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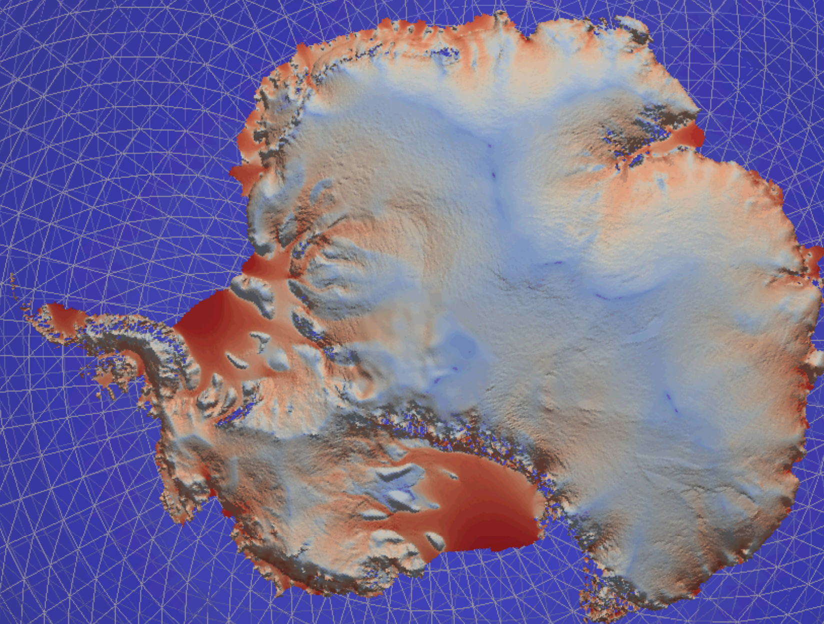
PISCEES Project for Land-Ice Modeling

Irina K. Tezaur
Quantitative Modeling & Analysis Department
Sandia National Laboratories



In collaboration with A. Salinger, M. Perego, R. Tuminaro, S. Price, M. Hoffman, M. Eldred, J. Jakeman and I. Demeshko.

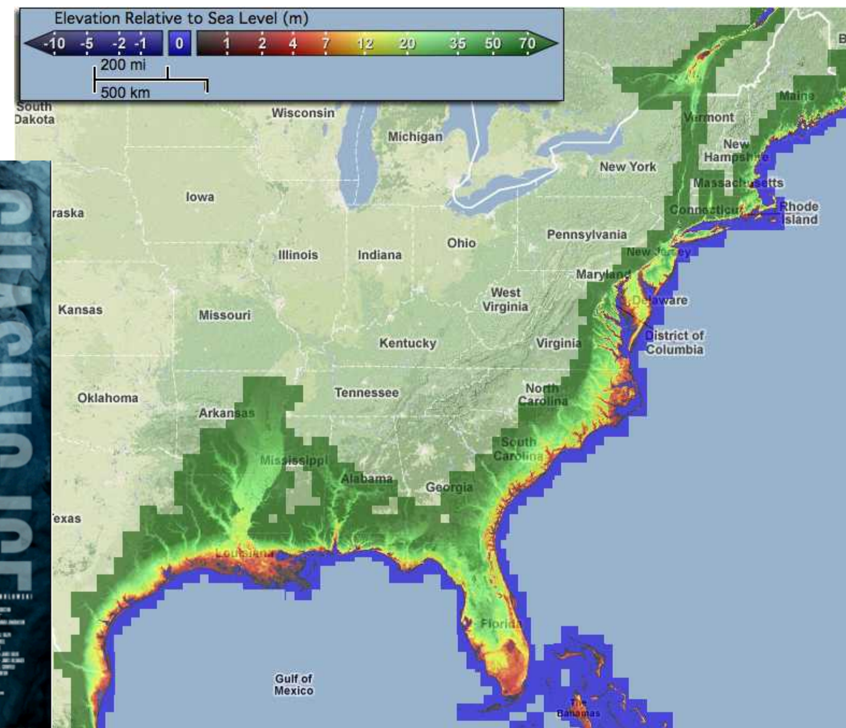
Wednesday, August 17, 2016

Motivation

Sea-level rise has received a lot of media attention in recent years!

- Full deglaciation: sea level could rise up to ~65 meters*
- Potential contributions to sea level rise by ice sheet:
    - Greenland ice sheet: ~7 meters
    - East Antarctic ice sheet: ~53 meters
    - West Antarctic ice sheet: ~5 meters

*Estimates given by Prof. Richard Alley of Penn State who testified in 1999 about climate change to Al Gore.



