Land-Ice and Atmospheric Modeling at Sandia: the *Albany/FELIX* and *Aeras* Solvers

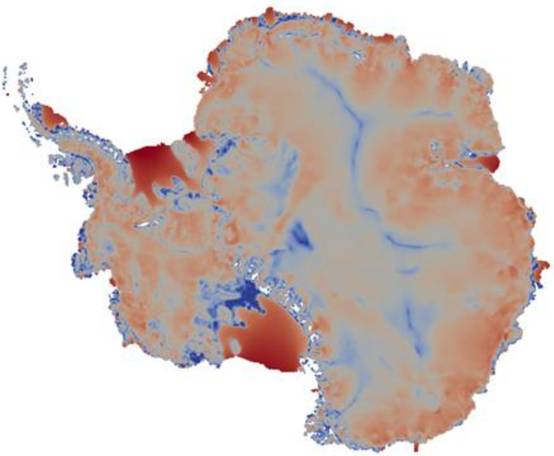
Irina K. Tezaur

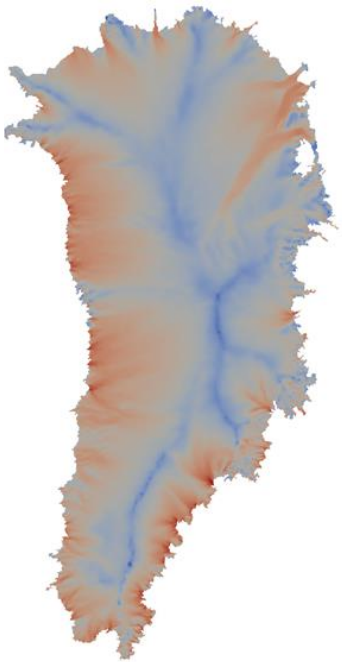
Org. 8954

Quantitative Modeling & Analysis Department

Sandia National Laboratories

Livermore, CA



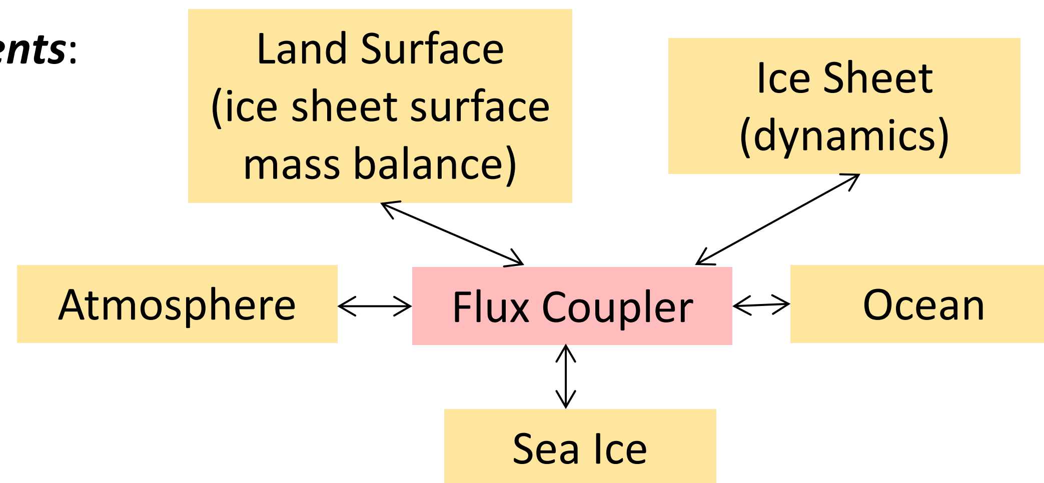


Wednesday, December 9, 2015

8300 Climate Kickoff

Earth System Models: CESM, DOE-ESM

- An ESM has ***six modular components***:
  1. Atmosphere model
  2. Ocean model
  3. Sea ice model
  4. Land ice model
  5. Land model
  6. Flux coupler



Goal of ESM: to provide actionable scientific predictions of 21st century sea-level rise (including uncertainty).

