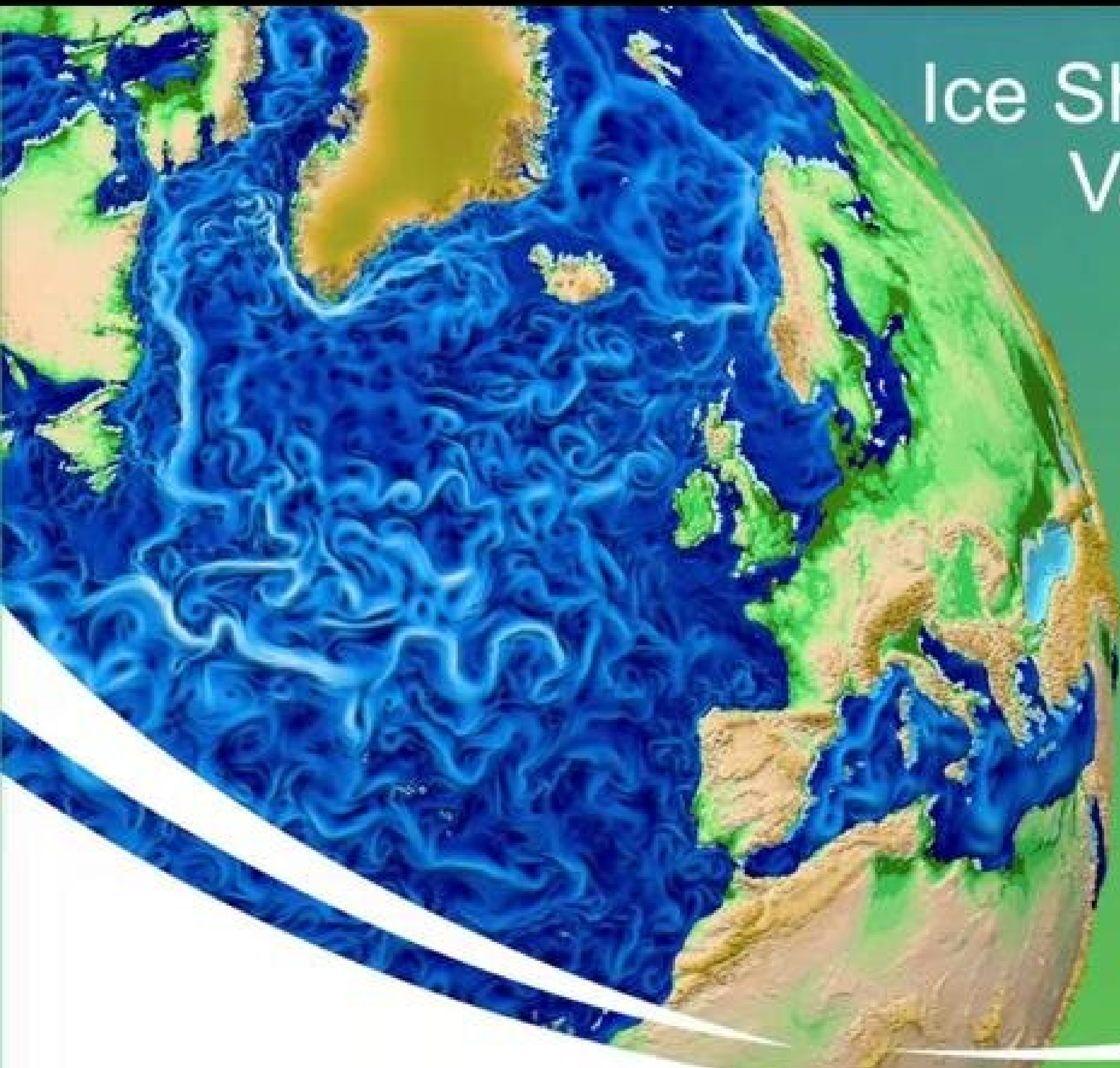

Ice Sheet Surface Mass Balance in E3SM: Validation of Improved Snow & Ice Processes

Chloe A. Whicker-Clarke[1], Charles S. Zender[1], Michael Kelleher[2], Adam Schneider[3], Christiaan T. van Dalum[4], Willem Jan van de Berg[4], Stephen Price[5], Matt Hoffman[5], Trevor Hillebrand[5]

1. Department of Earth System Science, UCI
2. Climate Change Science Institute, Oak Ridge National Laboratory
3. Cooperative Institute for Research in Environmental Sciences
4. Institute for Marine and Atmospheric Research, Utrecht University
5. Fluid Dynamics Group, Los Alamos National Laboratory

FANSSIE Framework for Antarctic System Science in E3SM

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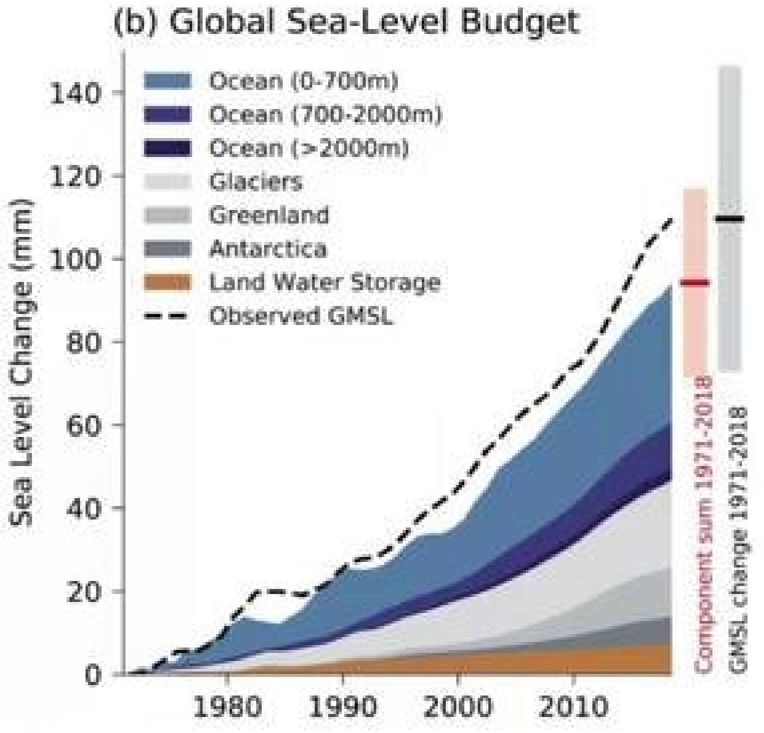
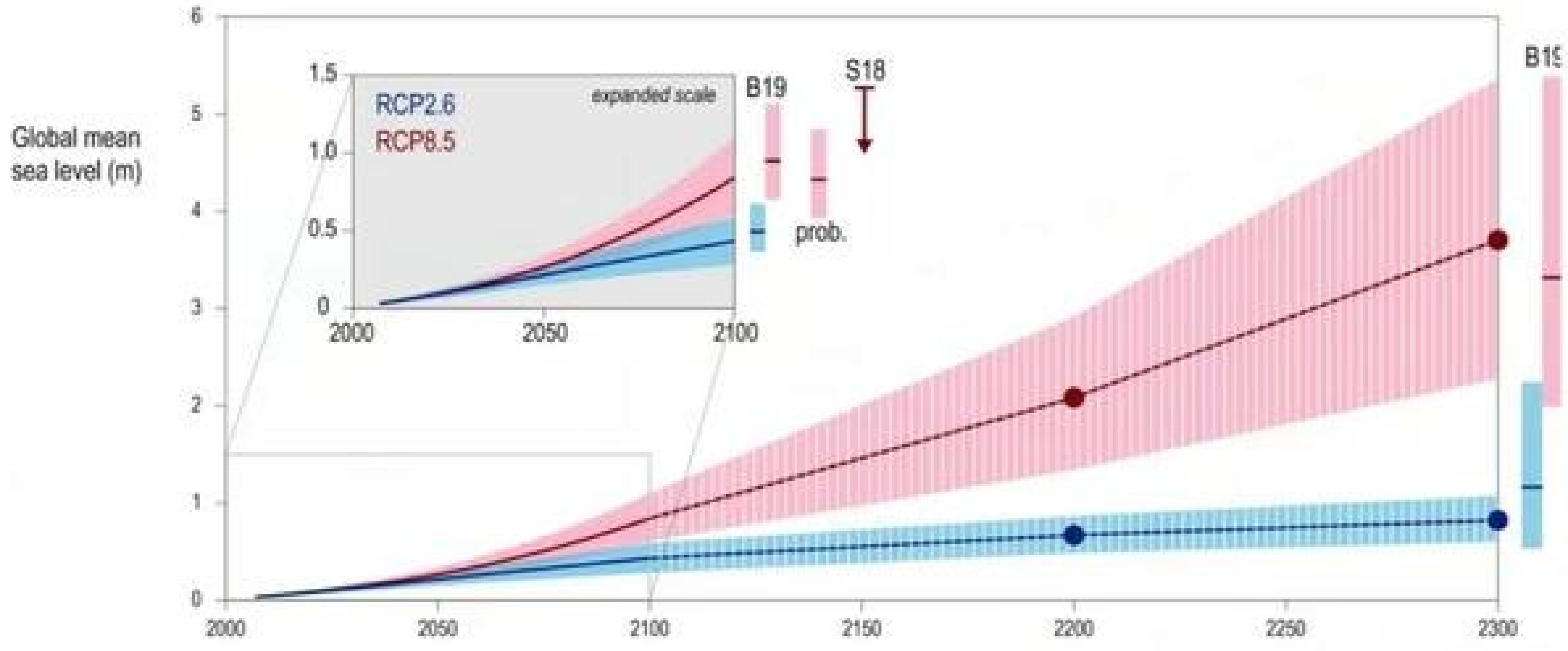
E3SM Energy Exascale Earth System Model

Land Ice Contributions to Global Mean Sea Level

- Melt of glaciers and ice sheets contribute ~1.5–2 mm/yr to sea level rise (SLR)
- Contributions are expected to increase
- SLR projections remain uncertain due to challenges in modeling glacier and ice sheet processes

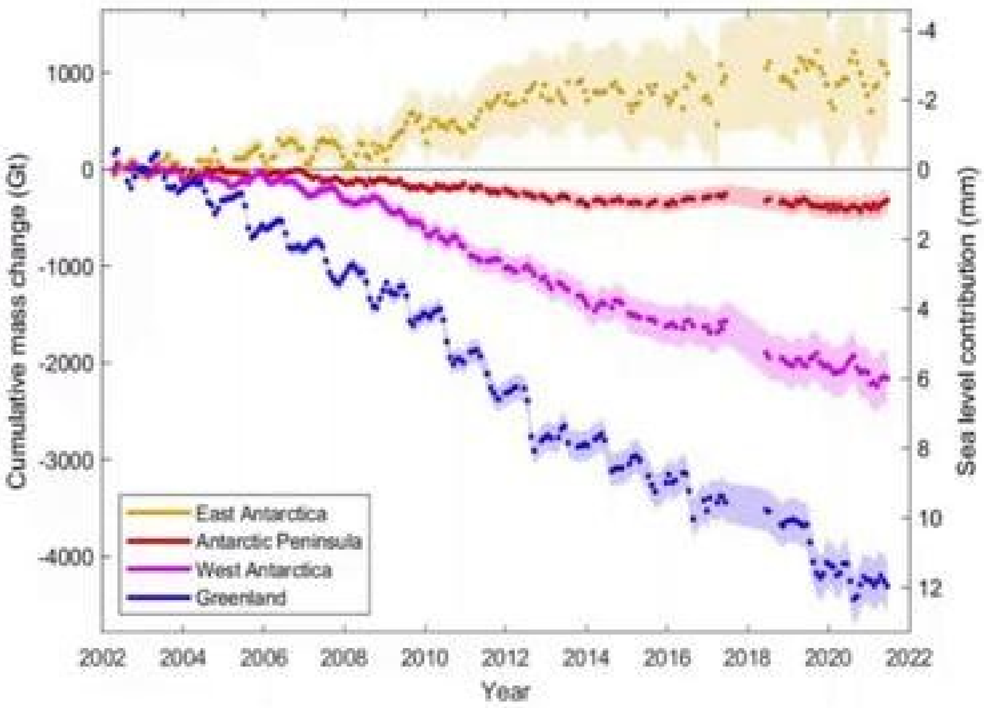




IPCC AR6

Ice Sheet Contributions to Global Mean Sea Level

- GIS and AIS have significantly raised sea level since the early 2000s
- Accurate ESM simulations of ice sheet mass balance are critical
- Ice sheets are challenging to model due to complex atmosphere-land-ocean interactions



