Progress on MPAS Land Ice Model Development

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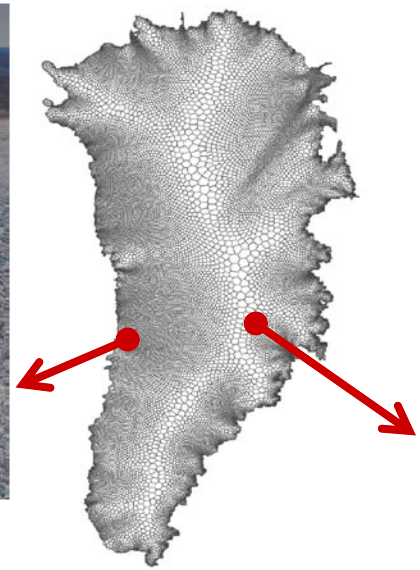
Outline

- **MPAS Overview**
- **Status of Velocity Solvers**
- **Coupling & Science Applications**

MPAS-Land Ice

- **MPAS** - **M**odel for **P**rediction **A**cross **S**cales: A climate modeling framework that supports dynamical cores on unstructured Voronoi (SCVT) meshes (MPAS Atmosphere, Land Ice, Ocean, Sea Ice cores)

- Funded under PISCEES project:
- LANL, ORNL, SNL, NCAR, FSU, USC, UT, MIT
- **Goal:** Hierarchical suite of FEM-based ice sheet dynamical cores (Stokes[1], 1st-order[2], LIL2[2], etc.) based on MPAS CVT mesh generation and modeling framework



Allows high resolution in regions of interest, reducing necessary number of grid cells by ~10x

[1]Leng et al., *JGR,* **117** (2012) [2]Perego et al., *J. Glac.* **58** (2012)

Current Breakdown of Responsibility

Ice flow equations

$$-\nabla \cdot \sigma = \rho \mathbf{g} \qquad \text{and} \qquad \nabla \cdot \mathbf{u} = 0,$$

with $\sigma = \tau - pI = 2\mu(\dot{\varepsilon})\,\dot{\varepsilon} - pI,$

where μ viscosity, $\dot{\varepsilon}$ shear rate

FO-FELIX (Using Trilinos); SNL
Stokes-FELIX (Using PHG); USC, FSU

Model for the evolution of the boundaries (thickness evolution equation)

$$\frac{\partial H}{\partial t} = H_{flux} - \nabla \cdot \int_z \mathbf{u}\, dz$$

Temperature equation

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) - \rho c \mathbf{u} \cdot \nabla T + 2\dot{\varepsilon}\sigma$$

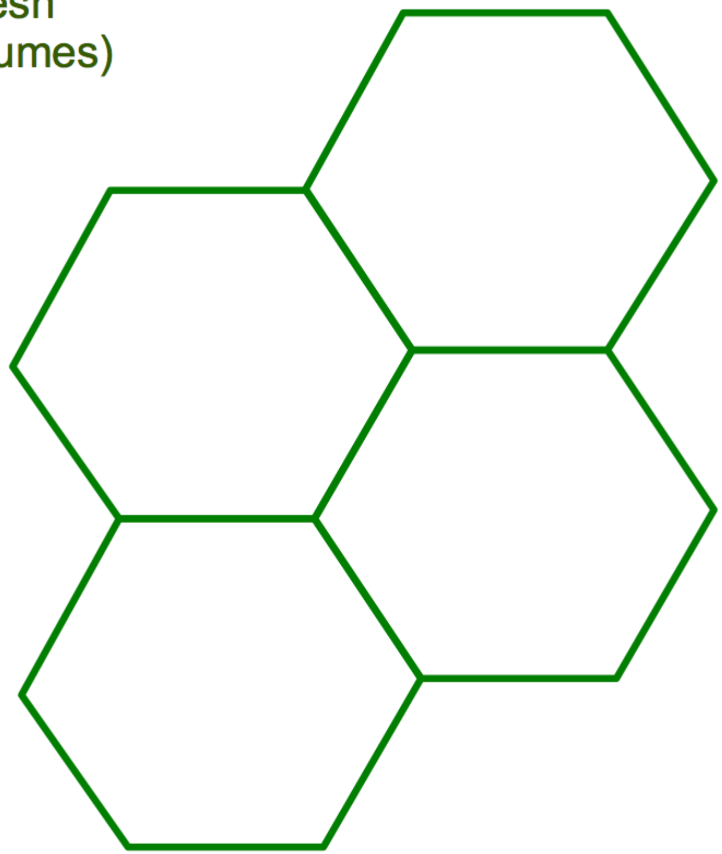
Additional physics (e.g., basal processes)

