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# Modeling Ice Shelf/Ocean Interaction in Antarctica: A Review

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# Modeling Ice Shelf/Ocean Interaction in Antarctica

## A REVIEW

**By Michael S. Dinniman, Xylar S. Asay-Davis, Benjamin K. Galton-Fenzi, Paul R. Holland, Adrian Jenkins, and Ralph Timmermann**

**ABSTRACT.** The most rapid loss of ice from the Antarctic Ice Sheet is observed where ice streams flow into the ocean and begin to float, forming the great Antarctic ice shelves that surround much of the continent. Because these ice shelves are floating, their thinning does not greatly influence sea level. However, they also buttress the ice streams draining the ice sheet, and so ice shelf changes do significantly influence sea level by altering the discharge of grounded ice. Currently, the most significant loss of mass from the ice shelves is from melting at the base (although iceberg calving is a close second). Accessing the ocean beneath ice shelves is extremely difficult, so numerical models are invaluable for understanding the processes governing basal melting. This paper describes the different ways in which ice shelf/ocean interactions are modeled and discusses emerging directions that will enhance understanding of how the ice shelves are melting now and how this might change in the future.

Iceberg B-15A, which calved from the Ross Ice Shelf, Antarctica, in March 2000. *Photo credit: Walker Smith*

## INTRODUCTION

Mass loss from the Antarctic Ice Sheet is accelerating (e.g., McMillan et al., 2014), with the most rapid ice loss observed where ice streams discharge into the ocean (Pritchard et al., 2012). Ice shelves form where these ice streams become thin enough to lose contact with the underlying bedrock and begin to float on the ocean at a location called the "grounding line." Ice shelves buttress the ice streams draining the ice sheet (DeAngelis and Skvarca, 2003; Gudmundsson, 2013), so changes in the ice shelves alter the discharge of grounded ice and therefore influence sea level.

Ice shelves gain mass from inflowing ice streams, snow accumulation, and in some areas basal freezing of seawater. They lose mass from iceberg calving, basal melting by the ocean, and in some areas, surface melting. Until about 2013, it was believed that the most significant loss of mass from the ice shelves during the current era was from iceberg calving. However, newer measurements show that more mass is lost from basal melting (Rignot et al., 2013; Liu et al., 2015) than from any other process, although this could change in the future (DeConto and Pollard, 2016).

The ice shelves also have a large effect on the ocean. They have thicknesses of up to 2,500 m, areas of up to 500,000 km$^2$ (e.g., the Ross Ice Shelf, which is approximately the same area as Spain and larger than California), and cover nearly 40% of the Antarctic continental shelf seas (Figure 1), thus blocking the direct influence of the atmosphere on much of the shelf ocean. Glacial meltwater from the ice shelves influences ocean circulation (e.g., Potter and Paren, 1985), water mass transformations (e.g., Jacobs and Giulivi, 2010; Figure 2), and even biology (as a source of micronutrients; Arrigo et al., 2015) in the marginal seas of the Southern Ocean. Its effect on the creation of Antarctic Bottom Water leaves a global footprint.

Ice shelf basal melting can be characterized by three modes (Jacobs et al., 1992; Figure 3). In Mode 1, Shelf Water (SW), a cold, saline and dense water mass formed on Antarctic continental shelves mostly due to brine rejection from sea ice formation, intrudes into the cavities below the ice shelves. The temperature of SW is close to the freezing point of seawater at the ocean surface (~ −1.9°C), but the freezing point decreases with increasing pressure (0.76°C per 1,000 m), so SW can melt the base of deep ice shelves. In Mode 2, relatively warm (~1°C) Circumpolar Deep Water (CDW) intrudes onto the continental shelves and, under some modification, into the sub-ice cavities. Because CDW can be >4°C warmer than the in situ freezing point at the ice shelf base, this leads to rapid melting. Finally, in Mode 3, Antarctic Surface Water (AASW), which has a cold core often termed Winter Water as well as a seasonally warmer and fresher upper layer, enters the cavity. Throughout most of the year, Mode 3 melting is controlled by the cold core of the AASW that, like SW, has a temperature near the surface freezing point. Melt rates are therefore similar to Mode 1, but Mode 3 is distinct in that the upper layer of AASW, which is warmed by interaction with the atmosphere in summer, can significantly increase melt rates in the outer cavity (e.g., Arzeno et al., 2014).

Ice shelves are often broadly classified as "cold water" or "warm water" depending on whether the deeper waters on the continental shelf adjacent to the ice shelf are dominated more by SW or relatively unmodified CDW (Petty et al., 2013), but a more inclusive way to think about this is in terms of the three main shelf water masses. Strong sea ice formation causes cold and dense SW to pervade the continental shelf in the western Ross and Weddell Seas and a number of locations around the East Antarctic coast, while wind-forced coastal downwelling causes the AASW layer to thicken sufficiently around the remainder of East Antarctica to exclude denser water masses. Together, these processes govern the slow (order 0.1–1 m yr$^{-1}$) melting of cold water ice shelves, including the three largest (Ross, Filchner-Ronne, and Amery), which all experience Mode 1 melting, and the smaller ice shelves of East Antarctica, which mainly experience Mode 3 melting. Relatively warm CDW floods the Amundsen and Bellingshausen Seas, causing rapid (order 10–100 m yr$^{-1}$) melting of the smaller warm water ice shelves. The differences between these three regimes seem to be imprinted by regional meteorological conditions, both through the direct effects of wind and snowfall and their forcing of sea ice growth, as well as ocean dynamics, including the proximity of the Antarctic Circumpolar Current to the shelf break, related to the transport of CDW onto the continental shelf (Petty et al., 2013).

Sampling the ocean near and beneath ice shelves is logistically challenging. Thus, over the last 30 years, numerical modeling studies of ice/ocean interaction have been invaluable in understanding and extending the sparse observations that exist. Such studies also underpin the latest coupled ocean/ice shelf/ice sheet models, which promise to revolutionize the projection of future Antarctic contributions to sea level.

In order to accurately simulate ice shelf basal melting, it is necessary to adequately capture the physics of the sub-ice boundary layer, water circulation and transport in the ice shelf cavity, and the processes in the open ocean involved in the delivery of heat in each of the three melting modes listed previously. The excellent review of Williams et al. (1998) summarized the state of the art in numerical modeling of ice shelf/ocean interactions at that time. We describe the significant advances that have been made since then, point out some future directions for research, and directly respond to some of their projections about research pathways made almost 20 years ago.

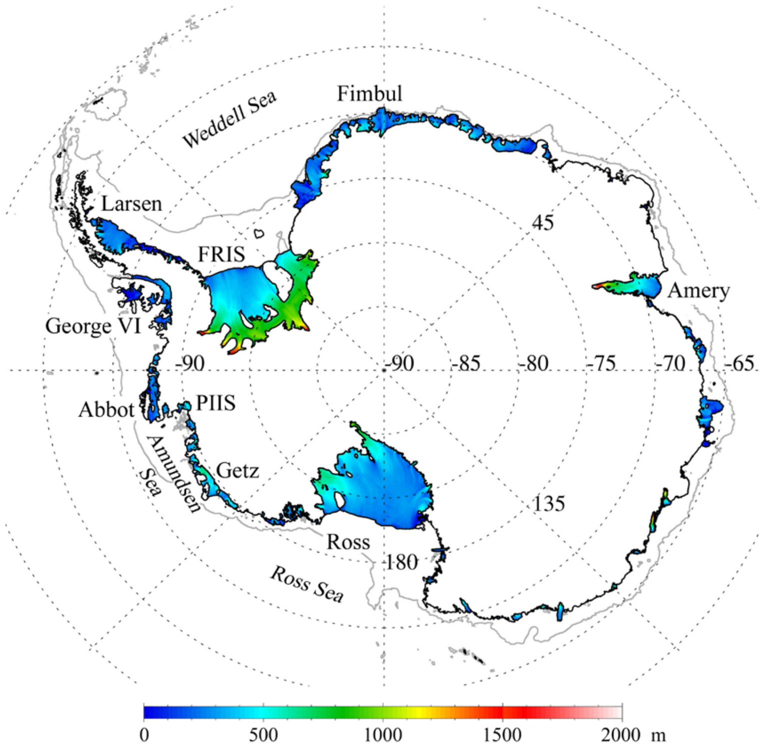


**FIGURE 1.** Depth (meters below sea level) of the base of Antarctic ice shelves from the RTopo-2 data set (Schaffer et al., 2016). Nine of the largest ice shelves are labeled and the thin gray line is the 1,000 m isobath. PIIS = Pine Island Ice Shelf. FRIS = Filchner-Ronne Ice Shelf.

