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Progress on the PISCEES FELIX Ice Sheet Dynamical Cores

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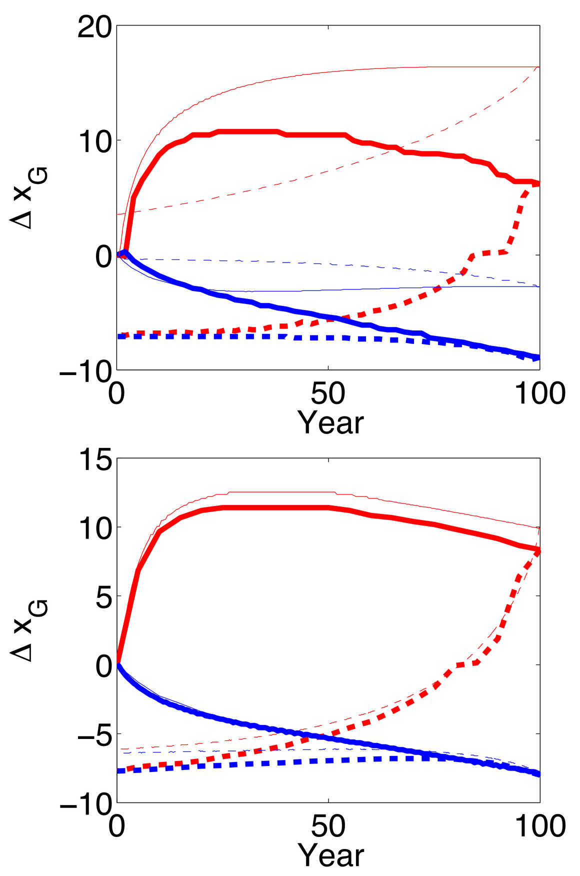
Motivation

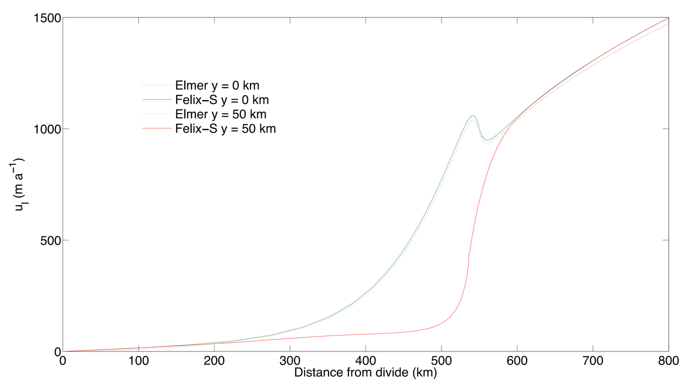
The Greenland and Antarctic ice sheets will likely make a dominant contribution to 21st-century sea-level rise (SLR) and their mass losses could also affect other parts of the climate system, such as the Atlantic Meridional Overturning Circulation and its poleward heat transport. Despite recent improvements in ice sheet modeling, much work is needed to make these models reliable and efficient, to couple them to earth system models, to calibrate the models against observations, and to quantify their uncertainties.

Verification of Marine Ice Sheet Dynamics

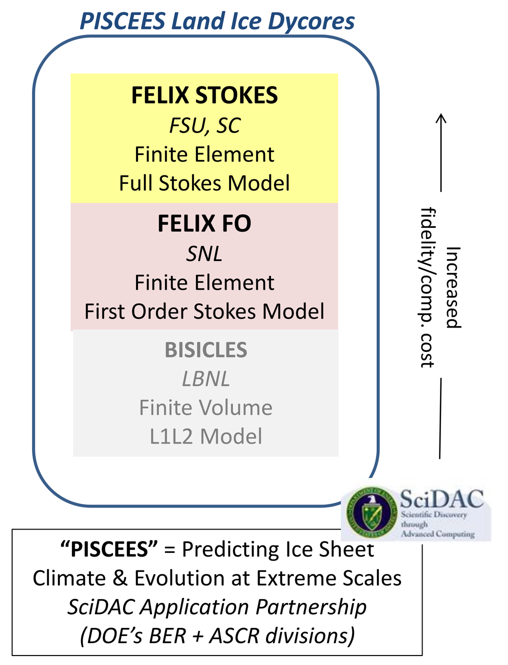
The primary uncertainty regarding future sea-level rise is the contribution from Antarctic marine ice sheet dynamics. FELIX-S will define benchmark solutions for verifying the accuracy of more cost effective, lower-order model approximations.

