- **Semi synchronous coupling.** The ice component has a larger time-step time step than the ocean component, but the ocean component's cavity geometry and grounding line position are allowed to evolve on the ocean time-step time step (e.g. by using ice velocities from a previous ice time-step time step or rates of change based on the most recent two time-stepstime steps).
- **Asynchronous coupling.** The ice component has a larger time-step time step than the ocean component. Cavity geometry is updated on the ice component time-step time step or less frequently.
- **Coupling interval.** The time interval at which the ice and ocean components exchange variables.

FISOC requires In the current study, FISOC sets the coupling interval to be equal to the ice component time step size. This is an exact multiple of both the ocean time-step sizeand the ice component time-step size. FISOC assumes that time-step sizes are not adaptive. Simulations in ocean model time step size. More generally (for potential future experiments), FISOC calls each component for a fixed time period and allows the component to determine its own time stepping within that period. In principal, adaptive time stepping could be implemented within this framework, so long as each component runs for the required amount of simulated time. FISOC does not currently provide an option to vary the coupling interval during a simulation, but this could be implemented if needed.

FISOC is flexible with regard to time processing of ocean or ice variables. It is possible to cumulate variables, calculate averages, or use snapshots. In the current studyset the coupling interval equal , the ocean components (both ROMS and FVCOM) calculate averaged basal melt rates over the coupling interval and pass these averages through FISOC to the ice componenttime-step size . In the current study, as the ice component time step size is equal to the coupling interval for all simulations, no time processing of ice component variables is needed.

In principal, FISOC supports all three synchronicity options, though fully synchronous coupling is not practical to achieve when solving the Stokes equations for the ice component. The experiments carried out for this paper use semi synchronous coupling with cavity geometry evolution as described in Section 2.5.

Goldberg et al. (2018) and Snow et al. (2017) implement fully synchronous coupling, whereas Seroussi et al. (2017) and Favier et al. (2019) implement asynchronous coupling with partial ocean restarts.

2.5 Handling cavity evolution

The evolution of cavity geometry under the ice shelf, defined by ice draft a reference ice draft, z_d (positive upward), and grounding line location, is calculated by the ice component using forced by the melt rates passed from the ocean component. But the ocean and ice components are typically run on different grids/meshes, and both components need to maintain a representation of the ice draft and grounding line position on their native grid or mesh. Information about the ice component cavity evolution must be passed We refer to z_d as a "reference" ice draft because the ocean component may further modify the ice draft according to the dynamic pressure field. The ocean component's "free surface" variable, ζ, represents, for the open ocean, the height of the upper surface of the ocean domain relative to a mean sea level. Under the ice shelf, ζ represents the deviation of the upper surface of the ocean domain relative to the reference ice draft z_d (similar to Goldberg et al. (2018)). To summarise the meaning of the key variables: $z_{d[I]}$ is the reference ice draft computed by the ice component; $z_{d[O]}$ is the same but regridded for the ocean component; $(z_{d[O]} + \zeta)$ is the actual ice draft according to the ocean component.

Given the potential for non-synchronicity of the ice and ocean component time-steppingtime stepping, several methods are implemented in FISOC for the ocean to update its representation of the ice draftz_d. All the processing options described below are applied on the ocean grid after the ice component representation of ice geometry has been regridded (i.e. $z_{d[I]}$ regridded to $z_{d[O]}$). We use subscripts with square brackets, $_{[X]}$, where X is either O (ocean component) or I (ice component), to denote a variable that exists in both ice and ocean components with the same physical meaning, but potentially different values due to being represented on different grids/meshes.

Most recent ice. The simplest option is that the ocean component uses the ice draft directly from the most recent ice component time-steptime step. If fully synchronous coupling is used, this option should be chosen. The main disadvantage of this approach for semi or asynchronous coupling is that, due to the much longer time-step time step of the ice component, the ocean component will experience large, occasional changes in ice draft instead of smoothly evolving ice draft. This could be both physically unrealistic and potentially numerically challenging for the ocean component.

Rate. The vertical rate of change of ice draft, $\frac{dz_d}{dt}$, is calculated by FISOC from after each ice component time step using the two most recent ice component time-steps: time steps. If we assume that the ice component completes a time step at time t, the rate at this time is given by

$$\frac{dD_{[O,t]}}{dt}\frac{dz_{d[O,t]}}{dt} = D_{[I,t]} - D_{[I,t-\Delta t_i]}/\Delta t_I \frac{z_{d[I,t]} - z_{d[I,t-\Delta t_I]}}{\Delta t_I} \tag{1}$$

where $D_{[O,t]}$ $z_{d[O,t]}$ is the ocean component's representation of reference ice draft at time t, $D_{[I,t]}$ $z_{d[I,t]}$ is the ice component's representation of reference ice draft at time t, $D_{[I,t-\Delta t_I]}$ $z_{d[I,t-\Delta t_I]}$ is the ice component's representation of reference ice draft at time $t - \Delta t_I$, and Δt_I is the ice component time-step time step size. This rate of change is used by the ocean component to update the cavity geometry . until the next ice component time step completes. In this sense the ocean component lags the ice component as mentioned in Section 2.1.1. This approach provides temporally smooth changes to the ocean representation of the ice draft, but has the potential for the ice and ocean representations to diverge over time as a result of regridding artefacts.

Corrected rate. The same as above, except that a drift correction is applied to ensure ice and ocean representations of cavity geometry do not diverge.

$$\frac{dD_{[O,t]}}{dt}\frac{dz_{d[O,t]}}{dt} = \frac{D_{[I,t]} - D_{[I,t-\Delta t_I]} + f_{cav}\left(D_{[I,t]} - D_{[O,t]}\right)}{\Delta t_I}\frac{z_{d[I,t]} - z_{d[I,t-\Delta t_I]} + f_{cav}\left(z_{d[I,t]} - z_{d[O,t]}\right)}{\Delta t_I} \tag{2}$$

where f_{cav} is a cavity correction factor between 0 and 1. Equation 2 is applied at coupling time-stepstime steps, and the calculated rate of cavity change is then held constant during ocean component evolution until the next coupling time-step. coupling interval completes. Conceptually, this option prioritises ice - ocean geometry consistency over mass conservation.

Linear interpolation. The ocean representation of the ice draft is given by temporal linear interpolation between the two most recent ice sheet time-stepstime steps. This imposes additional lag of the ocean component behind the ice component.

The above options are all implemented in FISOC, but only the "rate" and "corrected rate" approaches are used in the current study.