Coupling to Earth Systems Models

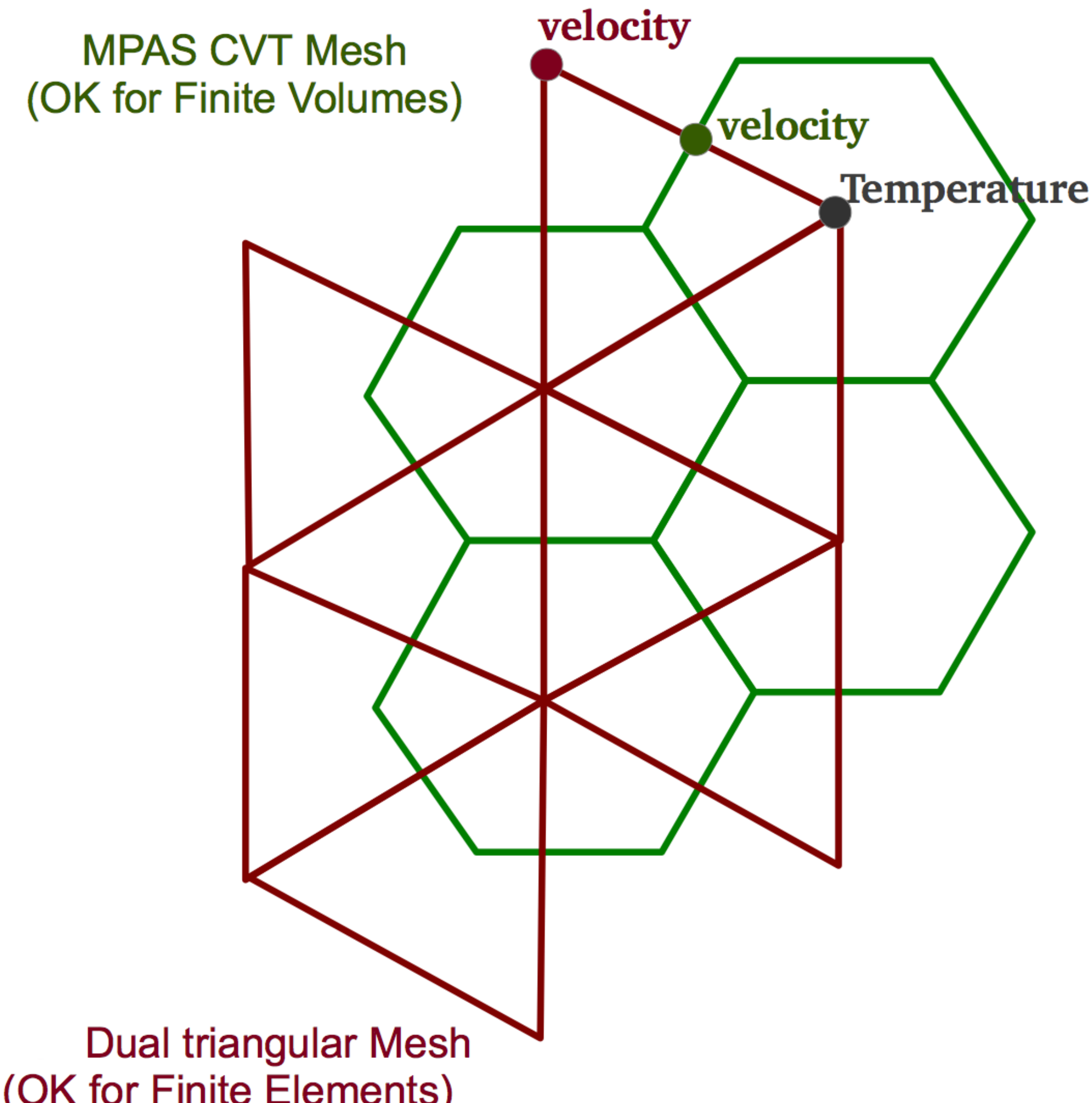
MPAS-LI; LANL

Interface - Grids

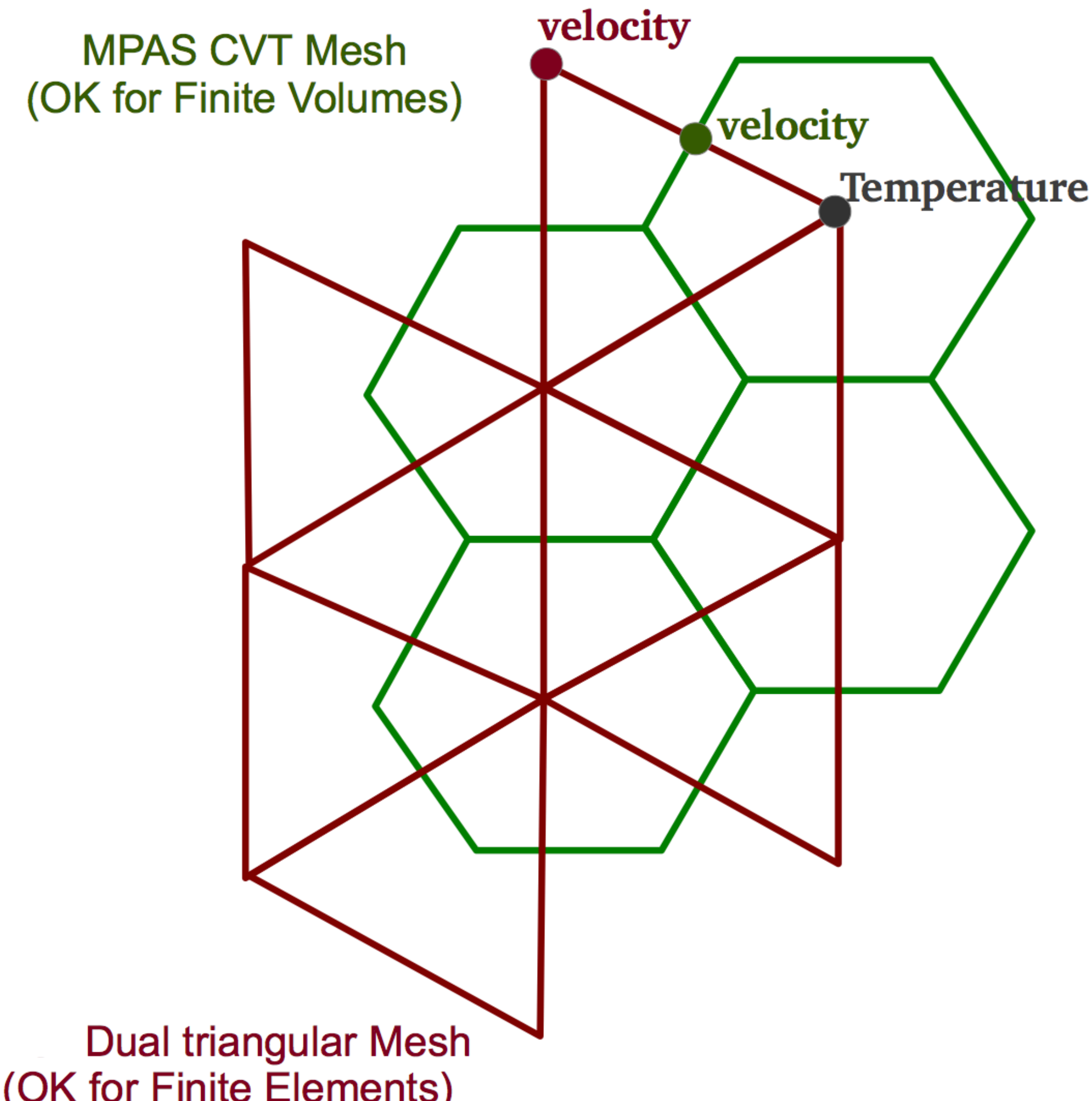
MPAS CVT Mesh
(OK for Finite Volumes)



Interface - Grids

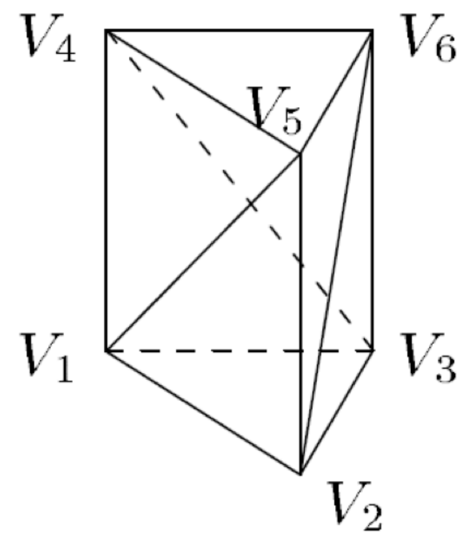


Interface - Grids



Based on 2D grid and thickness and layers build vertically structured **3D grid.**

Build prisms with triangular base and split them in tetrahedra.



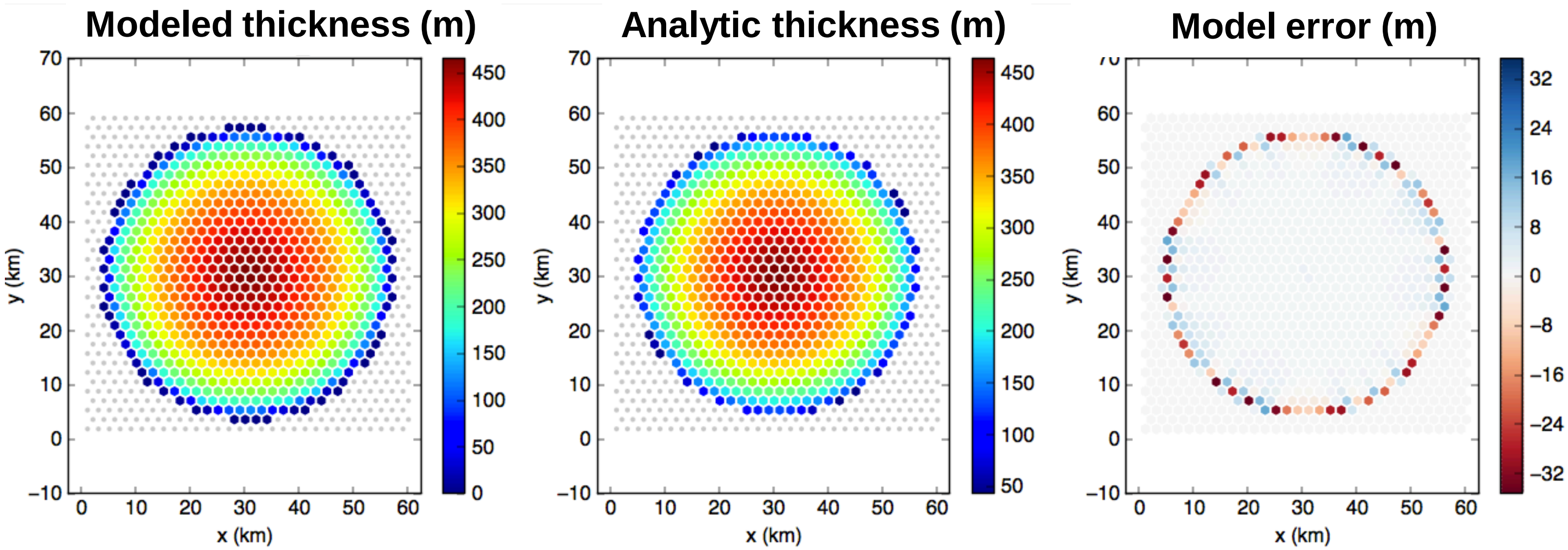
Status of MPAS-Land Ice

- **Initial Public Release**, November 2013: http://mpas-dev.github.io/
- Native SIA solver
- Interfaces to LiveV (SSA, L1L2, FO, Stokes solvers), Albany-FELIX (FO solver), PHG (Stokes solver)
- Forward Euler Time Integration
  - Optional adaptive time stepping
- Thickness evolution
  - FO Upwind
  - Margin advance & retreat
  - Surface Mass Balance
  - Higher-order Flux Corrected Transport
- Tracer (temperature) transport: First-Order & Flux Corrected Transport (FCT) scheme
- Tools external to MPAS (written mostly in python)
  - Setup land ice grids on regular planar hex mesh or variable resolution spherical mesh
  - Ability to setup test cases: Halfar dome, EISMINT, ISMIP-HOM (in progress)
  - Copy CISM datasets to MPAS grids
  - Visualization tools (not many off-the-shelf options)
  - Automated testing using 'lettuce'
  - 'loose' coupler to MPAS-Ocean

Status of Velocity Solvers

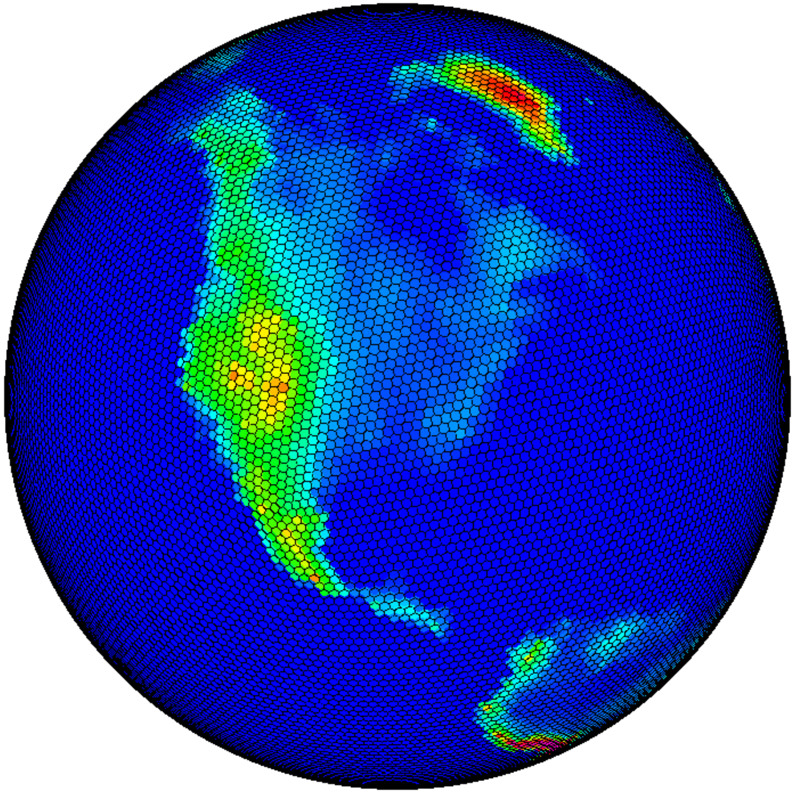
- Native Fortran SIA (LANL)
- Albany-FELIX First Order (SNL)
- PHG-FELIX Stokes (USC, FSU)

Halfar analytic test case for SIA after 1000 years on 2 km mesh

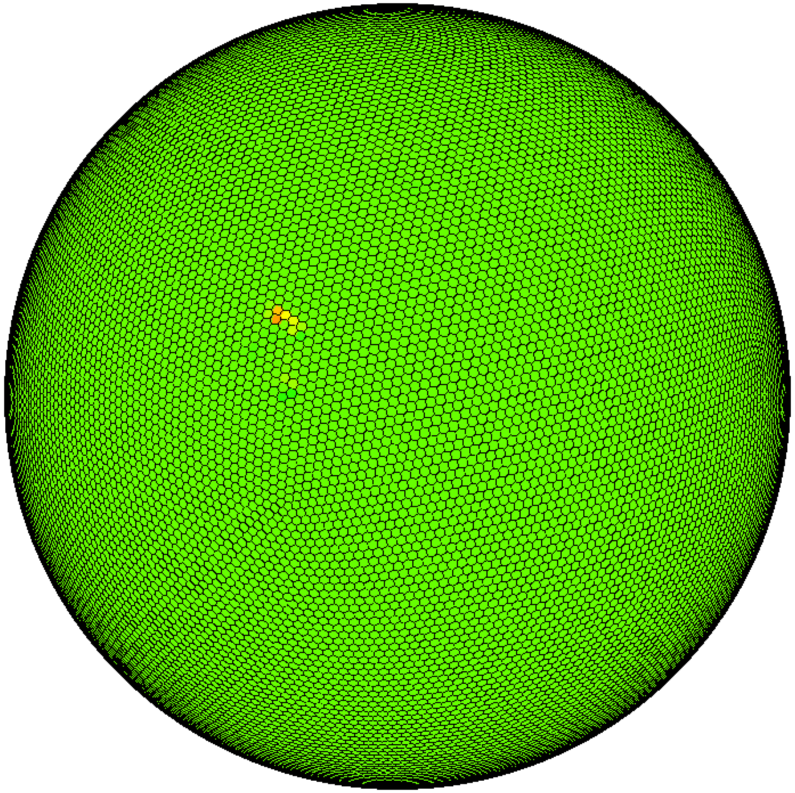


MPAS SIA solver running on a sphere (FO, Stokes can too)

