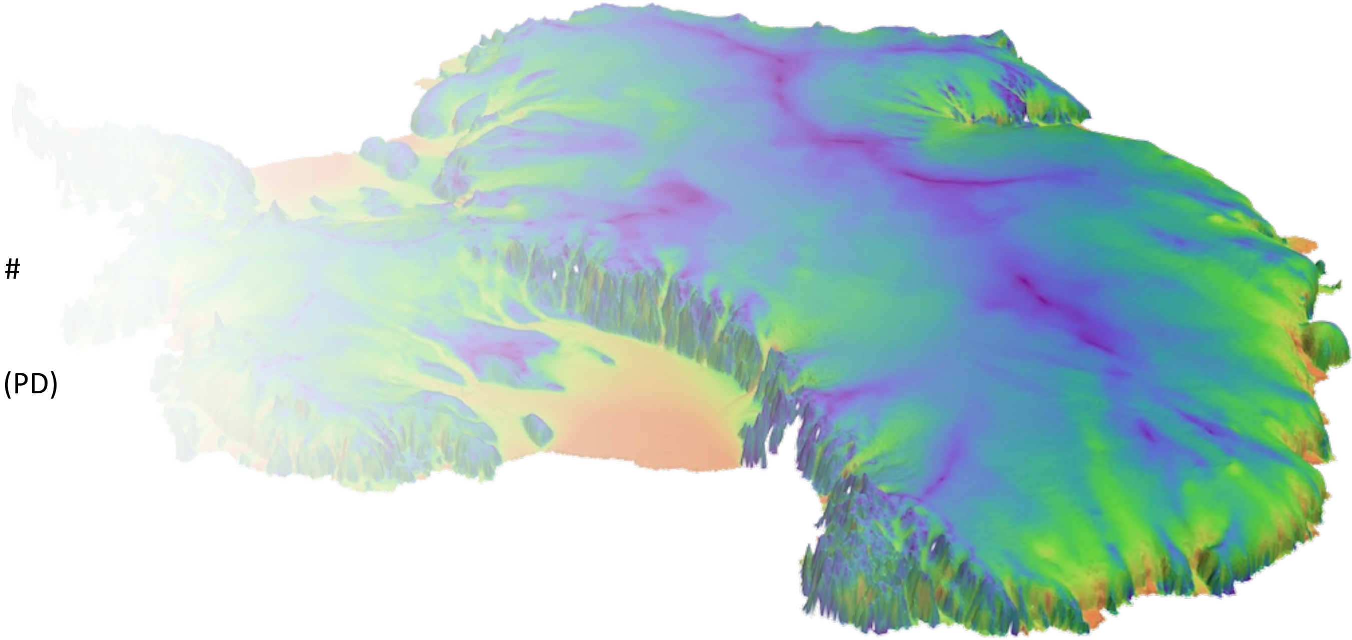
Framework for Antarctic System Science in E3SM

Matt Hoffman

Los Alamos National Laboratory



= SciDAC Institute Member: FASTMath
* = SciDAC Institute Member: RAPIDS2
^ = E3SM Project Member

Los Alamos National Laboratory

- **Matt Hoffman**
- Steve Price ^
- Xylar Asay-Davis ^
- **Carolyn Begeman** ^
- Trevor Hillebrand ^
- Trevor Hillebrand ^
- **Alice Barthel** ^
- Alex Hager (PD)
- Irena Vankova (PD)

Sandia National Laboratories

- **Mauro Perego** #^
- Jerry Watkins ^
- Luca Bertagna ^
- John Jakeman #
- Jonathan Hu #
- Irina Tezaur
- Kim Liegeois
- Max Carlson (PD)

Berkeley Lab

- Sam Williams *
- Oscar Antepara

Brookhaven National Laboratory

- Nathan Urban
- Sanket Jantre (PD)

Rensselaer

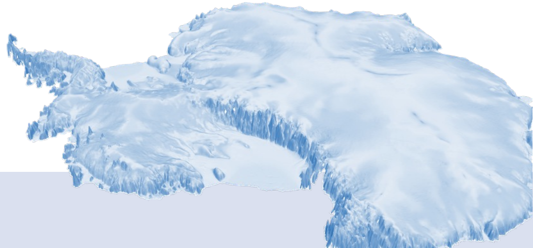
- **Mark Shephard** #
- Cameron Smith #
- Angel Castillo

University of Michigan

- Jeremy Bassis
- Sam Kachuck

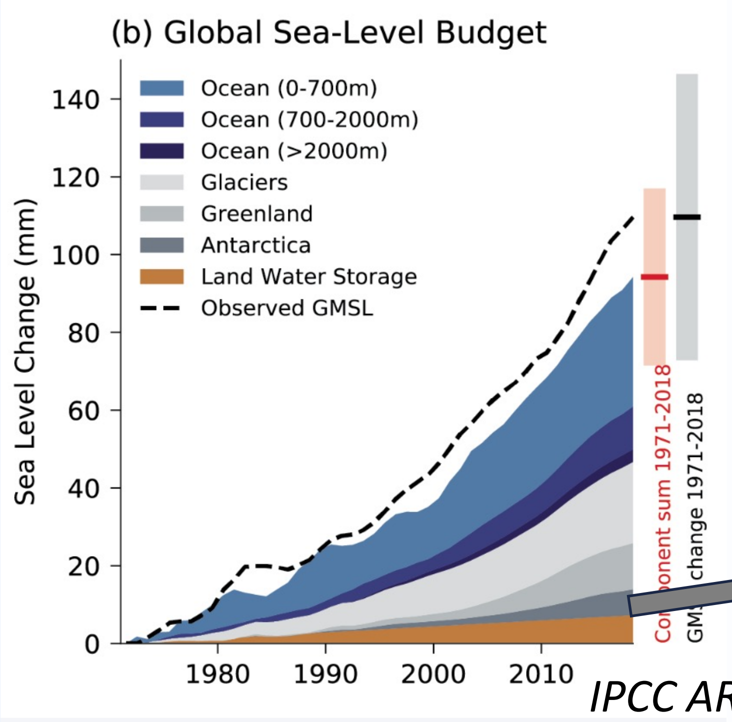
UCI University of California, Irvine

- Charlie Zender ^
- Chloe Whicker (Ph.D. student UM)



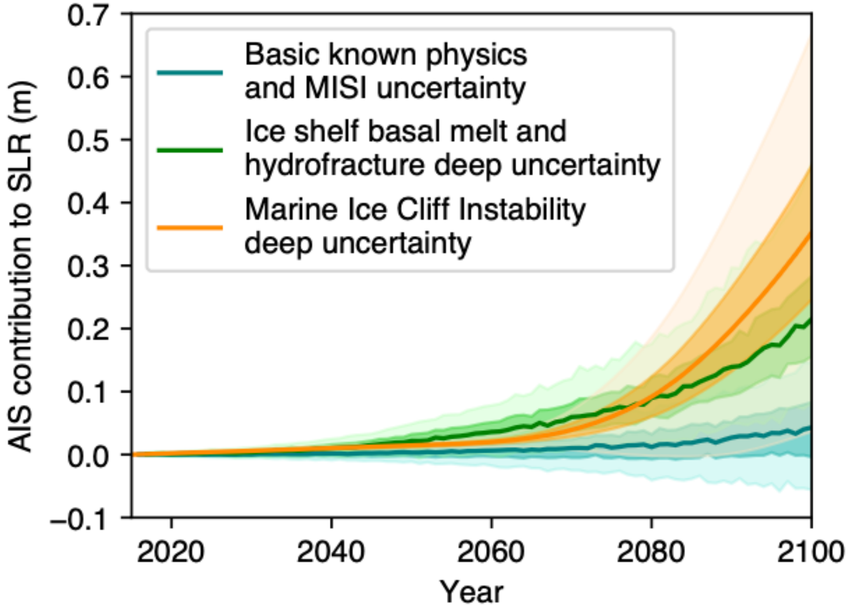
Motivation: Antarctic Ice Sheet is largest uncertainty in future sea-level change

