U.S. DEPARTMENT OF ENERGY | Office of Science

DOE/SC-CM-16-001

FY 2016 First Quarter Performance Metric: Develop Robust and Computationally Efficient Ice Sheet Model(s) Capable of Accurately Simulating Marine Ice Sheet Dynamics

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DISCLAIMER

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1.0 Product Definition

Approximately one third of the present day rate of sea-level rise (SLR) is from ice sheet mass loss and that fraction is expected to increase significantly in the coming decades and centuries (Church et al., 2013). Of concern is the potential for increased rates of SLR due to the future initiation of dynamic instabilities within the Antarctic ice sheet (c.f., Schoof, 2007). Indeed, some recent research speculates that such an instability may have already begun (Joughin et al., 2014; Rignot et al., 2014) and uncertainties in the future evolution of Antarctica have been cited as the single biggest uncertainty with respect to projecting rates of future SLR (Church et al., 2013).

Accurate simulations of marine ice sheet dynamics require an ice sheet model with very specific features and capabilities. Two features of utmost importance are that the model must employ a "higher-order," more accurate treatment of the governing Stokes flow equations than used in the previous generation of simpler models, and the model must be capable of very-high grid resolution (~1 km or less) within isolated portions of the domain.

In accordance with these and other necessary features, new marine ice sheet models have been designed according to the following requirements: (1) numerically and computationally robust solutions of the relevant partial differential equations, representing the conservation of momentum, mass, and energy; (2) the ability to employ extremely high spatial resolution within limited, dynamically complex areas of the computational domain; (3) solvers that allow the models to run efficiently on thousands to tens of thousands of processor cores on current and future Leadership Class computers.

2.0 Product Documentation

Under the DOE SciDAC Predicting Ice Sheet and Climate Evolution at Extreme Scales (PISCEES) project, two new ice sheet model dynamical cores, BISICLES and FELIX, have been developed in response to the requirements listed above. The application of high-fidelity, high-performance ice sheet models to large-scale simulations of marine ice sheet evolution is new territory for ice sheet modeling and, for this reason, PISCEES has pursued two different, but complementary, modeling approaches.

BISICLES includes a depth-integrated, higher-order approximation to the Stokes flow equations, using a (computationally less expensive) two-dimensional solution with local corrections to recover a fully three-dimensional solution. While a regular, structured mesh is used, BISICLES can refine that mesh locally so that successively finer resolution "blocks" are nested within coarser resolution ones. This block-structured refinement is done adaptively during the course of a solution, based on solution error metrics, to ensure adequate solution accuracy in regions of dynamic complexity (Figure 1). FELIX uses a fully three-dimensional, higher-order approximation to the Stokes flow equations but, through advanced numerical and computational methods, "flattens" the problem so that the bulk of the computational work effectively occurs in two dimensions. Adequate mesh resolution in regions of dynamic complexity is achieved through the use of fully unstructured, variable resolution meshes (Figure 3). Both models have proven to be robust and computationally efficient on a range of idealized and realistic, large-scale (whole ice sheet) problems (see Figures 1-4).

3.0 Results

Accurate simulations of marine ice sheet dynamics require an ice sheet model with very specific features and capabilities. Two important features are that the model must employ a "higher-order", more accurate treatment of the governing Stokes flow equations than used in the previous generation of simpler models, and the model must be capable of very-high grid resolution (~1 km or less) within isolated portions of the domain. The first feature accounts for horizontal (in addition to vertical) stress gradients in the momentum balance, which is essential for accurate simulation of ice stream and ice shelf flow. The second feature, needed for resolving the narrow boundary layer that separates grounded and floating ice (the "grounding line"), has been shown to be critical for accurate simulations of grounding line advance and retreat within marine ice sheets (e.g., Schoof, 2007; Durand et al., 2009; Cornford et al., 2013; Pattyn et al., 2013). Under the DOE SciDAC PISCEES project, two new ice sheet model dynamical cores, BISICLES and FELIX, have been developed in response to these requirements.

