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PISCEES
Progress Toward Advanced Ice Sheet Models

Phil Jones (LANL), acting PI for Bill Lipscomb

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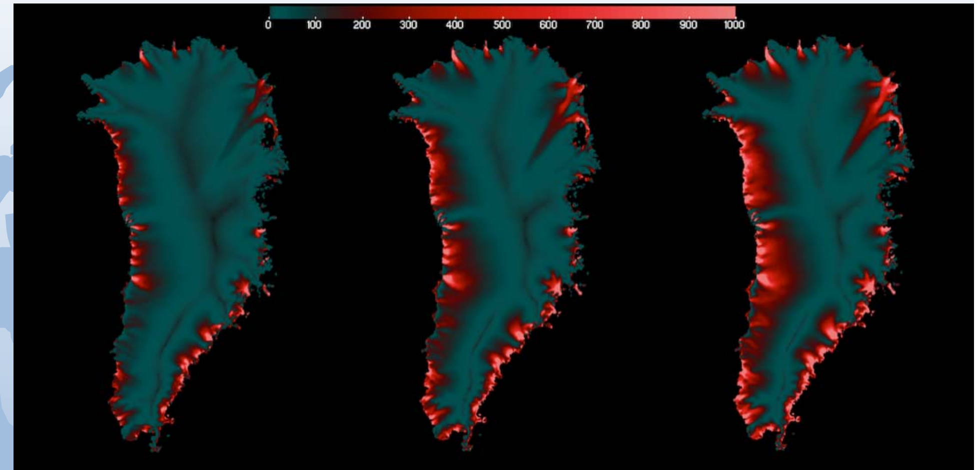
Representing work by…

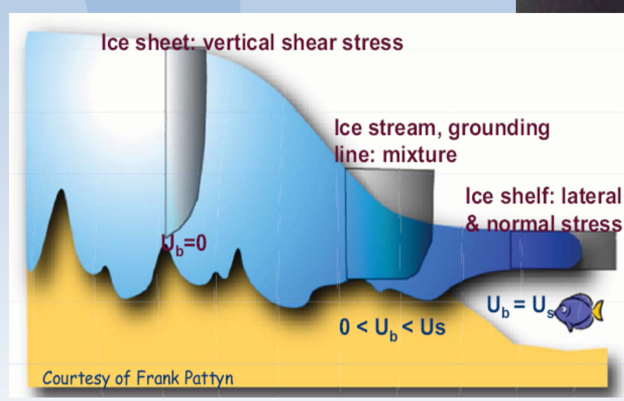
- LANL
  - Bill Lipscomb, Steve Price, Xylar Asay-Davis, Jeremy Fyke, Matt Hoffman, Gunter Leguy, Doug Ranken, John Dukowicz
- LBL
  - Dan Martin, Esmond Ng (Chombo/FASTMath/ASCR)
- SNL
  - Irina Kalashnikova, Mauro Perego, Andy Salinger, Ray Tuminaro (Trilinos/FASTMath/ASCR), Michael Eldred, John Jakeman (QUEST/ASCR)
- ORNL
  - Kate Evans, Matt Norman, Ben Mayer, Adrianna Boghozian (V&V), Pat Worley (SUPER)
- NCAR
  - Bill Sacks, Mariana Vertenstein
- Academic partners
  - Charles Jackson, G. Stadler, G. Gutowski (U. Texas), Max Gunzburger (FSU), Lili Ju (U. S. Carolina), Patrick Heimbach (MIT), Tony Payne, Stephen Cornford (U Bristol)

Ice Sheet and Ocean Models Inform Sea Level Rise

- Sea level rise one of the biggest potential threats of climate change
- 6m of sea level rise if Greenland melts, 6m if W. Antarctic ice sheet melts
- Slow melt over 1000 years or more rapid?
  - 1m over 100 years, largely extrapolation
- Small-scale ice sheet dynamics
  - Ocean/ice shelf interactions
  - Basal sliding
  - Internal dynamics
- Thresholds
  - Likely committed this decade?



Stephen Leatherman



Goals

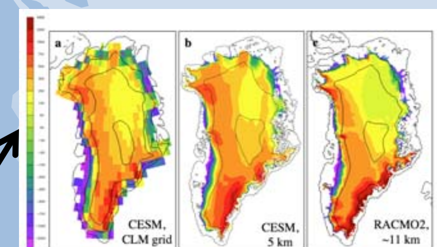
- Predictive model for quantifying sea level rise due to current and future climate change
- Within coupled climate models
  - Community Earth System Model or its DOE branch (DOE-ESM)
- PISCEES
  - Predicting Ice Sheet and Climate Evolution at Extreme Scales
  - Follow on to ISICLES
  - Work with Institutes to…
  - Improve ice sheet models, especially variable resolution dynamical cores (solvers, meshing, frameworks for discretizations and adjoints)
  - Verification and validation framework
  - Uncertainty quantification (UQ), both adjoint and ensemble approaches

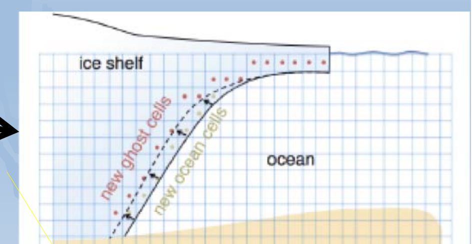
The CISM Zoo

- Stokes
- First-order
  - solvers
- Shallow Ice

Community Ice Sheet Model (CISM)

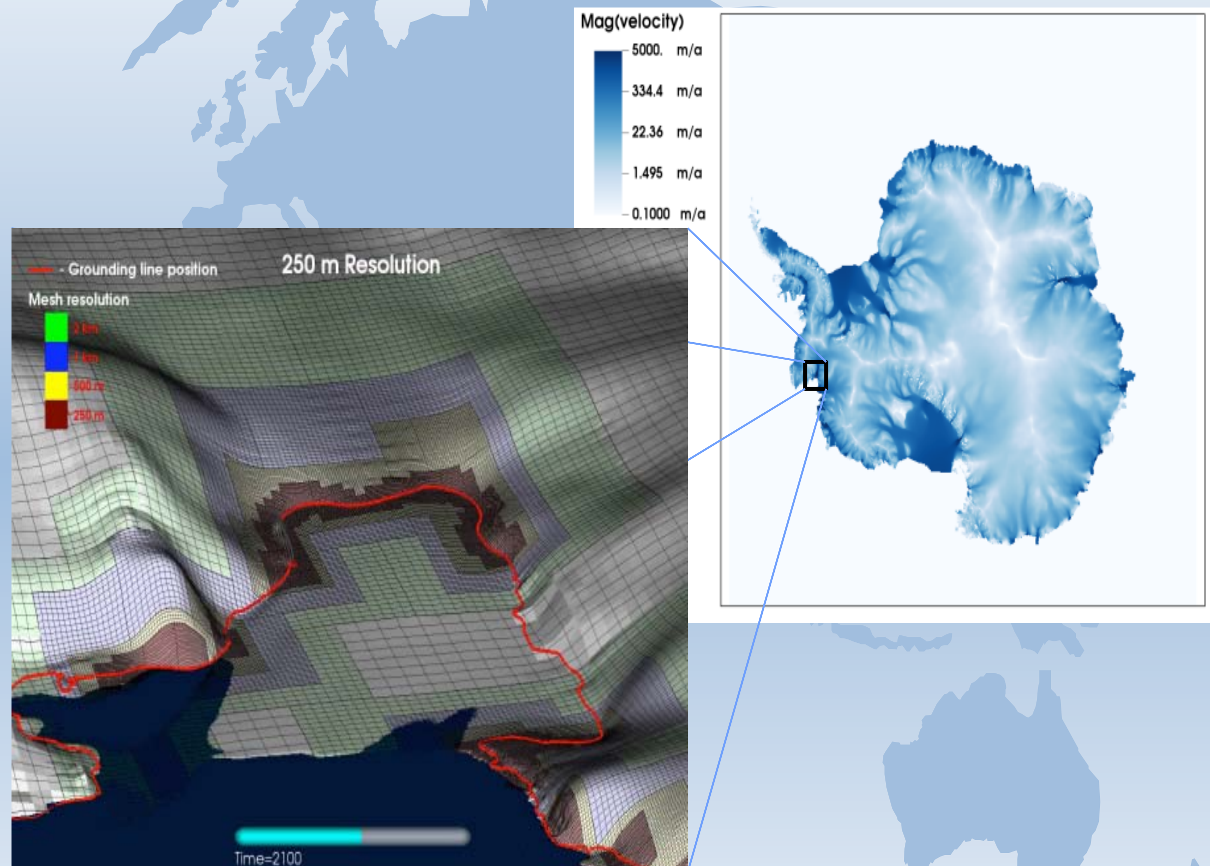
- Dynamics (Dycore)
  - Glimmer-CISM/ SEACISM/ CISM2 — Old structured FD model
  - BISICLES/ Chombo — Block structured AMR
  - MPAS/FELIX — Static unstructured SCVTs
- Physics
  - Temperature
  - Basal sliding/ hydrology
  - Calving
- Coupling
  - Surface Mass Balance
  - Ocean-ice interactions





