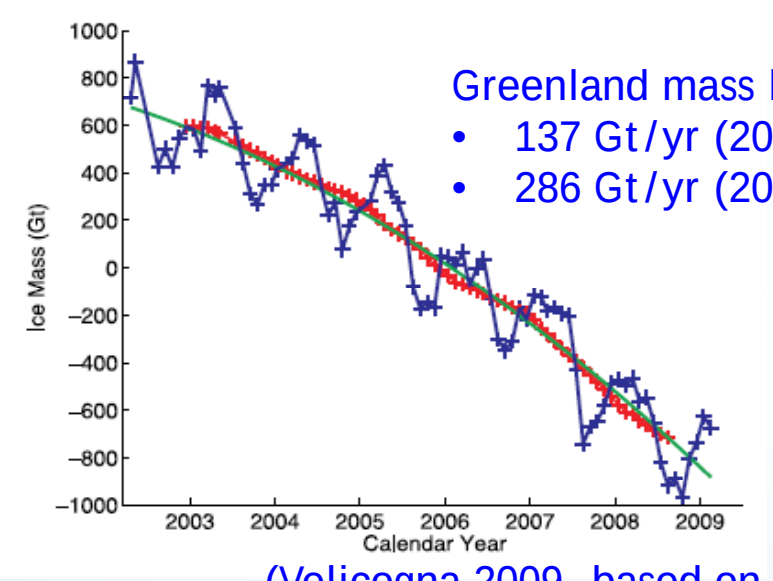
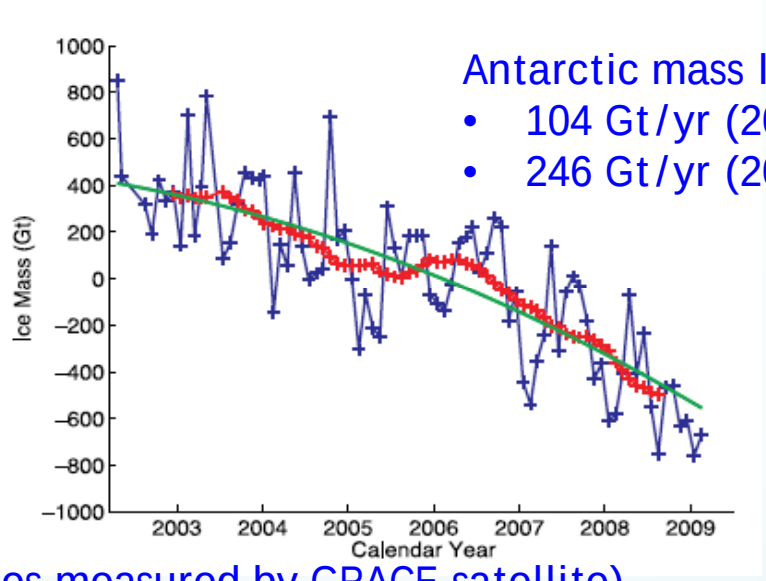
ISICLES
Ice Sheet Initiative for Climate Extremes

Esmond G. Ng
Lawrence Berkeley National Laboratory

Dynamics of Large Ice Sheets

- The Greenland and Antarctic ice sheets are losing mass at an accelerating rate.
  - Much of that mass loss can be attributed to dynamic changes (accelerating and thinning outlet glaciers).





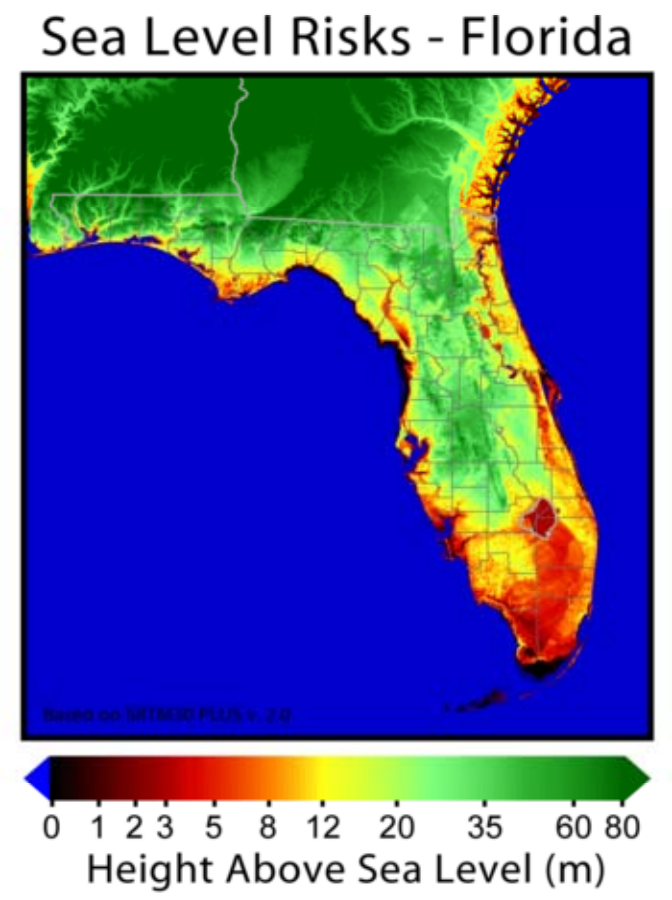
(Velicogna 2009, based on gravity changes measured by GRACE satellite)

- Loss of the Greenland ice sheet would raise global sea level by ~7 m.
- Loss of the West Antarctic ice sheet (grounded below sea level) would raise global sea level by ~3-5 m.

Sea Level Rise

- Climate Change 2007, Working Group I: The Physical Science Basis
  - Section 4.6.1: Background

    "The ice sheets of Greenland and Antarctica hold enough ice to raise sea level about 64 m if fully melted (Bamber et al., 2001; Lythe et al., 2001). Even a modest change in ice sheet balance could strongly affect future sea level and freshwater flux to the oceans, with possible climatic implications."



- Affect large population within the zone where rapid sea level rise would submerge land.
  - Maybe the most profound impact of sea level rise on humans.

IPCC 4th Assessment Report (2007)

- Climate Change 2007, Working Group I: The Physical Science Basis

  - Section 4.6: Changes and Stability of Ice Sheets and Ice Shelves

    "New and improved observational techniques, and extended time series, reveal changes in many parts of the large ice sheets. Greenland has experienced mass loss recently in response to increases in near-coastal melting and in ice flow velocity more than offsetting increases in snowfall. Antarctica appears to be losing mass at least partly in response to recent ice flow acceleration in some near-coastal regions, although with greater uncertainty in overall balance than for Greenland. Shortcomings in forcing, physics and resolution in comprehensive ice flow models have prevented them from fully capturing the ice flow changes."

  - Section 4.6.1: Background

    "Consequently, this assessment will not adequately quantify such effects."

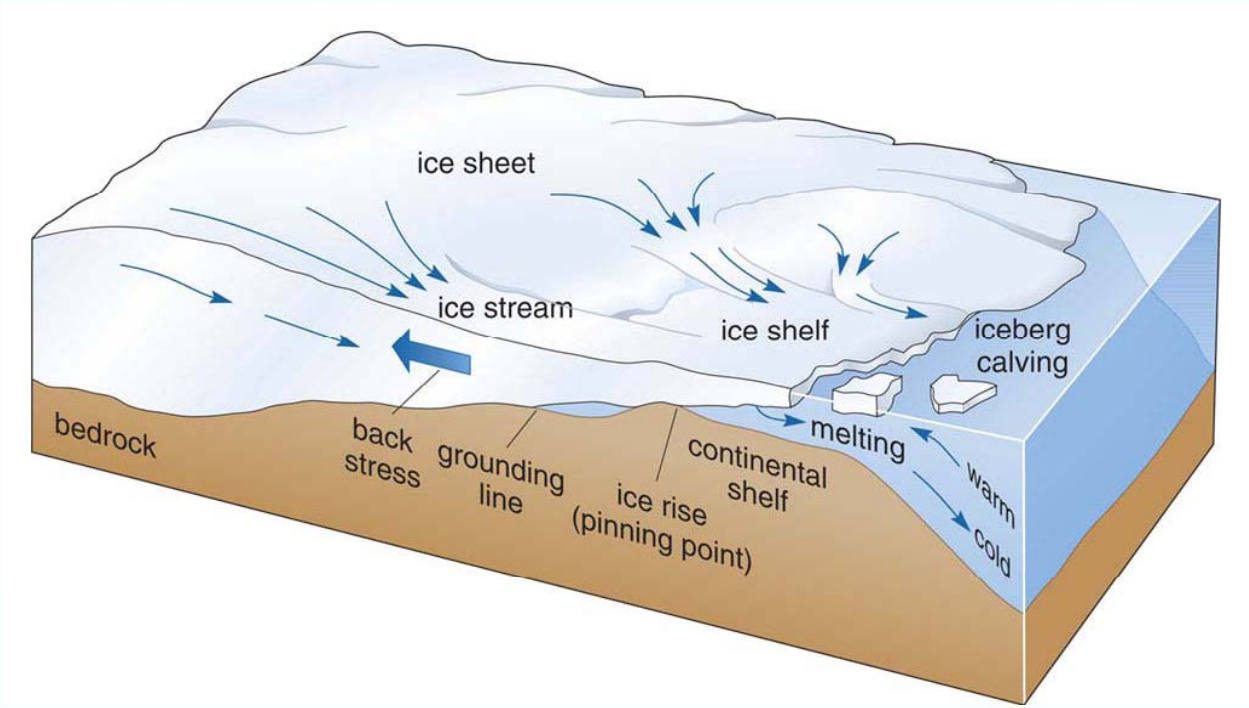
Urgent Needs …

- IPCC AR4 Synthesis Report:

  "Future changes in the Greenland and Antarctic ice sheet mass, particularly due to changes in ice flow, are a major source of uncertainty that could increase sea level rise projections. The uncertainty in the penetration of the heat into the oceans also contributes to the future sea level rise uncertainty."

- High fidelity, high resolution modeling of the dynamics of ice sheets, and quantification of uncertainties in the dynamics are needed to help the next IPCC assessment report (AR5 in 2014) to address these issues.

Modeling Dynamics of Ice Sheets



- Three typical ways to represent ice sheets:
  - Thermomechanical SIA: assumes that bedrock and ice surface slopes are sufficiently small.
  - "Higher order" model: a consistent approximation to the Full Stokes equations that minimizes stress-strain functional.
  - Non-Newtonian Stokes flow: viscous forces dominate and not time dependent, except to readjust to boundary conditions.

Modeling Dynamics of Ice Sheets

- Blatter-Pattyn (2003): Based on equations for conservation of mass, momentum, and energy.
  - 2D equation for ice thickness, coupled with steady nonlinear elliptic equation for the horizontal velocity components. The vertical velocity is obtained from the assumption of incompressibility.

$$\frac{\partial H}{\partial t} = b - \nabla \cdot H\bar{\mathbf{u}}$$

$$2\frac{\partial}{\partial x} f\left[2\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right] + \frac{\partial}{\partial y} f\left[\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right] + \frac{\partial}{\partial z} f\frac{\partial u}{\partial z} = -\rho g\frac{\partial s}{\partial x}$$

$$2\frac{\partial}{\partial y} f\left[2\frac{\partial v}{\partial y} + \frac{\partial u}{\partial x}\right] + \frac{\partial}{\partial x} f\left[\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right] + \frac{\partial}{\partial z} f\frac{\partial v}{\partial z} = -\rho g\frac{\partial s}{\partial y}$$

(u,v,w)	=	velocity field
H	=	ice sheet thickness
$\bar{\mathbf{u}}$	=	vertically-avg horizontal vel field
b	=	source due to surface mass balance
f	=	effective viscosity
s	=	surface height of top of ice sheet
ρ	=	ice density
g	=	gravitational constant
T	=	ice temperature
c	=	heat capacity
k	=	ice thermal conductivity
Φ	=	dissipation due to deformation

  - Advection-diffusion equation for temperature.

