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Representing grounding line migration in synchronous coupling between a marine ice sheet model and a *z*-coordinate ocean model

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ABSTRACT

Synchronous coupling is developed between an ice sheet model and a *z*-coordinate ocean model (the MITgcm). A previously-developed scheme to allow continuous vertical movement of the ice-ocean interface of a floating ice shelf ("vertical coupling") is built upon to allow continuous movement of the grounding line, or point of floatation of the ice sheet ("horizontal coupling"). Horizontal coupling is implemented through the maintenance of a thin layer of ocean (~ 1 m) under grounded ice, which is inflated into the real ocean as the ice ungrounds. This is accomplished through a modification of the ocean model's nonlinear free surface evolution in a manner akin to a hydrological model in the presence of steep bathymetry. The coupled model is applied to a number of idealized geometries and shown to successfully represent ocean-forced marine ice sheet retreat while maintaining a continuous ocean circulation.

1. Introduction

A number of important physical processes in coastal oceanography involve the horizontal influx of water into regions that were previously "dry", as well as the complete removal of water from other regions that were at some point "wet". In estuarine regions, submerged boundaries change with the tidal cycle, and numerical codes which attempt to model important biological and geomorphological processes must capture this "wetting and drying" accurately (Hardy et al., 2000; de Brye et al., 2010). Flood models of storm surge must properly capture the advance and retreat of the flooding front (van't Hof and Vollebregt, 2005). There is an extensive numerical literature which deals with the problem of encroaching and retreating coastal flows (Medeiros and Hagen, 2013).

There is, however, an important coastal-oceanographic process not often discussed in the computational literature surrounding wetting and drying problems. In Antarctica (and to a lesser extent Greenland, and likely elsewhere during past glaciations), the ice sheet is *marine terminating*: it extends into the ocean in the form of large floating ice shelves. Due to the relatively small ice/ocean density differential, this occurs at depths ~ 500–1000 m below sea level. The location where the ice sheet goes afloat, called the grounding line, is a topic of much discussion in the literature surrounding ice sheet dynamics. This is due to it being a sharp transition between two very different regimes of ice flow (Vieli and Payne, 2003; Pattyn et al., 2006; Schoof and Hewitt, 2013). From an ice dynamics perspective, determining the floatation point is equivalent to a viscous contact problem, one which requires very sophisticated numerical schemes (Schoof, 2011), although certain approximations make the problem more tractable (Goldberg et al., 2009; Cornford et al., 2013).

The focus of this paper, however, is not on the glaciological dynamics of grounding line migration, but rather on the coupling between the ice and the ocean underneath. The ocean circulates in a cavity bounded above and below by the ice shelf and bedrock, respectively, and on the landward side by the grounding line, where the water column depth pinches off. The circulation within the cavity is influenced by density variation, and by the topography of the ice shelf and sea bed (MacAyeal, 1984). From the ocean's perspective, the ice sheet/ice shelf presents itself as variable surface pressure, and when the surface pressure favors the flooding of previously "dry" domain, the ocean will do so. Aside from the spatially varying surface pressure, the problem is analogous to run-up on a sloped beach.

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This wetting/drying problem is quite an important one in the context of Antarctic Ice Sheet contributions to sea level rise. Melting and thinning of floating ice does not contribute significantly to sea level change (Jenkins and Holland, 2007), but retreat of the grounding line towards the interior represents loss of grounded ice, which does. Moreover, if the depth of the bed deepens inland (as is the case around much of the Antarctic coastline, Fretwell et al., 2013), retreat of the grounding line can lead to an increase in ice sheet thinning rates upstream, potentially leading to a positive feedback effect (Weertman, 1974; Schoof, 2007b; Vaughan and Arthern, 2007).

Yet most ocean models, including those adapted to study ice shelf-ocean interactions (e.g., Holland and Jenkins, 2001; Little et al., 2008; Walker and Holland, 2007; Gwyther et al., 2014), have not implemented such wetting and drying. There are two important differences between the ice sheet wetting/drying problem and the "standard" coastal wetting/drying problem. Firstly, while the latter can be addressed through shallow-water equations, the former must be addressed by a three-dimensional model representing baroclinic motions in the ocean, and therefore must represent active tracer (heat and salt) evolution, as well as an evolving upper boundary (the base of the ice shelf). Hence the approaches used for wetting/drying problems in coastal oceanography cannot be straightforwardly transferred to ocean models.