BISICLES

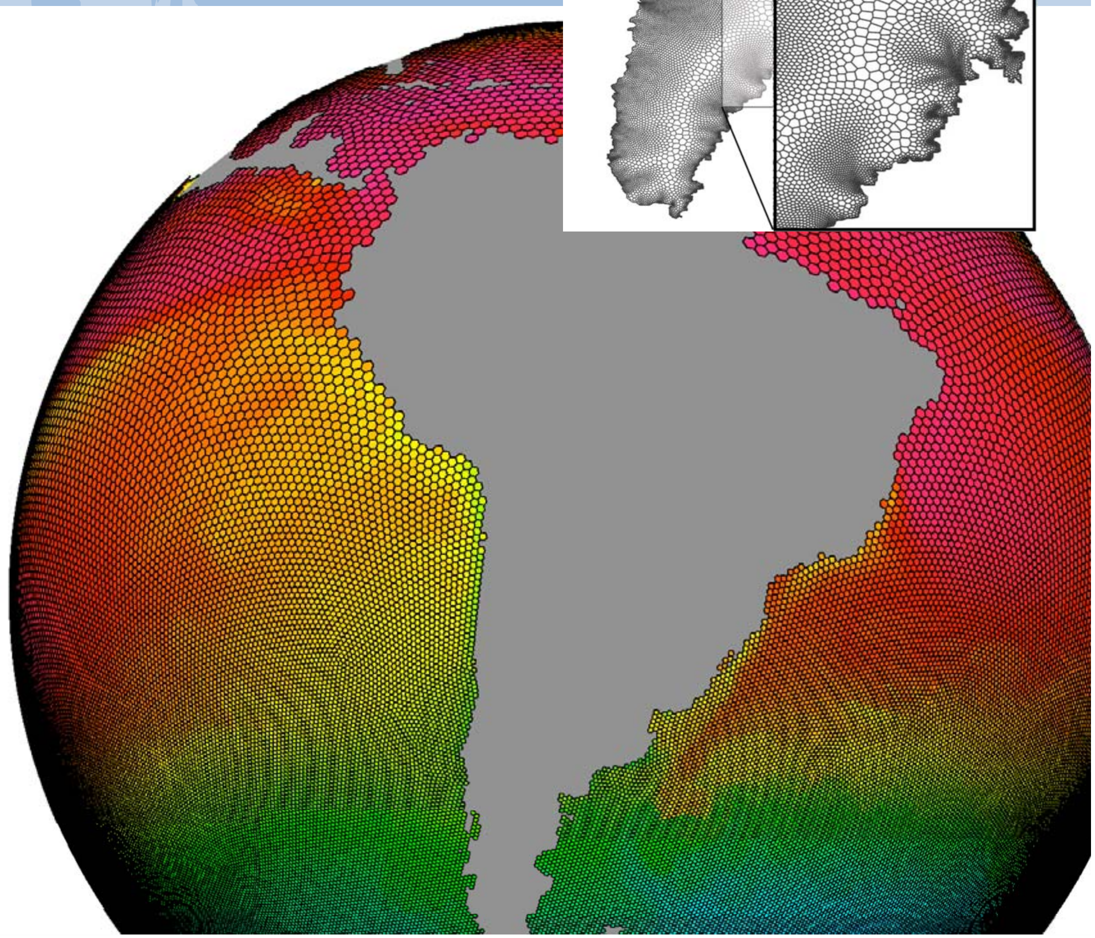
- Adaptive Mesh Refinement
  - Subdivide quads
- CHOMBO
  - LBL (Martin, Colella)
- FV formulation
- Ideal for moving boundaries and resolving grounding line

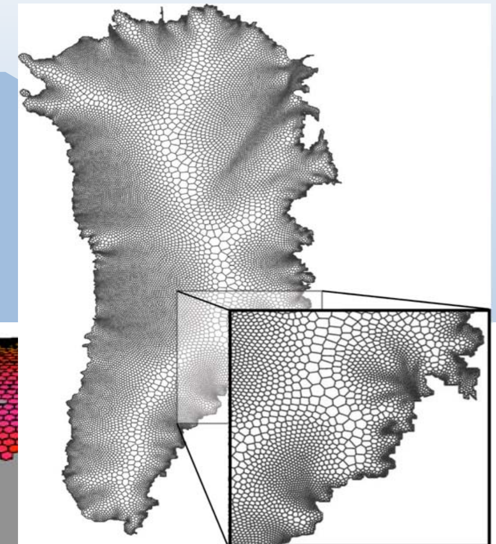


Model for Prediction Across Scales (MPAS)

- Spherical Centroidal Voronoi Tesselations (SCVT)
  - Static unstructured
- Enhance grid using arbitrary density function
- Shared framework (LANL-NCAR MMM)
  - Ocean, land ice, sea ice
  - Atm (NCAR)
- FV and FE
  - FELIX

Variable resolution:
120 km to 30km in
Southern Ocean





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MPAS Dycore

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MPAS and FASTMath

- Extensive use of Trilinos (SNL) and related software
  - FE discretizations with operators, solvers
  - Natural treatment of stress boundary conditions
  - Connections to adjoints, UQ (Dakota) tools
- Full Newton with analytic derivatives
  - Robust, efficient for steady-state solves
  - Matrix available for preconditioners and mat-vec operations
  - Analytic sensitivity analysis
  - Analytic gradients for inversion

FELIX 1st-order: applications with 'real' data

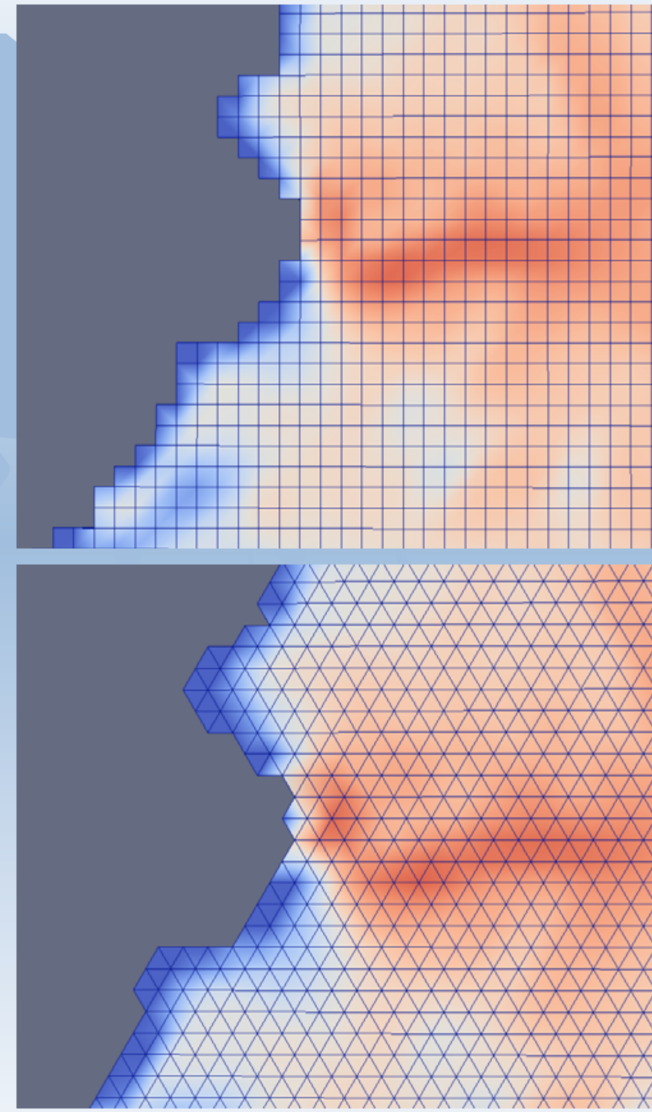
Approach #1: CISM/CESM

- Used older structured grid
- Square grid (extruded as Hexs)
- Allows us to into integrate with CESM immediately

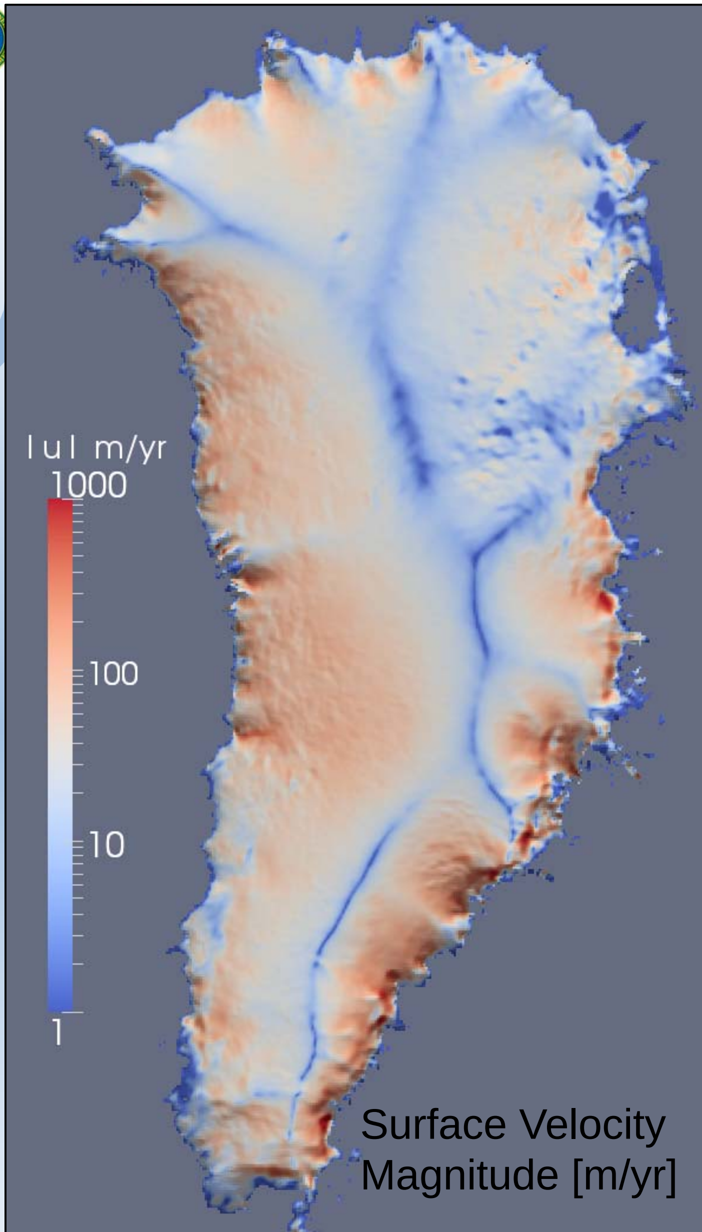
Approach #2: MPAS

- Unstructured SCVT Grid
- Construct triangular dual grid (extrude in z dir. as tets)
- Compatible with MPAS components
- Support not yet available in coupler

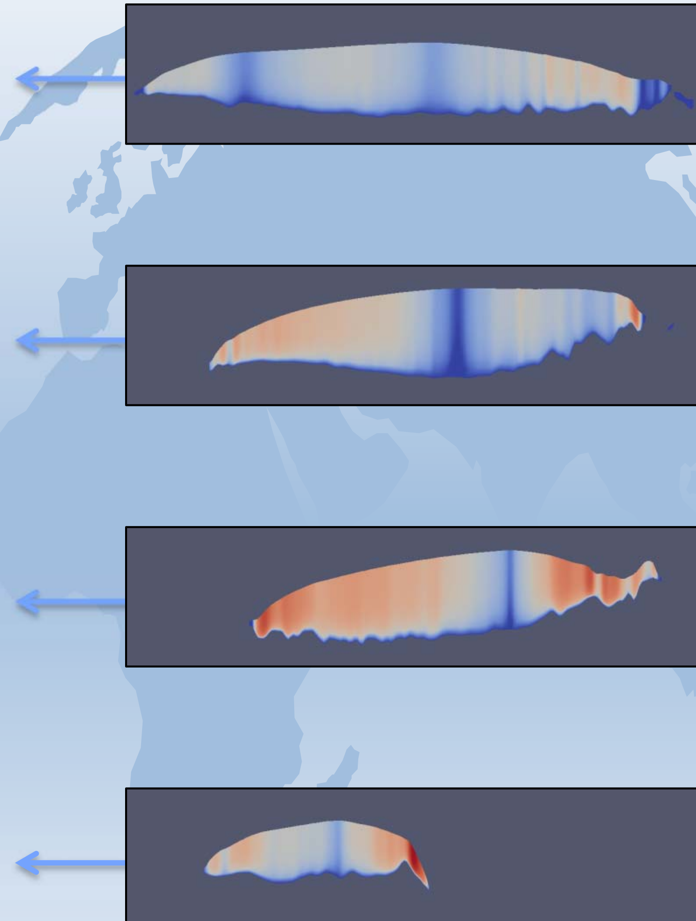
Jakobshavn, "5km" data sets



Regular Grid Greenland Results



Surface Velocity Magnitude [m/yr]



Velocity Magnitude [m/yr] in x-z planes. (Height "z" is stretched 100x.)