The cavity geometry may be initialised independently by ice and ocean components. In this case, the user must ensure consistency. It is also possible for the cavity geometry from the ice component to be imposed on the ocean component during FISOC initialisation. This ensures consistency.

Handling cavity evolution is a little more complicated in the case of an evolving grounding line, as discussed in Section 2.8 below.

2.6 Thermodynamics at the ice-ocean interface

Exchange of heat at the ice-ocean interface is handled within the ocean model. Like many ocean models, FVCOM and ROMS adopt the three-equation formulation for thermodynamic exchange ~~(Hellmer and Olbers, 1989; Holland and Jenkins, 1999)~~ (Hellmer and Olbers, 1989; Holland and Jenkins, 1999; Jenkins et al., 2010). This parameterisation assumes that the interface is at the in situ pressure freezing point, and that there is a heat balance and salt balance at the interface. ~~It assumes~~ Both ROMS and FVCOM assume constant turbulent transfer coefficients for scaling the heat and salt fluxes through the interface~~.~~, with thermal and saline exchange velocities calculated as the product of these coefficients with friction velocity. Further details of the ROMS and FVCOM specific implementations of the three-equation formulation are given by Galton-Fenzi et al. (2012) and Zhou and Hattermann (2020) respectively. An ablation or melt rate is calculated for each ocean model grid cell, which is then passed to FISOC as a boundary condition for the lower surface of the ice model at the coupling time interval.

Internally, both ocean models account for the thermodynamic effect of basal melting by imposing virtual heat and salt fluxes within a fixed geometry at each ocean model time step, to mimic the effects of basal melting, rather than employing an explicit volume flux at the ice-ocean interface. Independent of this, a geometry change is passed back from the ice model through FISOC at ~~the coupling time step~~ after each coupling interval (including the effect of melting/freezing, as well as any ice dynamical response), which is used to update the ocean ~~model ice shelf~~ component cavity shape (Section 2.5).

For some applications, conductive heat fluxes into the ice shelf due to vertical temperature gradients in the ice at the ice-ocean interface are required by the three-equation parameterisation to calculate the flux balance at the ice ocean interface. While ice-ocean thermodynamic parameterisations in ocean-only models must make an assumption about this temperature gradient, FISOC can pass the temperature gradient from the ice component directly to the ocean component. This feature is not demonstrated in the current study, but will be properly tested in future studies.

Non-zero basal melt rates may be calculated by the ocean component in regions that are defined as grounded by the ice model. This could occur due to isolated patches of ungrounding upstream of the grounding line or to discrepancies between the ice and ocean component's representation of the grounded region. Basal melt rates are masked using the ice component's grounded mask before being applied within the ice component. This has the potential to impact on mass conservation in the coupled system. Future studies utilising conservative regridding will ensure that passing masked field variables between components remains conservative.

2.7 Interface pressure

Aside from the geometry evolution, an ocean boundary condition for pressure at the ice-ocean interface, $P_{interface}$, must be provided to the ocean component. FISOC can pass pressure directly from ice to ocean components. However, using actual ice overburden directly as an upper ocean boundary condition results in higher horizontal pressure gradients at the grounding line (and for dry cells, see Section 2.8) than ocean models can typically handle (Goldberg et al., 2018). In the current study, the ocean component uses the reference ice draft (i.e. the depth of the ice-ocean interfacesee Section 2.5) to estimate a floation pressure. ROMS assumes a constant reference ocean density:

$$P_{interface} = -g\rho_{or} D_{[O]} z_{d[O]} \tag{3}$$

where g is acceleration due to gravity, ρ_{or} is a reference ocean density and $D_{[O]}$ $z_{d[O]}$ is the ocean representation of ice draft (positive upward). For the current study, all simulations with ROMS use $\rho_{or} = 1027\ \mathrm{kg\,m^{-3}}$. FVCOM assumes a constant vertical ocean density gradient following Dinniman et al. (2007):

$$P_{interface} = -g(\rho_{o1} - + 0.5\frac{d\rho_o}{dz} D_{[O]} z_{d[O]}) D_{[O]} z_{d[O]} \tag{4}$$

where ρ_o is ocean water density, ρ_{o1} is ocean water density of the top ocean layer and the vertical ocean water density gradient, $\frac{d\rho_o}{dz}$, is set to $8.3927 \times 10^{-4} kgm^{-4}$ $8.3927 \times 10^{-4}\,\mathrm{kg\,m^{-4}}$.

2.8 Grounding line evolution

Grounding line movement in FISOC requires that both ice and ocean components support it. Numerical convergence issues place constraints in terms of mesh resolution for representing grounding line movement in ice sheet models (Vieli and Payne, 2005; Pattyn et al., 2006; Gladstone et al., 2010a, b; Cornford et al., 2013; Gladstone et al., 2017). While FISOC allows ice draft to be passed to the ocean component (Section 2.5), FISOC does not impose the ice component grounding line position on the ocean component. Instead, the ocean component uses the evolving cavity geometry to evolve the grounding line.

A recent ice-ocean coupling study (Goldberg et al., 2018) used a "thin film" approach to allow grounding line movement. A thin passive water layer is allowed to exist under the grounded ice, and an activation criterion is imposed to allow the layer to inflate to represent grounding line retreat. The current study takes a conceptually similar approach, modifying the existing wetting and drying schemes independently in both ROMS (Warner et al., 2013) and FVCOM. "Dry" cells are used for the passive water column under grounded ice and "wet" cells are used for the active water column under floating ice or the open ocean. The wet - dry mask is two dimensional, so while it is conventional to talk about dry or wet cells, this actually refers to dry or wet columns. The grounding line evolves in the two horizontal dimensions, and is represented in the ocean component as the vertical surface between dry and wet columns.

The original criterion in both ROMS and FVCOM for a cell to remain dry is given by:

$$\eta\zeta - z_b < D_{crit} \tag{5}$$

where ~~η is the free surface variable,~~ z_b is the bottom boundary depth (bathymetry, ~~aka bedrock depth~~or bedrock depth, positive upward), and D_{crit} is a critical water column thickness ~~(or depth)~~ for wet/dry activation. D_{crit} is a parameter to be set by the user (typical values lie between 1 to 20m). ~~Both η and z_b are defined relative to sea level.~~ Thus, cells with a water column thickness less than D_{crit} are designated dry. Flux of water into dry cells is allowed, but flux of water out of dry cells is prevented.