Historical



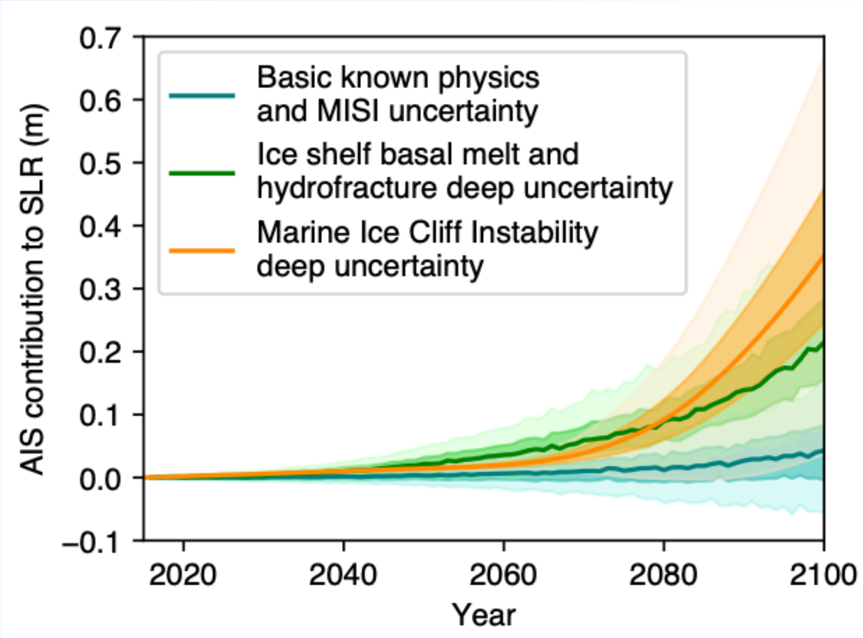
IPCC AR6

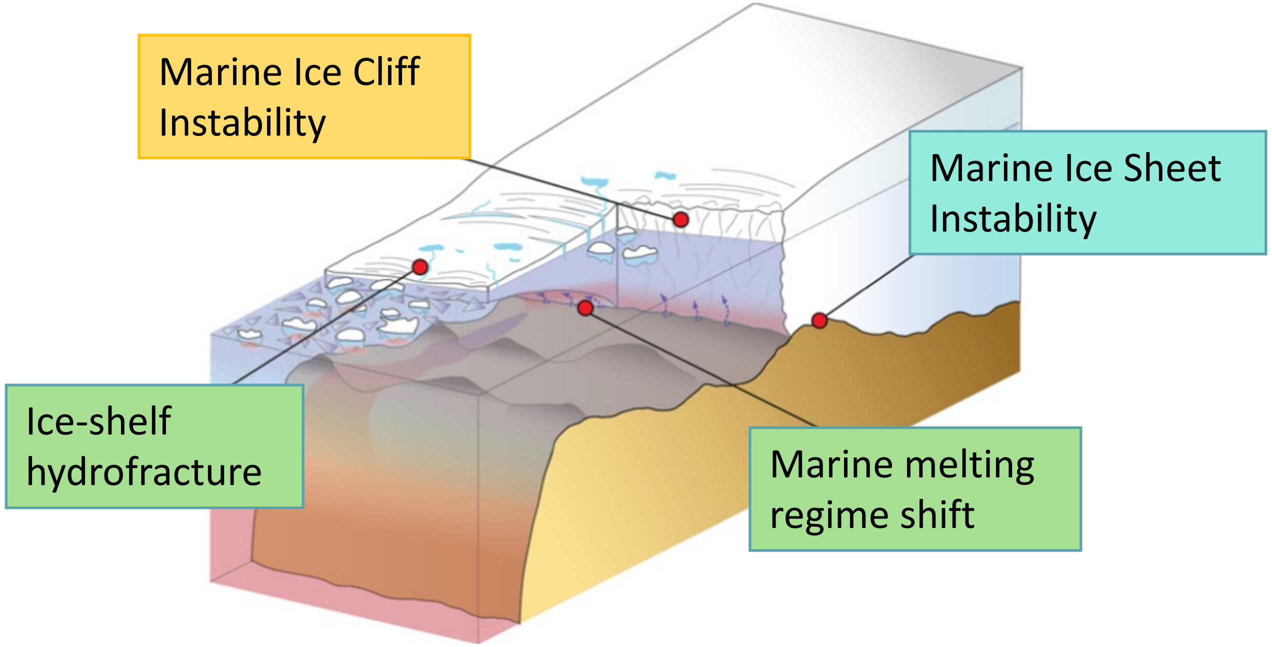
Future projections



Problem: Feedbacks and tipping points in AIS processes and coupling

Future projections

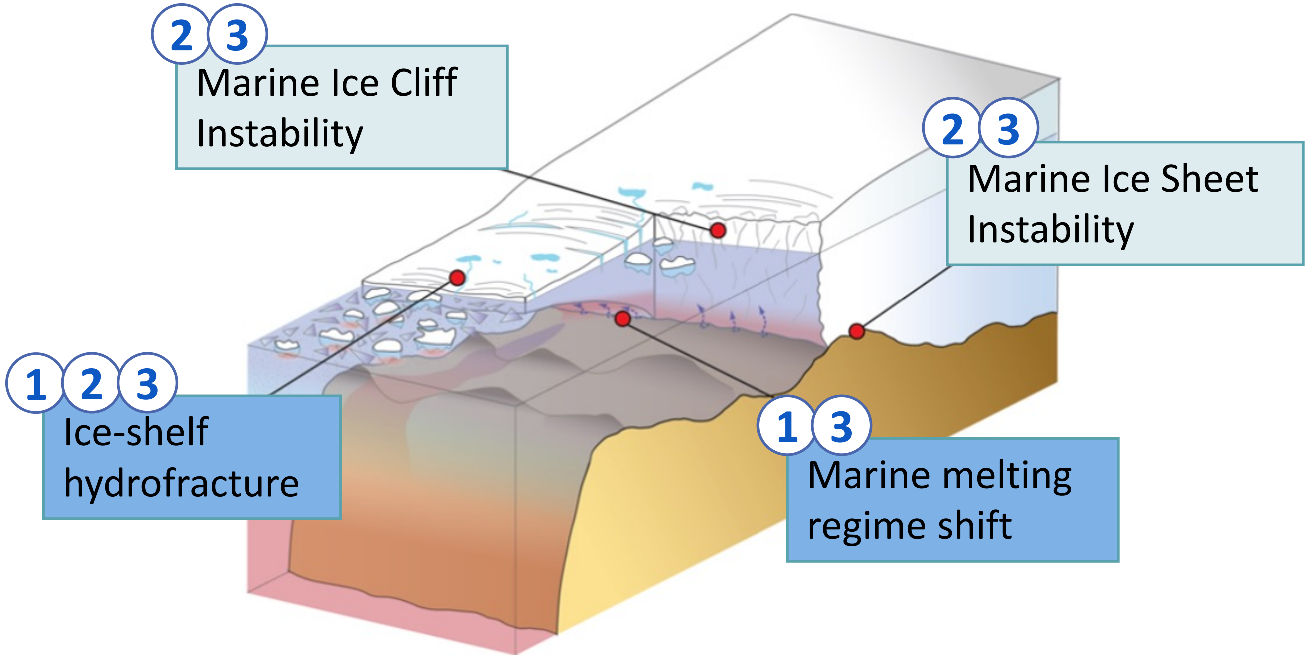




FAnSSIE Project Focus Areas

Framework for Antarctic System Science in E3SM

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

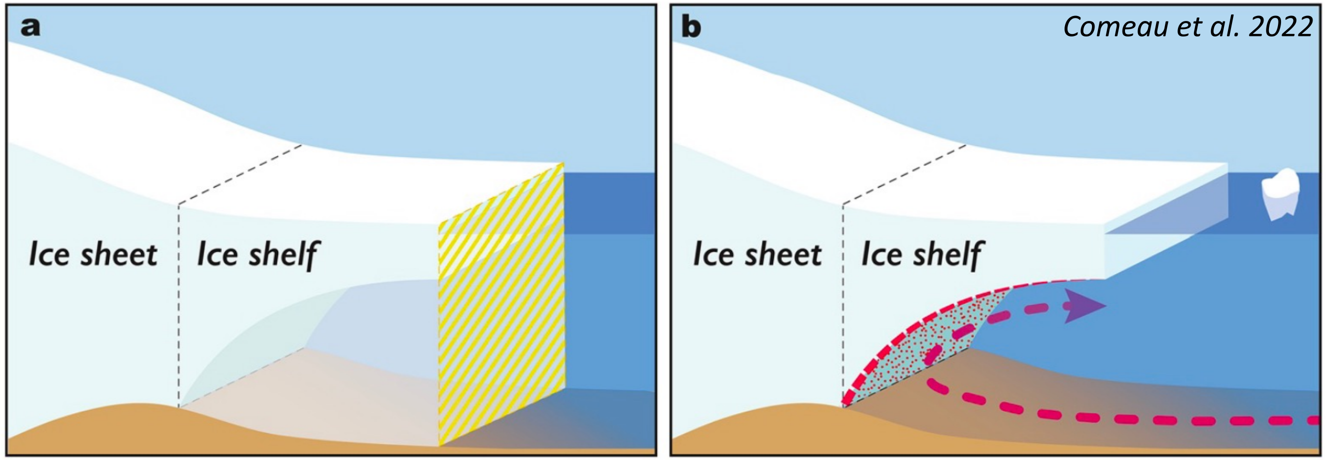


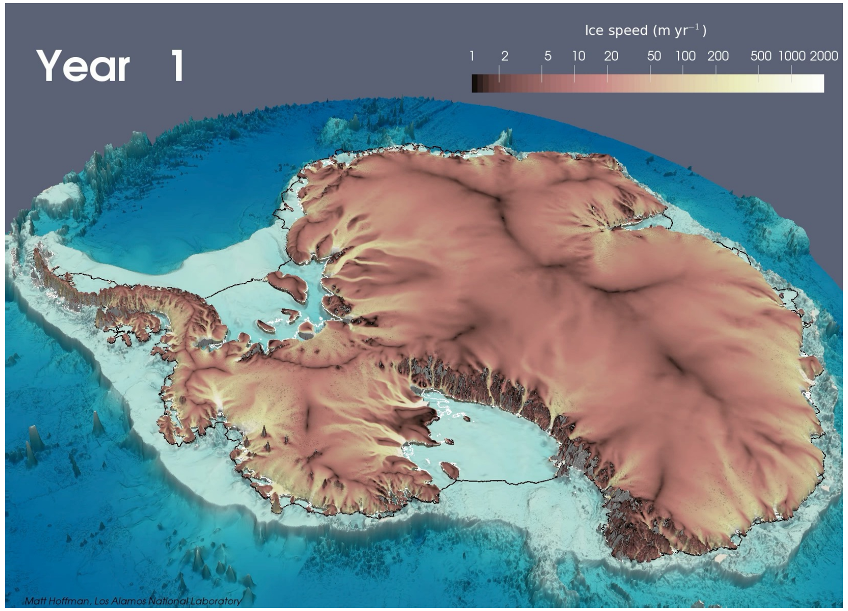