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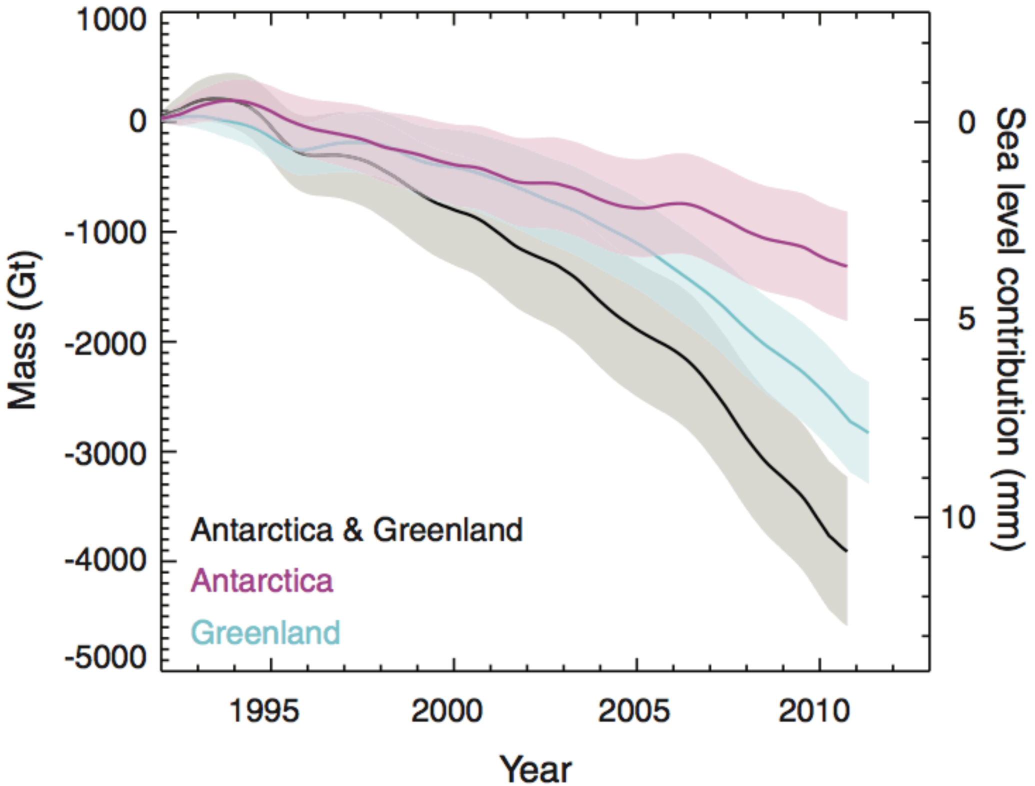
Motivation