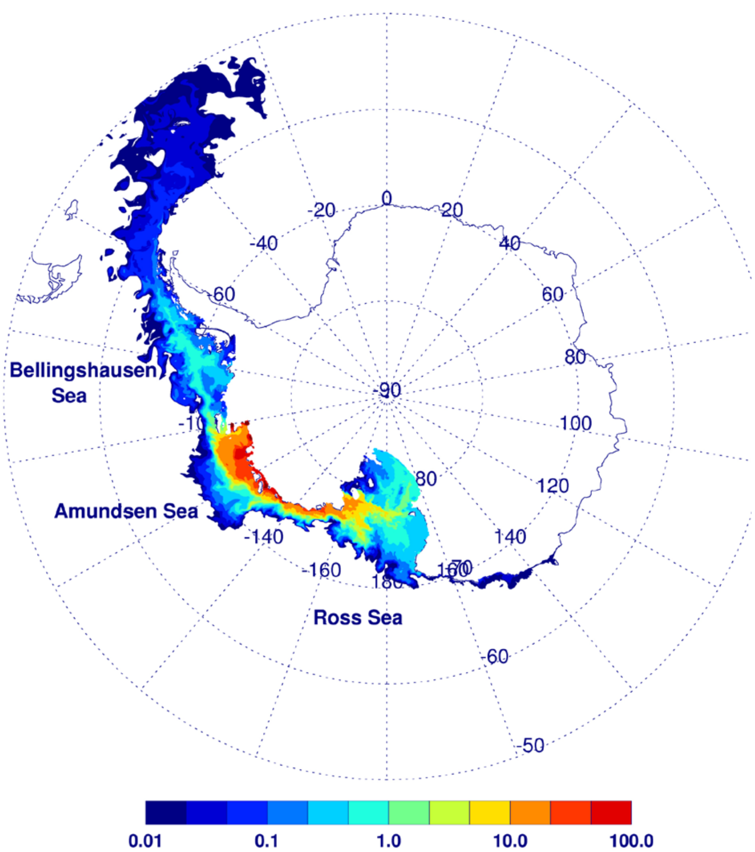


**FIGURE 2.** Model (Dinniman et al., 2015) surface layer meltwater (from Amundsen Sea ice shelves only) dye concentration (1 dye unit = freshwater concentration of $10^{-4}$) after four years of simulation. Note the high concentration of meltwater advecting in the coastal current counterclockwise into the Ross Sea where it can affect Shelf Water formation (e.g., Jacobs and Giulivi, 2010).

## PHYSICS OF ICE SHELF/OCEAN INTERACTION

A numerical model of ice shelf/ocean interaction must represent the transfers of heat, freshwater/salt, and momentum between the ice and ocean, as well as the mechanical pressure of the ice on the ocean.

### Thermodynamics

Heat and freshwater fluxes are due to phase changes at the ice/ocean interface that are typically assumed to occur in thermodynamic equilibrium so that the temperature at the interface (the freezing point) is expressed in terms of salinity and pressure (depth). Melting or freezing can then be represented by three fundamental equations (Hellmer and Olbers, 1989; Holland and Jenkins, 1999):

1. The freezing point of seawater is a weakly nonlinear function of salinity and pressure that is usually linearized to allow for an analytic solution of the three equations.

2. At the ice/ocean interface, in thermodynamic equilibrium, the sink (source) of latent heat caused by melting (freezing) must balance the difference between the heat loss into the ice and the heat supply from the water:

$$Q_I^T - Q_W^T = -\rho_I \, w_B \, L_f,$$

where $Q_I^T$ and $Q_W^T$ are the interface-ice and water-interface heat fluxes (W m$^{-2}$, both positive upwards), $\rho_I$ is the ice density (kg m$^{-3}$), $w_B$ is the rate (m s$^{-1}$) of ice melt (> 0) or freeze (< 0), and $L_f$ is the latent heat of ice fusion (J kg$^{-1}$). The heat flux from the water is usually much greater than that through the ice, so in some applications, the ice is assumed to be perfectly insulating and $Q_I^T$ is set to zero, which introduces a small (~10%) error in the calculated melt rates.

How best to characterize the turbulent heat flux from the water to the ice/ocean interface is still an area of active study. Typically, this flux is represented by a bulk turbulent transfer formulation:

$$Q_W^T = -\rho_W \, C_{pW} \, \gamma_T \, (T_B - T_W),$$

where $\rho_W$ is the seawater density (kg m$^{-3}$), $C_{pW}$ is the specific heat capacity of seawater (J kg$^{-1}$ deg$^{-1}$), $\gamma_T$ represents a thermal exchange velocity (m s$^{-1}$), $T_B$ the interface temperature (the freezing point), and $T_W$ is the water temperature some distance away from the ice/ocean interface. In practice, $T_W$ is either defined as the temperature in the uppermost model grid cell (Galton-Fenzi et al., 2012; Dansereau et al., 2014) or averaged over the modeled boundary layer (e.g., Losch, 2008). However, depending on the thickness of the model grid cells, $T_W$ could be in different parts of the ocean boundary layer at different locations (Gwyther et al., 2015) or well beyond the boundary layer, which can lead to significant differences in basal melt (e.g., Schodlok et al., 2016), showing the importance of model vertical resolution underneath the ice shelf.

The thermal exchange velocity ($\gamma_T$) represents the molecular and turbulent mixing of heat in the oceanic boundary layers adjacent to the ice. It is sometimes modeled with a constant value, but is more commonly (e.g., Holland, 2008; Timmermann et al., 2012) parameterized as a function of the friction velocity (Jenkins et al., 2010). The friction velocity relies on some estimate of the under ice drag, which is usually set to a value similar to the drag between the ocean and the seabed; however, little is actually known about the roughness characteristics of an ice shelf base, other than they can be highly variable depending on ice type (Nicholls et al., 2006; Craven et al., 2009). Jenkins et al. (2010) summarize different ways to parameterize the turbulent transfer.

3. At the ice/ocean interface, the freshwater flux due to the melting or freezing of ice having a salinity of $S_I$ must balance the flux of salt through the water to the interface (the flux of salt through the ice shelf is zero):

$$-Q_W{}^S = \rho_I \, w_B \, (S_I - S_B),$$

where $Q_W{}^S$ is the water-interface salt flux (psu-kg m$^{-2}$ s$^{-1}$), $S_I$ is the salinity of the ice, and $S_B$ is the interface salinity. Meteoric ice (glacial ice originating as compacted snow) has zero salinity. Marine ice that forms due to basal freezing of seawater has brine trapped in it, but observations show that the values are very low (0.10 or less) and so $S_I$ is modeled as being zero.

The salt flux from the water to the ice/ocean interface is typically represented as a turbulent diffusive flux similar to that of heat, with the form:

$$Q_W{}^S = -\rho_W \, \gamma_S \, (S_B - S_W),$$

where $\gamma_S$ represents a salt exchange velocity (m s$^{-1}$), and $S_W$ is the salinity some distance from the ice/ocean interface. The salt exchange velocity ($\gamma_S$) is not the same as the thermal exchange velocity due to the different molecular diffusivities of heat and salt, but like $\gamma_T$ it has been modeled as a constant or parameterized as a function of the friction velocity.