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c}\nabla^2 T - \mathbf{u}\cdot\nabla T + \frac{\Phi}{\rho c} - w\frac{\partial T}{\partial z}$$

Current Status of Land Ice Modeling

- Several recent efforts to model ice sheets on a continental scale – most are 3D and using the SIA model
  - Glimmer (Tony Payne, Univ. of Bristol, England)
    - finite difference, serial
    - Glimmer-CISM (part of CESM now)
  - PISM (ARSC)
    - finite difference, parallel
  - SICOPOLIS (Greve's thesis, Darmstadt University of Technology, Germany)
    - finite difference, serial
    - Good, sophisticated front-tracking
  - Elmer (Finland)
    - finite element, parallel, full Stokes
  - ISSM (JPL/UCI)
    - finite element, parallel
  - …

Simulating Dynamics of Ice Sheets

- Computationally intensive …
  - Simulating all of Greenland at 5-km resolution requires ~1.6M nodes.
    - Doable using Glimmer (which is a serial code).
    - Need to be able to reach higher resolution – 1-km resolution will require ~40M nodes, assuming 20 vertical layers per ice column, with a uniform mesh.
      - Even higher resolution may be needed, particularly near the grounding line.
  - The Antarctica ice sheet is much larger.
  - Need robust, reliable, efficient numerical tools.
    - Discretization and mesh generation.
    - PDE solvers.
    - Linear solvers.
    - Nonlinear solvers.
  - High-performance computing.

Applied Math & Computer Science R&D

- DOE Office of Advanced Scientific Computing Research (ASCR) has significant investments in research and development of applied mathematics and computer science.
  - Base programs
  - SciDAC Centers for Enabling Technologies
- Examples:
  - Chombo for structured-grid refinement [APDEC]
  - PETSc, Trilinos [TOPS]
  - Discretization and unstructured meshes [ITAPS]
  - Sensitivity analysis
  - Autotuning [PERI]
  - …
- ASCR also has significant investments in high performance computing facilities [NERSC @ LBNL, LCF @ ANL, LCF @ ORNL].

ISICLES: Ice Sheet Initiative for Climate Extremes

- ISICLES (Ice Sheet Initiative for Climate Extremes) is a 3-year (2009-2012) initiative of ASCR, in cooperation with BER.

- The goal of ISICLES is to use advanced numerical and computational methods (including tools developed by other ASCR projects) to develop accurate, efficient, scalable ice sheet models and characterize their uncertainties.
- These improved models will be used for projections of ice-sheet retreat and sea-level rise in climate and earth-system models.
- In particular, models developed under ISICLES will be incorporated in Glimmer, the Community Ice Sheet Model (Glimmer-CISM), which is being developed and coupled to CESM with support from BER and NSF.

- Project managers: Lali Chatterjee (until Feb. 2010), Bill Spotz
- Website: http://www.csm.ornl.gov/ISICLES/

ISICLES Projects

- ISICLES is a collective effort consisting of six projects:
  - SEA-CISM: A Scalable, Efficient, and Accurate Community Ice Sheet Model
    Kate Evans, PI (ORNL)
  - BISICLES: High-Performance Adaptive Algorithms for Ice Sheet Modeling
    Esmond Ng, PI (LBNL)
  - Uncertainty Quantification for Large Scale Ice Sheet Modeling and Simulation
    Omar Ghattas, PI (Univ. of Texas – Austin)
  - SISIPHUS: Scalable Ice Sheet Solvers and Infrastructure for Petascale, High-resolution, Unstructured Simulations
    Tim Tautges, PI (ANL)
  - Lagrangian Model for Ice Sheet Dynamics
    Alexandre Tartakovsky, PI (PNNL)
  - Modeling the Fracture of Ice Sheets on Parallel Computers
    Haim Waisman, PI (Columbia)

ISICLES Projects

- Common themes:
  - Modular dynamical cores (callable from Glimmer-CISM) that solve the full-Stokes or higher-order equations.
  - Iterative methods (e.g., Jacobian-free Newton-Krylov) using modern solver packages (e.g., PETSc and Trilinos).
  - Structured/unstructured grids with adaptive refinements to provide sufficient resolution in regions of interest.
  - Scalable algorithms.
  - Interaction with climate scientists at LANL, NCAR and elsewhere.
    - Most of the climate scientists are funded by BER.
- Differences:
  - Discretization/mesh approaches vary widely – finite differences, finite volumes, finite elements; structured, unstructured.
  - Some efforts are focused on short-term deliverables (e.g., AR5 simulations); others aim for a longer-term impact.

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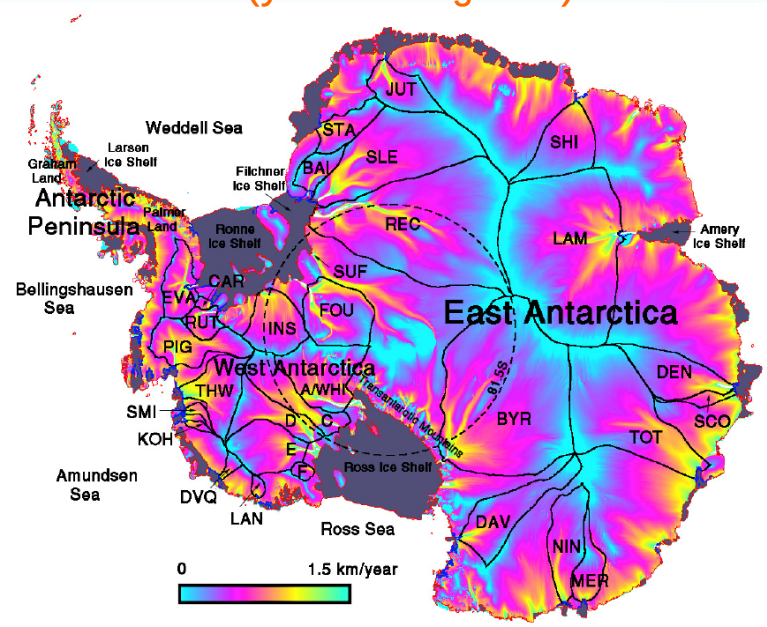
BISICLES Berkeley ISICLES

- Joint project between LBNL (Esmond G. Ng, PI) and LANL (Bill Lipscomb, co-PI).
  - Also collaborating with Tony Payne and Stephen Cornford (Univ. of Bristol).
- **Goal: Build a parallel, adaptive ice-sheet model.**
  - Problem is well-suited for adaptive mesh refinement (AMR).
    - 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).
  - Want good parallel efficiency.
  - Need good solver performance.

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

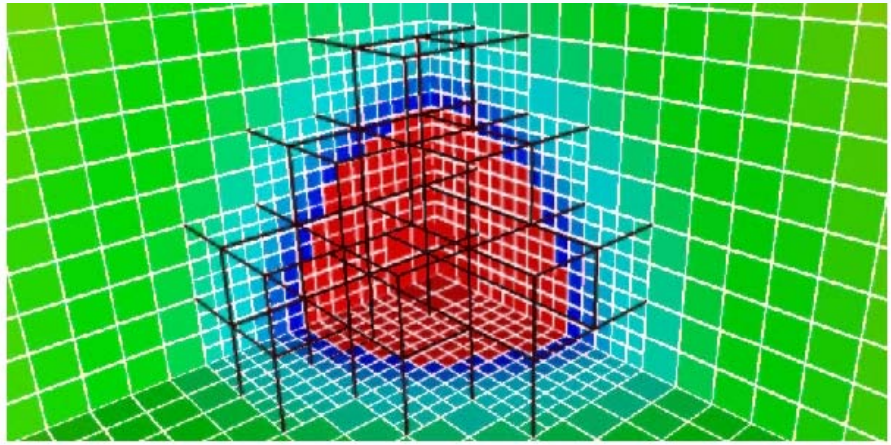


[Rignot & Thomas, 2002]

BISICLES Approaches

- Develop an efficient parallel implementation of Glimmer-CISM by
  - incorporating structured-grid AMR using the Chombo framework (supported by APDEC) to increase resolution in regions where finer resolution is needed,
    - Refined regions are organized into rectangular patches.
  - improving performance and convergence of multigrid/multilevel solvers,
  - deploying auto-tuning techniques to improve performance of key computational kernels.

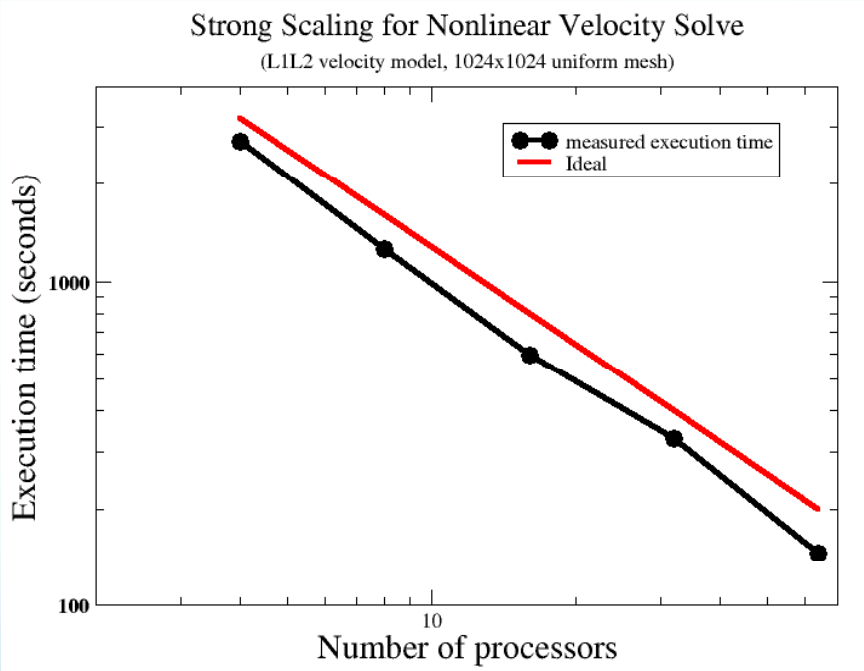
- Algorithmic advantages:
  - Build on mature structured-grid discretization methods.
  - Low overhead due to irregular data structures, relative to single structured-grid algorithm.



Progress and Plan

- 2D vertically-integrated AMR code (using L1L2 approximation).
  - Almost done …
  - Need improved nonlinear solver (Picard → JFNK).
  - Also need improved linear solver.
  - Semi-implicit time discretization?
  - Currently isothermal.
- 3D AMR higher-order model solver.
- Coupling with CCSM using existing Glimmer-CISM interface and by developing new interfaces as needed (in progress).