*Mass loss from the Greenland & Antarctic ice sheets is **accelerating**!*



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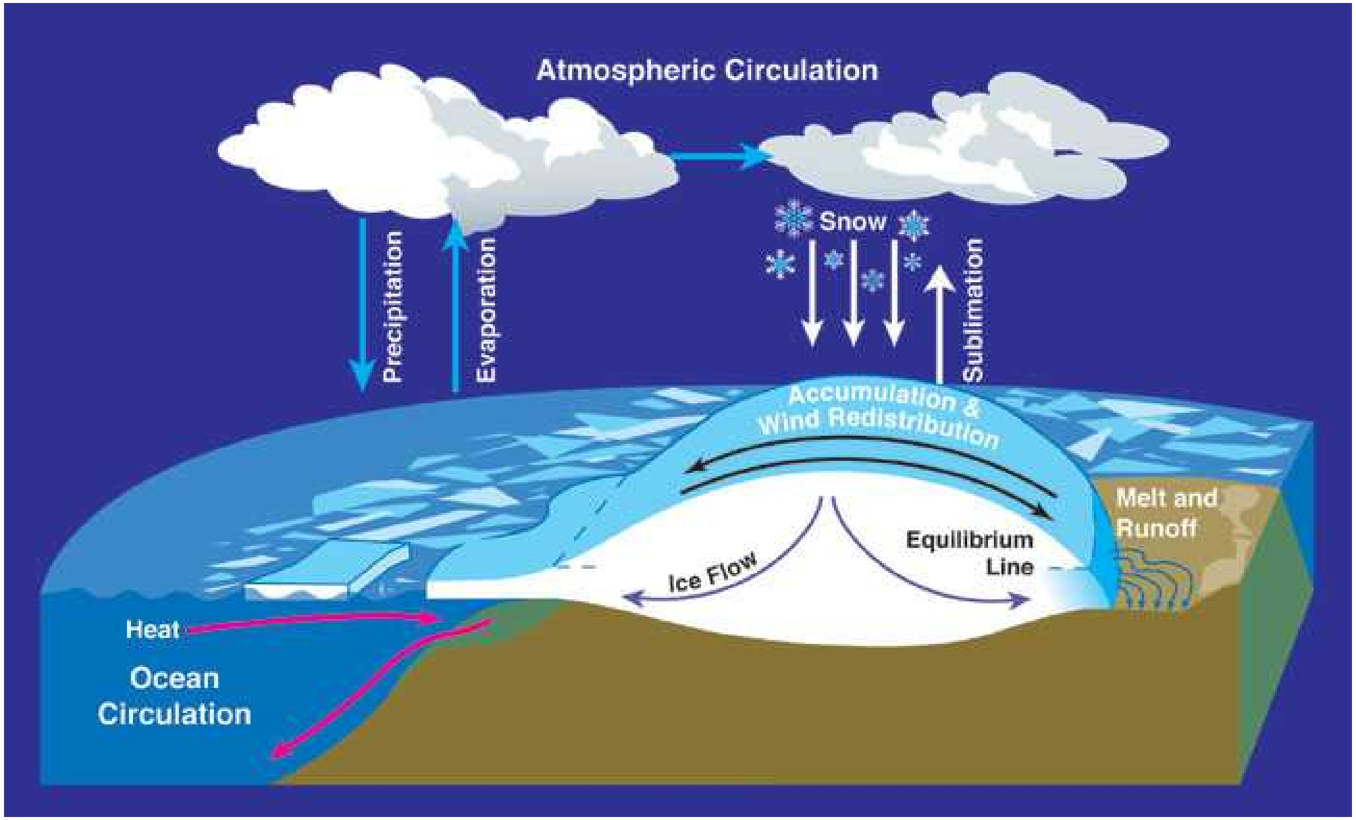
Earth System Models (ESMs)

Ice sheets are part of a **global** climate system.

