PISCEES: Development of the FELIX Dynamical Cores for Land Ice Modeling

M. Perego, I. Kalashnikova, A. Salinger, M. Eldred, J. Jakeman, R. Tuminaro [SNL]
S. Price, M. Hoffman, B. Lipscomb [LANL], M. Gunzburger [FSU], L. Ju [SC], Wei Leng [LSEC, CAS]

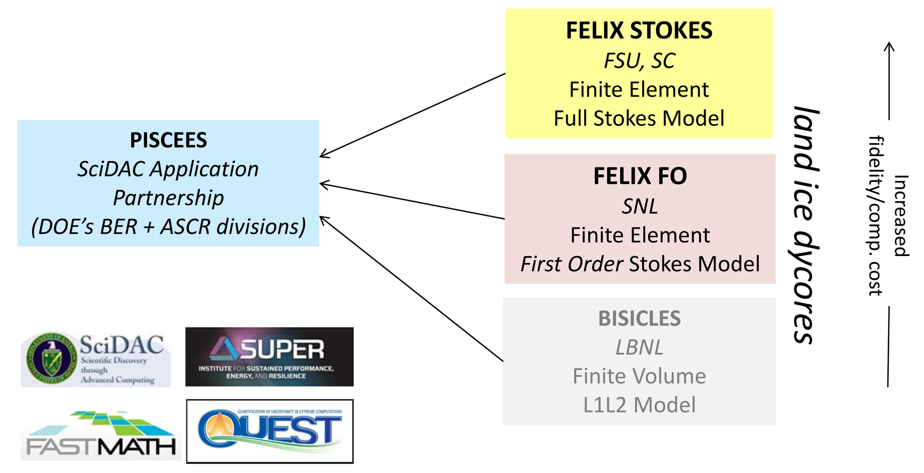
Introduction

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.

FELIX is a finite-element dynamical core (dycore) targeting unstructured meshes, like that from the Model for Prediction Across Scales (MPAS) framework, and using the Trilinos computational science libraries. FELIX includes a hierarchy of solvers that can be applied at variable spatial resolution and in regions of differing dynamical complexity, and is being engineered to optimize performance on new high-performance computers with heterogeneous architectures. These improved models are being implemented in 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.

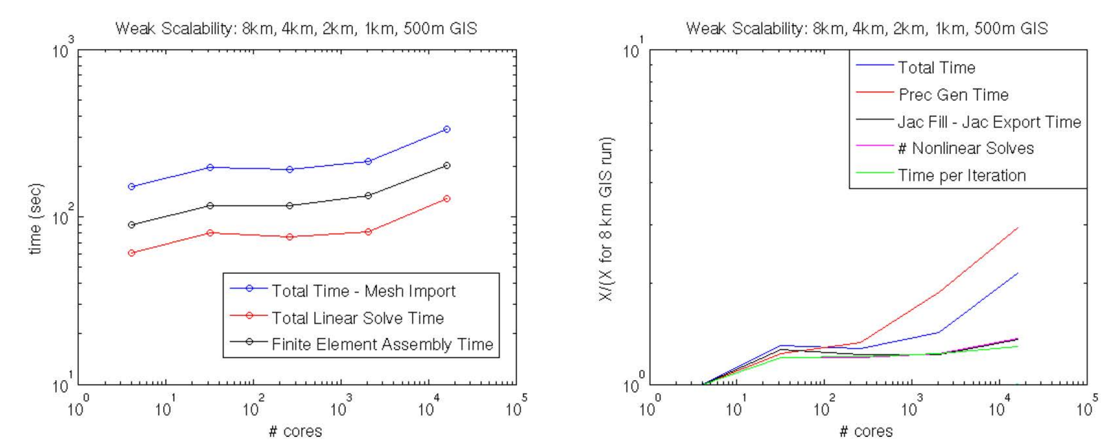
PISCEES is working closely with the **FASTMath**, **QUEST**, and **SUPER** institutes, leveraging linear and nonlinear solvers (FastMath), UQ software tools (QUEST), and ensuring that codes run efficiently on current and next-generation DOE HPC systems (SUPER).