Otosaka et al., (2024)

Ice Sheet Mass Balance

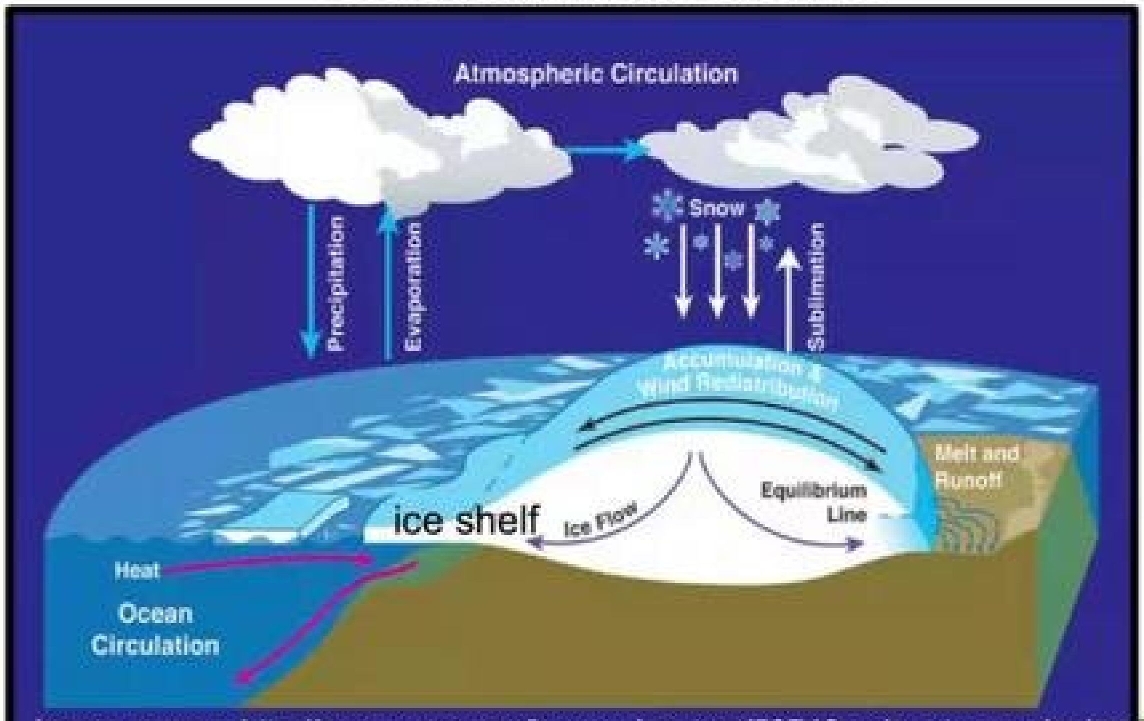
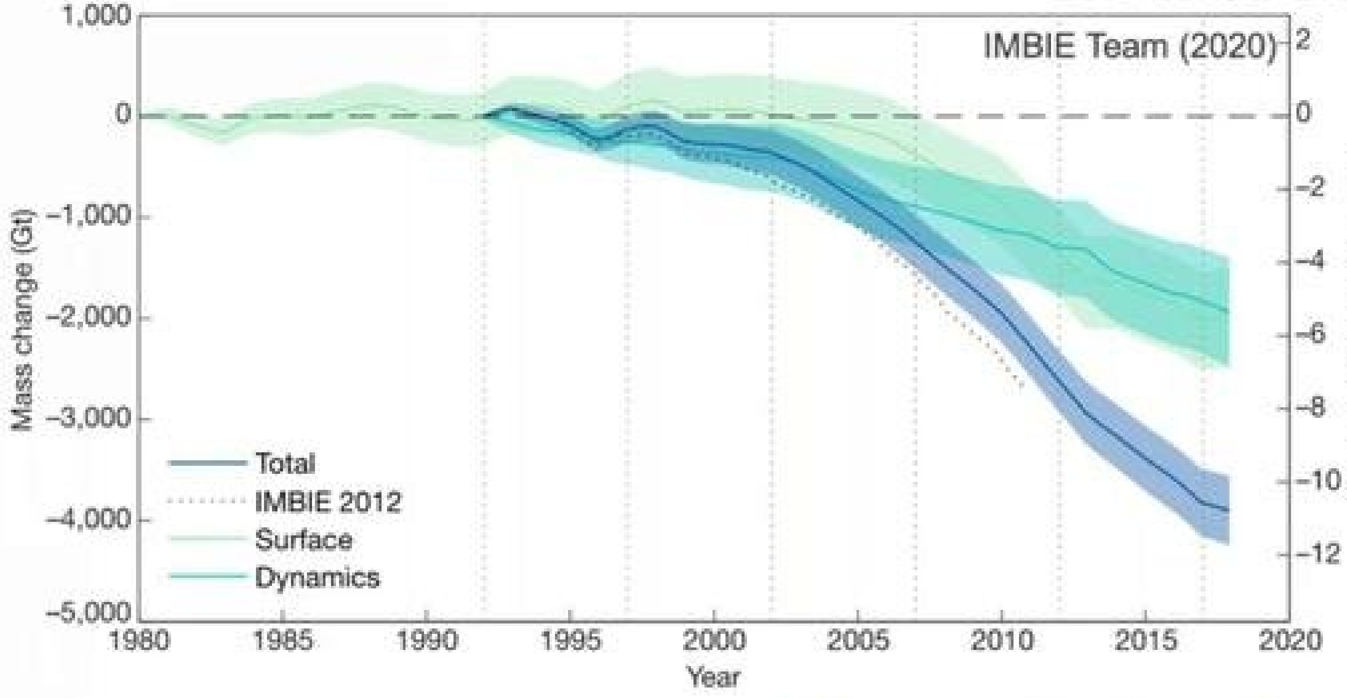


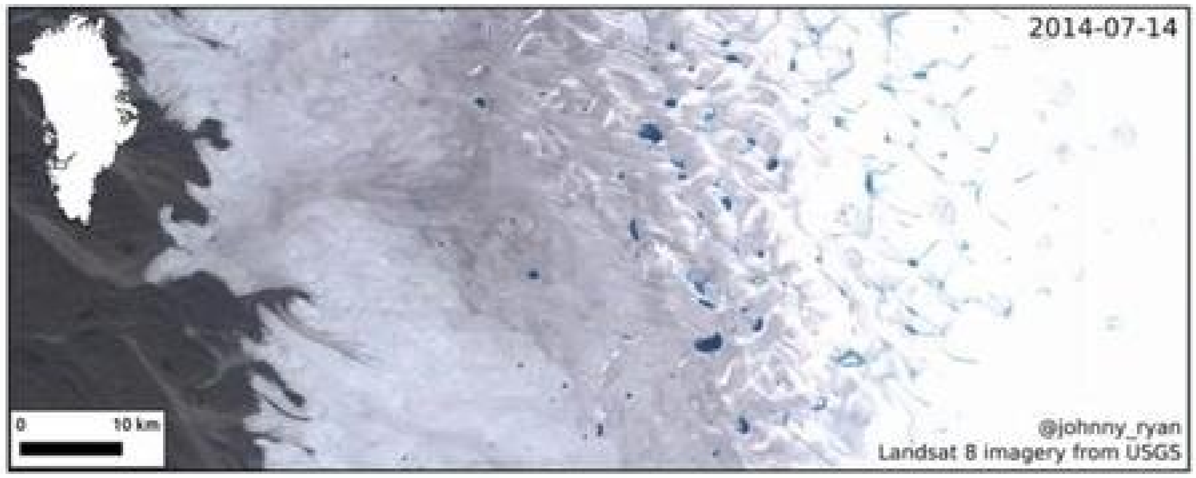
Image source: http://www.nasa.gov/images/content/53743main_atmos_circ.jpg

The Greenland Ice Sheet Surface Mass Loss

- Surface mass loss is rapidly increasing on the GIS

GIS Mass Change





Surface Mass Balance: Change in ice sheet mass = mass in – mass out

sea level change

snowfall

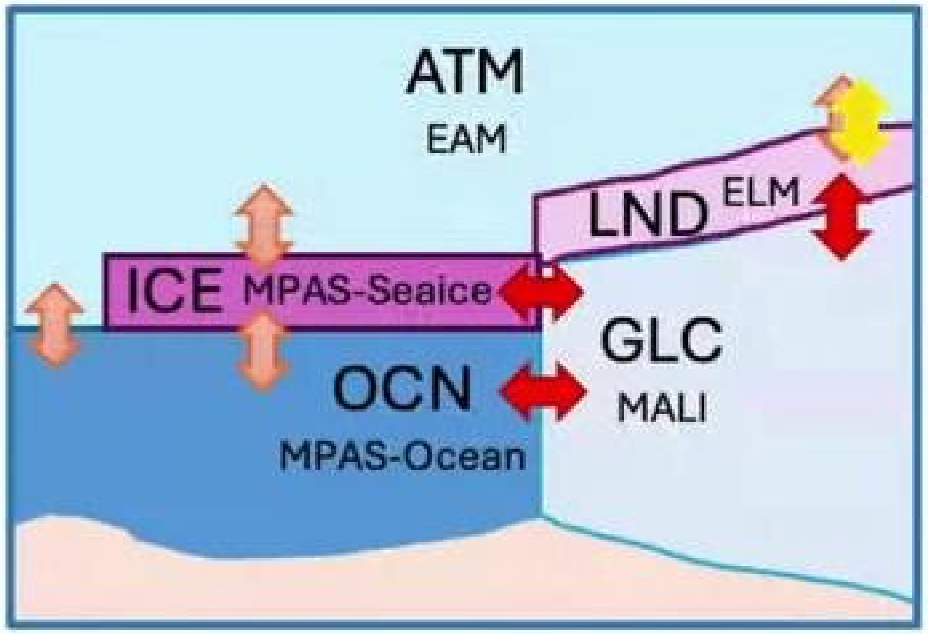
Melting/runoff

sublimation

E3SM & FAnSSIE's Goals & Progress Towards Accurate & Coupled Ice Sheet Simulations

Our goal is to improve E3SM's ability to accurately simulate and project the state of the ice sheets

1. **Improving the surface mass and energy budgets simulated in the land model (ELM), and our ability to validate ELM's SEB/SMB**
2. Improve coupling between ELM and the ice sheet model (MALI)
3. Complete coupling MALI to the MPAS-Ocean model, introducing more accurate thermal forcing from the ocean