Climate Model passes:

- Surface mass balance (SMB)
- Boundary temperatures
- Sub-shelf melting

Land Ice Model passes:

- Elevation
- Revised land ice distribution
- Oceanic heat and moisture fluxes (icebergs)
- Revised sub-shelf geometry

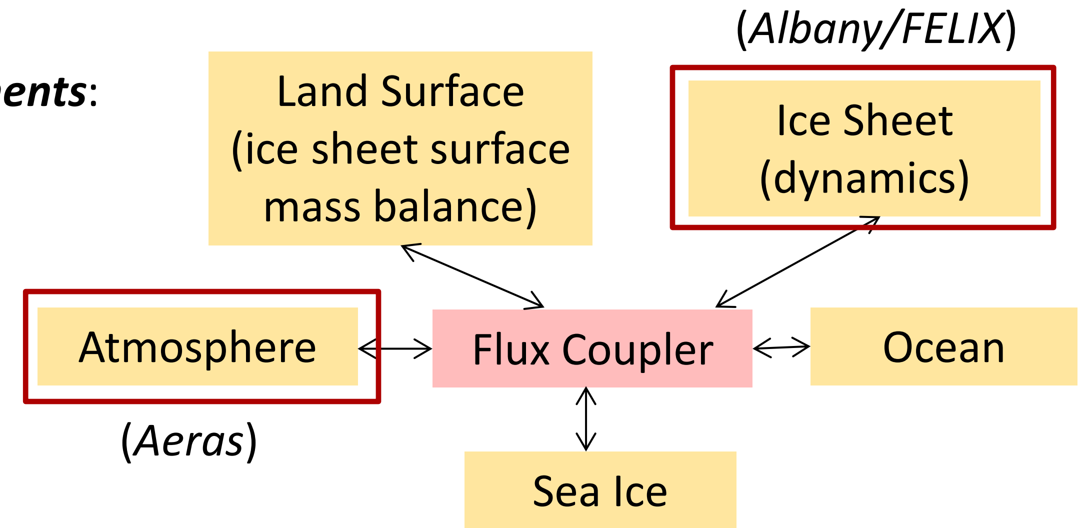
Earth System Models: CESM, DOE-ESM

NCAR NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

U.S. DEPARTMENT OF ENERGY

ACME Accelerated Climate Model for Energy

- An ESM has ***six modular components***:
  1. Atmosphere model
  2. Ocean model
  3. Sea ice model
  4. Land ice model
  5. Land model
  6. Flux coupler



Goal of ESM: to provide actionable scientific predictions of 21st century sea-level rise (including uncertainty).

Climate Model passes:

- Surface mass balance (SMB)
- Boundary temperatures
- Sub-shelf melting

Land Ice Model passes:

- Elevation
- Revised land ice distribution
- Oceanic heat and moisture fluxes (icebergs)
- Revised sub-shelf geometry

The *Albany* Code Base and *Trilinos* Libraries

The ***Albany/FELIX*** and ***Aeras*** solvers are implemented in a Sandia (open-source*) parallel C++ finite element code called…

Started by A. Salinger

Albany

Land Ice Physics Set (***Albany/FELIX code***)

Atmosphere Physics Set (***Aeras code***)

Other *Albany* Physics Sets (e.g., LCM)

"Agile Components"

- Discretizations/meshes
- Solver libraries
- Preconditioners
- Automatic differentiation
- Many others!

Trilinos

- Parameter estimation
- Uncertainty quantification
- Optimization
- Bayesian inference

DAKOTA

- Configure/build/test/documentation

*Use of **Trilinos** components and **Albany** code base has enabled rapid code-development: codes born **parallel**, **scalable**, **robust** and equipped with **advanced analysis / next generation** capabilities*

*Open-source code available on github: https://github.com/gahansen/Albany.

PISCEES Project for Land-Ice Modeling

Sandia National Laboratories

FASTMATH

SciDAC Scientific Discovery through Advanced Computing

SUPER INSTITUTE FOR SUSTAINED PERFORMANCE, ENERGY, AND RESILIENCE

PISCEES*
SciDaC Application Partnership
(DOE's BER + ASCR divisions)
2012-2017

3 land-ice dycores developed under PISCEES

FSU FELIX
FSU
Finite Element
Full Stokes Model

Albany/FELIX
SNL
Finite Element
"Higher-Order" Stokes Model

BISICLES
LBNL
Finite Volume
L1L2 Model

Increased fidelity

*Predicting Ice Sheet Climate & Evolution at Extreme Scales.