Simplistic "Laurentide-like" simulation:
inception, 10's ka simulation time, multiple ice masses



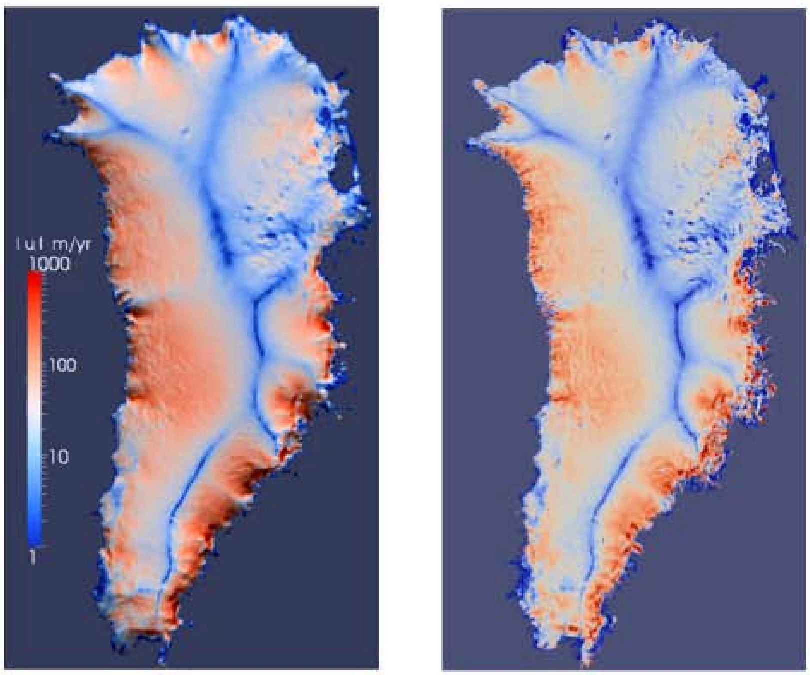
Surface Topography



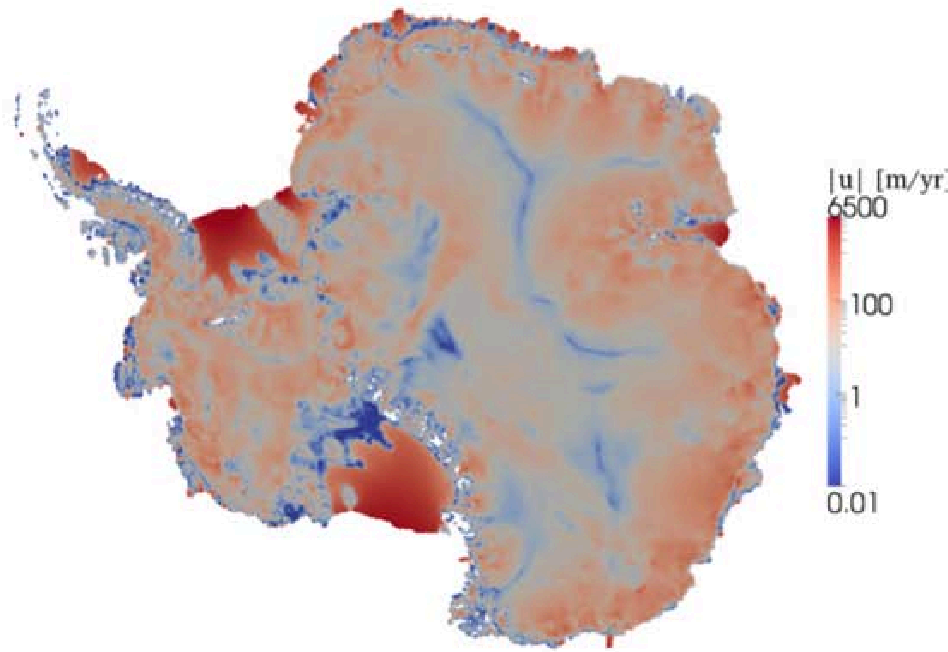
N-S Ice Speed

Albany-FELIX, First-Order Solver
(see talk by Irina Kalashnikova)

Sandia National Lab:
Andy Salinger
Irina Kalashnikova
Mauro Perego



Diagnostic surface speed for Greenland (log10 m/yr) from FELIX 1st-order at 5 km (left) and 1 km (right) resolution (no sliding and uniform rate factor assumed).

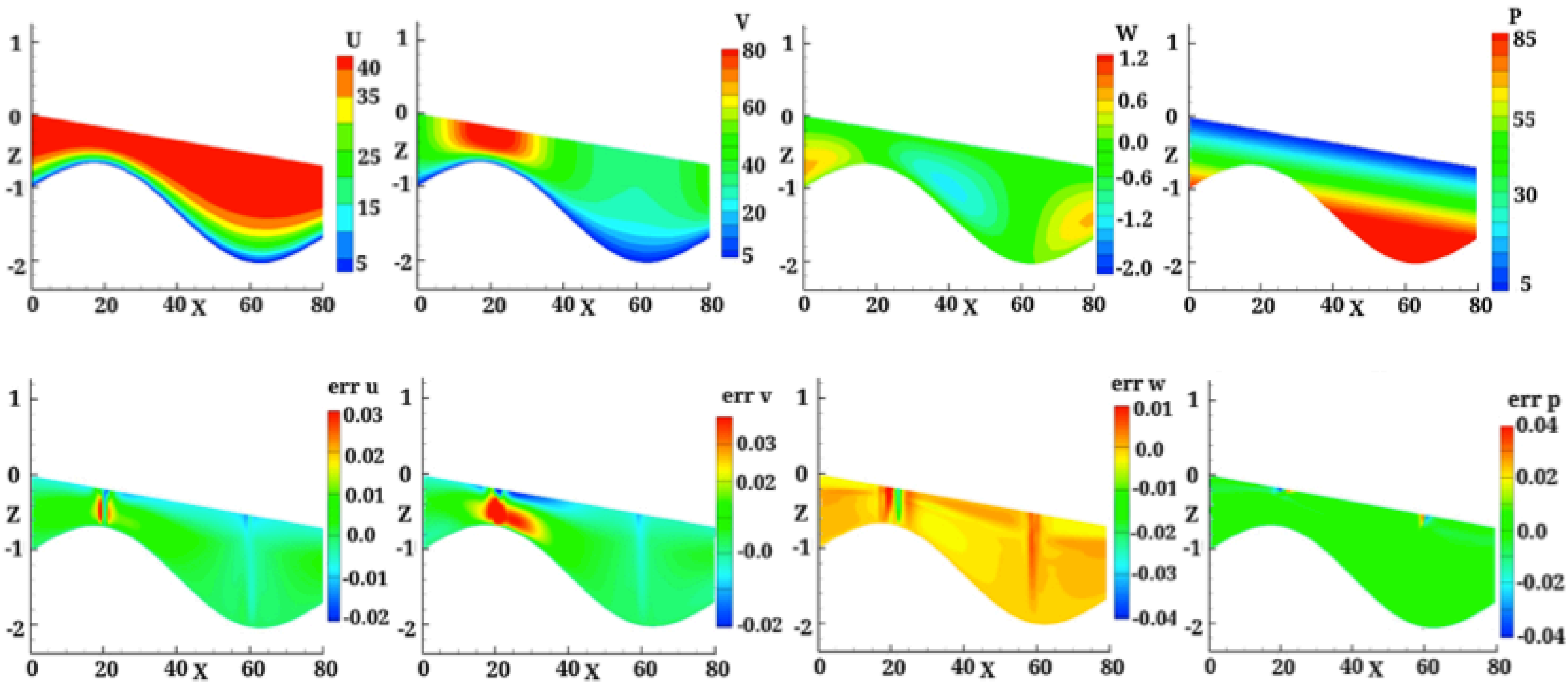


Surface speed for Antarctica (m/yr) calculated from FELIX 1st-order at 10 km resolution with uniform basal sliding coefficient on grounded ice of 10^5 Pa yr / m.

Stokes-FELIX

Univ. South Carolina: Lili Ju
Chinese Academy of Sciences: Wei Leng
Florida State Univ.: Max Gunzburger

Top: Manufactured solutions (Leng et al., 2012) for velocity (u,v,w) and pressure (P) used for verification of FELIX-Stokes.
Bottom: Solution errors for velocity and pressure.



