Ocean Modelling 130 (2018) 66–78

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Parameterizing the basal melt of tabular icebergs

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ARTICLE INFO

Keywords:
Icebergs
Melting
Meltwater
Modeling
Parameterization

MSC:
2017

ABSTRACT

In this study, we consider the influence of icebergs on the ocean when they are modeled as occupying physical space, to answer the question of how the melting of icebergs and subsequent distribution of meltwater in the water column might be accurately parameterized in climate models. Iceberg melt is analyzed by comparing in-situ melt rates calculated via the three-equation parameterization, which was developed for application under ice shelves, with the commonly used bulk parameterization of iceberg basal melt. Our results suggest an updated velocity-independent version of the basal melt parameterization for tabular icebergs for use in calculating the basal melt rate of icebergs that are large (relative to the deformation radius), to account for the changes in ocean properties caused by the physical presence of a large iceberg in the ocean.

1. Introduction

The Greenland and Antarctic ice sheets accumulate mass when snow falling on their surfaces does not melt over the course of the year, and compacts into ice over time. The ice sheets maintain equilibrium by losing mass through a combination of surface and subsurface melt, and discharging icebergs from their marine-terminating margins (Hanna et al., 2013). Recent estimates suggest that the discharge of icebergs accounts for approximately half of the mass loss from the Greenland and Antarctic ice sheets (Depoorter et al., 2013). From a climate modeling perspective, this mass flux to the ocean is of interest for several reasons. Firstly, the supply of meltwater to the ocean influences the properties of the water column, increasing stability if it is deposited in an almost undiluted surface layer (i.e. when there is not significant mixing with the saline ambient water as the melt plume rises to the surface), and potentially decreasing stability if it is released at depth. Increased water column stability in polar regions is associated with suppressed convection and enhanced sea ice formation, while decreased stability promotes convection and dampens sea ice growth (Gade, 1993; Stephenson et al., 2011; Helly et al., 2011; Merino et al., 2016). Secondly, enhanced nutrient availability has been observed in iceberg melt plumes, which promotes biological blooms and the sequestration of carbon by the ocean (Smith et al., 2007; Duprat et al., 2016). There has consequently been an increased interest in understanding iceberg trajectories and melt patterns in recent years, with a to improving the representation of their influence on the ocean in global climate models.

Two different parameterizations of glacial ice melting in seawater currently exist, depending on whether the ice is attached to an ice sheet (in the form of an ice shelf) or detached from it (as an iceberg that has calved into the ocean). Within the ice shelf modeling community, the three-equation model of melt (McPhee et al., 1987; Holland and Jenkins, 1999) is used, while in the iceberg modeling community, bulk melt rate parameterizations (Weeks and Campbell, 1973; Bigg et al., 1996; Gladstone et al., 2001; Martin and Adcroft, 2010) are usually employed to circumvent the need to explicitly resolve icebergs in the ocean. However, in both scenarios it is the same physical process, namely the melting of ice in seawater, that is being represented, and thus the two parameterizations should agree.

The bulk iceberg melt parameterizations used in current global climate models account for iceberg decay via wave erosion at their margins, surface melt by the air, and subsurface melt by the ocean (El-Tahan et al., 1987; Savage, 2001; Bigg, 2016). Of these, the rate of wave erosion is generally the largest, at 0.5–1 m d^{-1} even in calm ocean conditions, followed by the subsurface melt ($\leq$ 1 m d^{-1}), and then surface melt ($\leq$ 0.02 m d^{-1}; often neglected in climate models) (Bigg, 2016; Savage, 2001). The process of edge erosion is parametrized as a continuous decay rate (in units of m d^{-1}), and the wave erosion rate is only applied to the iceberg sides, which generally account for a smaller area than the base. In this study, we focus on subsurface melt as opposed to edge wasting since the predominant disagreement between the representation of iceberg and ice shelf decay occurs in the parameterization of subsurface melting. Subsurface melt may further be divided into subsurface side melt and subsurface basal melt, and it is

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https://doi.org/10.1016/j.ocemod.2018.08.005
Received 2 February 2018; Received in revised form 7 August 2018; Accepted 16 August 2018
Available online 18 August 2018

this latter process that is the focus of this study.

The bulk parameterization of iceberg basal melt (in units of m d^{-1}) is given by

$$M_b = C\frac{(T_o - T_i)\,|u_o - u_i|^{0.8}}{L^{0.2}}, \tag{1}$$

for ocean temperature T_o (°C), ice temperature T_i (generally taken to be constant at $T_i = -4$ °C), relative ice-ocean velocity $|u_o - u_i|$ ms^{-1}, iceberg length L (m), and dimensional constant $C = 0.58$ °C^{-1} $m^{0.4}$ d^{-1} $s^{0.8}$ (Weeks and Campbell, 1973; Bigg et al., 1996; Gladstone et al., 2001; Savage, 2001; Martin and Adcroft, 2010). For the bulk parameterization above, the ocean properties T_o and u_o are typically taken from a single grid cell (Kubat et al., 2007; Martin and Adcroft, 2010), although there have been recent modifications to spatially average these properties over the surface area occupied by the iceberg (Rackow et al., 2017). In the standard bulk parameterization, the surface T_o and u_o are used, although some recent models have taken the values of T_o and u_o at the basal depth (Silva et al., 2006; Marsh et al., 2015; Merino et al., 2016; Rackow et al., 2017).