5 km resolution (2km too)

640K hex elements

1.44M Unknowns

Const beta

Const T

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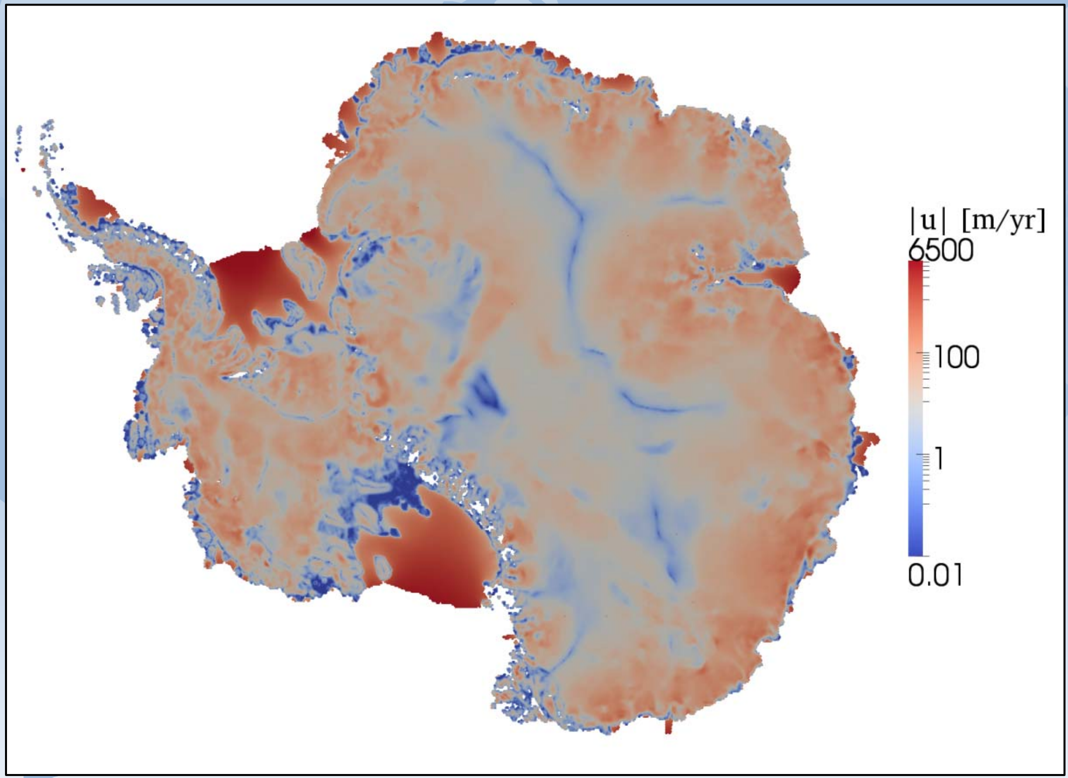
MPAS Grid Results: Antarctica

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



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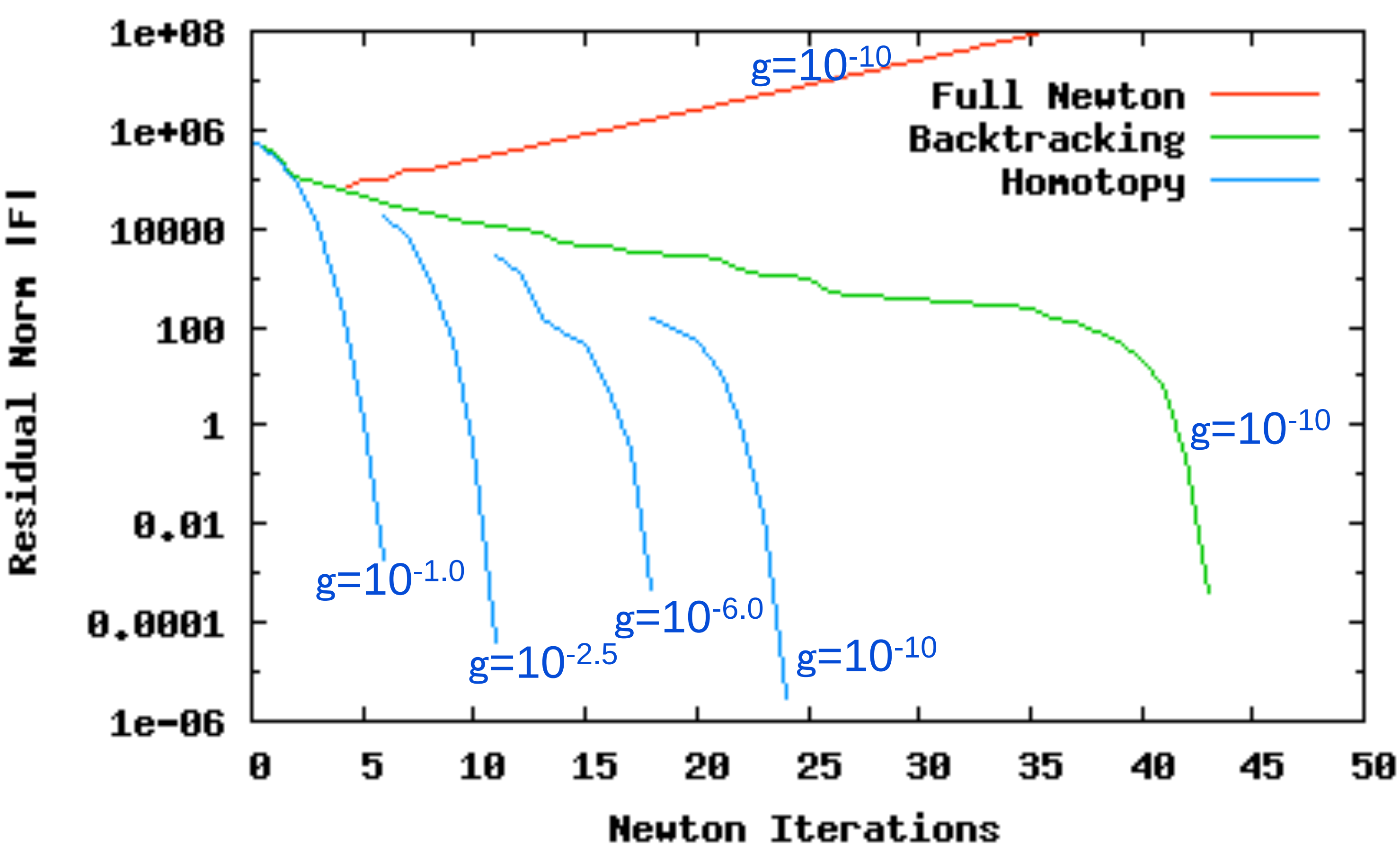
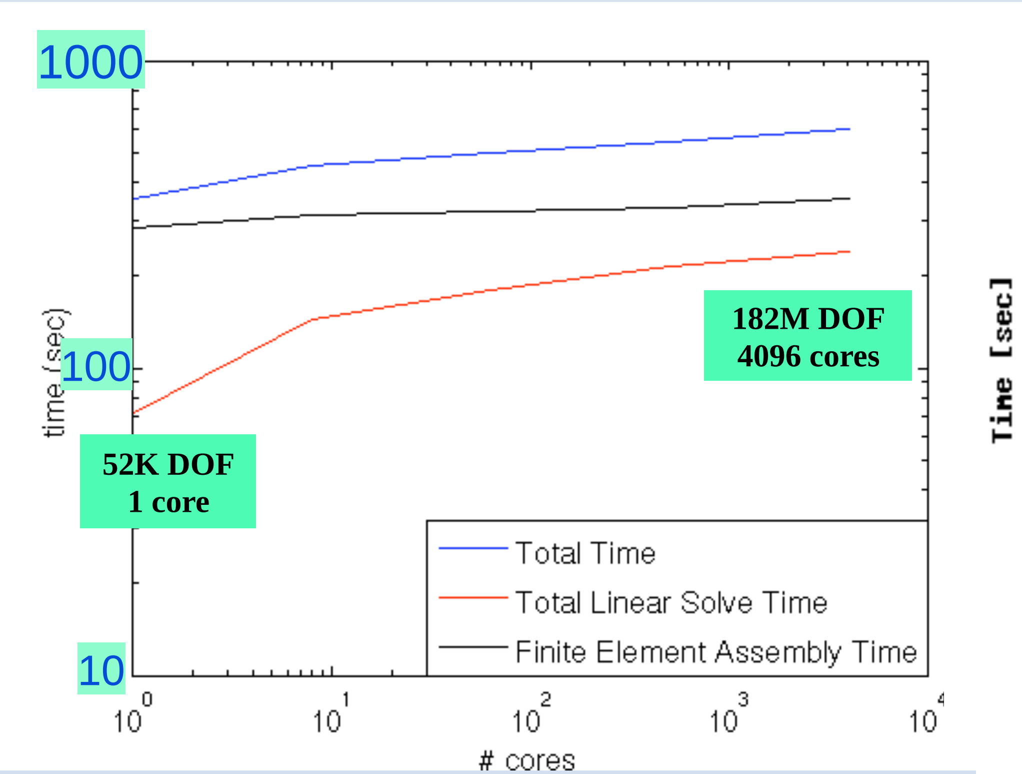
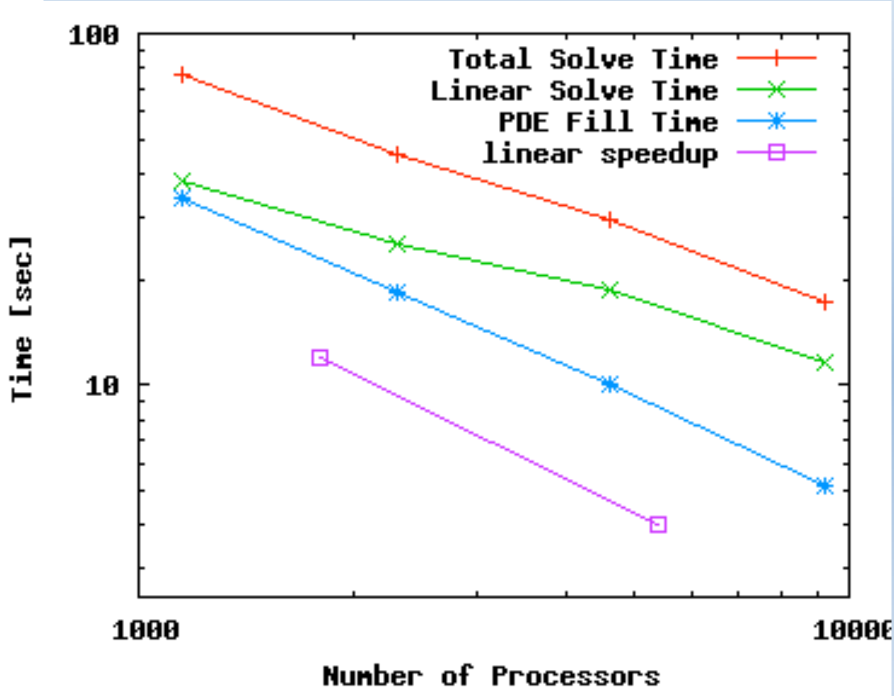
Robustness: Full Newton Method augmented with Homotopy Continuation