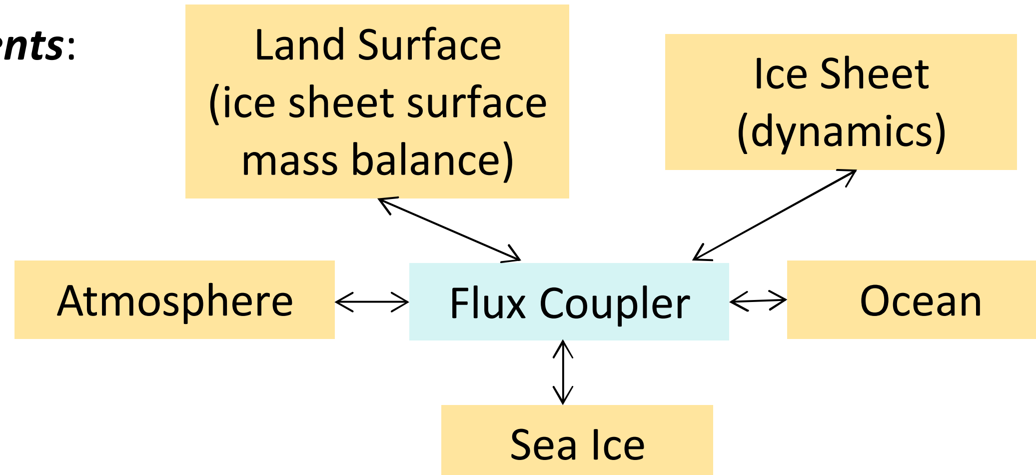


Mass balance: change in ice sheet mass = mass in – mass out

sea level change *snow fall* *melt,calving*

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

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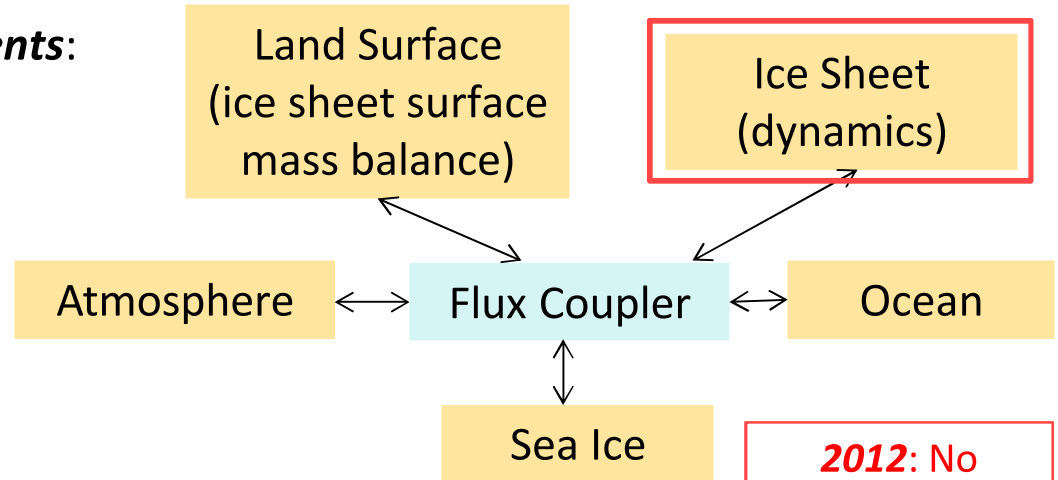

2012: No robust land ice model! ☹

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The PISCEES Project

- In its fourth assessment report (AR4)* in 2007, the Intergovernmental Panel on Climate Change (IPCC) declined to include estimates of future sea-level rise from ice sheet dynamics due to the ***inability*** of ice sheet models to mimic or explain observed dynamic behaviors, e.g., the acceleration and thinning then occurring on several of Greenland's large outlet glaciers.

* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., and Miller, H. "Climate change 2007: The physical science basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change", Cambridge Univ. Press, Cambridge, UK, 2007.

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- Although ice sheet models have improved in recent years, ***much work is needed*** to make these models robust and efficient on continental scales and to quantify uncertainties in their projected outputs.

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PISCEES (**P**redicting **I**ce **S**heet **C**limate & **E**volution at **E**xtreme **S**cales) aims to:

1. Develop/apply ***robust***, ***accurate***, ***scalable*** dynamical cores (dycores) for ice sheet modeling on structured and unstructured meshes.
2. Evaluate models using new tools and data sets for verification/validation and ***uncertainty quantification***.
3. Integrate models/tools into DOE-supported ***Earth System Models***.

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The PISCEES Project (cont'd)

PISCEES
SciDAC Application Partnership
(DOE's BER + ASCR divisions)
Start date: June 2012
5 years

3 land-ice dycores developed under PISCEES

FSU FELIX
FSU
Finite Element
Full Stokes Model

Albany/FELIX
SNL
Finite Element
"First Order" Stokes Model

BISICLES
LBNL
Finite Volume
L1L2 Model

Increased fidelity

Goal: support DOE climate missions (sea-level rise predictions)

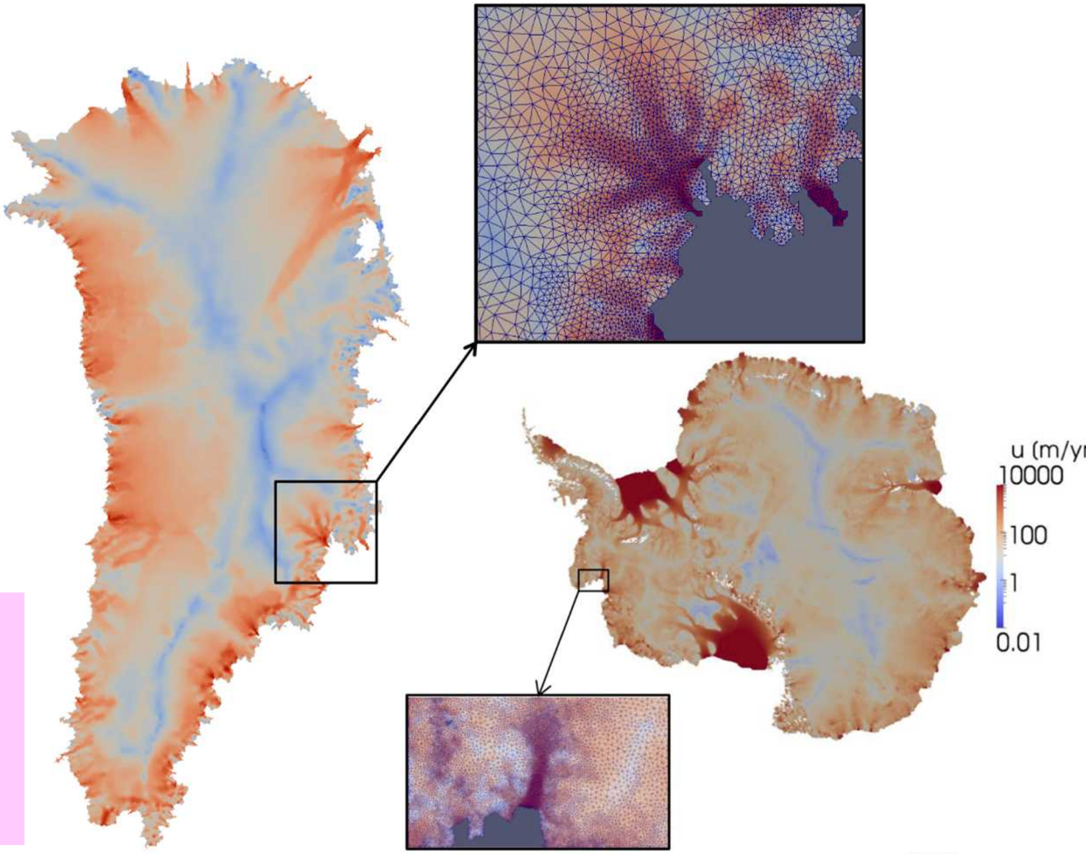
- ***Multi-lab/multi-university*** project involving mathematicians, climate scientists, and computer scientists.
- Leverages software/expertise from ***SciDAC Institutes*** (FASTMath, QUEST, SUPER) and hardware from ***DOE Leadership Class Facilities***.

