Title: ”Collaborative Research: Representing Calving and Iceberg Dynamics in Global Climate”
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Final report
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The project had three major goals: (1) development and testing of calving parameterizations; (2) developing a physically based iceberg –model component for inclusion in the large-scale ocean circulation model and implement it in the GFDL coupled climate model and (3) compilation of data sets of the glaciological and oceanographic observations relevant to calving. All these major goals have been achieved by the team. Several calving parameterizations have been developed by Co-PIs Basis (University of Michigan) and Amundson (University of Alaska Southeast). These parameterizations have been tested in a large-scale ice-sheet model by Co-PI Pollard (Pennsylvania State University) and in regional ice-flow models by PI Sergienko (Princeton University). A new, state-of-the-art framework for representation of icebergs (of any size) in a global circulation model has been developed, tested and implemented in the global ocean circulation model MOM6. Remote-sensing observations relevant to calving processes and icebergs have been compiled and analyzed by Co-PI Stearns (Kansas University).

2. Results and Accomplishments (Princeton University)
Development, evaluation and of a framework for iceberg representation and its coupling to a general ocean circulation model
A new, state-of-the-art framework for representation of icebergs in large-scale ocean models have been developed, tested and implemented in a GFDL ocean model MOM6, stand alone and as a part of a climate model. The framework is based on a collection of Lagrangian elements. The individual elements have a finite horizontal extent and can interact with each other via repulsive forces. Connecting these elements by numerical bonds allows to create structures with a much larger horizontal extent that can behave as large tabular icebergs, and in an extreme case, as ice shelves (Figure 1). By breaking these numerical bonds we can simulate calving of icebergs from ice shelves and break up of large tabular icebergs into smaller icebergs.

To demonstrate capabilities of this new framework we have used in several modes. In the first application described in Stern et al. (2016), the framework was used in global climate model simulations in a mode where Lagrangian particles do not interact with each. In these simulations we have investigated the effects of iceberg size distribution on the state of the Southern Ocean – its hydrography, fresh water transport, sea-ice formation, etc. The results of ensemble simulations (Figure 2) show that the iceberg size distribution significantly impact fresh-water flux distribution and water-mass formation around Antarctica water-mass formation and sea ice formation in the Southern Ocean. In the second application described in Stern et al. (2017), the framework was used to simulate, for the first time, calving of a large tabular iceberg that is submerged into the ocean from an idealized ice shelf, iceberg drift from the ice shelf, and consequent split of the iceberg into two smaller icebergs. Results of this study show that the developed framework is capable of simulating complex behavior of tabular icebergs from their

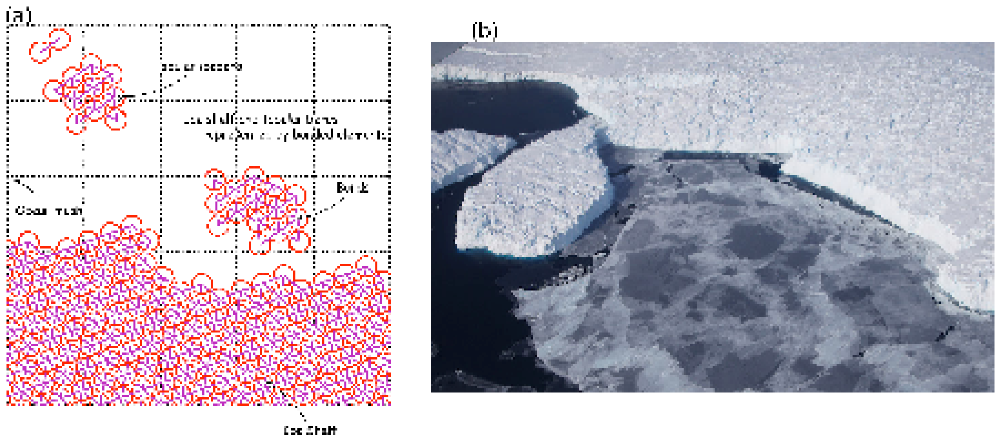

Figure 1. Schematic showing how an ice shelf and a tabular iceberg are constructed using Lagrangian elements. (a) Schematic of multiple ice elements jointed together by numerical bonds (magenta lines) to form large structures as tabulular icebergs and ice shelves. (b) Area photograph of an ice shelf and a tabular iceberg.

formation, as a result of the calving process, to their disintegration, due to break up into smaller icebergs, subsurface melting, wave erosion and other processes that contribute to iceberg decay. Results of this study also show that interactions of large tabular icebergs with surrounding ocean has significant effects on the ocean flow, vertical and horizontal mixing and water mass properties in the immediate vicinity of the iceberg and in its wake (Figure 3).

