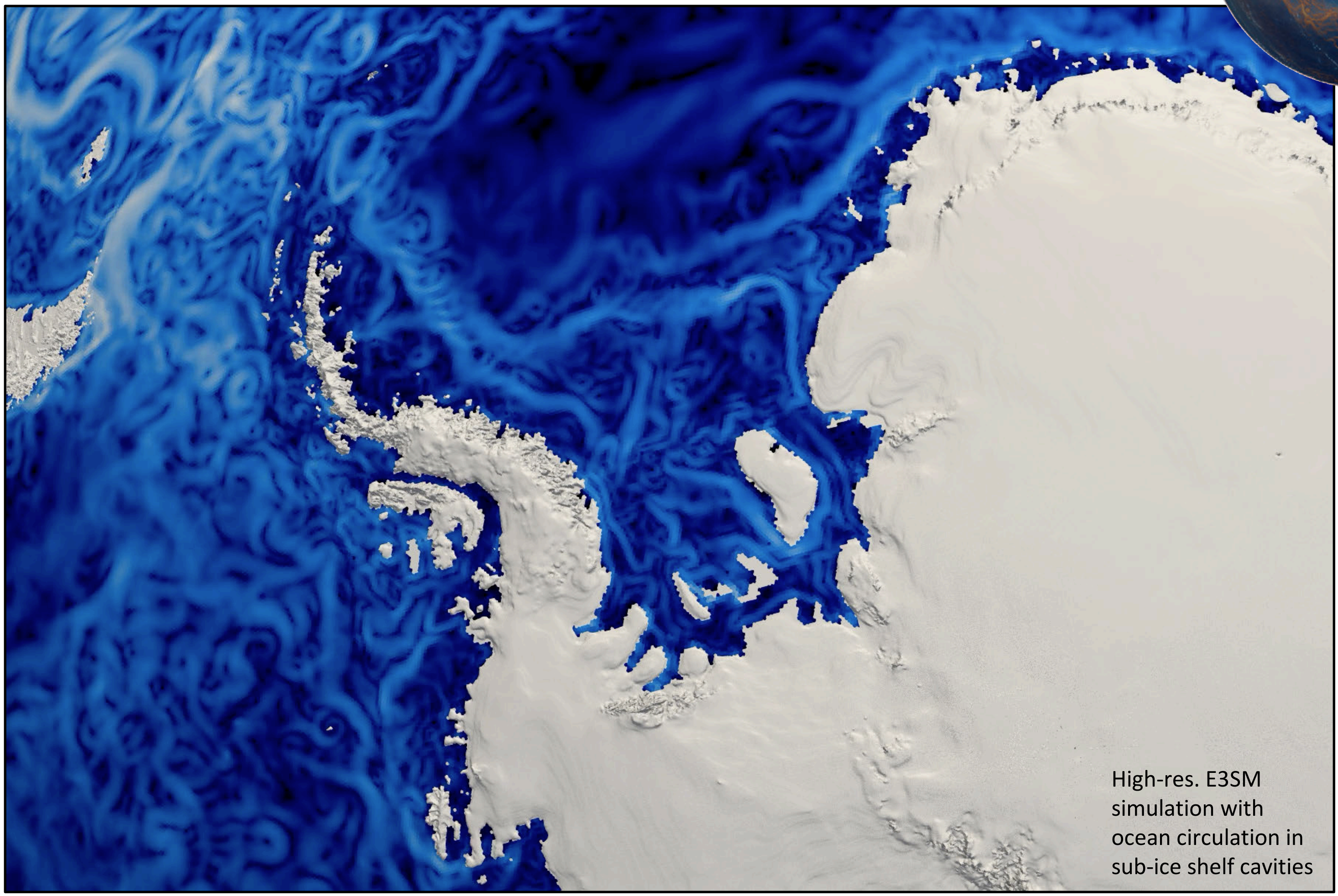
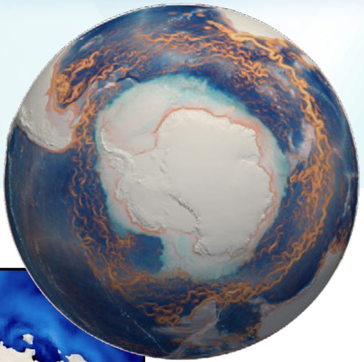
E3SM Cryosphere Campaign