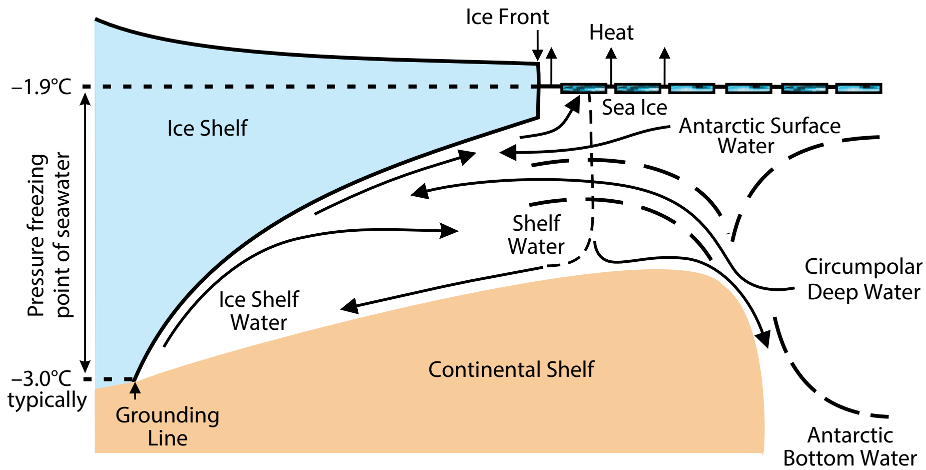


**FIGURE 3.** Schematic showing circulation over the Antarctic continental shelf and how it relates to the different ice shelf basal melting modes (see text). Sea ice formation generates cold (–1.9°C) and salty Shelf Water that, being the densest water mass on the shelf, can advect to the deepest parts of the ice shelf cavity where it causes melting due to the pressure dependence of the freezing point (Mode 1). The Shelf Water also is instrumental in the creation of Antarctic Bottom Water. Warm (~1°C) Circumpolar Deep Water advects onto the continental shelf and into the ice shelf cavities, leading to high melt (Mode 2). Antarctic Surface Water is often cold, but it can be warmed in the summer, leading to strong seasonality in the melt rate near the ice shelf front (Mode 3). Plumes of very cold, but fresh, Ice Shelf Water can rise along the ice shelf base and exit the cavity at different depths.

The equations shown above are typically applied to freezing at the ice base as well as melting, but the production of marine ice beneath ice shelves actually occurs primarily through the formation of tiny (~1 mm) disk-shaped frazil ice crystals within the water column below the ice shelf (Jenkins and Bombosch, 1995). These crystals settle upward under their buoyancy and accrete onto the ice base. The accreted crystals gradually compact into a relatively solid marine ice mass (e.g., Craven et al., 2009), which is credited with playing a significant role in the stability of some ice shelves (Holland et al., 2009; Galton-Fenzi et al., 2012).

## Mechanics

The transfer of momentum between the ice shelf and the ocean is modeled assuming that the ice is stationary and exerts a stress on the water underneath through a quadratic drag law with a constant, dimensionless, drag coefficient similar to that between the ocean and the seabed. However, as mentioned earlier, little is known about what drag coefficient should be used (Jenkins et al., 2010), and it may be important to include spatially and temporally varying values in order to represent different types of ice found at the ice shelf base (Gwyther et al., 2015). Recent observations from ice-penetrating radar and autonomous underwater vehicles (AUVs) reveal important ice topographic features on a wide range of spatial scales (Nicholls et al., 2006; Dutrieux et al., 2014b).

Models vary in the details of how the pressure loading of the floating ice is imposed on the water underneath, adjusting the top ocean model surface to conform to the ice base (which can be kilometers below sea level). In most cases, the ice is assumed to be floating in isostatic equilibrium, and the basal pressure is an integral over depth of an ocean density profile that represents the ocean displaced by the floating ice. The applied pressure adjusts the active ocean surface to some mean position that represents the "reference" ice shelf draft. In a dynamic ocean, the actual ice base represented by the model fluctuates about this reference surface according to the details of the free-surface scheme. There is assumed to be no flexural rigidity or "bridging stresses" between grid cells, so the ice in each grid cell rises and falls freely with changes in the ocean free surface. This is a reasonable assumption, except within a few kilometers of the grounding line or within small-scale ice topography, provided the grid cells are wide relative to the ice thickness.

## CURRENT STATE OF MODELING

### One- and Two-Dimensional Models

Some of the earliest models of ice shelf/ocean interaction were cast as one-dimensional "plume" models (MacAyeal, 1985; Jenkins, 1991). These models represent the flow of a steady buoyant ocean current up the base of an ice shelf in one spatial dimension, with the plume speed, thickness, and temperature and salinity influenced by meltwater from above and the "entrainment" of warmer, saltier water from below. Despite the simplicity of these models, they have produced significant insight into melting and freezing beneath ice shelves and at the vertical face of glaciers in fjords (e.g., Jenkins, 1991; Jenkins and Bombosch, 1995). Recently, Jenkins (2016) used a one-dimensional model to investigate the structure of the ice/ocean boundary layer perpendicular to the interface that is removed by depth-averaging in the plume formulation. The current structure and stratification through the boundary layer found in this approach have implications for our parameterization of turbulent transfer to the ice, as discussed in the previous section.

The plume formulation has been extended to an unsteady model of a meltwater layer in two horizontal dimensions (Holland and Feltham, 2006), offering the possibility of producing maps of ice melting using a relatively simple and computationally inexpensive approach. This formulation has been useful in explaining patterns of melting and marine ice formation (e.g., Holland et al., 2009) and in coupled ice/ocean models of the evolution of melt channels observed in the base of ice shelves (e.g., Sergienko, 2013). However, due to its neglect of the influence of seabed geometry, and its simply parameterized "entrainment" of deeper waters into the plume, there are many science questions, such as the exchange of waters well below the boundary layer into/out of the ice shelf cavity, that are unsuited to this type of approach.

### Full Three-Dimensional Models with Static Ice Shelves

Williams et al. (1998) mention several examples of early work using fully three-dimensional primitive equation ocean models with ice shelves in idealized and realistic regional domains. The first circum-Antarctic model to include ice shelves was the Bremerhaven Regional Ice-Ocean Simulations (BRIOS), which added static ice shelves to the hydrostatic s-coordinate primitive equation model (SPEM); it was initially used to study interactions between the Weddell Sea and the broader Southern Ocean, including the effects of sub-ice shelf forcing on water mass characteristics (Beckmann et al., 1999).

Many models are now available (Table 1) for simulating ice shelf/ocean interaction in a full three-dimensional primitive equation model, and there are regional implementations (often more than one) for every major ice shelf cavity and adjacent coastal ocean in the Antarctic, as well as several circum-Antarctic simulations. One of the main distinguishing characteristics between these models is the choice of the vertical coordinate system (Griffies et al., 2000). Almost all three-dimensional ocean models that include ice shelves use a terrain-following (sigma or s-coordinate), z-level (level surfaces), or isopycnal (density layers) vertical discretization, or some hybrid combination of the three. All three systems have their advantages and disadvantages (see the discussion in Kimura et al., 2013, for more details). Kimura et al. (2013) implemented ice shelves in a finite-element ocean model with an unstructured adaptive mesh in all three dimensions. This allows melting to occur on arbitrarily oriented ice faces, including

**TABLE 1.** An incomplete list of ocean primitive equation models that have been modified to include static ice shelves. References given are for the initial implementation of ice shelves; current versions of the models may have more advanced features.