How will threshold processes linking the coupled ice sheet, ocean, and atmosphere impact the contribution of the Antarctic Ice Sheet to sea-level change in the coming decades and centuries?

① 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

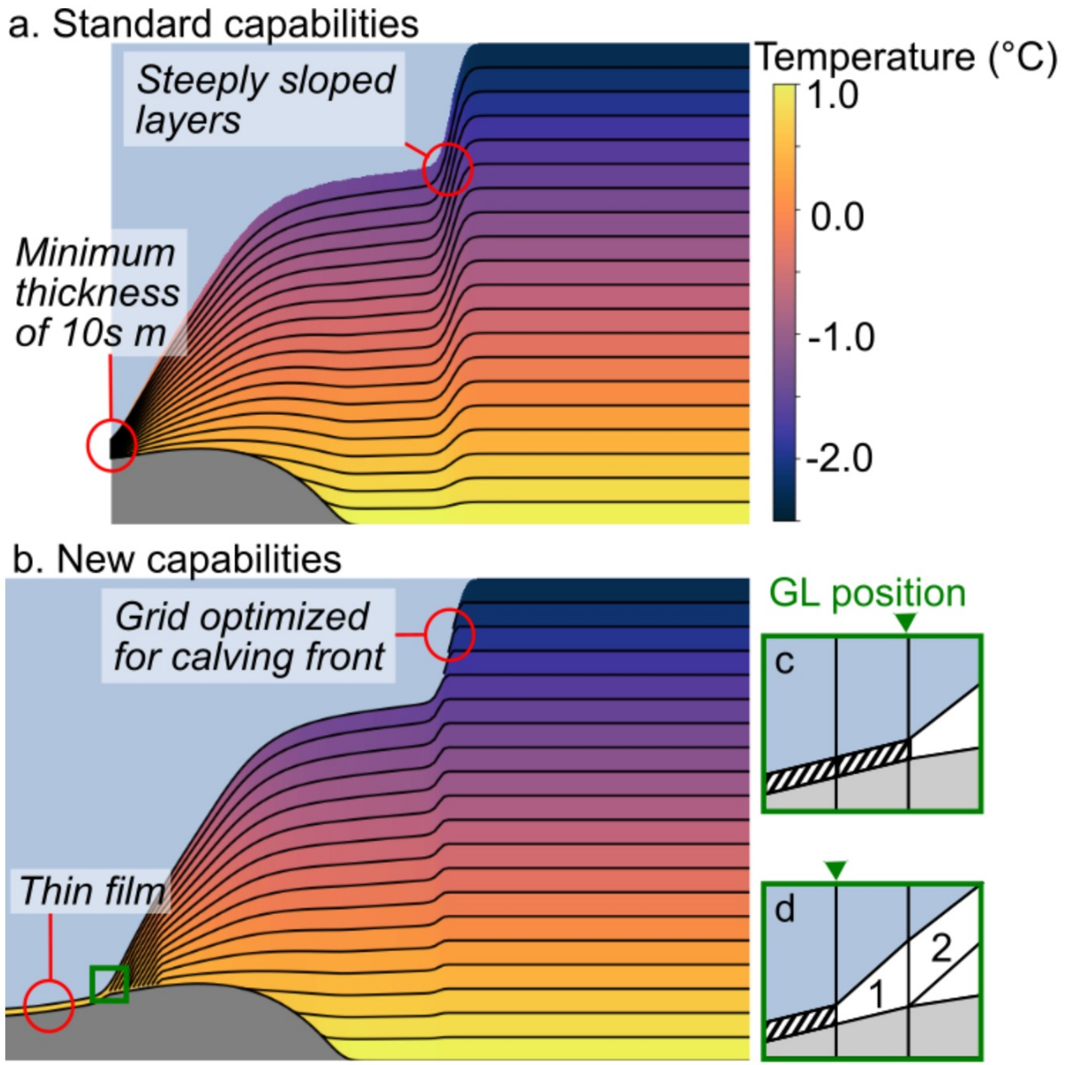




1 Coupling AIS to E3SM: Ice-sheet/Ocean

LANL

- 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



Carolyn Begeman, Xylar Asay-Davis (LANL)

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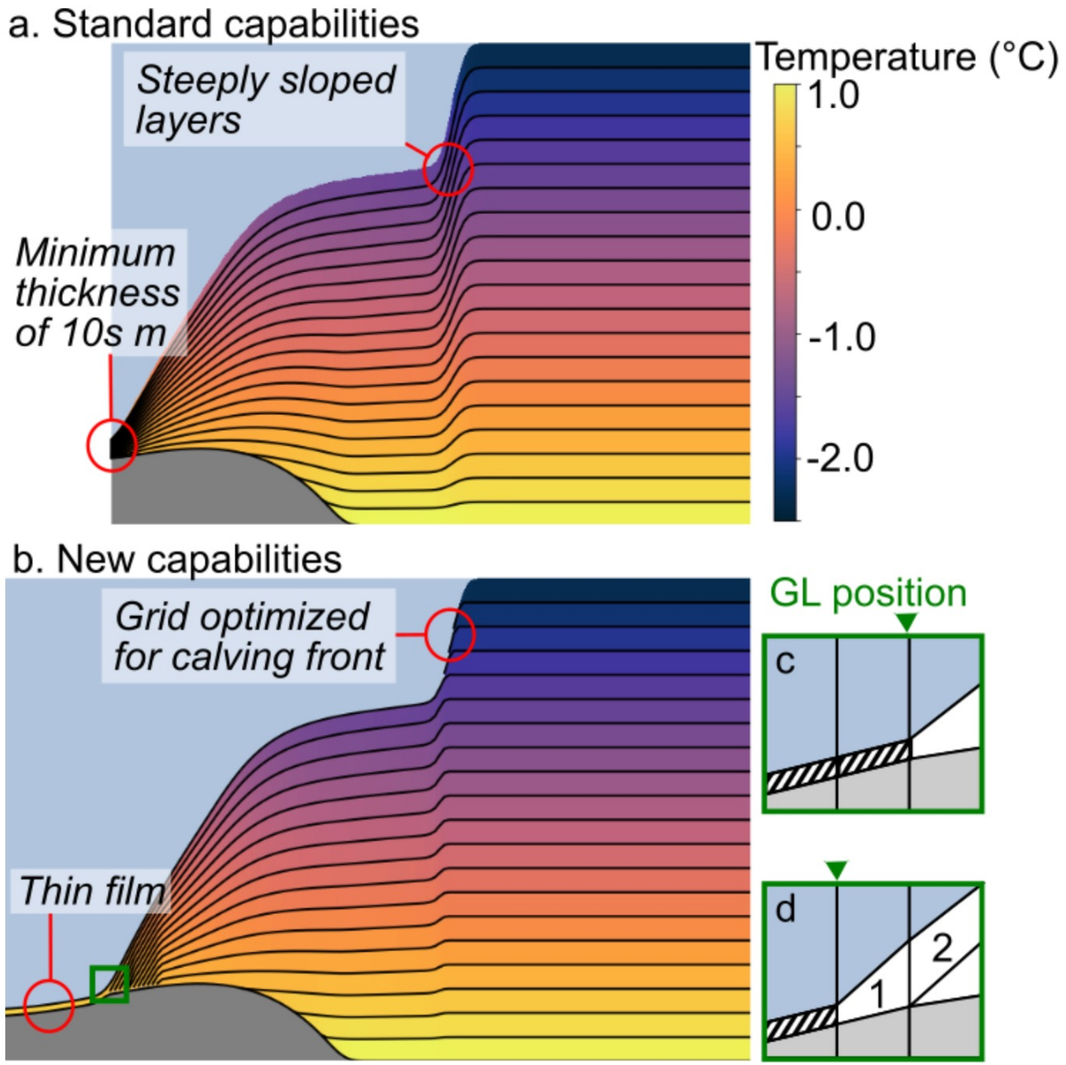
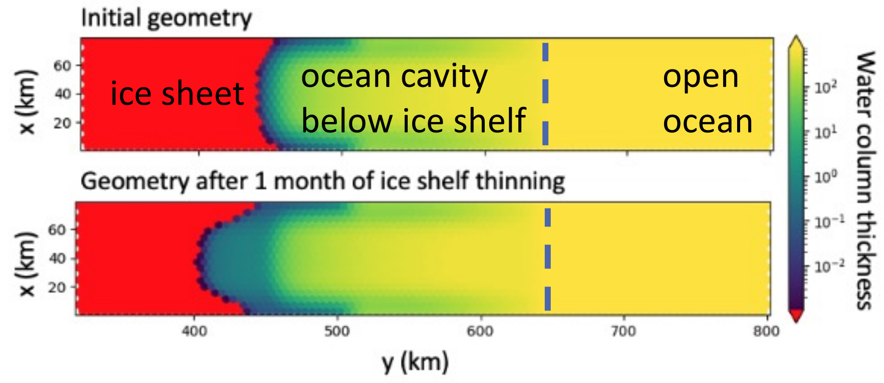


