Understanding the Implications of Using the Shallow Shelf Approximation for Marine Ice Sheets

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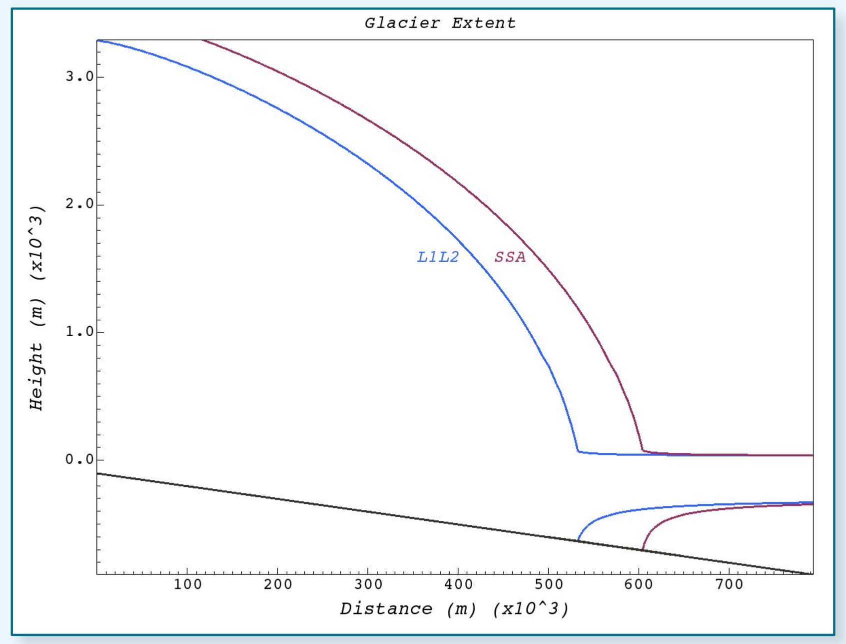
THE EXPERIMENT

The MISMIP3D experiment was an intercomparison project that compared multiple plan-view marine ice sheet models and assessed their ability to represent grounding line migration. The participating models varied among discretization used as well as other factors such as approximation (to the full-Stokes equations) and spatial resolution. Specific model parameters were prescribed for the experiment that the models used to set up their simulations and it was observed that the steady-state grounding line positions produced from models using SSA varied wildly compared to the higher-order models such as L1L2 and the full-Stokes models. A main question since then has been left unanswered:

"...in a realistic simulation with the model parameters chosen to match geometry and velocity derived from observations, and thus with prescribed initial conditions, does the SSA provide a good approximation to the Stokes model?" (Asay-Davis et al., 2016)



Steady-State grounding line positions for L1L2 and SSA from the MISMIP3D experiment

We tackle this question in this experiment by treating MISMIP3D like a ***realistic*** modeling problem rather than use pre-determined parameters. We use the steady-state L1L2 intial grounding line results as "observations" and solve for the needed parameters through an inversion to initialize the SSA model in question. The inverted parameters are then tested to verify their efficacy in reproducing the initial steady-state grounding line, and finally, we introduce a perturbation to observe the model's dynamic response.

INVERSION PROBLEM

Inverse methods are used to determine parameters that are naturally difficult or impossible to observe directly. Information from a known system can be used to tune the parameters of a model such that the model matches what is known. In this case, we use our chosen L1L2 observations as known input and search for the basal friction coefficient C(x,y) and viscosity coefficient φ(x,y) to tune our SSA model such that the difference between the known velocities and modeled velocities is minimized.