FANSSIE Framework for Antarctic System Science in E3SM

E3SM Energy Exascale Earth System Model

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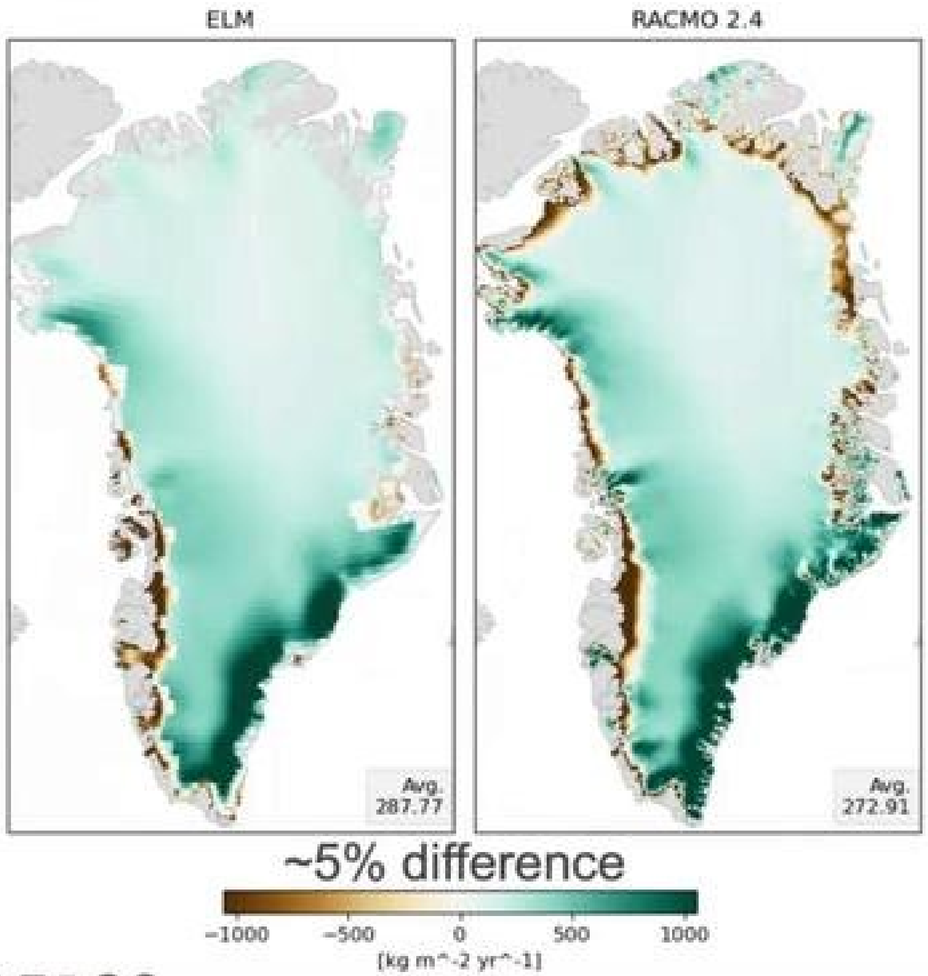
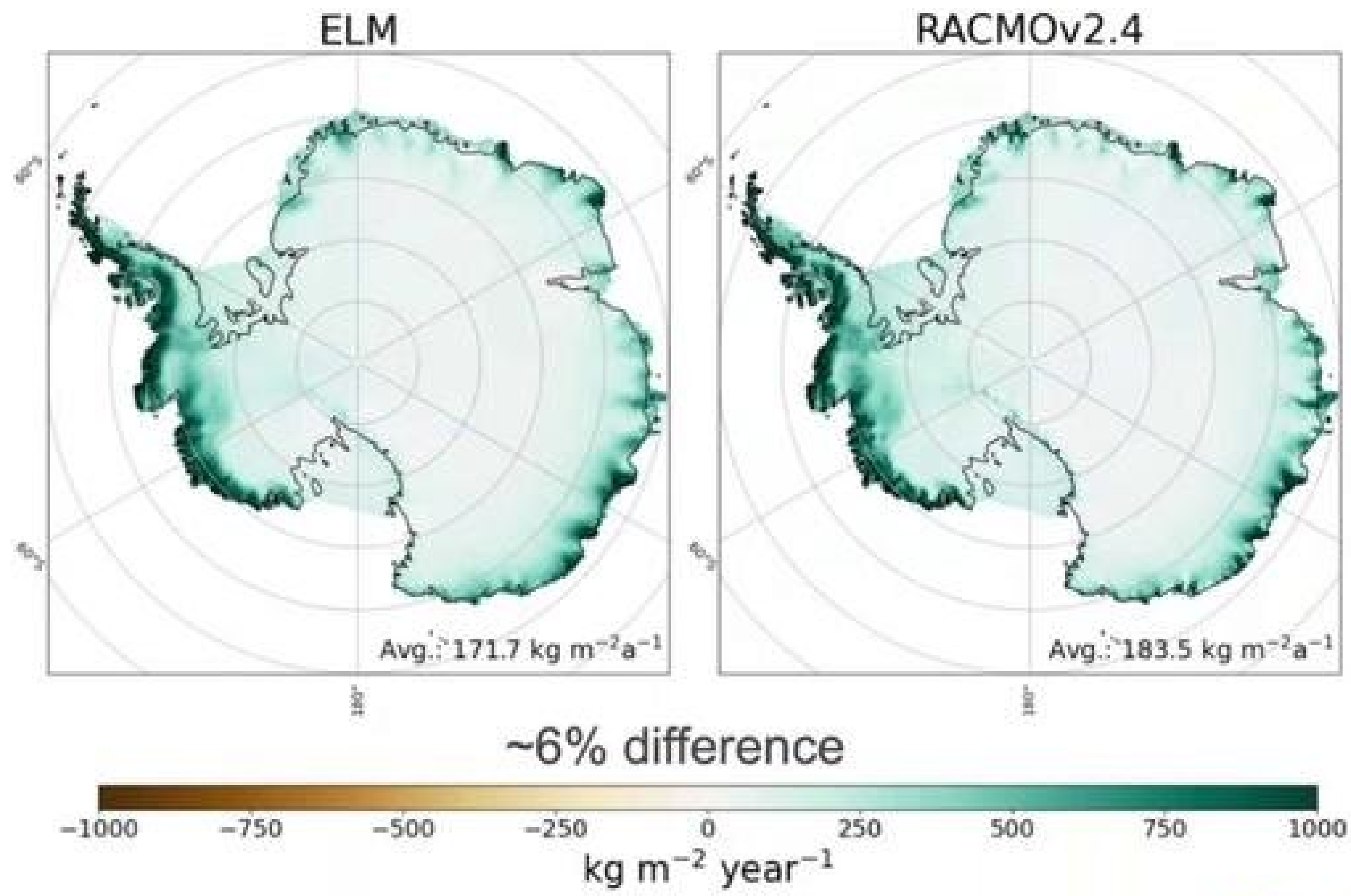
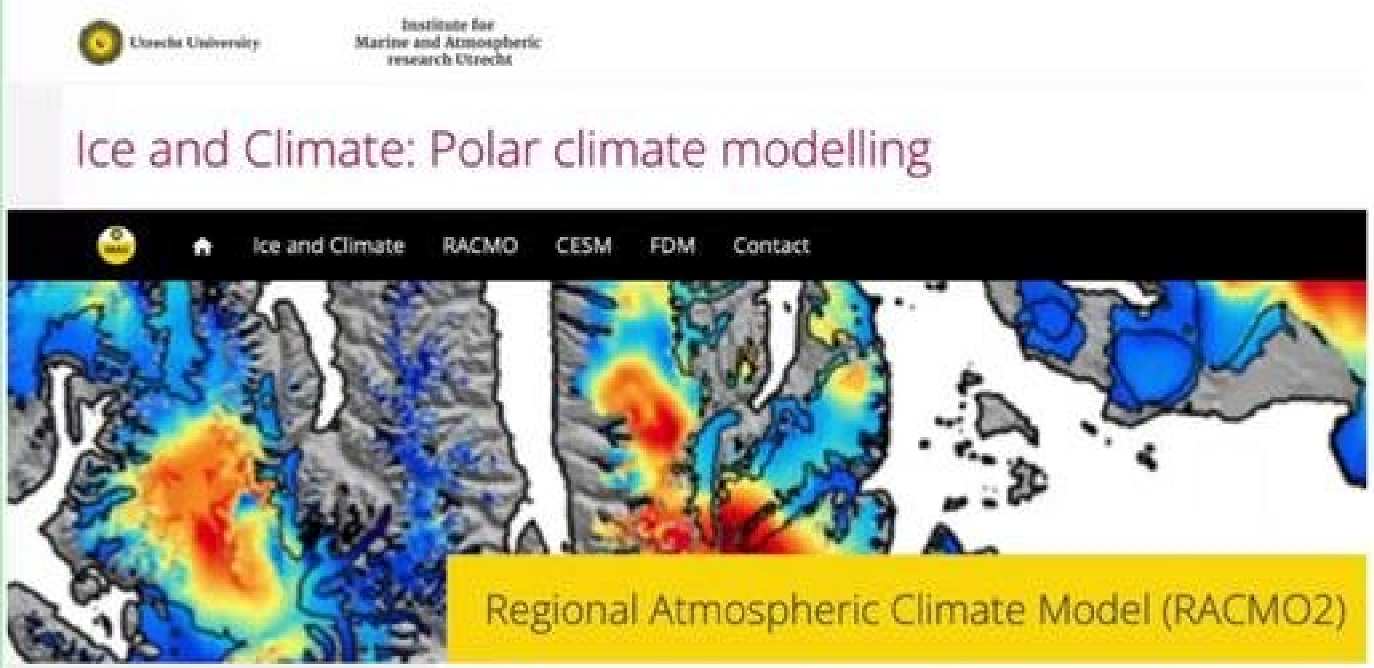
Surface Mass Balance in ELM

- ELM agrees well with RACMOv2.4 SMB (forced by ERA5 reanalysis data atm)





Regional Atmospheric Climate Model (RACMOv2.4)

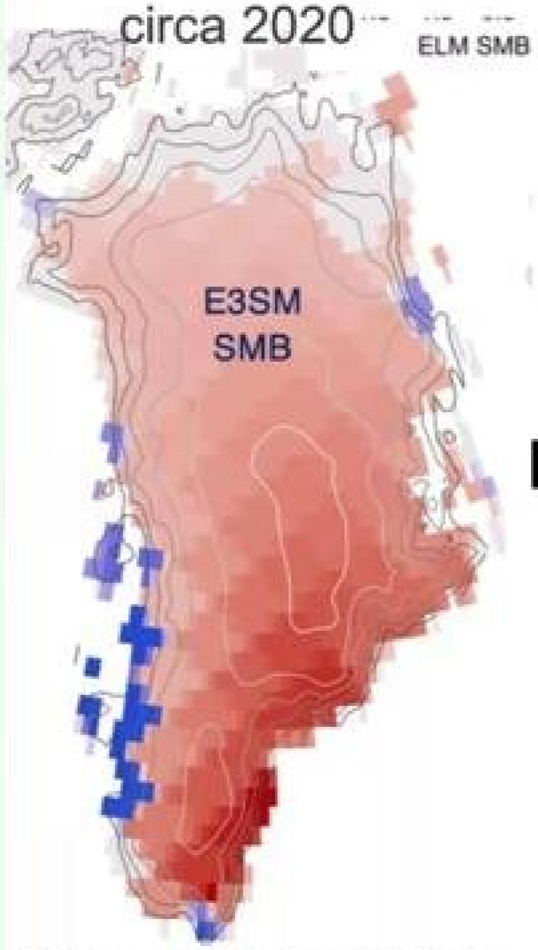


- State-of-the-art regional climate model
- Well-evaluated against observations
- Developed specifically to simulate GIS and AIS
- Best available comparison for validating GIS and AIS SMB
- Simulates historical and present-day conditions