Progress:
Thin film wetting & drying operational

Coordination with ICoM



Carolyn Begeman, Xylar Asay-Davis (LANL)

① Coupling AIS to E3SM: Ice-sheet/Ocean

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:

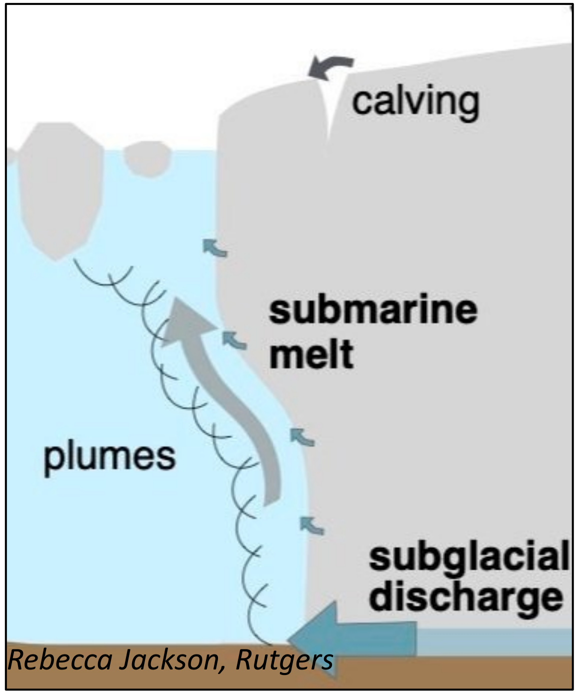
- maintain an unsupported branch of E3SM with MPAS-Ocean's ice-shelf capabilities to achieve FAnSSIE (and E3SM) science objectives.
- preserve these capabilities in E3SM through the ocean model transition.

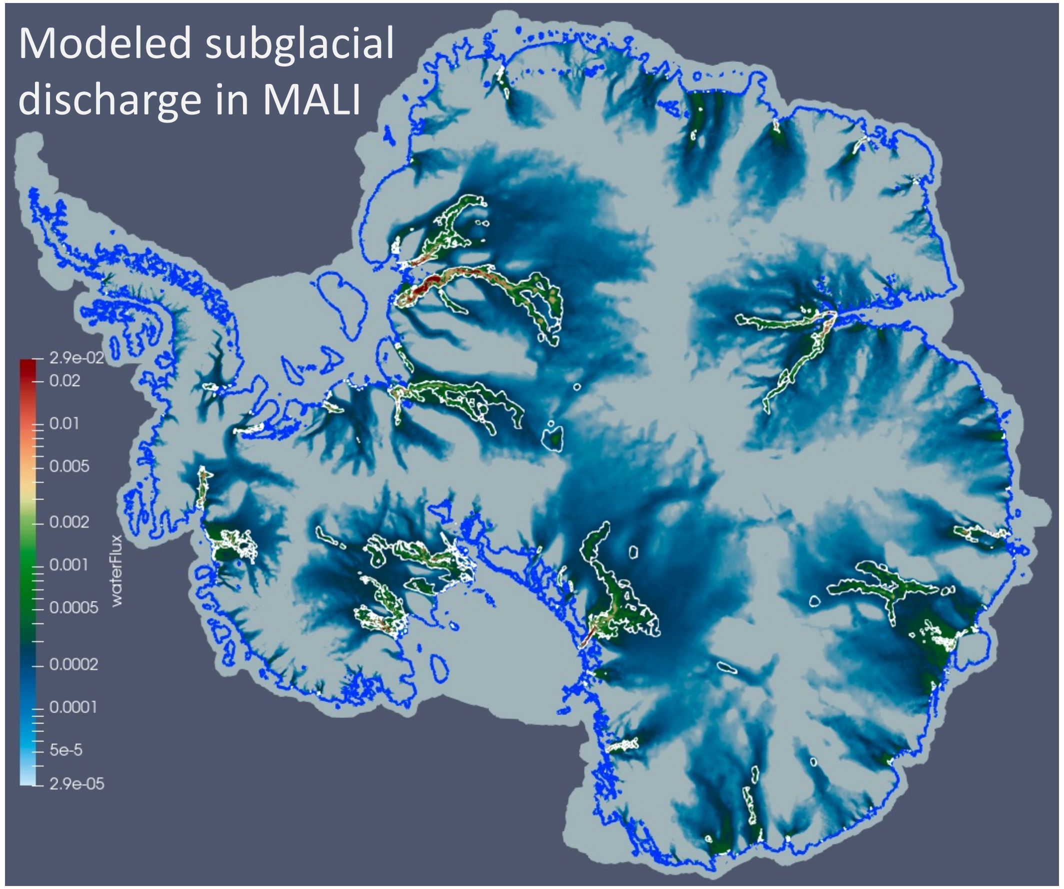
① Coupling AIS to E3SM: Ice-sheet/Ocean

LANL

Adding subglacial discharge to ocean

- Subglacial discharge of meltwater known to enhance submarine melting in Greenland, but typically assumed to be negligble 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





Courtney Shafer, University of Buffalo
(DOE Computational Science Graduate Fellow)
Alex Hager, LANL

① Coupling AIS to E3SM: Ice-sheet/Surface climate

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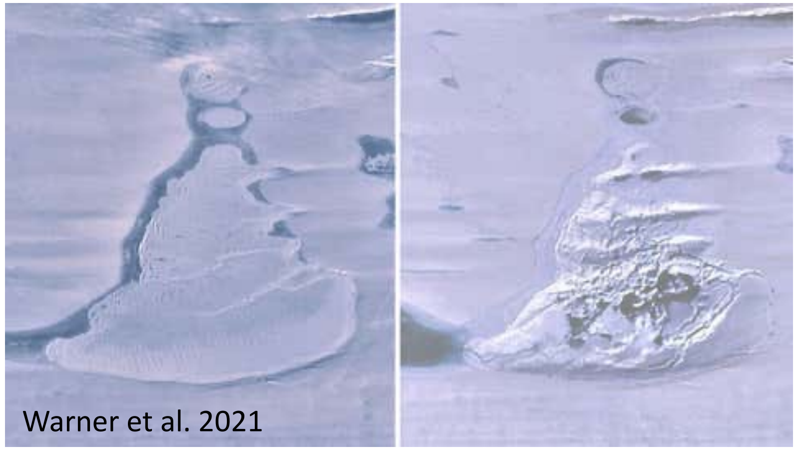
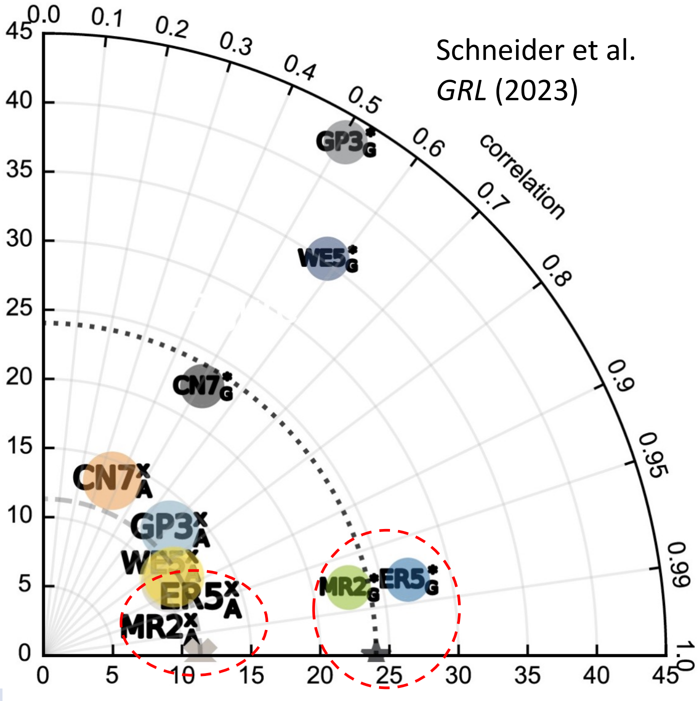
LANL

- 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





Taylor diagram shows ERA5 (ER5), MERRA2 (MR2) agree best with GrIS, AIS SUMup data (dashed).