Main Goal: support DOE climate missions (sea-level rise predictions)

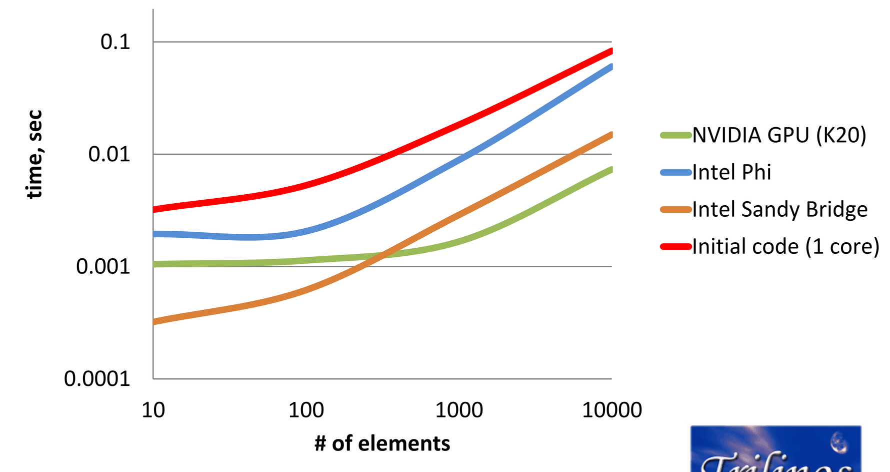


Parallel efficiency

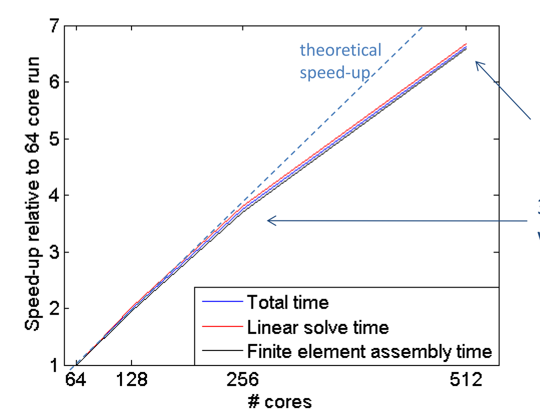
FO solver: Weak scalability results on Greenland ice-sheet

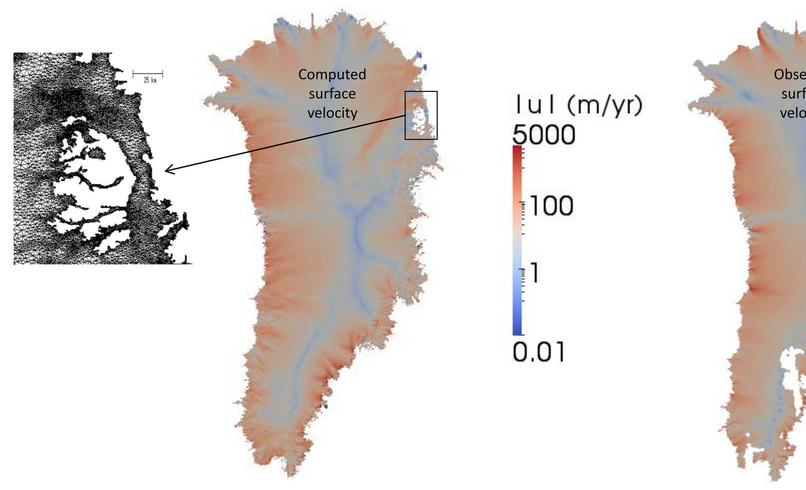


FO Solver: Assembling efficiency on different architectures using Kokkos (courtesy of Irina Demeshko).