| Ocean PE Model | Vertical Coordinate | Description of Ice Shelf Implementation |
|---|---|---|
| SPEM (BRIOS: Bremerhaven Regional Ice-Ocean Simulations) | S-coordinate | Beckmann et al. (1999) |
| MICOM (Miami Isopycnic Coordinate Ocean Model) | Isopycnal | Holland and Jenkins (2001) |
| ROMS (Regional Ocean Modeling System) | S-coordinate | Robinson et al. (2003) |
| HIM (Hallberg Isopycnal Model) | Isopycnal | Little et al. (2008) |
| MITgcm (MIT General Circulation Model) | Z-level | Losch (2008) |
| FESOM (Finite Element Sea-ice Ocean Model) | Hybrid sigma (Antarctic shelf) and z-level | Timmermann et al. (2012) |
| Fluidity-ICOM (Imperial College Ocean Model) | Unstructured mesh | Kimura et al. (2013) |
| COCO (Coupled Ice-Ocean General Circulation Model) | Hybrid sigma (near surface) and z-level | Kusahara and Hasumi (2013) |
| NEMO (Nucleus for European Modeling of the Ocean) | Z-level | (in prep) |
| POP2x (Parallel Ocean Program v. 2x) | Z-level | (in prep) |
| MOM6 (Modular Ocean Model) | Arbitrary-Lagrangian-Eulerian | (in prep) |
| MPAS-Ocean (Model for Prediction Across Scales-Ocean) | Arbitrary-Lagrangian-Eulerian | (in prep) |

vertical (e.g., Jordan et al., 2014), easily allows water columns to decrease to zero thickness at the grounding line (which can reduce the penetration of warm water at depth into the ice shelf cavity), and avoids many problems of the other vertical coordinate systems. However, the use of an unstructured vertical coordinate is still somewhat experimental.

## Horizontal Resolution and Horizontal Grids

One issue that has become clearer in the almost 20 years since Williams et al. (1998) was published is the importance of a model's horizontal resolution, not only in simulating the conditions underneath the ice shelf that lead to basal melt but also for the conditions in the open ocean that deliver heat to ice shelf cavities. For example, many circum-Antarctic models with a grid resolution of 10–20 km on the continental shelf feature deep shelf waters that are too cold in the Amundsen Sea, greatly underestimating the basal melt of the critically important ice shelves in the region (Timmermann et al., 2012; Dinniman et al., 2015). Nakayama et al. (2014) showed that, while the particular atmospheric forcing used was partially responsible for the cold shelf temperatures, increasing the ocean model resolution from 10 km to 5 km greatly improved the Amundsen Sea temperatures (Figure 4) by increasing the transport of warm water onto the continental shelf with better resolution of the mean flow-topography interactions along the shelf break.

An even stricter constraint on horizontal resolution is due to the fact that heat transport at the Antarctic continental shelf break can be influenced by the presence of eddies that have horizontal scales of just a few kilometers. Due to the weak stratification in coastal Antarctic waters, and the large Coriolis parameter at high latitudes, the internal Rossby radius of deformation on many Antarctic continental shelves is small, about 5 km, by global standards (Hallberg, 2013). Observations show that in some locations heat from warm CDW intrudes onto the continental shelf in the form of small-horizontal-scale (~4–8 km) CDW core eddies (Martinson and McKee, 2012). Accurately resolving this transport requires model horizontal resolutions of 1–2 km (Stewart and Thompson, 2015; Figure 5). Årthun et al. (2013) found that getting SW into ice shelf cavities, which is important for Mode 1 melting, also requires about 1 km horizontal resolution.

Regional Antarctic ice shelf/ocean models with horizontal resolution fine enough to resolve mesoscale eddies on the continental shelf are now being created for several areas (e.g., Hattermann et al., 2014; St-Laurent et al., 2015), and plans are underway to use this resolution even for circum-Antarctic models. An important new development is the use of unstructured grids in the horizontal dimension, which allow high resolution to be placed where it is most needed (in this case, along continental shelves with low stratification and within ice shelf cavities near the grounding line). Unstructured models have already been used in domains from idealized ice shelf cavities (Kimura et al, 2013; Petersen et al., 2016) to global simulations with high resolution in the Antarctic (Timmermann et al., 2012).

## Tides

Williams et al. (1998) noted that: "the most obvious need is for a thermohaline model that incorporates tidal forcing," but, until recently, most realistic three-dimensional models did not include tides. Most formulations of the exchange coefficients of salt and heat ($\gamma_S$ and $\gamma_T$) are dependent on the currents at the base of the ice shelf, and tides heavily influence these currents in many instances (e.g., Nicholls and Makinson, 1998; Arzeno et al., 2014). Including tides in regional models of some cold water ice shelves such as Amery (Galton-Fenzi et al., 2012), Filchner-Ronne (Makinson et al., 2011), Larsen C (Mueller et al., 2012), and Ross (Arzeno et al., 2014) increased the average melt rate by between 25% and 100%. The effect of tides is typically weaker for warm water ice shelves because the current under the ice shelf is more strongly controlled by meltwater-driven flows (e.g., Dutrieux et al., 2014a). However, Robertson (2013) showed that tides could increase the melt underneath certain ice shelves in the Amundsen Sea by as much as 50% depending on the location of the ice shelf

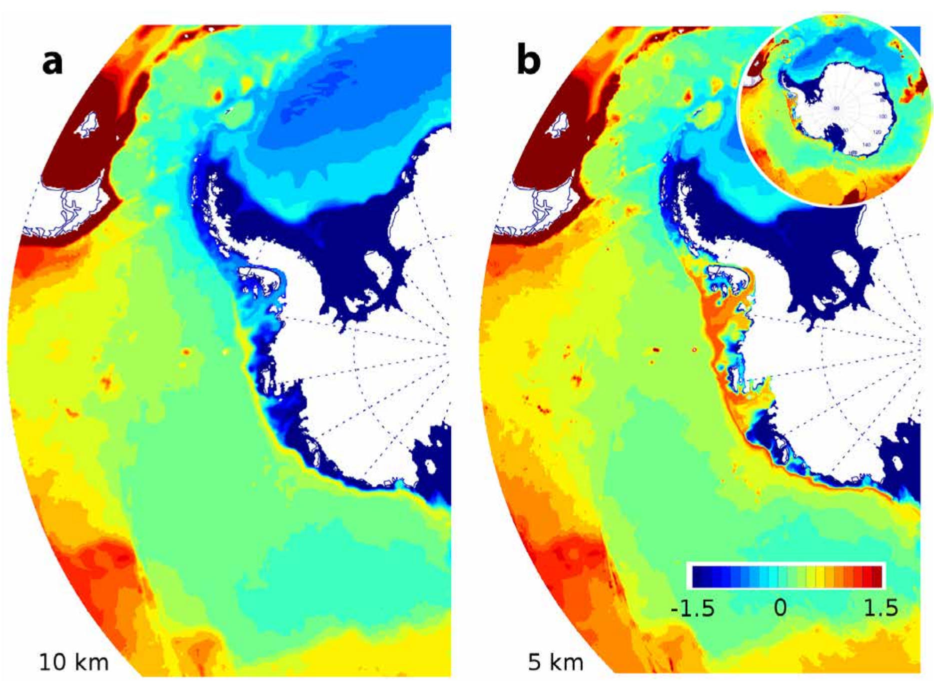


**FIGURE 4.** Model (Dinniman et al., 2015) bottom layer temperature in the Amundsen Sea and other parts of West Antarctica (inset shows circum-Antarctic view) at grid resolutions of (a) 10 and (b) 5 km. Similar to Nakayama et al. (2014), increasing the model resolution dramatically improves the representation of Circumpolar Deep Water on the Amundsen Sea continental shelf.

front with respect to the $M_2$ critical latitude (where the tidal frequency equals the inertial frequency). While most larger-scale circumpolar models with ice shelves do not explicitly include tides, the importance of tidal processes to melt rates around the entire continent will require future models to include, or at least parameterize, this process.

## EMERGING DIRECTIONS

### Projections with Static Ice Shelves

Models of ice shelf/ocean interaction with static ice shelves have advanced to the point where they are being used not only in hindcasts or sensitivity studies, but also in attempts to project future melt rates, either with idealized changes in forcing (e.g., Kusahara and Hasumi, 2013) or with atmospheric forcing from coupled climate model projections. Using atmospheric output from the HadCM3 climate model, Hellmer et al. (2012) found a possible rapid warming of the Weddell Sea continental shelf by a redirected coastal current, with Filchner-Ronne Ice Shelf shifting from Mode 1 to Mode 2 melting with dramatically increased melt rates. Timmermann and Hellmer (2013) showed that surface freshwater flux on the Weddell Sea continental shelf, which is governed by sea ice formation, is critical in allowing or preventing this transition in the melting mode.