- ***Multi-lab/multi-university*** project involving mathematicians, climate scientists, and computer scientists.
- Leverages software/expertise from ***SciDAC Institutes*** (FASTMath, QUEST, SUPER) and hardware from ***DOE Leadership Class Facilities***.
- ***Sandia staff:*** Irina Tezaur, Andy Salinger, Mauro Perego, Ray Tuminaro, John Jakeman, Mike Eldred.

BERKELEY LAB Lawrence Berkeley National Laboratory

Oak Ridge National Laboratory

Los Alamos NATIONAL LABORATORY EST.1943

Sandia National Laboratories

THE UNIVERSITY OF TEXAS AT AUSTIN

University of BRISTOL

UNIVERSITY OF SOUTH CAROLINA

FLORIDA STATE UNIVERSITY 1851 VIRES ARTES MORES

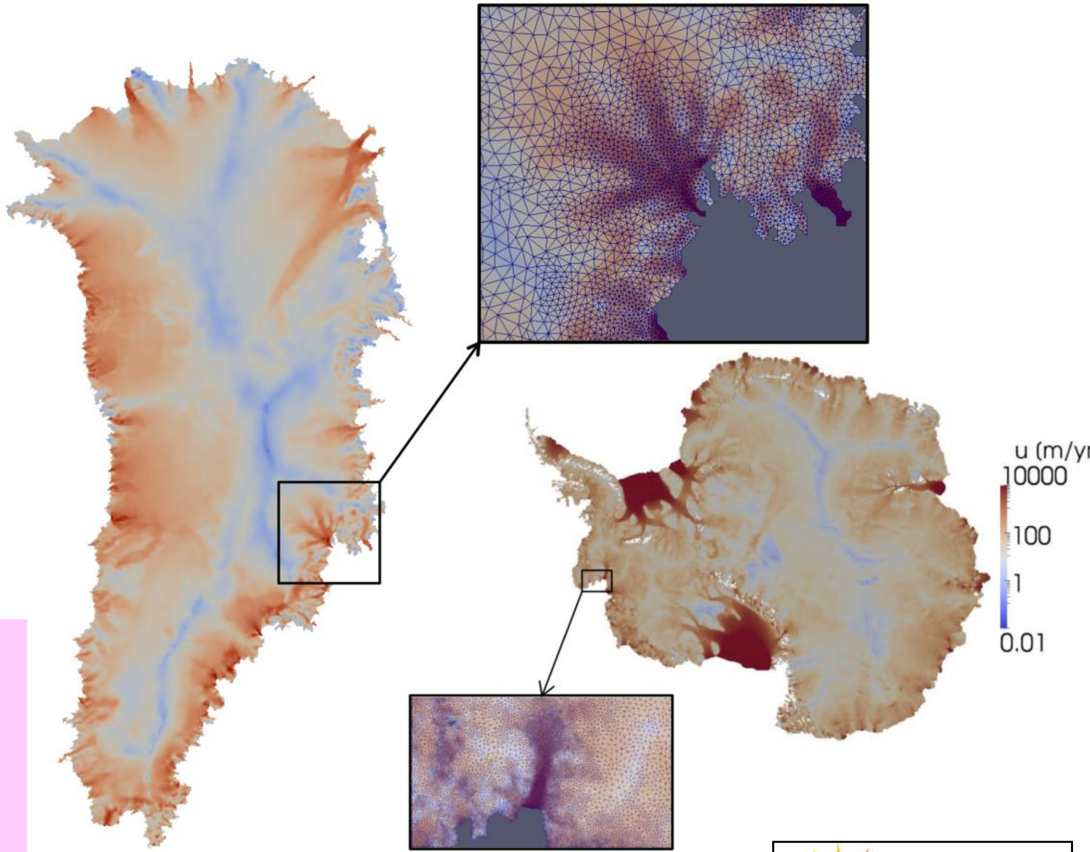
PISCEES Project for Land-Ice Modeling

Sandia's Role in the PISCEES Project: to **develop** and **support** a robust and scalable land ice solver based on the "First-Order" (FO) Stokes equations → *Albany/FELIX**

Requirements for *Albany/FELIX*:

- ***Unstructured grid*** finite elements.
- ***Verified, scalable, fast, robust***
- ***Portable*** to new/emerging architecture machines (multi-core, many-core, GPU)
- ***Advanced analysis*** capabilities: deterministic inversion, calibration, uncertainty quantification.