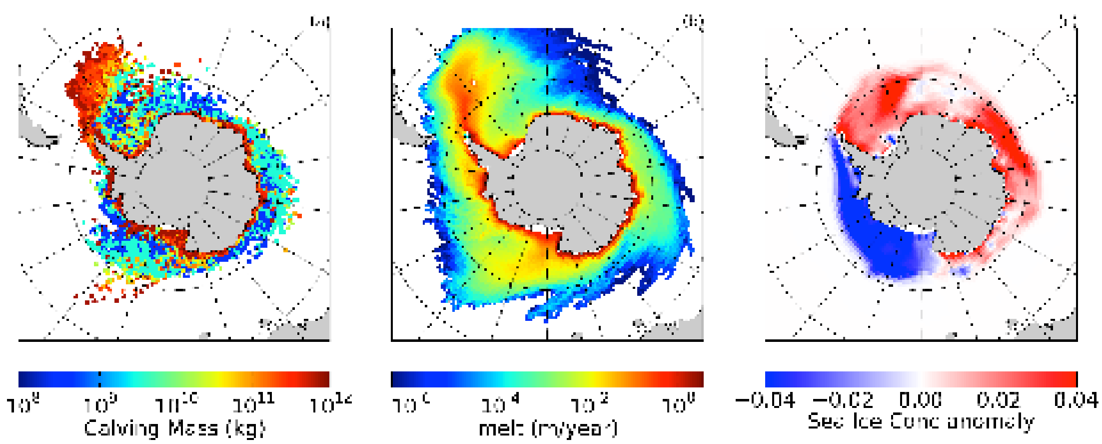

Figure 2. Results of the climate model simulations with the iceberg model component. (a) Positions of icebergs over a two year period, sampled monthly. The icebergs are colored according to their calving mass. (b) time-averaged iceberg melt-rate. (c) time-averaged sea-ice concentration anomaly relative to a simulation with no icebergs.

Another application of the framework (Stern et al., 2018) is aimed to investigate the effects of iceberg calving on the ocean circulation in the ice shelf cavity and sub-ice-shelf melting rates. In this application, the ice shelf is represented by the Lagrangian elements connected by numerical bonds, similar to the representation of a large tabular iceberg. The results of the study show that both calving process and iceberg drift affect the

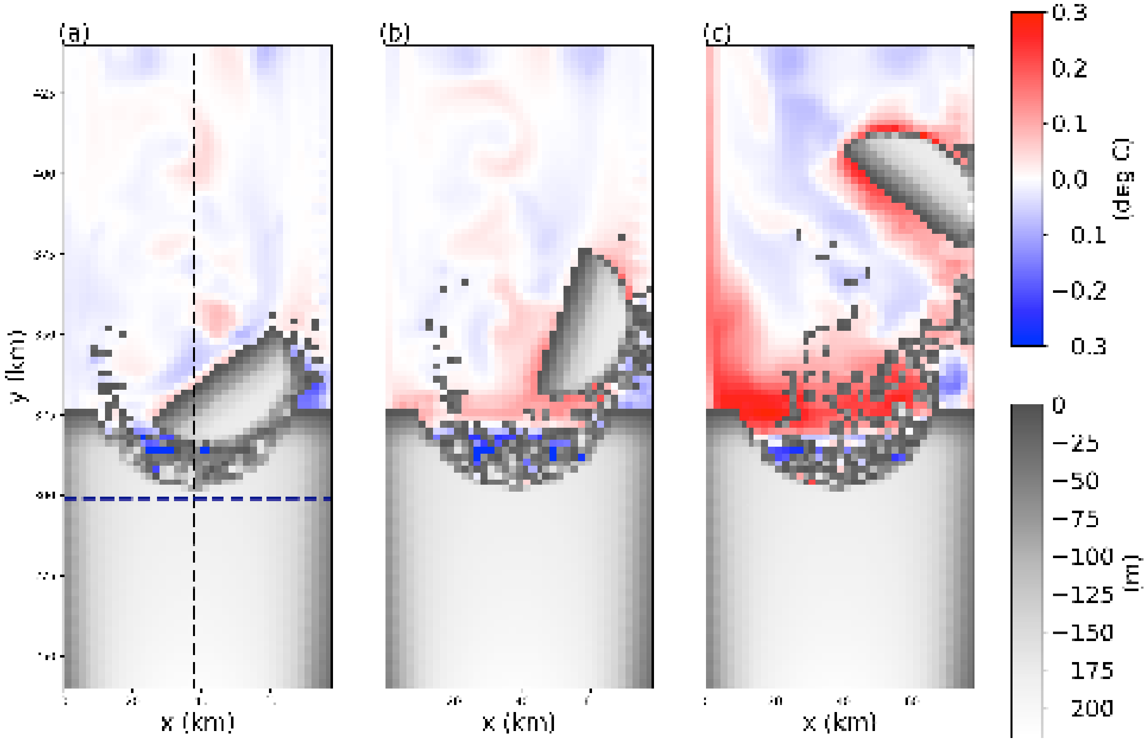

Figure 3. Snapshots of sea surface temperature anomalies in a model simulation of iceberg calving. Snapshots are taken (a) 7, (b) 15, and (c) 50 days after calving.