Initial tests show good strong scaling to at least 64 processors for nonlinear velocity solve (L1L2 approximation)

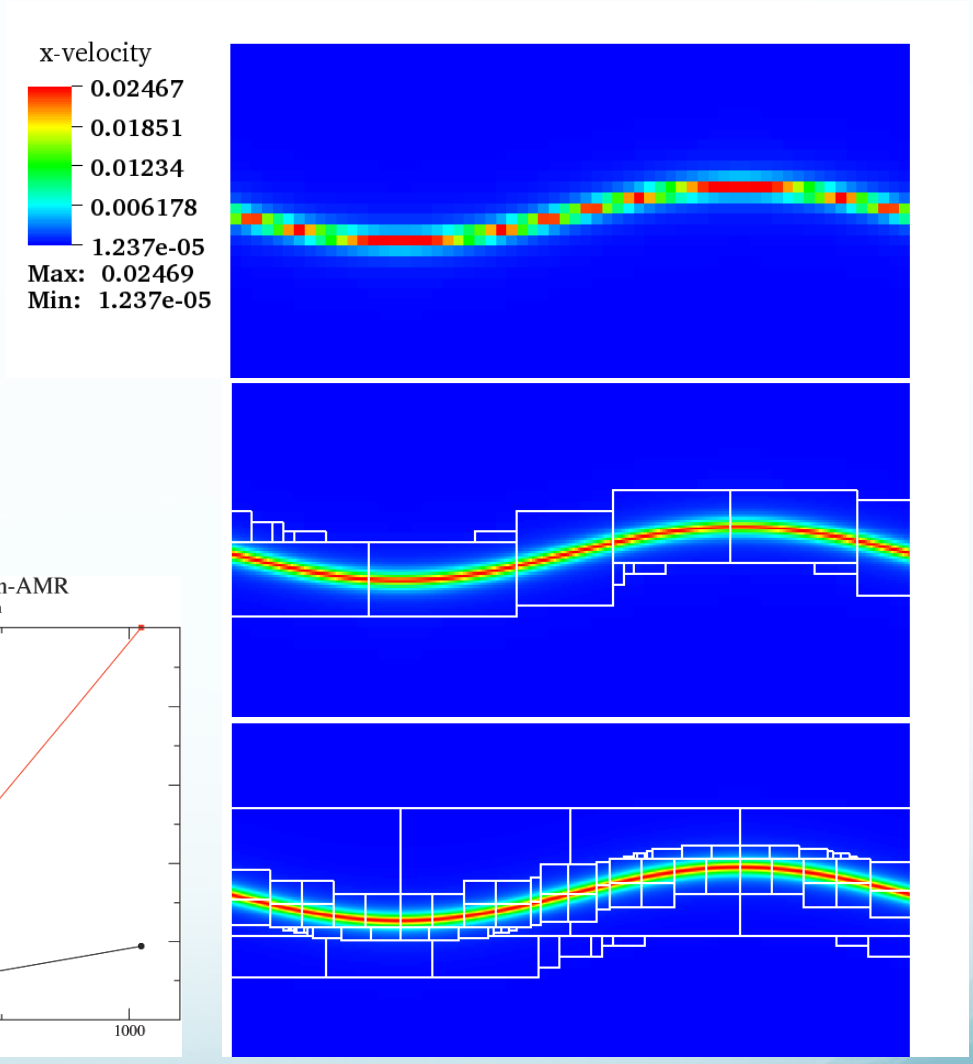


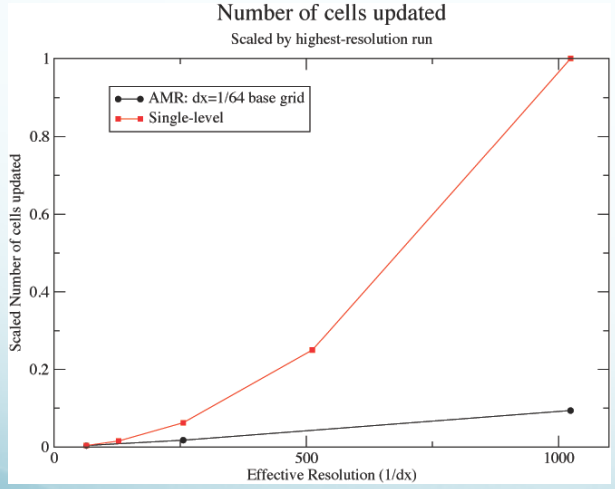
Recent Results

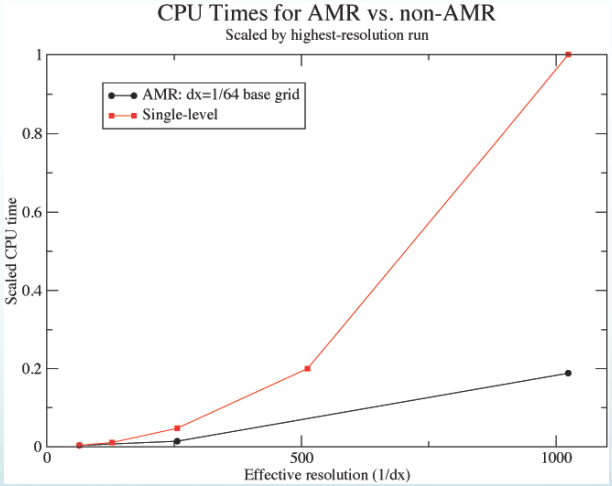
- Ice-stream Simulation

  [based on Pattyn et al (2008)]:

  - High resolution is required to accurately resolve the ice stream.
  - AMR simulation allows high resolution around the ice stream at a fraction of the cost of a uniformly refined mesh.

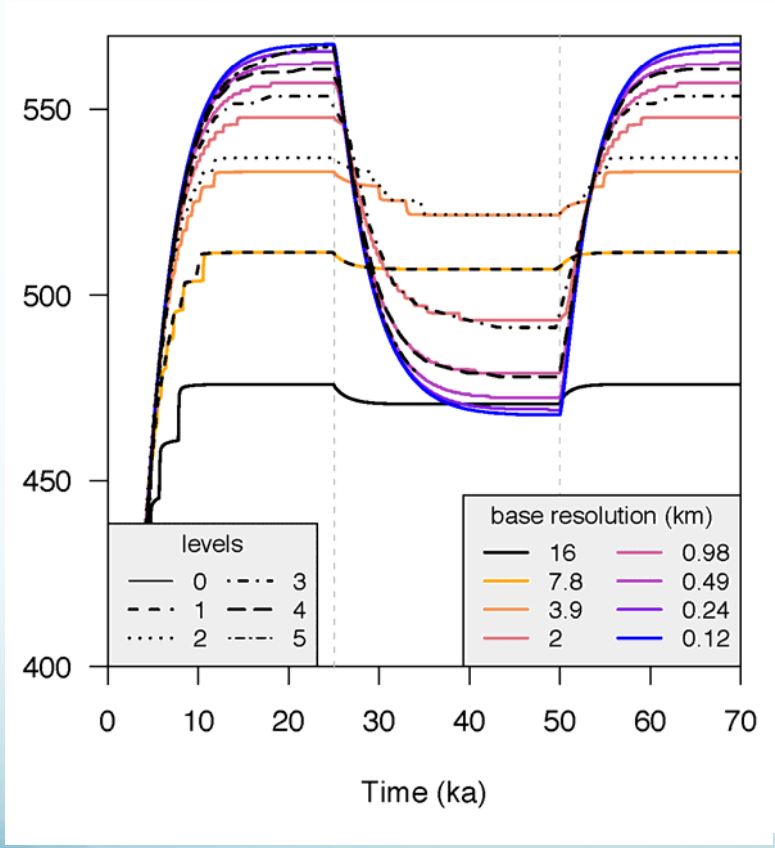


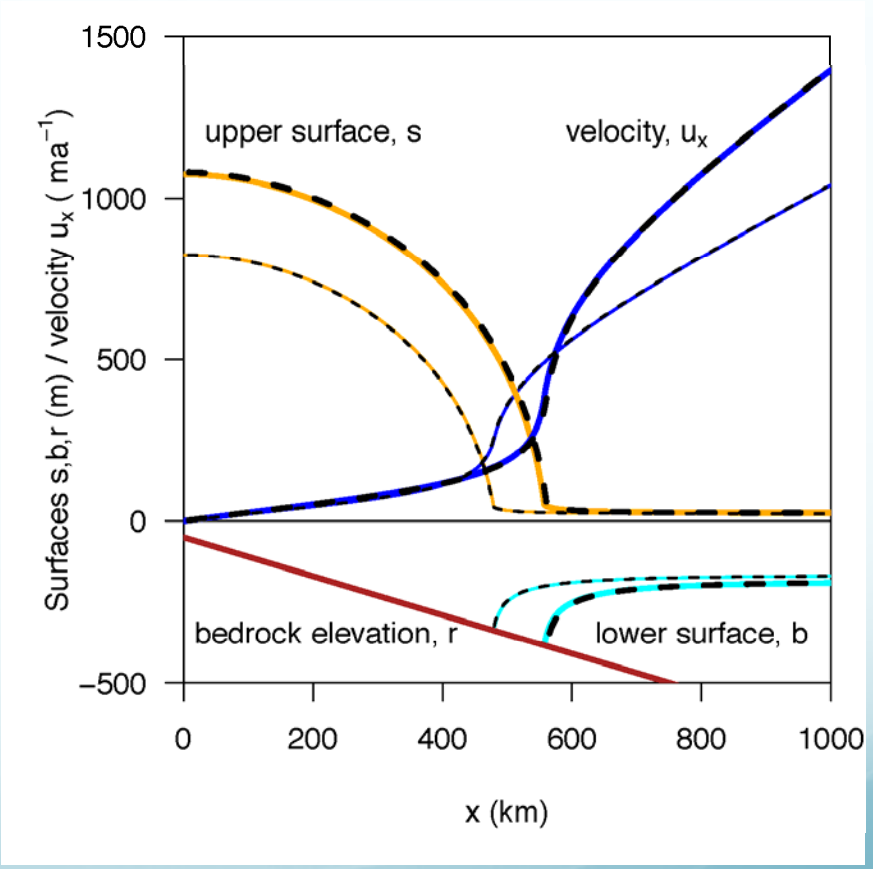




Recent Results

- Grounding-line Simulation [Vieli and Payne (2005), Gladstone et al (2010)]:
  - Demonstration that resolution is important (data provided by Stephen Cornford (Univ. of Bristol)).
  - AMR simulation captures behavior of uniform fine-mesh simulations.





SEACISM: A Scalable, Efficient and Accurate Community Ice Sheet Model

Project Members:

Kate Evans, ORNL

Dana Knoll, Los Alamos

J.-F. Lemieux, New York U

Jeff Nichols, ORNL

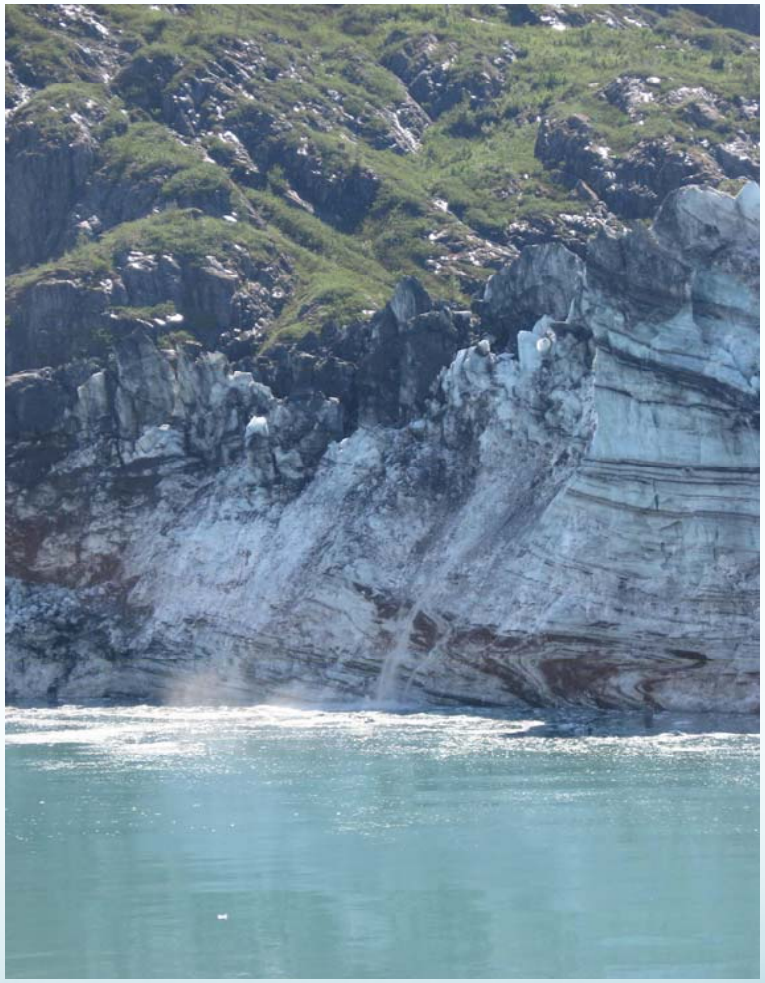
Andy Salinger, Sandia

Pat Worley, ORNL

Trey White*, NCAR

Consultation/Assistance from:
David Holland, NYU
Bill Lipscomb, Los Alamos
Steve Price, Los Alamos
GLIMMER Steering committee

*SEACISM alumni



SEA-CISM: Goals

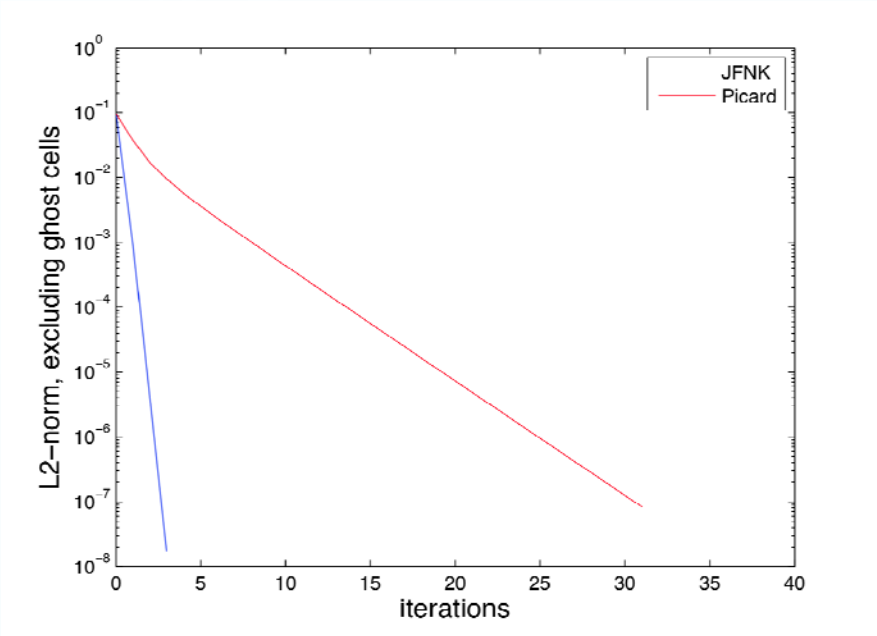
- Parallel Capability
  - hierarchical blocking structure
  - Incorporate features to take advantage of next generation computing resources
  - DOE/ASCR ALCC allocation given to SEACISM for development. Thanks!

