Simulating marine ice sheets with the Community Ice Sheet Model

William Lipscomb[1], Gunter Leguy[2], Xylar Asay-Davis[3]

[1] Climate, Ocean, Sea-ice and Ice-sheet Modeling, Los Alamos National Laboratory, [2] Department of Mathematics and Statistics, University of New Mexico, [3] Potsdam Institute for Climate Impact Research (PIK)

Abstract

Version 2 of the open-source Community Ice Sheet Model (CISM) includes a higher-order velocity solver. CISM uses finite-element methods on a structured grid to solve several sets of flow equations, including the shallow-shelf approximation (SSA), a higher-order depth-integrated-viscosity approximation (DIVA), and the Blatter-Pattyn approximation.

We have applied CISM to several test problems of the Marine Ice Sheet Model Intercomparison Project (MISMIP) and the Marine Ice Sheet–Ocean Model Intercomparison Project (MISOMIP). Here we show results for MISMIP3d (part of MISMIP) and MISMIP+ (the ice-sheet component of MISOMIP). Using a subgrid grounding-line parameterization (GLP), simulations at moderate resolution (~1 km) agree well with published benchmarks. For flow on a downward-sloping bed, SSA results are in good agreement with the boundary-layer solution of Schoof (2007). For cases with basal-sliding perturbations, CISM successfully simulates reversible migration of curved grounding lines. Without a GLP, much higher resolution is needed for similar accuracy. These results suggest that a resolution of ~1 km may be sufficient for accurate simulation of whole marine ice sheets.

MISMIP3d and MISMIP+

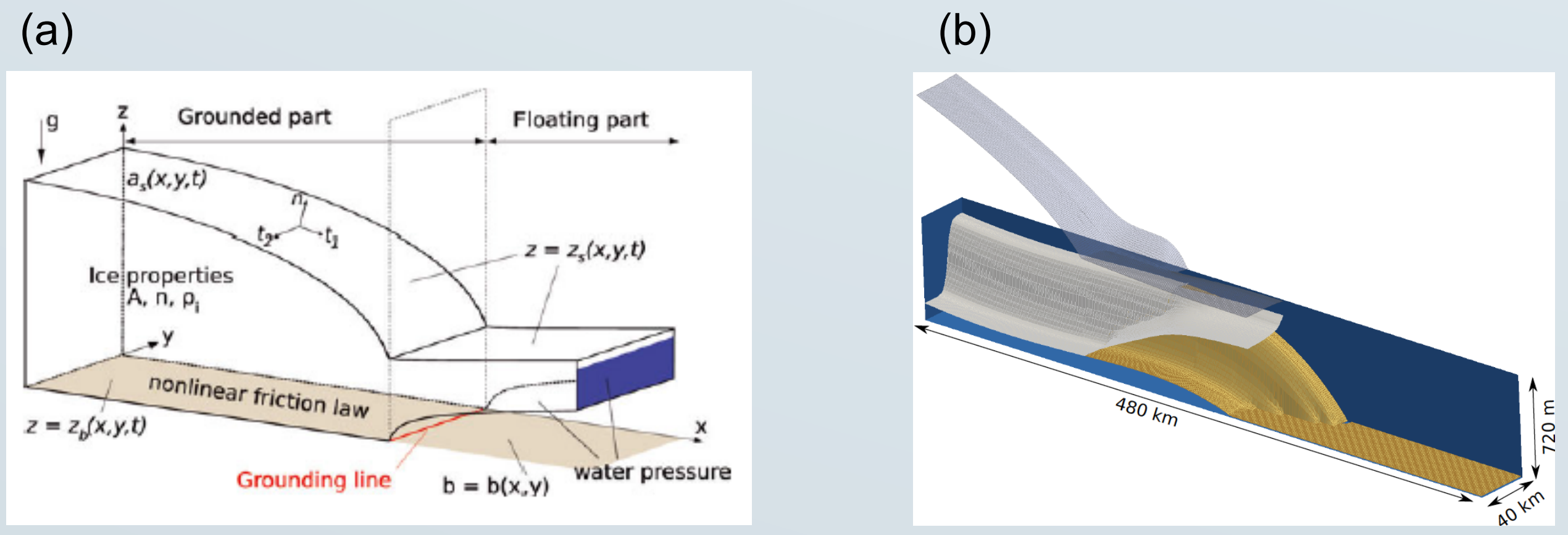

Fig. 1: (a) Schematic setup for (a) MISMIP3d and (b) MISMIP+.