To date, a single Stokes model, ELMER-Ice, has been used by the glaciological community to "verify" idealized but non-trivial marine ice sheet simulations. PISCEES is providing its own model for this purpose and contributing to results used by the international community. A comparison of FELIX-S and ELMER results is shown below. At right, convergence of ELMER (dashed) and FELIX-S (solid) results with increasing resolution (top to bottom).





The PISCEES Project & FELIX Ice Sheet Dycores

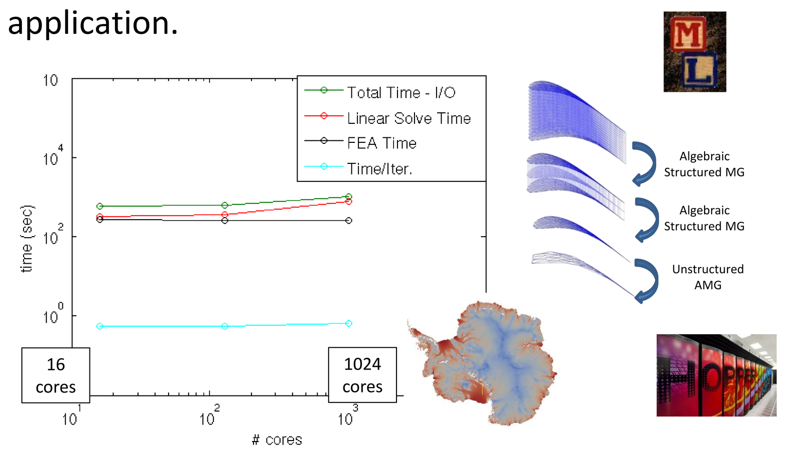


Two Finite Elements for Land Ice eXperiments (FELIX) dynamical cores (dycores) are being developed as a part of the **PISCEES** project: **FELIX STOKES (S)** and **FELIX First-Order (FO).** The dycores, which differ in the underlying model fidelity (Full Stokes vs. FO Stokes equations), target unstructured meshes to enable the focusing of the resolution and computational power in regions of dynamic complexity. Both codes employ computational science libraries from FASTMath, which enable scalable robust solves and performance optimization on new high-performance computers with heterogeneous architectures. The PISCEES FELIX models are being implemented in Model for Prediction Across Scales (MPAS)-Land Ice and the Accelerate Climate Model for Energy (ACME), providing a coherent structure for ongoing collaboration among glaciologists, climate modelers, and computational scientists.

Scalability

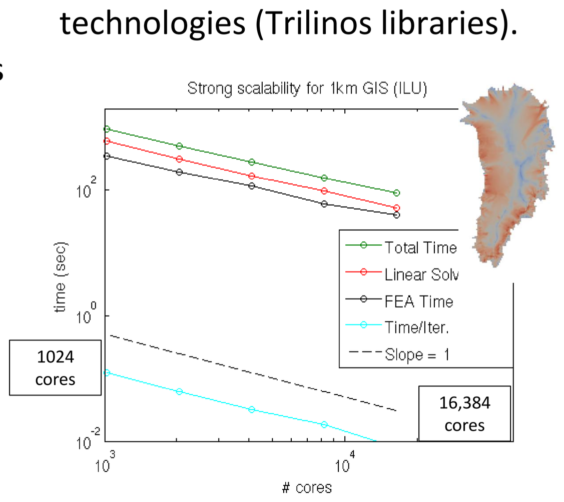
Each nonlinear solve in an ice sheet model requires hundreds of **linear solves**. The capability to solve these systems efficiently is thus critical to overall dycore **scalability**.

The **Antarctic Ice Sheet (AIS)** contains large floating ice shelves, which give rise to ill-conditioned linear systems that are difficult to solve. We achieve scalability using a *new* **algebraic multi-grid** (AMG) preconditioner based on **semi-coarsening** we have developed for this application.



Above: weak scaling study on moderate-resolution AIS problem using AMG solver (8km->2km). AMG solver is >10x faster than ILU solver.

We have demonstrated strong scalability of our FELIX FO solver on fine resolution (1 km) **Greenland Ice Sheet (GIS)** problem. The solver employs FASTMath technologies (Trilinos libraries).



Left: strong scaling study on fine-resolution (1km horiz. resolution + 40 layers) GIS problem using ILU solver. 3.2x speedup with 4x number cores; 7.6x speedup with 8x number cores.

