Developing a coupled ice sheet-ocean model: challenges and progress with terrain-following ocean coordinates

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November 26, 2022

Abstract

The ice sheet-ocean modeling community is making large strides toward developing coupled models capable of examining the interactions and feedbacks between ice shelves and ocean along the Antarctic margin. We present preliminary results and address some of the challenges that have arisen during the development of a coupled ice sheet-ocean model. The ice sheet model is icepack, a shallow-shelf finite element model written in Python. The ocean model is the Regional Ocean Modelling System (ROMS), a terrain-following vertical (sigma) coordinate model that has been modified to interface with a moving ice shelf. These two models are coupled in an online configuration using the Framework for Ice Sheet Ocean Coupling (FISOC). The use of a model with sigma coordinates for the ocean component introduces a simplification and a complication to modeling a moving ice draft. The sigma coordinate system retains the same number of vertical layers at any depth, eliminating the need to convert grid cells between ice and water, when using a fixed grounding line configuration. However, as the ice shelf draft evolves in time, topographic configurations develop that induce pressure gradient errors in ROMS. We quantify these errors in an idealized set-up with an artificially changing ice draft following the ISOMIP+ geometry. We compare results between an ice draft that is smoothed to meet standard ROMS smoothing criteria (rx0, rx1) and a non-smoothed ice draft. Finally, we present a simple parameterization in a buffer zone near the grounding line that uses interpolated melt rates from the ocean model, allowing us to maintain a steep ice topography in the ice model without inducing pressure gradient errors in the short water column in the ocean model. This model configuration will be applied to Pine Island Glacier and used to examine present and possible future states of the ice sheet-ocean system.
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Challenges and progress with terrain-following ocean coordinates

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The Models

Regional Ocean Modelling System¹ (ROMS)
- Primitive equation regional ocean model
- Finite difference schemes
- Regular horizontal grid
- Terrain following vertical coordinates

Framework for Ice Sheet-Ocean Coupling (FISOC)
- Built with the Earth System Modelling Framework (ESMF)
- Modular design - Use with your preferred models
- Synchronous ocean and ice simulations
- Handles variable exchange and re-gridding

Simulations (in progress)

Start with a smoothed version of the ISOMIP+ domain:

Case 1: Ice shelf draft is held fixed over time.
Case 2: Use prescribed ice shelf draft changes to incrementally violate the ROMS smoothing criteria.
Case 3: Use fully coupled system forced by cold conditions to trigger ice shelf advance and violate smoothing criteria.
Case 4+: Test on realistic example (Pine Island Glacier).

Smoothing Criteria

\( r_x \)

- How much does the topography change with respect to the total water column depth in two adjacent cells?
- How much are the vertical layers offset with respect to layer thickness?

Typically, a 'smooth' model has maximum \( r_x < 0.4 \), and \( r_x < 3-16 \). For the Pine Island Glacier domain, \( r_x < 0.35 \) and \( r_x < 3-16 \). For the Pine Island Glacier domain, \( r_x < 0.35 \) and \( r_x < 3-16 \).

Research Questions

1. How do we identify and handle pressure gradient errors in a fully coupled ice sheet-ocean model?
2. What is the relative effect of automated smoothing during simulation on ice dynamics versus the effect of no smoothing on ocean currents and tracer transport?
3. Can we parameterize or extrapolate ice-ocean interactions, i.e., basal melt rates, in regions that violate the smoothing criteria?

Pine Island Glacier Example

A transect of Pine Island Glacier ice shelf cavity shows downward sloping bedrock and ice shelf towards the grounding line. The model layers become thin and tilted, with high values of \( r_x \). The initial ice shelf draft is in red. We raised it by ~100m near the grounding line to meet smoothing criteria. When coupled, this will affect ice and ocean dynamics.

References

¹Shchepetkin and McWilliams, Ocean Model, 2005; http://myroms.org
²Backmann and Haidvogel, J. Phys. Oceanogr., 1993
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Acknowledgements
This research was funded by NSF, NASA, and the University of Washington’s Future of Ice Initiative. HPC support is partially provided by the NASA HECO system.

So, why ROMS?

Terrain following coordinates cause this many problems, why are we using them?

1. Terrain following coordinates do well in certain situations, e.g., gravity driven dense water cascades.
2. A changing ice shelf draft does not change the ocean grid - the vertical layers expand or contract to fit.
3. Finally, we simply don’t know enough yet. We don’t know which ocean or ice models are best, or what the downsides of certain pairings of models are.

The Marine Ice Sheet Ocean Model Intercomparison (MISOMIP) project was designed to address these other questions in the realm of ice sheet-ocean coupled models.

See www.climate-cryosphere.org/activities/targeted/misomip for more details.