$$\mu = \frac{1}{2}A^{-\frac{1}{n}}\left(\frac{1}{2}\sum_{ij}\dot{\epsilon}_{ij}^2 + \gamma\right)^{\left(\frac{1}{2n}-\frac{1}{2}\right)}$$



Scalability: Initial Data (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

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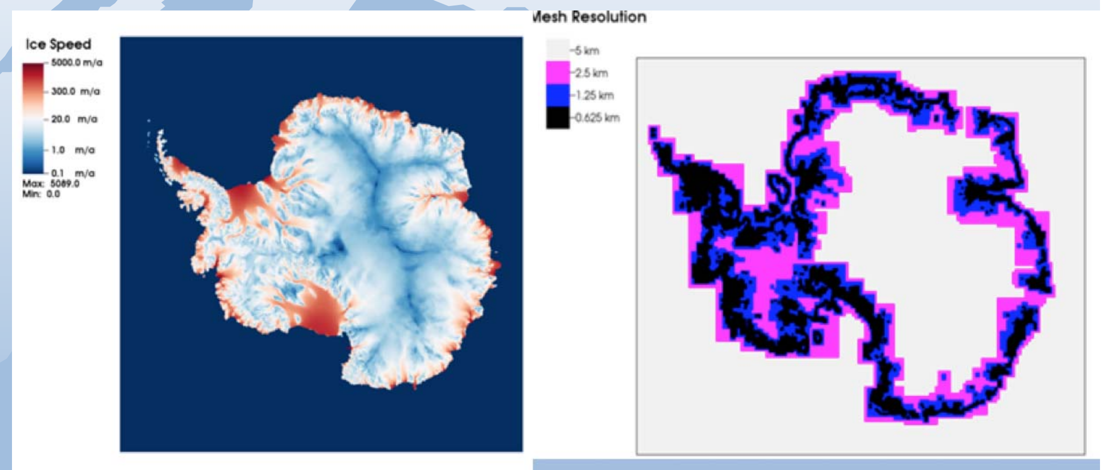
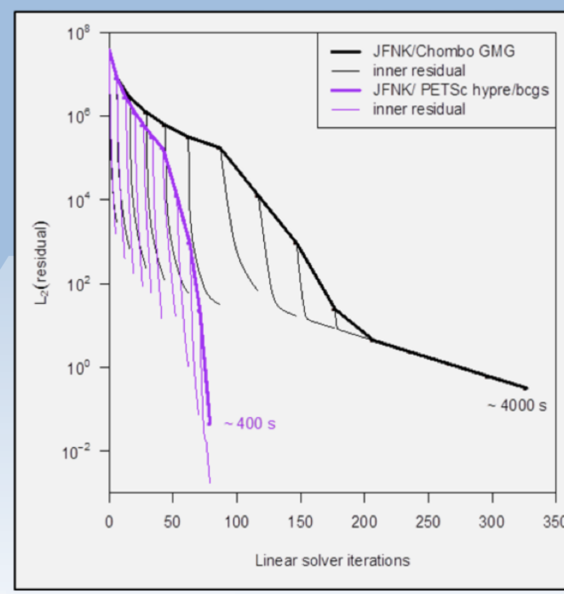
Linear Solvers – GAMG vs. Geometric MG

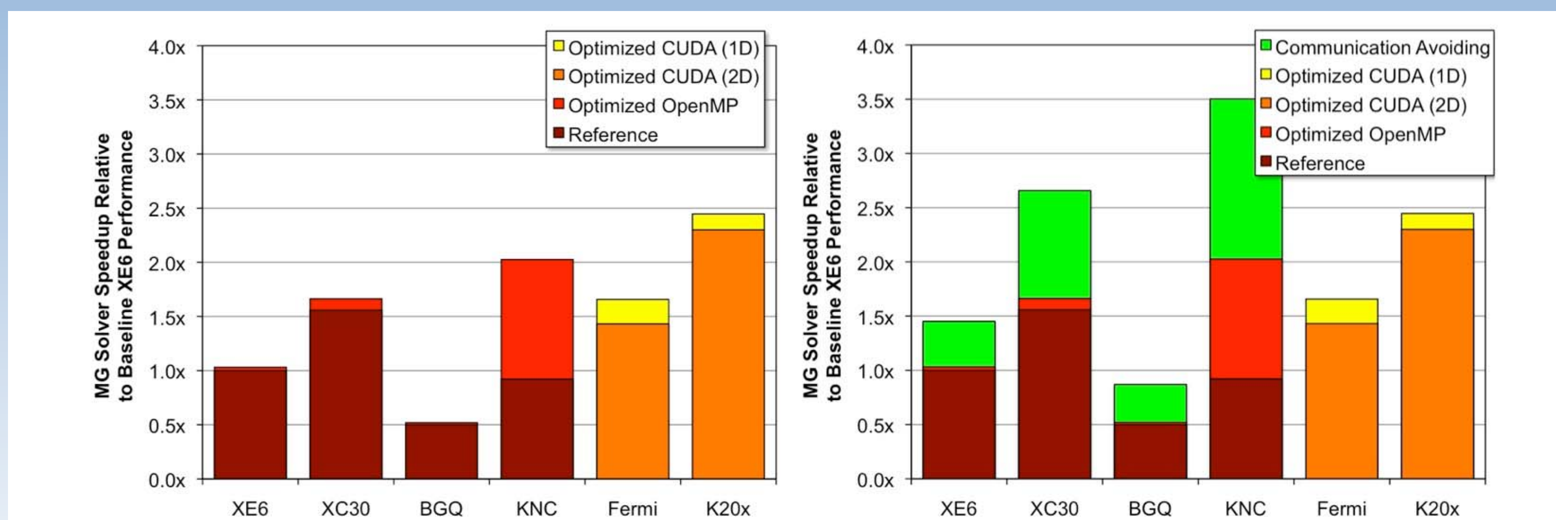
- Solver performance for 5km Antarctica benchmark
- Black – native Chombo GMG solver (stalls)
- Purple – BISICLES JFNK solver with PETSc GAMG linear solver
- PETSc AMG results in **dramatic** improvement (order of magnitude in time to solution for this case.)
- Work with Mark Adams (FASTMath)





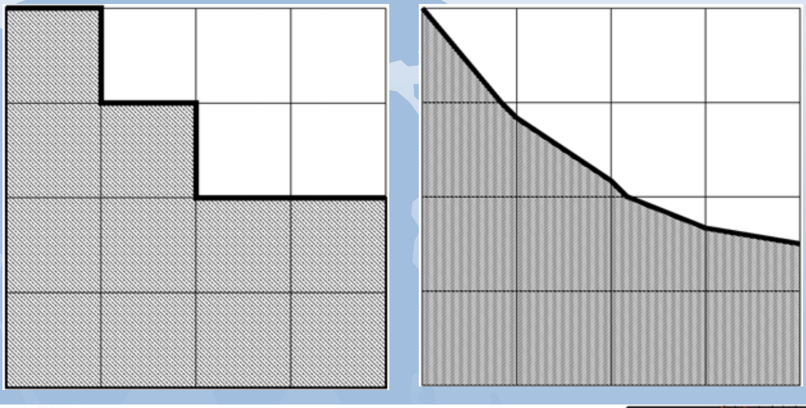
Solver Performance Characterization

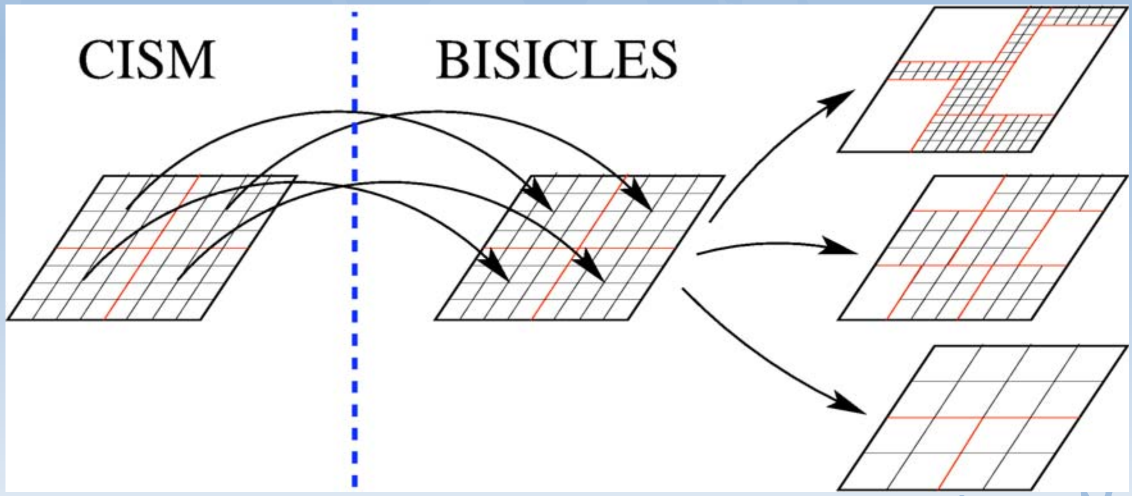
- Work with Sam Williams (SUPER).
- Previous work focused on Chombo geometric MG solvers.
- BISICLES likely transitioning (in some cases, at least) to AMG (see previous slide).
- Built simplified MG app with multiple OMP, CUDA implementations for performance tuning on Opterons, GPUs (Fermi/Kepler), BG/Q, MIC

