# MPAS-ALBANY LAND ICE (MALI): A VARIABLE-RESOLUTION ICE SHEET MODEL FOR EARTH SYSTEM MODELING USING VORONOI GRIDS

Researchers created MPAS-Albany Land Ice (MALI) v6.0, as a new, high-fidelity, variable-resolution ice sheet model for use on high-performance computing architectures and for coupling to the U.S. Department of Energy's new Energy Exascale Earth System Model (E3SM). The resulting new system paves the way for significant advances in research on how sea levels may evolve over coming decades.

During the past 10 years, numerical ice sheet models (ISMs) have undergone a renaissance relative to their predecessors. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4, 2007) pointed to deficiencies in ISMs of the time as being the single largest shortcoming with respect to the scientific community's ability to project future sea level rise stemming from ice sheets. The IPCC AR5 (2013) argues that the sea level contribution from Antarctica remains the single largest source of uncertainty when trying to assess the likelihood and range of future sea level rise. While model maturation efforts over the past decade represent significant steps forward, next-generation ISMs continue to confront new challenges – like the need for a spatial resolution of ~1 km in highly dynamic regions – that require them to be both accurate and computationally efficient.

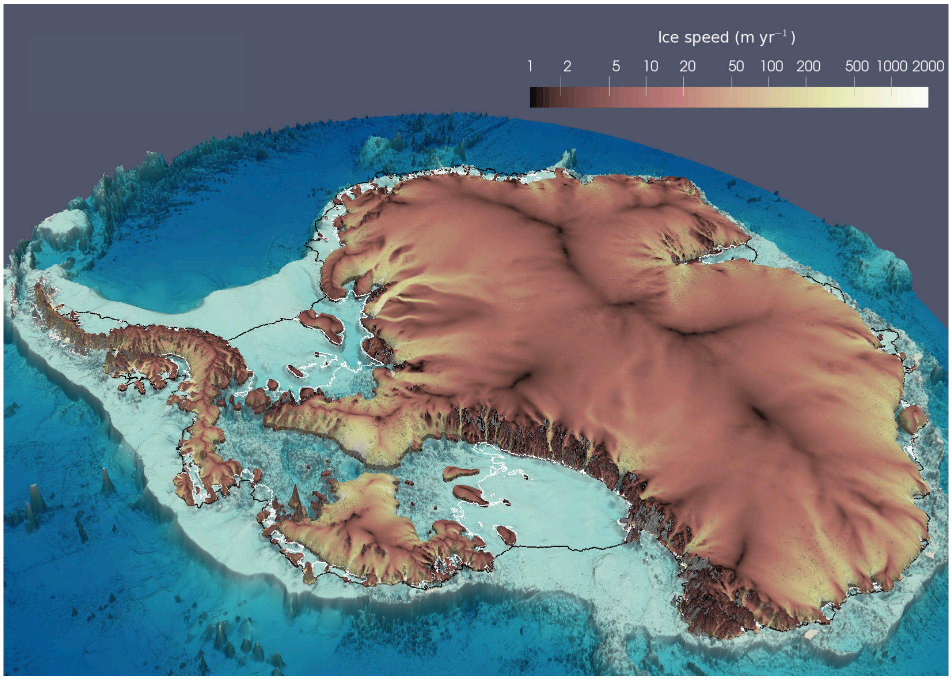


**Figure 1.** Simulated Antarctic ice sheet geometry and speed from MALI 200 years after the instantaneous removal of all floating ice shelves.

## *THE MODEL*

MALI is built using the Model for Prediction Across Scales (MPAS) framework for developing variable-resolution Earth system model components and the DOE multiphysics software library, Albany. MALI uses variable-resolution, unstructured Voronoi grids (Fig. 2) to provide high resolution only where needed such as in highly dynamic regions like ice streams and ice shelves, thereby applying computational power more efficiently.

## *ICE SHEET EXPERIMENTS*

Scientists use MALI to investigate ice sheet evolution under changing climate forcing. As an extreme example, Antarctica's response to the instantaneous removal of all floating ice shelves (Fig 1.) provides an upper-bound estimate for dynamic ice sheet loss and sea level rise. In this hypothetical experiment, MALI is spun up for ~100 years to optimize the sheet (Fig. 3) to represent present-day observed values, then the ice shelves are

## Get MALI

MALI is part of MPAS v6.0.

- Code – **https://github.com/MPAS-Dev/MPAS-Model/releases**
- Docs & test cases – **http://mpas-dev.github.io/land_ice/download.html**

removed. During the following 200 years, sea level rises ~2.5 meters.