Wei Leng, Lili Ju

Improved mass conservation of Enhanced Taylor-Hood Finite Elements

Wei Leng
Lili Ju
Max Gunzburger

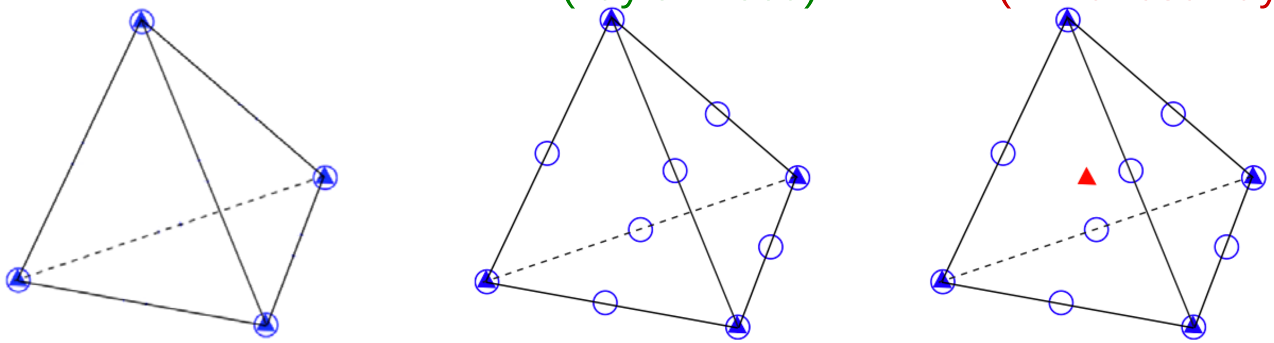
P1/P1

P2/P1 (Taylor-Hood)

P2/P1+P0 (Enhanced Taylor-Hood)

○ Velocity DOF

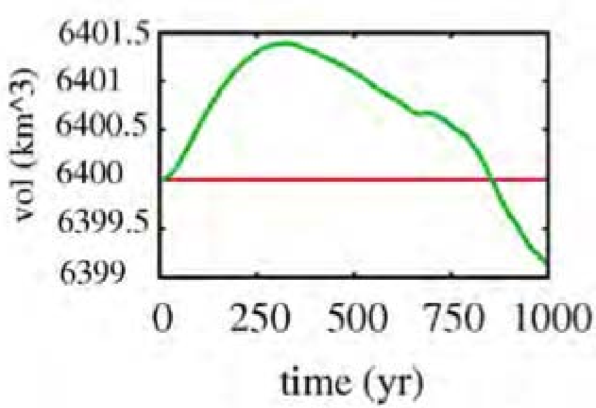
▲ Pressure DOF



Global mass conservation only

Local mass conservation

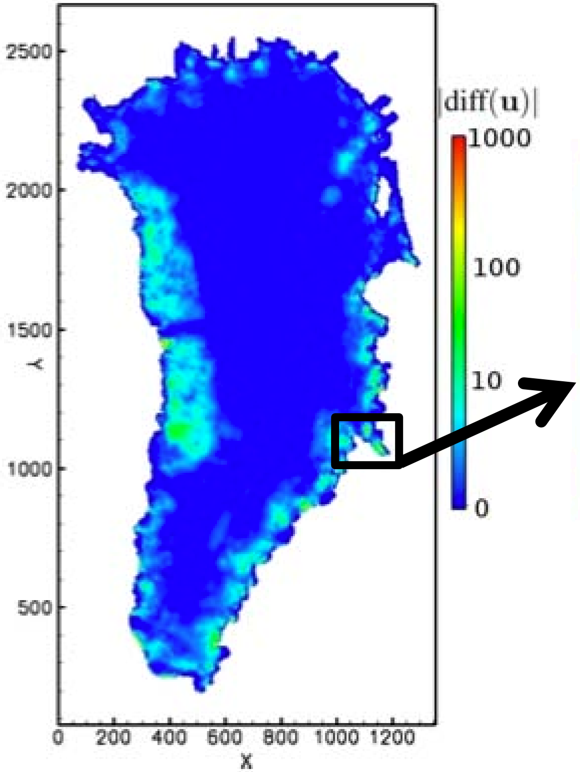
Volume of ice in manufactured solution test case over 1000 yr:



Application to Greenland

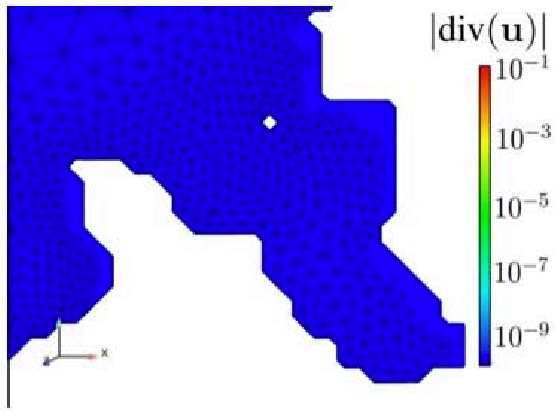
Wei Leng
Lili Ju
Max Gunzburger

Velocity Difference between
Taylor-Hood and
Enhanced Taylor-Hood elements

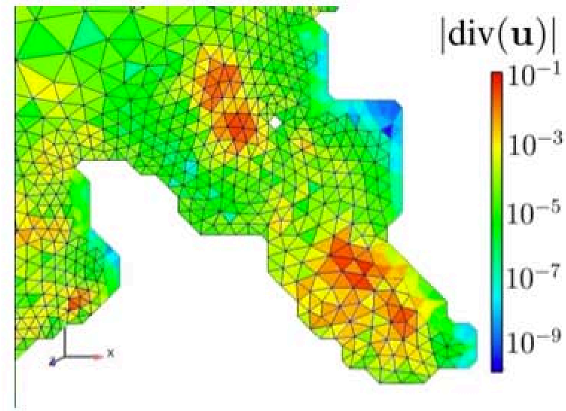


Flux Divergence

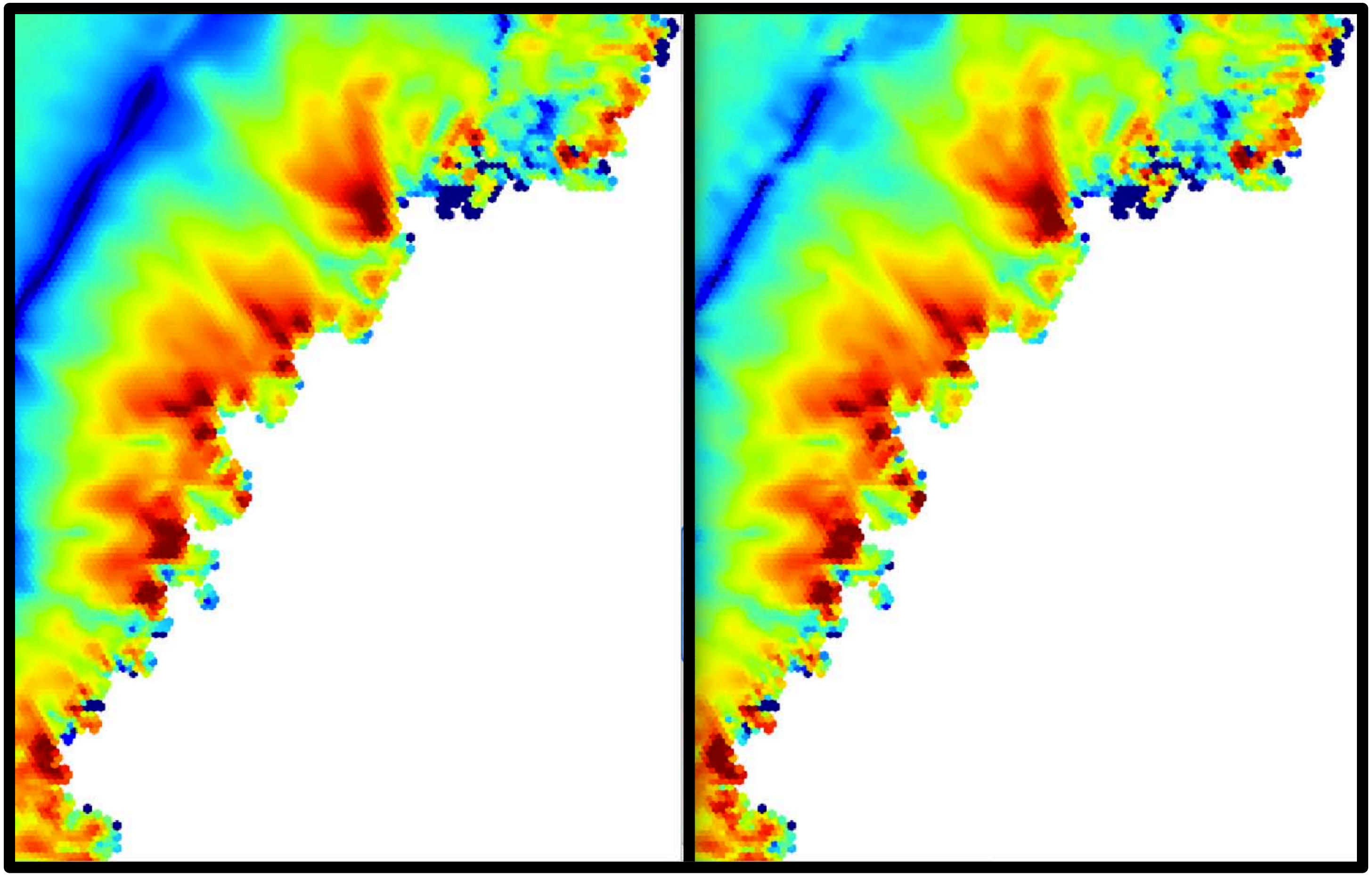
Enhanced Taylor-Hood



Taylor-Hood



5km Greenland:
FO vs. Stokes



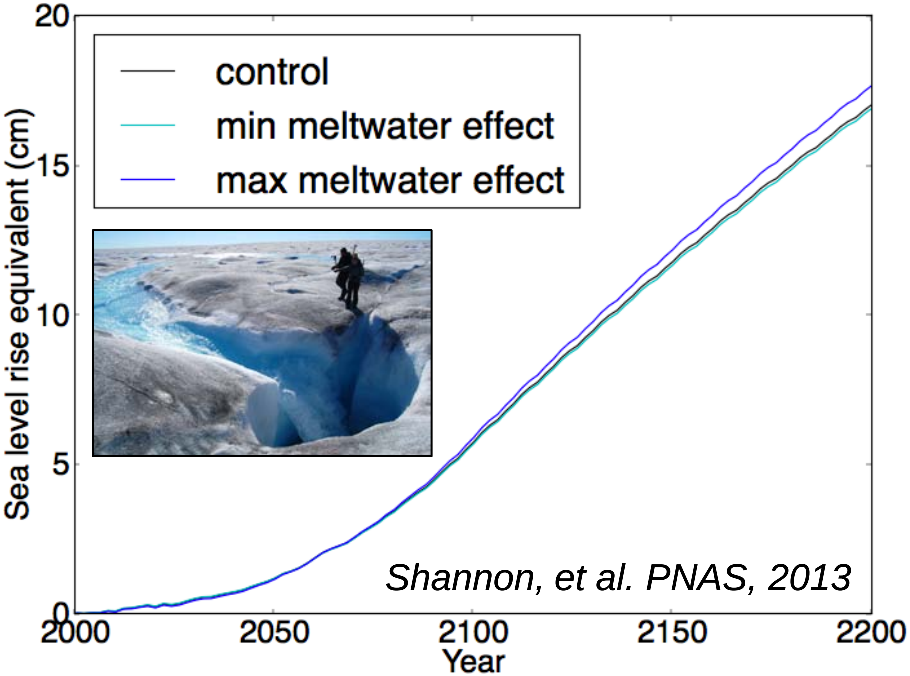
UNCLASSIFIED

ice2sea Model Intercomparison: Greenland Sea Level Rise Predictions

Results using MPAS model

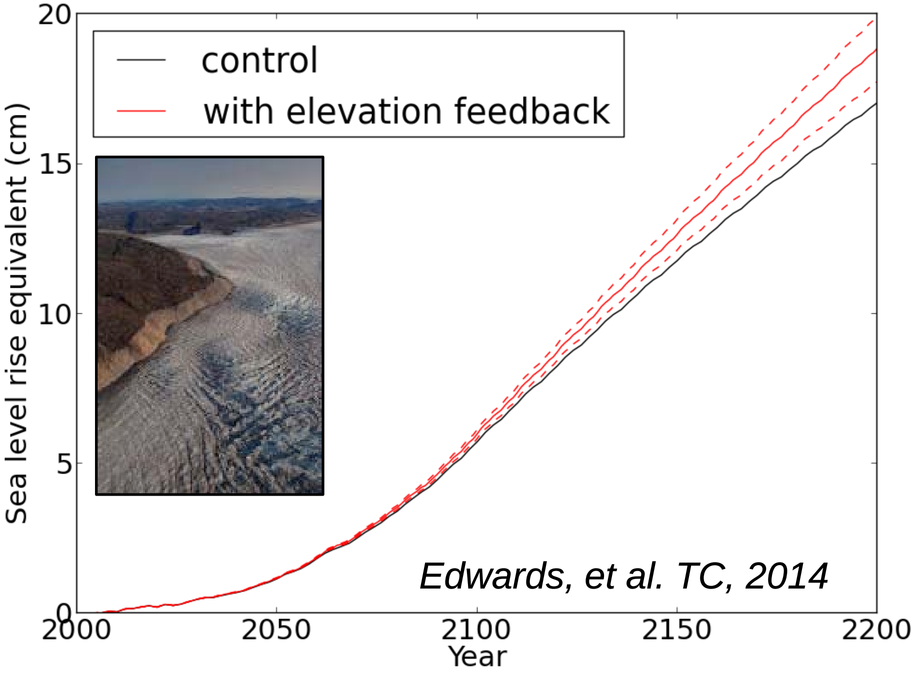
Meltwater induced speedup

Sliding = f(runoff)

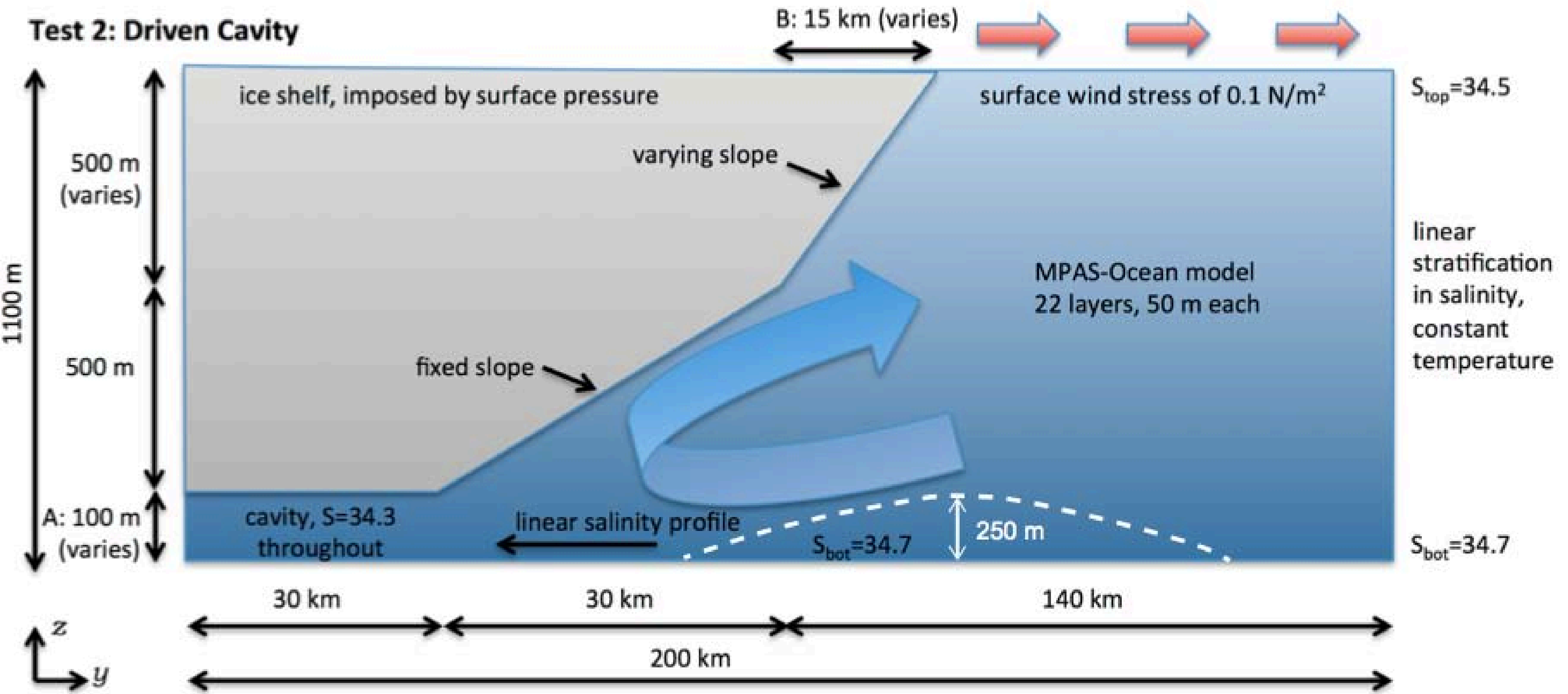


Elevation feedback

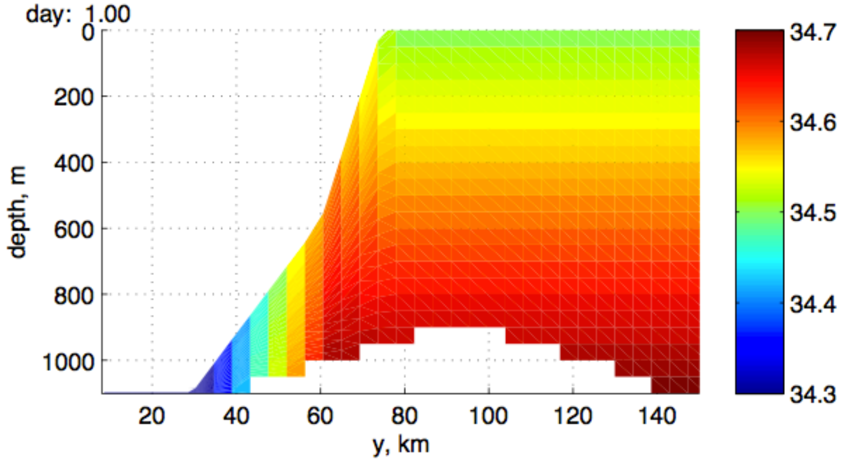
SMB = f(elevation)



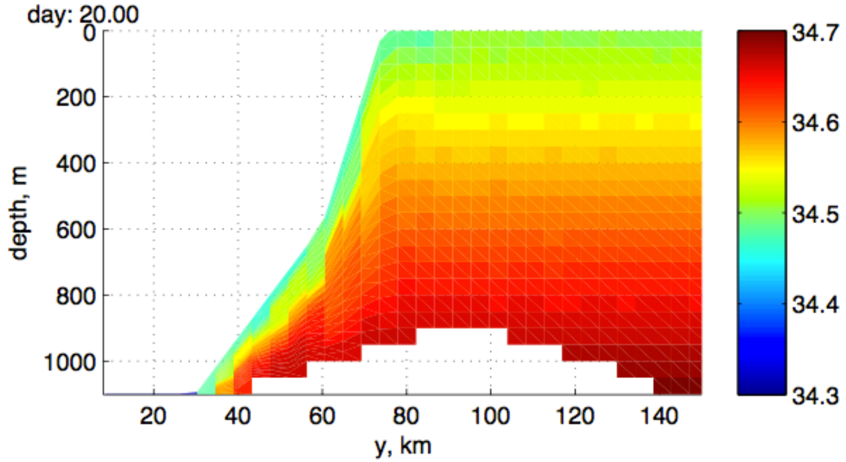
MPAS-Ocean: Support for sub-shelf circulation



Mark Petersen, LANL



Initial sub-shelf salinity for the idealized test case with a subglacial cavity 1 m in height. Other parameters for the problem are detailed in the figure above.



After 20 days of foward model integration, a plot of the sub-shelf salinity indicates turbulent mixing relative to the initial condition and the development of a stable, relatively fresh-water plume circulation beneath the shelf.

Mark Petersen, LANL

Questions?

Implementation Overview

Trilinos:
- Parallel Data Structures (EPETRA)
- Parallel Linear Solvers (GMRES, CG...)
- Preconditioners (Multilevel, Multigrid, Incomplete LU)
- Nonlinear Solvers (**NOX** package: Newton, JFNK methods)

⇧

ice-sheets FE dynamics component

LifeV: Parallel, object oriented, C++ Finite Element Library:
- linear and quadratic finite elements
- assembling of finite element matrices
- handling of boundary conditions

⇧

MPAS (land ice component):
- Voronoi unstructured grids
- Evolution equation solvers (temperature and thickness equation)
- ...

MPAS Framework
- I/O
- MPI
- Grid management
- Timekeeping
- Shared operators
- ...

