Ice Sheet Models, PISCEES, and CESM Software Engineering

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Outline

- Motivation for coupling ice sheet models and climate models
- Current status of ice sheet models in CESM
- CISM 2.0 (new ice sheet dycores)
- PISCEES project
- Ocean / ice-sheet coupling

Why couple ice sheets to climate models?

As ice sheets evolve, they interact with the **atmosphere** in ways that modify their own evolution.

- **Albedo feedback:** Warmer temperatures result in increased melting, a darker surface, and additional warming.
- **Ice geometry feedbacks**: As an ice sheet shrinks, its surface warms (temperature-elevation feedback), and regional circulation can change (e.g., Ridley et al. 2005).

Why couple ice sheets to climate models?

As ice sheets evolve, they interact with the **ocean** in ways that modify their own evolution.

- Sub-shelf growth and melting rates depend on time-varying interactions among various water masses, including glacier meltwater.
- Sub-shelf circulations are likely to change as ice shelves advance and retreat over complex topography.

One-way v. two-way coupling

On **short time scales** (a few decades or less), changes in ice-sheet/shelf geometry are small.

- We can pass fields from the AOGCM to the ice-sheet model without modifying the bathymetry or topography of the land/atmosphere/ocean.

On **long time scales** (centuries to millennia), changes in ice-sheet/shelf geometry are important and must be returned to the AOGCM.

- Land topography and surface type (glacier v. vegetated) must evolve.
- The ice-sheet/ocean boundary must evolve.

Traditional climate model assumptions

- The extent and elevation of ice sheets are fixed.
- The boundary between the land surface and the atmosphere is fixed.
- The boundary between the land and the ocean is fixed.
- The upper surface of the ocean is the atmosphere (possibly with a thin layer of sea ice in between). At the lateral edge of an ice shelf, the ocean sees a vertical wall.

Changing these assumptions requires **major** software engineering changes.

Ice sheets in CESM 1.0

- CESM 1.0 (released in June 2010) includes the **Glimmer Community Ice Sheet Model (Glimmer-CISM).**
  - Supports a dynamic Greenland ice sheet on a 5 km grid
  - Serial shallow-ice model (Glimmer-CISM 1.6)
  - One-way coupling between land/atmosphere and ice sheet models
- CESM also includes a **surface-mass-balance scheme for land ice**.
  - The surface mass balance is computed by the land surface model (CLM) in multiple elevation classes, then sent to the coupler and downscaled to the local ice sheet grid.