The PISCEES Project (cont'd)

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

<u>Requirements for *Albany/FELIX*</u>:

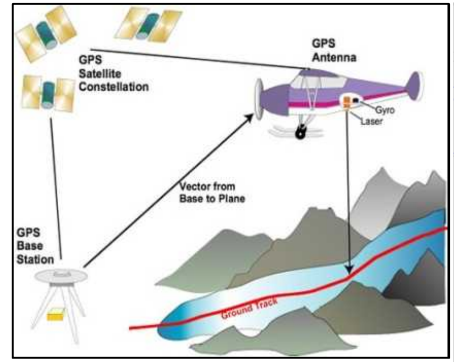
- ***Unstructured grid*** finite elements.
- ***Verified, scalable, fast, robust***
- ***Portable*** to new/emerging architecture machines (multi-core, many-core, GPU)
- ***Advanced analysis*** capabilities: deterministic inversion, calibration, uncertainty quantification.

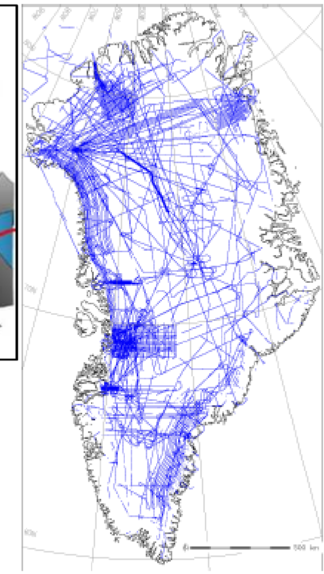


As part of **ACME *DOE earth system model***, solver will provide actionable predictions of 21st century sea-level rise (including uncertainty).

*Finite Elements for Land Ice eXperiments

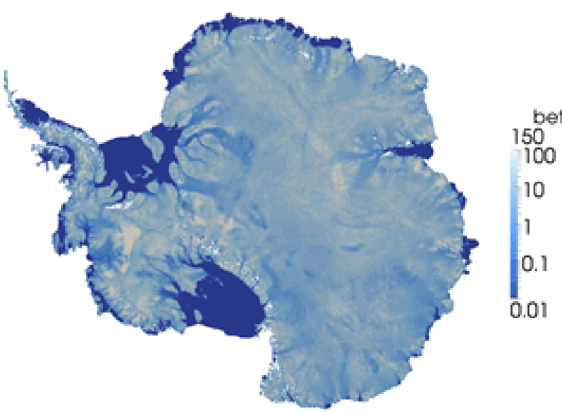
Data & Deterministic Inversion for Ice Sheet Initialization



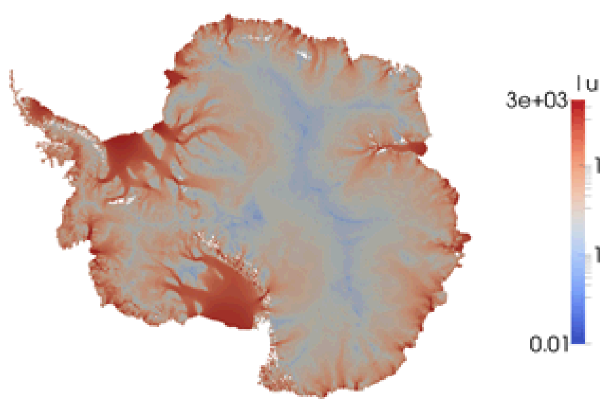


Data: needs to be imported into code to run “real” problems (Greenland, Antarctica).