MISMIP (Pattyn et al. 2012) and MISMIP3d (Pattyn et al. 2013) test the ability of marine ice-sheet models to simulate grounding-line migration. Flow is in the *x* direction from a grounded ice sheet onto a floating shelf (Fig. 1a). The basal stress is discontinuous at the grounding line. For the experiments shown here, the bed geometry is linear, implying that there is a unique steady-state grounding-line position for a given set of input parameters (Schoof 2007). MISMIP3d includes perturbation experiments with a spatially varying basal traction field to generate curved grounding lines with buttressing effects. Fixed-grid models with grid resolution of ~1 km typically make large errors compared to the analytic solution unless a GLP is used (Leguy et al. 2014).

MISMIP+ (Asay-Davis et al. 2015) includes a set of ice-sheet-only experiments with idealized bed topography (Fig. 1b) and forcing. These experiments complement ocean-only (ISOMIP+) and ice-sheet/ocean coupled (MISOMIP1) experiments. The ice sheet is run to steady state without basal melting, then is forced to retreat by strong sub-shelf melting, and finally is allowed to re-advance with the melting turned off.

Grounding Line Parameterization

CISM2 (http://oceans11.lanl.gov/cism/) is a 3D, parallel, higher-order ice sheet model that runs on a rectangular horizontal mesh. We plan to use CISM2 for whole-ice-sheet simulations that are cost-prohibitive at resolutions finer than ~1 km. In order to robustly simulate grounding-line migration at this resolution, we have developed a GLP based on Gladstone (2010), but extended to a 2D bed. As in Seroussi et al. (2014), the basal traction is weighted by the grounded ice fraction in the cell surrounding a velocity point.

A GLP greatly improves accuracy at a given resolution when there is a discontinuous transition in basal friction at the grounding line. The GLP in CISM can be used with three flow approximations: (1) SSA, (2) DIVA (Goldberg 2011), or (3) Blatter-Pattyn (Pattyn 2003).

MISMIP3d Results

The SSA assumes that vertical shear stresses are negligible compared to horizontal-plane stresses. If the GLP works well, CISM results with the SSA should be close to the benchmark solutions of Schoof (2007). The upper panels of Fig. 2 show results for MISMIP3d. Without a GLP (left), the steady-state grounding line (before applying a basal perturbation) lies at 515 km, ~100 km from the benchmark solution. It advances by ~20 km but retreats only ~10 km. With a GLP (right), the initial steady state is at 598 km, only 13 km from the benchmark of ~611 km, and the motion is reversible as desired.

The lower panels of Fig. 2 show MISMIP3d results for DIVA, with and without a GLP. DIVA results are similar to Blatter-Pattyn (not shown) but are less computationally costly by an order of magnitude. Without a GLP, the grounding line initially lies at 505 km and fails to return to its starting position. With a GLP, the grounding line starts at 558 km, about 40 km upstream of the initial SSA position. The flow is reversible in agreement with theory. No analytic benchmark is available, but the steady-state grounding line lies at 537 km for a Stokes model, Elmer/Ice (Pattyn et al. 2013).