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

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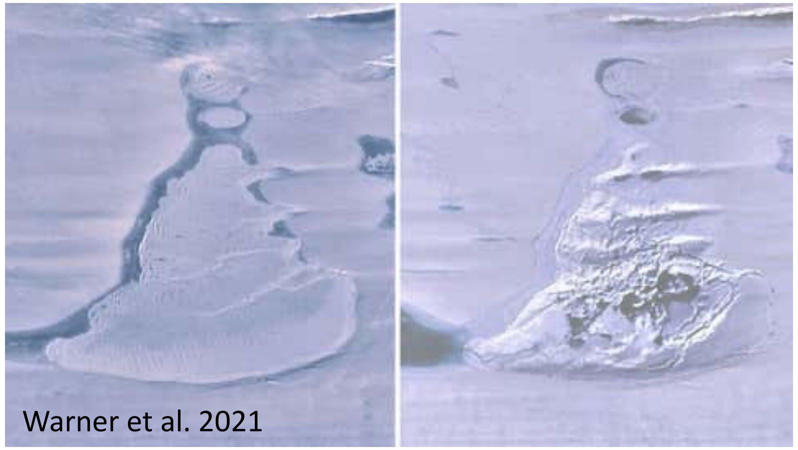
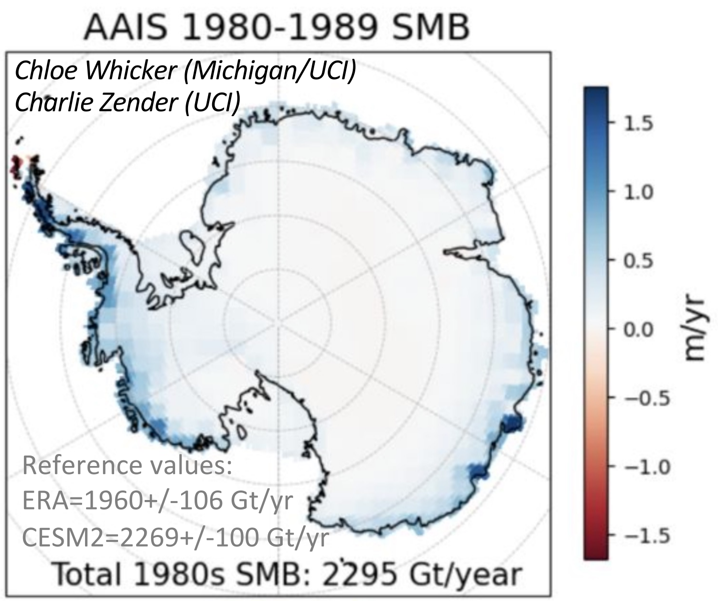


Progress: 300-yr firn spin-up with reanalysis climate forcing produces AIS surface mass balance similar to reference values



② Advanced Discretizations

SNL
LANL
UM

FASTMath

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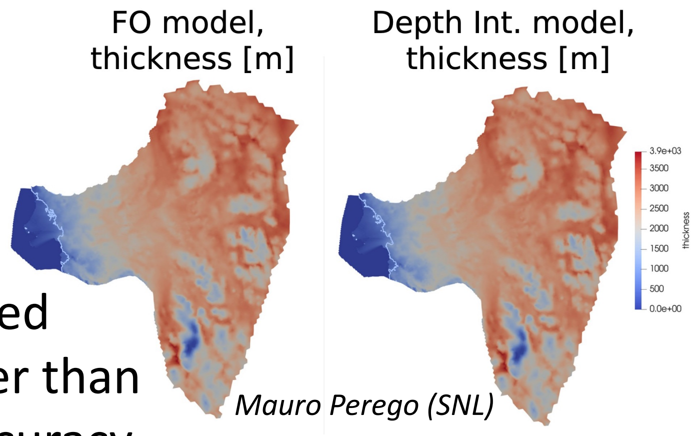
Progress: depth-integrated velocity solver 3x cheaper than 3d solver with similar accuracy



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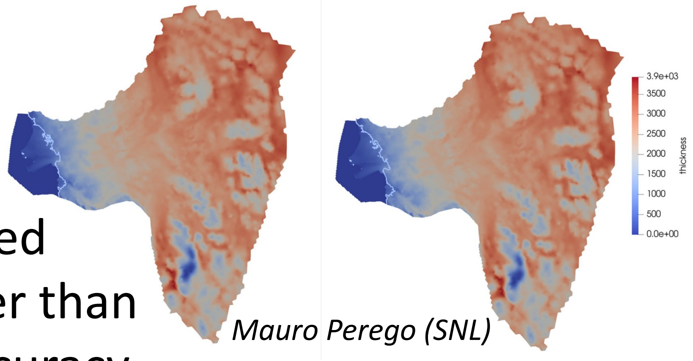
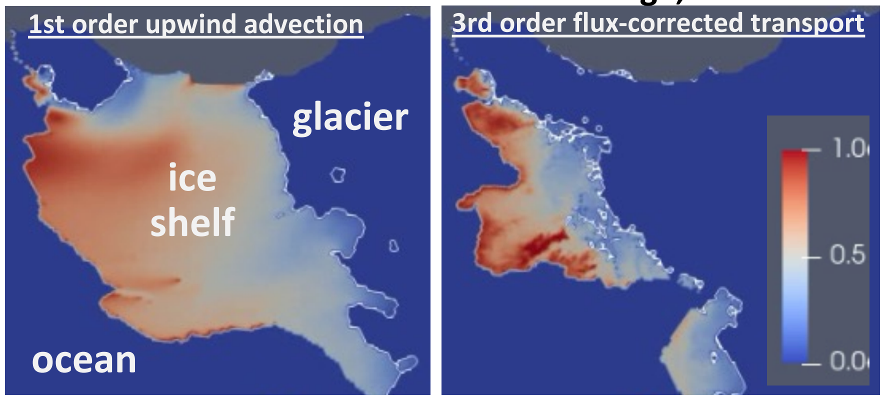


Mauro Perego (SNL)

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

Simulated Thwaites Ice Shelf damage, 2050



Trevor Hillebrand (LANL)

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

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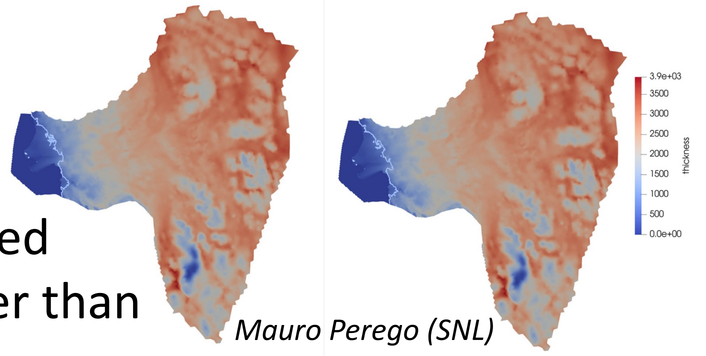

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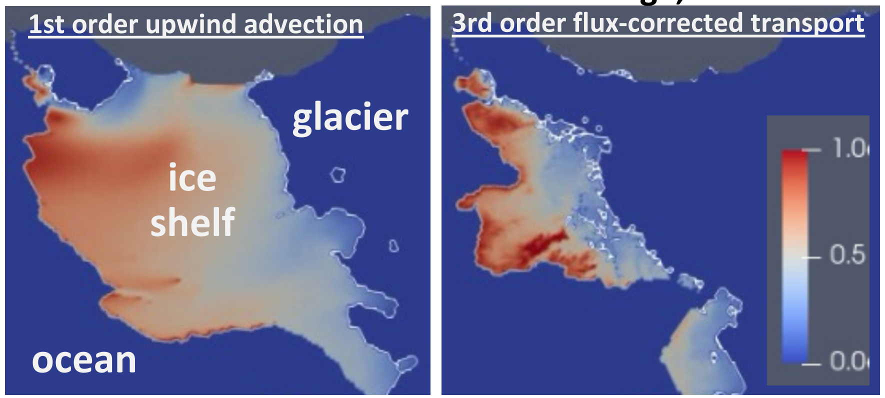

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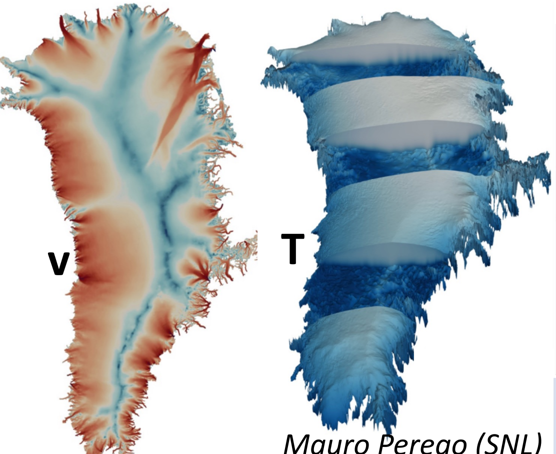