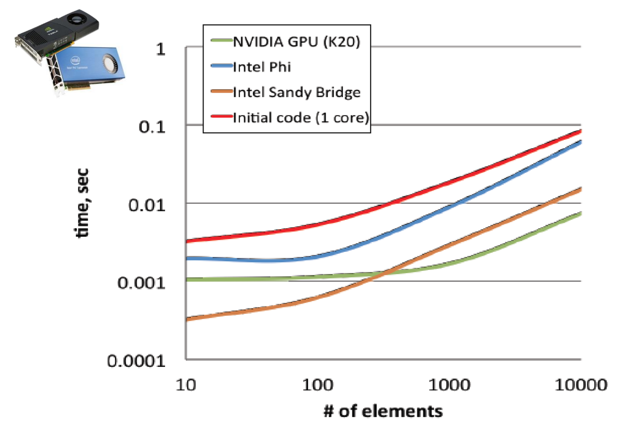
Collaboration with SciDAC Institutes

PISCEES is working closely with the **FASTMath**, **QUEST**, and **SUPER** institutes, leveraging linear and nonlinear solvers (FASTMath), UQ software tools (QUEST), and ensuring that codes run efficiently on current and next-generation DOE HPC systems (SUPER).

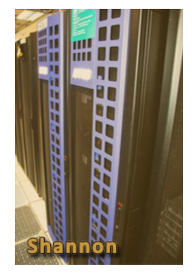
Performance Portability

We are actively preparing the FELIX dycores to run on ***manycore devices*** (multi-core CPU, NVIDIA GPU, Intel Xeon Phi) and ***future architectures***.

Our performance-portability strategy is to use the ***Kokkos*** Trilinos library and programming model. Kokkos provides an abstraction for portability across diverse devices with different memory models.



Top right: performance portability results for FELIX FO mini-app (courtesy of I.Demeshko [SNL]). Number of threads required before the Phi and GPU accelerators start to get enough work to warrant overhead: ~100 for the Phi and ~1000 for the GPU.



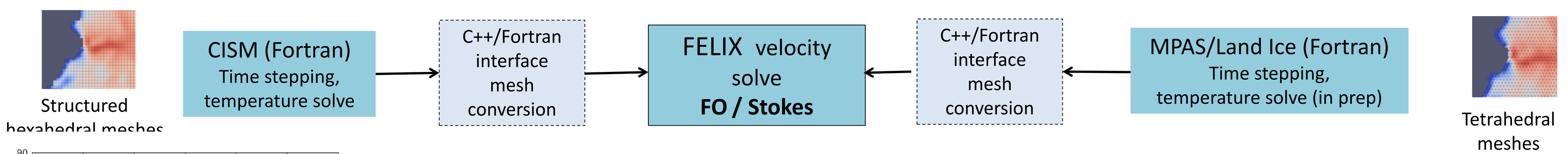
Kernel	Serial	16 OpenMP Threads	GPU
Viscosity Jacobian	20.39 s	2.06 s	0.54 s
Basis Functions w/ FE Transforms	8.75 s	0.94 s	1.23 s
Gather Coordinates	0.097 s	0.107 s	5.77 s

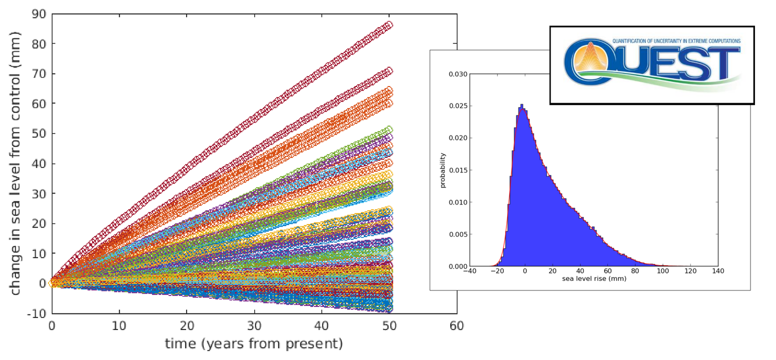
Above: ilustrative results for three of the finite element assembly kernels, as part of a **full** FELIX FO code run.

Note: *Gather Coordinates routine requires copying data from host to GPU.*

Interfaces to CISM and MPAS LI

To enable **prognostic** runs of ice sheet evolution and facilitate coupling to Earth System Models (ESMs), we have written interfaces between the FELIX FO solver and two land ice codes: **CISM** and **MPAS-Land Ice**

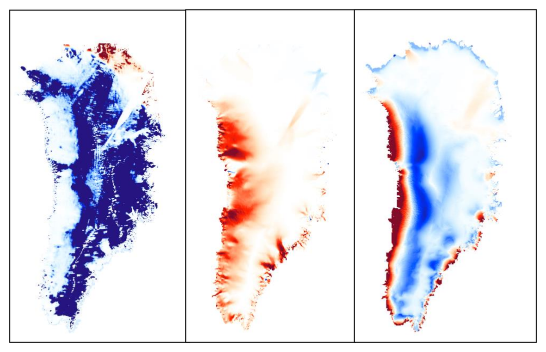




Above: sea-level rise (SLR) realizations (left) and probability density function (right) from 66 runs for 50 yrs differenced against a control.