Interface MPAS- FELIX

MPAS

Land ice component

FELIX

ice-sheets component

2D CVT mesh
(Stereographic projection)

thickness/elevation/layers

temperature/ice flow factor

bedrock sliding coefficient

Solver options:
model (FO, L1L2, SSA, SIA)
nonlinear solver (Newton, Picard, JFNK)
Boundary condition (free-slip, no-slip, robin, coulomb)

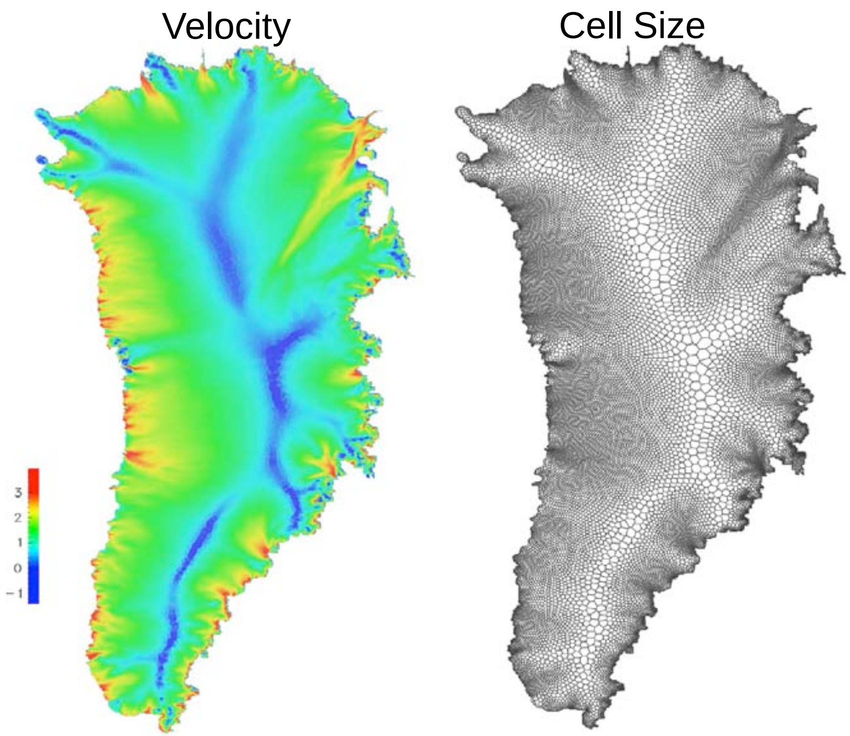
velocity

heat dissipation

viscosity

What's missing (short to medium term goals)

- Variable resolution planar hex meshes (talking with MPAS-A)
- Finish temperature implementation (vertical diffusion)
- Higher order thickness advection (using modified MPAS framework methods)
- Coupling to CESM
- More physics… (e.g. basal processes)

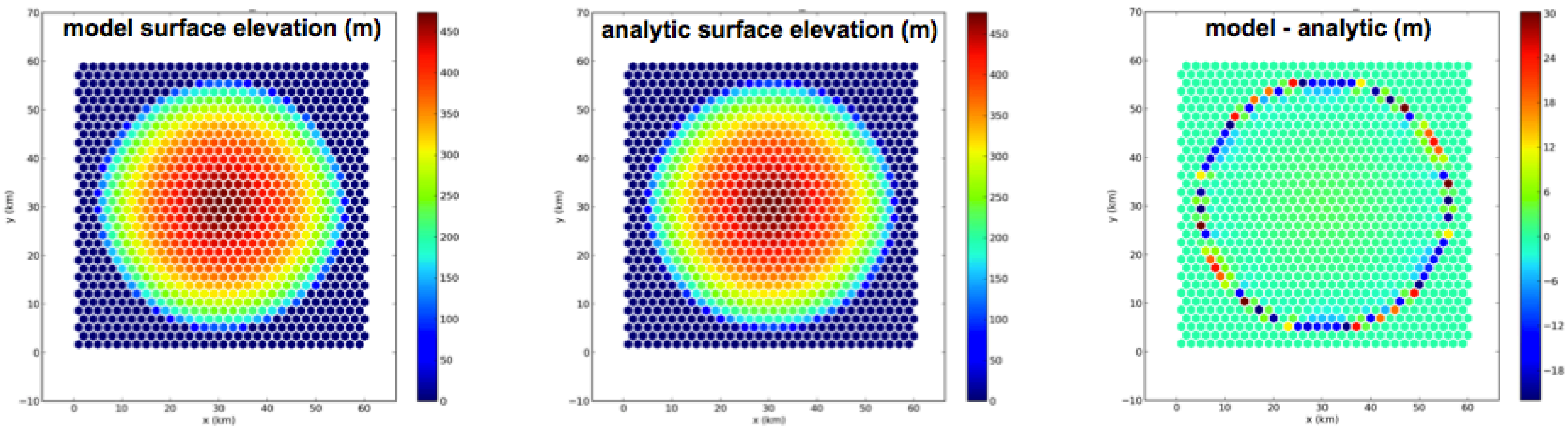


Ringler et al., *Ocean Dyn.* (2008)

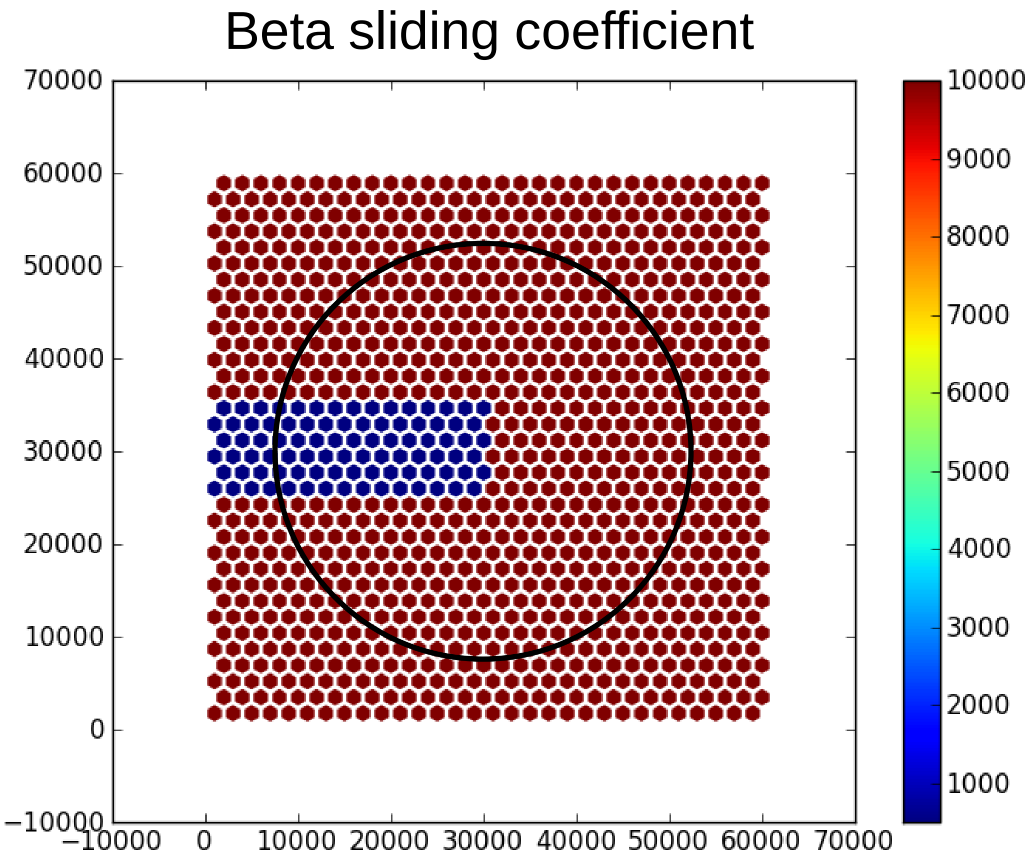
Status of Velocity Solvers

- Native Fortran SIA (LANL)
- Albany-FELIX First Order (SNL)
- PHG-FELIX Stokes (USC, FSU)

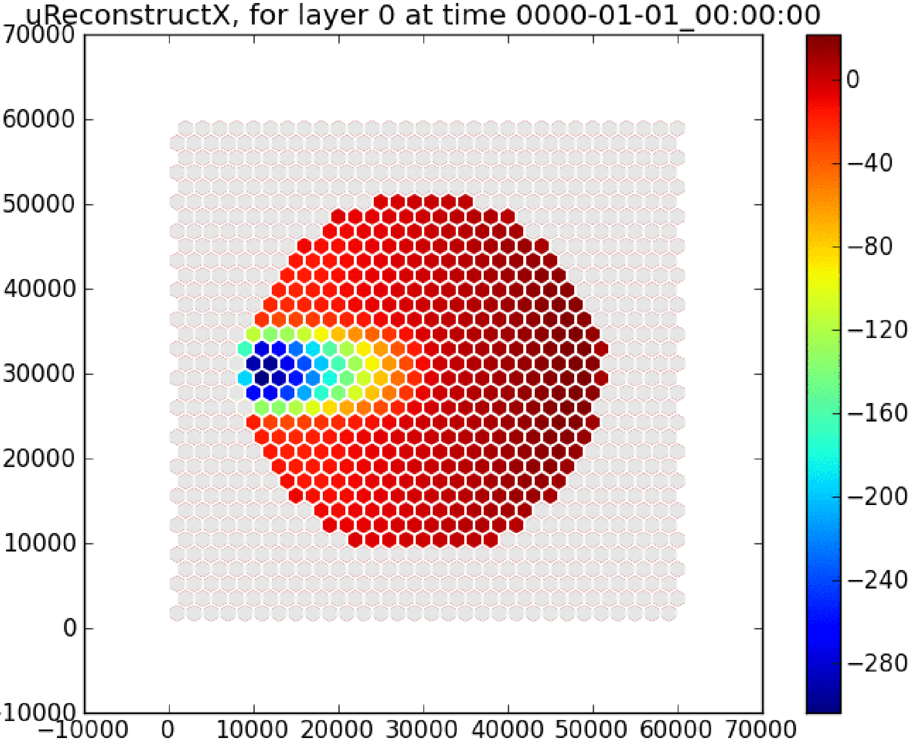
Below: Analytic (left) and SIA-modeled (middle) solutions for the Halfar test case after t=1000 yrs, and their difference (right).

