On Rolling Icebergs

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ABSTRACT

Iceberg drift and decay and the associated freshwater release are increasingly seen as important processes in Earth's climate system, yet a detailed understanding of their dynamics has remained elusive. A particular source of uncertainty is associated with the roll-over of small icebergs. This roll-over occurs spontaneously when the ratio of horizontal extent to depth of the iceberg falls beneath a critical threshold. The passing of such a threshold and the resulting rollover has been considered in iceberg models since the late 1970s. However, there has been some confusion in the exact formulation and, as a result, a number of erroneous accounts in previous studies. Here, we aim to clear up this confusion and provide an accurate account of rollover. This enables us to put into context the impact of rollover on iceberg dynamics and large-scale freshwater input.

1. Introduction

XX The following will have to be rewritten some, as it is just the first paragraphs of the Drift paper.

Recent years have seen an increased interest in the fate of icebergs shed from high-latitude glaciers. They remain a threat to shipping as well as offshore oil and gas exploration efforts. This is of particular relevance as retreating Arctic sea ice and increasing hydrocarbon demands have garnered the attention of industrial developers interested in both shipping and drilling in the Arctic Ocean (Pizzolato et al. 2014; National Energy Board Canada 2014).

Concurrently, ongoing global climate change is being held responsible for an observed increase in calving fluxes from Antarctic and Greenland glaciers, an increase that is projected to accelerate during the coming decades (e.g., Rignot and Kanagaratnam 2006; Copland et al. 2007; Rignot et al. 2011; Joughin et al. 2014) and that is expected to impact regional ecosystems and oceanographic conditions (e.g., Vernet et al. 2012; Smith et al. 2013; Stern et al. 2015; Duprat et al. 2016).

Furthermore, rapid shedding of icebergs from Northern Hemisphere ice sheets during the Heinrich Events of the last glacial period are believed to have affected oceanic and atmospheric conditions on a global scale (see reviews in Hemming 2004; Stokes et al. 2015).

Motivated by factors such as these, icebergs have recently begun to be implemented in state-of-the-art GCMs (e.g., Hunke and Comeau 2011; Stern et al. 2016). An improved physical understanding of iceberg dynamics is crucial for this model development.

Modeling icebergs is a challenging task, due to the multitude of different and interconnected processes that determine an iceberg's fate. For one, the trajectory of an iceberg is strongly dependent on the iceberg's size and shape. And as the iceberg decays, the drag forces acting on it change. Much of this decay is continuous and takes place in the form of gradual bottom and top surface melt and sidewall erosion. However, there is two discontinuous processes that complicate a realistic representation of iceberg decay – and hence iceberg drift. These are (a) breakup events and (b) rollover. In this study we are concerned with the latter phenomenon.

This study is structured as follows: in Section 2 we introduce two modeling frameworks with which we will investigate the impact of rollover on iceberg dynamics. These are (i) an idealized 'offline' iceberg drift and decay model, and (ii) a comprehensive 'online' iceberg model. Section 3 is concerned with different rollover schemes and the clarification of some sources of confusion in the literature. Section 4 looks at the impact of rollover on iceberg trajectories and large-scale freshwater release, using the two model frameworks introduced in Section 2. Section 5 presents the conclusion.

2. Iceberg models

In order to study the impact of the rollover process on iceberg trajectories and freshwater release we consider two modeling frameworks. The first one is an idealized formulation that considers only the leading components

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of the momentum balance and melt processes. This model operates in the "offline" mode, meaning that the iceberg trajectories are computed as non-interactive Lagrangian particles, using precomputed GCM model surface velocity and temperature (SST) fields. This allows for a rapid and physically intuitive integration of large numbers of iceberg trajectories. The second model presents a comprehensive account of the iceberg drift and decay process, which is computed in full interactive mode using the GFDL-GCM.

a. Idealized "offline" iceberg model

We use a recently developed drift model, which evolves iceberg velocity, $\vec{v}_i$, under the influence of air drag, water drag, pressure gradient force, and Coriolis force (**?**). This formulation is somewhat idealized compared to previous iceberg models (e.g., Bigg et al. 1997; Gladstone et al. 2001; Roberts et al. 2014), which allows an analytical solution for iceberg velocity as a function of surface air velocity, $\vec{v}_a$, and surface water velocity, $\vec{v}_w$. This solution enables us to efficiently compute large numbers of iceberg trajectories from specified circulation fields.