RACMO2.4 data credit: Christiaan T. van Dalum & Willem Jan van de Berg

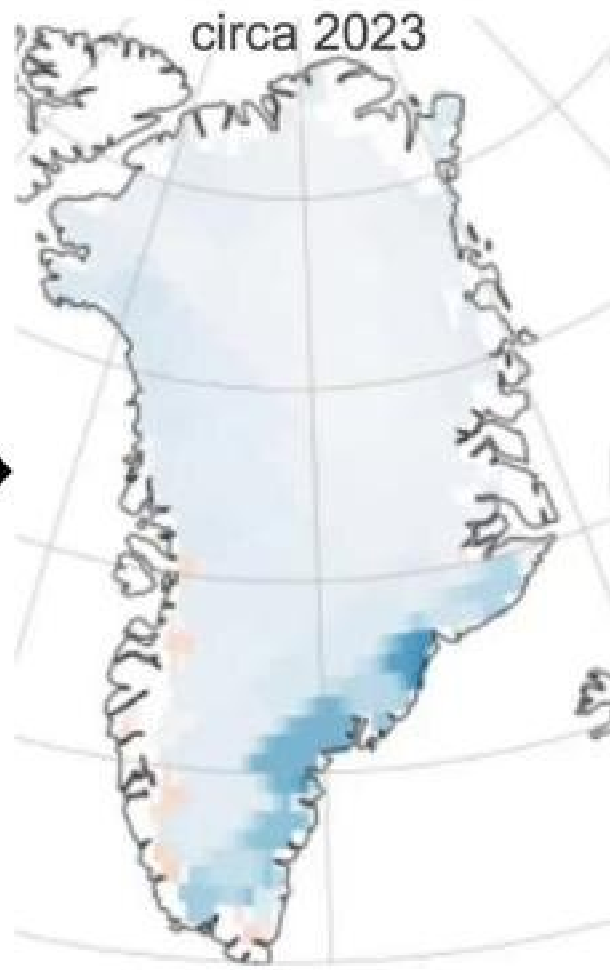
Progress towards improving ELM GrIS SMB

ELM GIS SMB sims
circa 2020

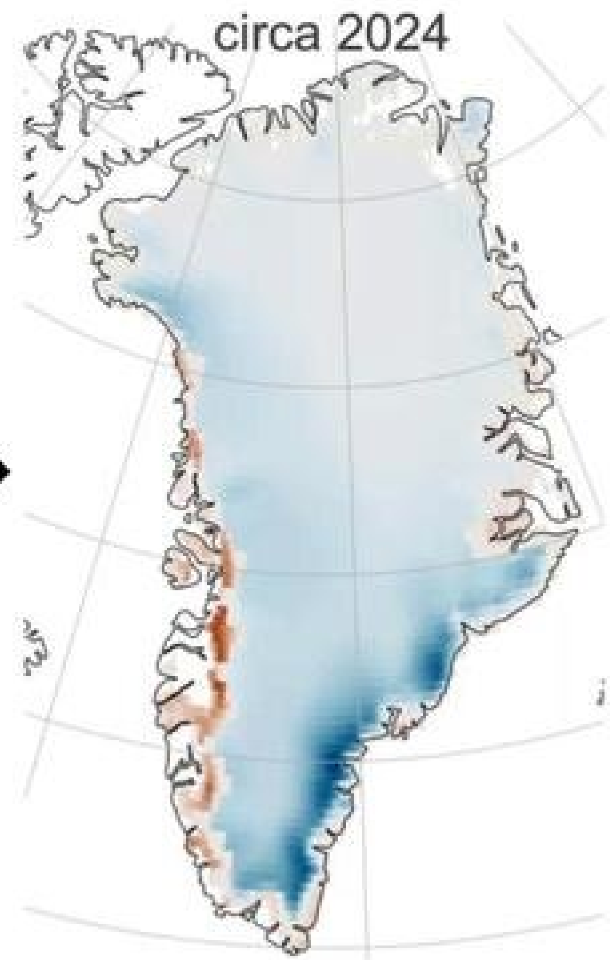


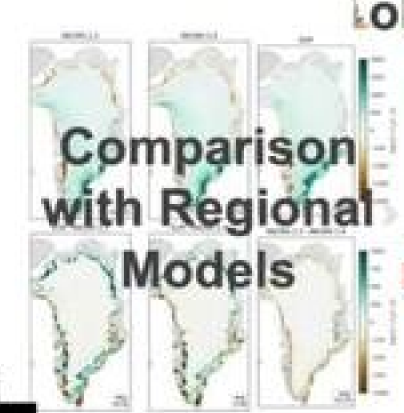
Note opposite color scale here

ELM GIS SMB sims
circa 2023

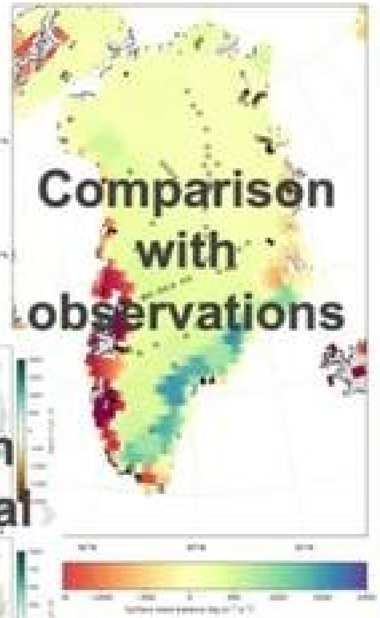


ELM GIS SMB sims
circa 2024

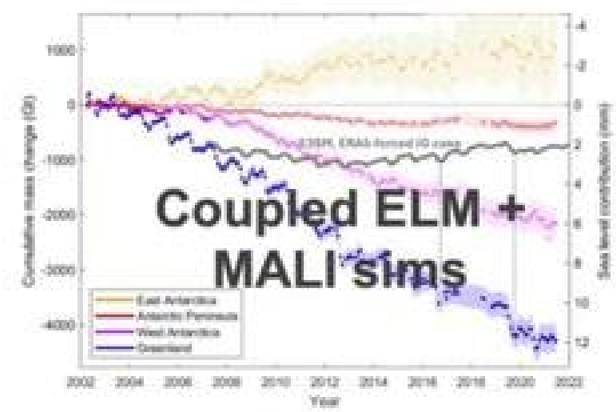




Comparison with Regional Models



Comparison with observations



Coupled ELM + MALI sims

Otosaka et al. (2024)

Simulating an Accurate Ice Sheet Surface Mass Balance in ELM
How'd we get here? What is left to be done?

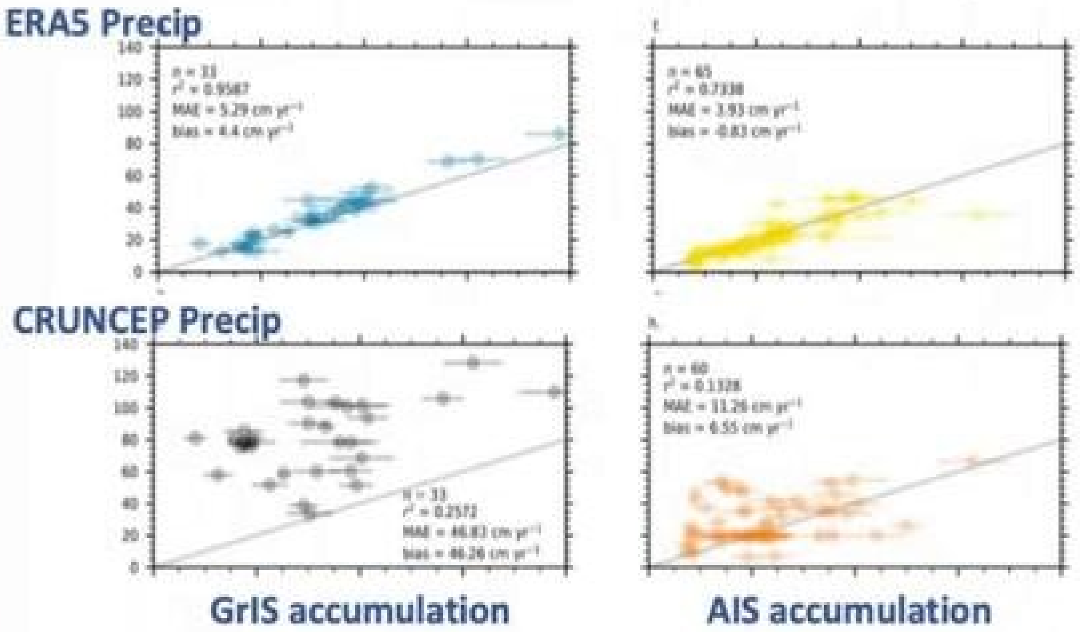
- Improve the representation of snow and ice physical processes
  - Snow and firn densification ✅ (Schneider et al., 2022)
  - Formation of melt ponds and ice lenses ⭐
- Improve radiative properties of snow and ice
  - More advanced representation of bare ice albedo ✅ (Whicker-Clarke et al., 2024)
  - Incorporated an improved snow thermal conductivity ✅
  - Improving refrozen snow grain size ⭐
- Improving atmosphere to land forcing
  - Introduced a new data atmosphere forcing option (ERA5) with more realistic snow accumulation rates ✅ (Schneider et al., 2023)
  - Improve the downscaling of atmospheric drivers to the ice sheet elevation ⭐

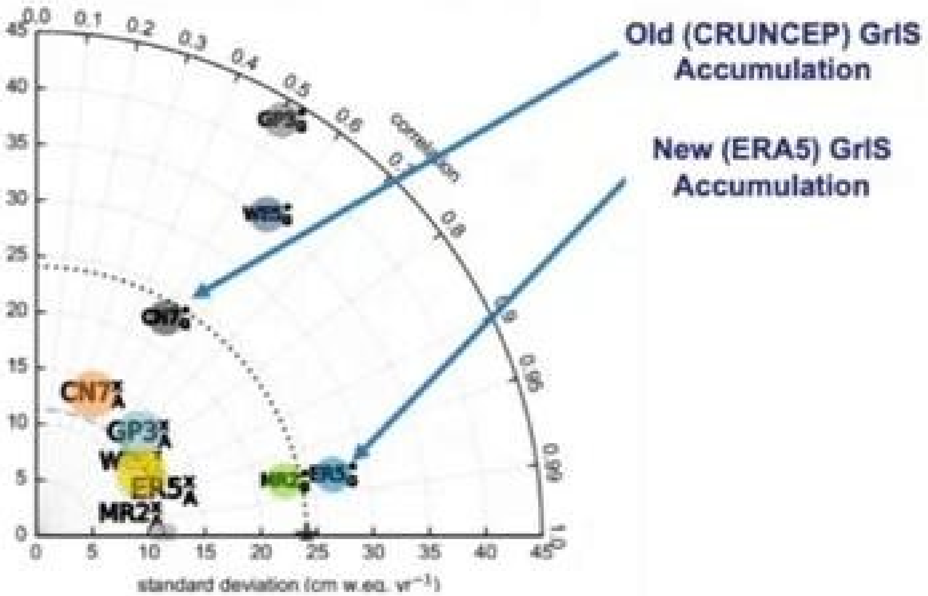
✅ = done, ⭐ = to be done

E3SM Energy Exascale Earth System Model

Newly Added: Support for ERA5 Data Atm Forcing

- ERA5 precipitation closely matches accumulation data from shallow ice cores
- Outperforms other global reanalysis products





Schneider et al., (2023)

ERA5 1 hourly and 6 hourly data atmosphere forcing from 1980-2020 is available to use on Perlmutter w/ a tested compset