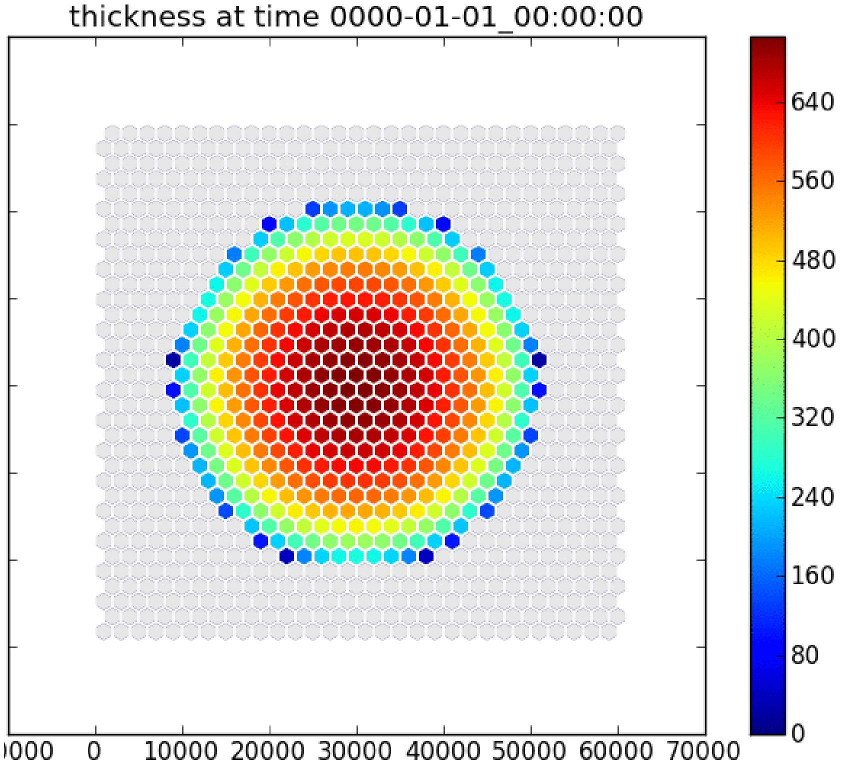


Dome: FO Velocity Solver – 'ice stream'

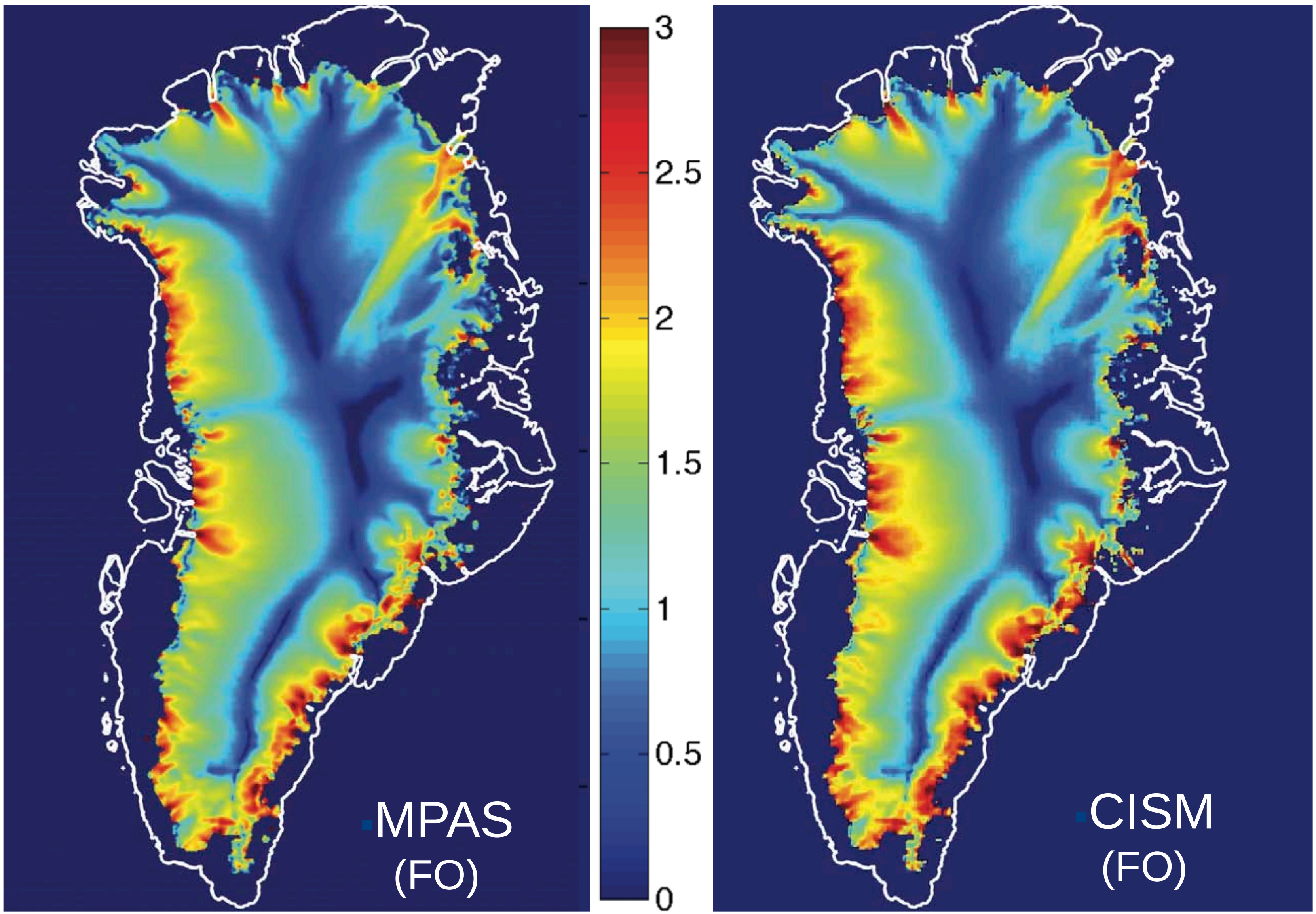


Dome: FO Velocity Solver – 'ice stream'