The first ice sheet model, based on the BISICLES dynamical core, is built with DOE supported Chombo and PETSc libraries and uses a finite volume discretization of a quasi-3d, first-order accurate approximation to the three-dimensional Stokes equations governing glacier and ice sheet flow (Schoof and Hindmarsh, 2010). Robustness and scalability of solvers on advanced computers follows from the use of algebraic multi-grid preconditioning and Newton's method , while sub-km grid resolution is dynamically updated at each time step using block-structured, adaptive mesh refinement (Figure 1).

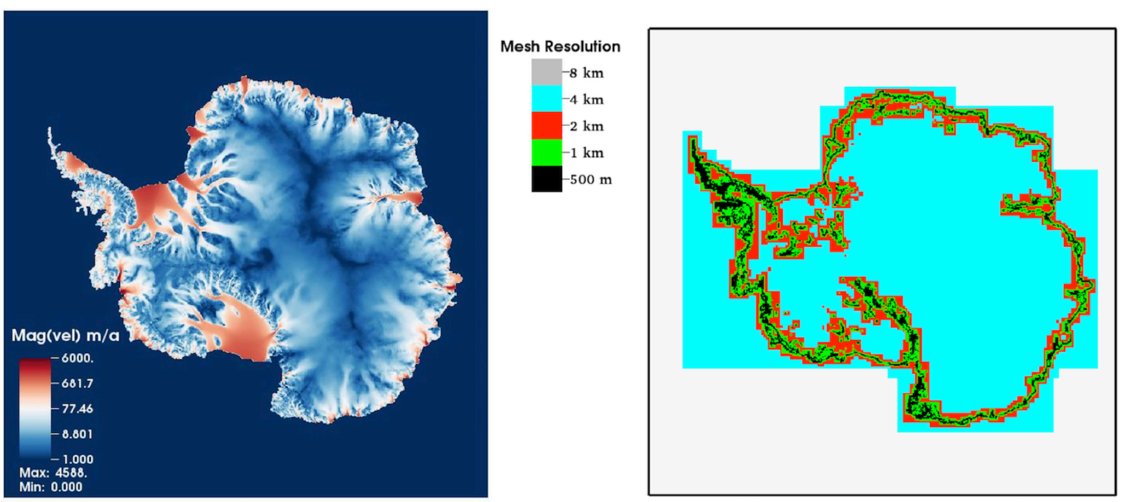

Figure 1. Modeled Antarctic ice sheet surface speed from BISICLES, optimized to match observed surface speeds(left). Map showing base horizontal grid resolution of 4 km and areas of successive refinement based on location of regions with grounding lines near the ice sheet margins and / or in regions of dynamic ice flow complexity (right).

The second ice sheet model, based on the FELIX dynamical core, is built with DOE supported Trilinos and Albany libraries and uses a finite element discretization of the fully-3d, first-order accurate approximation to the Stokes flow equations for glacier ice (Pattyn, 2003; Dukowicz et al., 2010). Robustness and computational scalability of linear and non-linear solvers follows from the use of algebraic multi-grid preconditioning[1], homotopy parameter continuation[2], and Newton's method[3], while sub-km grid resolution is achieved through the use of unstructured, variable resolution meshes (Tezaur et al., 2015a; 2015b - Figure 3).