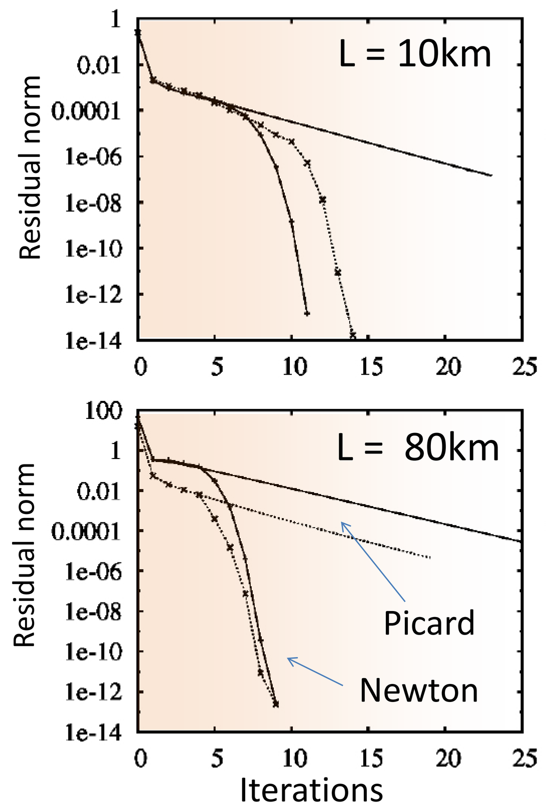


FO solver: Strong scalability results for Greenland ice-sheet using a ***non-uniform unstructured*** grid.



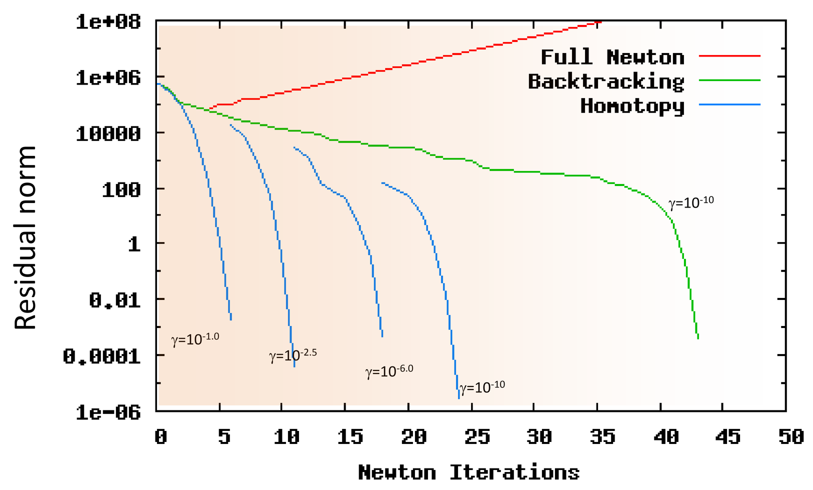


Robust, nonlinear solvers



Stokes solver, Newton vs Picard convergence for ISMIP-HOM tests A (solid) and C (dash).

First-Order (FO) Solver, Greenland ice sheet.
Continuation for regularization parameter.

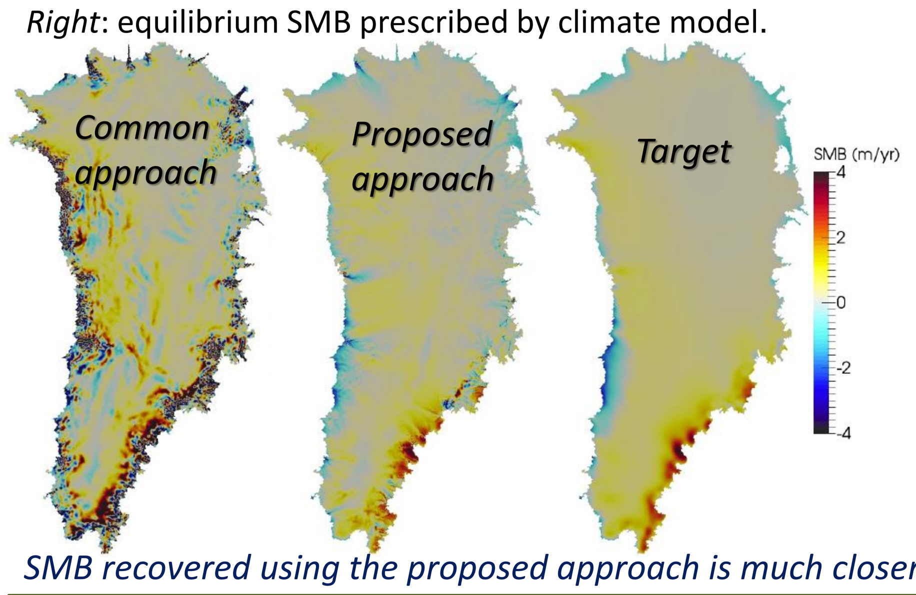


Regularized viscosity: $\mu = \frac{1}{2}A^{-\frac{1}{n}}\left(\frac{1}{2}\sum_{ij}\dot{\epsilon}_{ij}^2+\gamma\right)^{\left(\frac{1}{2n}-\frac{1}{2}\right)}$

Ice sheet Initialization

Scalable and robust initialization procedure are needed for ice sheet models to be used for ***sea level rise*** projections in full Earth System Model runs (FO solver).