The FVCOM criterion for an element to be dry has been modified for the presence of a marine ice sheet/shelf system as follows:

$$\eta - z_b + D_{[O]} z_{d[O]} < D_{crit} \tag{6}$$

This is a purely geometric criterion based entirely on the geometry determined by the ice component. The ROMS criterion for a cell to be dry has been modified for the presence of a marine ice sheet/shelf system as follows:

$$\eta + \zeta - z_b - (S_{[O]} z_{s[O]} - z_{d[O]} - D_{[O]} + D_{crit}) * \frac{\rho_i}{\rho_{or}} \leq 0 \tag{7}$$

where ~~$S_{[O]}$~~ $z_{s[O]}$ is the ocean representation of ice sheet/shelf upper surface height~~and $D_{[O]}$ is the ocean representation of ice draft.~~ . $z_{s[O]}$ is needed in this equation because the floatation assumption cannot be made for grounded ice. This equation essentially compares ζ against the height above buoyancy of the grounded ice. In other words, if the dynamic variations in ocean pressure are sufficient to overcome the higher ice pressure due to the positive height above buoyancy, the cell can become ungrounded. The conceptual difference between the FVCOM and ROMS wetting criteria is that ROMS allows dynamic ocean pressure variations to make minor grounding line adjustments relative to the grounding line determined by the ice geometry, whereas FVCOM uses just the ice geometry to determine grounding line position.

FISOC allows the ice component to pass any geometry variables to the ocean, such as ice draft, ice thickness, upper surface elevation, or rates of change of any of these. In the event that geometry variables other than ~~D~~ z_d are passed to the ocean, the same processing method is used as for ~~D~~z_d, as described in Section ~~2.8.~~

2.5. In the current study ~~$\frac{dD}{dt}$~~, $\frac{dz_d}{dt}$ is passed to the ocean component, and in one case both ~~$\frac{dD}{dt}$ and $\frac{dS}{dt}$~~ $\frac{dz_d}{dt}$ and $\frac{dz_s}{dt}$ are passed (details in Section 3). When ~~$\frac{dS}{dt}$~~ $\frac{dz_s}{dt}$ is passed, ~~$\frac{dS}{dt}$~~ $\frac{dz_s}{dt}$ is processed the same way as ~~$\frac{dD}{dt}$.~~
$\frac{dz_d}{dt}$.

If the grounding line problem is solved, and if ~~D~~ z_d is processed for passing to the ocean using the **Corrected rate** method, equation 2 is modified to account for the dry water column thickness, which is initialised to D_{crit}. The correction term changes from ~~$f_{cav}\left(D_{[I,t]} - D_{[O,t]}\right)$ to $f_{cav}\left(\max(D_{[I,t]}, zb + D_{crit}) - D_{[O,t]}\right)$~~ $f_{cav}\left(z_{d[I,t]} - z_{d[O,t]}\right)$ to $f_{cav}\left(\max(z_{d[I,t]}, z_b + D_{crit}) - z_{d[O,t]}\right)$.

There are no connectivity restrictions on wetting and drying in either of the ocean components in the current study. This means that it is possible for individual cells, or regions containing multiple cells, that are upstream of the grounding line to become wet (i.e. to unground). This occurs on small spatial and temporal scales in ROMS (individual cells a short distance upstream of the grounding line sometimes become temporarily wet) but not at all in FVCOM (likely due to choice of wetting criterion).

Table 2. Model choices and input parameters used in verification experiment 1 (VE1, Section 3.1) and verification experiment 2 (VE2, Section 3.2) comprising four simulations in total: VE1_ER, VE1_EF, VE2_ER and VE2_EF. Component abbreviations in these simulation names are E (Elmer/Ice), R (ROMS), and F (FVCOM). "Semi-structured" refers to a mesh that is in principal unstructured, but in practice structure can be seen (See Figure 3 middle and lower panes).

Choice or input	**VE1_ER**	**VE1_EF**	**VE2_ER**	**VE2_EF**
Ice component	Elmer/Ice	Elmer/Ice	Elmer/Ice	Elmer/Ice
Ocean component	ROMS	FVCOM	ROMS	FVCOM
Ice mesh	Unstructured	Semi-structured	Unstructured	Semi-structured
Ocean mesh or grid	Structured, staggered	Semi-structured	Structured, staggered	Semi-structured
Domain size	30 km × 100 km	31 km × 99 km	30 km × 100 km	31 km × 99 km
Regrid method	Bilinear	Nearest STOD	Bilinear	Nearest STOD
Ocean ~~time-step~~ time step size	200 s	20 s	100 s	20 s
Ice ~~time-step~~ time step size	10 days	10 days	10 days	10 days
Coupling interval	10 days	10 days	10 days	10 days
Run length	100 a	47 a	46 a	40 a
Cavity update method	**Rate**	**Rate**	**Corrected rate**	**Rate**
Cavity correction factor, f_{cav}	n/a	n/a	0.01	n/a
Minimum water column D_{crit}	n/a	n/a	5m	5m
Ocean density ρ_{or}	1027 $\mathrm{kg\,m^{-3}}$	~~1027.9 $\mathrm{kg\,m^{-3}}$~~ n/a	1027 $\mathrm{kg\,m^{-3}}$	~~1027.9 $\mathrm{kg\,m^{-3}}$~~ n/a
Ice density ρ_i	910 $\mathrm{kg\,m^{-3}}$	910 $\mathrm{kg\,m^{-3}}$	910 $\mathrm{kg\,m^{-3}}$	910 $\mathrm{kg\,m^{-3}}$
Ice temperature	−5 °C	−5 °C	−5 °C	−5 °C

3 Verification experiment design

Simulations are carried out on idealised domains as a proof of concept to demonstrate the coupling rather than to address scientific questions. Verification experiment 1 (VE1) aims to assess whether the coupled system conserves mass. Verification experiment 2 (VE2) aims to assess whether the ocean and ice representations of grounding line evolution are consistent.

3.1 Verification experiment 1: Floating adjustment

Verification experiment 1 (VE1) is a simple experiment in which a linearly sloping ice shelf is allowed to adjust toward steady state. The experiment is not run long enough to attain steady state, but enough to demonstrate evolution of the coupled system. See Table 2 for run length and a summary of other model choices and parameter values used in VE1.

All ice and ocean vertical side boundaries are closed: There is no flow in or out of the domain. There is mass exchange between the ice and ocean (and therefore also heat exchange). The coupling ~~is purely geometric in that the~~ centers on the evolution of ice geometry: the ocean component passes an ice shelf basal melt rate to the ice component and the ice component passes a rate of change of ice draft to the ocean component.

We expect adjustment toward a uniform thickness uniform-thickness ice shelf to occur by two mechanisms:

1. Ice dynamics. The gravitational driving force will tend to cause flow from thicker to thinner regions.
2. Melt/freeze. The greater pressures at greater depth should result in higher melt rates, with the potential for refreezing under thinner regions.