CISM-Albany was recently used for a forward propagation of uncertainty study: 66 50 yr 4km Greenland runs with highly perturbed β/thickness fields converged **robustly** on Hopper!

Right: Perturbation to β (left; Pa yr/m) and the resulting change in the velocity field (center; m/yr) and ice thickness (right; m) at the end of the 50 yr run, for a single ensemble member. Ice thickness changed >500 m in some places .



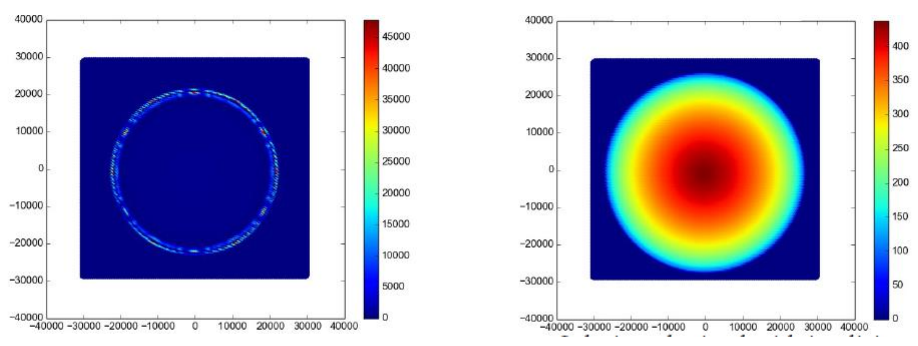
Semi-implicit Coupling of Momentum Balance & Thickness Evolution

Explicit treatment of the thickness evolution equation may prove to be a bottleneck when coupled to ESMs: very small time steps may be required for stability. We have begun work on a **semi-implicit** scheme that allows **larger time steps.**

$$-\nabla\cdot\left(\mu \tilde{\mathbf{D}}(\mathbf{u})\right) = -\rho g \nabla(b+H) \quad \text{in } \Omega_{H^n} \qquad \frac{H-H^n}{\Delta t} + \nabla\cdot(\bar{\mathbf{u}}\, H^n) = \theta^n$$

Momentum eq. Thick. evolution eq.

Below: thickness computed using explicit (left) vs. semi-implicit (right) scheme for dome test case



Instability with dt = 1 yr

Correct solution with dt = 5 yr

Deterministic Inversion for Estimation of Ice Sheet Initial State

Earth System Model (ESM) climate projections require a scalable and robust initialization procedure for current ice sheet conditions.

We have developed an approach to invert for unknowns model parameters and the ice sheet initial state by solving a large scale PDE-constrained optimization problem that minimizes the mismatch with observed data $J(\beta)$.

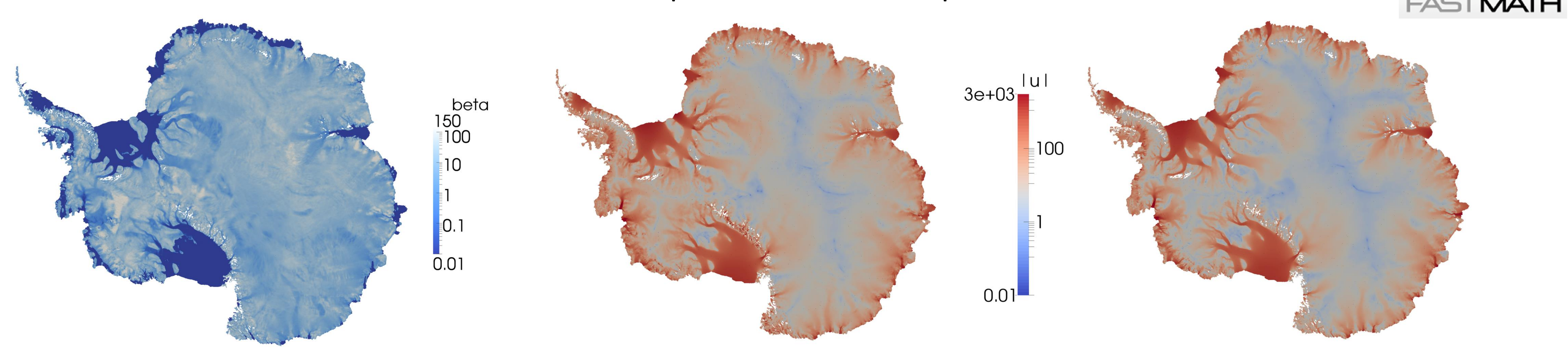
FO Stokes PDE Constrained Optimization Problem:

$$J(\beta) = \frac{1}{2}\int_{\Gamma_{top}} \alpha|\mathbf{u}-\mathbf{u}^{obs}|^2 ds + \mathcal{R}(\beta)$$

