Berkeley-ISICLES (BISICLES): High Performance Adaptive Algorithms For Ice Sheet Modeling

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Goal: Build a parallel, adaptive ice-sheet model

- Localized regions where high resolution needed to accurately resolve ice-sheet dynamics (500 m or better at grounding lines)
- Large regions where such high resolution is unnecessary (e.g. East Antarctica)
- Problem is well-suited for adaptive mesh refinement (AMR)
- Want good parallel efficiency
- Need good solver performance

Much higher resolution (1 km versus 5 km) required in regions of high velocity (yellow → green).

[Rignot & Thomas, 2002]
Develop an efficient parallel implementation of Glimmer-CISM by

- Incorporating structured-grid AMR using the Chombo framework to increase resolution where needed
- Exploring new discretizations and formulations where appropriate (L1L2)
- Improving performance and convergence of linear and nonlinear solvers, and
- Deploying auto-tuning techniques to improve performance of key computational kernels.
Block-Structured Local Refinement

- Refined regions are organized into rectangular patches.

- Algorithmic advantages:
  - Build on mature structured-grid discretization methods.
  - Low overhead due to irregular data structures, relative to single structured-grid algorithm.
“L1L2” Model *(Schoof and Hindmarsh, 2010).*

- Uses asymptotic structure of full Stokes system to construct a higher-order approximation
  - Expansion in $\varepsilon$ -- ratio of length scales $\frac{[h]}{[x]}$
  - Computing velocity to $O(\varepsilon^2)$ only requires $\tau$ to $O(\varepsilon)$

- Computationally much less expensive -- enables fully 2D vertically integrated discretizations. (can reconstruct 3d)

- Similar formal accuracy to Blatter-Pattyn $O(\varepsilon^2)$
  - Recovers proper fast- and slow-sliding limits:
    - SIA $(1 \ll \lambda \leq \varepsilon^{-1/n})$ -- accurate to $O(\varepsilon^2 \lambda^{n-2})$
    - SSA $(\varepsilon \leq \lambda \leq 1)$ - accurate to $O(\varepsilon^2)$
Baseline model is the one used in Glimmer-CISM:

- Logically-rectangular grid, obtained from a time-dependent uniform mapping.
- 2D equation for ice thickness, coupled with 2D steady elliptic equation for the horizontal velocity components. The vertical velocity is obtained from the assumption of incompressibility.
- Advection-diffusion equation for temperature.

Use of Finite-volume discretizations (vs. Finite-difference discretizations) simplifies implementation of local refinement.

Software implementation based on constructing and extending existing solvers using the Chombo libraries.
Interface with Glimmer-CISM

- Glimmer-CISM has coupler to CESM, additional physics
  - Well-documented and widely accepted
- Our approach - couple to Glimmer-CISM code as an alternate “dynamical core”
  - Allows leveraging existing Glimmer-CISM capabilities
  - Use the same coupler to CESM
  - BISICLES code sets up within Glimmer-CISM and maintains its own storage, etc.
  - Communicates through defined interface layer
  - Instant access to a wide variety of test problems
  - Interface development almost complete
  - Part of larger alternative “dycore” discussion for Glimmer-CISM
Recent Progress (Since January LIWG)

- Added temperature solver
  - Horizontal and vertical advection, vertical diffusion
  - Currently testing

- Linear and nonlinear solver improvements (improved robustness)

- Improvements to Glimmer-CISM/BISICLES dycore interface and design

- Some software redesign

- Basic calving model
**BISICLES Results - Pine Island Glacier**

- Poster by Cornford, et al
- PIG configuration from LeBrocq:
  - AGASEA thickness
  - Isothermal ice, $A = 4.0 \times 10^{-17} \text{ Pa}^{-\frac{1}{3}} \text{ m}^{-1/3} \text{ a}$
  - Basal friction chosen to roughly agree with Joughin (2010) velocities
- Specify melt rate under shelf:
  - $M_s = \begin{cases} 
  0 & H < 50m \\
  \frac{1}{9} (H - 50) & 50 \leq H \leq 500m \\
  50 & H > 500 m
  \end{cases} \text{ m/a}$
- Constant surface flux = 0.3 m/a
- Evolve problem - refined meshes follow the grounding line.
- Calving model and marine boundary condition at calving front
Pine Island, cont

Ice shelf, grounding line, $t = 0$
Ice shelf, grounding line, $t = 7.75\text{yr}$
Pine Island, cont

Ice shelf, grounding line, $t = 15.65\text{yr}$
Ice shelf, grounding line, $t = 23.56 \text{yr}$
Pine Island, cont

Ice shelf, grounding line, \( t = 31.125 \text{yr} \)
Pine Island, cont

Refined mesh, t = 0
Refined mesh, $t = 7.75$yr
Pine Island, cont

Refined mesh, $t = 15.625\text{yr}$
Pine Island, cont

Refined mesh, $t = 23.575\text{yr}$
Refined mesh, $t = 30.125\text{yr}$
Basal ice velocity, $t = 0$
Basal ice velocity, $t = 7.75$
Pine Island, cont

Basal ice velocity, \( t = 15.625 \)
Basal ice velocity, $t = 23.375$
Basal ice velocity, $t = 31.125$
Uses new “model-friendly” problem setup
(Le Brocq, Payne, Vieli (2010))
Antarctica, cont

- 10 km base mesh with 2 levels of refinement (5 km, 2.5 km)
  - base level (10 km): 258,048 cells (100% of domain)
  - level 1 (5 km): 431,360 zones (41.8% of domain)
  - Level 2 (2.5 km): 728,832 cells (17.7% of domain)
Parallel scaling, Antarctica benchmark
BISICLES - Next steps

- More work with linear and nonlinear velocity solves.
- Semi-implicit time-discretization for stability, accuracy.
- Finish coupling with existing Glimmer-CISM code and CESM
  - Testing with more complex and fully coupled problems
- Performance optimization and autotuning.
- Refinement in time?