- 1k years of spun up deep snowpack using ERA5 data atm forcing

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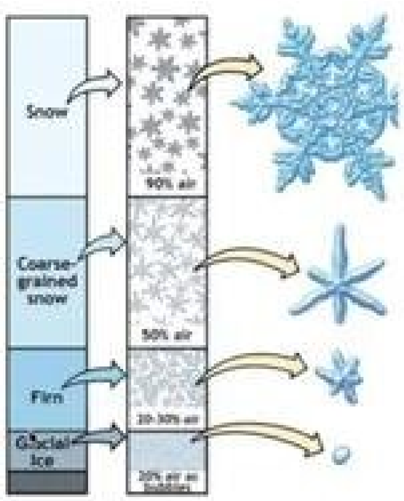
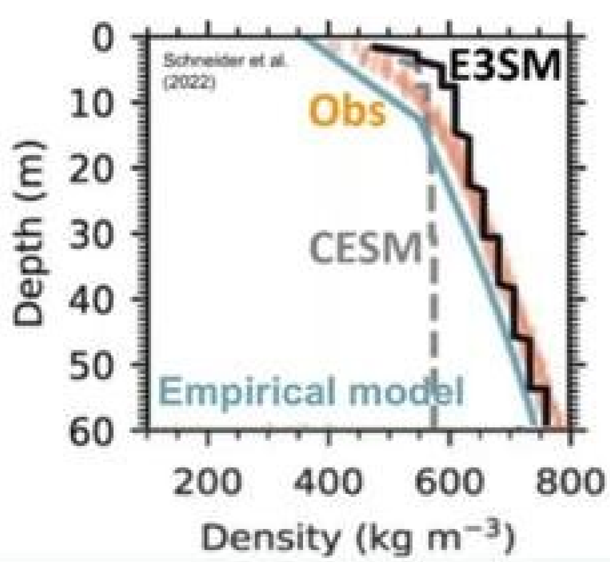
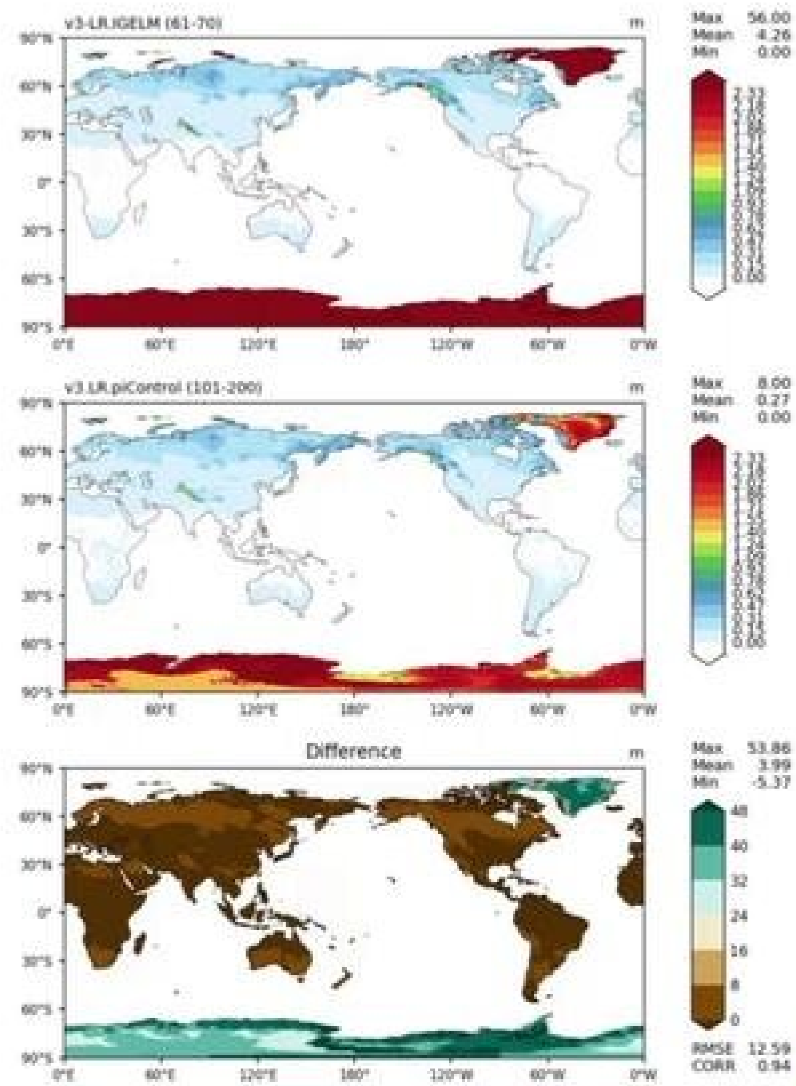
New & Improved Snowpack Scheme

- New firn densification & snow routing scheme
- Improved firn representation
- More realistic deep snowpacks
- Deep firn snowpack modifications are available in E3SMv3
- Prepping fully coupled (B case) tests



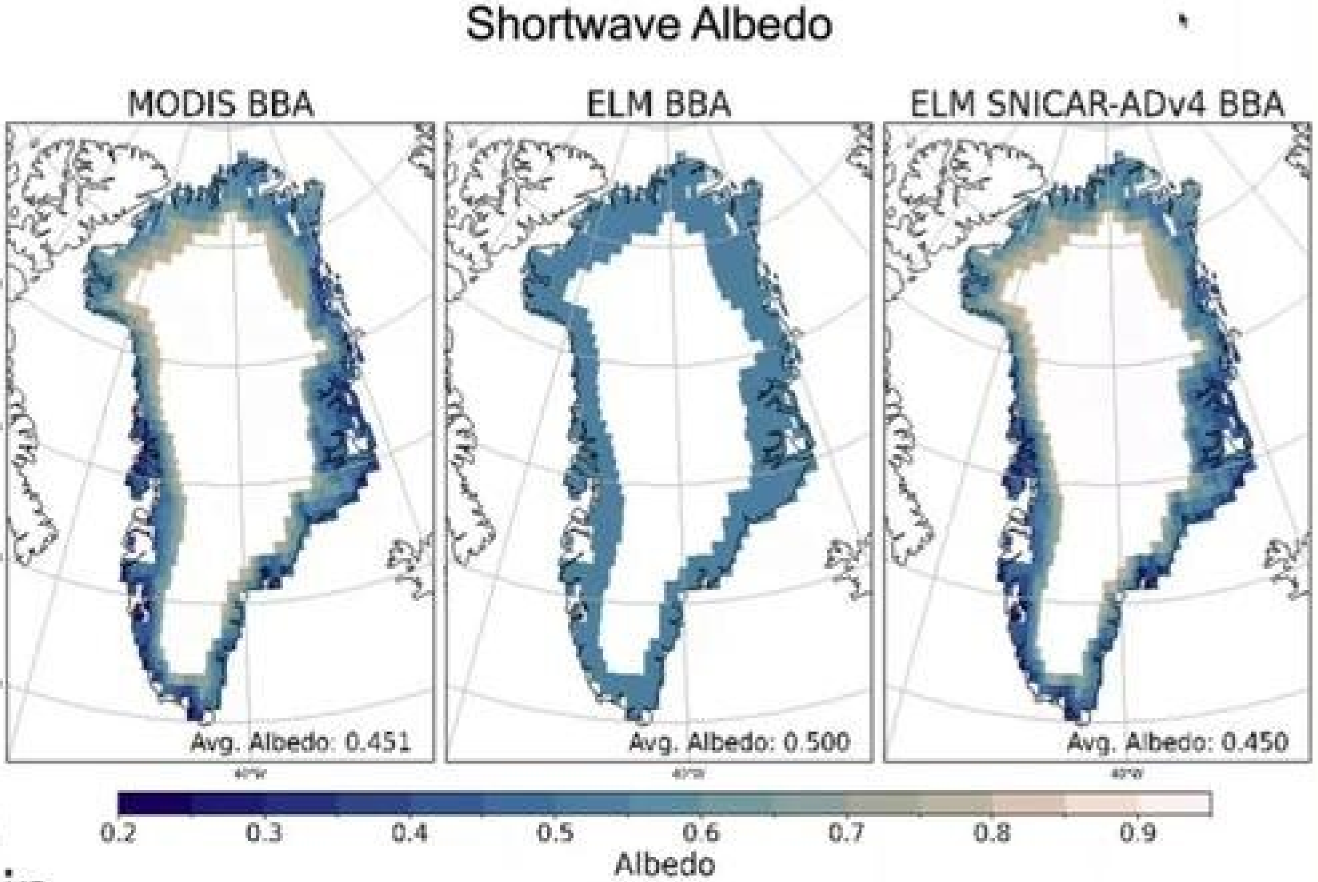




(figure: Shixuan Zhang)

Improving Bare Ice Albedo

- ELM utilizes constant bare ice albedo (0.6=VIS, 0.4=NIR)
- Bare ice albedo is highly variable
- New ice radiative transfer model -
  - calculates albedo based on ice physical properties
- Improved bare ice albedo with MODIS-informed ice properties



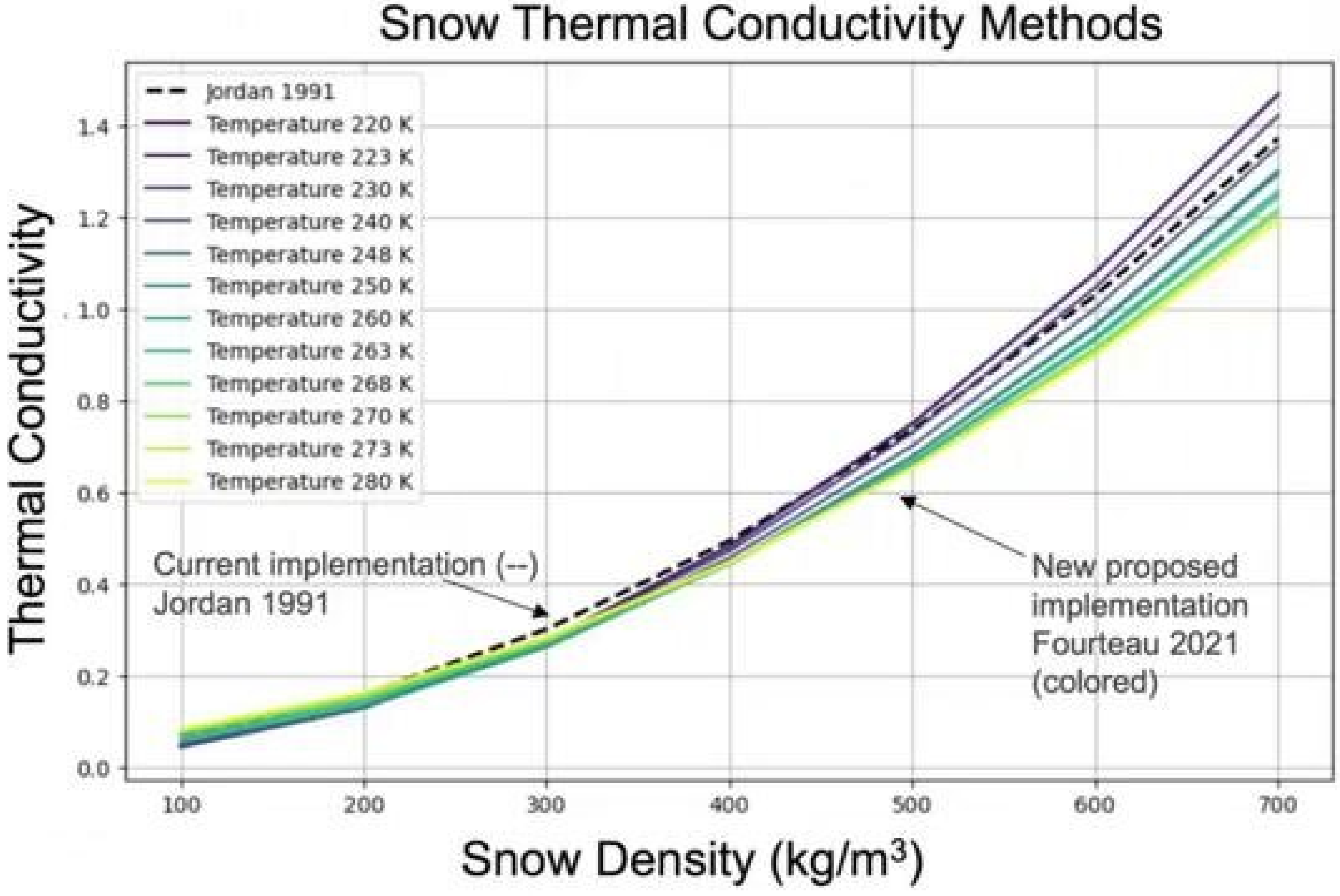
Whicker-Clarke et al., (2024)

- Future/current work: develop a MODIS era climatology of bare ice properties to utilize in different time periods/regions

Improving Snow Thermal Conductivity

- New snow thermal conductivity relies on snow density & temperature
- Previous representation relied on snow density
- Much more variability in snow thermal conductivity

- Future work: include this modification in longer sims for SMB and SEB tests



Utilizing and Extending LIVVkit
Land Ice Verification and Validation Toolkit

- Generates
  - Publication quality plots of SMB& SEB variables
  - Intercompares models & evaluates against available observations and reanalysis data

