Supporting Information for "Effect of a Sheared Flow on Iceberg Motion and Melting"

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S1 Model Details

To supplement our observations of iceberg speed and draft range, we used a simplification of the canonical model of iceberg motion of *Bigg et al.* [1997] and *Gladstone et al.* [2001] to obtain the direction of iceberg motion and a single value of the draft for each iceberg that passed over the PIES. We assumed a one-dimensional along-fjord frame, in which icebergs were modelled as cuboids in steady state with the wind and ocean current forcing.

S1.1 Forcing Terms

Hydrographic surveys of Sermilik Fjord *Straneo et al.* [2010], the study site from which our data are drawn, show that variability predominantly occurs in the along-fjord direction, justifying the use of a one-dimensional frame. Further, except for a two-week period from 26$^{\text{th}}$ February to 10$^{\text{th}}$ March 2012, the region of the fjord containing the mooring was generally free from land-fast sea ice during the period of our study *Andres et al.* [2015]. The ice stress term $\vec{\tau_i}$ is negligible unless thick pack ice is present *Bigg* [2016], so given the lack of land-fast sea ice, τ_i is likely to be small throughout our study. Despite the absence of land-fast sea ice, satellite imagery during the study period shows that there was ice coverage of the fjord from drifting sea ice, bergy bits and icebergs at all times. This coverage acts to rapidly damp waves in the fjord, implying a small wave radiation force F_w. In general, the wave radiation force is thought to account for under 5% of the iceberg force balance in the Arctic *Bigg* [2016]. Finally, the pressure gradient force F_p results from the difference in surface pressure across the iceberg. While this is one of the dominant terms in the force balance of large tabular Antarctic icebergs *Bigg* [2016], we assume that it is relatively small for more moderately sized Greenlandic icebergs.

To determine the ocean forcing on the icebergs, it was necessary to prescribe an ocean velocity in the top 40 m of the water column, in which there is no ocean velocity data from the ADCP. To obtain the velocity in this layer, the velocity gradient in the three 10 m bins closest to the surface was extrapolated. If instead a constant velocity was assumed over the top 40 m of the water column, equal to the velocity in the shallowest ADCP bin, the correlation between the modelled and observed speeds drops from 0.80 to 0.76. There was therefore only a slight sensitivity of the data set as a whole to the method used to prescribe the surface layer velocity.

S1.2 Iceberg Shape

Two shapes of iceberg were considered; cuboid icebergs (which are equivalent to cylindrical icebergs in a one-dimensional model) and conical icebergs. For a cuboid iceberg of draft D, freeboard F and velocity u, the stress terms have the form

$$\tau_a = \rho_a C_a |u_a - u|(u_a - u)F, \quad (1)$$

$$\tau_o = \rho_o C_o \int_{-D}^{0} |u_o(z) - u|(u_o(z) - u)\,\mathrm{d}z. \quad (2)$$

The subscripts a and o indicate atmospheric and oceanic properties respectively, with ρ the fluid's density, and C the fluid's dimensionless drag coefficient. For a conical iceberg this is modified to

$$\tau_a = \rho_a C_a |u_a - u|(u_a - u)(DF + \tfrac{1}{2}F^2), \quad (3)$$

$$\tau_o = \rho_o C_o \int_{-D}^{0} (D - z)|u_o(z) - u|(u_o(z) - u)\,\mathrm{d}z, \quad (4)$$

where the freeboard F of the iceberg is calculated as the solution to $F^3 + 3DF^2 + 3D^2F - D^3/9 = 0$ to ensure that 90% of the iceberg's volume is submersed.

The modelling of icebergs as cuboids versus cones was assessed by comparing the fit between u_{obs} and u_{model} for these two shapes. It was found that cuboid shaped icebergs had a marginally better fit than conical ones (with correlation coefficients of 0.80 and 0.72 between the modelled and PIES-observed speeds, respectively), but this result suggested that the shape of icebergs is of second order importance, with the modelling of icebergs as cuboids being a reasonable assumption. There was likewise low sensitivity to the freeboard ratio $D/(F+D)$ within the plausible range of 0.8 to 0.9. In what follows, our modelling results assume a cuboid iceberg shape and a freeboard ratio of 0.8.