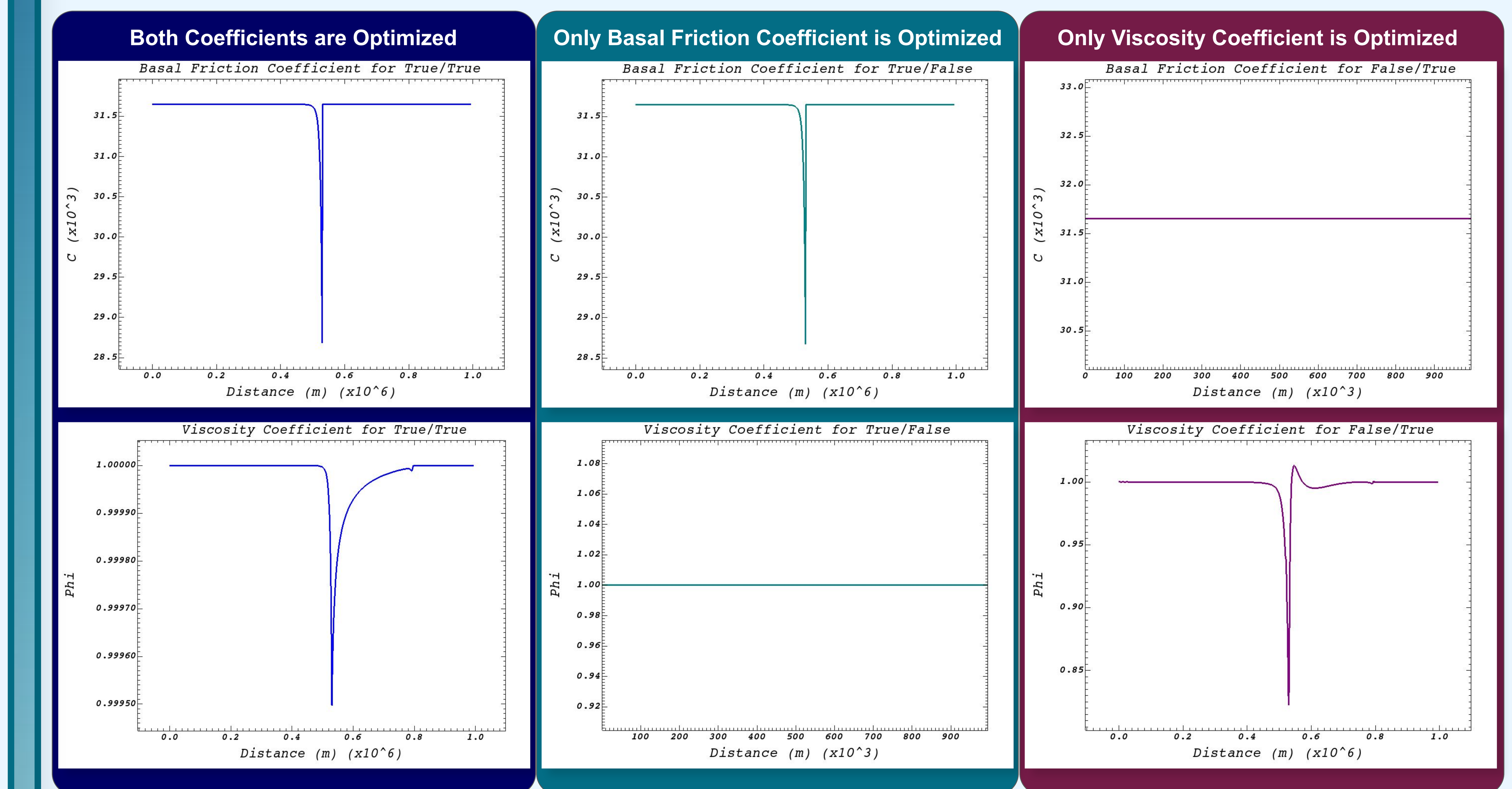
$$J = J_m + J_p$$

$$J_m = \frac{1}{2}\int_{\Omega_V} \alpha_u^2(x,y)(|\boldsymbol{u}| - |\boldsymbol{u}_o|)^2 \, d\Omega$$

$$J_p = \frac{\alpha_C^2}{2}\int_{\Omega_V} |\nabla C|^2 \, d\Omega + \frac{\alpha_\phi^2}{2}\int_{\Omega_V} |\nabla \phi|^2 \, d\Omega$$