Left, Center: SMB needed by ice-sheet model for equilibrium.
Right: equilibrium SMB prescribed by climate model.



Invert for unknowns parameters by *minimizing* mismatch observed data and climate forcing.

$$\mathcal{J}(\beta, H) = \int_\Sigma \frac{1}{2\sigma_u^2}|\boldsymbol{u}-\boldsymbol{u}^{\mathrm{obs}}|^2\,ds \quad \text{surface velocity mismatch}$$

$$+\int_\Sigma \frac{1}{2\sigma_\tau^2}|\nabla\cdot(\boldsymbol{U}H)-\tau_s|^2\,ds \quad \text{SMB mismatch}$$

$$+\int_\Sigma \frac{1}{2\sigma_H^2}|H-H^{\mathrm{obs}}|^2\,ds \quad \text{thickness mismatch}$$

$$+\mathcal{R}(\beta, H) \quad \text{Regularization terms}$$

Common / Proposed

SMB recovered using the proposed approach is much closer to the target one.

A SMB mismatch can lead to unphysical transients lasting decades to centuries.

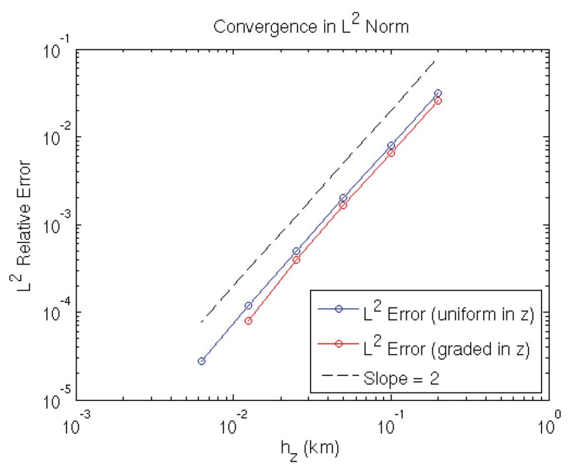
Accurate, stable, mass-conserving, implicit discretizations

FELIX FO: convergence study on 3D Greenland simulation.

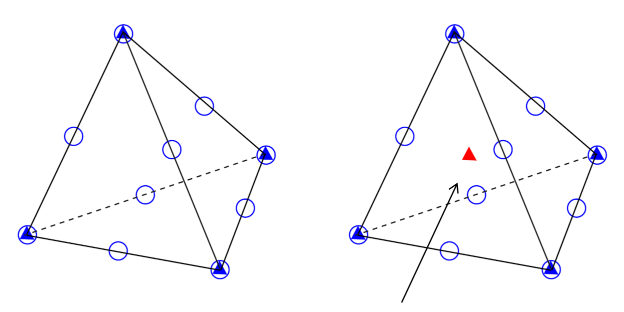
How many vertical layers do you need? Convergence study for GIS 1km mesh:

# vertical layers/# cores	# dofs	Total Time – Mesh Import (sec)	Solution Average	Error
5/128	21.0M	519.4	2.827	3.17e-2
10/256	38.5M	525.4	2.896	8.04e-3
20/512	73.5M	499.8	2.924	2.01e-3
40/1024	143M	1282	2.937	4.96e-4
80/2048	283M	1294	2.943	1.20e-4
160/4096	563M	1727	2.945	2.76e-5