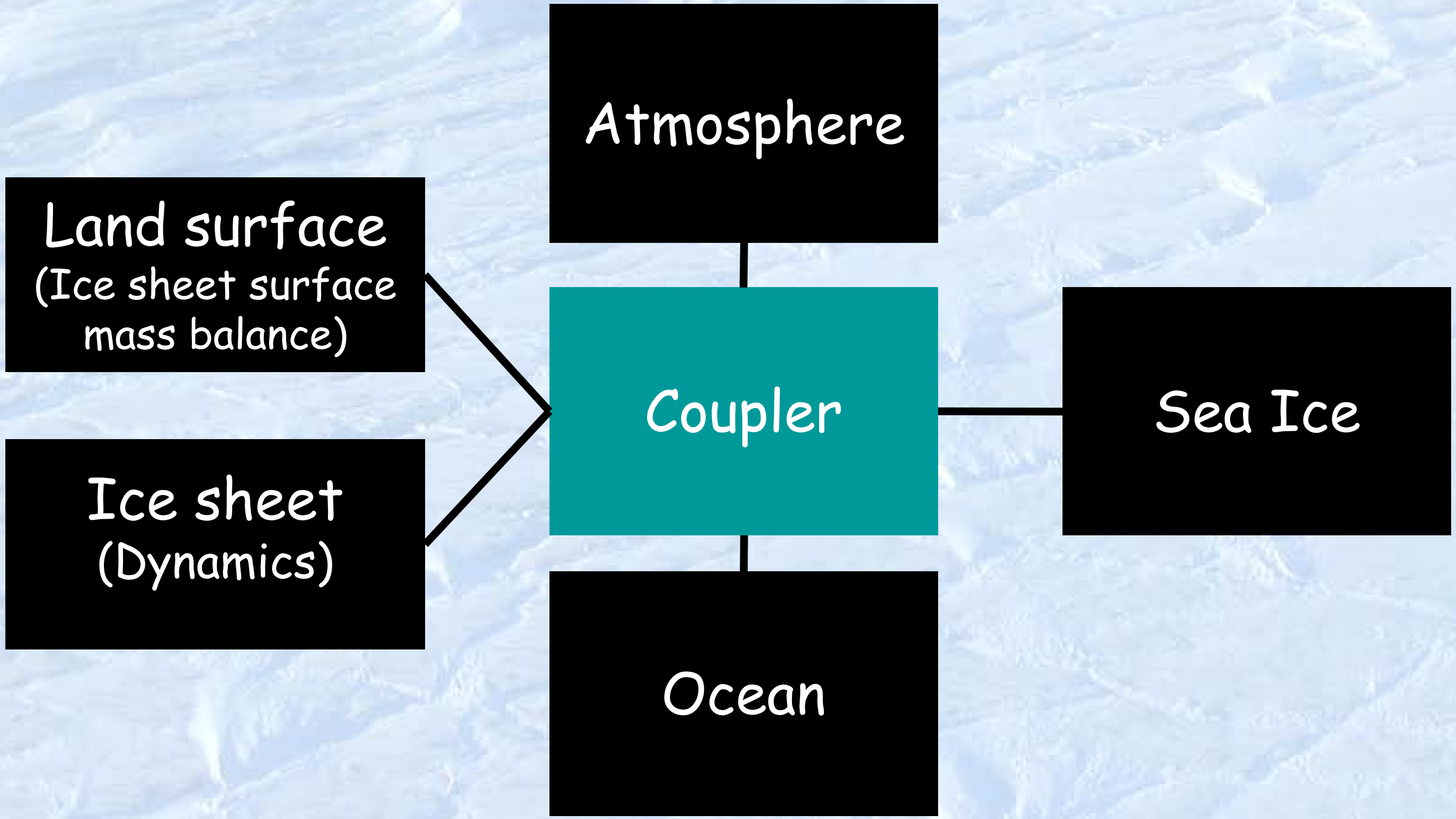
Current status of ice sheets in CESM

Land -> Ice sheet (10 classes)

- Surface mass balance
- Surface elevation
- Surface temperature

Ice sheet -> Land (10 classes)

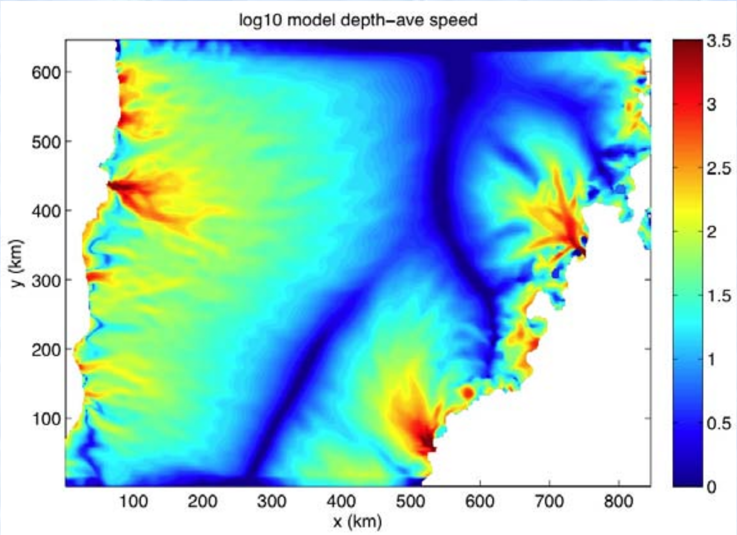
- Ice fraction and elevation
- Runoff and calving fluxes
- Heat flux to surface



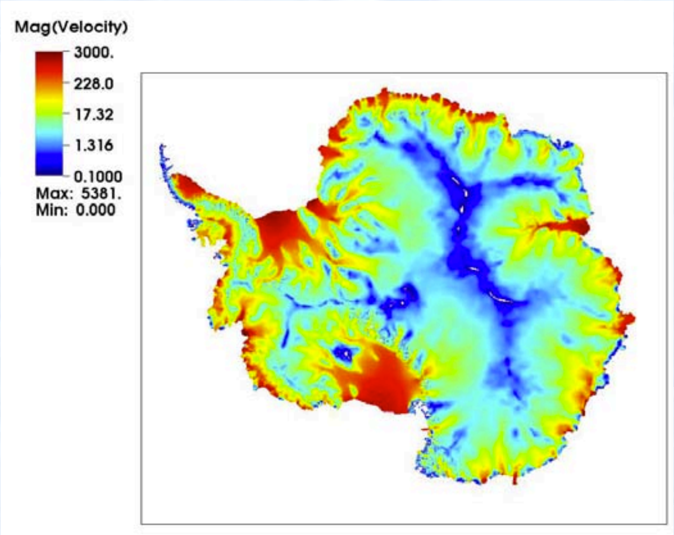
Ice sheets in CESM 1.1

CESM 1.1 will include **CISM 2.0**, with two new dycores:

- **SEACISM** (K. Evans, A. Salinger, S. Price, P. Worley, et al.)
  - Parallel code with 3D higher-order velocity solver
  - Uses Trilinos solver packages (C++)
- **BISICLES** (D. Martin, S. Cornford, et al.)
  - Parallel code with 2D higher-order velocity solver
  - Uses Chombo adaptive mesh refinement software (C++)



Greenland depth-averaged ice speed from SEACISM higher-order dycore (S. Price)



Antarctic ice speed from BISICLES higher-order dycore with an adaptive mesh (D. Martin)

Ice sheets in CESM 1.1

- The new dycores will require linking to C++ libraries, which have not previously been supported in CESM.
  - Currently we build standalone CISM using autotools (fragile, hard to maintain)
  - We build CISM in CESM using the native CESM build system (lacks full functionality of standalone code)
  - We are considering moving to a common build system based on **cmake**.

PISCEES

Predicting Ice Sheet and Climate Evolution at Extreme Scales (PISCEES) is a 5-year (2012-2017) DOE SciDAC project with the following goals:

- To develop and apply robust, accurate, and scalable dynamical cores for ice sheet modeling on structured and unstructured meshes with adaptive refinements
- To evaluate ice sheet models using new tools and data sets for verification and validation (V&V) and uncertainty quantification (UQ)
- To integrate these models and tools in the Community Ice Sheet Model and Community Earth System Model

Participating institutions: LANL, LBNL, ORNL, SNL, FSU, MIT, USC, UT Austin, NCAR

PISCEES

PISCEES includes partnerships with three SciDAC institutes:

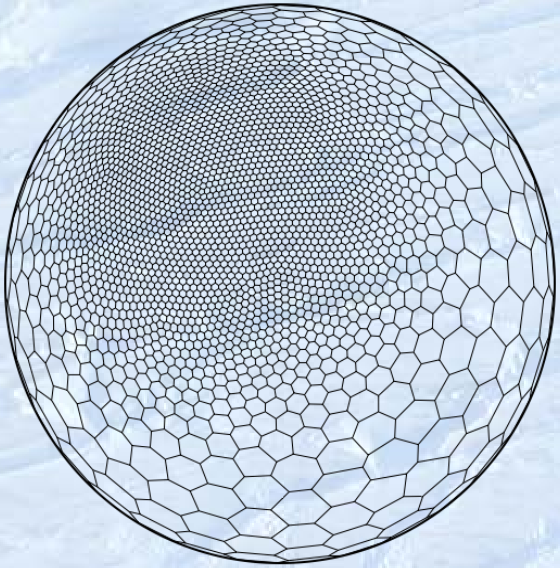
- **FASTMath** (solver, algorithms): Andy Salinger, Esmond Ng
- **SUPER** (computational performance): Pat Worley, Sam Williams
- **QUEST** (uncertainty quantification): Michael Eldred

We will also receive NCAR software engineering support.

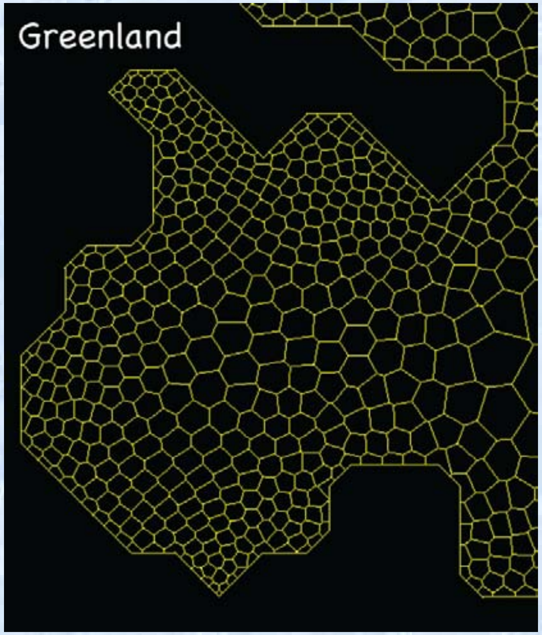
PISCEES

PISCEES includes development of two hierarchical (Stokes/higher-order/shallow-shelf/shallow-ice) dycores:

- BISICLES (finite-volume; structured adaptive mesh with Chombo)
- FELIX (finite-element solver; unstructured variable-resolution mesh in MPAS framework with Trilinos solvers)