3.1.1 Domain size and meshes

The domain is 30 km across the expected direction of ice flow (y direction) by 100 km along the flow (x direction) for simulation VE1_ER. However, ocean component FVCOM (used in VE1_EF) uses a semi-structured (in principal structured unstructured but in practice exhibiting some structure) mesh with dimensions 31 km by 99 km. Note that the FVCOM domain is in a slightly different size. This results from an auto-generated-mesh method using the required domain size and a uniform resolution of 2 km for its triangular elements. FISOC does not in general require that ice and ocean component domains precisely overlap. Indeed the region of overlap is allowed to be small relative to the domains (for example an Antarctic ice stream interacts with the ocean only in its floating shelf, and the majority of the catchment may be grounded with no possibility to interact with the ocean for the duration of an intended simulation). However, given that we aim to address mass conservation in the coupled system, we choose to require precise domain match between ice and ocean components for the current study. Thereforethe ice component for , for simulations presented in the current study, the ice component has a slightly different domain when coupled to ROMS as compared to when coupled to FVCOM. For VE1_EF the ice component runs on an almost identical mesh to the ocean component. The only difference is at two diametrically opposite corners, where FVCOM prefers to maintain element shape but Elmer/Ice prefers to maintain a strictly rectangular domain (in order to facilitate imposition of consistent boundary conditions at the corners of the domain). These mesh differences are visually summarised in Figure 3.

3.1.2 Ice component setup

The initial geometry is of an ice shelf at floatation (i.e. hydrostatic equilibrium). The initial ice draft is given in m by

$$Dz_d = -450 + 400\left(\frac{x}{100000}\right), \tag{8}$$

where x is distance in m along the domain. The initial geometry does not vary across the ice flow (y direction). Ice and ocean water densities used in the ice component are $\rho_i = 910\ \mathrm{kg\,m^{-3}}$ and $\rho_{or} = 1027\ \mathrm{kg\,m^{-3}}$ respectively. These densities, along with the floatation assumption, determine the ice upper surface.

The pressure , P, acting on the underside of the ice shelf is given by

$$P(z) = -\rho_{or} g D.$$

where z is height relative to sea level (positive upward) and g is gravitational acceleration (set to 9.81)Equation 3.

Temperature in the ice component is constant through space and time at -5 °C.

VE1 includes ice flow and geometry evolution solving the Stokes equations directly. Glen's power law rheology with $n = 3$ is implemented (Glen, 1952; Gagliardini et al., 2013).

Zero ~~net~~ accumulation is prescribed at the upper ice surface. The melt rate from the ocean component is applied at the lower surface. Flow through the vertical side boundaries is not allowed.

Elmer/Ice specific details. The Stokes equations are solved within Elmer/Ice (Gagliardini et al., 2013). A 2D horizontal mesh of triangles with an approximate element size of $1\mathrm{km}$ (VE1_ER) or $2\mathrm{km}$ (VE1_EF) is extruded in the vertical to give 11 equally spaced terrain-following layers with the bulk element shape being triangular prisms.

3.1.3 Ocean component setup

The ocean bathymetry is set to $500\ \mathrm{m}$ throughout the domain. The wet/dry scheme (Section 2.8) is not used in this experiment, as the whole domain is ice shelf cavity with no grounded ice. Boundaries are closed and rotation is disabled. ~~Temperature~~ Ocean potential temperature is initialised at -1.85 °C and salinity at 34.6 ~~.~~ on the practical salinity scale. Ice-ocean thermodynamics are captured by means of the three-equation parameterisation (Section 2.6).

The ocean conditions are chosen to represent a cold cavity ice shelf, such as the Amery Ice Shelf. In this configuration, both basal melting and refreezing can occur.

ROMS specific details.

The horizontal resolution is a constant $1\ \mathrm{km}$. There are 11 vertical layers, with a sigmoidal terrain-following distribution configured to provide increased resolution near the top and bottom surfaces. The ROMS baroclinic (slow) ~~time-step~~ time step size is 200 seconds, and there are 30 barotropic (fast) ~~time-steps~~ time steps for every slow ~~time-step.~~ time step. Interior mixing is parameterised with the K-Profile Parameterisation (Large et al., 1994). Background vertical mixing coefficients for tracers and momentum are set to constant values of $5.0e-5\ \mathrm{m^2s^{-1}}$ and $1.0e-3\ \mathrm{m^2s^{-1}}$, respectively, while horizontal viscosity and diffusivity are set to $6.0\ \mathrm{m^2s^{-1}}$ and $1.0\ \mathrm{m^2s^{-1}}$ respectively.

FVCOM specific details. The horizontal grid resolution is $2\ \mathrm{km}$ (defined by the distance between adjacent nodes within a uniform triangular grid) and there are 11 uniformly spaced vertical terrain-following layers. Interior vertical mixing is parameterized using the Mellor and Yamada level 2.5 (Mellor and Yamada, 1982) turbulent closure model (vertical Prandtl Number = 0.1) together with a constant background viscosity and diffusivity of $10^{-6}\ \mathrm{m^2s^{-1}}$. An eddy closure parameterisation (Smagorinsky, 1963) is used for the horizontal mixing of momentum (viscosity) and tracers (diffusivity) with both the scaling factor and the Prandtl Number being 0.1. ~~The turbulent heat- and salt-transfer coefficients are 0.05 and 0.0014, respectively.~~ Both the barotropic ~~time-step~~ time step and the baroclinic ~~time-step~~ time step sizes are 20 seconds.

3.1.4 Coupling

The coupling interval is 10 days, the same as the ice component ~~time-step~~time step size. Cavity update method is **Rate** (Section 2.5). For VE1_ER, the regridding method is bilinear with nearest STOD extrapolation for ocean cells that lie outside the ice domain due to grid stagger. For VE1_EF, nearest STOD regridding is used, which results in a one to one mapping between ice and ocean nodes due to the meshes being nearly identical (Section 3.1.1). There is no grounding line in this experiment.