### Dynamic Ice Shelves and Coupled Ice Shelf/Ice Sheets

Probably the most critical advance in modeling ice shelf/ocean interactions is the coupling of ocean models to dynamic ice sheet/shelf models that allow grounded and floating ice to react to ocean changes. Many such models have used idealized ice geometry and bathymetry to perform studies of processes such as calving, hysteresis in grounding line dynamics, melt channels, and the effects of a seabed ridge on grounding line retreat, as well as parameter studies such as variations in basal sliding and far-field ocean temperature. Many of the ice sheet or ocean components in these studies are simplified, operating in one or two dimensions. Coupling is often performed in an asynchronous manner through offline operations on model restart files. Typically, this means that coupling intervals are relatively long (months to years), compared with typical climate model couplers (hours to days). In some studies (e.g., Goldberg et al., 2012; De Rydt and Gudmundsson, 2016) the ocean model is run to steady state after changes in the ice cavity geometry at each coupling interval. Although one coupled ice sheet/ocean model was used to simulate subglacial Lake Vostok (Thoma et al., 2010), we are not aware of any existing publications of coupled ice sheet/ocean modeling in a realistic configuration.

However, several ongoing activities are working toward creating a framework in which ocean and ice models can be run synchronously and the coupling interval is short enough for each model to respond to transient behavior in the other (e.g., having the ocean model be able to handle changes in the cavity geometry such as grounding line movement, which can happen on time scales as rapid as the ocean tides). For example, a global configuration of the Finite Element Sea Ice-Ocean Model (FESOM; see Table 1) is being coupled to a regional ice sheet/ice shelf model that covers Filchner-Ronne Ice Shelf and the ice streams in its catchment basin. The US Department of Energy has developed the POPSICLES coupled ice sheet-ocean model (Martin et al., 2015), which has been used in both idealized and pan-Antarctic configurations (Figure 6).

The calving of icebergs causes nearly as much ice shelf mass loss as basal melting. A suite of models has been developed to represent the drift and melting of icebergs in the ocean (e.g., Merino et al., 2016). Several physics-based models have recently been suggested for the calving process (e.g., Christmann et al., 2016), but to derive calving rates within ice sheet models, more phenomenological approaches (e.g., Albrecht et al., 2011) have prevailed so far. A robust, physics-based description of the calving process and the embedding of drifting icebergs in ocean models will be one of the major challenges in the upcoming years in order to allow for a full description of the ice mass budget and ocean freshwater fluxes.

### CliC and MISOMIP

The Marine Ice Sheet-Ocean Model Intercomparison Project (MISOMIP) is a targeted activity of the World Climate Research Programme's Climate and Cryosphere (CliC) project aimed at designing and coordinating model intercomparison projects (MIPs) for model evaluation and verification, and for

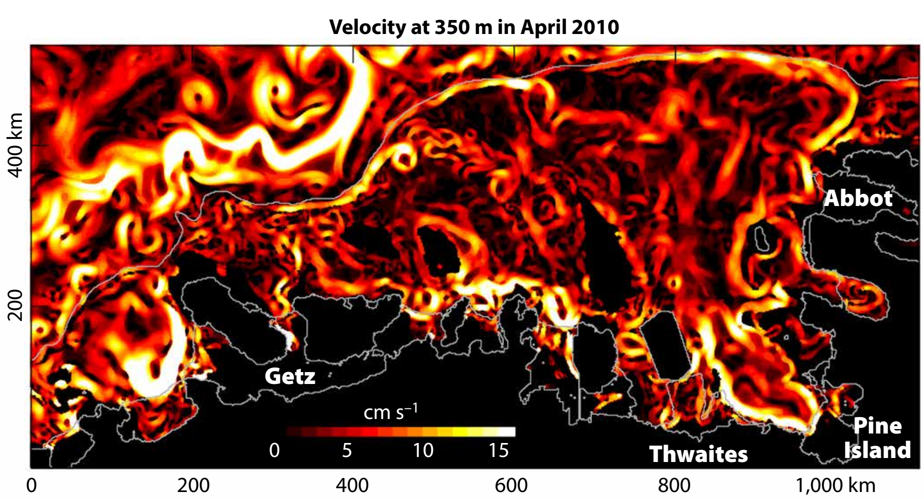


**FIGURE 5.** Regional eddy-resolving (1.5 km horizontal resolution) Amundsen Sea model (St-Laurent et al., 2015) current speed at 350 m depth showing the intense eddying at this resolution. Note the many smaller eddies (closed circles of high velocity) over the continental shelf compared to the larger eddies in the deep ocean to the north.

producing future projections of sea level rise from the West Antarctic Ice Sheet. In the longer term, MISOMIP will focus on the Amundsen Sea region, where the largest rates of ice loss are presently observed. In the near term, MISOMIP will perform idealized intercomparisons of the ice and ocean models involved. The first phase of MISOMIP consists of three MIPs, one for standalone ice-sheet models, one for stand-alone ocean models with ice shelf cavities, and one for coupled ice sheet/ocean models (Asay-Davis et al., 2016).

### Adjoint Modeling

Adjoint models are useful in many tasks, including sensitivity studies and parameter optimization. Briefly, the adjoint modeler selects an objective function, which is a scalar quantity of interest (e.g., ice shelf melt rate), and a control space (e.g., ocean model wind forcing), and then generates and runs the consequent adjoint of the basic "forward" model. The adjoint simulation yields the sensitivity as a function of space and time of the objective function to all elements of the control space and also all intermediate variables. For example, Heimbach and Losch (2012) used an MITgcm adjoint model to demonstrate the sensitivity of ice shelf melt rates underneath Pine Island Ice Shelf to changes in the ice shelf cavity circulation. Adjoint modeling of sub-ice shelf cavities is in its infancy and shows considerable promise in the optimization of sub-ice models and the estimation of hard-to-observe parameters, such as heat and salt exchange coefficients.

### Large Eddy and Direct Numerical Simulation

Another promising avenue for future research is the application of ultra-high-resolution models to the physics of the ice/ocean boundary layer. The heat and salt exchange coefficients and the drag coefficient in the ice melting parameterization sit at the heart of all ice/ocean models, but the physics represented by these parameters is uncertain, and the processes involved will remain subgrid scale in general ocean models for the foreseeable future. Novel observational approaches are needed to clarify the physics, but there is also the possibility of directly modeling the oceanic boundary layer by applying Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS). These approaches avoid the empirical turbulence closures in traditional Reynolds-averaged Navier-Stokes models by either resolving all motions above the length scale (~1 m) at which turbulence is homogeneous and isotropic (LES) or by resolving all motions down to molecular (~1 mm) length scales (DNS). DNS studies of the ice/ocean boundary layer are already underway (Gayen et al., 2015).

## SUMMARY

Williams et al. (1998) included specific aspirations for future modeling, some of which have been achieved in the intervening decades ("the most obvious need is for a thermohaline model that incorporates tidal forcing") while others are still in progress ("we should be able to define and parameterize the important processes that need to be included in the next generations of global climate models"). They also highlighted the pressing need for observations to test numerical models. The technological advances they suggested (deployment of AUVs beneath ice shelves and phase-sensitive radars to measure melt rates from the ice surface) now exist, but such observations are not yet routine.

