Ice Sheet Model Dynamical Core Development for PISCEES

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Background

If recent trends continue, the Greenland and Antarctic 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, to calibrate the models against observations, 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) is developing 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 computational science libraries.

Both include a hierarchy of solvers which can be applied at variable spatial resolution and in regions of differing dynamical complexity, and are being engineered to optimize performance on new high-performance computers with heterogeneous architectures. These improved models are being 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 is working closely with the FASTMath, QUEST, and SUPER institutes; team members from these institutes are integral members of the PISCEES team.

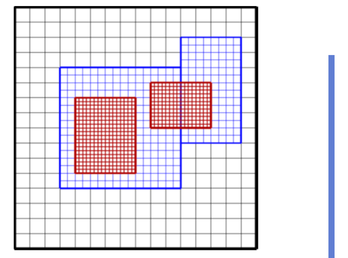
- <u>FASTMath:</u> By using FASTMath-developed scalable algorithms and libraries, PISCEES is leveraging ongoing ASCR investments. Of particular relevance are the solution of large systems of linear and nonlinear equations and block-structured AMR. Chombo and Trilinos – essential components of the dynamical cores in development under PISCEES - are both supported by FASTMath.
- <u>QUEST:</u> PISCEES relies 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.
- <u>SUPER:</u> Tools and techniques developed by SUPER 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 – AMR for Ice Sheets

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).

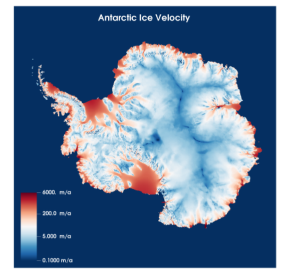
Developed as part of the ISICLES initiative, and in collaboration with the University of Bristol in the U.K., we have developed a scalable AMR ice-sheet code built upon the FASTMath-supported Chombo framework. AMR allows BISICLES to achieve unprecedented spatial resolution to resolve behavior like grounding 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.

Block-Structured AMR

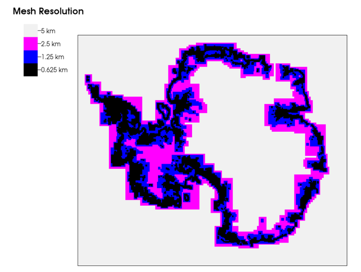


- Amortize cost of irregular operations over large number of regular structured-mesh operations.
- Refine in logically-rectangular patches.
- Finite-volume discretizations simplify coarse-fine coupling.
- Simplifies dynamic remeshing, to follow changing features.
- The LBNL-developed Chombo AMR C++/Fortran framework enables rapid code development and provides built-in scalability.

Antarctica

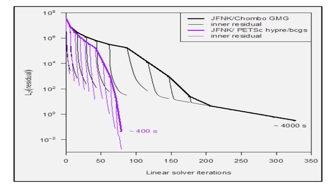


- Ice velocity field (right) computed using AMR -- mesh spacing from 5 km (base mesh) to 625 m (finest level)
- Refinement based on grounding lines, Laplacian(velocity)
- Mesh resolution (at right):
  5 km base mesh with 3 refinement levels:
  - base level (5 km): 409,600 cells (100% of domain)
  - level 1 (2.5 km): 370,112 cells (22.5%)
  - Level 2 (1.25 km): 955,072 cells (14.6%)
  - Level 3 (625 m): 2,065,536 cells (7.88%)



Solvers

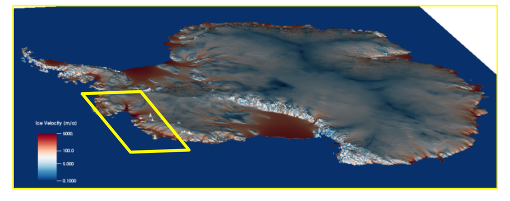
- Solution of coupled nonlinear elliptic system for ice velocity dominates execution time.
- Linear and nonlinear solver improvements from FASTMath reduce time to solution and improve robustness