Secondly, the wetting front advance and retreat associated with grounding line change is much slower than in flooding and storm surge problems, with observed retreat rates of up to $\sim 3\,\text{km/year}$ (Rignot et al., 2014) but often much slower. The separation of time scales allows for quasi-static ("discontinuous") approaches, in which a sequence of ocean runs are carried out with fixed cavity geometries, with the geometry sequence arising from the evolution of the ice sheet model (Grosfeld and Sandhager, 2004; Goldberg et al., 2012; De Rydt and Gudmundsson, 2016). Such an approach makes the assumption that a given geometry and far-field oceanic conditions will lead to a unique circulation, which may not be the case (e.g. if the ocean cavity is still in a transient state when the ice adjusts). Additionally, the ocean model must be spun up with each coupled time step, making the approach unsuitable for regional or global ocean models. More recently efforts have been made to retain the ocean "state" during adjustments to the cavity geometry. Such "asynchronous" approaches are still not ideal: typical coupling frequencies of a month to a year may lead to significant depth changes in the ice-ocean interface upon geometry updates. The necessary infilling with predefined water properties can lead to violations of mass and tracer conservation, as well as significant nonphysical adjustments. In one instance, the latter has been addressed through imposing that barotropic velocities remain fixed between updates (Asay-Davis et al., 2016). Still, it seems clear that a synchronous approach, i.e. one in which the ocean geometry is adjusted on or close to the ocean time step, is a preferable approach to modelling ice sheet-ocean interactions on continental and global scales, particularly if the ocean is subject to forcing on fast time scales, such as changes in wind stress (Christianson et al., 2016) and episodic additions of fresh water (Smith et al., 2017).

In this paper, we modify the Massachusetts Institute of Technology general circulation model (MITgcm, Marshall et al., 1997) to allow for synchronous coupling of an ice sheet and ocean model. MITgcm is a general-purpose fluid solver for simulating process-level to global-scale ocean circulation that is usually configured in hydrostatic and Boussinesq approximations in vertical z-coordinates (as has been done in the present study). Components of the development have been completed previous to this study – the most important of which allows continuous thinning and thickening of a floating ice shelf, which we term "vertical coupling" (Jordan et al., 2017). Here we focus primarily on a scheme to allow for both grounded and floating ice and a dynamic grounding line ("horizontal coupling"). In the following, we briefly discuss the vertical coupling scheme and demonstrate how it can be used to allow for grounding line migration over a flat bed topography with minimal code changes. We then discuss the difficulties involved with variable bed topography (which are common to all z-coordinate models), and present a strategy to overcome them, which involves combining the ocean model algorithm with a scheme akin to flow through a porous medium. Finally, we present results from the first three-dimensional synchronously coupled ice-ocean model of marine ice sheet retreat.

2. Flat topography: methodology

With a flat bed topography, we are able to cleanly simulate synchronous coupled grounding line migration by making use of recent novel developments within MITgcm to allow for "vertical coupling", defined above. The work builds on previous developments to allow thermodynamic ice shelf-ocean interactions within MITgcm (Losch, 2008; Dansereau et al., 2014) as well as the development of an ice sheet component within the modelling framework (Goldberg and Heimbach, 2013). Vertical coupling is described in detail in Jordan et al. (2017), but we briefly describe those components which are relevant to our study in order to provide context for our results and for our further developments of the model. Note that we refer below to the z–coordinate implementation, not the z^* implementation (Adcroft and Campin, 2004).

2.1. Vertical coupling

In this subsection we give details of vertical coupling and the MITgcm glacial flow model, which are also described in Jordan et al. (2017). Readers familiar with this paper might skip to Section 2.3.

Vertical coupling within MITgcm hinges on the nonlinear free surface capabilities of the model (Campin et al., 2004). The free surface elevation η defined relative to a reference surface elevation $z = d$, which for the ice-free ocean is $d = 0$, but for a cell occupied by the ice shelf is generalised to the height of the ocean-ice shelf, $z = -d$, in Losch (2008). η is updated in each time step in a fully mass-, heat-, and salt-conserving fashion, and responds both to barotropic pressure gradients and to gradients in surface load p_{surf} – which is imposed as the weight per unit area of the ice shelf. As flexural stresses within the ice shelf are not presently considered,

$$p_{surf} = \rho_i g H \tag{1}$$

under the ice shelf, where g is gravitational acceleration, ρ_i is ice density and H is ice thickness, which is updated at each time step in response to ice dynamics and basal melting or freezing. The ice model, rather than updating its velocity and thickness at the same time (as is common practice in ice sheet modelling), updates its thickness on the ocean time step. (Velocity updates, which are more costly, take place every 12 h – but this is acceptable as velocity change induced by thickness changes on this time scale is very small.) In this manner, the surface load can be updated smoothly without exposing the ocean to sudden, large changes in surface pressure. As the ice and ocean codes are both components of MITgcm, there is no issue passing ice thickness to the ocean code and melt rate to the ice code.

In the z-coordinate free surface implementation of MITgcm, the height of the top-level cell grows with η (in contrast to the z^*-coordinate implementation, in which cells thicken and thin uniformly in a column). Without intervention this can either lead to poor representation of the ice-ocean boundary layer (Jenkins, 2016) as the ice thins, or to negative cell height as the ice thickens. To this end a "remeshing" algorithm has been implemented. Upon initialisation of MITgcm, model cells are flagged as being either ice or ocean. The remeshing process essentially allows cells to switch from ice to ocean, and vice versa, within a model run and without the need to reinitialise ice and ocean masks. Whilst the topmost ocean cell thickness in a given column evolves every time step, at predetermined intervals we check to see if it has grown above a "splitting threshold" or below a "merging