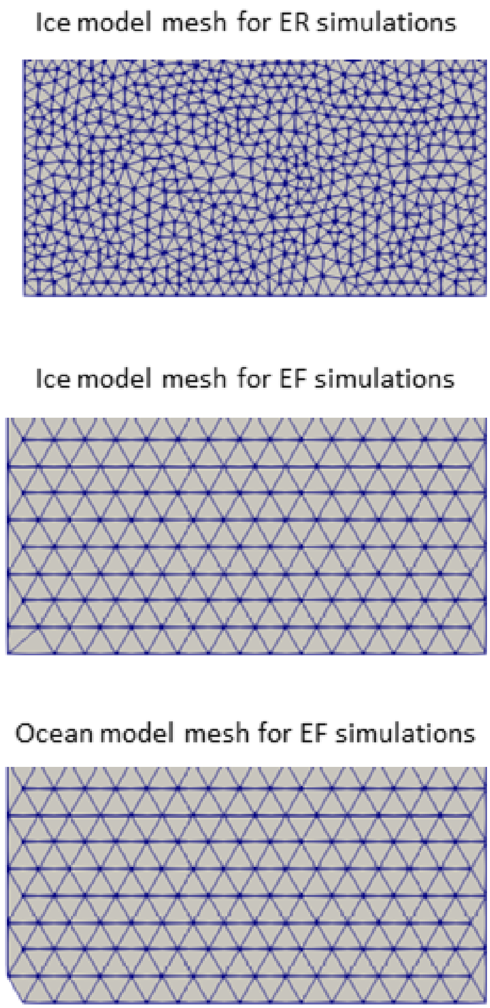

Figure 3. Unstructured meshes used in the current study. The first 15 km are shown. The ocean model in the ER simulations uses a structured grid.

3.2 Verification experiment 2: grounding line evolution

Verification experiment 2 (VE2) is a modified version of VE1, but with part of the region grounded and a net ice flow through the domain allowed. The setup is identical to VE1 except where stated otherwise in this section. This experiment aims to combine design simplicity with an evolving grounding line rather than to represent a system directly analogous to a real world example.

3.2.1 Ice component setup

The VE2 initial geometry is given by

$$z_b = -20 - 980\left(\frac{x}{100000}\right), \quad (9)$$

$$H = \frac{\rho_{or}}{\rho_i}\left(470 - 400\left(\frac{x}{100000}\right)\right), \quad (10)$$

where z_b is bedrock elevation relative to sea level and H is ice thickness. Then ~~D and S~~ z_d and z_s are calculated based on floatation and the same densities as in VE1.

~~No restrictions to ice flow are imposed at the upstream and down stream boundaries given by~~ The depth dependent inflow ($x = 0$~~and either $x = 100$ (~~) and outflow ($x = 100$ km for VE2_ER~~) or~~ ; $x = 99$ km ~~(~~for VE2_EF) boundary conditions for the ice component are given by

$$P_{inflow}(z) = \rho_i g(z_s - z) \quad (11)$$

$$P_{outflow}(z) = \rho_o g z \quad (12)$$

where P_{inflow} and $P_{outflow}$ are pressures prescribed at the inflow and outflow boundaries respectively and z is height relative to sea level (positive up). Zero normal velocity and free slip tangential velocity conditions are imposed at the side walls given by $y = 30$ km and either $y = 0$ (for VE2_ER) $y = -1$ km (for VE2_EF).

The grounding line is allowed to evolve solving a contact problem (Gagliardini et al., 2013). The pressure acting on the underside of ungrounded ice is given by Equation 3.

A sliding relation with a simple effective pressure dependency is used under the grounded ice (Budd et al., 1979, 1984; Gladstone et al., 2017),

$$\tau_b = -C u_b^m z_*, \quad (13)$$

where τ_b is basal shear stress, u_b is basal ice velocity, z_* is the height above buoyancy (related to effective pressure at the bed, N, by $N = \rho_i g z_*$), m is a constant exponent (set to $m = \frac{1}{3}$), and C is a constant sliding coefficient (set to C = 10^{-4} MPa m$^{-\frac{4}{3}}$ a$^{\frac{1}{3}}$).

Height above buoyancy is calculated by:

$$z_* = \begin{cases} H, & \text{if } z_d >= 0 \\ H - z_d \frac{\rho_{or}}{\rho_i}. & \text{if } z_d < 0 \end{cases} \quad (14)$$

This is equivalent to assuming a sub-glacial hydrology system fully connected to, and in pressure balance with, the ocean.

3.2.2 Ocean component setup

Ocean bathymetry matches the bedrock prescribed in the ice component (Equation 9). The wet/dry scheme (Section 2.8) is used in this experiment, with a critical water column thickness of $D_{crit} = 5$ m. Temperature Ocean potential temperature is initialised at -1.9 °C and salinity at 34.6 . on the practical salinity scale.

ROMS specific details. The horizontal resolution is a constant 1 . The slow time-step ROMS setup is identical to Verification Experiment 1 except that the baroclinic (slow) time step size is 100 seconds, with 30 fast time-steps barotropic (fast) time steps for every slow time-steptime step. ROMS has 11 layers in the vertical.

FVCOM specific details. The FVCOM model setup is identical to that of Verification Experiment 1.

3.2.3 Coupling

The cavity update method for VE2_EF is **Rate** (Section 2.5). For VE2_ER it is **Corrected Rate** with a correction factor of $f_{cav} = 0.01$. With the 10 day coupling interval, this equates to a full correction timescale of approximately 3 years. Other coupling details are as in VE1.

4 Verification experiment results

4.1 VE1: Floating adjustment

This is a floating only experiment in which ice and ocean components adjust together towards an equilibrium state (described in Section 3.1). We do not run long enough to achieve equilibrium, but instead investigate the conservation of mass in the coupled system as it evolves.

Figure 4 summarises the coupled system state at the start and end of simulation VE1_ER (see also Table 2 for a summary of the experiments). After the first coupling interval (10 days), the ocean component demonstrates a vigorous overturning circulation and high melt rates, especially in the deeper part of the domain. After the last coupling interval (100 years) the combination of melting and ice flow has caused a redistribution of the ice shelf, with an overall reduction in the along-domain gradients. The melt rates and overturning circulation are much weaker than at the start.

The ocean circulation throughout the simulation is predominantly a buoyancy driven overturning along the domain, with very little cross-domain flow. The peak ocean flow speeds are always located at the top of the ocean domain directly under the ice shelf, where a fast, shallow buoyancy driven flow from deeper to shallower ice draft is balanced by a much deeper return flow.