Since $\vec{v}_i$ depends on iceberg size, the drift depends on iceberg decay. The model accounts for iceberg decay using a representation adapted from Bigg et al. (1997), which includes three main melt processes (**?**). These are (i) wind-driven wave erosion, M_e; (ii) turbulent basal melt, M_b; and (iii) side wall erosion from buoyant convection, M_v.

Other processses, such as surface melt, have been found to be small compared to these terms (Savage 2001).

We further assume that these processes are linearly additive, such that iceberg volume evolves as $dV/dt = d(LWH)/dt$, with $dL/dt = dW/dt = M_e + M_v$, and $dH/dt = M_b$.

b. "Online" iceberg model in GFDL-GCM

3. Rolling Criteria

Weeks and Mellor (1978) developed a criteria for iceberg rolling using ideas developed in the ship design literature [reference]. We consider cuboid icebergs that don't vary along their length, which allows us to consider a 2-D cross-sectional picture. In this framework the vertical stability of a body is determined by its metacentric height, H_m (Fig 2). The metacentric height is defined as the vertical distance between the center of gravity, G, and the metacenter, $M \equiv I/A_s + B$, where B is the center of buoyancy, A_s is the submerged cross-sectional area of ice, and $I = W^3/12$ is the second moment of area. The submerged area is given as $A_s = (\rho_i/\rho_w)HW$ and the center of buoyancy as $B = (\rho_i/\rho_w)H/2$. For an iceberg of uniform density, the center of gravity is simply at $G = H/2$. However, Weeks and Mellor (1978) account for an increase in ice density with depth. This is done by introducing a correction height, Δ, such that $G = H/2 - \Delta$. The metacentric height can then be written as

$$H_m \equiv \frac{I}{A_s} - (G - B) = \frac{\rho_w}{\rho_i}\frac{W^2}{12H} - \frac{H}{2}\left(1 - \frac{\rho_i}{\rho_w} - \frac{2\Delta}{H}\right) \quad (1)$$

The iceberg will become unstable and roll over when $H_m < 0$. By setting (1) to zero, we can solve for the critical height-to-width ratio, $(W/H)_c \equiv \varepsilon_c$, where

$$\varepsilon_c = \sqrt{6\frac{\rho_i}{\rho_w}\left(1 - \frac{\rho_i}{\rho_w}\right) - 12\frac{\rho_i}{\rho_w}\frac{\Delta}{H}}. \quad (2)$$

Primarily concerned with an idealized iceberg of thickness $H = 200$ m, Weeks and Mellor (1978) approximate the center of gravity correction to be constant, with $\Delta = 6$ m. Furthermore, under the assumption of a 200 m-thick iceberg of non-uniform density, the authors find the effective mean density ratio to be $\rho_i/\rho_w = 0.81$. However, in their derivation Weeks and Mellor (1978) erroneously replace Δ with $-\Delta$ (see their equation (9)). By substituting $\rho_i/\rho_w = 0.81$ in (2), we find that this mistake leads to $\varepsilon_c > 1$ for $H < 730$ m (Figure 2). This has the unphysical consequence that an iceberg in this regime will continuously roll at every time step once $W/H < \varepsilon_c$. This behavior was observed

The rolling criterion of Weeks and Mellor (1978) was conceived to predict the point of an initial rolling event for an iceberg of approximately 200 m height. However, the criterion was subsequently adopted by multiple studies of continuous iceberg evolution, for a broad range of iceberg dimensions. For example, the rolling criterion (including the sign error) is adopted by Bigg et al. (1997) who consider icebergs of 10 different size classes, ranging from $100 \times 66 \times 66$ m to $1500 \times 1000 \times 300$ m. In addition to the sign error, Bigg et al. (1997) erroneously take icebergs to rotate along the long axis L (not W). Both errors are adopted by Gladstone et al. (2001), Jongma et al. (2009), and Martin and Adcroft (2010), with the latter study further replacing the iceberg height H with the iceberg draft, $H\rho_i/\rho_w$ in one of the terms. Other studies that adopted these erroneous rolling schemes are Bigg et al. (1997) include: Death et al. (2006); Jongma et al. (2013); Death et al. (2014); Roberts et al. (2014); van den Berk and Drijfhout (2014); Bügelmayer et al. (2015); Merino et al. (2016).