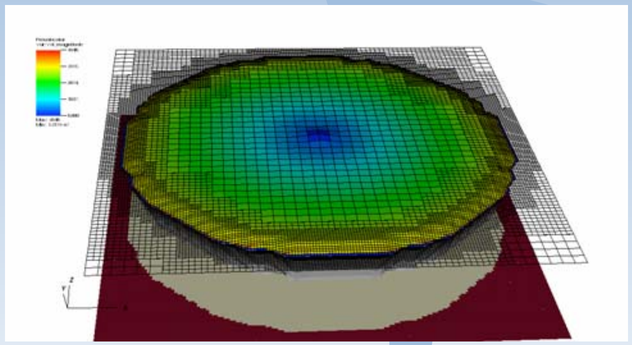


Other BISICLES

- Coupling
- Imbedded boundaries
- And more…







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LIVV:
Verification and Validation

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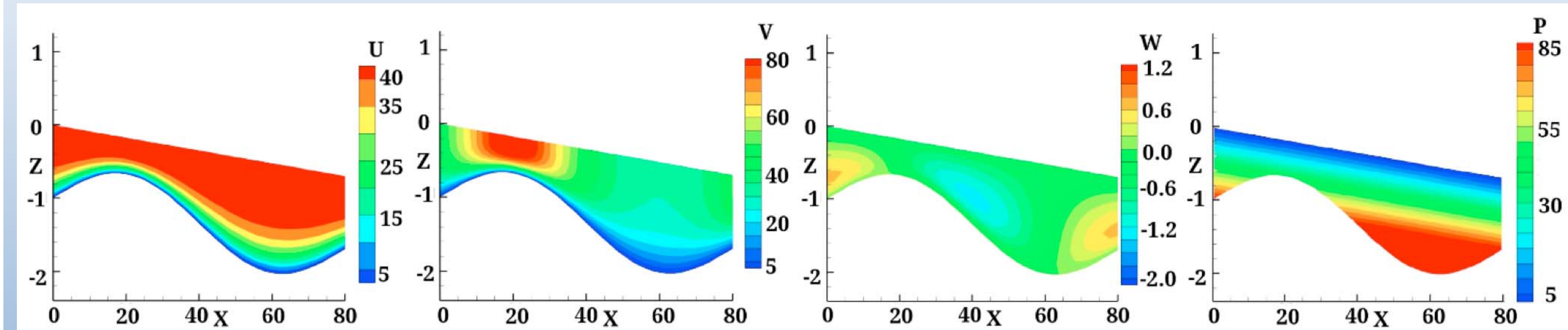
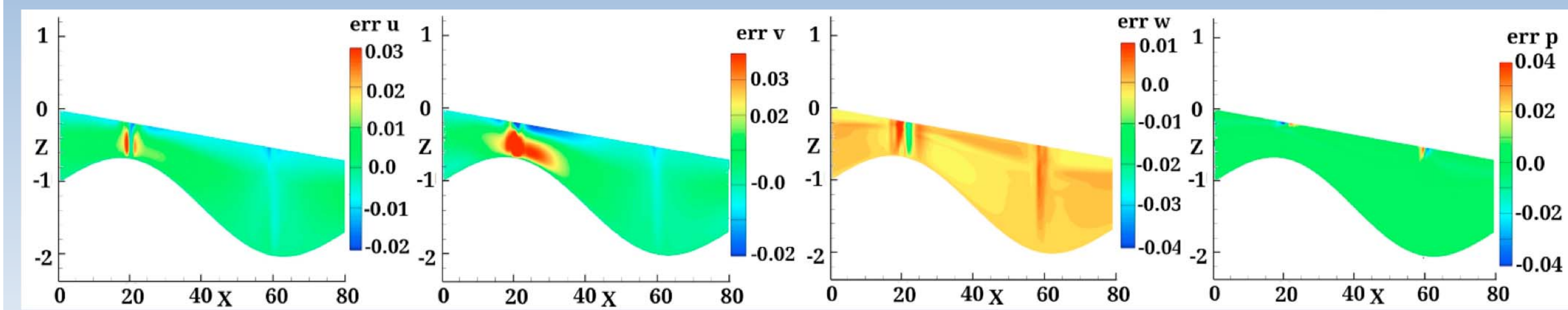
Stokes Model Solution Verification



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



Errors in velocity and pressure components for Stokes FELIX.

Leng et al. (Gunzburger/Ju collaboration), *The Cryosphere*, 7, 2013

1st-Order Model Solution Verification

Nonlinear Stokes' Model for Ice Sheet Stresses

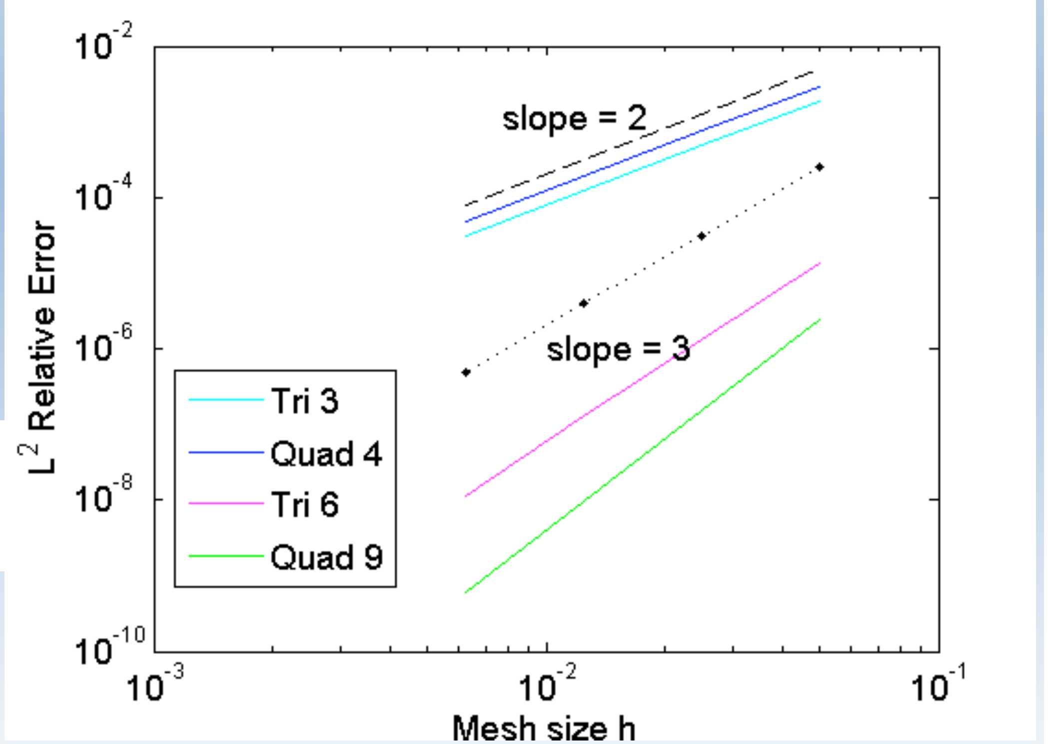
$$-\nabla\cdot(2\mu\dot{\epsilon}_1) = -\rho g\frac{\partial s}{\partial x}$$
$$-\nabla\cdot(2\mu\dot{\epsilon}_2) = -\rho g\frac{\partial s}{\partial y}$$

Method of Manufactured solutions:

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

Solution Verification

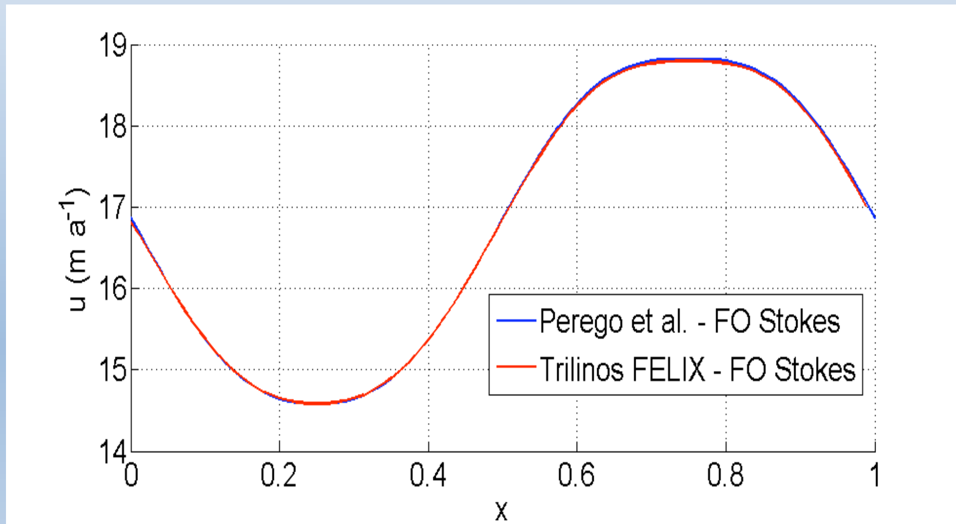
For 2D model using 4 different finite elements



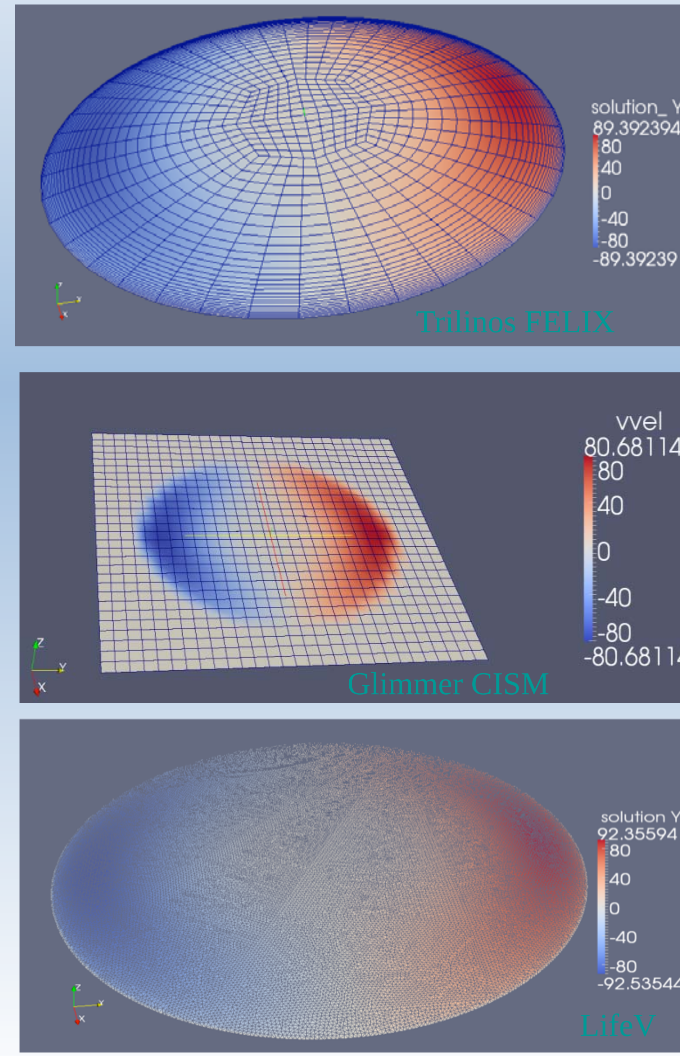
- Ack: Irina Kalashnikova (SNL)