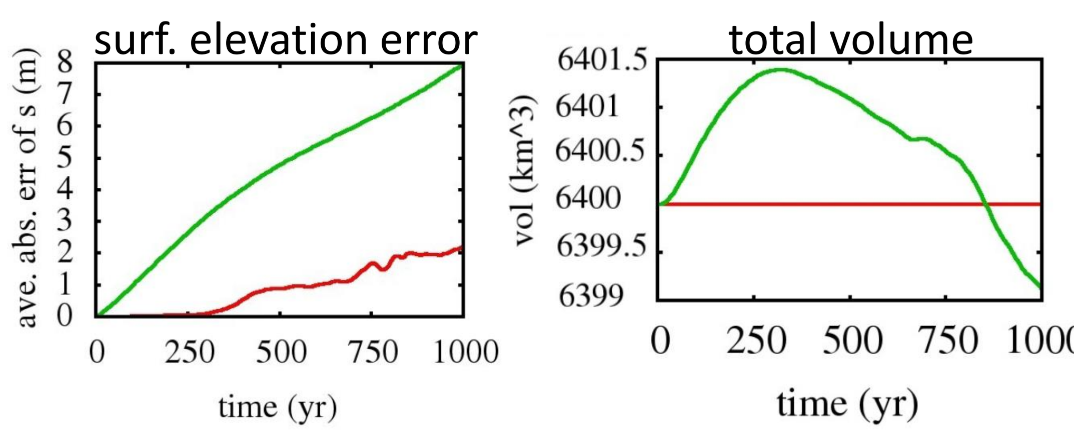
Theoretical 2nd order convergence achieved on 3D mesh convergence study.



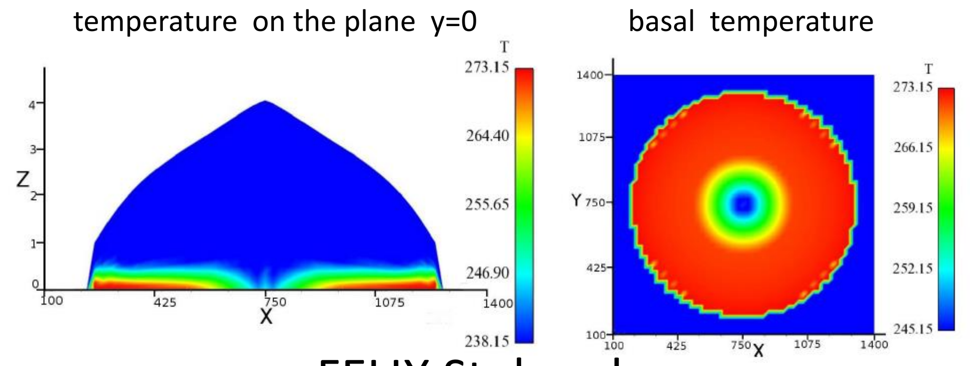
FELIX Stokes: mass-conserving stable discretization
FE: **Taylor-Hood** (left)
enhanced Taylor-Hood (right)



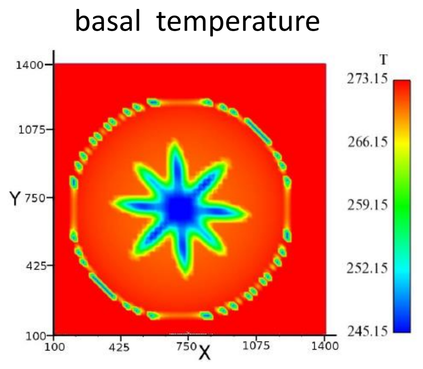
Additional Pressure DOF to enforce mass conservation
(circles denotes velocity DOFs, triangles pressure DOF)



Implicitly coupled thermo-mechanical flow: EISMINT II benchmark.