Stephen Price, Wuyin Lin, Mark Petersen, and the E3SM Cryosphere Team



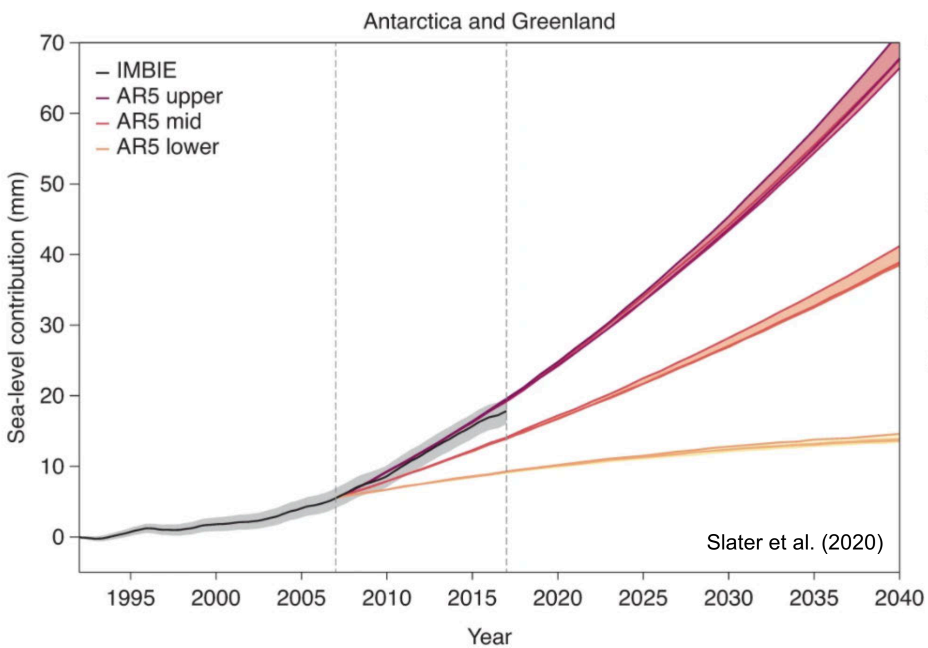


High-res. E3SM simulation with ocean circulation in sub-ice shelf cavities

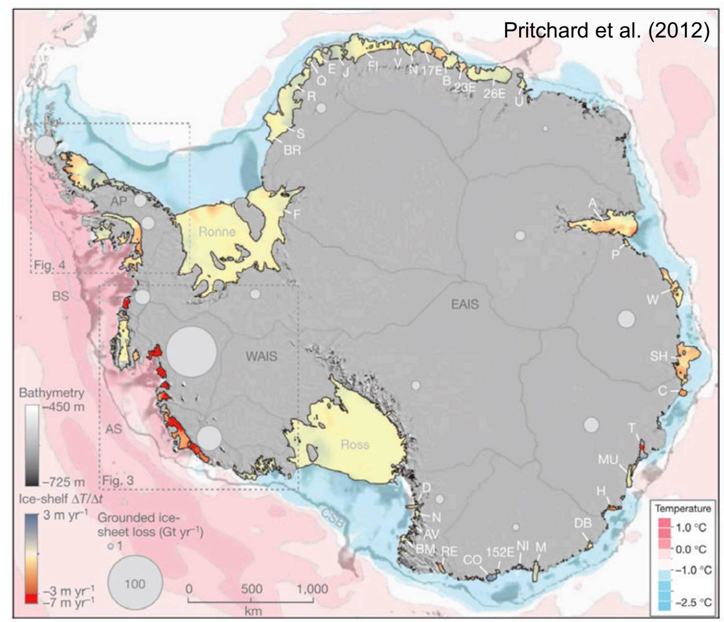
Cryosphere Campaign Highlights

Antarctica’s future evolution remains the largest uncertainty in projecting future sea-level rise (IPCC, AR4-5).

Antarctic ice sheet mass loss is controlled by ice shelf & ocean interactions.



Ice sheet mass losses are tracking the high end of projections.



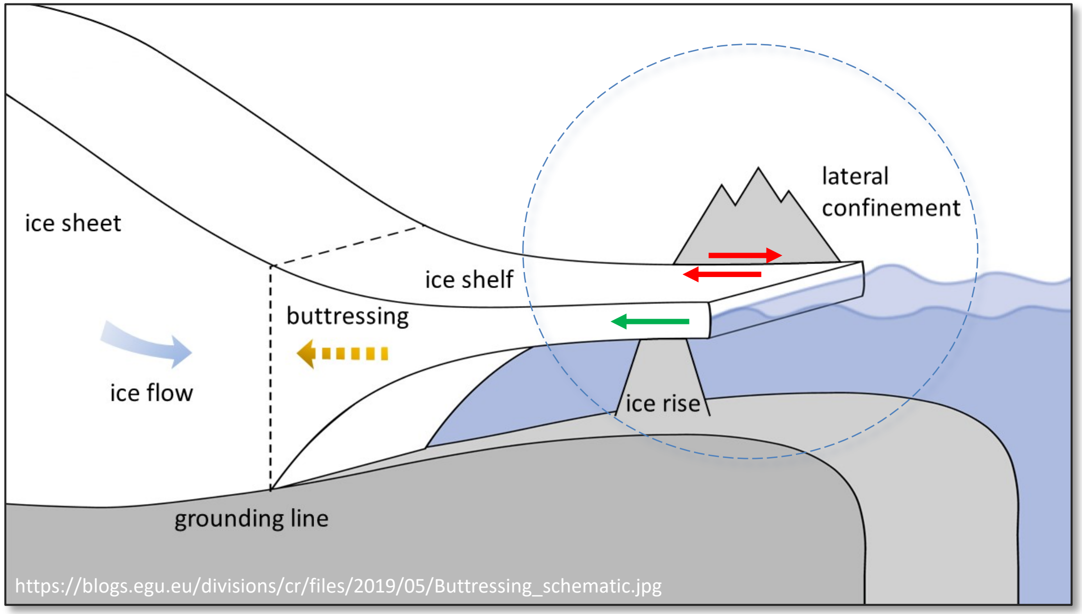
Regions of Antarctic mass loss correspond to ocean melting of ice shelves.