Code-to-Code Comparisons

ISMIP-HOM Test C



Dome Problem



…as well as:
ISMIP-HOM Test A,
Confined Shelf,
Circular Shelf

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LIVV updates: test suite

Test Suite Diagnostics

Test Suite Descriptions

Diagnostic Dome 30 Test: NOT Bit-for-Bit

Diagnostic Dome 30 Velocity Solver Details
Solver Parameter Settings: Diagnostic Dome 30 XML Details
Diagnostic Dome 30 Case Details
Diagnostic Dome 30 Plots
Time of last access: 06/18/2013 09:15 AM

Evolving Dome 30 Test: Bit-for-Bit

Evolving Dome 30 Velocity Solver Details
Solver Parameter Settings: Evolving Dome 30 XML Details
Evolving Dome 30 Case Details
Evolving Dome 30 Plots
Time of last access: 06/18/2013 09:15 AM

Velocity Solver Settings:

Preconditioner: Picard

Block GMRES: Convergence Tolerance = 1e-11
Block GMRES: Maximum Iterations = 200
Preconditioner Type = Ifpack
Prec Type = ILU
Overlap = 0
Fact: Level-of-Fill = 0

Solver: NK

Newton: Jacobian Operator = Matrix-Free
Newton: Forcing Term Method = Type 2
Newton: Maximum Iterations = 30
Matrix-Free Perturbation = 1.0e-4
Linear Solver Type = Belos
Solver Type = Block GMRES
GMRES: Convergence Tolerance = 1e-4
GMRES: Maximum Iterations = 100
GMRES: Flexible GMRES = 1

- Added BFB top level test, each test within
- Added times of last access
- Velocity Solver Details
  - Iteration count
  - Nonlinear and Linear information in plot or list form
- Case Details
  - Relevant settings provided as a reference and comparison to the benchmark
  - Changes from benchmark are highlighted in red with both values
- Output plots for comparison to the benchmarks
- Solver settings for performance

Connection to FASTMath

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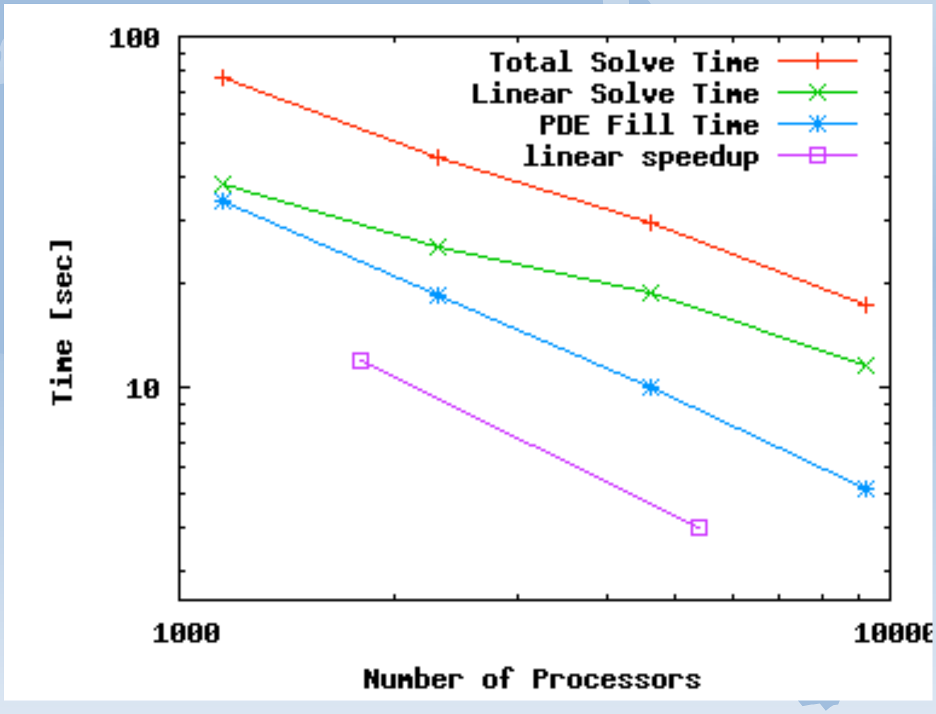
Scaling and general performance behavior of FELIX performed

- Timers in F90 code already in SEACISM, but majority of work is in solver.
- In move to FELIX, CESM timers now included within C++ code of Trilinos
- Next step: to include within LIVV test framework
- Comparison to seacism will be implemented in the LIVV kit



Pat Worley

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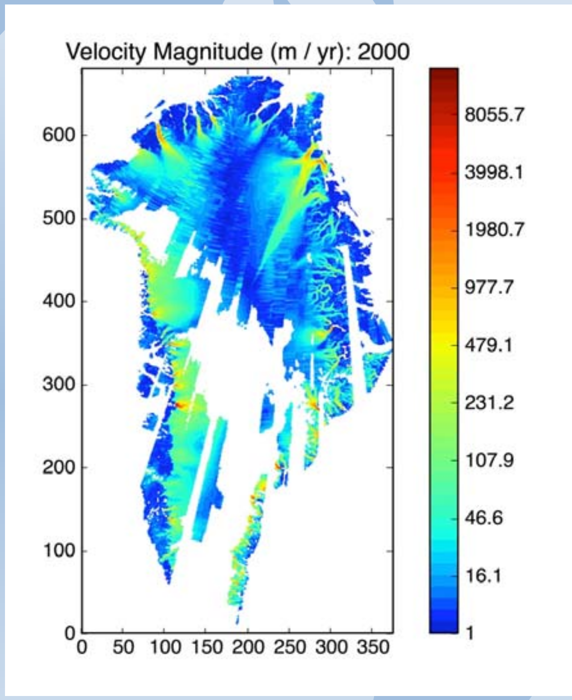
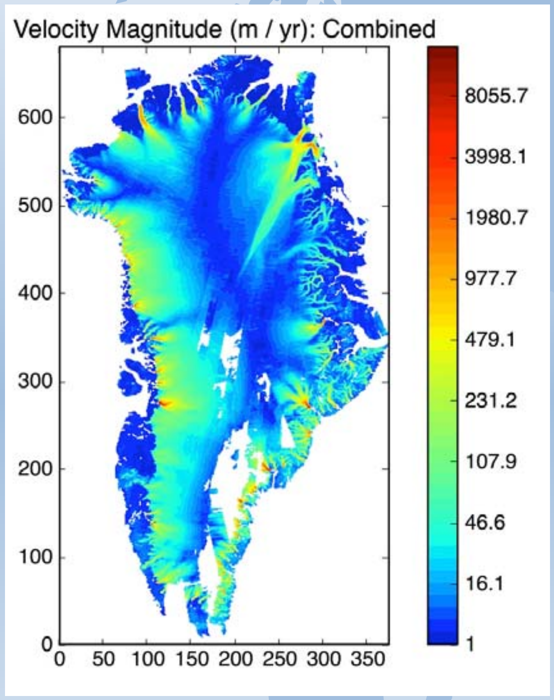
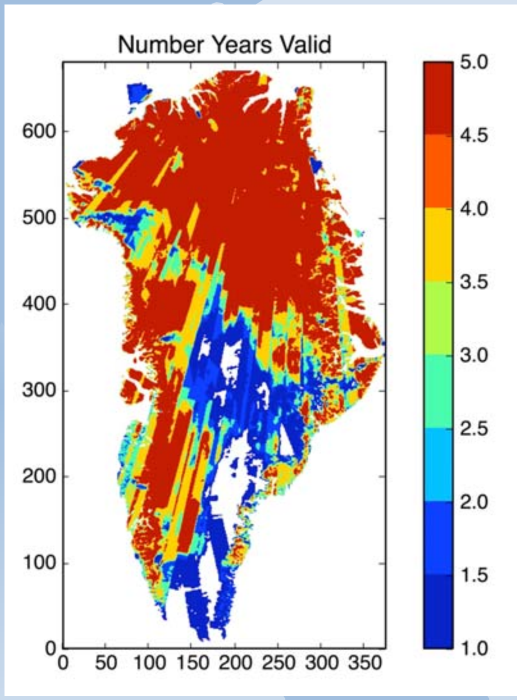
Incorporation of newest observational datasets: Initial collection and processing
Building SDAV collaborations



Year 2000



Avg of all years



# of years contributing to avg

MEaSUREs Greenland Ice Sheet Velocity Map from InSAR Data, Joughin et al '10

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Uncertainty Quantification

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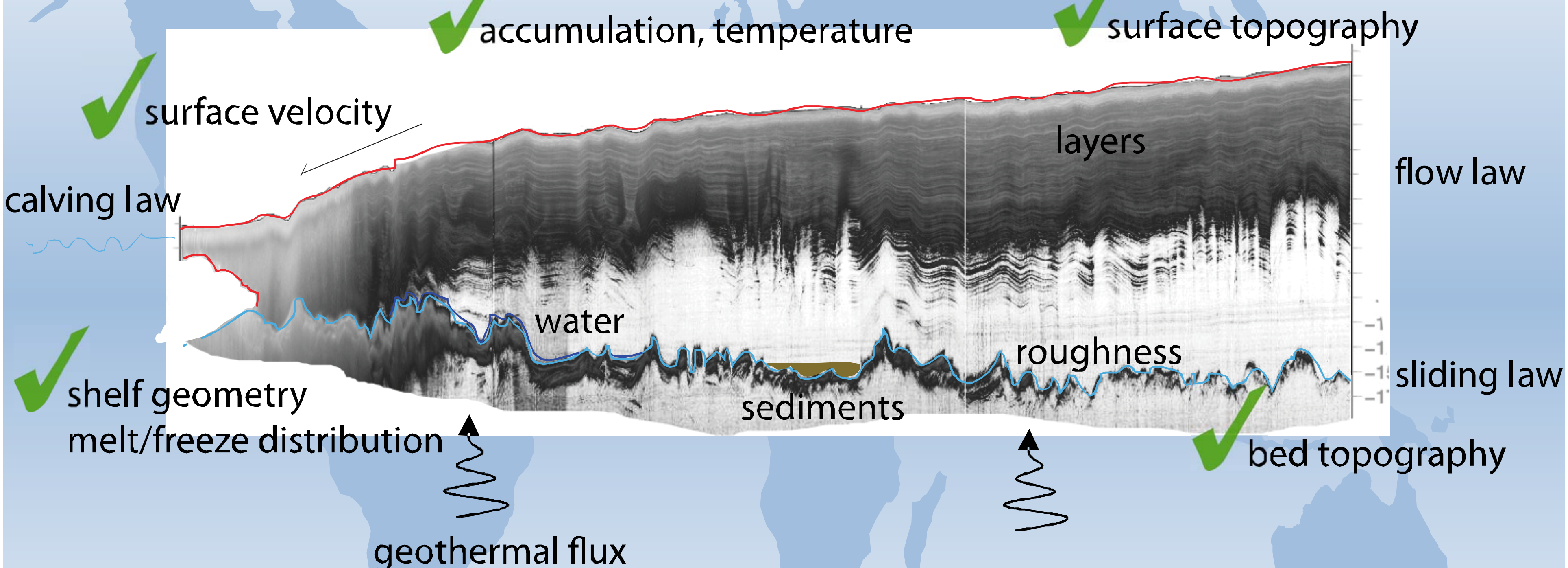
Processes affecting ice sheet initialization



Sampling and Adjoint-based approaches can address different challenges to the initialization problem.