## MODEL PERFORMANCE

To test model accuracy, mass, energy, and momentum conservation formulations for the model are verified using analytical solutions and a range of community benchmark experiments (e.g., Fig. 2). When employing MALI's variable resolution capability, the same solution accuracy can be achieved for approximately half the number of unknowns relative to a uniform, high-resolution model. For computational performance, scalable solvers allow for realistic, multi-century simulations of Antarctic ice sheet evolution at unprecedented spatial resolution; the simulations shown in Figs. 1 and 3 solve for ~32 million unknowns on 6400 processors with average model throughput of ~120 simulated years per wall clock day. Model fidelity, performance, and reliability under offline, extreme climate forcing experiments lend confidence in MALI's ability to perform robustly as a coupled component of E3SM.

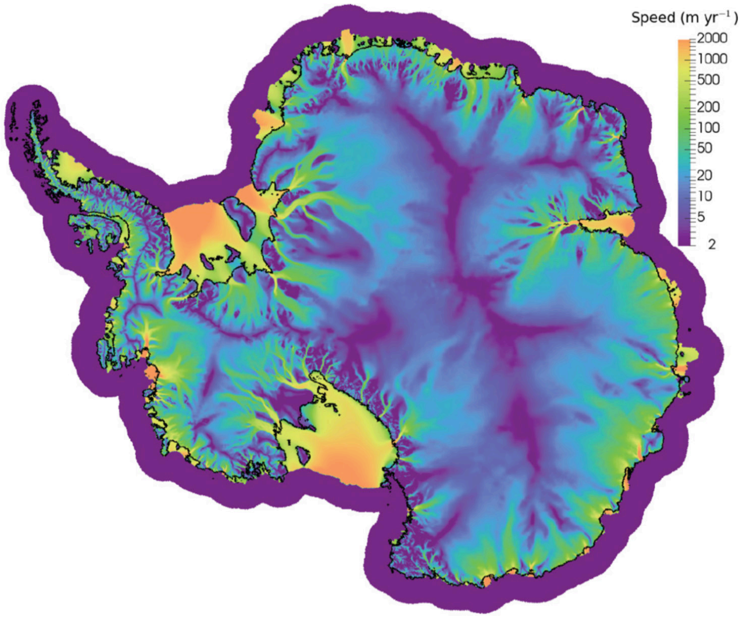


**Figure 3.** Simulated Antarctic ice sheet surface speed at the end of an ~100 year spin-up. Prior to the spin-up, formal optimization methods provide a best match between modeled and observed ice speeds. The black line represents the modeled grounding line where ice goes afloat by buoyancy.

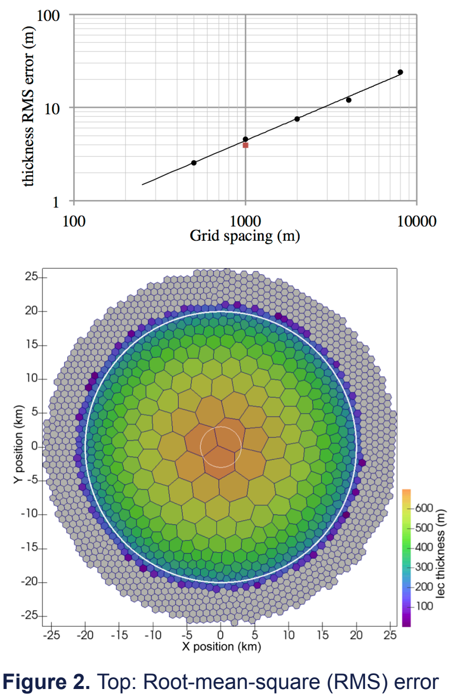


**Figure 2.** Top: Root-mean-square (RMS) error in ice thickness (black dots) as a function of grid cell spacing after 200 years of evolution for an idealized, dome-shaped test case with an analytical solution. The red square shows the RMS thickness error for the variable-resolution mesh. Bottom: The variable-resolution mesh focuses resolution towards the more dynamic ice sheet margins. Grid spacing decreases from 5000 m near the dome center, at a radius of 3 km (thin white line) to 1000 m beyond a radius of 20 km (thick white line). The colors show the ice thickness initial condition for the analytical test problem.

## MALI AND FRONTIER SCIENCE

By solving a more complete description of ice motion, MALI is more accurate than most existing large-scale, high-resolution, whole-ice-sheet models. MALI achieves computational efficiency by using a model grid that focuses resolution in the most important geographic regions and by taking advantage of advanced numerical and computational methods developed by DOE scientists. Currently, very few ice sheet models are dynamically coupled to atmospheric and ocean dynamics within Earth system models. MALI is being coupled to DOE's E3SM and will soon be suitable for simulations as a fully-coupled component of E3SM. Coupled E3SM-MALI simulations will be used to estimate the potential impacts of ice sheets on future sea level and to better understand how ice sheets interact with the global climate system.

## SUPPORT

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