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

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8300 Climate Kickoff
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
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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*

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

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

Atmosphere Physics Set (*Aeras code*)

"Agile Components"

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

- Parameter estimation
- Uncertainty quantification
- Optimization
- Bayesian inference
- 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](https://github.com/gahansen/Albany).*
PISCEES Project for Land-Ice Modeling

- **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.

*Predicting Ice Sheet Climate & Evolution at Extreme Scales.*
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.

**Verified**

**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.

**Adjoint-based PDE-constrained optimization** for ice sheet initialization

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

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.

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

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).

- Sandia staff: Bill Spotz, Irina Tezaur, Andy Salinger, Pete Bosler, Oksana Guba, Irina Demeshko, Mark Taylor, Tom Smith.
**Aeras Next-Generation Atmosphere Model**

**Sensitivity calculations:** utilizes built-in automatic differentiation Albany capability

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

Number of Concurrent Ensembles | Scalar Evaluations
--- | ---
0 | ~2x increase in computational efficiency for large enough sample size
10 | Aeras is first demonstration of concurrent ensemble capability
20 |
30 |

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

**Sensitivity with respect to mountain height on shallow water test case**

- ~8.5x
- ~24x

**Total Run Time, 3000 Time Steps**

- Concurrent Ensembles
- Scalar Evaluations

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

**Hardware-appropriate speedups**
Follow-Up Funding?

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

  • Rumored to be pre-cursor to SciDAC4 call.
  • Several white papers have been submitted.

• Other ideas for subsequent funding are welcome!