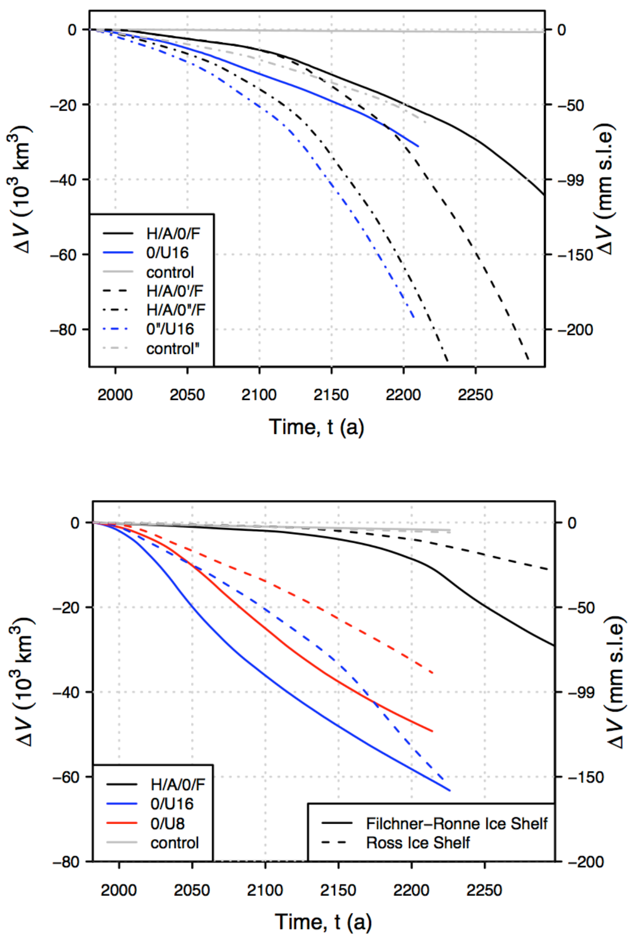

Figure 2. Projections of future sea-level rise (right axis) from the Amundsen Sea embayment (top) and Ross / Filchner-Ronne (bottom) regions of Antarctica, for a range of prescribed, offline-forced, submarine melting scenarios (after Cornford et al., 2015).

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[1] Multi-grid preconditioning uses a hierarchy of coarse-to-fine resolution discretizations of a problem in order to more effectively solve problems that exhibit multiple scales of behavior. For example, if a problem solution has both very long and very short wavelength components, numerical methods will converge on the solution for these different components at very different rates. Multi-grid effectively normalizes rates of convergence so that a single wavelength in the solution does not hold up or prevent convergence of the entire solution.
[2] Parameter continuation is used to solve a nonlinear problem by solving a series of successively more difficult linear problems, with previous solutions serving as good initial guesses and aiding in convergence. The continuation "parameter" varies between problems, but can be altered in steps to make a problem more linear (initially) or more nonlinear (near convergence). In the case of ice sheets, the continuation parameter is a regularization parameter that prevents the shear-thinning viscosity from becoming infinite at low strain rates.
[3] This is simply an application of the well-known *Newton-Rhapson method* for finding roots or minima of a function. Here, it is used in solving the discrete approximation of a non-linear PDE.

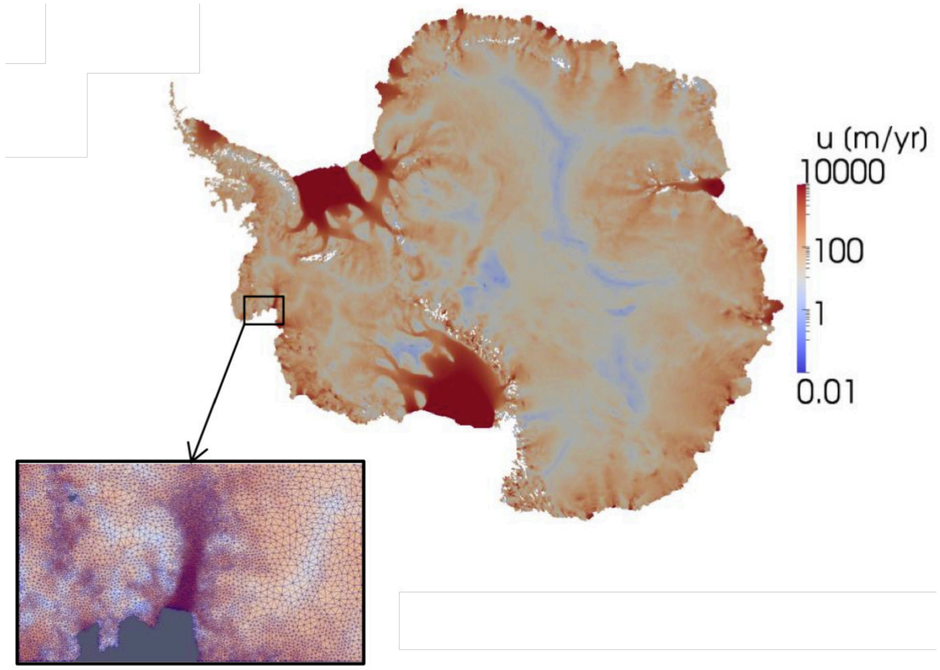

Figure 3. Modeled Antarctic ice sheet surface speed from FELIX, optimized to match observed surface speeds. Inset shows variable mesh resolution around Pine Island glacier, within the Amundsen Sea embayment region (after Tezaur et al., 2015b).