Figure 5 shows the evolution over time of the total mass of both ice and ocean components and the total coupled system from experiments VE1_ER and VE1_EF. Note that both ocean models employ the Boussinesq approximation, and that the mass in Figure 5 is calculated as volume multiplied by the reference ocean density from Table 2. Relatively rapid mass transfer from the ice to the ocean occurs during the first few years as the relatively warm ocean water transfers its energy to the ice. After this initial period of net melting, the ocean water temperature is close to freezing point, and a long term freezing trend can be

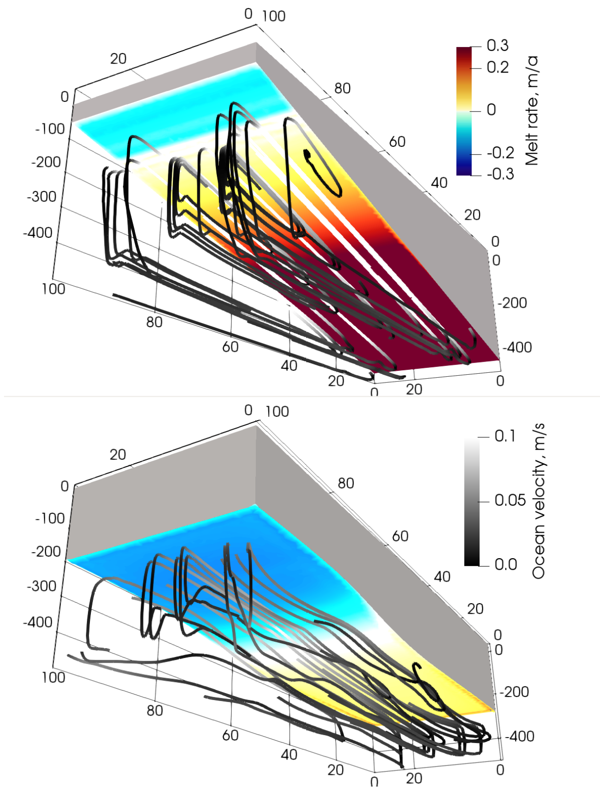

Figure 4. Coupled system state after the first (top) and last (bottom) coupling intervals from the experiment VE1_ER (Table 2). The ice shelf is shown in grey, with basal melt rate computed by the ocean shown in colour on the underside of the ice shelf. Ocean streamlines are shown beneath the ice shelf with the grayscale indicating magnitude of simulated ocean velocity. The vertical coordinate is given in m; the horizontal coords are given in km. This was a 100 year simulation.

seen, stronger and more sustained in the ROMS ocean component than FVCOM. In a physically realistic coupled system, the ice and ocean would come into thermodynamic equilibrium and the spatial net mass transfer would approach zero.

The net mass change of the coupled system is more than an order of magnitude smaller than the mass change of the individual components for both experiments VE1_ER and VE1_EF. The current study does not use conservative regridding (Section 2.3), and so machine precision conservation is not expected. There are additional potential sources of error. The lag of ocean component behind ice component (Section 2.1.1) will cause a similar lag in total mass evolution. Use of the "**Corrected rate**" cavity option (Section 2.5) prioritises geometry consistency between components above mass conservation. The aim of analysing mass conservation in the current study is to ensure that the cumulative impact of these potential error sources is small compared to the signal. This has been achieved, and it will be possible to quantify and minimise or eliminate all sources of error in future studies using conservative regridding methods.

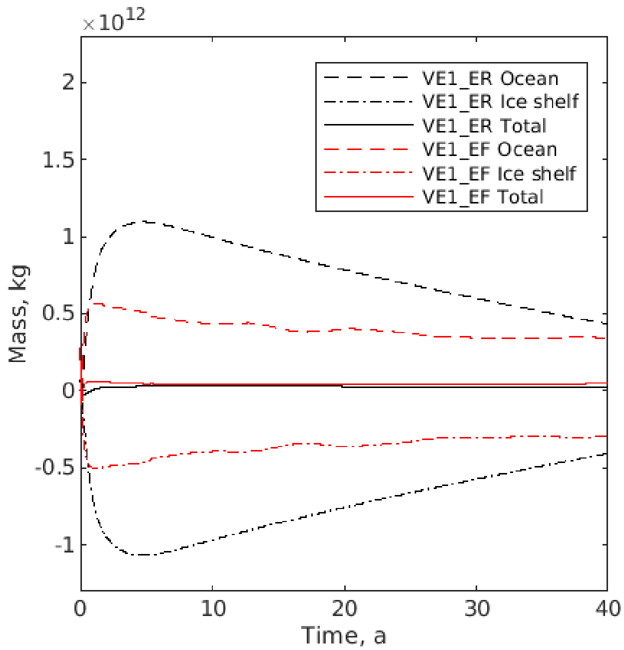

Figure 5. Simulated mass evolution over time for the ocean component (dashed lines), the ice component (dash/dot lines) and the total across both components (solid lines) from experiments VE1_ER (black) and VE1_EF (red).

4.2 VE2: grounding line evolution

This is a partially grounded experiment in which the ice component boundaries are not closed, a through-domain flow of ice is allowed, and the grounding line is allowed to evolve in the coupled system (described in Section 3.2). While the initial slope of the lower surface of the ice shelf is the same in both VE1 and VE2, the open inflow and outflow boundaries in the ice component ~~,~~ and the relatively shallower ice in the grounded region ~~,~~ both lead to a shelf that is much shallower in slope for VE2 than for VE1 for most of the simulation period. Figure ~~??~~ 6 illustrates the shape of the ice sheet/shelf at the start of the simulation and after 25 years (from simulation VE2_ER~~–~~). Note that the ice outflow boundary is more active than the inflow, with the flux into the domain through the inflow boundary remaining small and positive throughout the simulation. The ice draft is deepest in the middle of the domain, at around 30km downstream (in terms of ice flow direction) from the grounding line. The ice draft impacts on circulation and melt, with the strong overturning of VE1_ER not present here. Melting occurs under the deepest ice, with refreezing elsewhere (Figure 7).