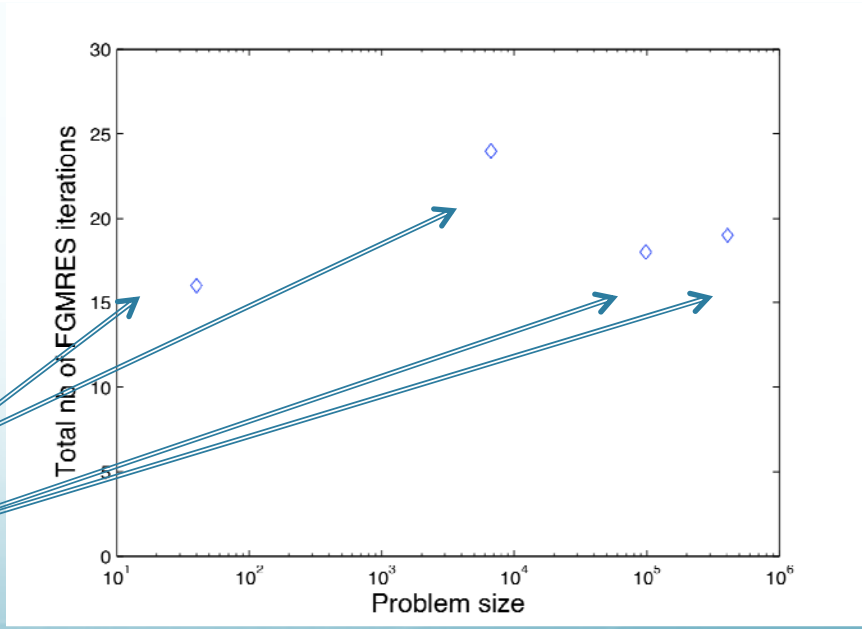
- Fully implicit solution method, JFNK
  - Option in 2 development track climate components
  - Use current Picard solver as a physics-based preconditioner, extend with ML
  - Link to Trilinos to solve equations at scale

- Ice sheet modeling is going to undergo significant growth of complexity in the short term
  - Algorithm design must account for increased coupling and multiscale behavior
  - Equations will no longer be SPD nor lend themselves to explicit Jacobian formation
  - Extend initial parallel, efficient scalable model to unstructured grids for greater flexibility and complexity

Solver progress in Glimmer-CISM*

- Improved convergence with the GIS test case using JFNK method with Picard as a preconditioner versus Picard as a solver
- # GMRES iterations are reduced by using JFNK, amount is tolerance dependent and will be explored to maximize performance
- Picard preconditioner produces rather flat growth of iterations with problem size for initial test cases
- JFNK used here will be replaced with Trilinos NOX JFNK, which will link to parallel code





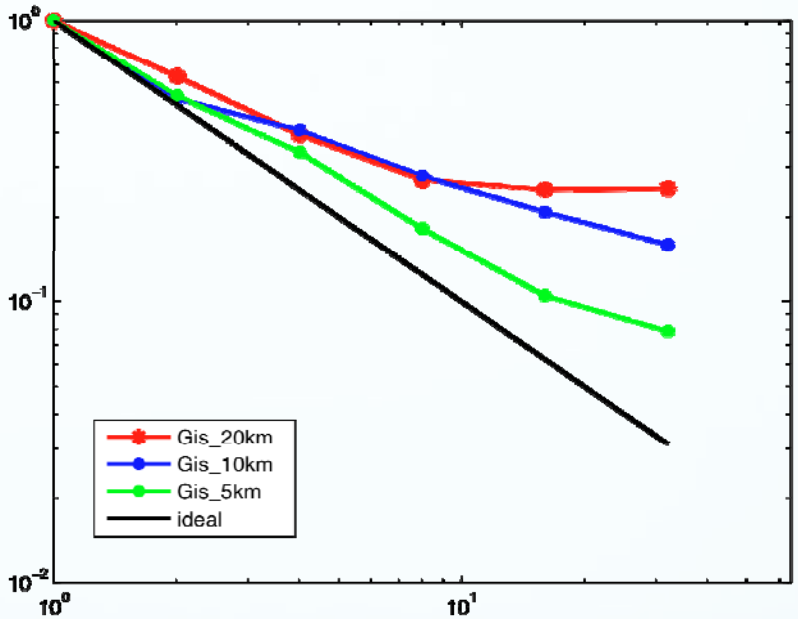
HUMP test case

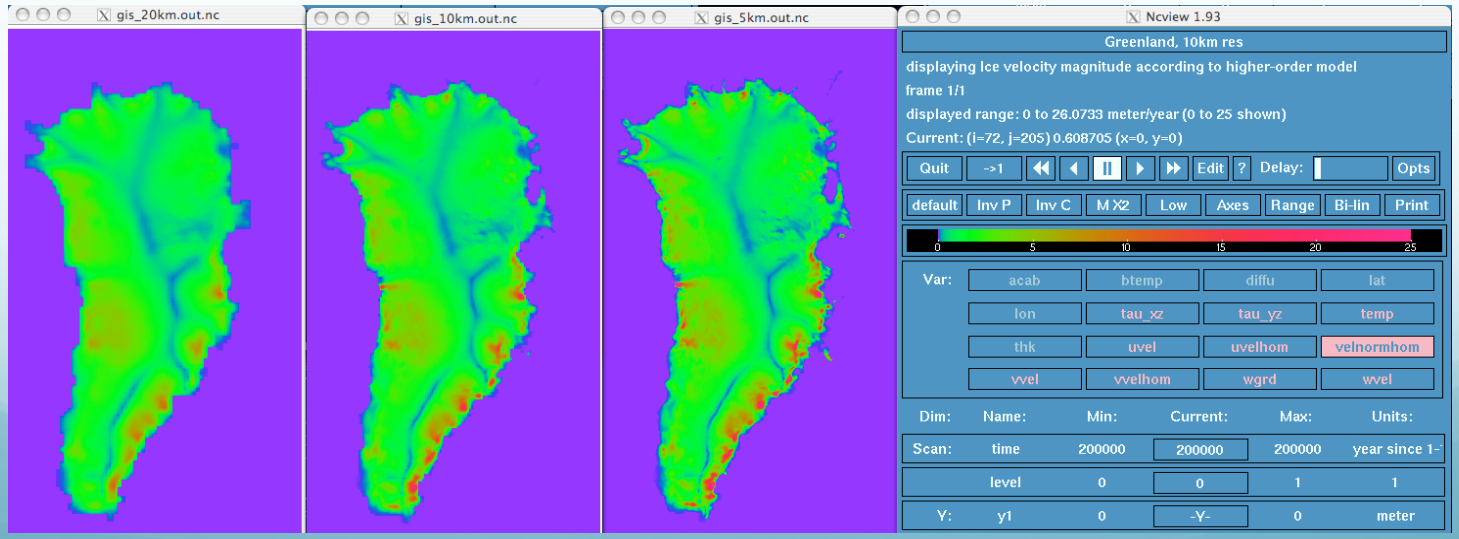
GIS test case

* Hot off the presses, still validating

Performance Analysis of “GIS” test case in CISM using Trilinos

- Test case of Greenland, key for evaluating numerical methods
- 20km, 10km, 5km resolutions run using Trilinos (GMRES for linear solve)
- As the number of grid points increases, total linear solve time decreases
- Scalability is approaching ideal





UT/LANL Project: Uncertainty Quantification for Large-Scale Ice Sheet Modeling and Simulation

University of Texas at Austin Co-PIs:

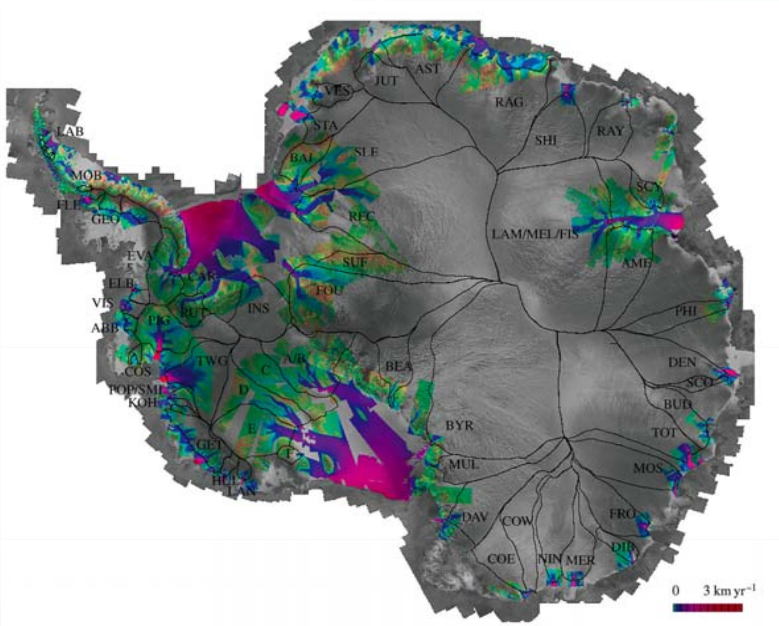
Don Blankenship (glaciology), *Carsten Burstedde* (computational math), *Omar Ghattas* (PI, computational science), *Charles Jackson* (climate science), *Georg Stadler* (applied math), *Lucas Wilcox* (scientific computing)

Los Alamos National Laboratory Co-PIs:

Jim Gattiker (statistics), *Dave Higdon* (statistics), *Steve Price* (glaciology)

Overall goal:

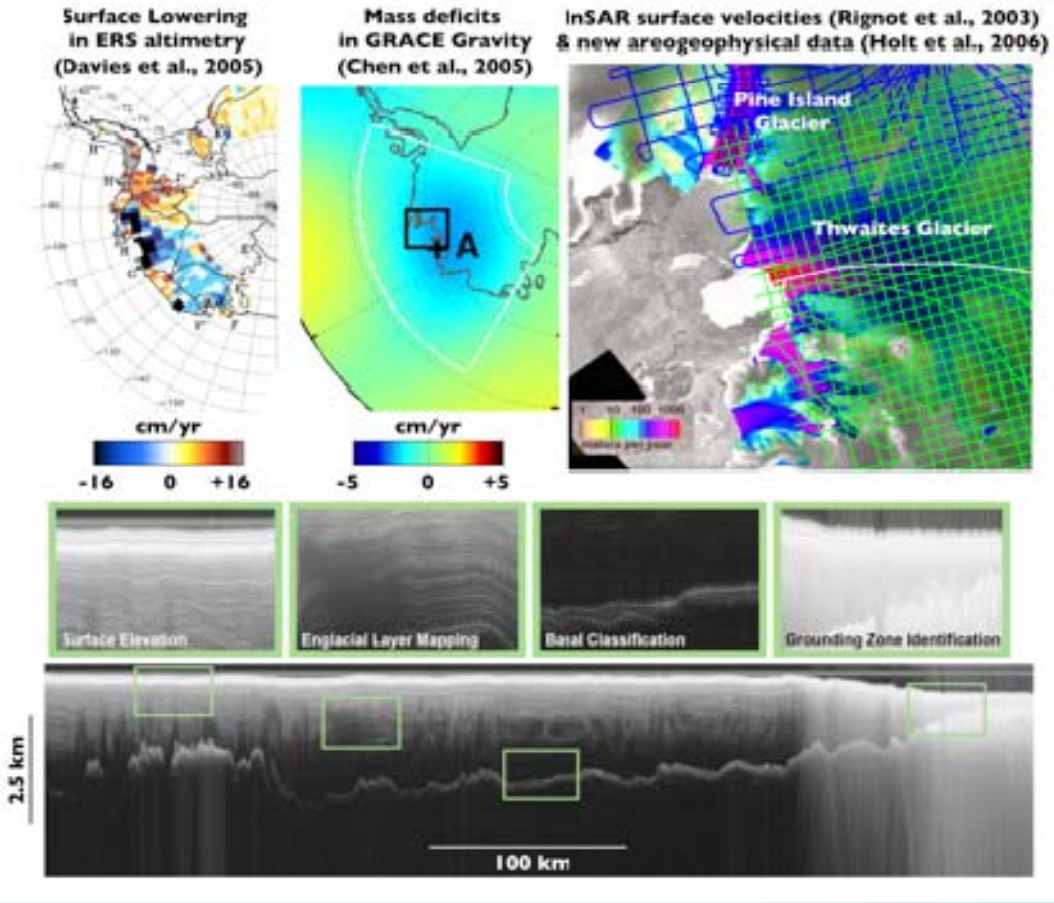
Develop *scalable uncertainty quantification techniques* for inferring uncertain parameters in ice sheet dynamics models by assimilating noisy observations into advanced adaptive petascale full Stokes forward models via solution of *large-scale statistical inverse problems.*



Observed surface velocities from InSAR

Uncertainty quantification for inverse problem

- Inferring unknown ice parameters and basal boundary conditions requires solution of ill-posed inverse problem (involves numerous forward solutions)
- Sparse and noisy data require statistical approach to inverse solution (must confront curse of dimensionality)
- Bayesian framework for statistical inverse problem: solution of inverse problem expressed as probability density function
- Current method of choice to sample this pdf employs Markov chain Monte Carlo (MCMC); however, for expensive forward simulations such as full Stokes ice sheet dynamics, contemporary “black-box” MCMC methods become prohibitive
- Goal: develop methods that exploit the structure of the parameter-to-observable map (including adjoint-based derivatives), as has been done successfully for deterministic inverse problem
- Build on our parallel adaptive full Stokes forward solver, incorporate adjoint solver



Different data that can be used to infer uncertainties in ice sheet parameters and basal boundary conditions

Scalable Ice-sheet Solvers and Infrastructure for Petascale, High-resolution, Unstructured Simulations

Timothy J. Tautges (PI), Barry Smith, Dmitry Karpeev, Jean Utke (ANL)

Jed Brown (ETH-Zurich), Patrick Heimbach (MIT) Bill Lipscomb (LANL)

Non-Newtonian Stokes system:

$$-\nabla\cdot(\eta Du)+\nabla p-f=0$$
$$\nabla\cdot u=0$$

with boundary conditions for:

$$(Du-p1)\cdot n=\begin{cases}0 & \text{free surface}\\ -\rho_w z n & \text{ice-ocean}\end{cases}$$

$$u=0 \quad \text{frozen bed}$$

$$\left.\begin{aligned}u\cdot n&=g_{melt}(Tu,\ldots)\\ T(Du-p1)\cdot n&=g_{slip}(Tu,\ldots)\end{aligned}\right\} \quad \text{non-linear slip}$$

Navier, Weerman, or Coulomb power law for g_{slip}

Mesh motion:

$$-\nabla\cdot\sigma=0$$

$$\sigma=\mu\left[2Dw+(\nabla w)^T\nabla w\right]+\lambda\, tr(\nabla w)1,\quad w=x-x_o$$

$$\text{surface: } (\dot{x}-u)\cdot n=q_{BL},\ T\sigma\cdot n=0$$

Enthalpy transport:

$$\rho\left[\frac{\partial}{\partial t}\Theta+(u-\dot{x})\cdot\nabla\Theta\right]-\nabla\cdot\left[\kappa(\Theta)\nabla\Theta+q_D(\Theta)\right]-\eta\, Du:Du=0$$

ALE — Fourier/Fick diffusion — Darcy flow — Strain heating

Modeling:

- Method of lines approach (discretize over space – DAE, then over time)
- hp-adaptive FEM with assembly-free solution

Preconditioning:

- "Dual-order" over space – high-order FEM, preconditioned with low-order linear elements from high-order nodes
- Block-ILU, replacing sub-blocks with physics-based equivalents

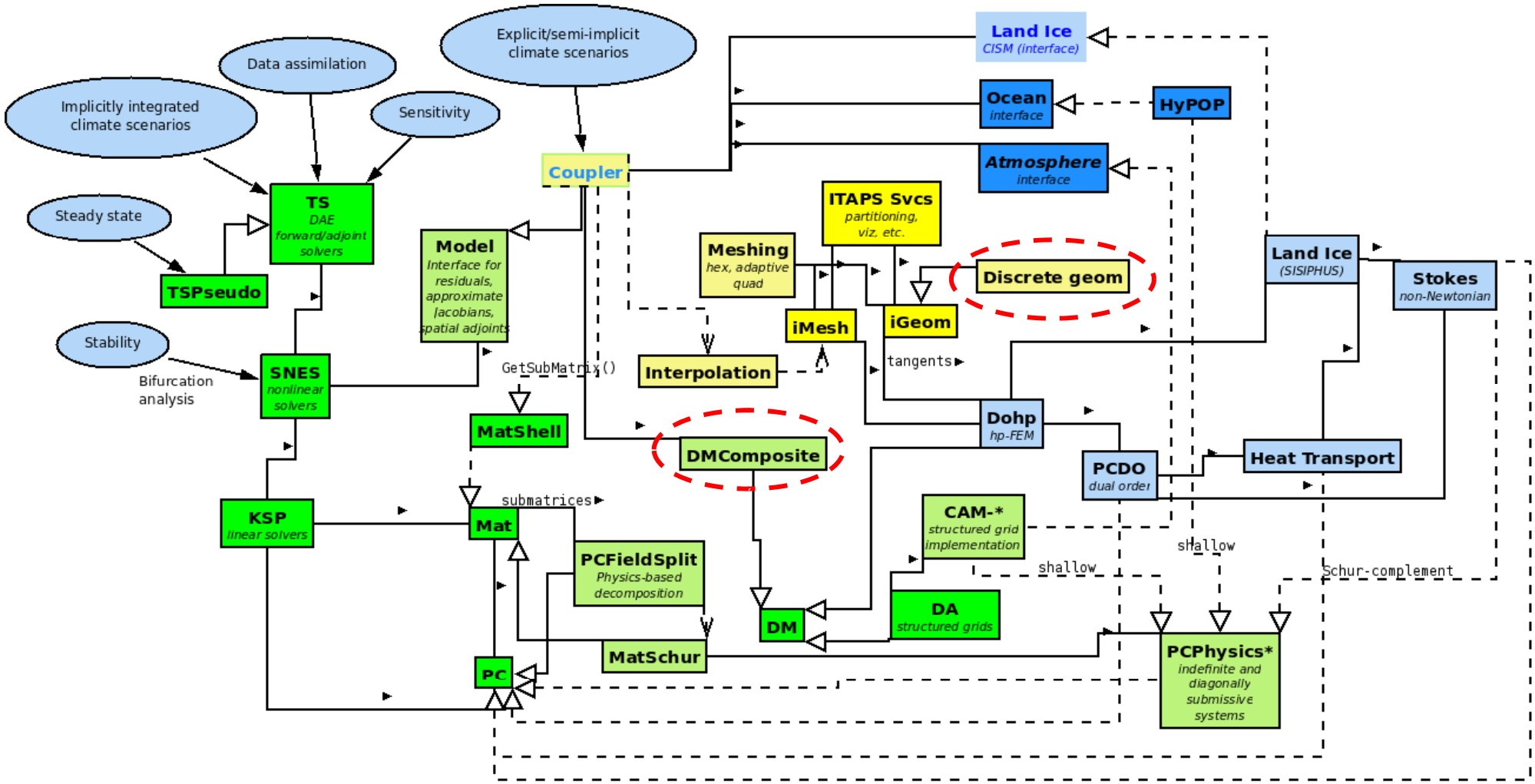
Geometry/mesh:

- Unstructured, hexahedral extruded mesh
- Mesh-based geometry w/ smooth normals for bed, ice surface
- Adaptive mesh near bed, coastline

Implementation:

- Use component-based solvers (PETSc), tools (ITAPS)
- Higher-level interface to Petsc for expressing physics and physics-based preconditioners
- Use Petsc Data Manager (DM) implementation based on ITAPS mesh interface

SISIPHUS Software Component View



PETSc | MOAB/CGM | ice physics

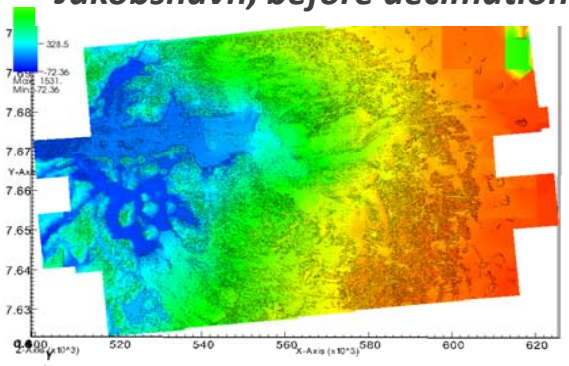
Task #1: Representation of ice sheet bed, surface as geometric model

- 2 primary sources of data:
  - CReSIS flight path data (<< 5km)
  - ISIS (J. Johnson, UMT) data sets (5km)

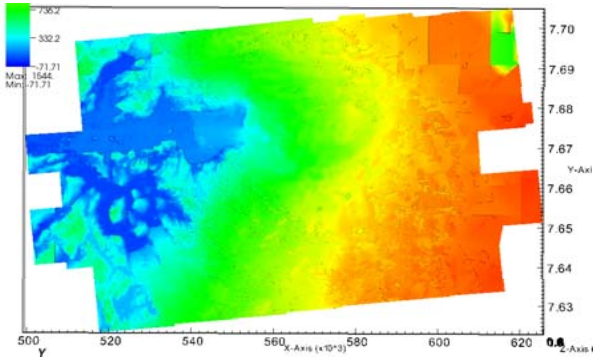
- CRESIS data
  - Read as points, elevations
  - Triangulate using Triangle
  - Decimate

- Decimation
  - Using Qslim algorithm (Garland & Heckbert, Siggraph ’97)
  - Implemented on MOAB
  - Challenge: noisy data, reasonable run-times

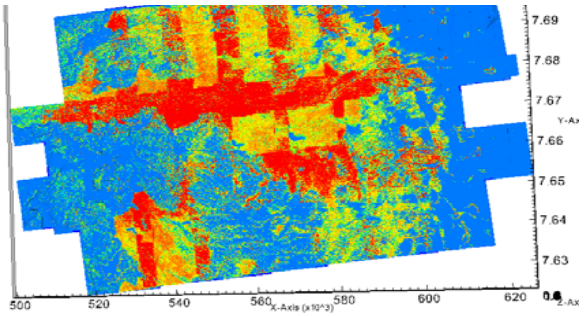
Jakobshavn, before decimation (5M tri)



Jakobshavn, after decimation (200k tri)