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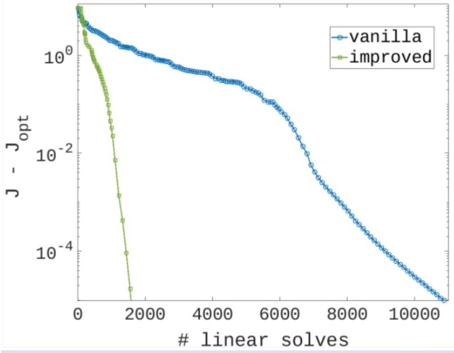

Progress: higher-order advection and time-stepping preserve sharp features in ice thickness and damage

② Ice-shelf Fracture Mechanics

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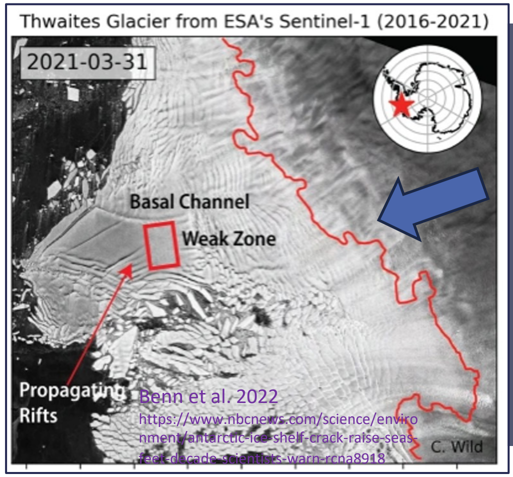
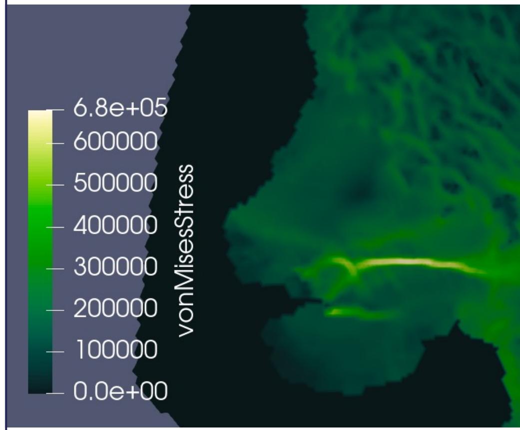
LANL

FASTMath

- Existing fracture models use simple stress or strain rate based parameterizations





② Ice-shelf Fracture Mechanics

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SNL
LANL

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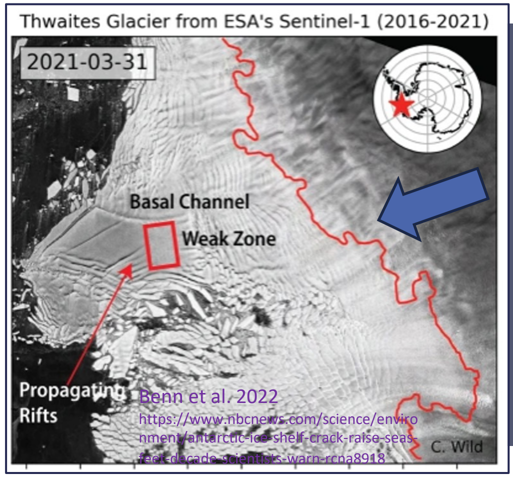
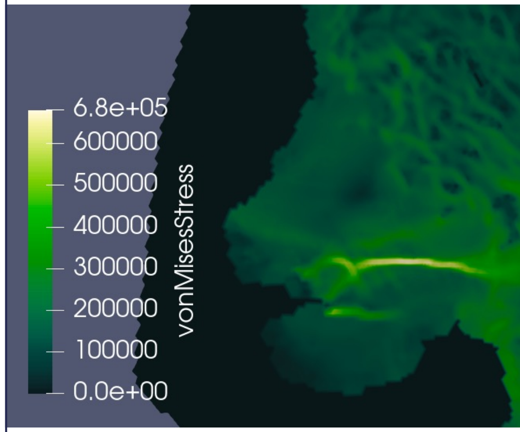
- Goals:
    - Utilize a damage state variable that:
        - triggers calving of failed ice
        - weakens ice viscosity





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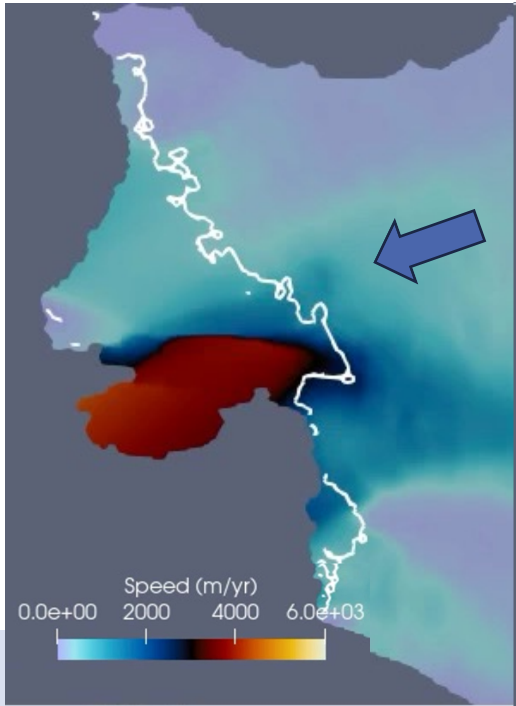

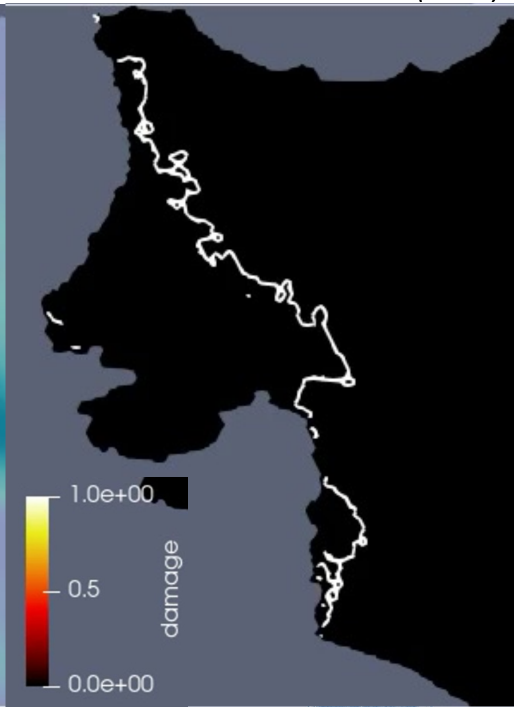

Progress: higher-order advection and time-stepping preserve sharp features in damage

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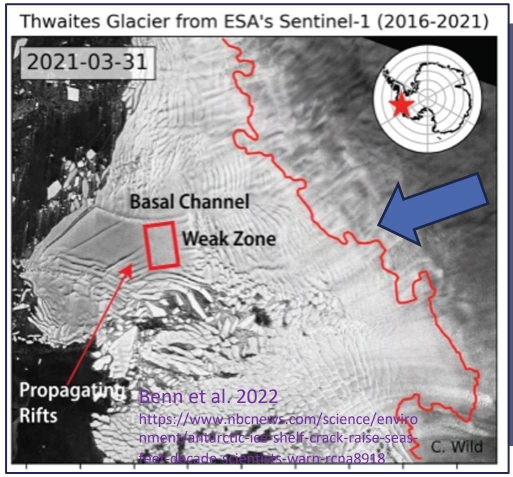
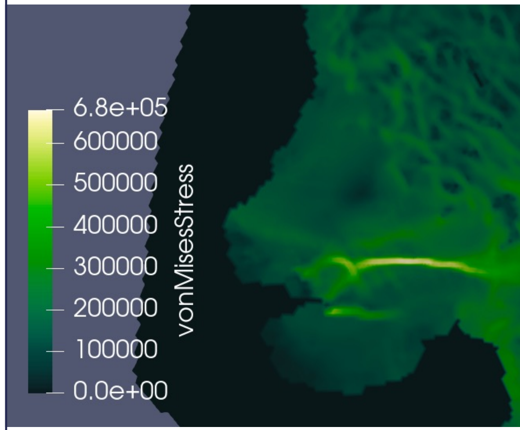
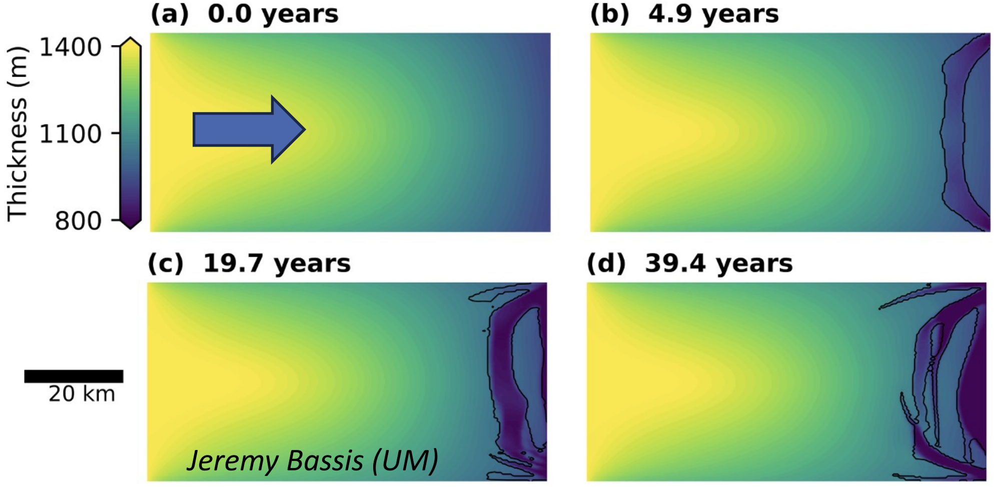
- Goals:
  - Utilize a damage state variable that:
    - triggers calving of failed ice
    - weakens ice viscosity
  - Implement ductile+brittle methods that can form rifts and tabular icebergs
    - Couple fracture and ice rheology