In the continued absence of widespread observations of conditions within sub-ice cavities, the evaluation of numerical models remains a problem. Our lack of knowledge of basic parameters, such as sub-ice bathymetry, hampers our ability to learn about deficiencies in model physics by comparing model results and observation. While the MIPs provide a framework for intermodel comparison, consensus between models is no guarantee of correctness. We therefore see a continued role for low-order models that can provide benchmarking of fundamental processes. For example, an analytical solution to the problem of pure buoyancy-forced

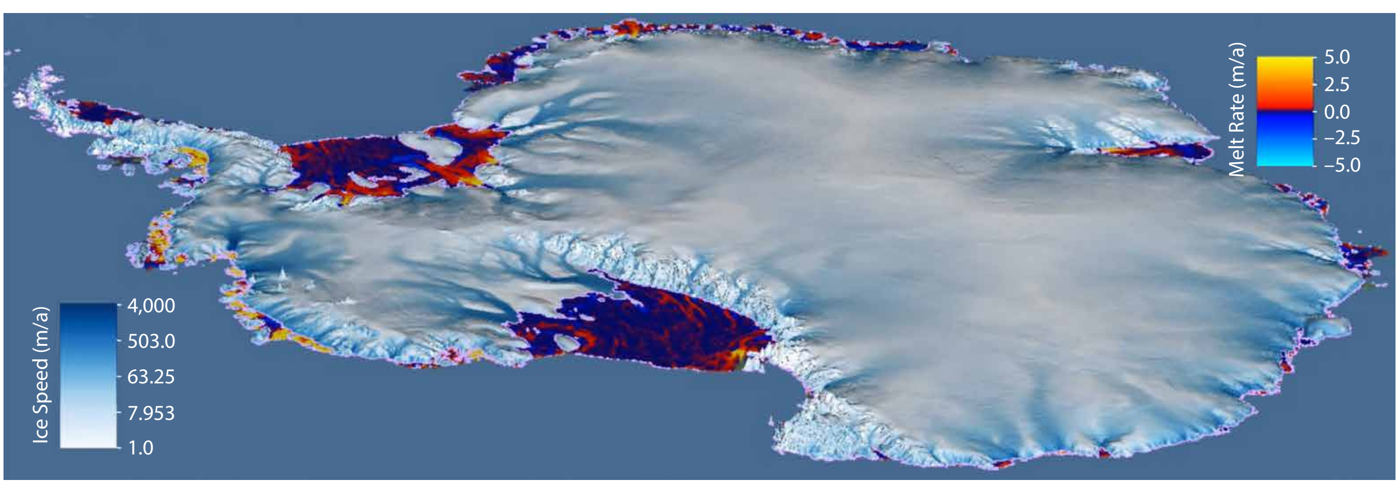


**FIGURE 6.** Melt rates (plotted on ice shelves) and ice velocities (plotted on grounded ice) from a coupled ice sheet/ocean pan-Antarctic simulation with the POPSICLES model (Martin et al., 2015). The ocean horizontal resolution (~4 km) permits eddies in the open ocean but not on the continental shelf. The variable-resolution ice sheet model (BISICLES) has sufficient horizontal resolution (500 m) to accurately capture grounding-line motion.

circulation in a domain of simple geometry would permit a much better test of the skill of current models and highlight where deficiencies in the representation of physics might be preventing those models from simulating reality.

Williams et al. (1998) did "anticipate the continued application of increasingly sophisticated numerical models to the problems of sub-ice shelf circulation" and noted that three-dimensional models "are likely to be at the forefront of these developments." They also foresaw a role for reduced models in "the investigation of sub-ice shelf cavity evolution over time scales as long as those associated with glacial/interglacial cycles." However, such long time scales have been rendered less important by the discovery that the time scales of glaciological response to ice shelf melting, and resulting marine ice sheet instability, could be as short as a century or two (Joughin et al., 2014). Ice/ocean interactions are now considered to be a key ingredient in century-scale climate projections, and with advances in computing power, coupling of dynamic ice sheet models with full three-dimensional ocean circulation models is now being actively pursued.

We anticipate that several of the emerging areas of research listed above, including the use of unstructured grids in both the vertical and horizontal dimensions and coupled ocean/ice shelf/ice sheet modeling, will become standard options over the next decade not only for regional models but also in some global Earth system models. If a physics-based description of the iceberg calving process becomes available in the next decade, then calving and the embedding of drifting icebergs are also likely to be explicitly simulated in regional and some global models. While LES and DNS simulations of the ice/ocean boundary layer will continue to be too computationally expensive for widespread use in large-scale models for quite a while, we do anticipate their contribution to the development of new subgrid-scale schemes for modeling the ice/ocean boundary layer.

## REFERENCES


Albrecht, T., M.A. Martin, R. Winkelmann, M. Haseloff, and A. Levermann. 2011. Parameterization for subgrid-scale motion of ice-shelf calving-fronts. *The Cryosphere* 5:35–44, https://doi.org/10.5194/tc-5-35-2011.

Arrigo, K.R., G.L. van Dijken, and A.L. Strong. 2015. Environmental controls of marine productivity hot spots around Antarctica. *Journal of Geophysical Research* 120:5,545–5,565, https://doi.org/10.1002/2015JC010888.

Årthun, M., P.R. Holland, K.W. Nicholls, and D.L. Feltham. 2013. Eddy-driven exchange between the open ocean and a sub-ice shelf cavity. *Journal of Physical Oceanography* 43:2,372–2,387, https://doi.org/10.1175/JPO-D-13-0137.1.

Arzeno, I.B., R.C. Beardsley, R. Limeburner, B. Owens, L. Padman, S.R. Springer, C.L. Stewart, and M.J.M. Williams. 2014. Ocean variability contributing to basal melt rate near the ice front of Ross Ice Shelf, Antarctica. *Journal of Geophysical Research* 119:4,214–4,233, https://doi.org/10.1002/2014JC009792.

Asay-Davis, X.S., S.L. Cornford, G. Durand, B.K. Galton-Fenzi, R.M. Gladstone, G.H. Gudmundsson, T. Hattermann, D.M. Holland, D. Holland, P.R. Holland, and others. 2016. Experimental design for three interrelated marine ice sheet and ocean model intercomparison projects: MISMIP v. 3 (MISMIP +), ISOMIP v. 2 (ISOMIP +) and MISOMIP v. 1 (MISOMIP1). *Geoscientific Model Development* 9:2,471–2,497, https://doi.org/10.5194/gmd-9-2471-2016.

Beckmann, A., H.H. Hellmer, and R. Timmermann. 1999. A numerical model of the Weddell Sea: Large-scale circulation and water mass distribution. *Journal of Geophysical Research* 104:23,375–23,391, https://doi.org/10.1029/1999JC900194.

Christmann, J., C. Plate, R. Müller and A. Humbert. 2016. Viscous and viscoelastic stress states at the calving front of Antarctic ice shelves. *Annals of Glaciology*, https://doi.org/10.1017/aog.2016.18.

Craven, M., I. Allison, H.A. Fricker, and R. Warner. 2009. Properties of a marine ice layer under the Amery Ice Shelf, East Antarctica. *Journal of Glaciology* 55(192):717–728, https://doi.org/10.3189/002214309789470941.

Dansereau, V., P. Heimbach, and M. Losch. 2014. Simulation of subice shelf melt rates in a general circulation model: Velocity-dependent transfer and the role of friction. *Journal of Geophysical Research* 119:1,765–1,790, https://doi.org/10.1002/2013JC008846.

DeAngelis, H., and P. Skvarca. 2003. Glacier surge after ice shelf collapse. *Science* 299:1,560–1,562, https://doi.org/10.1126/science.1077987.

DeConto, R.M., and D. Pollard. 2016. Contribution of Antarctica to past and future sea-level rise. *Nature* 531:591–597, https://doi.org/10.1038/nature17145.

De Rydt, J., and G.H. Gudmundsson. 2016. Coupled ice shelf-ocean modeling and complex grounding line retreat from a seabed ridge. *Journal of Geophysical Research* 121:865–880, https://doi.org/10.1002/2015JF003791.

Dinniman, M.S., J.M. Kinck, L-S Bai, D.H. Bromwich, K.M. Hines, and D.M. Holland. 2015. The effect of atmospheric forcing resolution on delivery of ocean heat to the Antarctic floating ice shelves. *Journal of Climate* 28:6,067–6,085, https://doi.org/10.1175/JCLI-D-14-00374.1.