MPAS global mesh



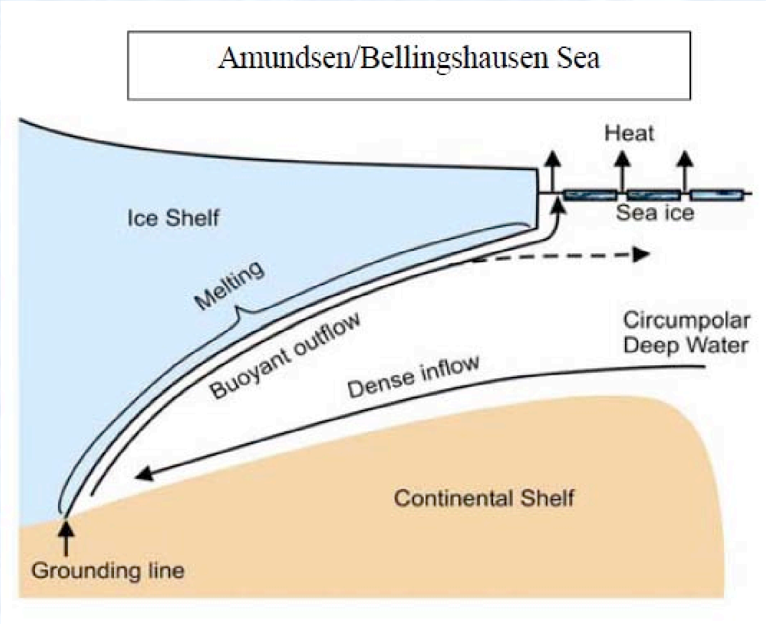
Variable-resolution mesh for Greenland

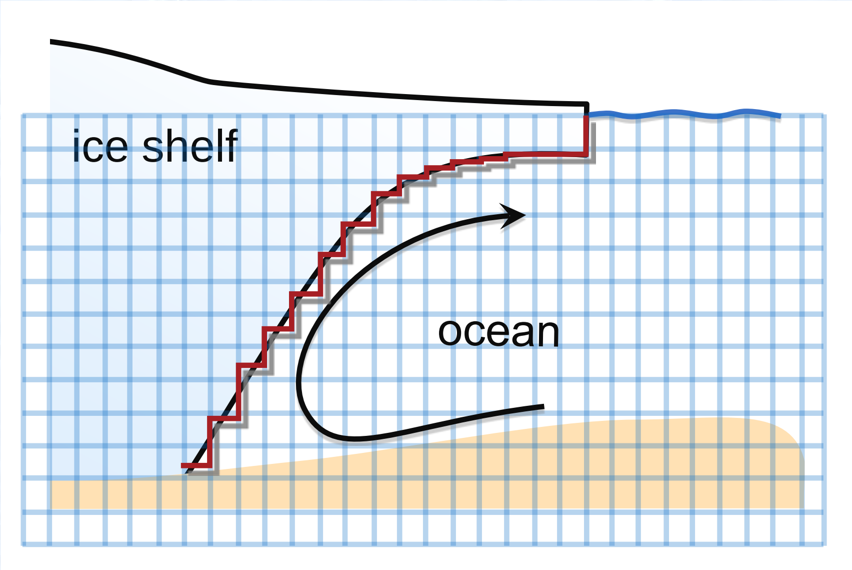
Regridding

- Currently the coupler passes fields to CISM on CLM's lat/lon grid.
  - Regridding to the 5-km ice-sheet grid takes place in CISM.
  - BISICLES uses the 5-km CISM grid as its base grid and does further regridding internally.
- In the future, the coupler will pass fields to CISM on the ice sheet grid.
  - We need support for unstructured MPAS grids.
  - The MPAS grid may change on scales of years to decades. We would like to be able to change grids during runtime.

Marine ice sheet instability

- We want to model the retreat of marine ice sheets, triggered by intrusions of warm water beneath ice shelves.
- As part of the DOE IMPACTS project on abrupt climate change, we have developed POP2X, which computes melting at the ice-ocean boundary. The boundary will change in time.