U : velocity

T : temperature

H : thickness

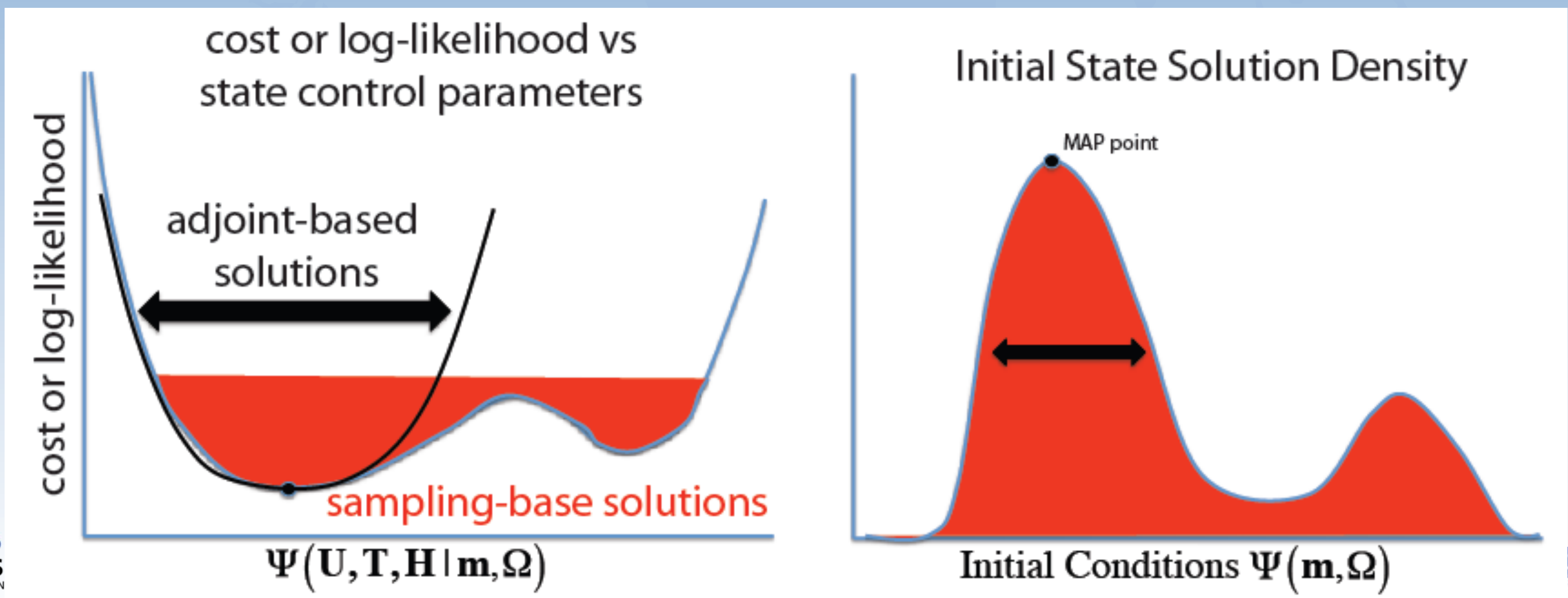
m : parameters

Ω : boundry conditions

$\mathbf{C}^{-1}$: inverse of covariance of errors

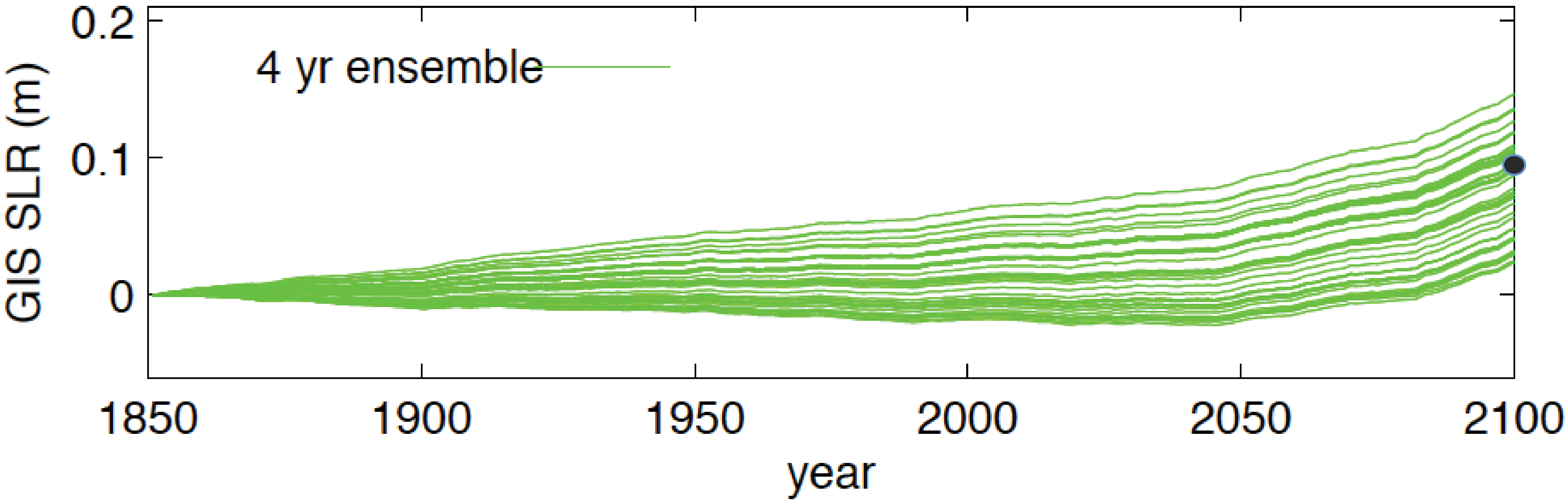
$\Psi(\mathbf{U},\mathbf{T},\mathbf{H}\,|\,\mathbf{m},\boldsymbol{\Omega}) \rightarrow$ initial state

$$\text{cost}(\mathbf{m},\Omega) \rightarrow \text{log-likelihood}(\mathbf{m},\Omega) =$$
$$\left(\Psi(\mathbf{U},\mathbf{T},\mathbf{H}\,|\,\mathbf{m},\boldsymbol{\Omega}) - \mathbf{Obs}\right)^T \mathbf{C}^{-1} \left(\Psi(\mathbf{U},\mathbf{T},\mathbf{H}\,|\,\mathbf{m},\boldsymbol{\Omega}) - \mathbf{Obs}\right)$$



Estimating and representing surface mass balance boundary condition uncertainties in projections of Greenland contribution to future sea level.

Ice Sheet Model Prediction of Sea Level Rise



Gutowski, G., C. S. Jackson, B. Sacks, J. Fyke, and B. Lipscomb. Estimates and impacts of surface mass balance biases on estimates of the Greenland Ice Sheet contribution to future sea level (in prep)

Participants:
Jackson and Gutowski (UT-Austin; PISCEES)
Sacks (NCAR; PISCEES)
Lipscomb, Fyke (LANL; PISCEES)

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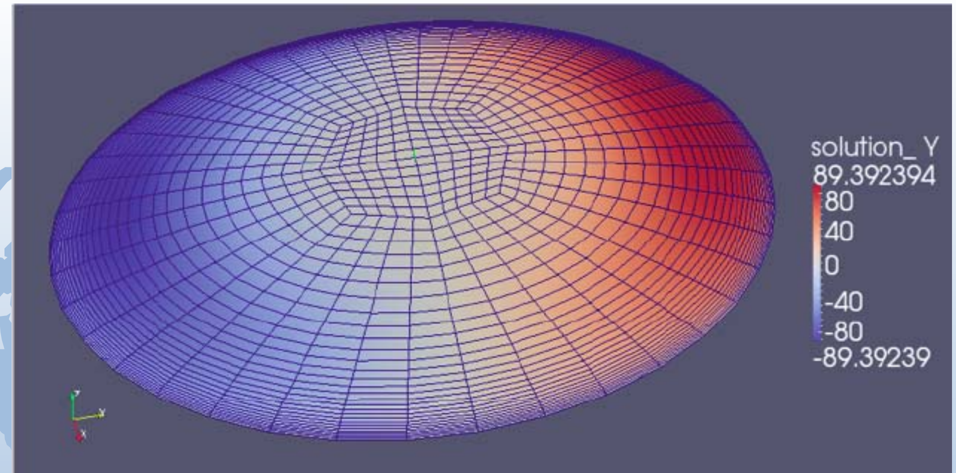
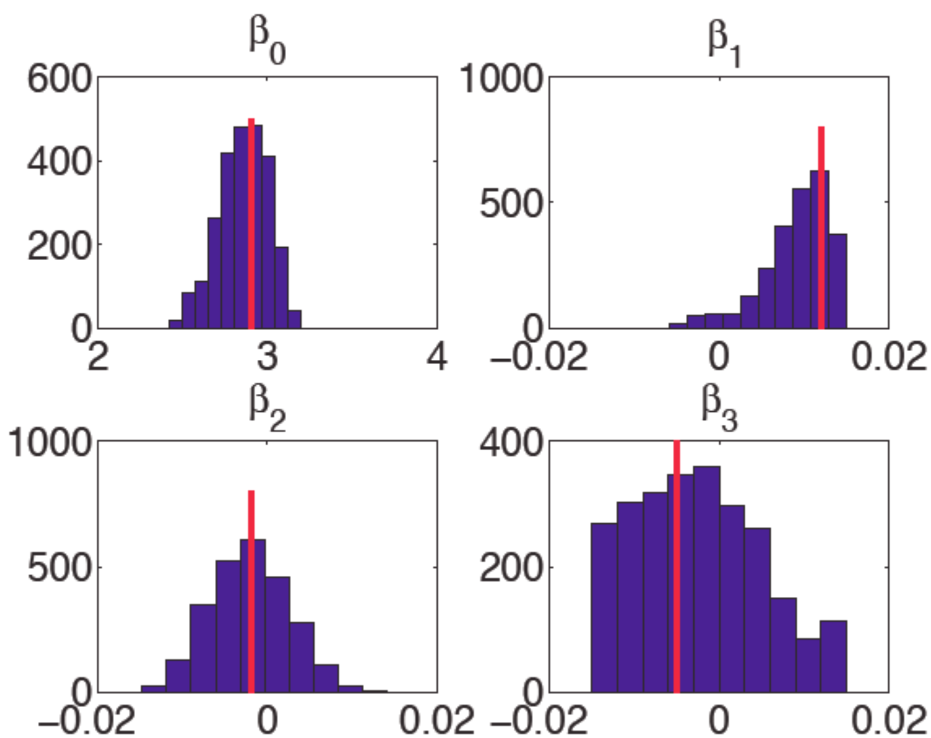
Sampling-based solutions to “Dome” test-case using DAKOTA and QUESO toolkit.