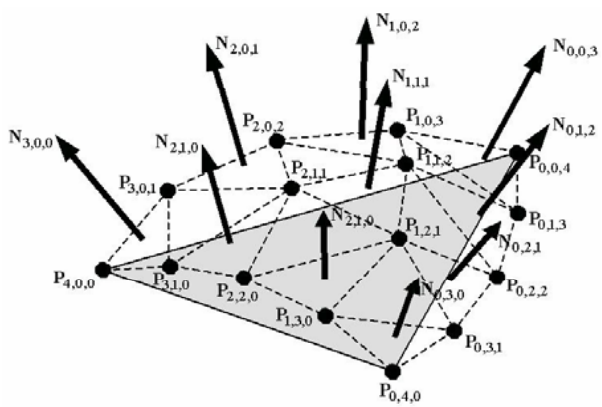


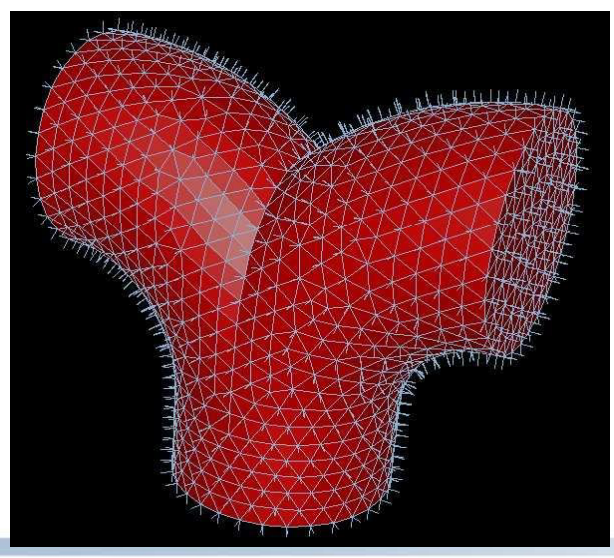
Thickness, before decimation

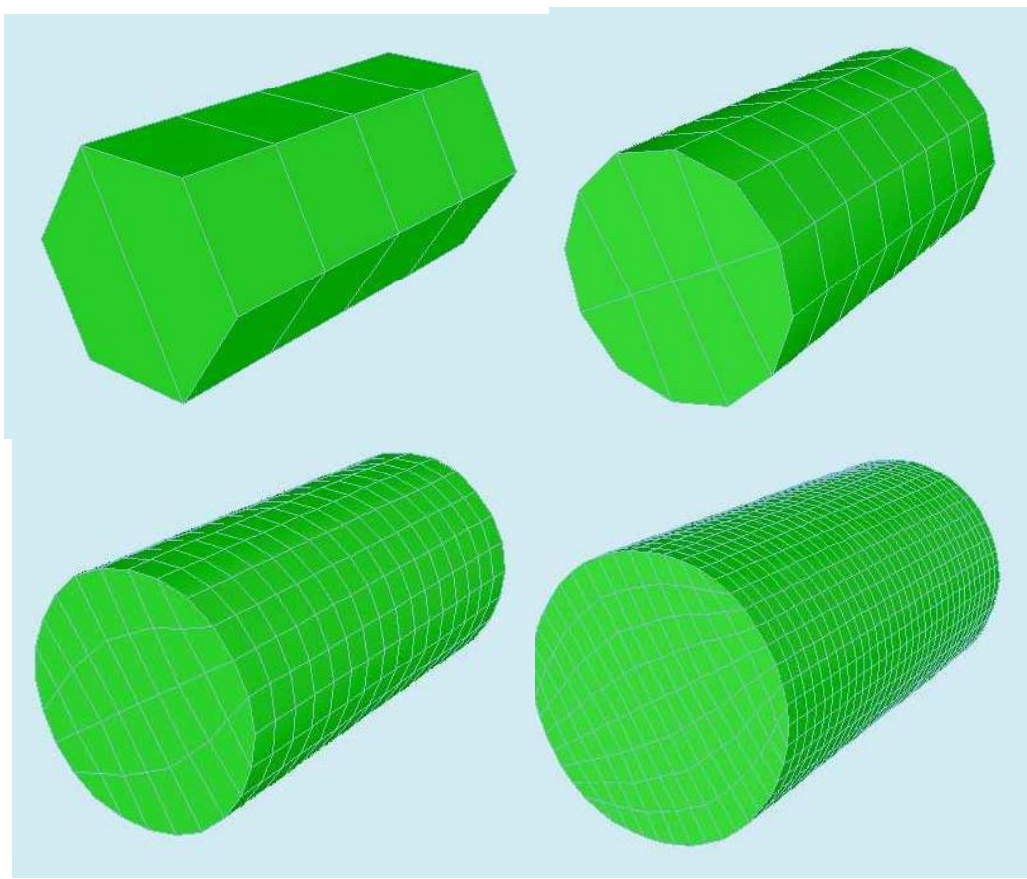


Task #2: Smooth tangents, normals on facet-based surface

- C1-continuous facet-based geometric representation to support meshing
  - Owen, White, Tautges, “Facet-based surfaces for 3d mesh generation”, 11th IMR, ’02)



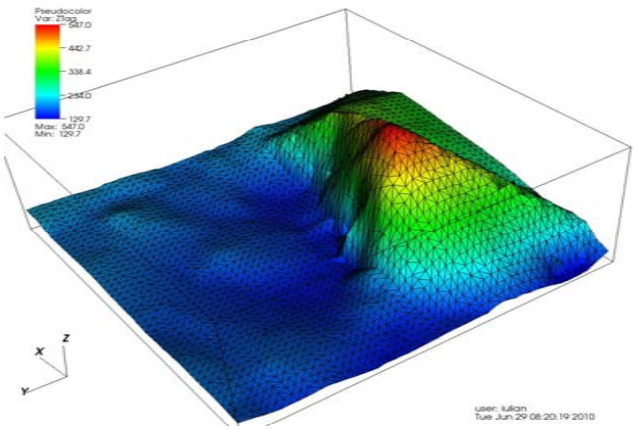




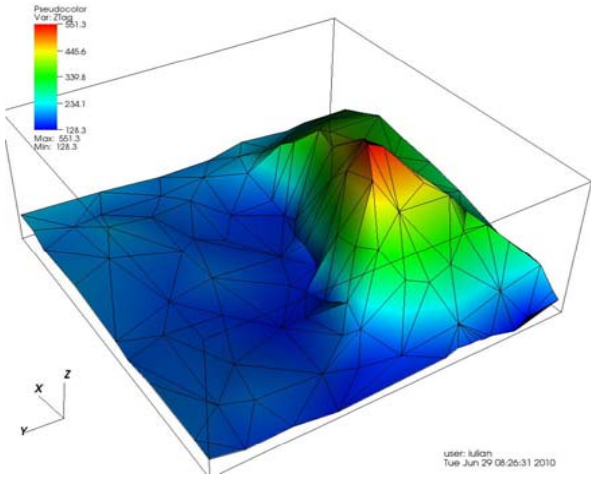
Task #2: Smooth tangents, normals on facet-based surface