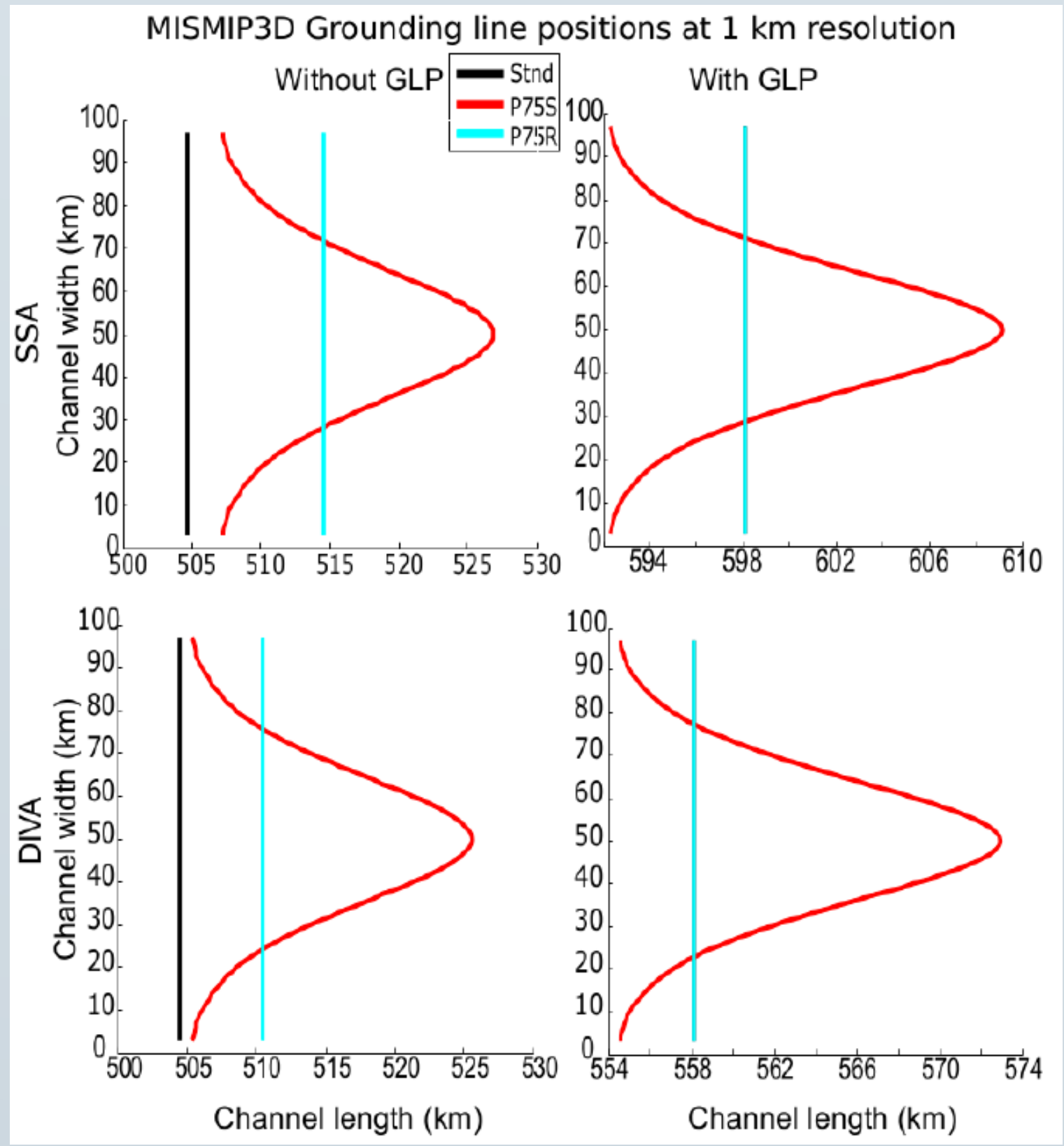

Fig. 2: MISMIP3d results using the SSA (top) and DIVA (bottom) stress approximations at 1 km resolution, without (left) and with (right) a GLP. The black line shows the initial steady state; the red line shows the position of maximum advance; and the turquoise line shows the retreated position. With a GLP the initial and retreated positions coincide, showing reversibility.

MISMIP+ Results

Fig. 3 shows the magnitude of the basal traction for various stages of MISMIP+ Experiment Ice1, which consists of 100 years of retreat driven by strong basal melting, followed by 900 years of re-advance with melting turned off. CISM was run at 2-km resolution using the SSA with a basal traction law that transitions from power-law to Coulomb behavior near the grounding line (Tsai et al. 2015). Results using DIVA (not shown) are similar, since the flow has little vertical shear.