However, even corrected Weeks and Mellor (1978) formulation is not appropriate for use in a continuous iceberg evolution. Firstly, the formula is not applicable to small icebergs where using a constant $Delta = 6$ places the center of gravity of the iceberg too low, and makes the iceberg unconditionally stable. A consequence of this is that icebergs do not roll when W¡???. This allows narrow, pin-like icebergs to occur in the model. This could be corrected by

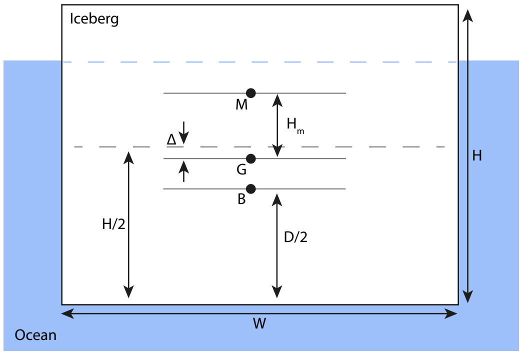

FIG. 1. Schematic of free-floating iceberg of width, W, height, H, draft D, including center of gravity, G, center of buoyancy, B, metacenter, M, metacentric height, H_m, and density correction, Δ.

letting allowing value of Δ to evolve as the iceberg melts. Secondly, the density profile of the iceberg assumed in the Weeks and Mellor (1978) derivation (i.e.: iceberg is densest near to the bottom) will be rotated by 90° upon the first instance of rolling, rendering (2) no longer adequate.

An independent formulation for iceberg rolling was developed by Burton et al. (2012), building on earlier work by MacAyeal et al. (2003). Burton et al. (2012) develop a stability criterion by minimizing the potential energy of the iceberg and confirm this with laboratory experiments. Considering icebergs of uniform density, Burton et al. (2012) find

$$\varepsilon_c = \sqrt{6\frac{\rho_i}{\rho_w}\left(1-\frac{\rho_i}{\rho_w}\right)}.$$

The stability considerations Burton et al. (2012) studies are mathematically equivalent to the formulation of Weeks and Mellor (1978) in (2) with $\Delta = 0$ (constant density). Based on observed Larsen A and B ice-shelf densities, MacAyeal et al. (2003) estimate $\varepsilon_c \simeq 0.8$, which is close to the value by Weeks and Mellor (1978) and subsequent studies, while Burton et al. (2012) take $\varepsilon_c = 0.75$.

The above considerations, together with Figure 2, suggests that using the rolling criteria of Weeks and Mellor (1978) with $\Delta \neq 0$ is not appropriate for use in an iceberg model, since (i) the formula is not applicable to small icebergs, (ii) the density structure is no longer consistent after a rolling events, (iii) the value of Δ should likely change as the iceberg melts. In order to continue to use $\Delta \neq 0$, a more complete theory of the evolution of Δ would have to be developed. However, since rolling is a relatively minor effect in the models, we suggest that setting $\Delta = 0$ is more appropriate for rolling schemes in iceberg models.

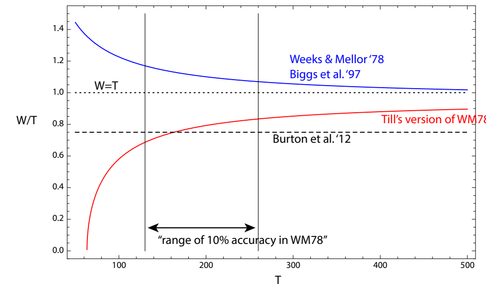

FIG. 2. ,

4. Impacts of Iceberg Rolling in Model Simulations

a. Idealized Model Simulations

b. GCM Model Simulations

c. Model description

Rollover is investigated using Geophysical Fluid Dynamics Laboratory (GFDL) coupled general circulation model CM2G (**??**). The coupled model components include the AM2 atmosphere model, MOM6 ocean model, SIS2 sea-ice model, and LM3 land model, as well as an iceberg component (**?**). The ocean model uses a $1^\circ \times 1^\circ$ grid, and 63 isopycnal layers in the vertical, which the atmospheric model has a 2° resolution. The model setup is exactly as described in (**?**).