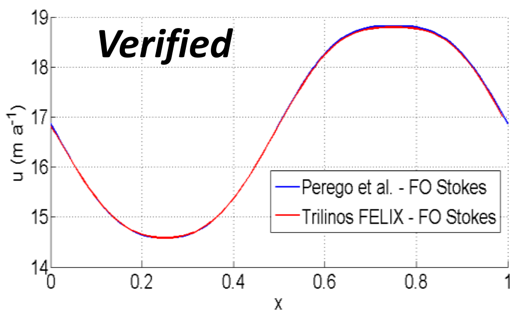
As part of **ACME DOE-ESM**, solver will provide actionable predictions of 21st century sea-level rise (including uncertainty).



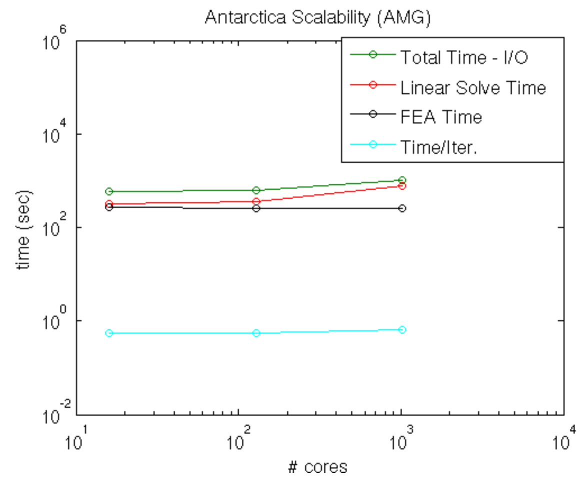
*Finite Elements for Land Ice eXperiments

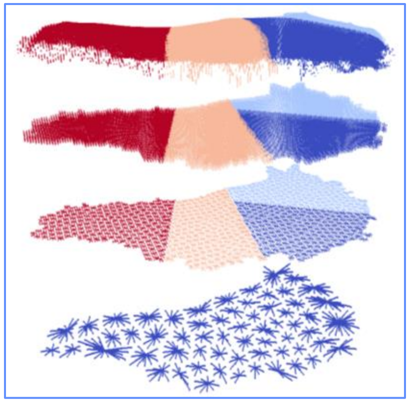
PISCEES Project for Land-Ice Modeling

Component-based code development approach (*Trilinos, Albany*) has enabled ***rapid*** development of ***production-ready*** ice-sheet climate application solver.

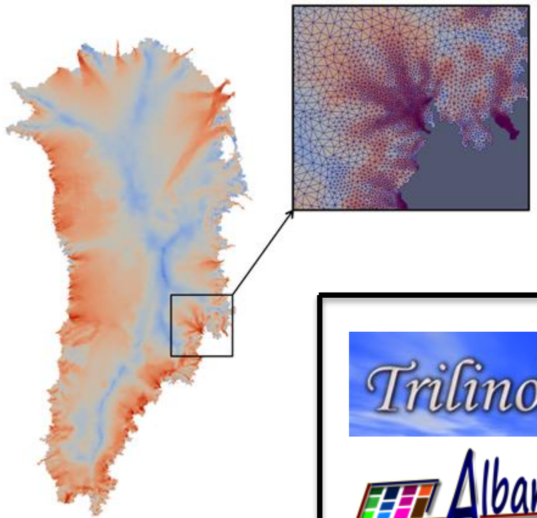


Scalable & fast multi-level linear solver (to 1.12B dofs, 16K cores)