Comparing the coupled simulation VE2_ER to the ice-only simulation (not shown) where the only difference is that the ice component features zero basal melt, it might be expected that the coupled simulation would exhibit a significantly thinner ice shelf due to melting. However, the ice dynamics partially compensate for this in terms of the ice geometry: the melt-induced thinning leads to acceleration in the ice and the thickness difference is smaller than expected. However, this should not be

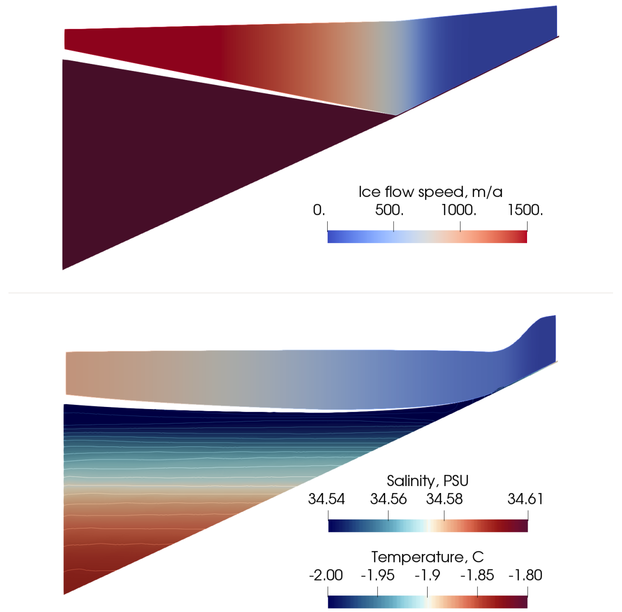

Figure 6. ~~Plan view of~~ Profiles through the center line for experiment VE2 after the first ice ~~sheet thickness~~ component time step (top) and after 25 years ~~of simulation VE2_ER~~(bottom). ~~The black contour indicates the ISM grounding line position~~Ice flow speed is shown (flow direction is right to left). ~~Distances~~ Ocean temperature (solid colour) and salinity (contours) are ~~given~~ shown after 25 years (these are uniform at the start of the run, hence the solid colour for the ocean in ~~km~~the upper plot). Vertical exaggeration is 50 times. The gap between ocean and ice shelf is half an ocean grid cell and is a plotting artefact (The upper extent of the plotted region for the ocean is the uppermost rho point, which is half an ocean grid cell below the top of the ocean domain).

interpreted as a stabilising feedback response of ice dynamics to ocean induced melting, as the increased ice flow would tend to drain the grounded ice more quickly, potentially triggering marine ice sheet instability (Schoof, 2007). Instead this effect may tend to partially mask an ocean-induced ice sheet destabilisation if the observational focus is on ice shelf geometry.

As described in Section 2.8, the ice and ocean component each evolve the grounding line on their own ~~time-step~~ time step and on their own grid or mesh. There is potential for discrepancy between ice and ocean grounded area due to method of cavity evolution (Section 2.5), regridding errors, the inherent differences between grids or meshes, and the methods used to determine grounding line position. While ice geometry is a key determinant of grounding line position, the ice component also tests for a contact force (Gagliardini et al., 2013) and the ocean component ROMS tests height above buoyancy against the free surface variable ~~η~~ ζ (Section 2.8). Here we look at consistency of grounded area between components.

The evolution of grounded area in both ice and ocean components is shown in Figure 8 for simulation VE2_ER. While the ice component employs an unstructured mesh of triangular elements (on the lower surface of the 3D ice body), the ocean component employs a regular grid of square cells. The ocean component appears to exhibit a step-like reduction over time

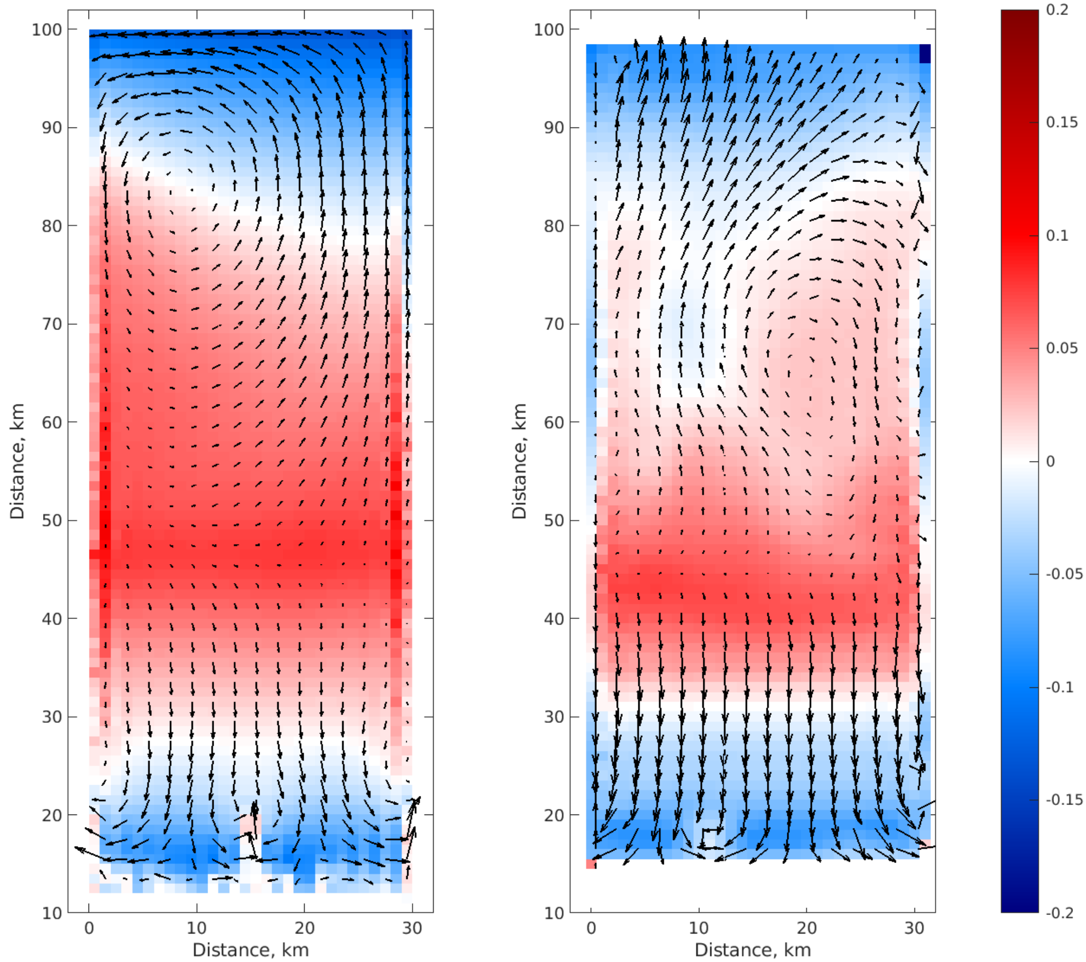

Figure 7. Ocean horizontal velocities in the upper layer (black arrows) and basal melt rate (red indicates melting, blue refreezing) after 25 years of simulation VE2_ER (left) and VE2_EF (right). Outputs on the FVCOM mesh were regridded onto a 1km regular grid. Both FVCOM and ROMS outputs were subsampled at 2km resolution for this plot.

