Ice Sheet Model Dynamical Core Development for PISCEES

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Background

If recent trends continue, ice sheets will make a dominant contribution to 21st-century sea-level rise (SLR), far exceeding projections from the IPCC's Fourth Assessment Report. Growing ice mass losses not only could raise sea level, but also could affect other parts of the climate system, such as the Atlantic Meridional Overturning Circulation and its poleward heat transport, through increased freshwater discharge to high-latitude oceans. Although ice sheet models have improved in recent years, much work is needed to make these models reliable and efficient on continental scales, to couple them to earth system models, and to quantify their uncertainties.

Goals

Building on recent successes of SciDAC and the ISICLES (Ice Sheet Initiative for CLimate ExtremeS) project, PISCEES (Predicting Ice Sheet and Climate Evolution at Extreme Scales) will develop two dynamical cores:

- **BISICLES**: a finite-volume core on an structured mesh, using the Chombo adaptive mesh refinement (AMR) software framework,
- **FELIX**: a finite-element core on an unstructured mesh, using the Model for Prediction Across Scales (MPAS) framework and the Trilinos software library.

Both will include a hierarchy of solvers which can be applied at variable resolution and in different regions of dynamical complexity, and will be engineered to optimize performance on new high-performance computers with heterogeneous architectures. These improved models will be implemented in the Community Ice Sheet Model (CISM) and the Community Earth System Model (CESM), providing a coherent structure for ongoing collaboration among glaciologists, climate modelers, and computational scientists.

Collaboration with SciDAC Institutes

PISCEES will work closely with the FASTMath, QUEST, and SUPER institutes; team members from these institutes are integral members of the PISCEES team.

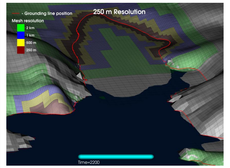
- **FASTMath:** By using FASTMath-developed scalable algorithms and libraries, PISCEES is leveraging ongoing ASCR investments. Of particular relevance are the solution of large systems of linear and nonlinear equations and block-structured AMR. Chombo and Trilinos – essential components of the dynamical cores in development under PISCEES - are both supported by FASTMath
- **QUEST:** PISCEES will rely on QUEST for expertise in modeling and algorithmic UQ, as well as for support in the use of the DAKOTA and other QUEST software tools.
- **SUPER:** Tools and techniques developed by SUPER will ensure that PISCEES-developed codes run efficiently on current and next-generation HPC systems supported by DOE PISCEES will leverage SUPER technologies in end-to-end instrumentation to enable performance characterization and tracking.

BISICLES

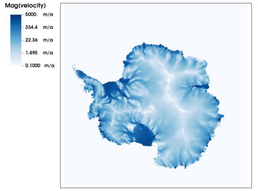
The dynamics of Ice sheets like those found in Antarctica and Greenland span a wide range of scales. Regions like grounding lines and the shear margins of ice streams require very fine (better than 1 km) resolution to resolve the dynamics. Resolving all of Antarctica at such fine resolutions is computationally prohibitive. However, there are also large regions where such fine resolution is unnecessary, making ice sheets an ideal candidate for adaptive mesh refinement (AMR).

Existing Code

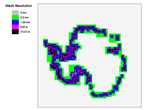
Developed as part of the ISICLES initiative, and in collaboration with the University of Bristol in the U.K., we have developed a scalable AMR ice-sheet code built upon the FASTMath-supported Chombo framework. AMR allows BISICLES to achieve unprecedented spatial resolution to resolve behavior like grounding line retreat. BISICLES uses a vertically-integrated formulation of the momentum balance based on that of Schoof and Hindmarsh[1] (2010) which captures the essential physics of the problem while also enabling additional computational efficiencies.



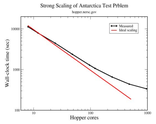
Frame from an animation showing a projection of grounding line retreat in the 21st and 22nd centuries, computed as a contribution to the Ice2Sea effort.



BISICLES-computed AMR solution of Antarctic ice velocity field with a finest resolution of 312.5 m.



(Left) Illustration showing the mesh resolution employed in the Antarctic simulation at left.

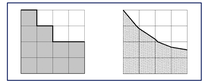


(Right) strong scaling on hopper.nersc.gov for the Antarctic test problem.