Both ice sheet dynamical cores have undergone extensive testing and verification, using mathematical-analytic and simple-geometric manufactured solutions and standard community benchmark problems (e.g., Pattyn et al., 2008; 2013). They have also proven to be robust and scalable for a range of both idealized and realistic, large-scale, marine ice sheet simulations (Cornford et al., 2013; 2015; Tezaur et al., 2015a; 2015b). Examples of preliminary testing are shown in Figures 2-4. Figure 2 shows projections of West Antarctic SLR from a stand-alone simulation using BISICLES driven by prescribed climate fields. Figure 3 shows a variable resolution, whole-Antarctic surface velocity solution from FELIX, optimized to match present day velocity observations. The excellent scaling of FELIX are shown in Figure 4. FELIX has been used for realistic ice sheet simulations with up to ~1 billion unknowns (such as velocity within each grid-element) solved on 16 thousand computer processor cores.

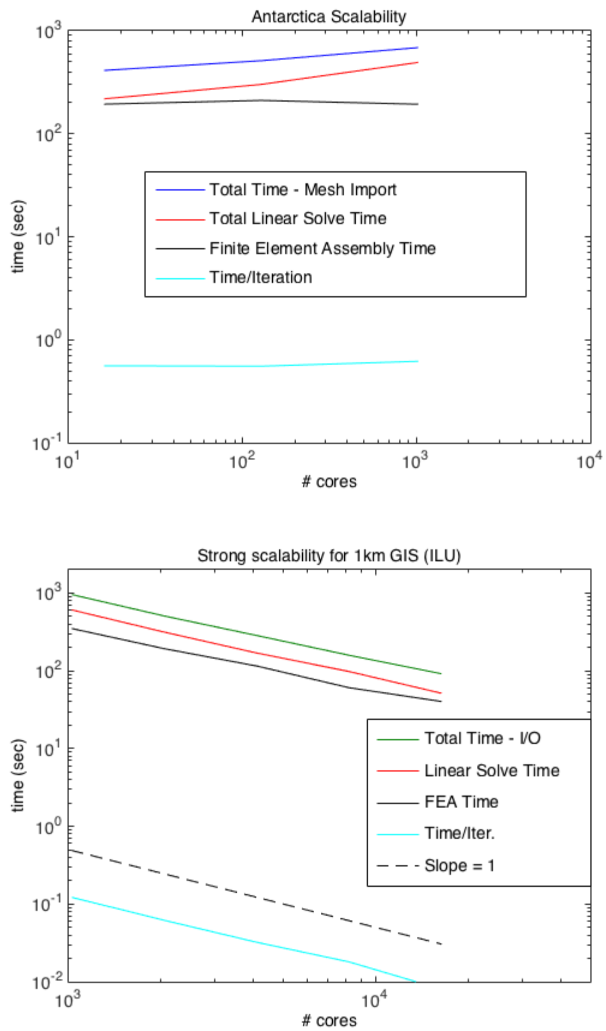

Figure 4. Scaling on multiple computer cores of FELIX dynamical core when applied to high-resolution, realistic Antarctic (top – weak scaling) and Greenland (bottom – strong scaling) ice sheet problems (after Tezaur et al., 2015b).

In preparation for efforts at coupling to Earth System Models, both dynamical cores have been incorporated into wider ice sheet modeling frameworks that will connect the dynamical cores noted above to the climate model. BISICLES has been coupled to the Community Ice Sheet Model (CISM) and FELIX has been coupled to both CISM and the Model for Prediction Across Scales (MPAS) land ice model.

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