Three model experiments are performed. Firstly, a control simulation is preformed where iceberg rolling is turned off. Rolling simulations are preformed using the Burton rolling scheme and the original and corrected Weeks and Mellor schemes. All simulations are run for 150 years. The results below are time-averaged over the final 90 years (allowing 60 years for the model to become fully spun up).

d. Model results

Adding iceberg rolling Figure ? shows the

Figure 5: Antarctic GCM runs with and without rolling.

5. Conclusion

Since iceberg calving rates from Greenland and Antarctica appear to be accelerating, iceberg dynamics are seen increasingly to be an important process in the climate system, and hence it is paramount to develop a more comprehensive understanding of how icebergs drift and decay.

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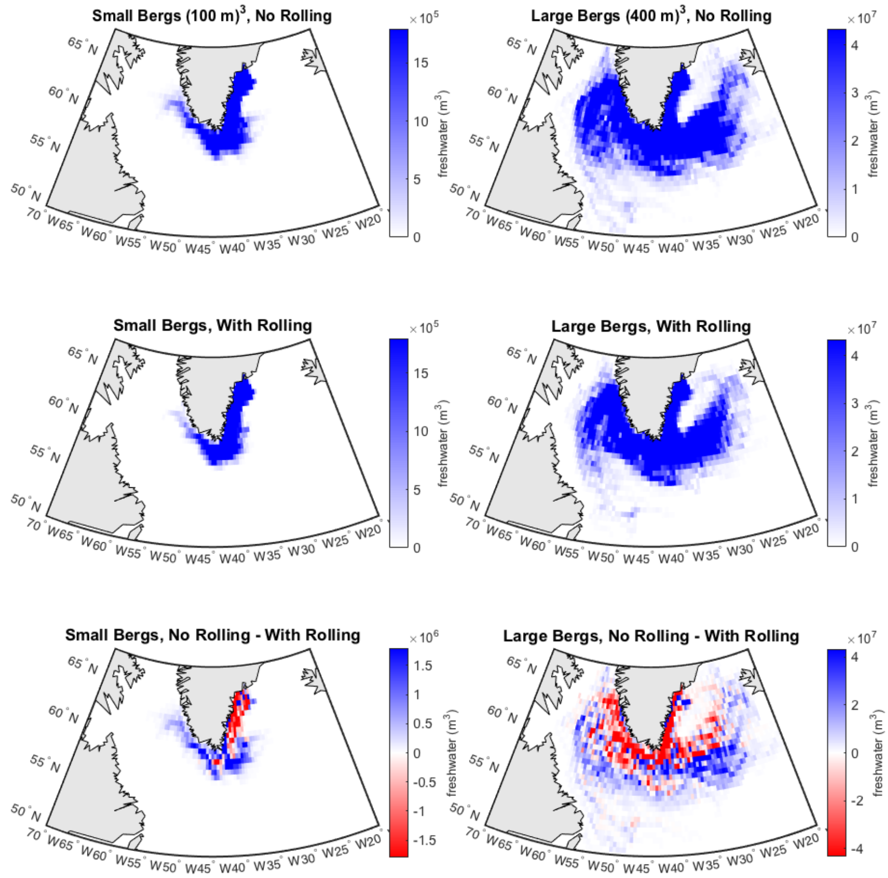

FIG. 3. Freshwater flux for small icebergs ($L_0 = 100$ m, left column) and large icebergs ($L_0 = 500$ m, right column), released near the outlet of Sermilik Fjord (red square). Shown are simulations without iceberg roll (first row), without iceberg roll (second row), and the difference (third row), which illustrates the further spread of freshwater from rolling icebergs.