sub-ice-shelf cavity circulation, which in its turn cause reduction of sub-ice-shelf melting. The results of simulations suggest complex interactions between calving process, sub-ice-shelf cavity circulation and sub-ice-shelf melting.

Development of a theoretical framework for evaluation of calving effects on ice discharge through the grounding line

Iceberg calving alters not only ocean circulation in the ice-shelf cavity and its vicinity, but it also alters the ice-shelf stress regime that controls the rate of ice discharge from the grounded parts of an ice sheet into floating ice shelves. To investigate the effect of calving process on mass discharge through the grounding line, a new theory has been developed (Haseloff and Sergienko, 2018). This theory suggest that calving can strongly influence the stability of grounding lines of ice sheets whose bedrock becomes deeper towards the interior, similar to the West Antarctic Ice Sheet. Depending on calving conditions, the grounding lines of laterally confined ice shelves can be stable or unstable. Calving parameterizations developed in the course of the project have been applied to investigate their effects on stability of the grounding line and the rate of ice discharge into surrounding ocean.

The effects of ocean waves on ice shelves

Ocean waves continuously impact ice shelves and affect their stress regime. The flexural stresses that are caused by the impact of ocean waves can contribute to ice fracturing and rift development that eventually result in iceberg calving (Sergienko, 2017). The ocean waves excite flexural gravity waves that represent coupled motion in the water of the cavity and the ice covering above. Theoretical and numerical studies of the propagation of flexural gravity waves suggest that they propagate as focused beams. The location of these beams coincide with large gradients in the water column depth in the sub-ice-shelf cavity, suggesting that the ocean bathymetry and the ice-shelf base can focus the ocean wave energy and cause fracturing of an ice shelf. These results shed lights on formation and evolution of crevasses and rifts.

3. Highlights of Accomplishments

- A Lagrangian framework for representaion of icebergs and ice shelves has been developed. This framework can be used to represent icebergs of various sizes. It can simulate a lifecycle of an iceberg – from its formation as a result of calving process to its complete disintegration as a result of breakup to smaller icebergs, melting and decay due to wave errosion.

- The Lagrangian framework has been coupled to a global ocean circulation model (MOM6). The two-way coupling between this framework and the ocean circulation model for the first time allows to realsitically simulate behavior of large tabular icebergs submerged into the ocean.

- A new theory for assements of the calving impact on the ice discharge through the grounding line has been developed. This theory allows to compute ice flux from the grounded parts of an ice sheet into the ocean for different calving conditions. Analysis of the ice-sheet grounding line stability suggests that hat calving can have strong effects on stability of the grounding lines.

4. Publications from the Project (Princeton University)

Stern, A. A., A. Adcroft, and O. Sergienko (2016), The effects of Antarctic iceberg calving-size distribution in a global climate model, *J. Geophys. Res. Oceans*, 121, 5773–5788, doi:10.1002/2016JC011835.

Stern, A. A., A. Adcroft, O. Sergienko and G. Marques (2017), Modeling tabular icebergs submerged in the ocean, *J. Adv. Model. Earth Syst*., 9, 1948–1972, doi:10.1002/2017MS001002

Sergienko O.V. (2017) Behavior of flexural gravity waves on ice shelves: Application to the Ross Ice Shelf, *J. Geophys. Res. Oceans*, 122, 6147–6164, doi:10.1002/2017JC012947.

Haseloff, M., and O. V. Sergienko (2018), The effect of buttressing on grounding line dynamics, *J. Glaciol*., 65(243), doi:10.1017/jog.2018.30.

Fyke, J., Sergienko, O., Löfverström, M., Price, S., & Lenaerts, J. T. M. (2018). An overview of interactions and feedbacks between ice sheets and the Earth system. *Reviews of Geophysics*, 56, 361–408. https://doi.org/10.1029/2018RG000600

Stern, A. A., A. Adcroft, O. Sergienko and G. Marques (2018), Modeling large tabular icebergs and ice-shelf cavities using Lagrangian elements (in preparation).

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