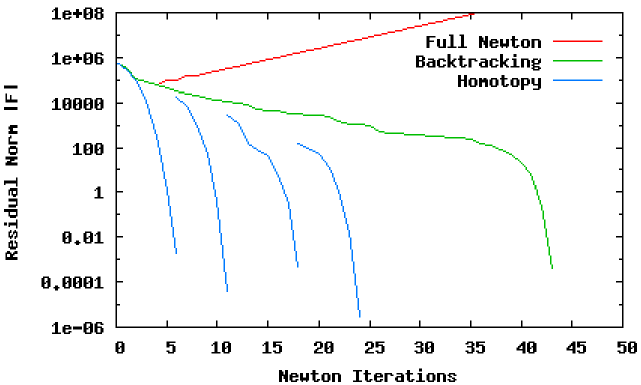




Unstructured grids with real data



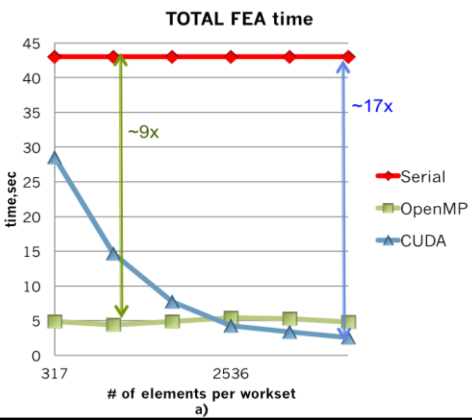
Robust non-linear solver with automatic differentiation and homotopy continuation



PISCEES Project for Land-Ice Modeling

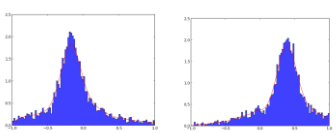
Solver is equipped with ***advanced analysis*** and ***next-generation*** capabilities.

Performance portability to new architecture machines (multi-core, many-core, GPUs) using *Kokkos Trilinos* library and programming model.

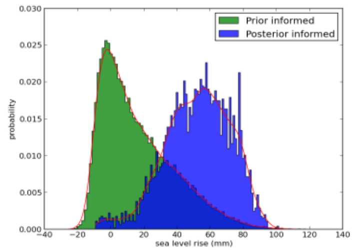


Trilinos

Uncertainty quantification algorithms and workflow for sea-level rise is being developed



Step 1: Bayesian Calibration



Step 2: Uncertainty propagation

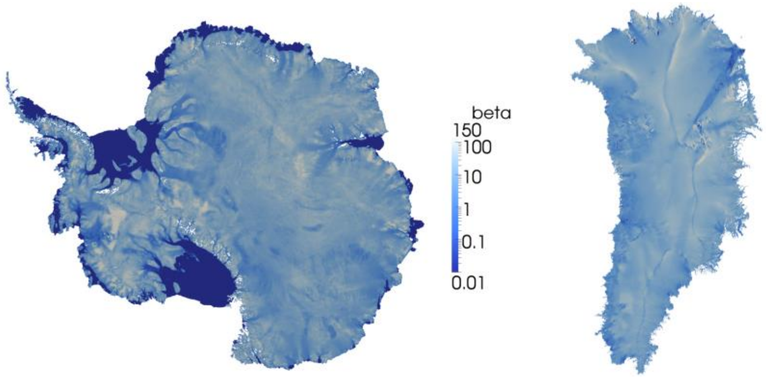
DAKOTA

Adjoint-based PDE-constrained optimization for ice sheet initialization

$$\min_{\beta,H} \left(\frac{1}{2}\alpha_v \int_{\Gamma_{top}} |\boldsymbol{u} - \boldsymbol{u}^{obs}|^2 ds\right)$$

s.t. FO Stokes PDEs

Objective: find ice sheet initial state that matches observations, matches present-day geometry and is in "equilibrium" with climate forcings.

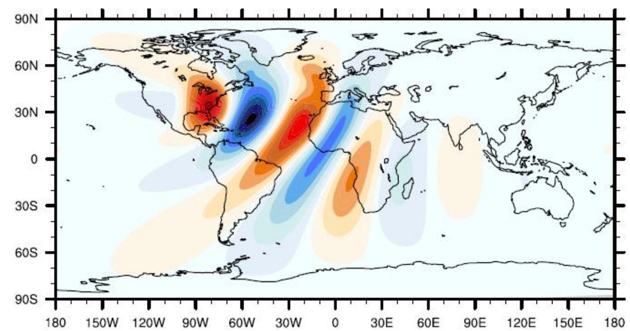


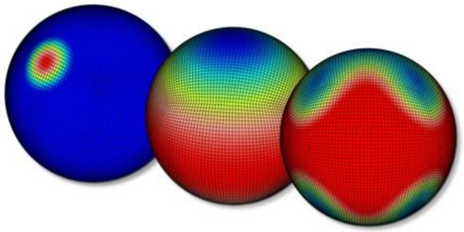
We have inverted for up to ***1.6M parameters***.