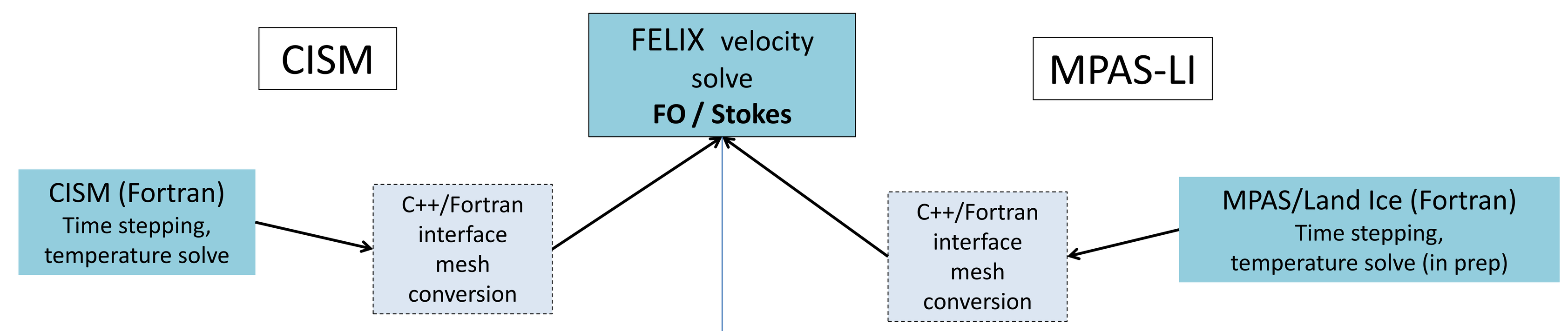
FELIX Stokes dycore



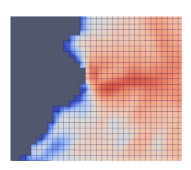
CISM, SIA dycore

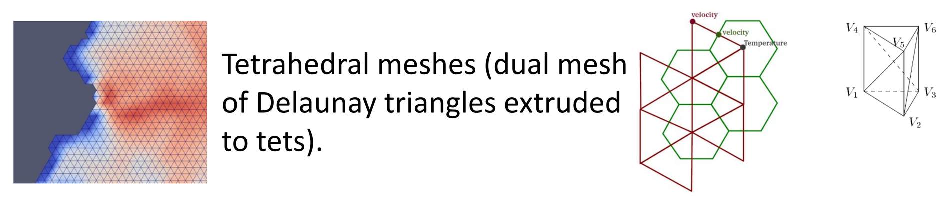
Coupling with CISM / MPAS

Needed to enable dynamic simulations and to facilitate coupling with Earth System Models.



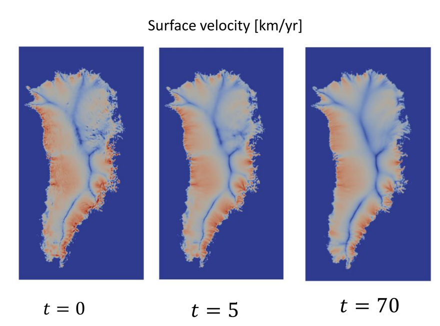
Structured hexahedral meshes (rectangles extruded to hexes).

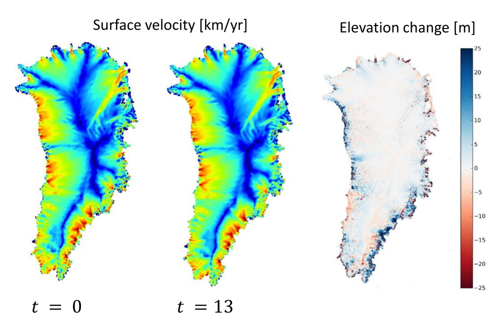




Tetrahedral meshes (dual mesh of Delaunay triangles extruded to tets).

100 year 4 km Greenland transient simulation using CISM-FELIX FO (run on Titan).





Preliminary 5 km Greenland transient simulation with realistic basal friction and temperature fields, Using MPAS-FELIX FO (run on Hopper).

Publications

W. Leng, L. Ju, M. Gunzburger and S. Price, *Manufactured solutions and the verification of three-dimensional Stokes ice-sheet models*, The Cryosphere, 2013.
Shannon, S. R., et al., Enhanced basal lubrication and the contribution of the Greenland ice sheet to future sea-level rise, Proceedings of the National Academy of Sciences, 2013.
Edwards, T. L., et al., Effect of uncertainty in surface mass balance elevation feedback on projections of the future sea level contribution of the Greenland ice sheet, The Cryosphere, 2014.
W. Leng, L. Ju, Y. Xie, T. Cui and M. Gunzburger, *Finite element, three-dimensional Stokes ice sheet dynamics model with enhanced local mass conservation*, J. of Comp. Physics, 2014.
W. Leng, L. Ju, M. Gunzburger and S. Price, *A parallel computational model for three-dimensional, thermo-mechanical Stokes of simulations of glaciers and ice sheets*, Comm. Comp. Physics, 2014.
M. Perego, S. Price, G. Stadler, *Optimal Initial Conditions for Coupling Ice Sheet Models to Earth System Models*, J. of Geophysical Research, accepted, 2014.
I. Kalashnikova, M. Perego, A. Salinger, R. Tuminaro, S. Price, and M. Hoffman, *A new parallel, scalable and robust, finite element, first-order Stokes approximation ice sheet model built for advanced analysis*, Geoscientific Model Development, in preparation, 2014.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.