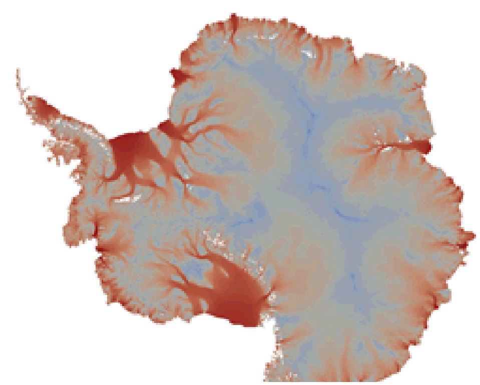
- ***Surface data*** are available from measurements (satellite infrarometry, radar, altimetry): ice extent, surface topography, surface velocity, surface mass balance.
- ***Interior ice data*** (ice thickness, basal friction) cannot be measured; estimated by solving an inverse problem for initial ice sheet state.



β (kPa y/m) obtained through inversion



$|\boldsymbol{u}|$ (m/yr) computed with estimated β



$|\boldsymbol{u}|$ (m/yr) for observed surface velocity

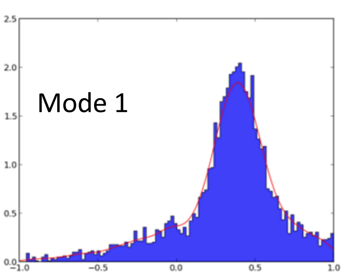
Uncertainty Quantification (UQ) Problem Definition

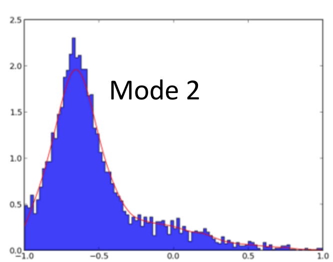
Quantity of Interest (QoI) in Ice Sheet Modeling:
total ice mass loss/gain during 21st century
→ ***sea level rise prediction.***

Sources of uncertainty: climate forcings (e.g., surface mass balance), basal friction (β), bedrock topography, geothermal heat flux, model parameters.

Step 1: Bayesian Calibration

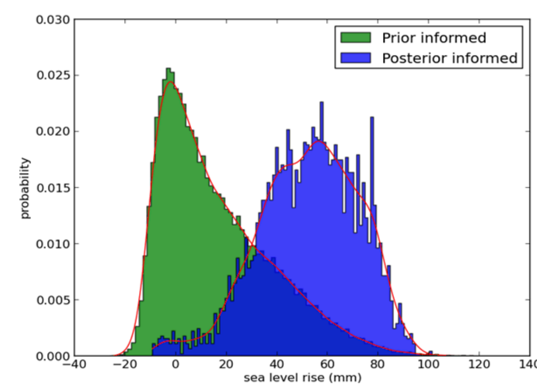
What are the **model parameters** that render a given a set of **observations**?





Step 2: Uncertainty propagation

What is the impact of **uncertain parameters** in model on **quantities of interest**?



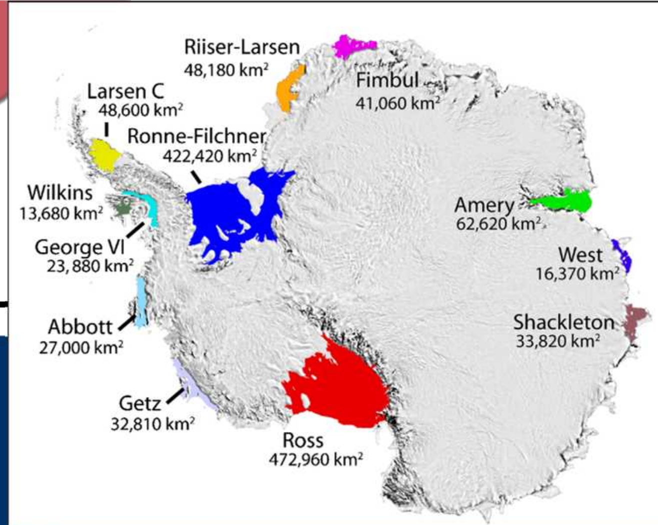
Greenland Transient Simulations & Validation