- For ice sheet data…

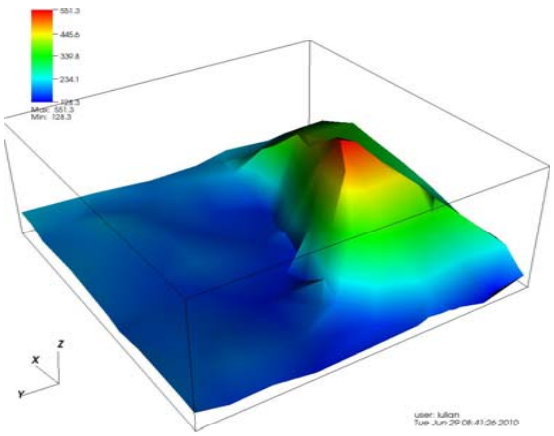
Original

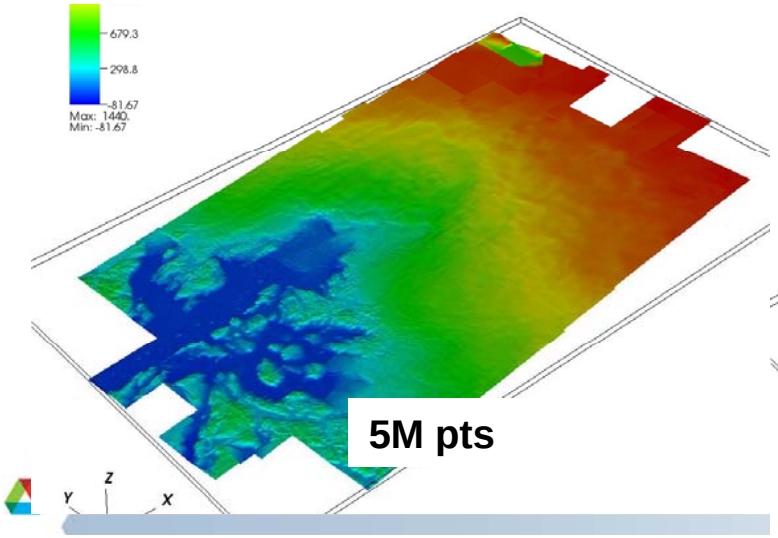


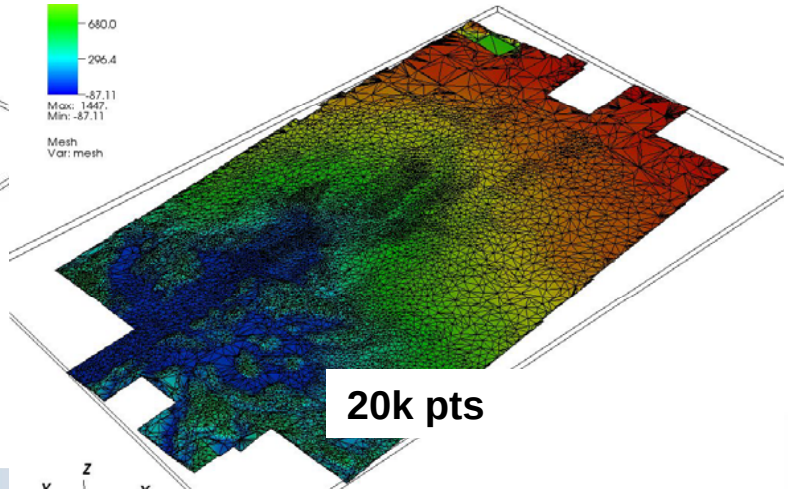
Decimated

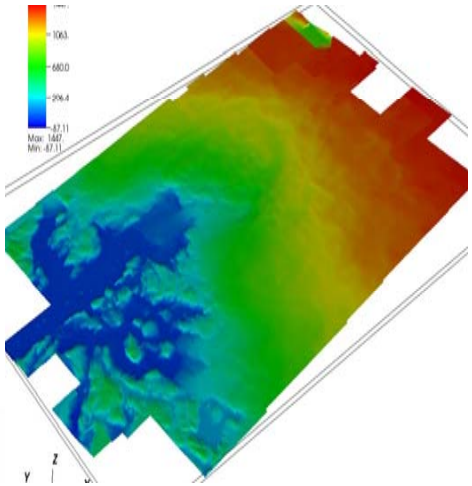


Smoothed



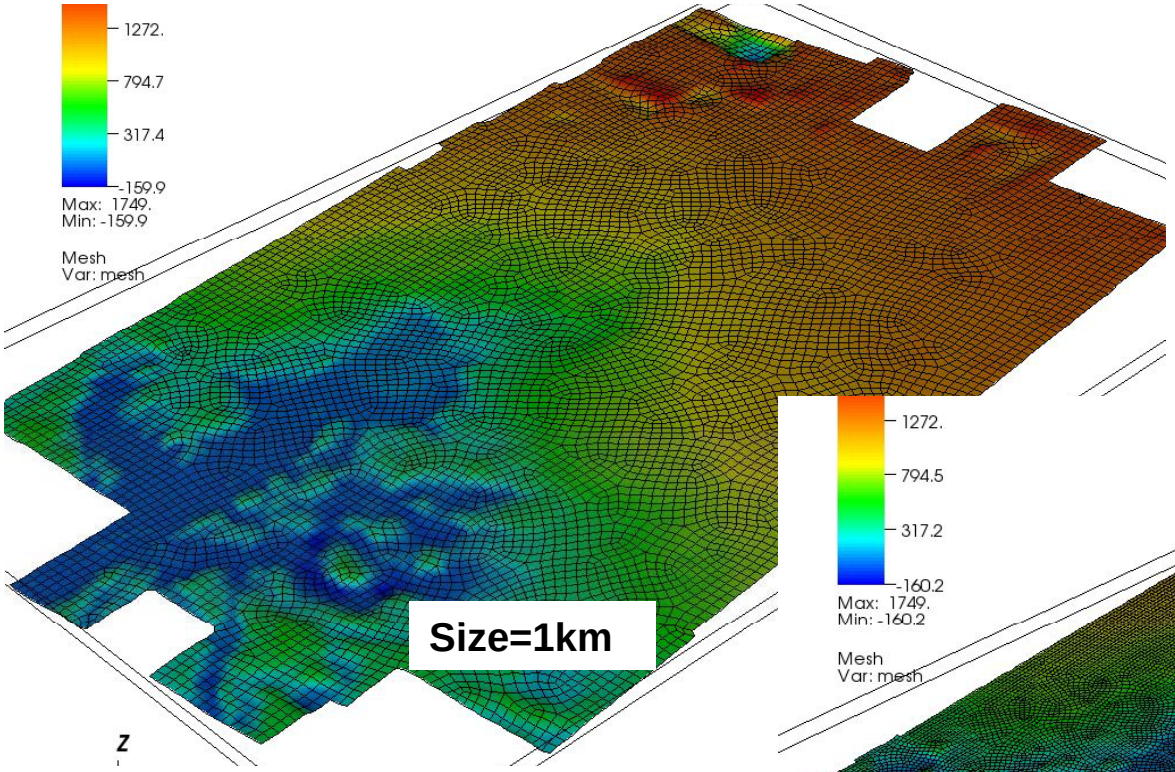


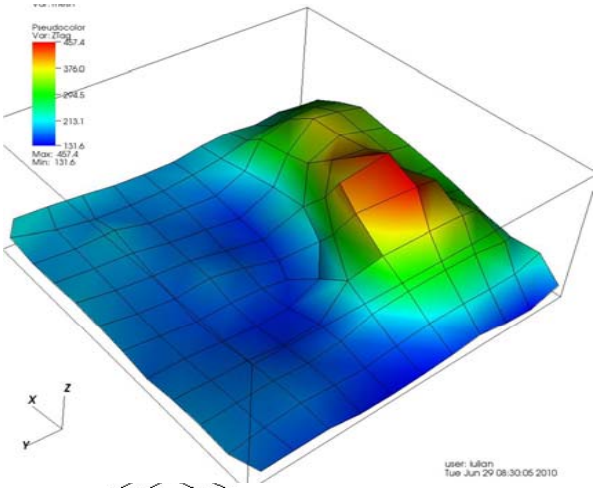


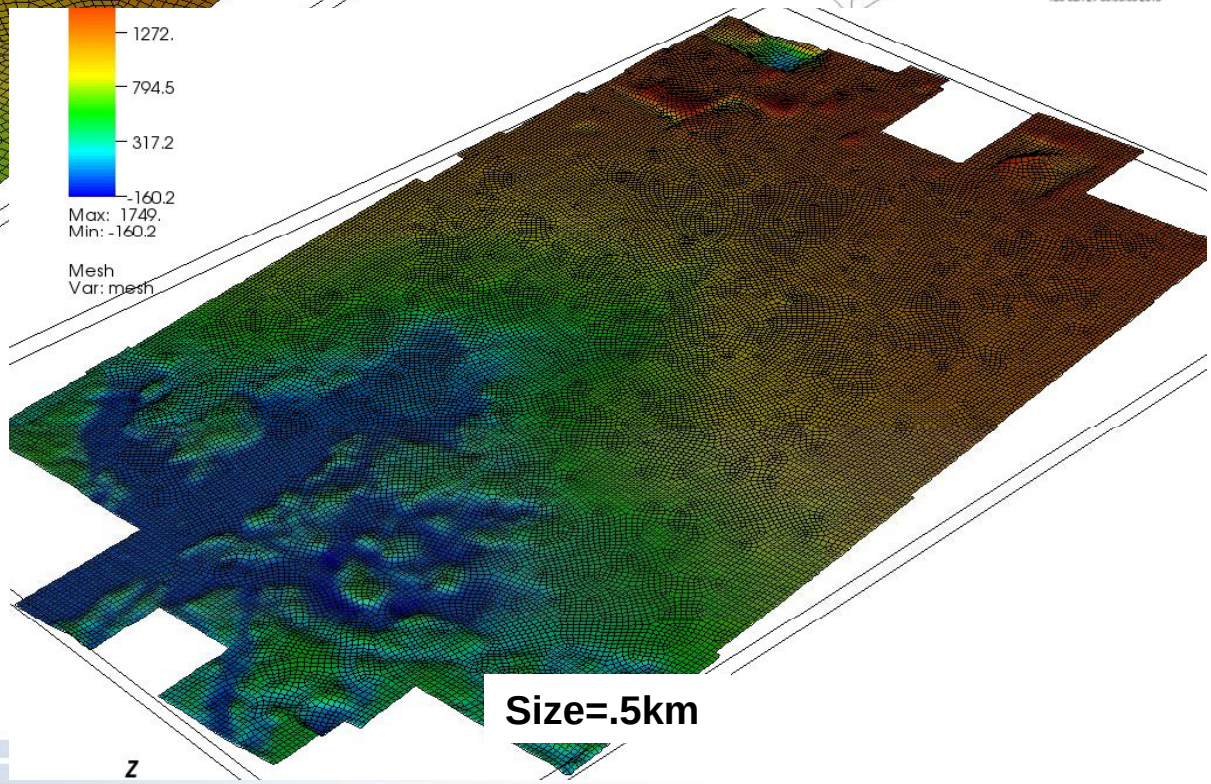


Task #3: Quad meshing on smoothed surfaces

- Present an iGeom interface for smoothed surface representation
  - Can feed directly to quadrilateral mesh generator







- Other mesh algs also apply
- Need to improve eval speed

Lagrangian Smoothed Particle Hydrodynamics Model for Ice Sheet Dynamics

PI: Alexandre Tartakovsky

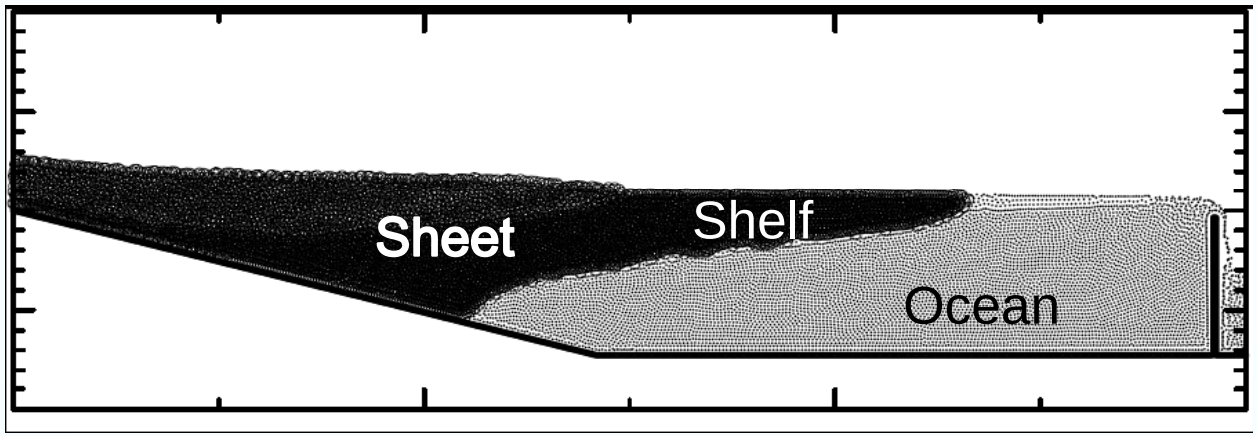
Pacific Northwest National Laboratory

Main objectives:

- Develop a three-dimensional Lagrangian particle model for ice sheet dynamics and implement it on leadership class computers;
- Develop highly scalable meshless algorithms based on Smoothed Particle Hydrodynamics;
- Use the 3D model to investigate assumptions in simplified but computationally more efficient ice sheet models for different types of ice sheets and glaciers.

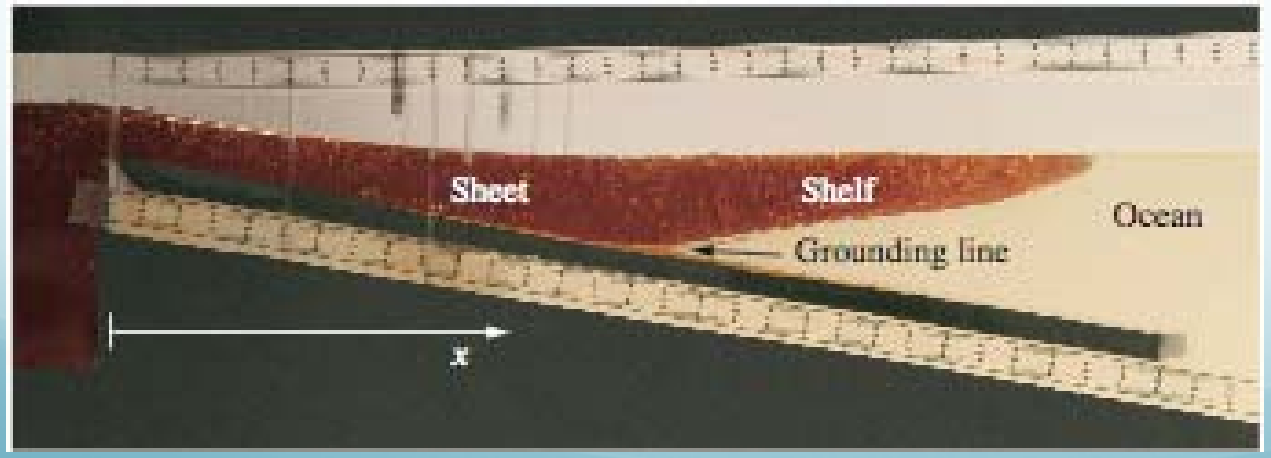
Progress

A novel 2D Smoothed Particle Hydrodynamics model for ice sheets and ice shelves has been developed.



The model allows for a seamless coupling between ice sheet and ice shelf computational domains.

The SPH model is being compared to laboratory experiments (Rosalyn et al., JFM, in press)



Modeling the Fracture of Ice Sheets on Parallel Computers

PI: Haim Waisman, David Keyes and Robin Bell (consultant)
Columbia University

Ray Tuminaro and Erik Boman
Sandia National Labs

Project website: http://www.civil.columbia.edu/waisman/ice/index.html

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Objective: Employ parallel computers to study the fracture of land ice to better understand how it affects global climate change. In particular the collapse mechanism of ice shelves, the calving of large icebergs and the role of fracture in the delivery of water to the bed of ice sheets.