Aeras Next-Generation Atmosphere Model

LDRD project (FY14-16) aimed to develop a new, next generation ***atmospheric dynamical core*** using *Trilinos/Albany* that promotes ***machine-portability*** and enable ***uncertainty quantification***.

- Shallow water, X-Z hydrostatic, 3D hydrostatic, non-hydrostatic equations.
- ***Spectral element*** discretization, ***explicit*** time-stepping.
- ***Next-generation capabilities:*** built-in sensitivity analysis, concurrent ensembles for UQ, performance-portability.
- Run time for shallow water equations ***within factor of 2*** of HOMME (Higher-Order Methods Modeling Environment).
- ***<u>Sandia staff:</u>*** Bill Spotz, Irina Tezaur, Andy Salinger, Pete Bosler, Oksana Guba, Irina Demeshko, Mark Taylor, Tom Smith.

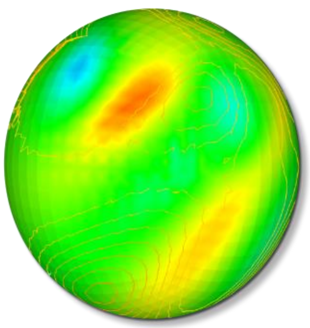




Aeras Next-Generation Atmosphere Model

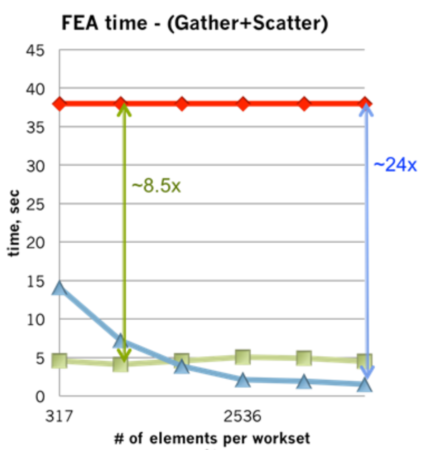
Sandia National Laboratories

Sensitivity calculations: utilizes built-in automatic differentiation Albany capability



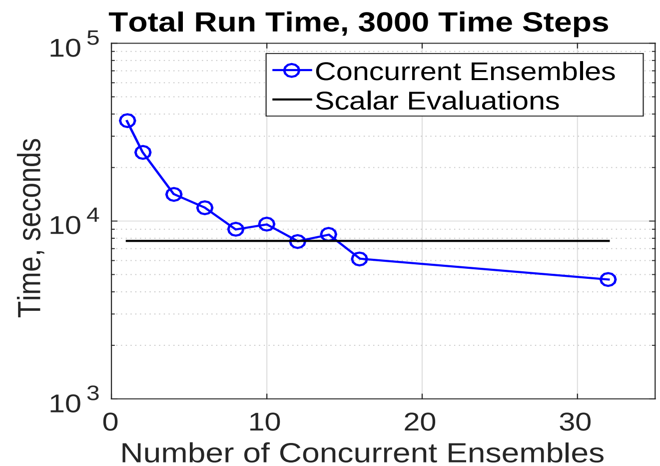
Sensitivity with respect to mountain height on shallow water test case

Performance portability: *single code base* for serial, threads, GPUs, etc.



hardware-appropriate speedups

Concurrent ensembles for UQ: allows computation of several models concurrently using abstract data types.



~2x increase in computational efficiency for large enough sample size

Aeras is first demonstration of concurrent ensemble capability

Follow-Up Funding?

- SciDAC4 call expected to come out in Fall of 2016.
  - Plan to apply for subsequent land-ice and atmospheric funding.

- Advancing X-cutting Ideas for Computational Climate Science (AXICCS) Workshop in Rockville, MD – January 2016: http://www.csm.ornl.gov/workshops/AXICCS/index.html
  - Rumored to be pre-cursor to SciDAC4 call.
  - Several white papers have been submitted.

- Other ideas for subsequent funding are welcome!