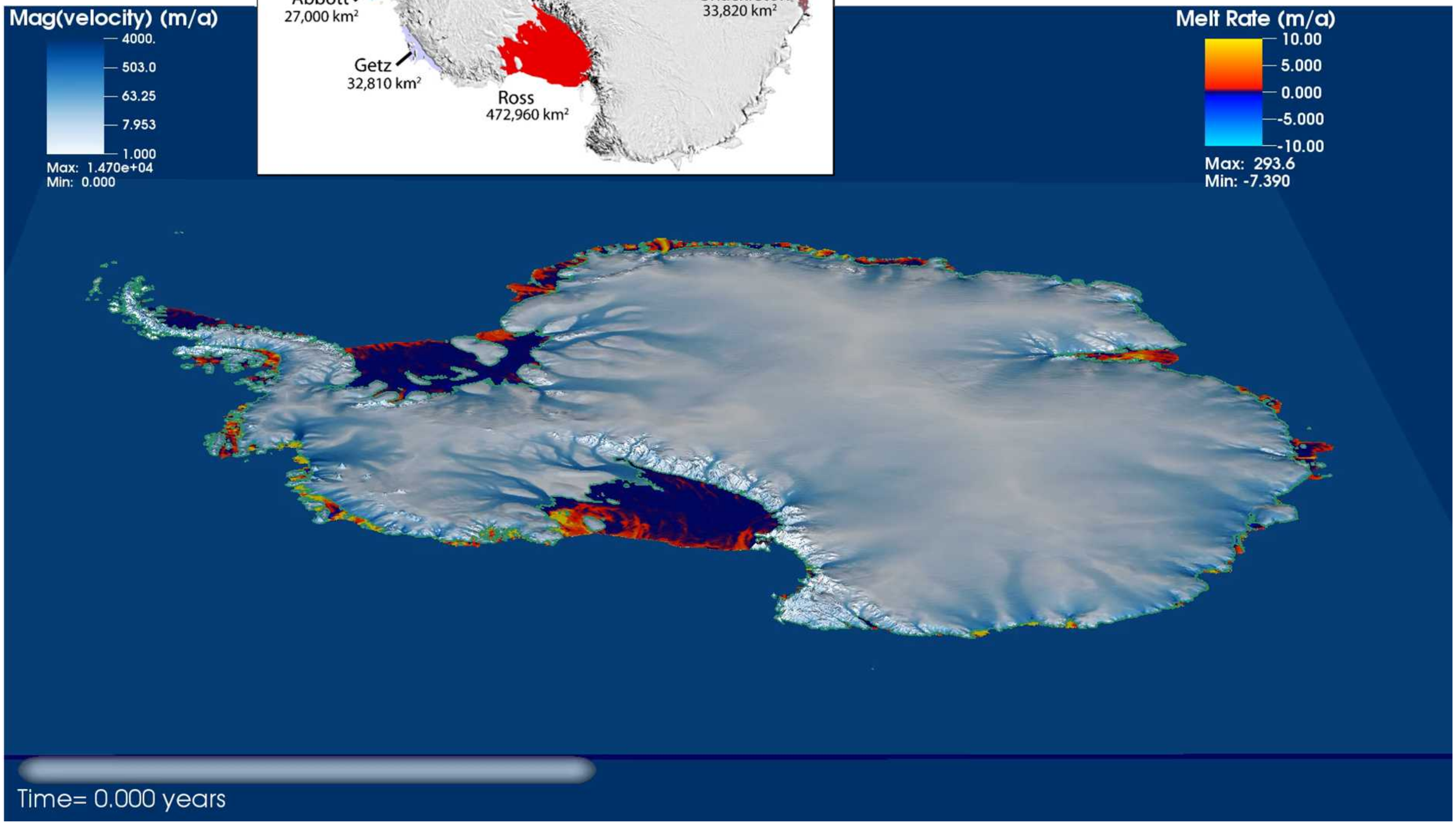
- The PISCEES Greenland ice sheet was recently ***validated*** for 2003-2013 using data from the Ice, Cloud, and land Elevation Satellite (***ICESat***) and from the Gravity Recovery 45 and Climate Experiment (***GRACE***) satellites in collaboration with NASA.