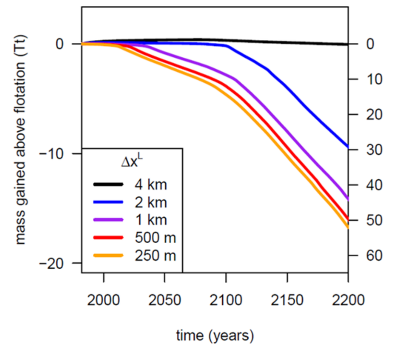
Norm(residual) vs. solver iteration for 5 km Antarctica test case. Black – Chombo GMG, purple – PETSc GAMG.

Ice2Sea Amundsen Example

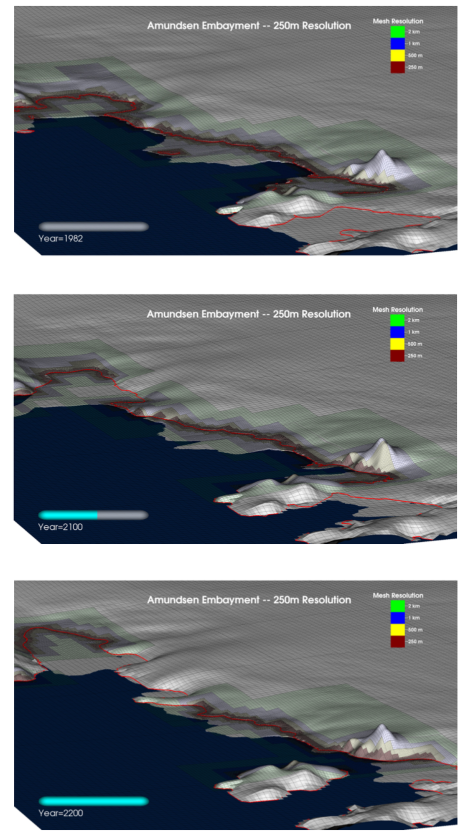
- Study of effects of warm-water incursion into Amundsen Sea sector in Antarctica
- Results from Payne, et al (2012), submitted.
- Frames (right) show ice surface, grounding lines (in red) and meshes for 1982 (initial time), 2100, and 2200 (final time) for 250m-resolution run. Adaptive meshing follows evolving solution. Note grounding line retreat, particularly Pine Island Glacier (upper left).
- Plot (below) shows contribution to sea level rise for various mesh resolutions.



Location of Amundsen Sea Sector (yellow box)



Amundsen Sea Sector SLR Contribution vs. Year for a Range of Mesh Resolutions



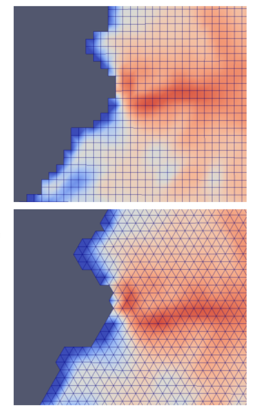
Resolution dependence: dynamics under-resolved until $\Delta x \leq 1$ km.

FELIX

The FELIX (Finite Elements for Land Ice eXperiments) dycores will leverage libraries (e.g., Trilinos, Dakota, & MPAS) to deliver an unstructured grid Finite Element Model (FEM) simulator that is born with advanced software tools, robust and scalable solvers, and embedded analysis capabilities.

New Code Development under PISCEES

FELIX includes 3d Stokes[4] and 1st-order[3] Stokes approximation dycores. The 1st-order dycore uses *Trilinos* finite element and solver libraries, and is coupled to *Dakota/QUESO* to allow uncertainty propagation and calibration. The parallel Stokes dycore uses *hypre* and *Boomer AMG*. FELIX is being used to conduct whole-ice-sheet simulations of both Greenland and Antarctica. The data for these simulations can be imported as a hexahedral, structured grid, or an unstructured central voronoidal tesselation (CVT) grid for flexible coupling to global climate models.