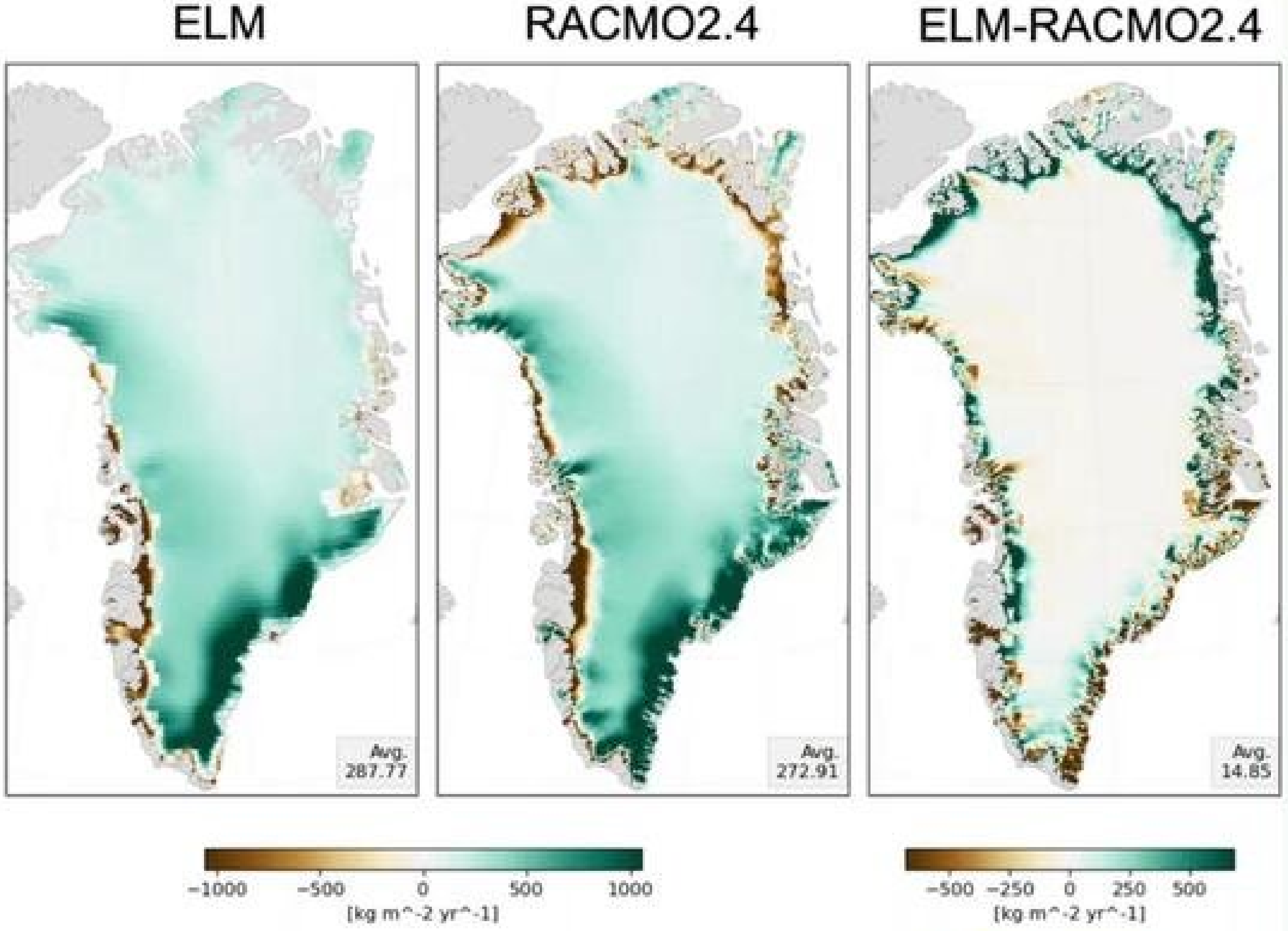
- Currently limited to GIS
- Future work: extending analysis over AIS, include GIS & AIS analysis in zppy

(credit: Michael Kelleher kelleherme@ornl.gov)

E3SM
Energy Exascale
Earth System Model

ELM Accurately Simulates GIS SMB

- ELM simulates GIS SMB within ~5% of RACMO2.4
- ELM missing ablation in N. Greenland
  - Likely caused by the representation of snow melt and albedo
- ELM GIS SMB ~15kg $m^{-2}y^{-1}$ too high



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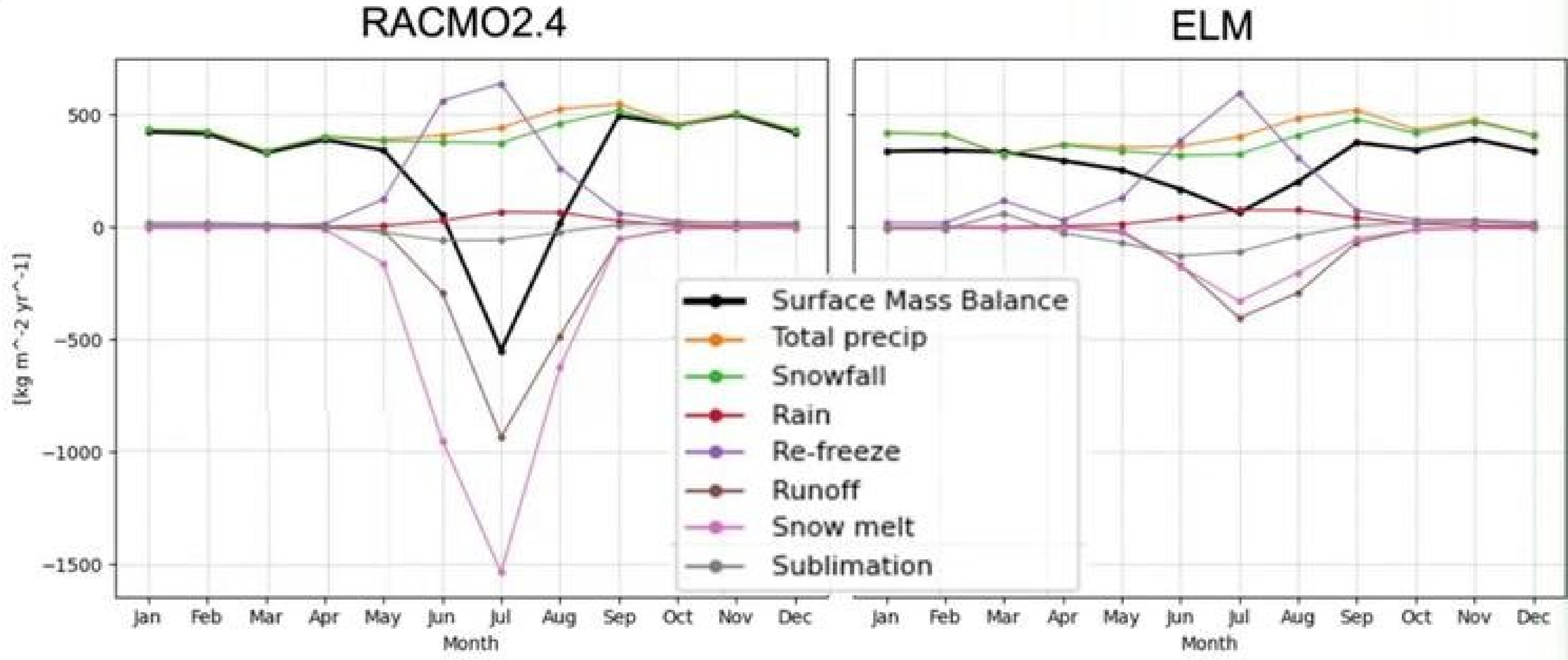
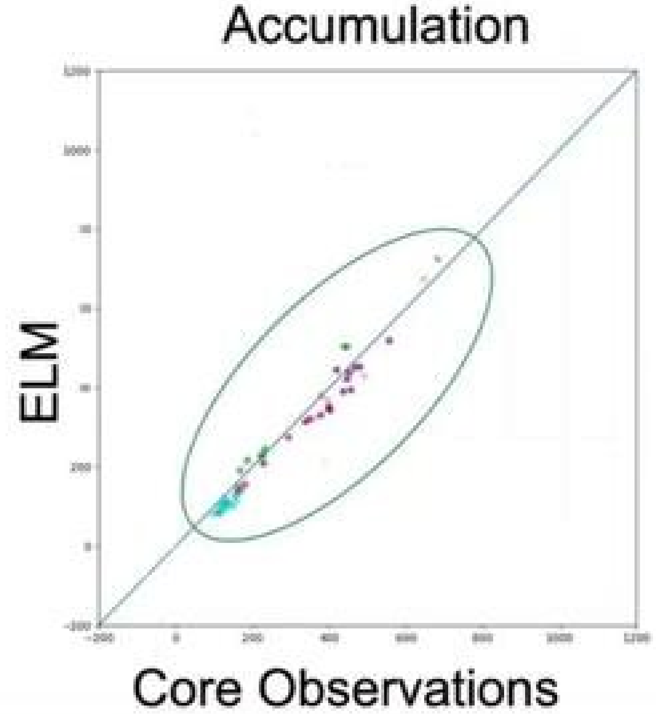
ELM's Seasonal SMB Trends

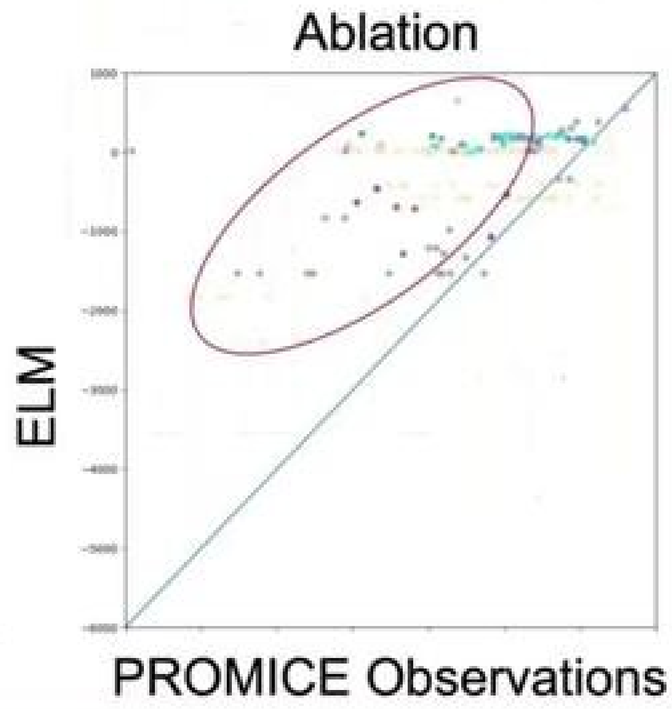
- ELM's seasonal cycle is weaker than RACMO2.4's
  - Results in similar SMB
  - Missing variability in snow melt & runoff
  - Improve wet/aged snow albedo scheme
  - Improve downscaling of precipitation & temperature to glacier elevations

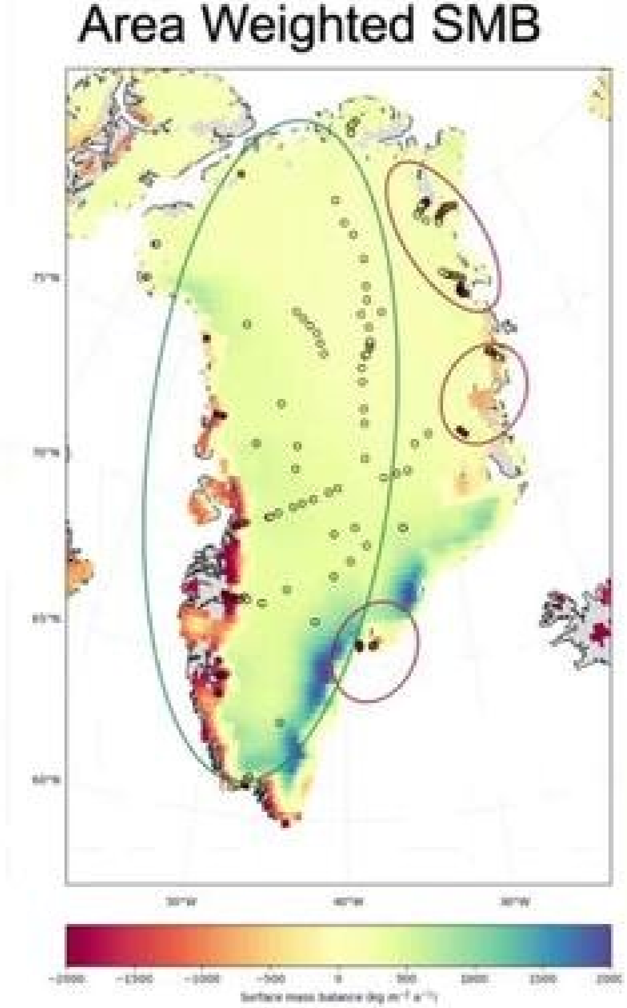


ELM Surface Mass Balance Compared to Observations

- ELM captures SMB trends and magnitude in central GIS and SW ablation zone
- Fails to capture ablation in northern and eastern ablation zones







