Framework for Antarctic System Science in E3SM

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Motivation: Antarctic Ice Sheet is largest uncertainty in future sea-level change

FAnSSIE Overview
Problem: Feedbacks and tipping points in AIS processes and coupling

Future projections

- Basic known physics and MISI uncertainty
- Ice shelf basal melt and hydrofracture deep uncertainty
- Marine Ice Cliff Instability deep uncertainty

Marine Ice Cliff Instability

Marine Ice Sheet Instability

Ice-shelf hydrofracture

Marine melting regime shift

FAnSSIE Overview
FAnSSIE Project Focus Areas

1. Coupling of climate and Antarctic Ice Sheet in E3SM
2. Ice-sheet dynamics and fracture mechanics
3. Probabilistic projections of the Antarctic Ice Sheet

How will threshold processes linking the coupled ice sheet, ocean, and atmosphere impact the contribution of the Antarctic Ice Sheet to sea-level change in the coming decades and centuries?
Coupling AIS to E3SM: Ice-sheet/Ocean

Ocean Model domain advance

- In E3SM v1.2, MPAS-Ocean supported circulation beneath ice shelves, necessary to simulate ice-shelf basal melting
- However, horizontal extent of ocean domain is fixed
- As AIS evolves, ocean domain must advance – major technical hurdle
Coupling AIS to E3SM: Ice-sheet/Ocean

- Ocean model domain needs to advance as ice-sheet retreats
- Goals:
  - active/inactive regions of mesh through addition of thin film
  - vertical coordinate improvements to avoid steeply sloping layers
  - higher-order pressure gradient calculation
Coupling AIS to E3SM: Ice-sheet/Ocean

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Progress:
Thin film wetting & drying operational

Coordination with ICoM

Carolyn Begeman, Xylar Asay-Davis (LANL)
Potential challenges with E3SM OMEGA transition

Ice-sheet/ocean coupling requires ocean model features that are not standard for global ocean models. ProSPect and FAnSSIE have been significant investments in those developments for *MPAS-Ocean*.

- MPAS-Ocean and MALI coupled simulations are expected to begin this year, with coupling capability already far along
- Ice shelf cavities and melt fluxes not planned for initial Omega release
- Wetting and Drying for ice-shelf cavities would come later yet
- Omega is only planning on limited eddy parameterizations but fully eddy parameterization (GM+Redi) required to resolve the small eddies present in polar regions

We are coordinating with OMEGA and E3SM Polar teams, but additional resources may be required to:

- maintain an unsupported branch of E3SM with MPAS-Ocean’s ice-shelf capabilities to achieve FAnSSIE (and E3SM) science objectives.
- preserve these capabilities in E3SM through the ocean model transition.
Adding subglacial discharge to ocean

- Subglacial discharge of meltwater known to enhance submarine melting in Greenland, but typically assumed to be negligible in Antarctica
- Used MALI’s subglacial hydrology model to simulate discharge around AIS
- Subglacial discharge ~10% of ice-shelf basal melt flux
- Addition of this freshwater flux to MPAS-Ocean to come

Modeled subglacial discharge in MALI

Courtney Shafer, University of Buffalo
(DOE Computational Science Graduate Fellow)
Alex Hager, LANL
Ice-shelf hydrofracture can occur when firn becomes saturated with meltwater.

Goals:
- Improve and validate snow & firn physics in ELM
- Connect firn water content in ELM to ice-shelf stress state in MALI

Progress: Evaluated 5 reanalysis products against AIS & GIS firn core records. Added ERA5 as data ATM option in E3SM.

Coordination with E3SM Polar Process Group
Coupling AIS to E3SM: Ice-sheet/Surface climate

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- Goals:
  - Improve and validate snow & firn physics in ELM
  - Connect firn water content in ELM to ice-shelf stress state in MALI

Progress: 300-yr firn spin-up with reanalysis climate forcing produces AIS surface mass balance similar to reference values
Most MALI algorithms are first-order; higher accuracy at reduced cost needed

Goals:
- High-order discretizations
- Lower-fidelity models for cost savings
- Initialization capabilities
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- High-order discretizations
- Lower-fidelity models for cost savings
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Progress: depth-integrated velocity solver 3x cheaper than 3d solver with similar accuracy.
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Goals:
- High-order discretizations
- Lower-fidelity models for cost savings
- Initialization capabilities

Progress: depth-integrated velocity solver 3x cheaper than 3d solver with similar accuracy.

Progress: higher-order advection and time-stepping preserve sharp features in ice thickness and damage.
Advanced Discretizations

- Most MALI algorithms are first-order; higher accuracy at reduced cost needed
- Goals:
  - High-order discretizations
  - Lower-fidelity models for cost savings
  - Initialization capabilities

Progress: depth-integrated velocity solver 3x cheaper than 3d solver with similar accuracy

Progress: higher-order advection and time-stepping preserve sharp features in ice thickness and damage

Mauro Perego (SNL)

Simulated Thwaites Ice Shelf damage, 2050

FAnSSIE Overview
Ice-shelf Fracture Mechanics

- Existing fracture models use simple stress or strain rate based parameterizations
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- Goals:
  - Utilize a damage state variable that:
    - triggers calving of failed ice
    - weakens ice viscosity

*Progress:* higher-order advection and time-stepping preserve sharp features in damage
Ice-shelf Fracture Mechanics

- Existing fracture models use simple stress or strain rate based parameterizations
- Goals:
  - Utilize a damage state variable that:
    - triggers calving of failed ice
    - weakens ice viscosity
  - Implement ductile+brittle methods that can form rifts and tabular icebergs
  - Couple fracture and ice rheology
Unstructured Mesh Adaptivity

- Solution accuracy degrades at calving front and rifts
- Goals:
  - Feature tracking with level-sets
  - GPU-based mesh adaptivity using *Omega_h* library
  - Mesh node movements and swaps to keep mesh aligned with key features

*Progress: Incorporated the *Omega_h* mesh adaptivity library in MALI and implemented operational testing*
MALI Performance Improvements

- New physics will impact performance
- Goals:
  - Algorithmic improvements to better utilize GPUs
  - Performance optimization using load balancing and autotuning
  - Software modernization, harmonization, and verification
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Goals:
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- Software modernization, harmonization, and verification

Progress: Velocity solver scaling on GPUs; first AIS production runs on Perlmutter-gpu (first of their kind(?))
Actionable projections require quantification of uncertainty

Goals:
- UQ using MALI large ensembles

**Progress:** MALI contribution to Ice-Sheet Model Intercomparison Project (ISMIP6-AIS-2300)
Actionable projections require quantification of uncertainty

Goals:
- UQ using MALI large ensembles
  - parametric uncertainty, multifidelity methods
  - statistical and ML emulation

Progress: Probabilistic projections of Amery Ice Shelf basin using Bayesian inference
Probabilistic AIS Projections

- Actionable projections require quantification of uncertainty
- Goals:
  - UQ using MALI large ensembles
    - parametric uncertainty, multifidelity methods
  - statistical and ML emulation
  - E3SM simulations with fully coupled AIS component
FAnSSIE Summary & Outlook

1. Coupling of climate and Antarctic Ice Sheet in E3SM
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- Addressing AIS deep uncertainty requires integrated computational/domain science collaboration
  - team built over multiple previous projects
- Close coordination with E3SM project and other ecosystem projects
- Maintaing DOE leadership in ice-sheet science and development