Dutrieux, P., J. De Rydt, A. Jenkins, P.R. Holland, H.-K. Ha, S.H. Lee, E.J. Steig, Q. Ding, E.P. Abrahamsen, and M. Schröder. 2014a. Strong sensitivity of Pine Island Ice-Shelf melting to climatic variability. *Science* 343:174–178, https://doi.org/10.1126/science.1244341.

Dutrieux, P., C. Stewart, A. Jenkins, K.W. Nicholls, H.F.J. Corr, E. Rignot, and K. Steffen. 2014b. Basal terraces on melting ice shelves. *Geophysical Research Letters* 41:5,506–5,513, https://doi.org/10.1002/2014GL060618.

Galton-Fenzi, B.K., J.R. Hunter, R. Coleman, S.J. Marsland, and R. Warner. 2012. Modeling the basal melting and marine ice accretion of the Amery Ice Shelf. *Journal of Geophysical Research* 117, C09031, https://doi.org/10.1029/2012JC008214.

Gayen, B., R.W. Griffiths, and R.C. Kerr. 2015. Melting driven convection at the ice-seawater interface. *Procedia IUTAM* 15:78–85, https://doi.org/10.1016/j.piutam.2015.04.012.

Goldberg, D.N., C.M. Little, O.V. Sergienko, A. Gnanadesikan, R. Hallberg, and M. Oppenheimer. 2012. Investigation of land ice-ocean interaction with a fully coupled ice-ocean model: Part 1. Model description and behavior. *Journal of Geophysical Research* 117, F02037, https://doi.org/10.1029/2011JF002246.

Griffies, S.M., C. Böning, F.O. Bryan, E.P. Chassignet, R. Gerdes, H. Hasumi, A. Hirst, A.-M. Treguier, and D. Webb. 2000. Developments in ocean climate modelling. *Ocean Modelling* 2:123–192, https://doi.org/10.1016/S1463-5003(00)00014-7.

Gudmundsson, G.H. 2013. Ice-shelf buttressing and the stability of marine ice sheets. *The Cryosphere* 7:647–655, https://doi.org/10.5194/tc-7-647-2013.

Gwyther, D.E., B.K. Galton-Fenzi, M.S. Dinniman, J.L. Roberts, and J.R. Hunter. 2015. The effect of basal friction on melting and freezing in ice shelf–ocean models. *Ocean Modelling* 95:38–52, https://doi.org/10.1016/j.ocemod.2015.09.004.

Hallberg, R. 2013. Using a resolution function to regulate parameterizations of oceanic mesoscale eddy effects. *Ocean Modelling* 72:92–103, https://doi.org/10.1016/j.ocemod.2013.08.007.

Hattermann, T., L.H. Smedsrud, O.A. Nøst, J.M. Lilly, and B.K. Galton-Fenzi. 2014. Eddy-resolving simulations of the Fimbul Ice Shelf cavity circulation: Basal melting and exchange with open ocean. *Ocean Modelling* 82:28–44, https://doi.org/10.1016/j.ocemod.2014.07.004.

Heimbach, P., and M. Losch. 2012. Adjoint sensitivities of sub-ice-shelf melt rates to ocean circulation under the Pine Island Ice Shelf, West Antarctica. *Annals of Glaciology* 53:59–69, https://doi.org/10.3189/2012/AoG60A025.

Hellmer, H.H., F. Kauker, R. Timmermann, J. Determann, and J. Rae. 2012. Twenty-first-century warming of a large Antarctic ice shelf cavity by a redirected coastal current. *Nature* 485:225–228, https://doi.org/10.1038/nature11064.

Hellmer, H.H., and D. Olbers. 1989. A two-dimensional model for the thermohaline circulation under an ice shelf. *Antarctic Science* 1:325–336, https://doi.org/10.1017/S0954102089000490.

Holland, P.R. 2008. A model of tidally dominated ocean processes near ice shelf grounding lines. *Journal of Geophysical Research* 113, C11002, https://doi.org/10.1029/2007JC004576.

Holland, P.R., H.F.J. Corr, D.G. Vaughan, A. Jenkins, and P. Skvarca. 2009. Marine ice in Larsen Ice Shelf. *Geophysical Research Letters* 36, L11604, https://doi.org/10.1029/2009GL038162.

Holland, P.R., and D.L. Feltham. 2006. The effects of rotation and ice shelf topography on frazil-laden ice shelf water plumes. *Journal of Physical Oceanography* 36:2,312–2,327, https://doi.org/10.1175/JPO2970.1.

Holland, D.M., and A. Jenkins. 1999. Modeling thermodynamic ice-ocean interactions at the base of an ice shelf. *Journal of Physical Oceanography* 29:1,787–1,800, https://doi.org/10.1175/1520-0485(1999)029<1787:MTIOIA>2.0.CO;2.

Holland, D.M., and A. Jenkins. 2001. Adaptation of an isopycnic coordinate ocean model for the study of circulation beneath ice shelves. *Monthly Weather Review* 129:1,905–1,927, https://doi.org/10.1175/1520-0493(2001)129<1905:AOAICO>2.0.CO;2.

Jacobs, S.S., and C.F. Giulivi. 2010. Large multidecadal salinity trends near the Pacific-Antarctic continental margin. *Journal of Climate* 23:4,508–4,524, https://doi.org/10.1175/2010JCLI3284.1.

Jacobs, S.S., H.H. Helmer, C.S.M. Doake, A. Jenkins, and R.M. Frolich. 1992. Melting of ice shelves and the mass balance of Antarctica. *Journal of Glaciology* 38:375–387.

Jenkins, A. 1991. A one-dimensional model of ice shelf-ocean interaction. *Journal of Geophysical Research* 96:20,671–20,677, https://doi.org/10.1029/91JC01842.

Jenkins, A. 2016. A simple model of the ice shelf–ocean boundary layer and current. *Journal of Physical Oceanography* 46:1,785–1,803, https://doi.org/10.1175/JPO-D-15-0194.1.

Jenkins, A., and A. Bombosch. 1995. Modeling the effects of frazil ice crystals on the dynamics and thermodynamics of ice shelf water plumes. *Journal of Geophysical Research* 100:6,967–6,981, https://doi.org/10.1029/94JC03227.

Jenkins, A., K.W. Nicholls, and H.F. Corr. 2010. Observation and parameterization of ablation at the base of Ronne Ice Shelf, Antarctica. *Journal of Physical Oceanography* 40:2,298–2,312, https://doi.org/10.1175/2010JPO4317.1.

Jordan, J.R., P.R. Holland, A. Jenkins, M.D. Piggott, and S. Kimura. 2014. Modeling ice-ocean interaction in ice shelf crevasses. *Journal of Geophysical Research*, 119:995–1,008, https://doi.org/10.1002/2013JC009208.

Joughin, I., B.E. Smith, and B. Medley. 2014. Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. *Science* 344:735–738, https://doi.org/10.1126/science.1249055.

Kimura, S., A.S. Candy, P.R. Holland, M.D. Piggott, and A. Jenkins. 2013. Adaptation of an unstructured-mesh, finite-element ocean model to the simulation of ocean circulation beneath ice shelves. *Ocean Modelling* 67:39–51, https://doi.org/10.1016/j.ocemod.2013.03.004.

Kusahara, K., and H. Hasumi. 2013. Modeling Antarctic ice shelf responses to future climate changes and impacts on the ocean. *Journal of Geophysical Research* 118:2,454–2,475, https://doi.org/10.1002/jgrc.20166.

Little, C.M., A. Gnanadesikan, and R. Hallberg. 2008. Large-scale oceanographic constraints on the distribution of melting and freezing under ice shelves. *Journal of Physical Oceanography* 38:2,242–2,255, https://doi.org/10.1175/2008JPO3928.1.

Liu, Y., J.C. Moore, X. Cheng, R.M. Gladstone, J.N. Bassis, H. Liu, J. Wen, and F. Hui. 2015. Ocean-driven thinning enhances iceberg calving and retreat of Antarctic ice shelves. *Proceedings of the National Academy of Sciences of the United States of America* 112(11):3,263–3,268, https://doi.org/10.1073/pnas.1415137112.