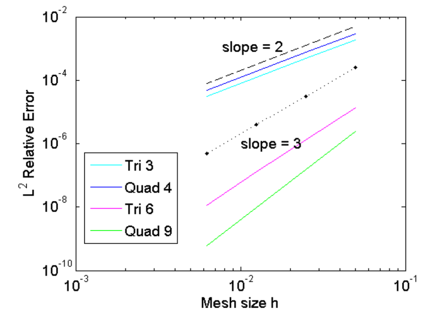


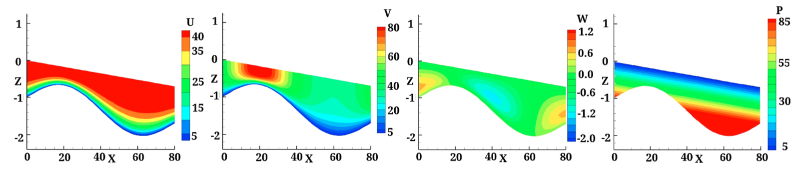
Left: Close-up of structured hexahedral (top) and tetrahedral (bottom) grid of Jakobshavn glacier as part of full Greenland simulation

Solution/Convergence Verification

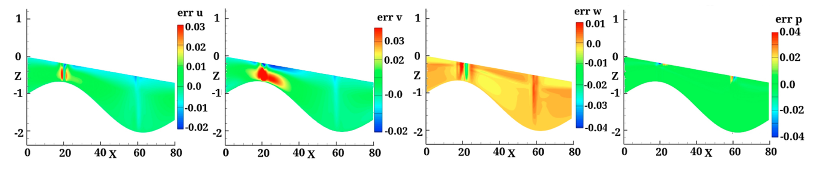
Solution verification of 2D, 1st-order FELIX using 4 different finite elements on a method of manufactured solutions problem with exact solution:

$$u = \sin(2\pi x)\cos(2\pi y) + 3\pi x,$$
$$v = -\cos(2\pi x)\sin(2\pi y) - 3\pi y$$



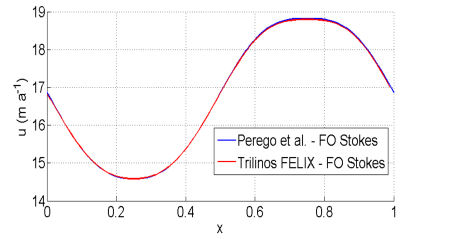


Manufactured solutions[8] for velocity (u,v,w) and pressure (P) (top) for use in verification of Stokes FELIX[4].

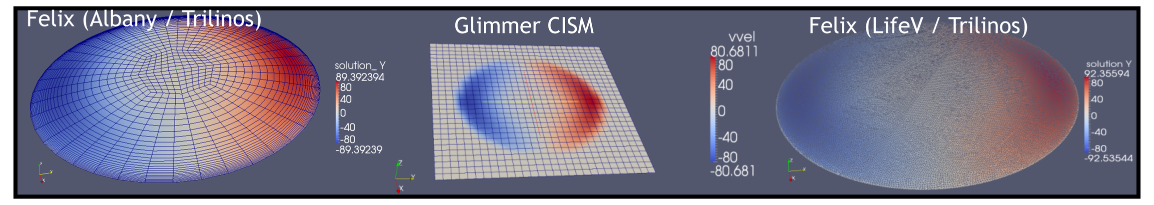


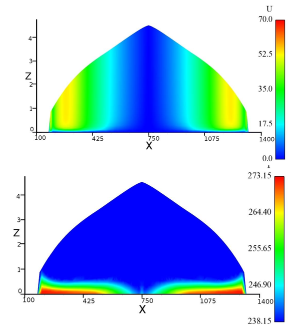
Errors in velocity and pressure components for Stokes FELIX[8].