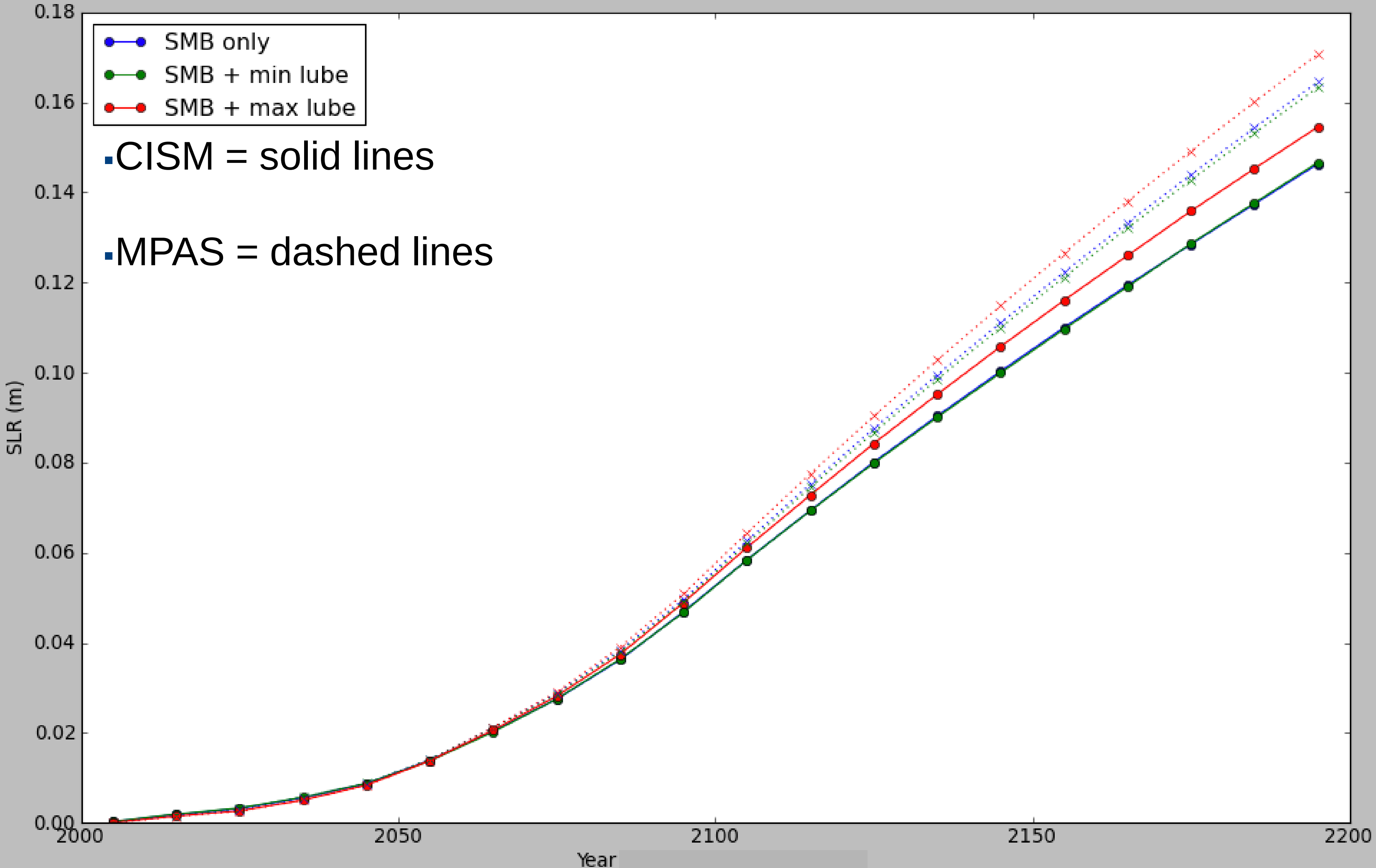




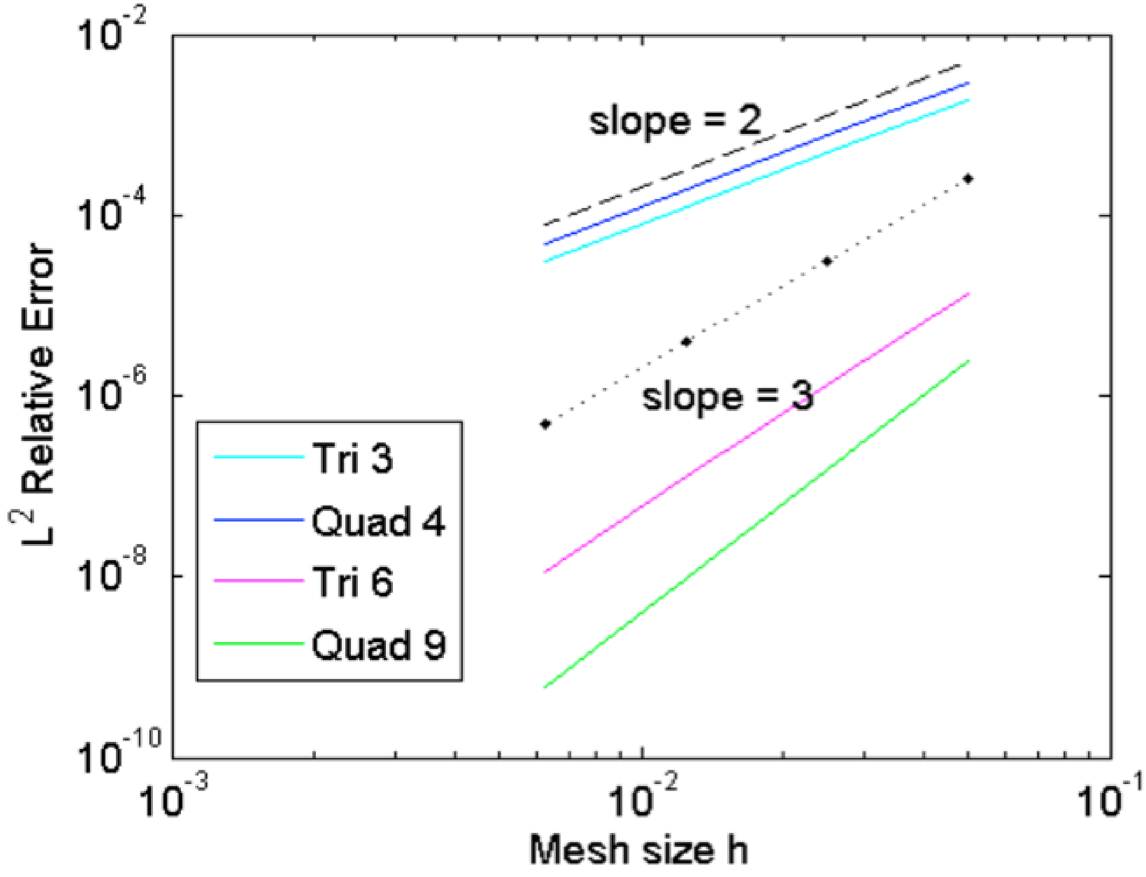
5km Greenland, 2048 processors



Greenland Ice Sheet sea level rise
ice2sea basal lubrication experiments



Right: Vertification of FELIX 1st-order using manufactured solutions. Plots show convergence to analytical solutions with mesh refinement when using finite elements of differing order.



Below: Weak scaling of 1st-order FELIX using ISMIP-HOM test case (Pattyn et al., 2008), showing ~60% efficiency after a 4096x scale-up. Finite element assembly time remains nearly constant.

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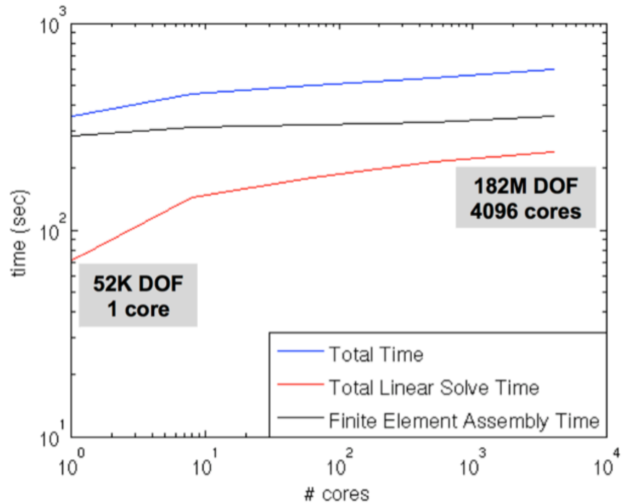
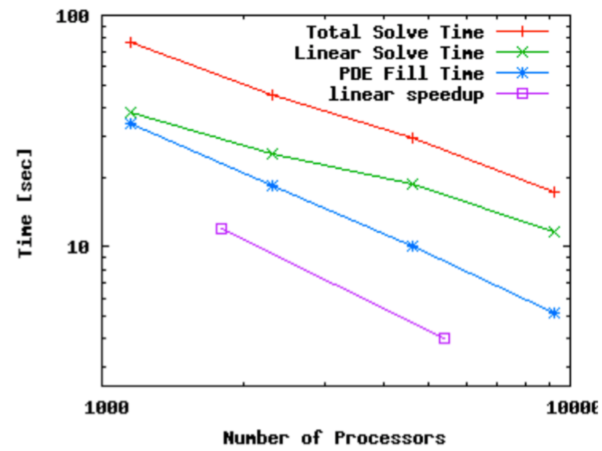
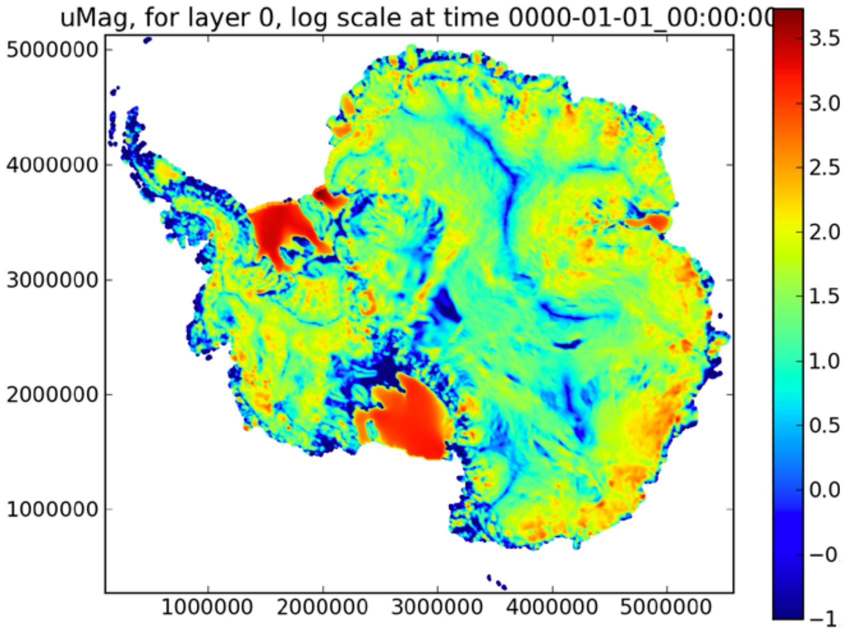
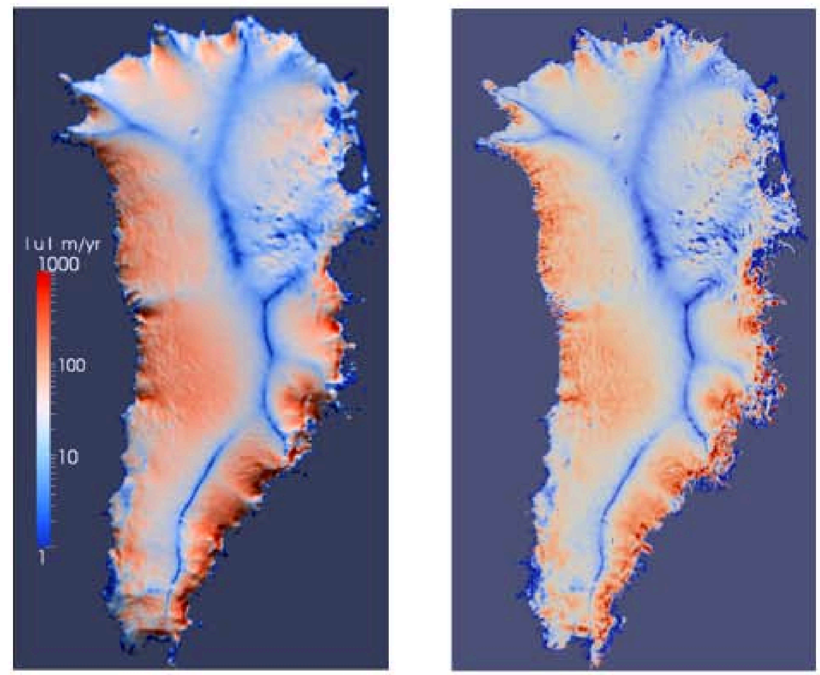


Below: Strong scaling of 1st-order FELIX up to 9k processors, based on diagnostic solve of 2 km resolution Greenland ice sheet test case. 8x processors result in a ~4.5x speedup.

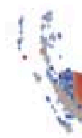


10 km Antarctica, no slip, with ice shelves, LifeV FO



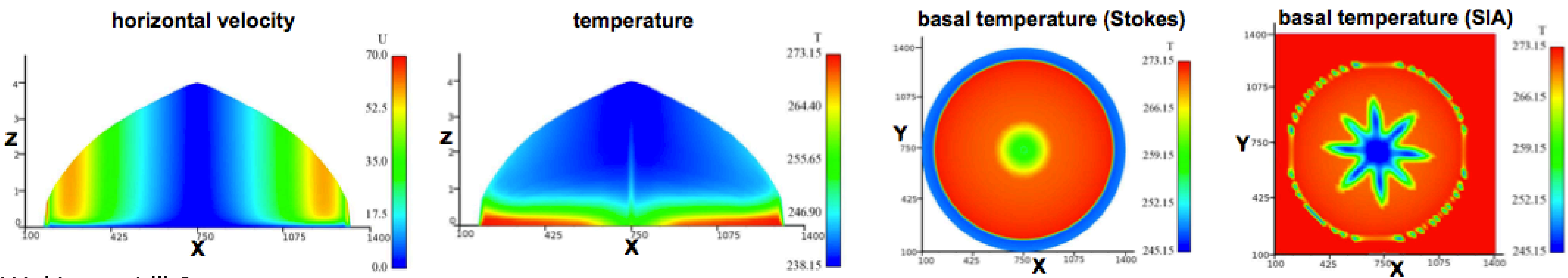


Diagnostic surface speed for Greenland (log10 m/yr) from FELIX 1st-order at 5 km (left) and 1 km (right) resolution (no sliding and uniform rate factor assumed).



Su
1st
coe

Below: Horizontal velocity and temperature with depth and basal temperature at equlibrium for EISMINT II test A (Payne et al., 2000), as calculated from thermomechanically coupled FELIX-Stokes. Note the lack of "cold-ice spokes" in the basal temperatures (as seen at far-right for SIA model (Rutt et al., 2009)). Additional tests are being conducted to understand if the lack of spokes is due to the FEM discretization, the use of Stokes, or a combination of factors.



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