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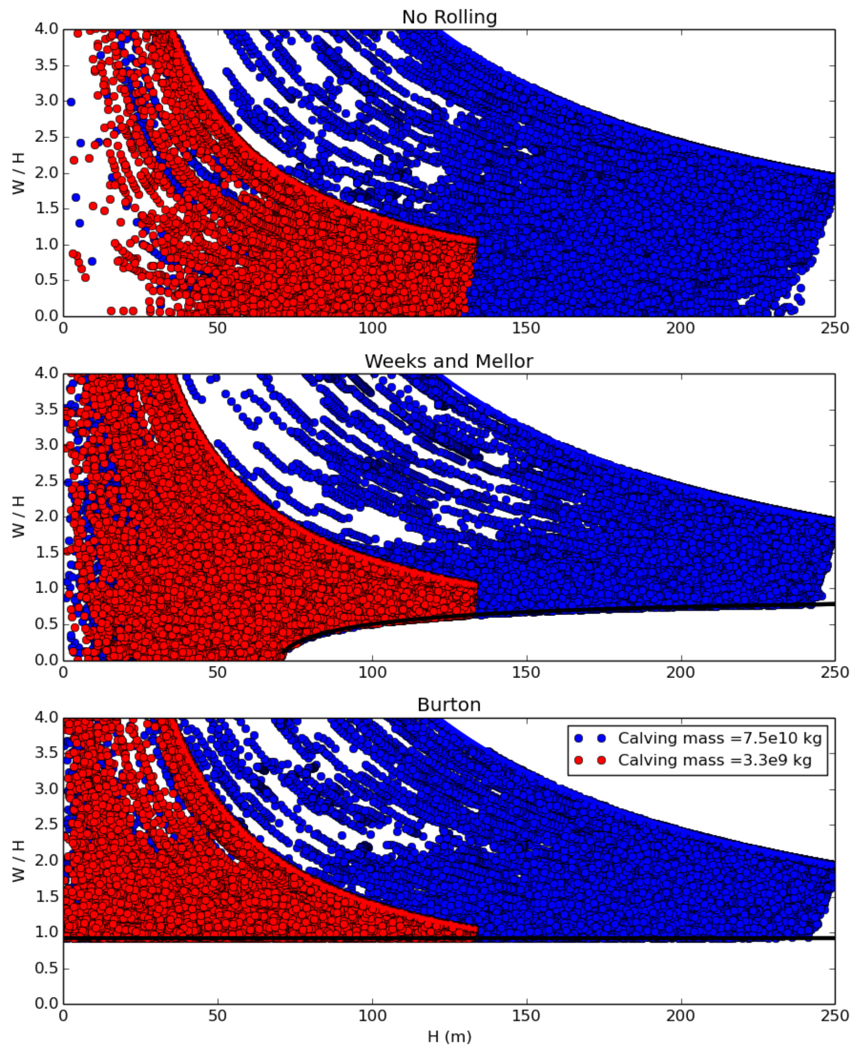

FIG. 5. The dimensions of icebergs all icebergs occurring in the simulations with (a) No rolling, (b) Weeks and Mellor rolling scheme ($\Delta = 6$ m), (c) Burton rolling scheme ($\Delta = 0$). The dimensions of icebergs are sampled monthly over a three year period. The red and blue dots are icebergs with an initial calving mass of 3.3×10^9 kg and 7.5×10^7 kg respectively. The rolling criteria $W/H = \sqrt{6\frac{\rho_i}{\rho_w}\left(1-\frac{\rho_i}{\rho_w}\right) - 12\frac{\rho_i}{\rho_w}\frac{\Delta}{H}}$ is plotted with a black line with (b) $\Delta = 6$ m and (c) $\Delta = 0$ m. The lines blue W/H=W_0/H are plotted for reference with (blue) $W_0 = 485.1$ m and (red) $W_0 = 139.5$ m, and indicate the limit where side melt is zero and basal melt is non-zero.