Code-to-Code Comparisons



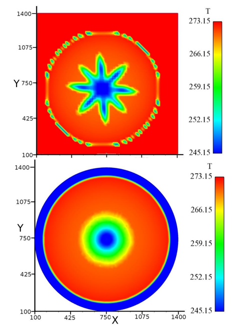
Code-to-code comparisons between 1st-order FELIX and existing codes (LifeV, Glimmer CISM) have been made on ISMIP-HOM Test C (left), Dome (bottom) and a number of other benchmarks. Agreement is excellent.



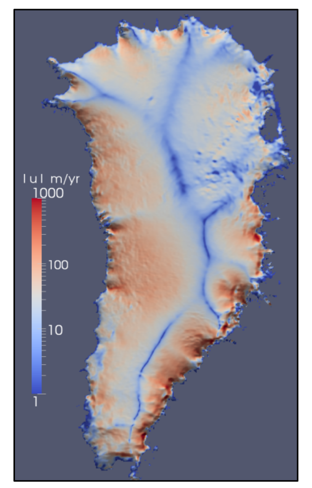


***Left**: Steady-state, thermo-mechanical Stokes FELIX solutions for EISMINT II test F, showing speed (top) and temperature (bottom).*

***Right**: SS basal temperature map from shallow-ice approx. model (top) - showing "cold spokes instability" - vs. from Stokes FELIX[7] (bottom).*

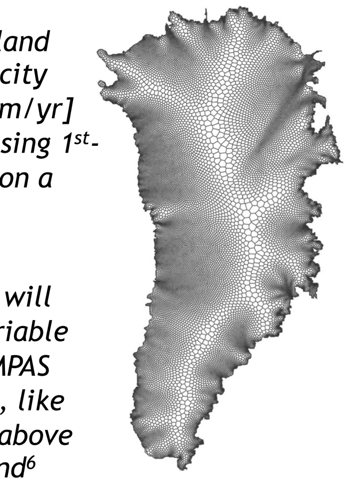


Greenland Results

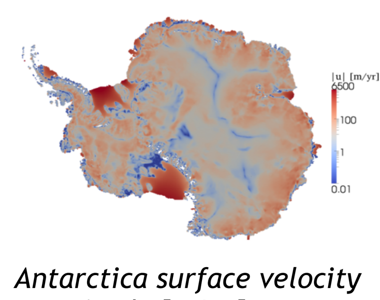


***Left**: Greenland surface velocity magnitude [m/yr] calculated using 1st-order FELIX on a structured*

***Right**: Simulations will soon use variable resolution MPAS CVT meshes, like that shown above for Greenland[6]*



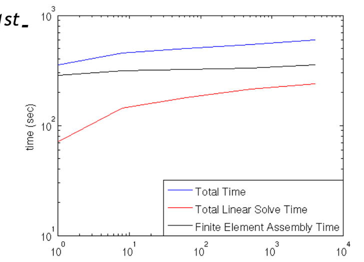
Antarctica Results



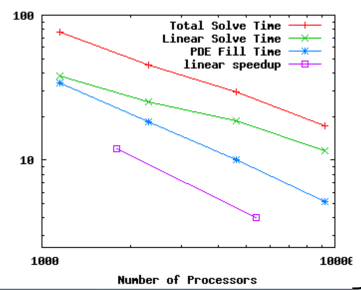
Antarctica surface velocity magnitude [m/yr] calculated using 1st-order FELIX on a 10km MPAS CVT mesh. $b=10^5$ [Land]; 10^{-5} [Floating]; Temperature = Linear

Scalability on Hopper

***Right Top**: Weak scaling of 1st-order FELIX on ISMIP test problem showing 60% efficiency after 4096x scale-up, nearly constant finite element assembly, and fast linear algebra.*



***Right Bottom**: Strong scaling of 1st-order FELIX on gis2km steady solve showing 4.5x speed-up on 8x processors, and small absolute times.*



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) [7]Leng et al., *JCP* (submitted) [8]Leng et al., *The Cryosphere*, **7** (2013)

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