S1.3 Drag Coefficients

In addition to the effect of iceberg shape, the choice of drag coefficients was assessed. Traditionally, these have been based loosely on empirical observations of the drag coefficients for sea ice *Gladstone et al.* [2001], with $C_a = 1.3$ and $C_o = 0.9$ for the face of the ice orthogonal to the flow direction. In the steady state, which is governed by a balance between τ_o and τ_a, the drag coefficients only appear in the ratio C_o/C_a. The best correlation between the modelled and observed speeds (with correlation coefficient 0.8) occurred at $C_o/C_a = 0.75$, with this correlation dropping off to zero as the ratio decreased to zero, and asymptoting to 0.7 as the ratio tended to infinity. This asymmetry illustrates the dominance of ocean currents in determining iceberg motion. The values of the drag coefficients currently used in climate models ($C_o = 0.9$ and $C_a = 1.3$) give a ratio of $C_o/C_a = 0.69$, which is close to this best fit value, so we employ these values for the drag coefficients in our following modelling results.

The value of the drag coefficients is related to the time taken for the iceberg to reach steady state and be in equilibrium with the currents and wind, with larger drag coefficients leading to faster equilibration. Considering the spin-up from a simplified momentum equation $\mathrm{d}u/\mathrm{d}t = \tau_o/M$, an iceberg of aspect ratio 2 spins up to its steady state velocity on the timescale of a day or two with the choice of drag coefficients above. The highest correlation between the modelled and observed iceberg speeds was obtained when the ocean currents and surface winds were averaged over a period beginning only 6 hours before the observed passage

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0094-8276/16/$5.00

of the iceberg over the PIES and ending when the iceberg left the field of view of the sensor, rather than one to two days before the iceberg passed the PIES. Based on previous measurements of the ocean velocity during non-summer months *Jackson et al.* [2014], the circulation in Sermilik Fjord is dominated by shelf-forced flows, which have a timescale of several days. However, there are anomalies on top of the shelf-forced flow due to the tides and along-fjord winds *Oltmanns et al.* [2015]. Therefore in winter we expect the icebergs to have adjusted to the shelf-forced flows and consequently to be in steady state.

S2 Full Model Results

The distributions of the observed and modelled iceberg drafts and speeds are shown in Figure S1. The observed draft is the minimum possible iceberg draft, obtained by assuming the iceberg passed directly over the PIES. This is consequently skewed lower than the modelled iceberg draft with a mean of 149 m, compared to the modelled mean of 200 m. To model the iceberg draft, three drafts were considered for each observational record: the minimum possible iceberg draft associated with the iceberg passing directly over the sensor, the maximum possible iceberg draft associated with the iceberg passing tangentially to the ensonified region, and the mean of these two values. The modelled iceberg draft was taken as the one of these that gave a modelled speed closest to the observed speed. For icebergs with minimum drafts less than the critical value $d_{\rm lim}$ defined in *Andres et al.* [2015], their maximum draft was equal to $d_{\rm lim} = 252$ m. There is consequently a peak in modelled drafts around this value.

Panels C and D of Figure S1 show a fair qualitative agreement between the distribution of observed and modelled iceberg speeds. The correlation between the observed and modelled speeds is shown in full in Figure S2. The high correlation coefficient of 0.80 is supportive of the fact that a one-dimensional model of along-fjord winds and ocean currents is able to account for the leading order motion of icebergs in the fjord.

References

Andres, M., A. Silvano, F. Straneo, and D. R. Watts (2015), Icebergs and Sea Ice Detected with Inverted Echo Sounders, *Journal of Atmospheric and Oceanic Technology*, *32*(5), 1042–1057.

Bigg, G. R. (2016), The Physics of Icebergs, in *Icebergs: Their Science and Links to Global Change*, chap. 3 - pp. 52–81.

Bigg, G. R., M. R. Wadley, D. P. Stevens, and J. A. Johnson (1997), Modelling the dynamics and thermodynamics of icebergs, *Cold Regions Science and Technology*, *26*(2), 113–135.

Gladstone, R. M., G. R. Bigg, and K. W. Nicholls (2001), Iceberg trajectory modeling and meltwater injection in the Southern Ocean, *Journal of Geophysical Research*, *106*(C9), 19,903–19,915.