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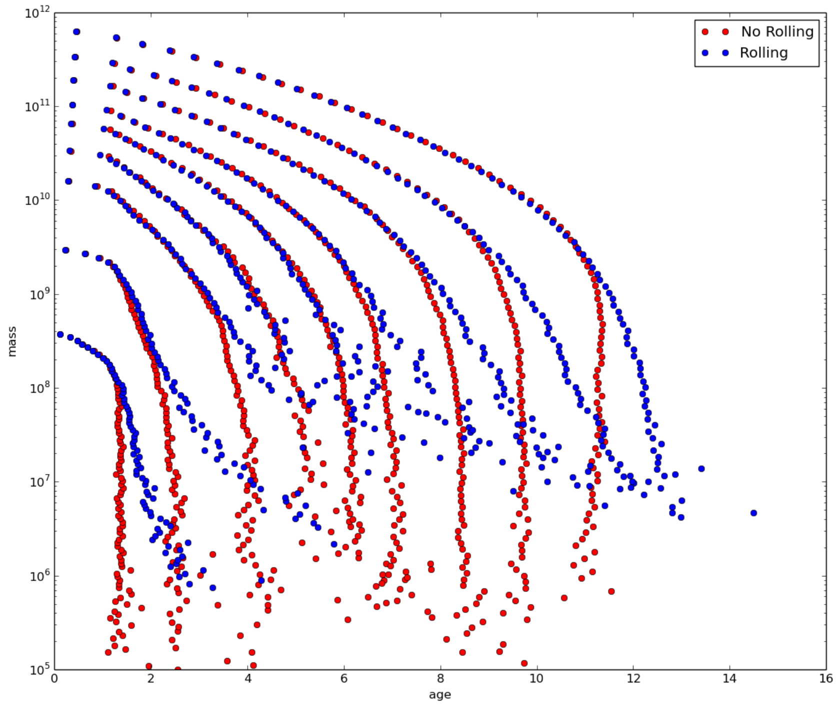

FIG. 6. Median age of icebergs of a given mass in simulations using (red) no rolling and (blue) Burton rolling scheme. The age and mass of all icebergs are sampled monthly over a period of 50 years.

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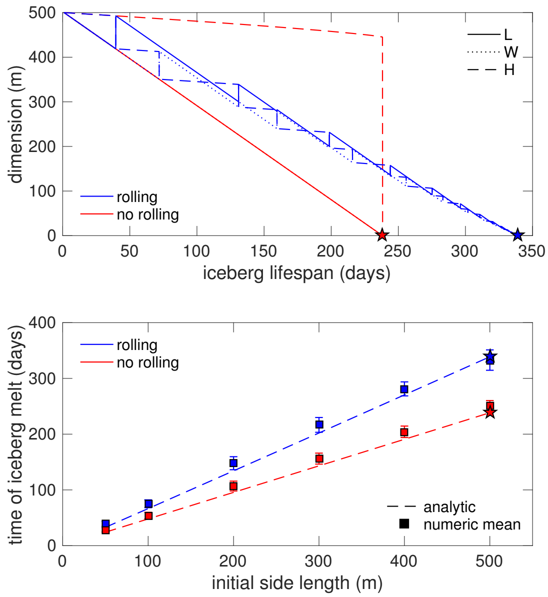

FIG. 4. (a) Reduction of iceberg dimensions over time. The iceberg is initialized as a cube of side length 500m. Melt rates are computed for fixed ocean, atmosphere, and ice conditions. We use the mean values experienced by icebergs released from Helheim Glacier in the numerical experiment. These are: $|v_a| = 5.7$ m/s, $|v_w - v_i| = 0.08$ m/s, and $T_w = 2.3°$C. $T_i = -4°$C is fixed in the original simulations. The red lines are the length, L (solid), W (dotted), and H (dashed) of the iceberg when no rolling occurs. L and W are identical in this case. It is readily appreciated that this scenario leads to unrealistic iceberg dimensions, with its height being increasingly larger than its horizontal dimensions. The tall, skinny iceberg is a result of the faster erosion rates of the sidewalls, compared to the bottom surface, and is statically unstable. The blue lines give the corresponding dimensions for the "rolling" scenario, where rolling is accounted for by swapping iceberg height and width when $H/W < \varepsilon_c$. This leads to L, W, and H being tightly coupled. We note that the rolling iceberg lives notably longer, with its time of melt at 341 days (blue star) compared to 244 days for the non-rolling case (red star). (b) Length of iceberg life as a function of initial iceberg size. The dashed lines give the analytic life spans for the mean climate conditions of (a). The red and blue stars for correspond to those of (a). The red and blue squares show the average lifespans of icebergs of different initial sizes as computed from the numerical simulations, where 500 icebergs of each size class were released near Helheim Glacier. The close correspondence between the analytical approximation and the numerical simulations shows that, in the long term mean, the numerical iceberg life span is similar to that obtained from the simplified analytic calculation. The errorbars indicate one standard deviation in the lifespan of individual icebergs. The divergence between the rolling and non-rolling lines entails that rolling has a greater impact for larger icebergs.

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