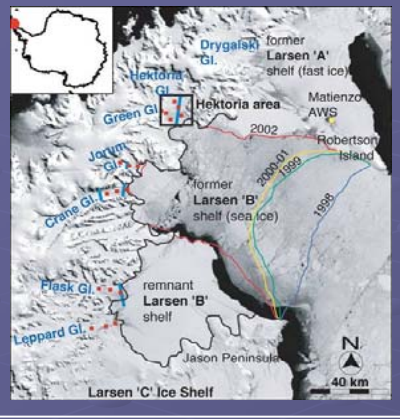
Columbia University

Sandia National Laboratories

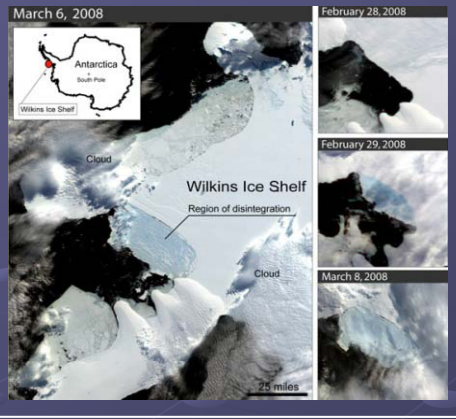
Motivation: Importance of Ice Fracture

Example 1: global warming leading to collapse of ice shelves in Antarctica

Larsen B diminishing shelf 1998-2002



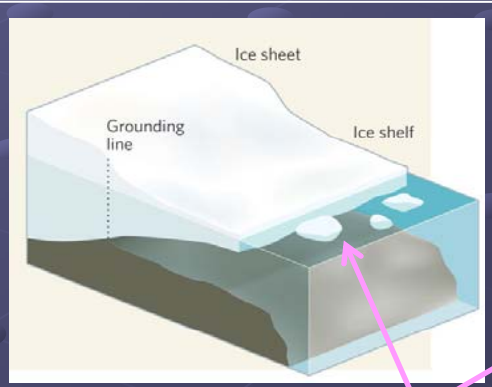
Wilkins ice shelf
Recent 2008 collapse



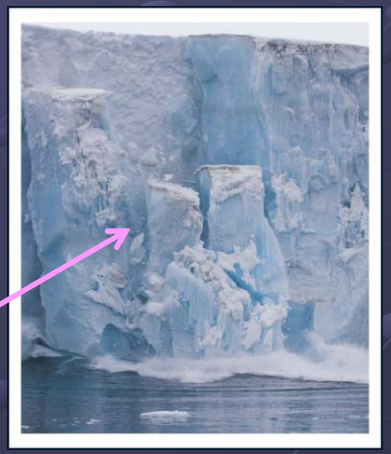
Example 2: ice calving from an ice shelf

ice calving: Fracture and disintegration to smaller Icebergs

The proposed research will be used to validate theories, for example:
Alley et. al., Science [2008]: a simple law for ice shelf calving



ice calving



Example 3: role of fracture in delivery of water to the bed of ice sheets

Main Consequence: the water driven fracture flows directly to the base of the ice sheet, raising the surface of the ice sheet (orders of meters) and lubricating its base. The net effect is that the ice sheet flow is accelerated due to this lubrication.

Proposed research

(strong ties with DOE programs: TOPS, CSCAPES)

Exploration: examine/learn and evaluate existing ice sheet models as base code development platform and seek new partners in the ice and climate communities

Problem definition: define geometry (from terrain data), Boundary condition and loads (self weight) and generate a mesh

Modeling: continuum damage mechanics (crack initiation and propagation), elasticity and extended finite element (XFEM) for crack modeling

Solution: developing specialized highly parallel multigrid solvers for XFEM

Verification & Validation of the code with available experimental data

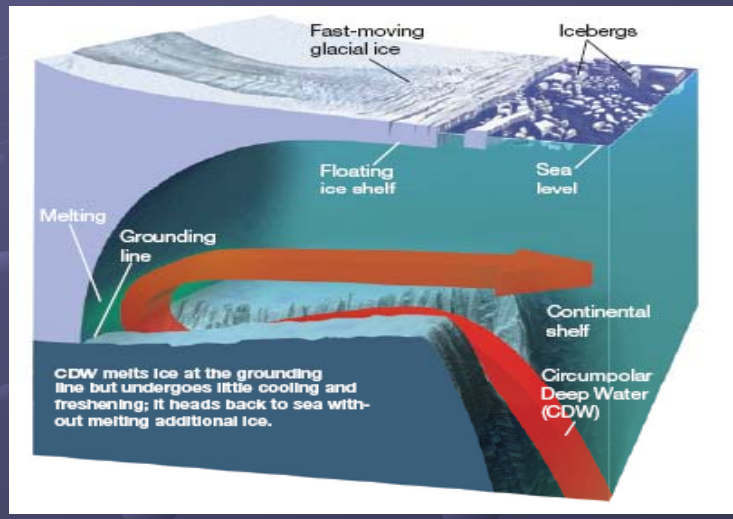
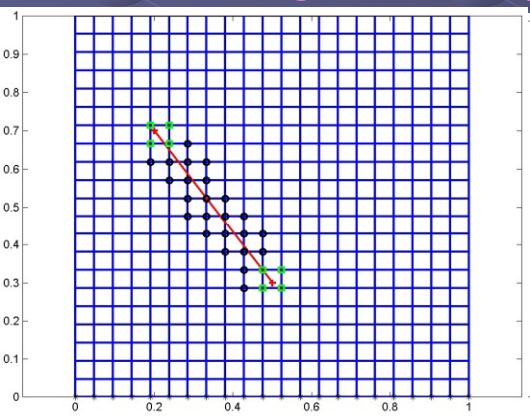
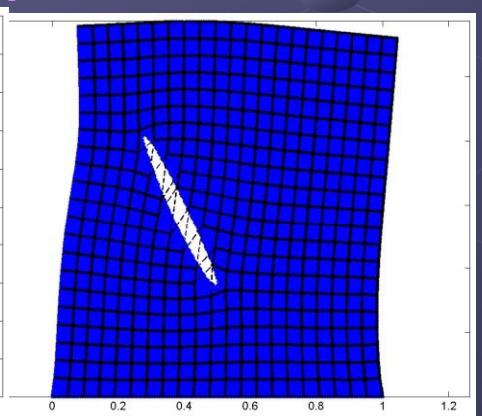
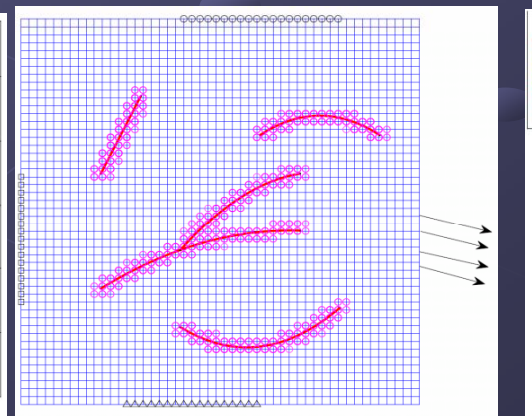


Image from Dr. Bindschadler presentation, DOE workshop Sep. 2009
Showing the complex Fracture of an ice shelf

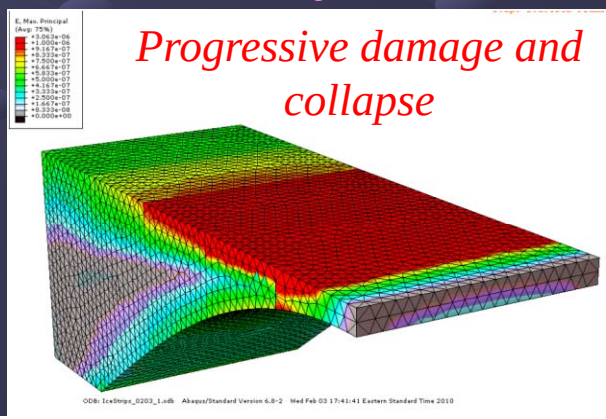
Modeling cracks by Extended Finite Element Method

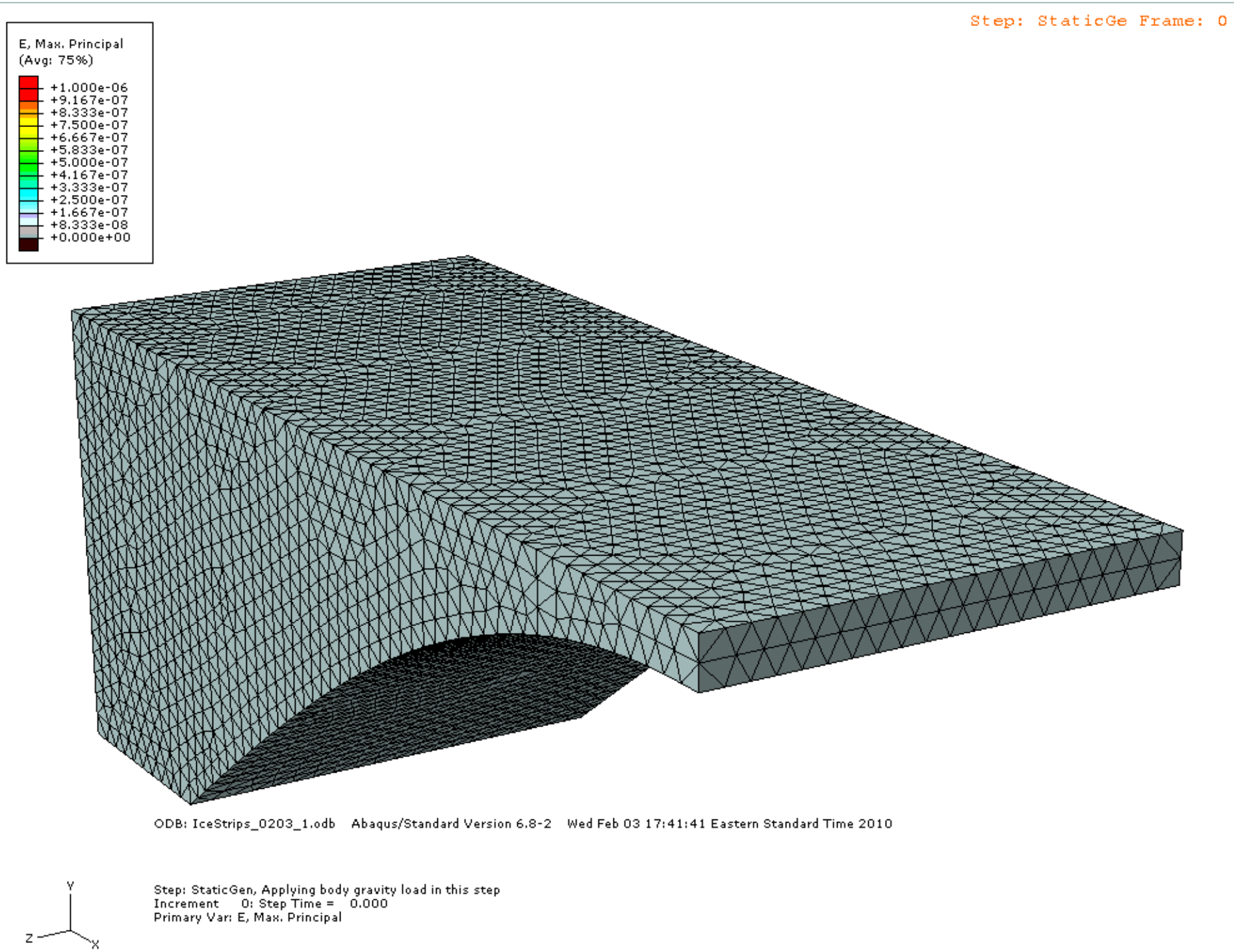






Preliminary results

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+5.833e-07
+5.000e-07
+4.167e-07
+3.333e-07
+2.500e-07
+1.667e-07
+8.333e-08
+0.000e+00
ODB: IceStrips_0203_1.odb Abaqus/Standard Version 6.8-2 Wed Feb 03 17:41:41 Eastern Standard Time 2010
Y
Z
X
Step: StaticGen, Applying body gravity load in this step
Increment 0: Step Time = 0.000
Primary Var: E, Max. Principal

Concluding Remarks

- ISICLES addresses the importance and complexity of ice sheet dynamics and predictability by taking advantage of ASCR capabilities developed in the base programs and SciDAC.

- The six ISICLES projects are separate but complementary efforts.
  - Some have overlap of tasks.
  - Some focus on short term deliverables in order to provide results for IPCC AR5; some are longer term.
  - Almost all are leveraging tools developed through various ASCR-funded projects and are targeting at high performance computing.
  - Interaction with climate scientists.

Acknowledgments

- ASCR – funding support

- Input from all project PIs …
  - Kate Evans, Oak Ridge National Laboratory
  - Omar Ghattas, Univ. of Texas, Austin
  - Alexandre Tartakovsky, Pacific Northwest National Laboratory
  - Tim Tautges, Argonne National Laboratory
  - Haim Waisman, Columbia Univ.

- Special thanks to
  - William Lipscomb, Los Alamos National Laboratory

- Also special thanks to
  - Daniel Martin, Lawrence Berkeley National Laboratory