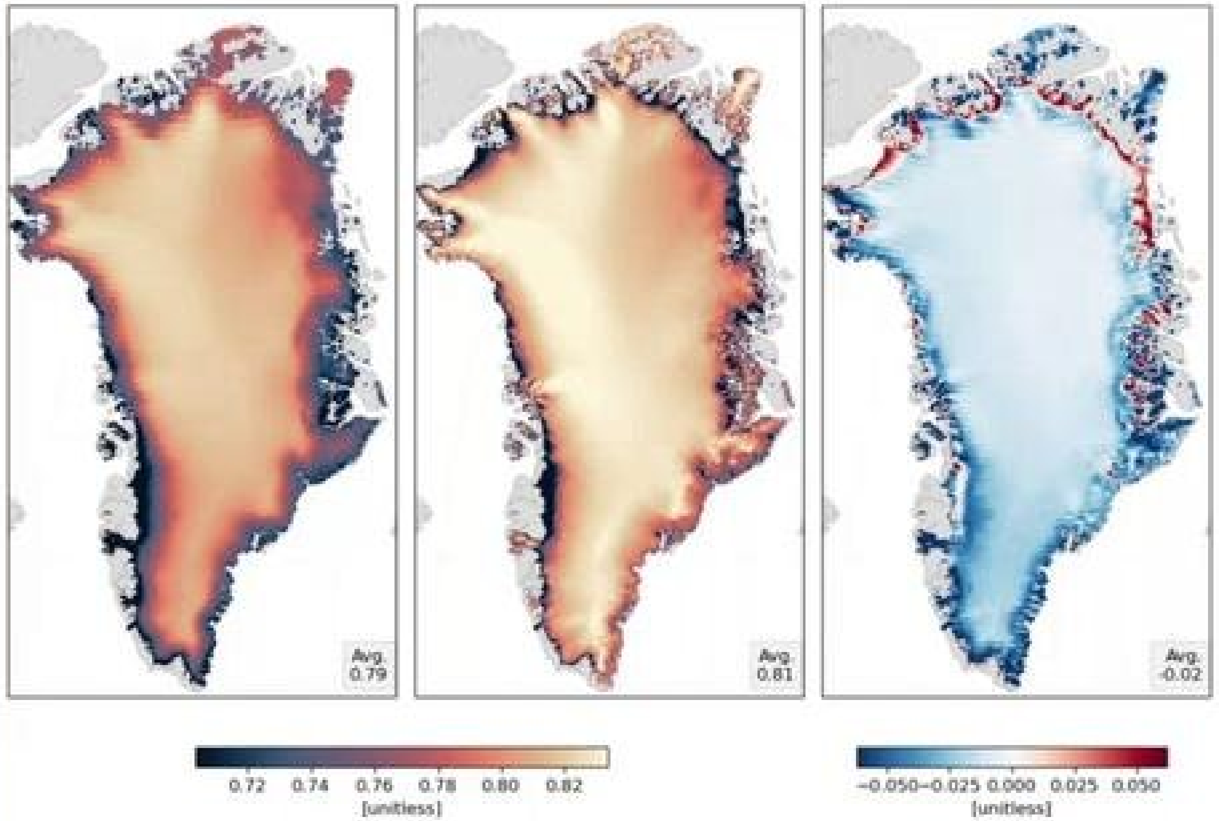
E3SM Energy Exascale Earth System Model

ELM Albedo Compared to RACMO2.4 and CERES Reanalysis

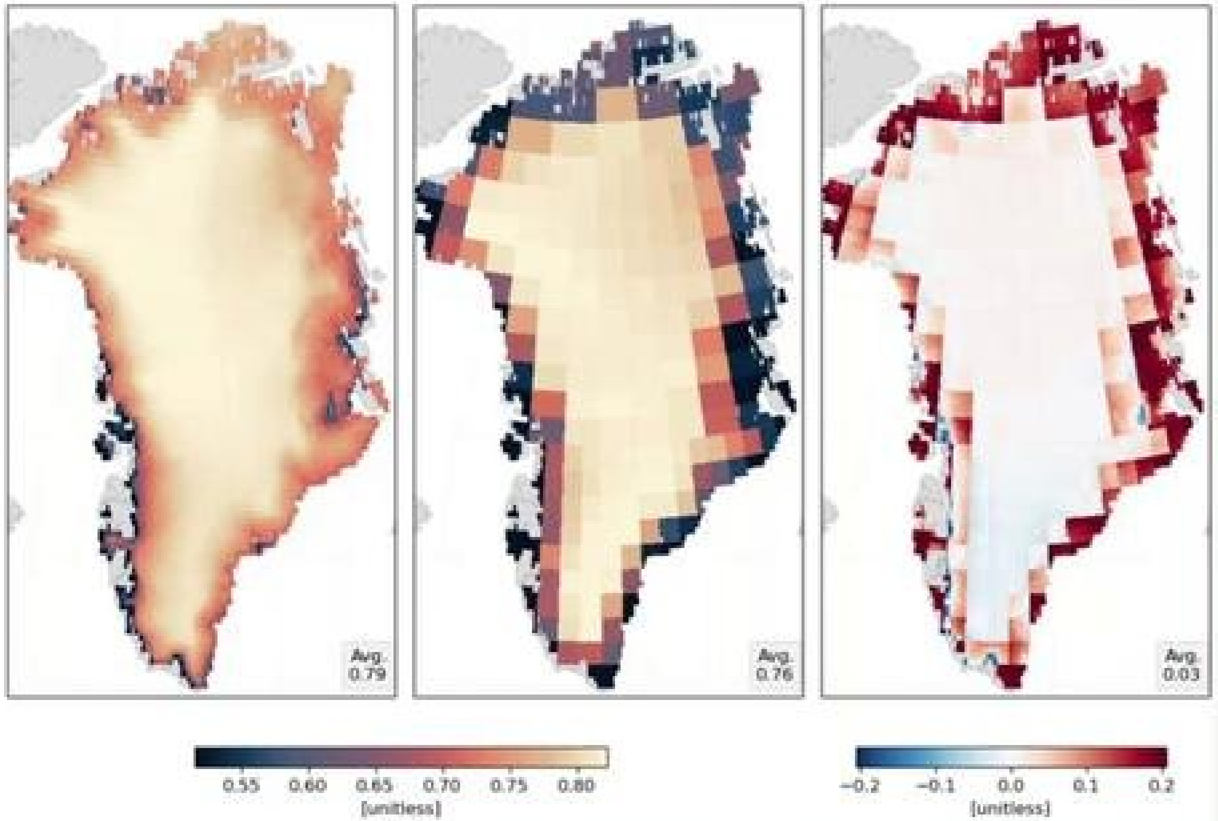
- RACMOv2.4 albedo is
  - ~2% higher than ELM
  - ~5% higher than CERES