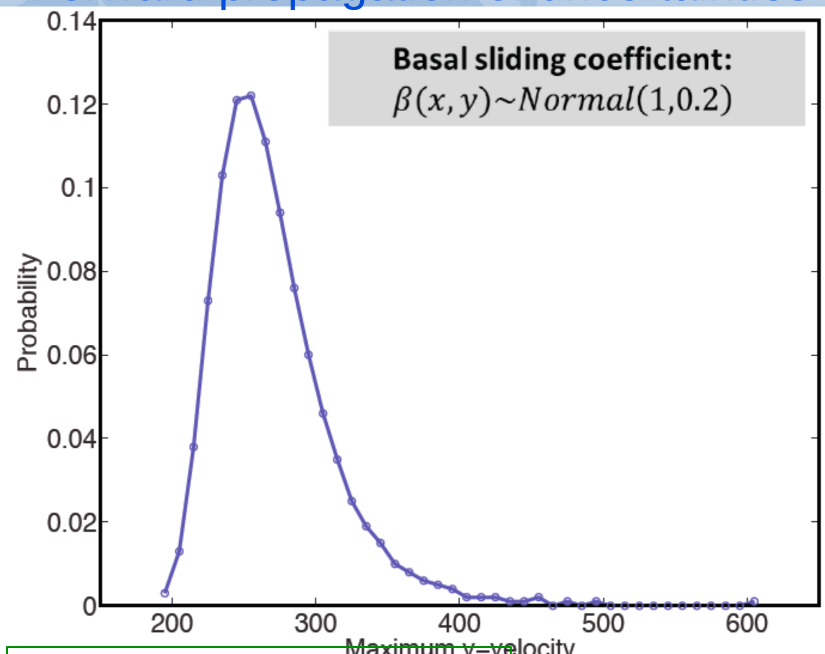
Bayesian Calibration

Basal sliding coefficient:

$$\beta(x,y) = \beta_0 + \beta_1 x + \beta_2 y + \beta_3 r$$



Forward propagation of uncertainties



Salinger (SNL; PISCEES)
Kalashnikova (SNL; PISCEES)
Eldred (SNL; PISCEES/QUEST)

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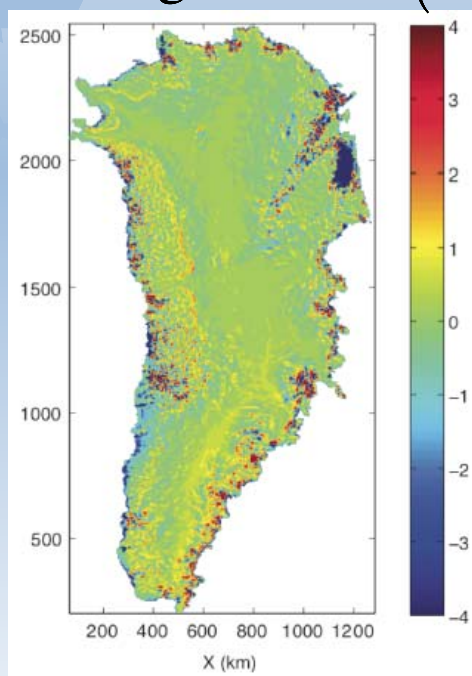
Adjoint-enabled initialization: Solve for basal traction coefficients and topography that maintains equilibrium with observed surface mass balance.

At equilibrium: $\mathrm{div}\left(\mathbf{U}H\right) = \tau_s$

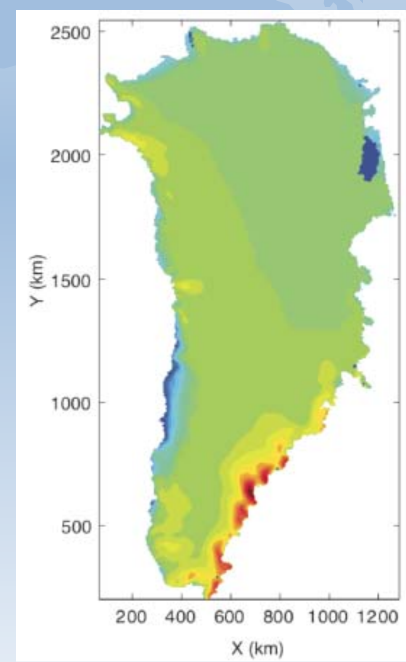
U : Model depth-averaged velocity
H : Ice thickness
β : Basal sliding coefficient
τ_s : Surface mass balance

mass flux divergence: $\mathrm{div}\left(\mathbf{U}H\right)$



$\neq$

surface mass balance: τ_s



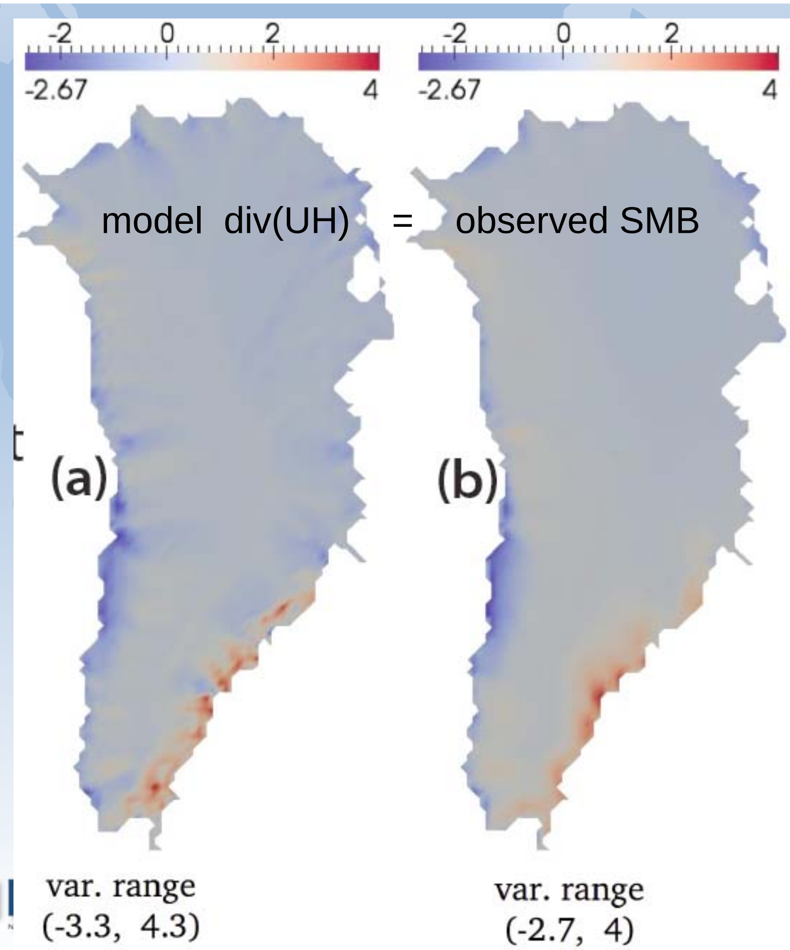
Bad initial state can lead to long-term transients that can swamp signal.

Optimization Problem: Find β and H that minimize the cost functional $\mathcal{J}$:

$$
\begin{aligned}
\mathcal{J}(\beta, H) = \;& \tfrac{1}{2}\alpha_d \int_\Gamma |\mathrm{div}(\boldsymbol{U} H) - \tau_s|^2 \, ds + && \text{- flux div. vs. surf. mass bal. mismatch -}\\
& \tfrac{1}{2}\alpha_v \int_{\Gamma_{top}} |\mathbf{u} - \mathbf{u}^{obs}|^2 \, ds + && \text{- model vs. observed velocity mismatch -}\\
& \tfrac{1}{2}\alpha_H \int_\Gamma |H - H^{obs}|^2 \, ds + && \text{- model vs. observed thickness mismatch -}\\
& \mathcal{R}(\beta) + \mathcal{R}(H) && \text{- regularization terms -}
\end{aligned}
$$

After optimization, observed and modeled mass flux divergence is very close to observed surface mass balance.

Perego (SNL; PISCEES)
Stadler (UT-Austin; PISCEES)
Price (LANL; PISCEES)



Adjoint-based Uncertainty

- Open research question.
- Feasibility with DAKOTA is being discussed between PISCEES's Heimbach (MIT), Stadler (UT Austin), and Salinger (SNL) and QUEST's Eldred (SNL).
- Demonstrated capacity for estimating basal traction uncertainty (Stadler and colleagues at UT Austin) and ice-ocean coupling (Heimbach and colleagues at MIT)

Heimbach (MIT; PISCEES)
Stadler (UT-Austin; PISCEES)
Ghattas (UT-Austin; PISCEES/QUEST)
Salinger (SNL; PISCEES)
Eldred (SNL; PISCEES/QUEST)

Conclusions

- Much progress in creating advanced dynamical cores
  - Not Mezzacappa level, but…
  - Significant contributions from Institutes
  - Capabilities that we haven't had before
- Improved V&V
- Significant application of UQ techniques
  - Beyond parameter estimation
  - Initialization problem

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So long and thanks for all the fish…

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