Jackson, R. H., F. Straneo, and D. A. Sutherland (2014), Externally forced fluctuations in ocean temperature at Greenland glaciers in non-summer months *Nature Geoscience*, *7*(7), 503-508.

Martin, T., and A. Adcroft (2010), Parameterizing the freshwater flux from land ice to ocean with interactive icebergs in a coupled climate model, *Ocean Modelling*, *34*(3-4), 111–124.

Oltmanns, M., F. Straneo, H. Seo, and G. W. K. Moore (2015), The Role of Wave Dynamics and Small-Scale Topography for Downslope Wind Events in Southeast Greenland, *Journal of the Atmospheric Sciences*, *72*(7), 2786–2805.

Savage, S. B. (2001), Aspects of Iceberg Deterioration and Drift, *Geomorphological Fluid Mechanics*, *582*, 279–318.

Straneo, F., G. S. Hamilton, D. a. Sutherland, L. a. Stearns, F. Davidson, M. O. Hammill, G. B. Stenson, and A. Rosing-Asvid (2010), Rapid circulation of warm subtropical waters in a major glacial fjord in East Greenland, *Nature Geoscience*, *3*(3), 182–186.

Sutherland, D. a., G. Roth, G. S. Hamilton, S. Mernild, L. a. Stearns, and F. Straneo (2014), Quantifying flow regimes in a Greenland glacial fjord using iceberg drifters, *Geophysical Research Letters*, *41*(23), 8411-8420.

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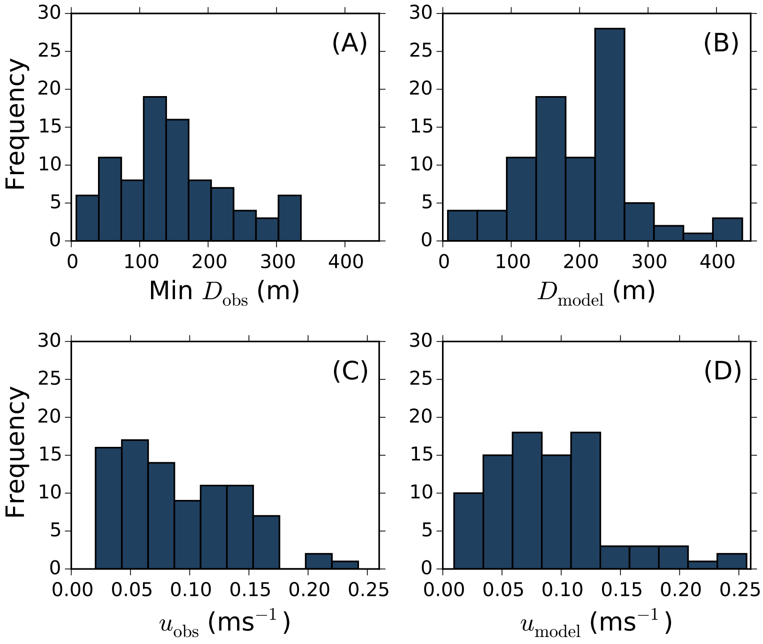

Figure S1. Distributions of observed and modelled iceberg speed and drafts: (A) Observed minimum iceberg draft; (B) modelled iceberg draft; (C) observed iceberg speed; and (D) modelled iceberg speed.

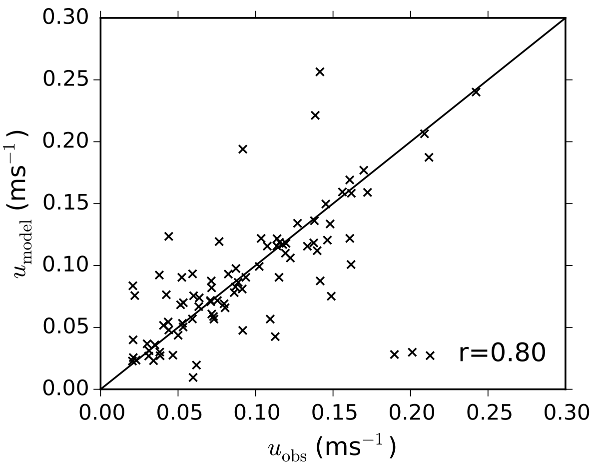

Figure S2. Correlation between observed and modelled iceberg speed, using the 1D simplified model of iceberg motion.