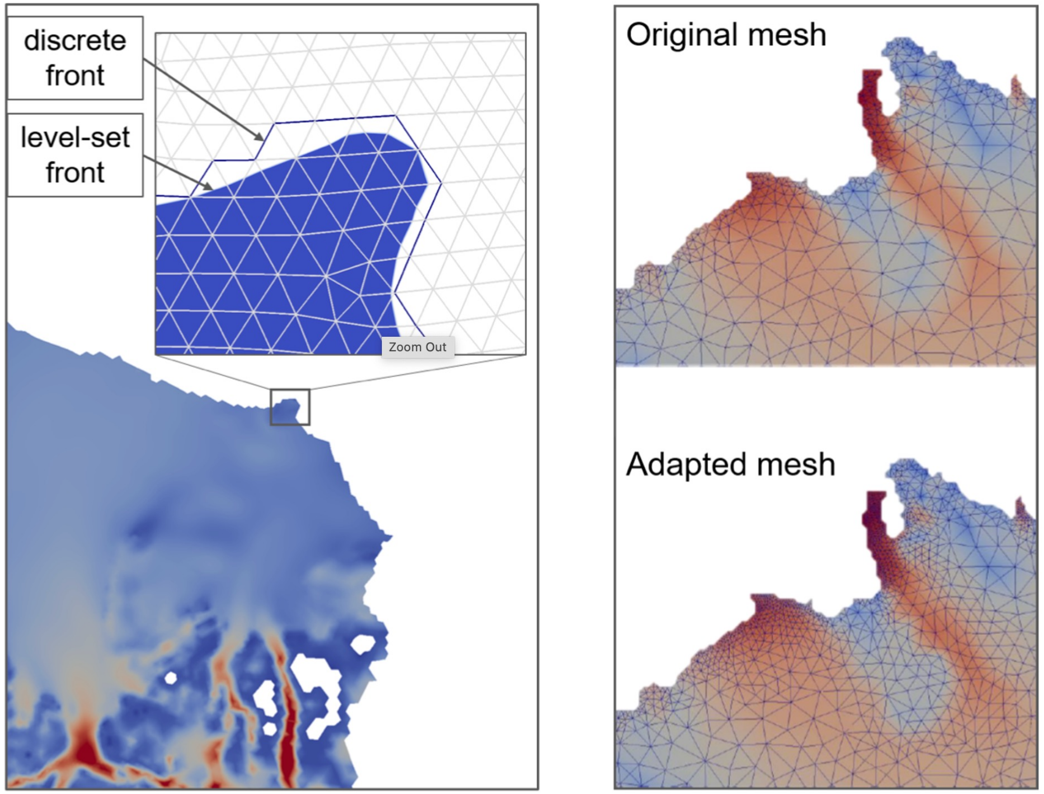
Simulated evolution of rifts in an idealized ice shelf using prototype model.

② Unstructured Mesh Adaptivity

RPI
SNL

FASTMath

- 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



Mauro Perego (SNL), Cameron Smith (RPI)

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

② MALI Performance Improvements

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RAPIDS2

- 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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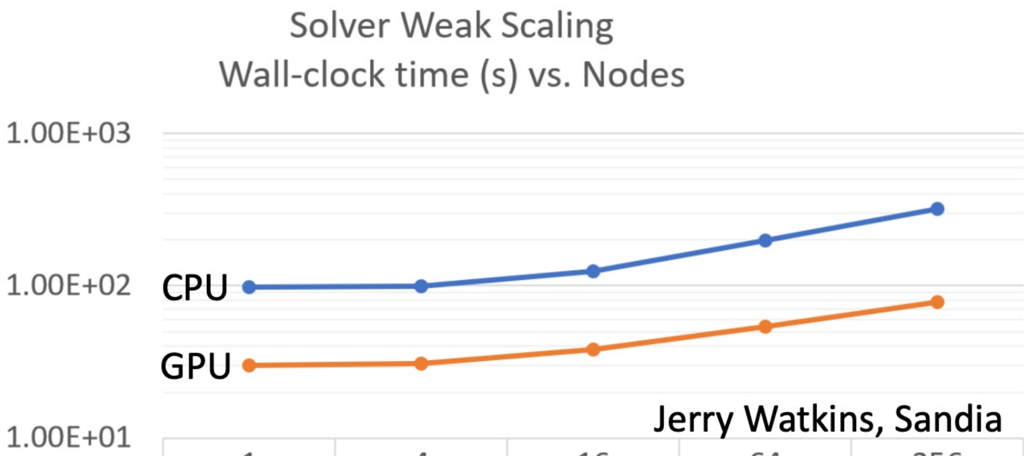

	1	4	16	64	256
Cori (Haswell)	9.86E+01	9.92E+01	1.25E+02	1.97E+02	3.22E+02
Summit (V100)	3.01E+01	3.08E+01	3.81E+01	5.40E+01	7.78E+01
Speedup	3.27	3.22	3.27	3.65	4.13
DOFs/GPU	367255	367773	368086	368401	368566

Problem size ranges form 2M to 566M unknowns.

Progress: Velocity solver scaling on GPUs; first AIS production runs on Perlmutter-gpu *(first of their kind(?))*

③ Probabilistic AIS Projections

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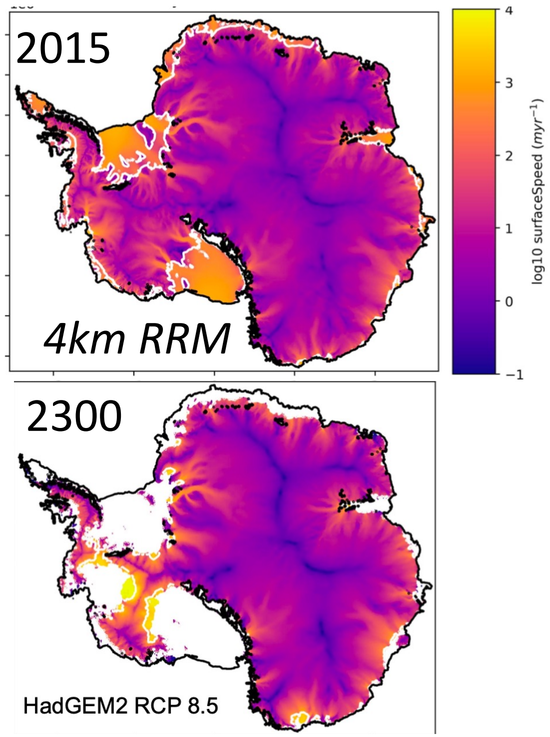
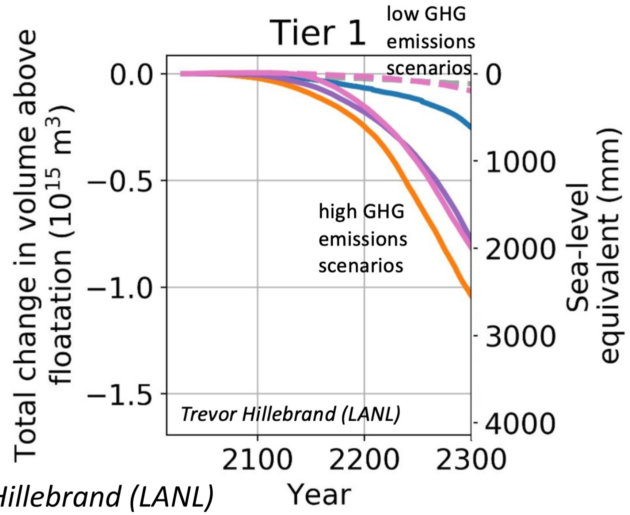
FASTMath