Software tools:

- ***Albany*** (assembly)
- ***Trilinos*** (linear/nonlinear solvers)
- ***ROL*** (gradient-based optimization)

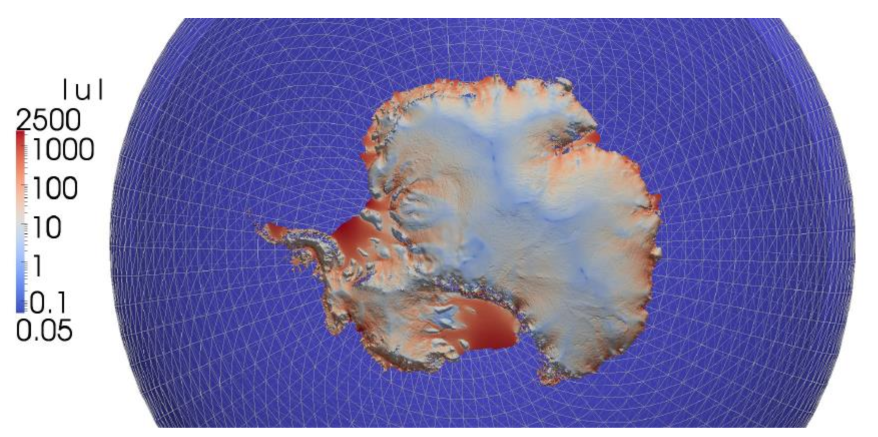
Antartic ice sheet Inversion performed on **700K** parameters

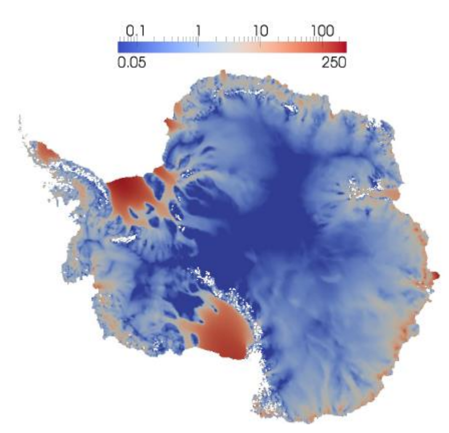


Left: Estimated beta (kPa yr/m) obtained minimizing the mismatch between the computed surface velocity and the observed surface velocity. Center: Magnitude of surface velocity (m/yr) computed with the estimated β. Right: magnitude of the observed surface velocity (m/yr) .

Ongoing Work: FO Model on the Sphere

Current ice sheet models are derived assuming planar geometries. The effect of earth curvature is largely unknown. We have recently derived a FO model that accounts for the earth curvature and are investigating differences between this model and the classical planar model.





Spherical FO -planar FO Relative difference smaller than10%

Left: Magnitude of surface velocity (m/yr) computed solving the FO model on the sphere. Right: magnitude of the difference between the surface velocity computed using the "spherical" FO model and the one computed using "planar" FO model.

Publications

I. Tezaur, M. Perego, A. Salinger, R. Tuminaro, S. Price. "*Albany/FELIX*: A Parallel, Scalable and Robust Finite Element Higher-Order Stokes Ice Sheet Solver Built for Advanced Analysis", *Geosci. Model Develop.* 8 (2015) 1-24.
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R.S. Tuminaro, I. Tezaur, M. Perego, A.G. Salinger. "A Hybrid Operator Dependent Multi-Grid/Algebraic Multi-Grid Approach: Application to Ice Sheet Modeling", *SIAM J. Sci. Comput.* (in prep).
M. Perego, S. Price, G. Stadler. "Optimal Initial Conditions for Coupling Ice Sheet Models to Earth System Models", *J. Geophys. Res.* 119 (2014) 1894-1917.
Leng, W., L. Ju, Y. Xie, T. Cui, and M. Gunzburger, 2014: Journal of Computational Physics. *Journal of Computational Physics*, **274**, 299–311,
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Leng, W., L. Ju, M. Gunzburger, S. Price, and T. Ringler, 2012: A parallel high-order accurate finite element nonlinear Stokes ice sheet model and benchmark experiments. *J. Geophys. Res*, **117.**

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