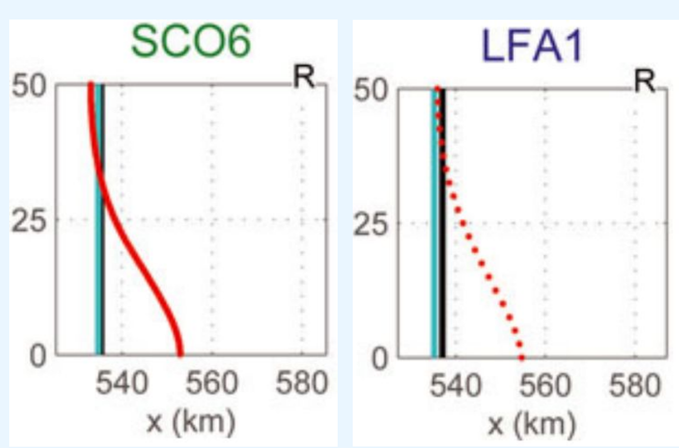
Our goal is to choose a basal friction and viscosity coefficient that will minimize the objective function J. With two parameters to tune, this can be done in **three** ways. The results from each of the inversion solves are shown to the right.

INVERSION RESULTS



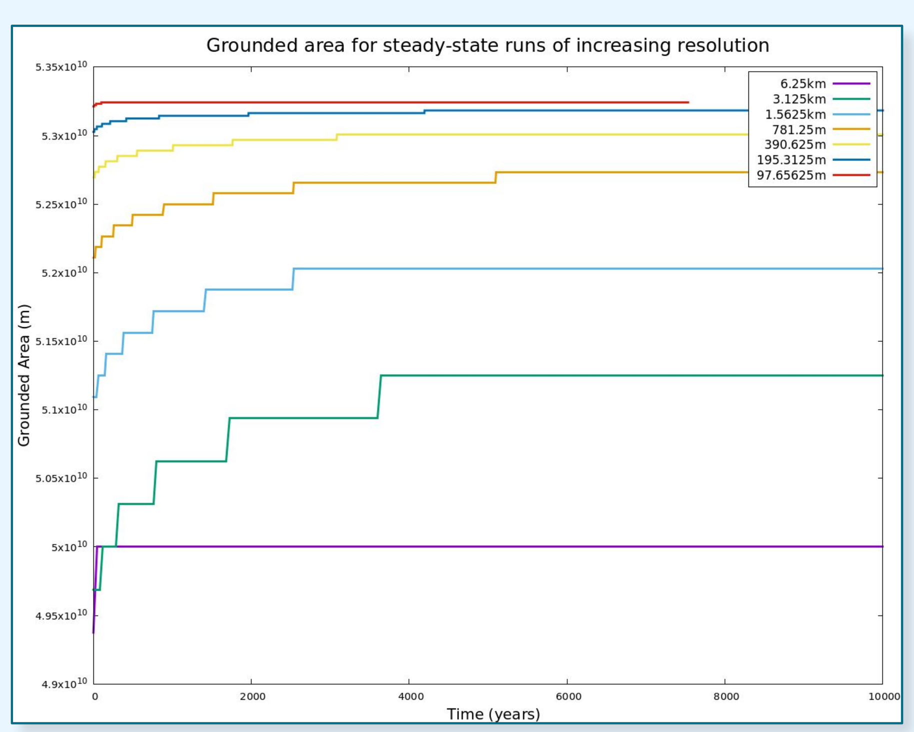
GENERATING OBSERVATIONS

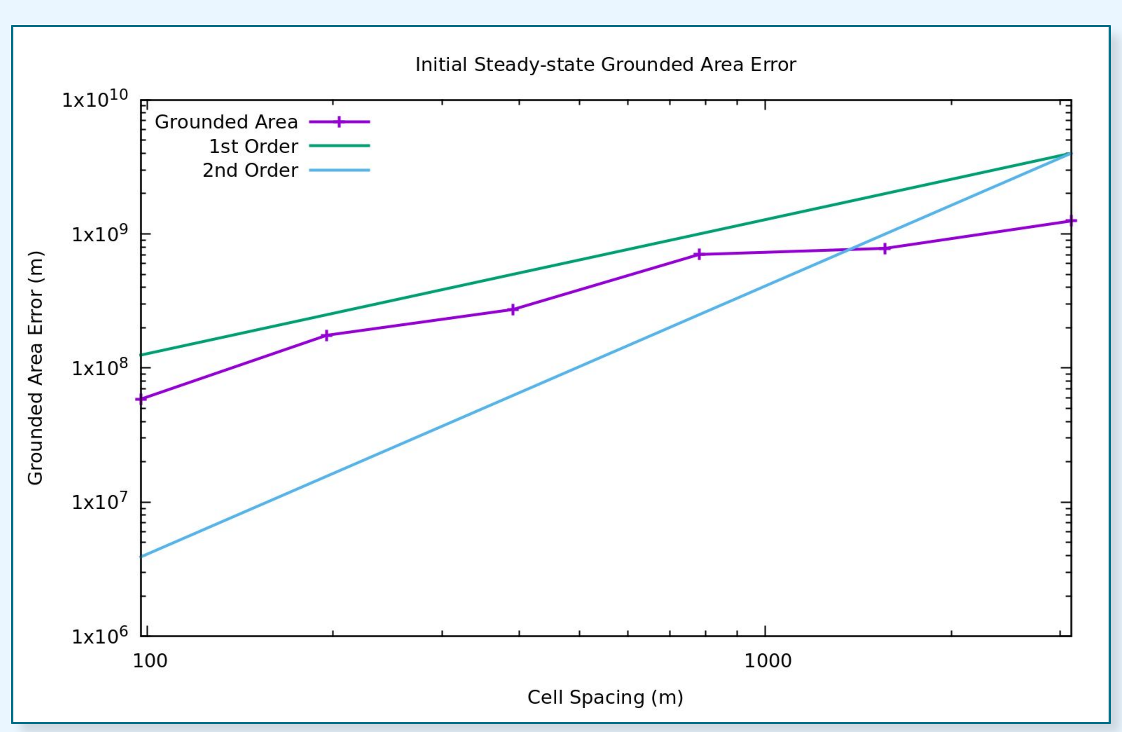
To ensure accurate projections of future ice sheet behavior, ice sheet models rely on real-world observations for input. Similarly, for this experiment, we need "real observations" in order to initialize our SSA model. The L1L2 results from the MISMIP3D experiment closely align with that of the Full-Stokes model (the gold standard for modeling flow) and thus provide a good basis for the experiment.



