Recent progress with the BISICLES dynamical core in CISM

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Berkeley-ISICLES (BISICLES)

- DOE ISICLES-funded project to develop a scalable adaptive mesh refinement (AMR) ice sheet model/dycore
  - Local refinement of computational mesh to improve accuracy
- Use Chombo AMR framework to support block-structured AMR
  - Support for AMR discretizations
  - Scalable solvers
  - Developed at LBNL
  - DOE ASCR supported (FASTMath)
- Alternate dycore interface to CISM
- Collaboration with LANL and Bristol (U.K.)
- Continuation in SciDAC-funded PISCEES.
“L1L2” Model (Schoof and Hindmarsh, 2010).

- Uses asymptotic structure of full Stokes system to construct a higher-order approximation
  - Expansion in $\varepsilon = \frac{H}{L}$ and $\lambda = \frac{[\tau_{shear}]}{[\tau_{normal}]}$ (ratio of shear & normal stresses)
    - Large $\lambda$: shear-dominated flow
    - Small $\lambda$: sliding-dominated flow
  - 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 $O(\varepsilon^2)$
“L1L2” Model (Schoof and Hindmarsh, 2010), cont.

- Can construct a computationally efficient scheme:
  1. Approximate constitutive relation relating \( \text{grad}(u) \) and stress field \( \tau \) with one relating \( \text{grad}(u|_{z=b}) \), vertical shear stresses \( \tau_{xz} \) and \( \tau_{xz} \) given by the SIA / lubrication approximation and other components \( \tau_{xx}(x, y, z) \), \( \tau_{xy}(x, y, z) \), etc.
  2. leads to an effective viscosity \( \mu(x, y, z) \) which depends only on \( \text{grad}(u|_{z=b}) \) and \( \text{grad}(z_s) \), ice thickness, etc.
  3. Momentum equation can then be integrated vertically, giving a nonlinear, 2D, elliptic equation for \( u|_{z=b}(x, y) \)
  4. \( u(x, y, z) \) can be reconstructed from \( u|_{z=b}(x, y) \)
Modified “L1L2” Model (SSA*)

- Can construct a computationally efficient scheme:
  1. Approximate constitutive relation relating $\text{grad}(u)$ and stress field $\tau$ with one relating $\text{grad}(u|_{z=b})$, vertical shear stresses $\tau_{xz}$ and $\tau_{xz}$ given by the SIA / lubrication approximation and other components $\tau_{xx}(x, y, z)$, $\tau_{xy}(x, y, z)$, etc
  2. leads to an effective viscosity $\mu(x, y, z)$ which depends only on $\text{grad}(u|_{z=b})$ and $\text{grad}(z_s)$, ice thickness, etc
  3. Momentum equation can then be integrated vertically, giving a nonlinear, 2D, elliptic equation for $u|_{z=b}(x, y)$
  4. $u(x, y, z)$ can be $u(x, y, z) = u|_{z=b}(x, y)$ (neglect vertical shear in flux velocity)
Experiment P75R: (Pattyn et al (2011))

- Begin with steady-state (equilibrium) grounding line.
- Add Gaussian slippery spot perturbation at center of grounding line.
- Ice velocity increases, GL advances.
- After 100 years, remove perturbation.
- Grounding line should return to original steady state.
- Figures show AMR calculation:
  - $\Delta x_0 = 6.5\text{km}$ base mesh,
  - 5 levels of refinement
  - Finest mesh $\Delta x_4 = 0.195\text{km}$.
  - $t = 0, 1, 50, 101, 120, 200\text{ yr}$
- Boxes show patches of refined mesh.
- GL positions match Elmer (full-Stokes)
MISMIP3D (cont): L1L2 (SSA*) Spatial Resolution

• Very fine (~200 m) resolution needed to achieve reversibility!
MISMIP3D: SSA vs. “L1L2” or “SSA*”

- Direct comparison of SSA vs. SSA*
  - (fully resolved spatially, same numerics, etc)
  - Note difference in steady-state GL positions
BISICLES Results - Ice2Sea Amundsen Sea

- Study of effects of warm-water incursion into Amundsen Sea.
- Results from Payne et al, (2012), submitted.
- Modified 1996 BEDMAP geometry (Le Brocq 2010), basal traction and damage coefficients to match Joughin 2010 velocity.
- Background SMB and basal melt rate chosen for initial equilibrium.
- SMB held fixed.
- Perturbations in the form of additional subshelf melting:
  - derived from FESOM circumpolar deep water
  - ~5 m/a in 21st Century,
  - ~25 m/a in 22nd Century.
Amundsen Sea Ice Sheet Simulation

One possible climate scenario (Payne et al.) simulated using SciDAC-funded BISICLES code
Ice2Sea Amundsen (cont)

- Need at least 2 km resolution to get any measurable contribution to SLR.
- Appears to converge at first-order in $\Delta x$
Ice2Sea Amundsen (cont) - Thwaites?

- In 400 year run, Thwaites destabilizes as well.
- Same forcing as previous run, subshelf melting held constant past 2200.
- Thwaites is very stable, until it tips.
Recent Code developments

- BISICLES/CISM coupling
- FAS multigrid solver
- Embedded boundary for Grounding lines
CISM/BISICLES coupling update

- Extension of existing serial coupled code to work in the fully distributed case (no serial bottlenecks)
- CISM (F90) to BISICLES (C++)
- General API design for coupling alternate dynamical cores into CISM
- Moderately complex build process (working to streamline)
- CISM owns “main”, problem setup, coupler to CESM, other physics (like isostasy, hydrology, etc)
- CISM hands control to BISICLES, which evolves the ice sheet
- BISICLES passes fields like thickness, velocity back to CISM
CISM/BISICLES coupling update (cont)
Embedded Boundary (EB) for Grounding Lines

- Embedded Boundary (EBChombo)
  - Currently force GL and ice margins to cell faces
  - “Stair-step” discretization
    Known to be inadequate from experience with Stefan Problem in other contexts!
  - Use Chombo Embedded-boundary support to improve discretization of GL’s and ice margins.
  - Can solve as a Stefan Problem, with appropriate jump conditions enforced at grounding line.
    (as in Schoof, 2007)
**New FAS Multigrid nonlinear solver**

- Full Approximation Storage (FAS) - nonlinear multigrid

- Picard, JFNK:
  - linear solver nested inside of nonlinear one
  - Linear Multigrid solvers (residual-correction form) work well.

- FAS Multigrid - fully nonlinear solver (no outer solver)
  - Can outperform JFNK/MG
  - More robust (don’t need good initial guess)
  - Simpler to implement and maintain
  - Nonlinear convergence similar to MG linear convergence
Antarctica (*Ice2Sea*)

- Refinement based on Laplacian(velocity), grounding lines
- 5 km base mesh with 3 levels of refinement
  - base level (5 km): 409,600 cells (100% of domain)
  - level 1 (2.5 km): 370,112 cells (22.5% of domain)
  - Level 2 (1.25 km): 955,072 cells (14.6% of domain)
  - Level 3 (625 m): 2,065,536 cells (7.88% of domain)
Next Steps

- Continue work with CISM/BISICLES hybrid code
  - Fully 2-way coupling
  - Eventual coupling to CESM

- Embedded boundary approach is promising

- More solver improvements

- Full-Stokes dynamical core
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Linear Solvers - GAMG vs. Geometric MG

SeaRise/Ice2Sea Antarctica Ice velocity solve

- MG-JFNK outer
- MG-JFNK inner
- petsc
- petsc

L2(residual) vs outer iteration