A New Finite Element Ice Sheet Dycore Built for Advanced Analysis

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PISCEES SciDAC Project: Lipscomb (PI), Jones (Actg PI)
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The Objectives of our Development Effort under PISCEES:

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<th>To Develop:</th>
<th>robust &amp; scalable unstructured-grid finite element ice sheet code:</th>
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<td>• Higher-Order model for stress-velocity solves (non-linear Stokes with Glen’s law viscosity, 3D, 2 velocities)</td>
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<td>• Stand-alone steady-state model for initialization and calibration</td>
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<td>• Dynamic model when linked to CISM or MPAS for advection</td>
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<td>• Future land ice component for earth system models</td>
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| To Support: | climate decision support missions, such as providing Sea Level Rise predictions |

| To Leverage: | software and expertise from SciDAC Institutes (FASTMath, QUEST, SUPER) and hardware from DOE Leadership Class Facilities. |
Key Algorithm and Software Choices Help Meet our Objectives

Unstructured Grid Finite Element Discretization:
- Regional refinement
- Natural treatment of stress Boundary Conditions

Full Newton with Automatic Analytic Derivatives, Preconditioned Iterative Solvers:
- Most robust and efficient for steady-state solves
- Scalability

Born for Decision Support Role:
- Verification
- Analytic sensitivity analysis; Analytic gradients for inversion

Scalability of Software Development:
- Software tools & processes (e.g. nightly regression/integration tests)
- Leveraging of capabilities (e.g. from SciDAC Institutes)
New Code Developed using Libraries for everything but PDE Description

Software Quality
- Version Control
- Regression Testing
- Build System
- Backups
- Verification
- Continuous Integration

Linear Algebra
- Data Structures
- Iterative Solvers
- Direct Solvers
- Eigen Solver
- Preconditioners
- Multi-Level Methods

Analysis Tools (embedded)
- Nonlinear Solver
- Time Integration
- Continuation
- Sensitivity Analysis
- Stability Analysis
- Optimization
- UQ Solver

Mesh Tools
- Mesh Database
- Mesh I/O
- Inline Meshing
- Partitioning
- Load Balancing
- Adaptivity
- DOF map

Discretizations
- Discretization Library
- Field Manager

Derivative Tools
- Sensitivities
- Derivatives
- Adjoint
- UQ / PCE Propagation

Utilities
- Input File Parser
- Parameter List
- Memory Management
- I/O Management
- Communicators

Analysis Tools (black-box)
- Optimization
- UQ (sampling)
- Parameter Studies
- Bayesian Calibration
- Reliability

PostProcessing
- Visualization
- Verification
- Model Reduction

40+ packages; 120+ libraries
Higher-Order Model Verification #1: Solution Verification

Nonlinear Stokes’ Model for Ice Sheet Stresses

\[-\nabla \cdot (2\mu \dot{e}_1) = -\rho g \frac{\partial s}{\partial x}\]
\[-\nabla \cdot (2\mu \dot{e}_2) = -\rho g \frac{\partial s}{\partial y}\]

Method of Manufactured solutions:

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

• Ack: Irina Kalashnikova
Higher-Order Model Verification #2: Code-to-Code Comparisons

ISMIP-HOM Test C

...as well as:
ISMIP-HOM Test A
Confined Shelf
Circular Shelf

Dome Problem

Trilinos FELIX
Glimmer CISM
LifeV
Q: How to import Real data (Geometry, Topography, Surface height, Basal traction, Temp.)?

Answer #1: Glimmer-CISM-Glissade
- Structured Grid
- Square grid (extruded as Hexs)
- Compatible with CESM, CISM, POP
- Serial Glissade → file → FELIX → Mesh, then rerun in parallel

Greenland (Jakobshavn close-up) “5km” data sets

Answer #2: MPAS-Ice
- Unstructured CVT Grid
- Triangular dual grid (extruded as Tets)
- Compatible with MPAS-Ocean
- Parallel, using MPAS decomposition
Regular Grid Results: Greenland

Surface Velocity Magnitude [m/yr] in x-z planes. (Height “z” is stretched 100×.)

5 km resolution
640K hex elements
1.44M Unknowns
Const $\beta>>1$
Const $T$
MPAS Grid Results: Greenland & Antarctica

Greenland (Jakobshavn close-up)
Const $\beta, T$

Antarctica (10km)
$\beta=10^5$ [Land]; $10^{-5}$ [Floating]
Temperature = Linear

Variable $\beta, T$
Robustness: Full Newton Method augmented with Homotopy Continuation

\[ \mu = \frac{1}{2} A^{-\frac{1}{n}} \left( \frac{1}{2} \sum_{ij} \hat{e}_{ij}^2 + \gamma \right)^{\left(\frac{1}{2n} - \frac{1}{2}\right)} \]
Scalability: Initial Data (On Hopper)

Weak Scaling on ISMIP Test problem:
- 60% Efficiency after 4096x scale-up
- Finite Element Assembly nearly constant
- Linear algebra fast but not constant
- Ack: Ray Tuminaro

Strong Scaling on gis2km steady solve:
- 4.5x speed-up on 8x processors
- Absolute times are small
- Setup/PostProcessing cost not shown
- Ack: Pat Worley
Uncertainty Quantification #1: Propagation of Uncertainties

Uncertainty Propagation for 1-Parameter Sliding law for Dome Problem

\[ \beta = \text{Normal Distribution (mean}=1.0; \text{std deviation }= 0.2) \, [\text{kPa a / m}] \]

- 1000 samples using Dakota
- Library-mode Dakota \(\Rightarrow\) 1 run of code, only 1 setup cost
Bayesian Calibration against Synthetic Data for 4-Parameter Sliding law for Dome Problem

\[ \beta = \beta_0 + \beta_1 x + \beta_2 y + \beta_3 r \]

Using QUESO tool via Dakota framework in collaboration with QUEST SciDAC Institute
Summary and Future Work

Summary:
• New Finite Element dycore is being developed, nearly ready for Science
• Higher-Order PDEs, sliding BCs, floating BCs are implemented
• Through use of libraries/frameworks code already has:
  • Configuration, build, porting, test, verification
  • Parallel, robust, scalable, sensitivities, UQ propagation and calibration
  ➢ All for ~1 FTE of effort!

Ongoing/Future Work:
• Dynamic evolution driven by MPAS, CISM
• Deterministic inversion with adjoint-based gradients
• Stochastic calibration with subsequent propagation for predictions
• Improvements to: porting, integration testing, scalability, performance, robustness, UQ

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