- ELM fails to simulate low albedo in N. ablation zone

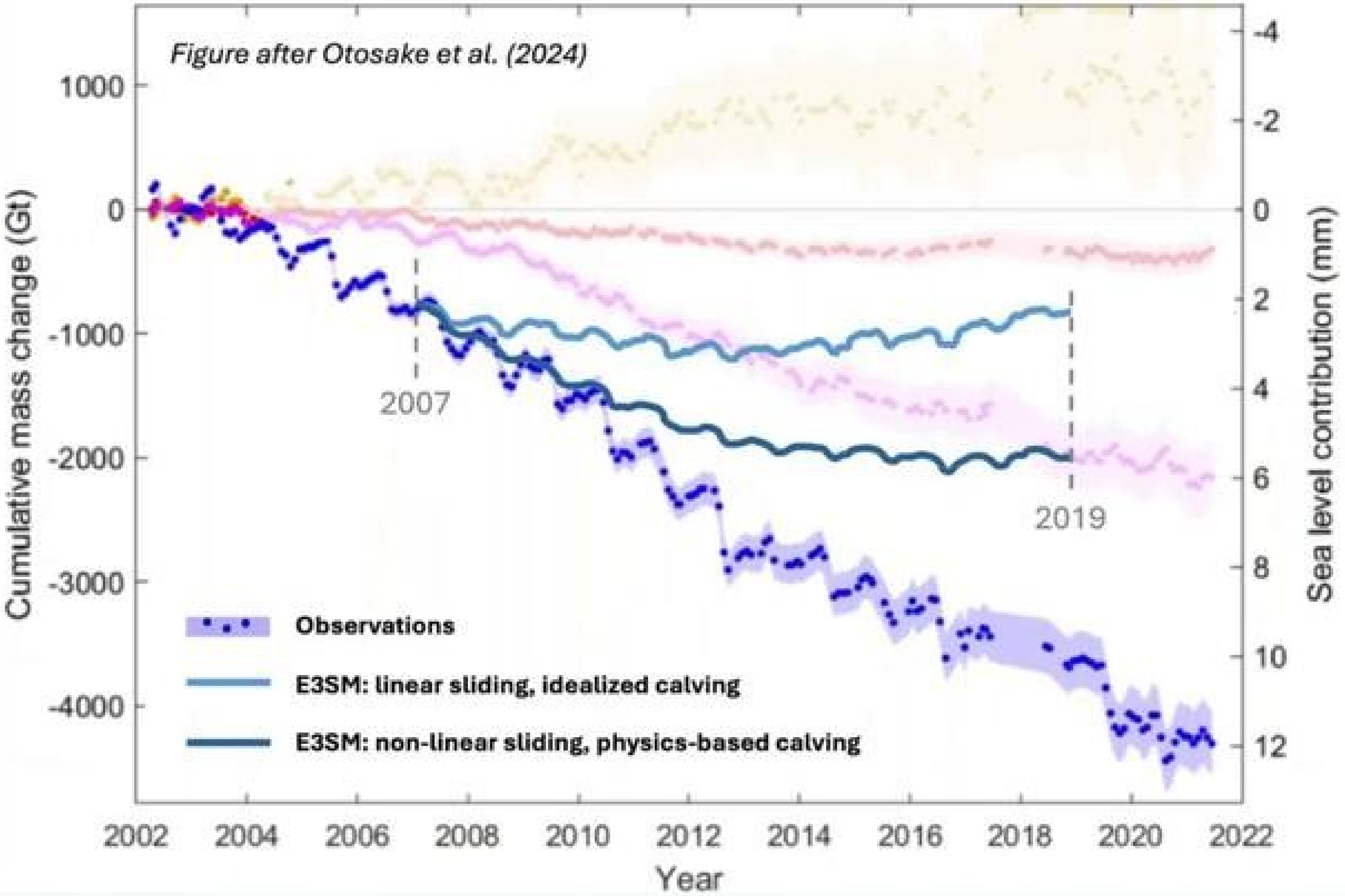
ELM RACMO2.4 ELM-RACMO2.4



ELM CERES ELM-CERES



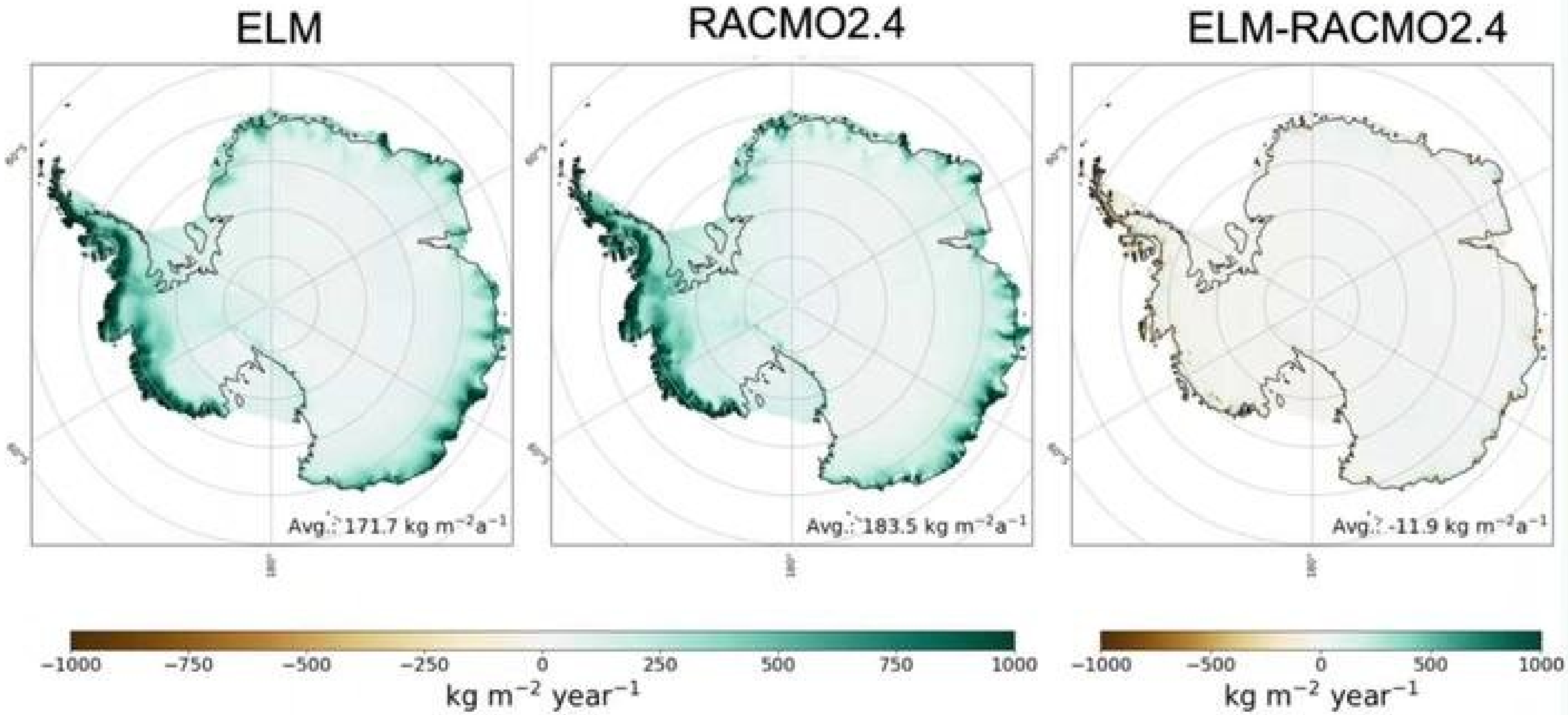
Working Towards a Coupled Ice Sheet Model



- In progress …
- Coupled MALI simulations
  - ERA5 data atmosphere
  - New deep firn
- Improved SMB and calving is improving our comparisons to observations

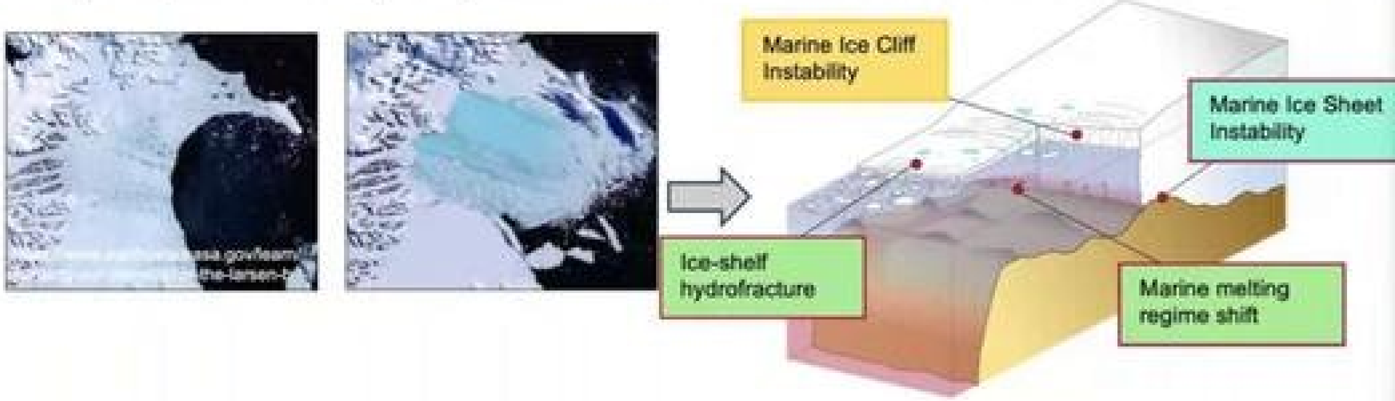
ELM Accurately Simulates AIS SMB

- ELM simulates AIS SMB within ~6% of RACMO2.4
- ELM accurately simulates spatial trends in AIS SMB
- ELM AIS SMB ~12kg $m^{-2}y^{-1}$ low biased
  - Requires further analysis to attribute low bias
  - Possibly missing blowing snow from ocean grid cells



AIS Future Work: Improving Snow/Ice Physics & Capturing Tipping Points

- Accurately simulating SMB processes is important –
  - Ice shelves surface melt can lead to hydrofracture, rapid collapse, acceleration of inland ice flow
  - Requires complex surface physical processes
    - snow and ice melt/slush and melt ponds
    - percolation and refreezing of water
    - radiative active surface liquid water

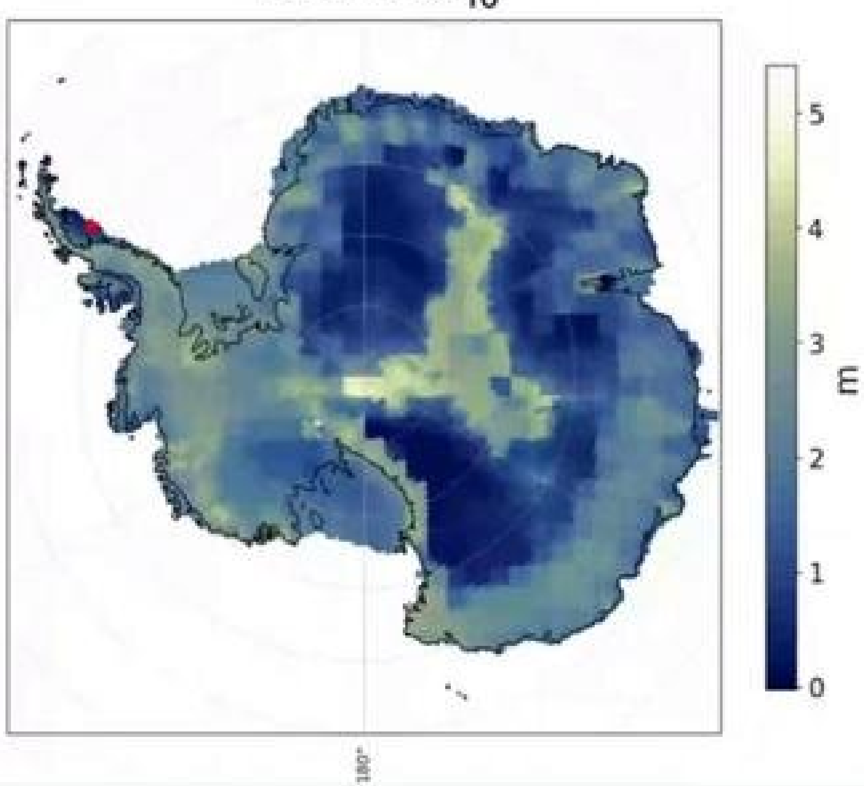


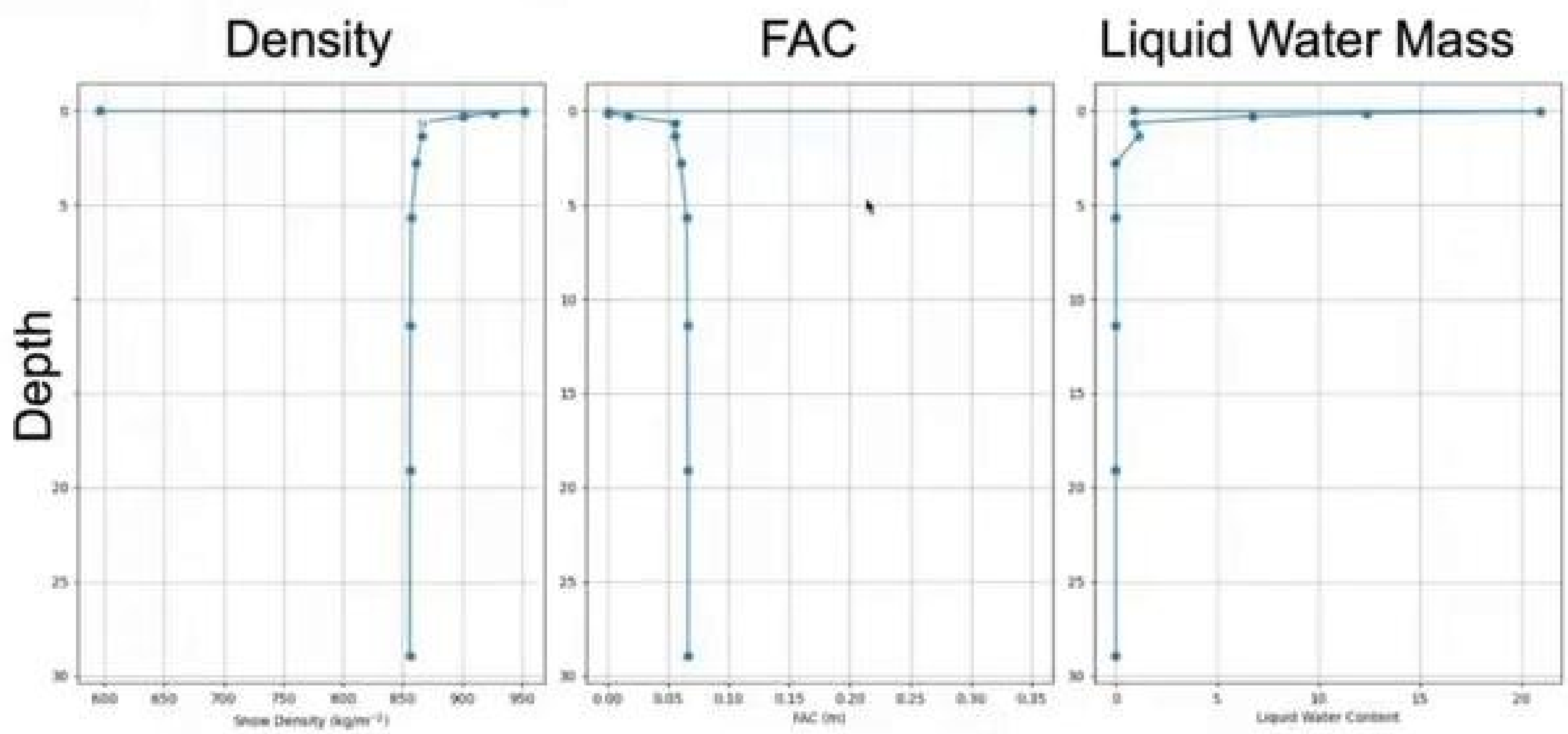
Surface melting of ice shelves from both above and below contributes to thinning, loss of buttressing, and unstable retreat.

- Hydrofracture, snow and ice albedo feedback, surface water content are all important for projecting polar tipping points

AIS Future Work: Improving Snow/Ice Physics & Capturing Tipping Points

- Preliminary analysis of snow properties with depth
  - Projection simulations can capture ice sheet/shelf sensitivity to high emission scenarios





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Summary

- Improved Science
  - Improved representation of the surface mass balance with new snow physics, a new snow/ice routing scheme, improved coupling to the Ice Sheet Model (MALI)
  - Improved SMB & SEB
  - New diagnostic fields to analyze snow physical processes
  - Improved data atmosphere forcing options and grid resolution
- Model Development
  - Snow and firn compaction scheme (B case tests in progress in e3sm main branch)
  - Ice albedo radiative transfer scheme (IG simulations, results published)
  - Improved snow thermal conductivity (untested in e3sm main branch)
  - Improving refrozen snow grain size
  - Formation of melt ponds and ice lenses

Thank you!
Any Questions?

Framework for Antarctic System Science in E3SM