Losch, M. 2008. Modeling ice shelf cavities in a z coordinate ocean general circulation model. *Journal of Geophysical Research* 113, C08043, https://doi.org/10.1029/2007JC004368.

MacAyeal, D.R. 1985. Evolution of tidally triggered meltwater plumes below ice shelves. Pp. 133–143 in *Oceanology of the Antarctic Continental Shelf*. S.S. Jacobs, ed., American Geophysical Union Antarctic Research Series, Vol. 43, Washington, DC.

Makinson, K., P.R. Holland, A. Jenkins, K.W. Nicholls, and D.M. Holland. 2011. Influence of tides on melting and freezing beneath Filchner-Ronne Ice Shelf, Antarctica. *Geophysical Research Letters* 38, L06601, https://doi.org/10.1029/2010GL046462.

Martin, D., X. Asay-Davis, S. Cornford, S. Price, E. Ng, and W. Collins. 2015. A tale of two forcings: Present-day coupled Antarctic Ice-sheet/Southern Ocean dynamics using the POPSICLES model. Paper presented at the European Geosciences Union General Assembly, Vienna, Austria, April 12–17, 2015, no. 7564.

Martinson, D.G., and D.C. McKee. 2012. Transport of warm Upper Circumpolar Deep Water onto the western Antarctic Peninsula continental shelf. *Ocean Science* 8:433–442, https://doi.org/10.5194/os-8-433-2012.

McMillan, M., A. Shepherd, A. Sundal, K. Briggs, A. Muir, A. Ridout, A. Hogg, and D. Wingham. 2014. Increased ice losses from Antarctica detected by CryoSat-2. *Geophysical Research Letters* 41:3,899–3,905, https://doi.org/10.1002/2014GL060111.

Merino, N., J. Le Sommer, G. Durand, N.C. Jourdain, G. Madec, P. Mathiot, and J. Tournadre. 2016. Antarctic icebergs melt over the Southern Ocean: Climatology and impact on sea ice. *Ocean Modelling* 104:99–110, https://doi.org/10.1016/j.ocemod.2016.05.001.

Mueller, R.D., L. Padman, M.S. Dinniman, S.Y. Erofeeva, H.A. Fricker, and M.A. King. 2012. Impact of tide-topography interactions on basal melting of Larsen C Ice Shelf, Antarctica. *Journal of Geophysical Research* 117, C05005, https://doi.org/10.1029/2011JC007263.

Nakayama, Y., R. Timmermann, M. Schröder, and H.H. Hellmer. 2014. On the difficulty of modeling Circumpolar Deep Water intrusions onto the Amundsen Sea continental shelf. *Ocean Modelling* 84:26–34, https://doi.org/10.1016/j.ocemod.2014.09.007.

Nicholls, K.W., E.P. Abrahamsen, J.J.H. Buck, P.A. Dodd, C. Goldblatt, G. Griffiths, K.J. Heywood, N.E. Hughes, A. Kaletzky, G.F. Lane-Serff, and others. 2006. Measurements beneath an Antarctic ice shelf using an autonomous underwater vehicle. *Geophysical Research Letters* 33, L08612, https://doi.org/10.1029/2006GL025998.

Nicholls, K.W., and K. Makinson. 1998. Ocean circulation beneath the western Ronne Ice Shelf, as derived from in situ measurements of water currents and properties. Pp. 301–318 in *Ocean, Ice, and Atmosphere: Interactions at the Antarctic Continental Margin*. S.S. Jacobs and R.F. Weiss, eds, American Geophysical Union Antarctic Research Series, Vol. 75, Washington, DC.

Petersen, M.R., X. Asay-Davis, T.D. Ringler, D. Jacobsen, S.F Price, and J.G. Fyke. 2016. Ocean-ice shelf interactions in the Accelerated Climate Model for Energy (ACME). Paper A14A-2524 presented at the Ocean Sciences Meeting, New Orleans, LA, February 21–26, 2016.

Petty, A.A., D.L. Feltham, and P.R. Holland. 2013. Impact of atmospheric forcing on Antarctic continental shelf water masses. *Journal of Physical Oceanography* 43:920–940, https://doi.org/10.1175/jpo-d-12-0172.1.

Potter, J.R., and J.G. Paren. 1985. Interaction between ice shelf and ocean in George VI Sound, Antarctica. Pp. 35–58 in *Oceanology of the Antarctic Continental Shelf*. S.S. Jacobs, ed., American Geophysical Union Antarctic Research Series, Vol. 43, Washington, DC.

Pritchard, H.D., S.R.M. Ligtenberg, H.A. Fricker, D.G. Vaughan, M.R. van den Broeke, and L. Padman. 2012. Antarctic ice-sheet loss driven by basal melting of ice shelves. *Nature* 484:502–505, https://doi.org/10.1038/nature10968.

Rignot, E., S. Jacobs, J. Mouginot, and B. Scheuchl. 2013. Ice shelf melting around Antarctica. *Science* 341:266–270, https://doi.org/10.1126/science.1235798.

Robinson, R., A. Beckmann, and H. Hellmer. 2003. M2 tidal dynamics in the Ross Sea. *Antarctic Science* 15:41–46, https://doi.org/10.1017/S0954102003001044.

Robertson, R. 2013. Tidally induced increases in melting of Amundsen Sea ice shelves. *Journal of Geophysical Research* 118:3,138–3,145, https://doi.org/10.1002/jgrc.20236.

Schaffer, J., R. Timmermann, J.E. Arndt, S. Savstrup Kristensen, C. Mayer, M. Morlighem, and D. Steinhage. 2016. A global high-resolution data set of ice sheet topography, cavity geometry and ocean bathymetry. *Earth Systems Science Data Discussions*, https://doi.org/10.5194/essd-2016-3.

Schodlok, M.P., D. Menemenlis, and E.J. Rignot. 2016. Ice shelf basal melt rates around Antarctica from simulations and observations. *Journal of Geophysical Research* 121:1,085–1,109, https://doi.org/10.1002/2015JC011117.

Sergienko, O.V. 2013. Basal channels on ice shelves. *Journal of Geophysical Research* 118:1,342–1,355, https://doi.org/10.1002/jgrf.20105.

Stewart, A.L., and A.F. Thompson. 2015. Eddy-mediated transport of warm Circumpolar Deep Water across the Antarctic shelf break. *Geophysical Research Letters* 42:432–440, https://doi.org/10.1002/2014GL062281.

St-Laurent, P., J.M. Klinck, and M.S. Dinniman. 2015. Impact of local winter cooling on the melt of Pine Island Glacier, Antarctica. *Journal of Geophysical Research* 120:6,718–6,732, https://doi.org/10.1002/2015JC010709.

Thoma, M., K. Grosfeld, C. Mayer, and F. Pattyn. 2010. Interaction between ice sheet dynamics and subglacial lake circulation: A coupled modelling approach. *The Cryosphere* 4(1):1–12, https://doi.org/10.5194/tc-4-1-2010.

Timmermann, R., and H.H. Hellmer. 2013. Southern Ocean warming and increased ice shelf basal melting in the 21st and 22nd centuries based on coupled ice-ocean finite-element modelling. *Ocean Dynamics* 63:1011, https://doi.org/10.1007/s10236-013-0642-0.

Timmermann, R., Q. Wang, and H.H. Hellmer. 2012. Ice-shelf basal melting in a global finite-element sea-ice/ice-shelf/ocean model. *Annals of Glaciology* 53:303–314, https://doi.org/10.3189/2012AoG60A156.

Williams, M.J.M., A. Jenkins, and J. Determan. 1998. Physical controls on ocean circulation beneath ice shelves revealed by numerical models. Pp. 285–299 in *Ocean, Ice, and Atmosphere: Interactions at the Antarctic Continental Margin*. S.S. Jacobs and R.F. Weiss, eds, American Geophysical Union Antarctic Research Series, Vol. 75, Washington, DC.

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