Improvements under PISCEES

Under PISCEES, the BISICLES code will receive several capability enhancements which will result in improved physical fidelity and numerical accuracy.

- Implement a full-Stokes formulation of the momentum balance for use in the regions where the current asymptotically-derived formulation breaks down (particularly near grounding lines)
- Use Chombo's embedded-boundary (EB) capability at grounding lines to improve discretization of grounding-line location and fluxes.
- Full integration into CISM and CESM.



(Left) Current "stair-step" representation of grounding line. On right, embedded boundary discretization of the same grounding line.

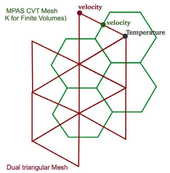
References [1]Schoof and Hindmarsh, *QJMAM*, **63** (2010) [2]http://www.lifev.org/ [3]Perego et al., *J. Glaciol.*, **58** (2012) [4]Leng et al., *J. Geophys. Res. Earth Surf.*, **117** (2012) [5]http://www.ice2sea.eu/ [6]Ringler et al., *Ocean Dynamics*, **58** (2008)

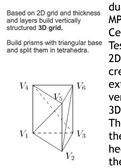
FELIX

The FELIX (Finite Elements for Land Ice eXperiments) dycore will take advantage of and build upon the Model for Prediction Across Scales (MPAS) climate modeling framework to deliver a robust, Finite Element Model (FEM) based suite of dynamical cores on adaptively refined, high-fidelity, unstructured meshes.

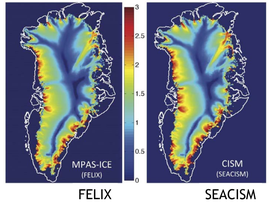
Prototype Code

The prototype FELIX dycore uses the MPAS meshing framework, the LifeV FEM library[2], and the Trilinos solver library. It currently allows for shallow shelf, shallow ice, "L1L2"[1], and first-order approximations to the full 3d Stokes system of equations[3] and work is ongoing to implement a Stokes solver[4]. The prototype dycore was used to conduct Greenland simulations as part of the Ice2Sea[5] contribution to IPCC AR5.





(LEFT) The FELIX prototype uses the dual mesh to the MPAS SCVT (Spherical Centroidal Veronoi Tesselation) mesh. A 2D mesh is first created and then extruded in the vertical to create a 3D prismatic mesh. These prisms are then split into tetrahedra suitable for the FEM code.



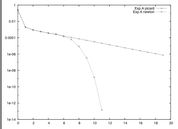
FELIX SEACISM

(Left) Steady-state initial condition for Greenland Ice2Sea experiments. Model velocities (in color on log10 scale) have been tuned to match balance velocities. FELIX results (left) use the internal temperature and basal sliding coefficient fields from SEACISM.

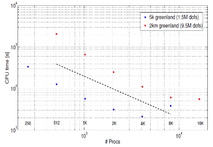
Improvements under PISCEES

FELIX's FEM capabilities will eventually be satisfied using Trilinos. FELIX will make full use of Trilinos (FASTMath) and Dakota (QUEST) capabilities, allowing for automatic differentiation, Newton-based solution methods, and gradient-enhanced uncertainty quantification. Current improvements within the prototype code demonstrate the added efficiency from Newton methods. Work on the verification of linear and nonlinear Stokes models within the Trilinos-based code is currently underway, as is work on accessing MPAS's refined meshing capabilities. Future work will allow for adaptive refinement of MPAS-based grids.

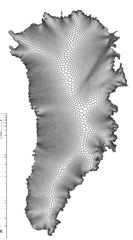
(Below) Improved convergence of the Stokes dynamical core[4] from Newtons method.

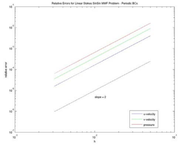


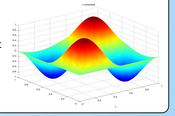
(Right) Scaling of the prototype FELIX dynamical core.



(Right) MPAS SCVT-based mesh for Greenland with refinement in regions of high velocity[6].





(Left) Expected convergence rate of 2x, for bilinear finite elements with (in Albany and Trilinos).

(Right) A validated solution for a constant viscosity Stokes flow problem (using Albany and Trilinos).