- Actionable projections require quantification of uncertainty
- Goals:
    - UQ using MALI large ensembles





Trevor Hillebrand (LANL)

Progress: MALI contribution to Ice-Sheet Model Intercomparison Project (ISMIP6-AIS-2300)

Coordination with Regional Sea Level ECR

③ Probabilistic AIS Projections

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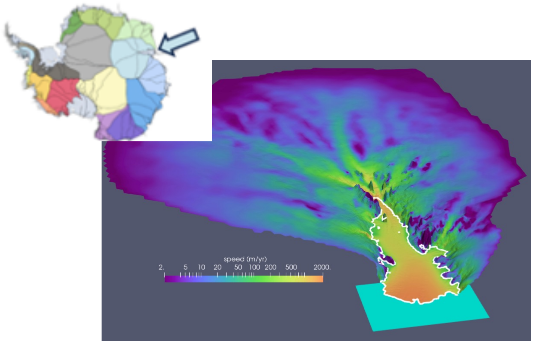
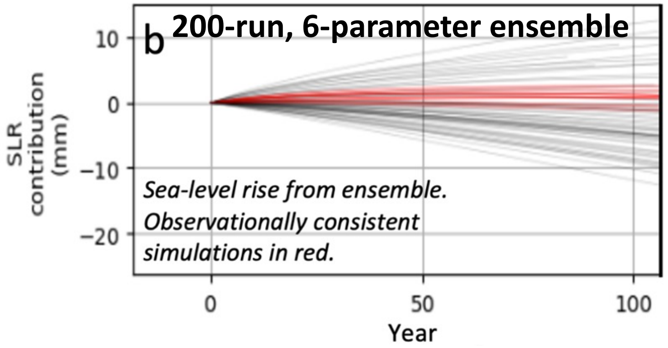
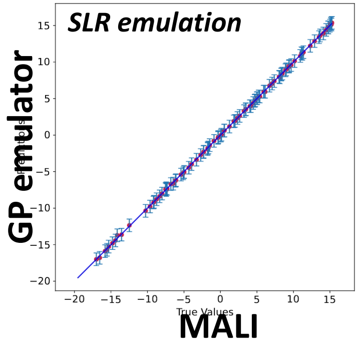
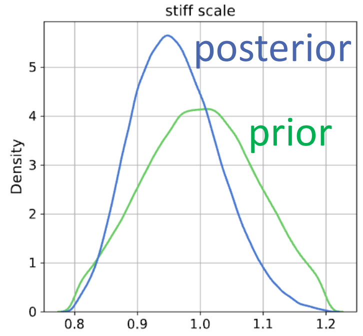
- Goals:
  - UQ using MALI large ensembles
    - **parametric uncertainty**, multifidelity methods
    - statistical and ML **emulation**

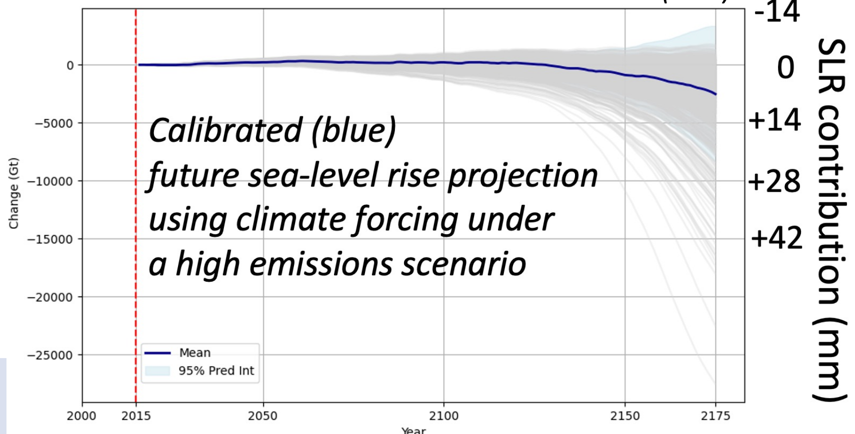








Sanket Jantre (BNL)



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

③ Probabilistic AIS Projections

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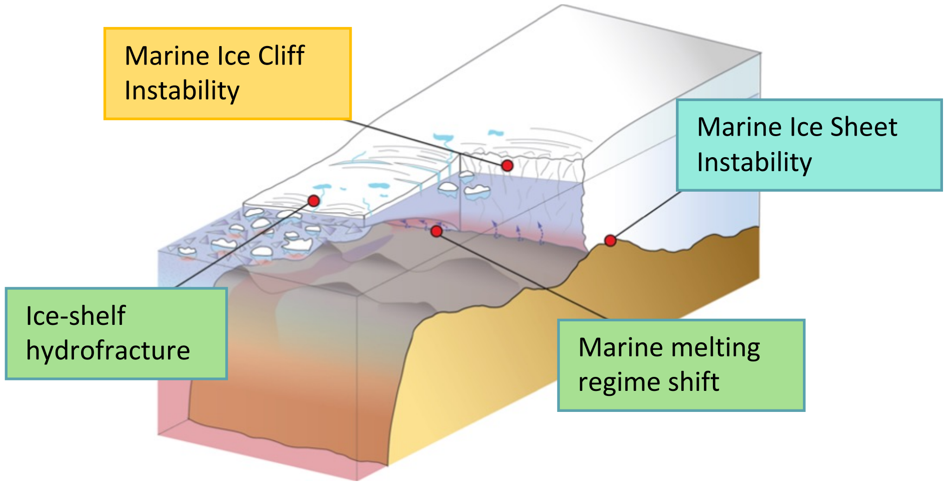
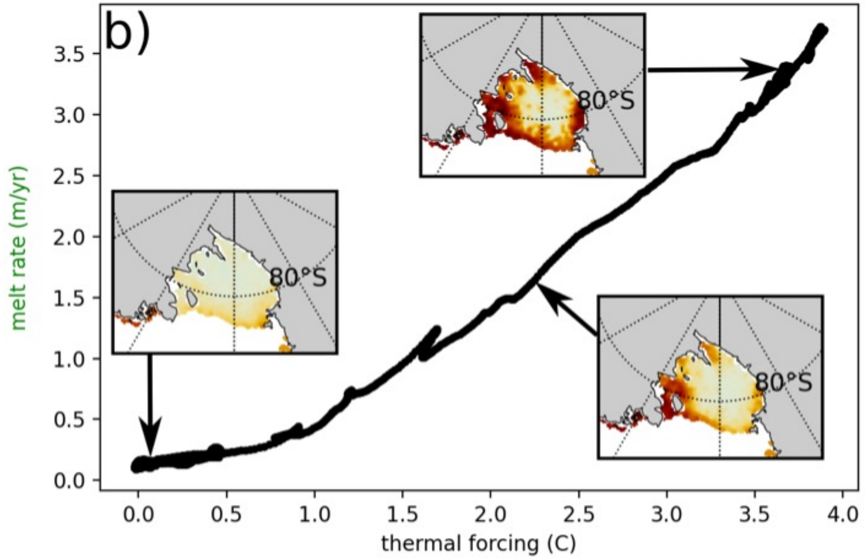
- Goals:
  - UQ using MALI large ensembles
    - parametric uncertainty, multifidelity methods
    - statistical and ML emulation
  - **E3SM simulations with fully coupled AIS component**





FAnSSIE Summary & Outlook

fanssie.github.io

FANSSIE Framework for Antarctic System Science in E3SM

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2. Ice-sheet dynamics & fracture mechanics
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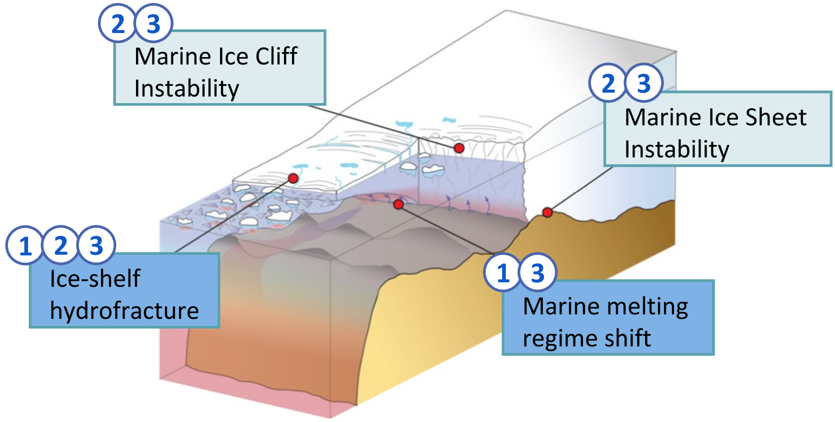

- Addressing AIS deep uncertainty requires integrated computational/domain science collaboration
  - team built over multiple previous projects
- Close coordination with E3SM project and other ecosystem projects
- Maintaing DOE leadership in ice-sheet science and development