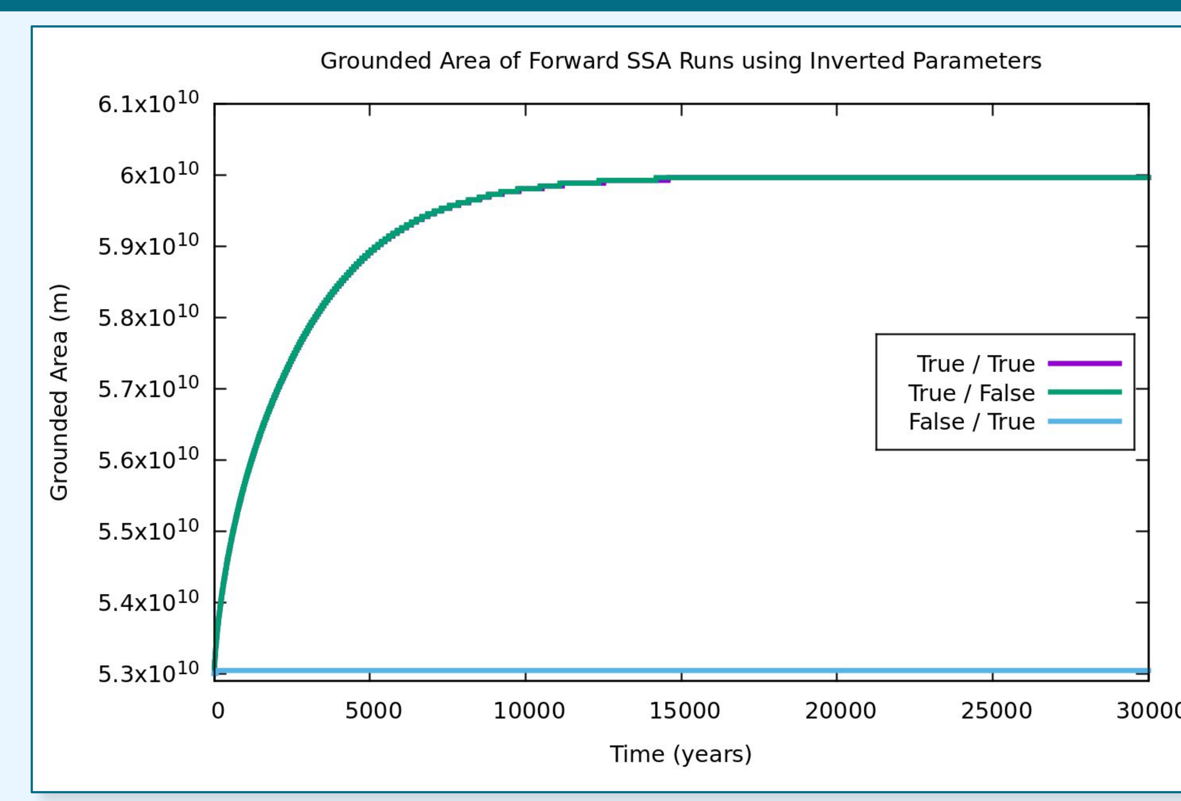
(Left) MISMIP3D grounding line positions for the BISICLES L1L2 model (SC06) compared to the Elmer/Ice Full-Stokes model (LFA1). The steady-state grounding line (black line) in both simulations are almost nearly identical and thus, the L1L2 approximation provides a good starting point that is inexpensive computationally compared to a Full-Stokes model.

Using the same problem specification as MISMIP3D, multiple steady-state L1L2 runs were generated with increasing levels of refinement using the BISICLES adaptive mesh refinement (AMR) model up to a resolution of ~97 meters. The grounded area begins to converge towards some value and the error of the grounded area enters the asymptotic regime at sub-kilometer levels of refinement. This shows that our model is behaving as expected. The L1L2 steady-state results at a spatial resolution of 390.625 meters are chosen as the observations for the inversion





STABLE STEADY STATE?