- ***<u>Conclusions:</u>***
  - Present-day ice sheet models with adequate representations of physics and boundary conditions, and when forced by realistic climate histories, can be expected to ***skillfully reproduce*** observed ice dynamical changes on decadal timescales.
  - This marks a ***clear improvement over a decade ago***, when sea-level rise projections from ice sheet models were not included in the IPCC's 4th Assessment Report because models of that time clearly lacked skill at explaining or mimicking observed ice dynamical behaviors

Greenland Transient Simulations & Validation (cont'd)

Antarctica Transient Simulations





* Simulation results performed using BISICLES; videos courtesy of D. Martin (LBNL)

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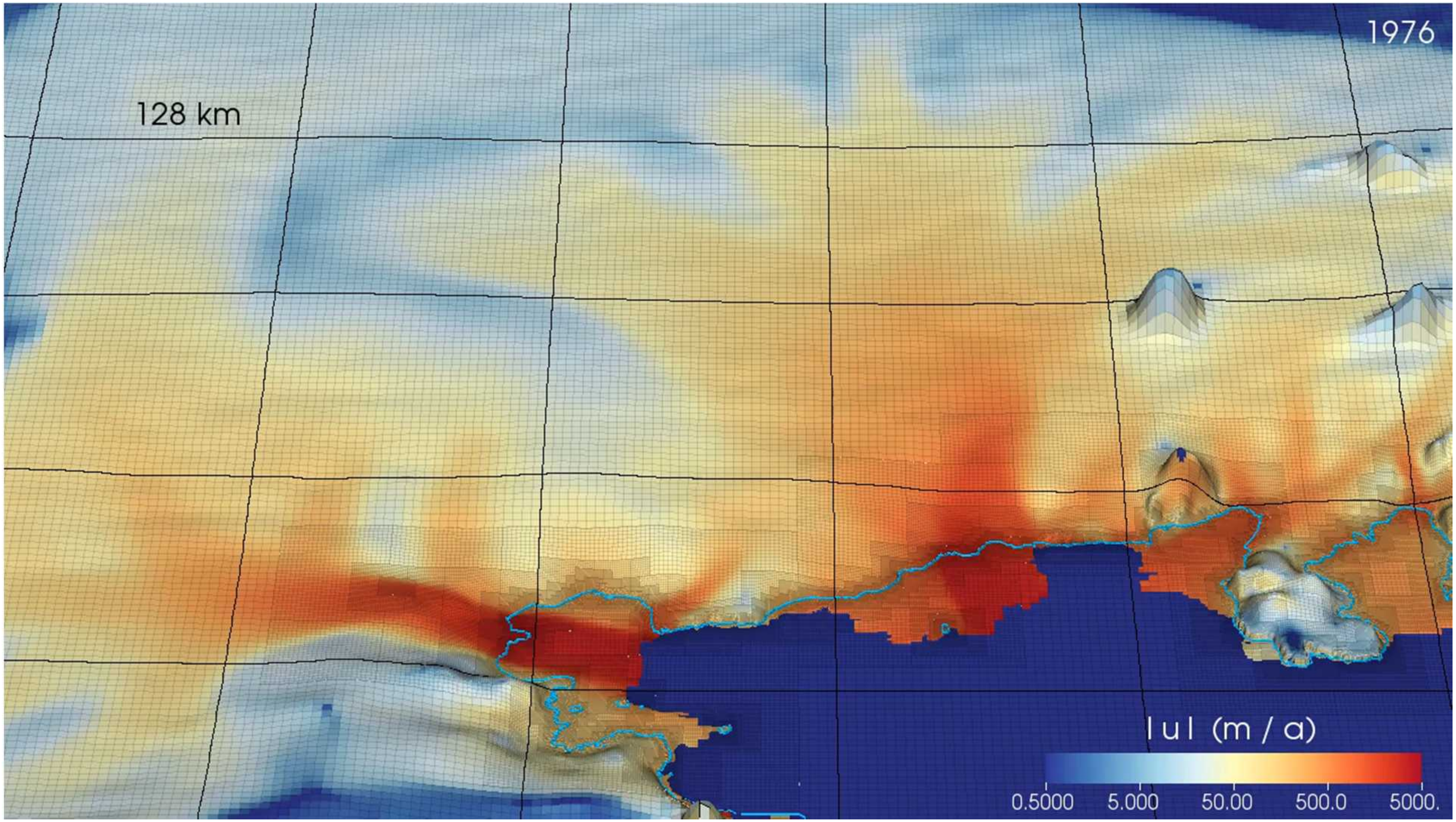
Antarctica Transient Simulations: Grounding Line Recession



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PISCEES team members: *K. Evans, M. Gunzburger, M. Hoffman, C. Jackson, P. Jones, W. Lipscomb, M. Perego, S. Price, A. Salinger, I. Tezaur, R. Tuminaro, P. Worley.*

Trilinos/DAKOTA collaborators*: M. Eldred, J. Jakeman, E. Phipps, L. Swiler.*

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