of grounded area. This is due to the row-by-row manifestation of grounding line retreat in the ocean component due to the alignment of grid rows with the linear downsloping geometry. Grounding line retreat starts at the lateral edges of a row (ungrounding near the sidewall boundary) and the "wetting" of dry cells propagates toward the centre of the row. This step-like behaviour (with the spacing of the green lines in Figure 8 indicating the total area of a row of cells) explains the main difference

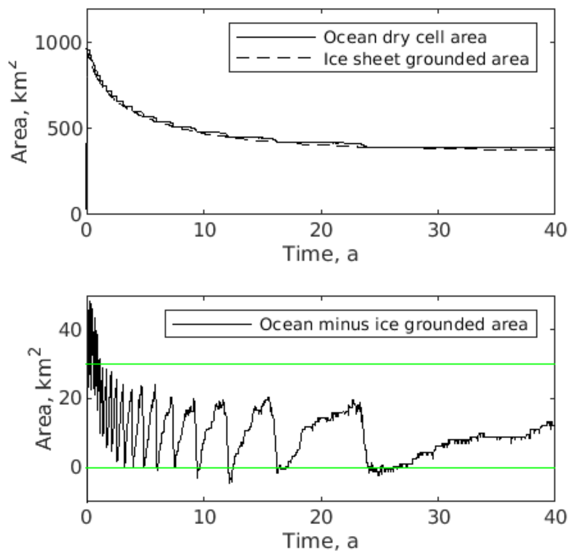

Figure 8. Top: A comparison of grounded area in the ocean component (total area of dry cells) against grounded area in the ice component (total area of grounded elements). Bottom: The difference between ocean and ice grounded area. These are from simulation VE2_ER. The green lines are drawn such that their distance apart is equivalent to the area of one row of ocean grid cells.

between ice and ocean grounded area. The evolution of grounded area is shown in Figure 9 for simulation VE2_EF. Behaviour is similar to VE2_ER.

The initial rapid reduction in grounded area is due to the initial geometry. A region immediately upstream of the grounding line is initially very lightly grounded, and this region quickly becomes floating. The ocean component lags the ice component in this un-grounding, as can be seen in the first part of the difference plot in Figures 8 and 9. This lag is in part due to the "**Rate**" and "**Corrected rate**" cavity update methods, in which the ocean component uses the most recent two ice component outputs to calculate a rate of change of geometry. This inevitably causes the ocean component to lag by approximately one coupling interval. The discrepancy may also be in part due to the fact that the region in question is close to floatation, thus the threshold for dry cells to become wet is highly sensitive to ~~η~~ζ, at least for the ROMS implementation. In both experiments, the ice - ocean grounded area discrepancy has a tendency to reduce over time.

The computational time spent in both the ice and ocean components was measured for simulation VE2_ER. The ice component is more expensive than the ocean component during the first coupling interval, but is significantly cheaper thereafter. Total time spent in the ice component over the 46 year simulation is approximately one third that spent in the ocean component. The computational time spent within the central coupling code (calling routines and regridding) was negligible compared to time spent in ice and ocean components. This is with a 10 day coupling interval. If fully synchronous coupling is approached (i.e. if the coupling ~~time-step~~ interval approaches the ocean ~~time-step~~time step size) the ice component will become much

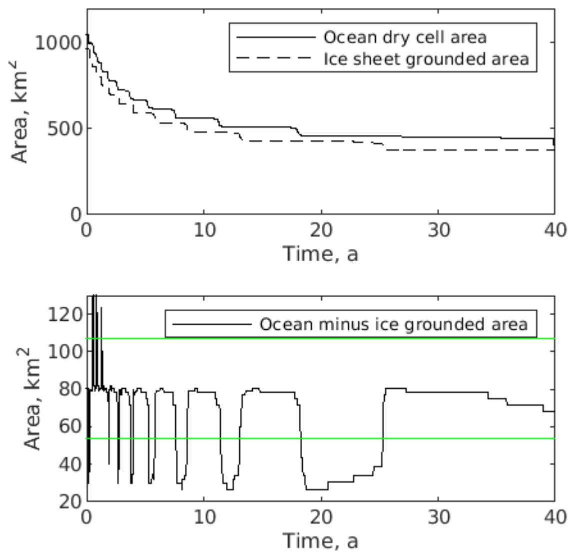

Figure 9. Top: A comparison of grounded area in the ocean component (total area of dry elements) against grounded area in the ice component (total area of grounded elements). Bottom: The difference between ocean and ice grounded area. These are from simulation VE2_EF. The green lines are drawn such that their distance apart is equivalent to the area of one row of ocean elements.

more expensive and it is possible the central coupling code may become significant. We do not anticipate fully synchronous ice-ocean coupling to become practical in the near future, at least not if the ice component directly solves the Stokes equations without simplifying assumptions, as is the case in the current study. The fully synchronous coupling of Goldberg et al. (2018); Snow et al. (2017) is achieved by using the “shallow shelf approximation” for the ice component and running both components on the same grid.

5 Conclusions

We have presented a flexible coupling framework for ice sheet/shelf and ocean models which allows the user to choose between different ice and ocean components. We have demonstrated the functioning of this framework in simple test cases, both with and without a moving grounding line. We have demonstrated conservation of mass and consistency of grounding line evolution using semi-synchronous coupling.

FISOC provides run time variable exchange on the underside of ice shelves. Providing such variable exchange at vertical ice cliffs, which are more common in Greenland than in Antarctica, will require minor developments to the coupling code, but the ocean components currently coupled through FISOC may need more significant developments in order to represent the buoyant plumes rising up ice cliffs.

Our coupled modelling framework is suitable for studying Antarctic ice sheet/shelf – ocean interactions at scales ranging from investigations of ice shelf channels (features with a spatial scale of typically a few km) up to whole Southern Ocean - Antarctic Ice Sheet coupled evolution. We are currently setting up simulations across this range of scales to address key processes surrounding Antarctic Ice Sheet stability and sea level contribution.

Code availability. The coupled modelling code is available from the FISOC github website https://github.com/RupertGladstone/FISOC under the GPL2 licence. The exact version of the FISOC code used to produce the results used in this paper, along with exact versions of ice and ocean model components, is given by code urls and specific commit hashes in a README file. This README file is archived along with the required input files on Finnish HPC machine Allas, and is publicly available from the Allas website https://a3s.fi/COLD_share/FISOC_GMD_files.tar.gz.

Author contributions. RG led development, implementation of experiments, and paper writing. BGF, DG, QZ, TH, DS, SM, CZ, LJ, XG, KP, TZ contributed to development and or testing. BGF, DG, QZ, TH, CZ, YX, TZ contributed to implementation of experiments. All authors contributed to paper writing.

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