Above right: Warm CDW reaching the grounding line (courtesy of A. Jenkins)

Below right: Ice-shelf/ocean boundary in POP2X (courtesy of X. Asay-Davis)

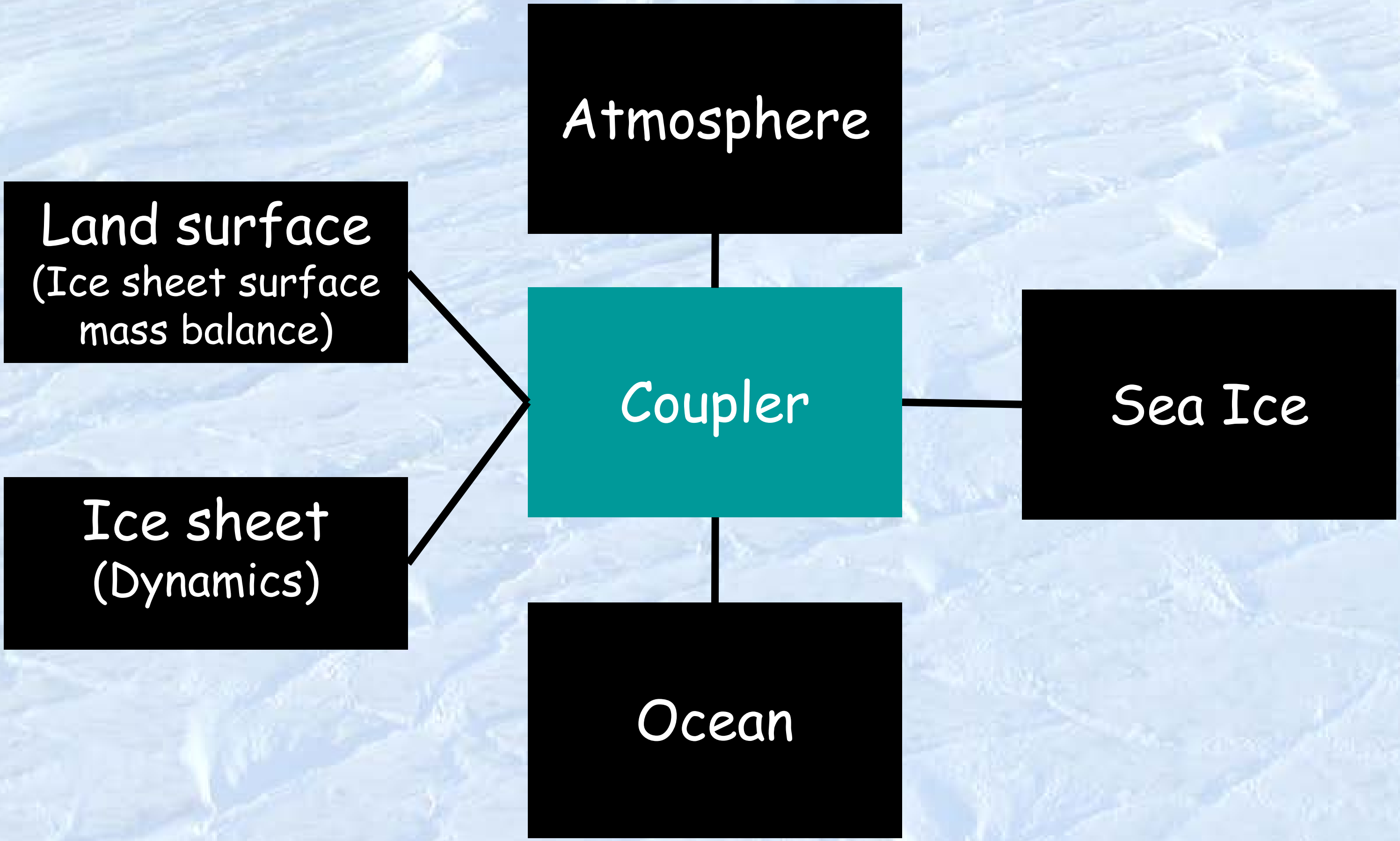
Ice-sheet/ocean coupling in CESM (in progress)

Ocean -> Ice sheet/shelf

- Basal heat flux
- Basal mass flux
- Ocean density (avg over ice column)

Ice sheet -> Ocean

- Lower surface elevation
- Grounded/floating ice fraction
- Basal temperature info (for computing heat flux)



Regional ice-sheet / ocean modeling

- For Southern Ocean experiments, we would like to use a regional, high-resolution ocean/sea-ice model (POP2X/CICE) fully coupled to the atmosphere.
  - On decadal time scales, ice-sheet/ocean interactions are likely to be important regionally but not globally.
- We cannot do this with the current version of CESM.
  - We can run standalone regional POP/CICE, but without coupling to the atmosphere.

Summary

- Dynamic ice sheets imply major software engineering changes in CESM, especially for two-way coupling where land/atmosphere/ocean/ice boundaries change in time.
- The new higher-order dycores in CISM 2.0 and beyond will require more flexible build systems (to handle C++ code), along with coupler support for unstructured and adaptive meshes.
- Software engineering support has been and will continue to be critical for ice-sheet science using CESM.