While bulk parameterizations are typically employed to represent the melting of glacial ice that is in the form of icebergs in global climate models, a different formulation of melting is generally applied to the glacial ice constituting ice shelves. This is the three-equation parameterization of melting (Holland and Jenkins, 1999), which comprises equations for the freezing point dependence on pressure and salinity, the conservation of heat, and the conservation of salt. For temperature T, salinity S, and pressure P, these may be expressed as

$$T_b = \alpha S_b + \beta + \delta P_b \tag{2}$$

$$\rho_i L_f M_b = \frac{k_i^T}{h}(T_b - T_i) + \gamma_T (T_o - T_b) \tag{3}$$

$$\gamma_S (S_b - S_o) = -\rho_i S_b M_b, \tag{4}$$

where the subscript o is used to denote far field ocean properties, b denotes boundary layer properties, and i denotes ice properties. The heat transfer coefficient γ_T is parameterized as a function of the velocity adjacent to the ice face, and the remainder of the variables are constants, defined in Table 1, and described fully in Section 4.1. In general, this parameterization is not applied to calculate iceberg melt, although in theory the same physics should apply to this problem as to the melting of sea ice and ice shelves. There have been some modeling attempts to apply the three-equation parameterization to calculate iceberg melt rates (Jansen et al., 2007; Rackow et al., 2017), but to date this has been done using far-field properties, without including an iceberg with physical mass in the flow (one notable exception is Stern et al. (2017) who model a drifting tabular iceberg submerged in the ocean using a melt parameterization which is a hybrid between the 3 equation model and the bulk parameterization).

In what follows, we use an idealized numerical model to compare the three-equation parameterization of ice shelf melt (Holland and Jenkins, 1999) and the bulk parameterization of iceberg basal melt

Table 1
A full explanation of the parameters in the three-equation formulation of melting (Eqs. (3) and (4)).

	Parameter	Units
α	Freezing equation salinity coefficient	°C PSU^{-1}
β	Freezing equation constant coefficient	°C
δ	Freezing equation pressure coefficient	°C Pa^{-1}
$\rho_{i,\ o}$	Ice/ocean reference density	kg m^{-3}
k_i^T	Molecular salt conductivity	m^2 s^{-1}
h	Boundary layer thickness	m
γ_T	Heat turbulent transfer coefficient	W m^{-2} K^{-1}
γ_S	Salt turbulent transfer coefficient	kg m^{-2} s^{-1}

(Weeks and Campbell, 1973), in a configuration that explicitly includes an iceberg that acts as an obstacle to the ocean flow in which it is situated. It is found that there are large discrepancies between the bulk formulation of melting and the parameterized three-equation melt rate if the far-field flow properties are used in the bulk formulation. In addition, there is a multiplicative difference between the two parameterizations even when the appropriate basal properties are used in the bulk parameterization. We find that this difference is a result of the representation of the heat transfer coefficient differing between the two parameterizations. Consequently, an updated bulk basal melt parameterization is proposed for large tabular icebergs ($R \geq 15$ km), which estimates the basal flow properties as a function of the free flow properties, for models that do not embed icebergs physically into the ocean, and accounts for the identified multiplicative difference between the two approaches mentioned above.

The structure of this paper is as follows. The numerical model used and simulations conducted are described in Section 2, and the results of these experiments are given in Section 3. Section 4 is a discussion of the results, in which we compare the theory underlying the three-equation and bulk models of melt to reconcile these two parameterizations, and thus make recommended adaptations to the parameterization of iceberg basal melt in global climate models. Conclusions follow in Section 5.

2. Methods

2.1. Ocean model

We consider the ocean-only Modular Ocean Model (MOM6) of the *Geophysical Fluid Dynamics Laboratory* (GFDL) (Hallberg et al., 2013) in an idealized configuration, at 5 km resolution. The domain is a zonally re-entrant channel in a rotating frame (Coriolis parameter $f = -1.4 \times 10^{-4}$ s^{-1}) with rigid meridional boundaries, of length $X = 1500$ km, width $Y = 1000$ km, and depth $Z = 1000$ m (Fig. 1). The flow is forced by a wind stress applied to the ocean surface of the form

$$(\tau_x, \tau_y) = \left(\tau_0 \sin\left(\frac{\pi y}{Y}\right), 0\right), \tag{5}$$

where $\tau_0 = 0.01$ Pa in the control experiment. The model is spun up for one year from an initial stationary state with a spatially uniform temperature field, of control value $T = 1$ °C. The initial salinity field is horizontally uniform and increases linearly with depth, between $S = 32$ PSU at the surface and $S = 38$ PSU at the ocean bed. This high salinity stratification was engineered to generate a realistic open-ocean value of the Rossby deformation radius ($R_d \approx 15$ km; a value that is representative of polar oceans (Chelton et al., 1998)) in the shallow model domain, which was employed for numerical tractability.

2.2. Ice model

The iceberg is modeled using GFDL's ice shelf module (Goldberg et al., 2012). This is achieved by holding the position of the iceberg fixed and considering the channel flow to be the relative velocity between the ice and the ocean, in the iceberg's frame of reference. While icebergs often drift in close agreement with the vertically averaged ocean velocity over their depth, the presence of strong wind forcing or any vertical shear in the ocean currents will result in a non-zero relative ice-ocean velocity at the iceberg base (FitzMaurice et al., 2016), and it is this relative velocity that the channel flow represents. The iceberg is positioned at $(x, y) = (250$ km, 500 km$)$. The iceberg has a circular cross-section, with edges that slope linearly upwards over a horizontal lengthscale $L_{\text{side}} = 20$ km (Fig. 1(C); note that the non-smooth iceberg perimeter is a consequence of the coarseness in the model resolution). For our control simulation we use an iceberg of tabular dimensions, with basal radius $R = 20$ km and maximum draft $D = 400$ m, and internal temperature of -10 °C. Due to