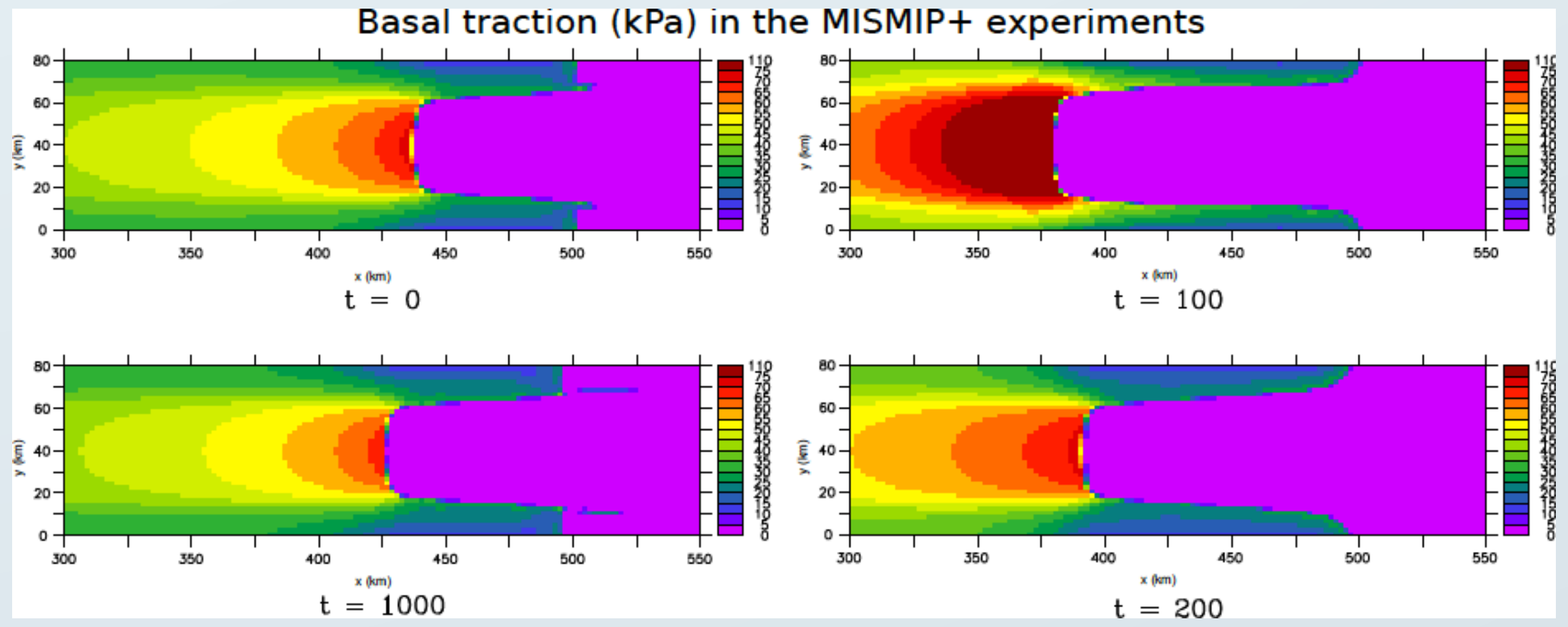

Fig. 3: Basal traction (kPa) for MISMIP+ Experiment Ice1. Clockwise from the upper left panel, the traction is shown (1) at t = 0 yr, after a long spin-up to steady state; (2) at t = 100 yr, following retreat forced by sub-shelf melting, (3) at t = 200 yr, after re-advance without subshelf melting, and (4) at t = 1000 yr, after further re-advance. Cf. Fig. 2 of Asay-Davis et al. (2015).

Future Work

These results suggest that DIVA with a GLP at 1-km resolution is an attractive option for simulating marine ice sheets with physics similar to MISMIP3d. Next, we will test CISM for more realistic geometries, including the whole Antarctic ice sheet. To improve efficiency and realism, CISM developers are working on more efficient, scalable preconditioners; implicit methods for thickness evolution to allow a longer time step; and a damage-based scheme for iceberg calving.

References

Asay-Davis, X. S., et al.: Experimental design for three interrelated Marine Ice-Sheet and Ocean Intercomparison Projects, Geosc. Model Dev. Discuss., 8, 9859-9924, 2015.

Gladstone, R. M., Payne, A. J., Cornford, S. L.: Parameterising the grounding line in flow-line ice sheet models, The Cryosphere, 4, 605–619, 2010.

Goldberg, D. N.: A variationally derived, depth-integrated approximation to a higher-order glaciological flow model, J. Glaciol, 57, 157–170, 2011.

Leguy, G. R., Asay-Davis, X. S., Lipscomb, W. H.: Parameterization of basal friction near grounding lines in a one-dimensional ice sheet model, The Cryosphere, 8, 1239–1259, 2014.

Pattyn, F.: A new three-dimensional higher-order thermomechanical ice sheet model: basic sensitivity, ice stream development, and ice flow across subglacial lakes, J. Geophys. Res, 108, 2382, 2003.

Pattyn, F., et al.: Results of the Marine Ice Sheet Model Intercomparison Project, MISMIP, The Cryosphere, 6, 573–588, 2012.

Pattyn, F., et al.: Grounding-line migration in plan-view marine ice-sheet models: results of the ice2sea MISMIP3d intercomparison, J. Glaciol., 59, 2013.

Schoof, C.: Ice sheet grounding line dynamics: steady states, stability, and hysteresis, J. Geophys. Res, 112, F03S28, 2007.

Seroussi, H., et al.: Hydrostatic grounding line parameterization in ice sheet models, The Cryosphere, 8, 2075-2087, 2014.

Tsai, V. C., Stewart, A.L., Thompson, A. F.: Marine ice-sheet profiles and stability under Coulomb basal conditions, J. Glaciol., 61 (226), 2015.