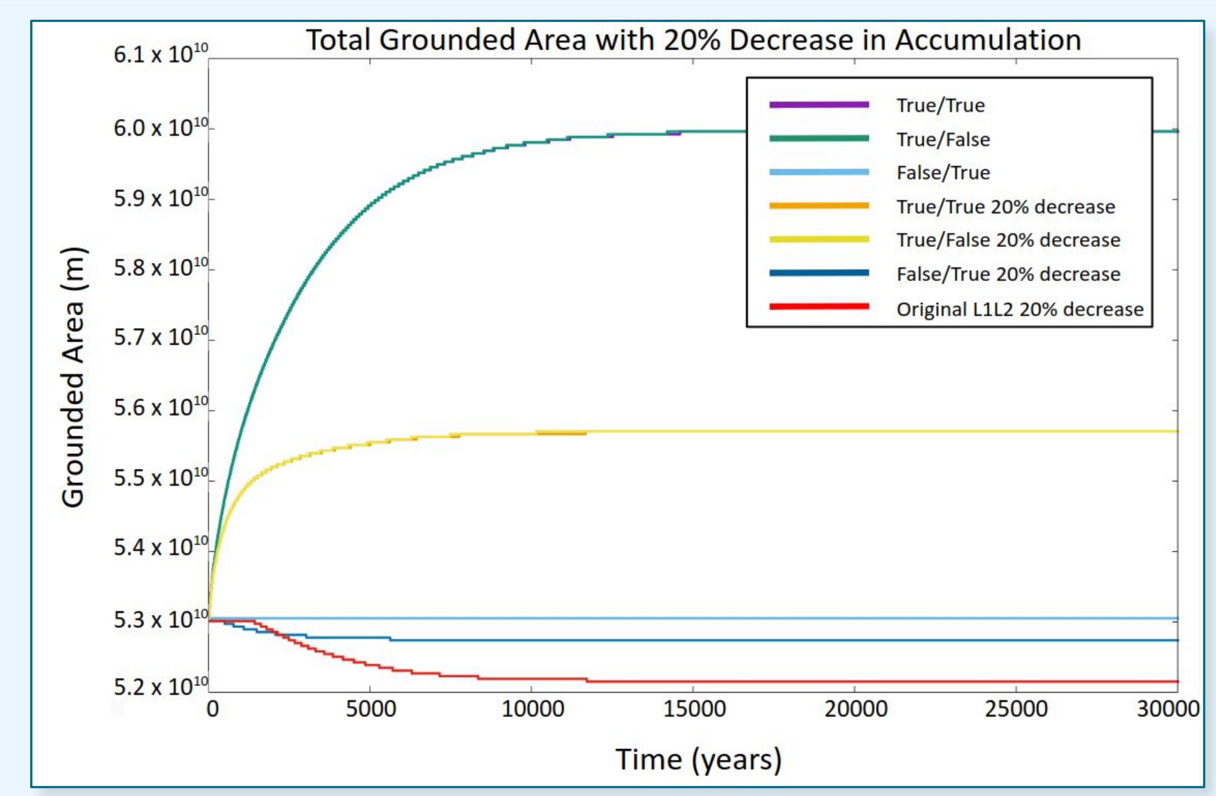


Forward runs of the initialized SSA models using the inverted parameters from each optimization scheme. True/True corresponds to the case where both coefficients are optimized in the inversion solve, True/False is the case where only basal friction is optimized, and False/True is the case where only the viscosity coefficient is optimized

Using the inverted parameters that were previously solved for, the SSA model is initialized and allowed to run for 30,000 years. For the cases where the basal friction coefficient was optimized in the inversion solve, the SSA model **fails** to maintain the initial steady-state grounding line position as shown by the green and purple lines. These lines describe the behavior in which the grounding line "fell off" the steep spike in basal friction and was then allowed to find a new steady-state position. The new steady-state position found is the original SSA steady-state grounding line position.

The case where only the viscosity coefficient was optimized **succeeded** in maintaining the steady-state grounding line position shown by the flat blue line in the above figure.

PERTURBATION and RESULTS



The response of the original L1L2 observations shows a steeper drop in total grounded area compared to the response of the case where only the viscosity coefficient was optimized, which was the only case successful in reproducing the initial steady-state grounding line position. Unfortunately, here, it failed at matching the dynamic response.

Accumulation was decreased by 20% in the above perturbation experiment to observe the dynamic response of the models. The case where only the viscosity coefficient was optimized was successful in reproducing the initial steady-state grounding line, however, here it failed at predicting the dynamic response. The model overpredicts the total grounded area as shown above in the dark blue line compared to the expected red line showing the L1L2 response. The other cases similarly failed which was expected since they failed to initially reproduce the initial steady-state grounding line position.

CONCLUSION: The narrow basal friction coefficient values made it impossible to force the SSA model to match the L1L2 steady-state grounding line, whereas the case where only the viscosity coefficient was optimized allowed for a successful match. However, it subsequently failed at predicting the dynamic response primarily because of the fact that the inverted viscosity coefficient is time-independent. Overall, by treating MISMIP3D like a real-world problem, we were unable to get the SSA model to behave as expected. Future plans include adding ice-shelf buttressing using the MISMIP+ set up to try to better match the initial steady-state position as well as exploring a real-world scenario such as the Amundsen Sea Embayment containing the Thwaites and Pine Island Glaciers.