Cryosphere Campaign Highlights

Antarctica's future evolution remains the largest uncertainty in projecting future sea-level rise (IPCC, AR4-5).

Antarctic ice sheet mass loss is controlled by ice shelf & ocean interactions.

- ice shelves are large, floating extensions of ice sheets
- primarily in Antarctica where they fringe most of the continent
- side shear and compression results in backpressure ("buttressing")
- as buttressing is reduced, ice flow into the ocean accelerates



- buttressing is reduced as ice shelves thin due to increased melting

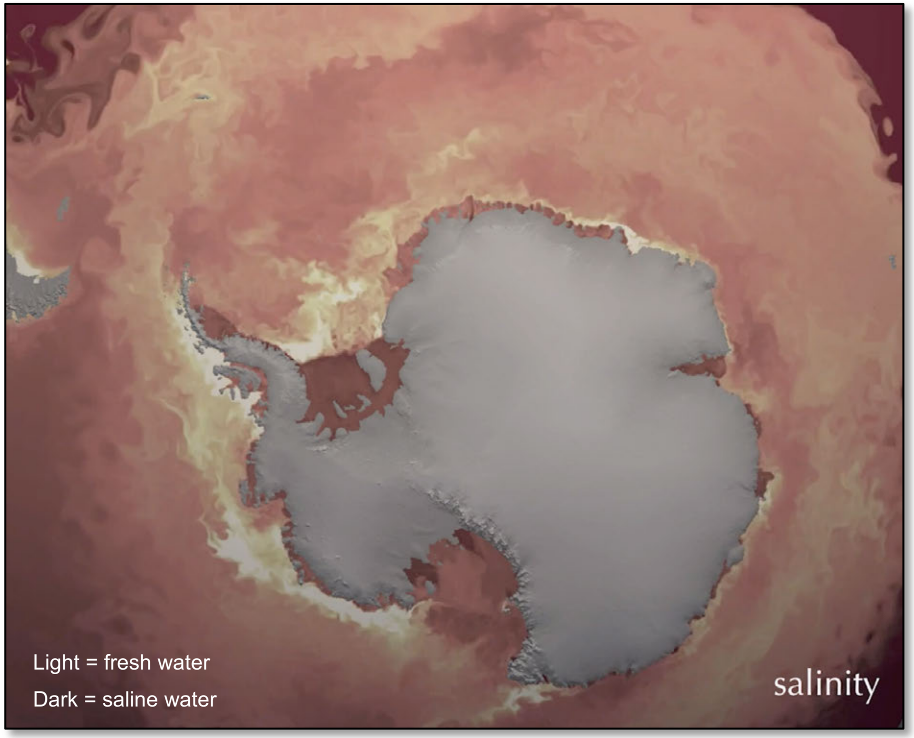
Cryosphere Campaign Highlights

E3SM has the new and unique capability among ESMs to calculate sub-ice shelf heat and freshwater fluxes in global, fully coupled simulations

This capability allows / is necessary for:

- realistic, stable, century-scale simulations of Antarctic submarine melting in low- (~CMIP) and high-resolution model configurations
- investigation of climate variability and climate change impacts on ice shelf melting (and vice versa)
- complete understanding and quantification of Antarctic-sourced sea-level rise in Earth system models

Visualization supported by BER Data Management Program



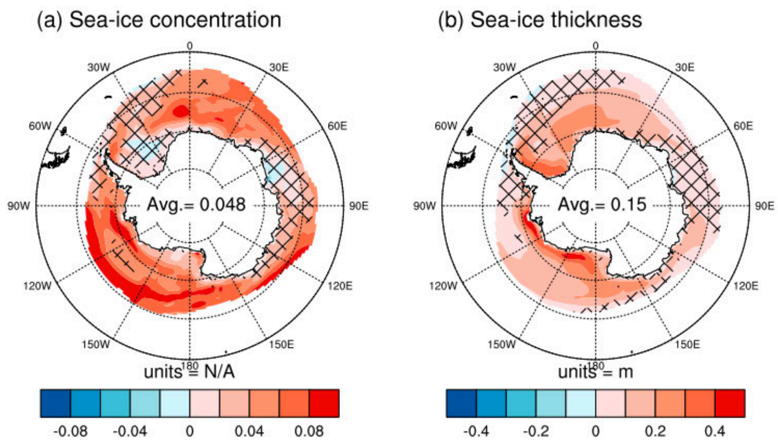
Phase 2 Science Questions

What are the impacts of ocean-ice shelf interactions on melting of the Antarctic Ice Sheet, the global climate, and sea level rise? [using V1 model]

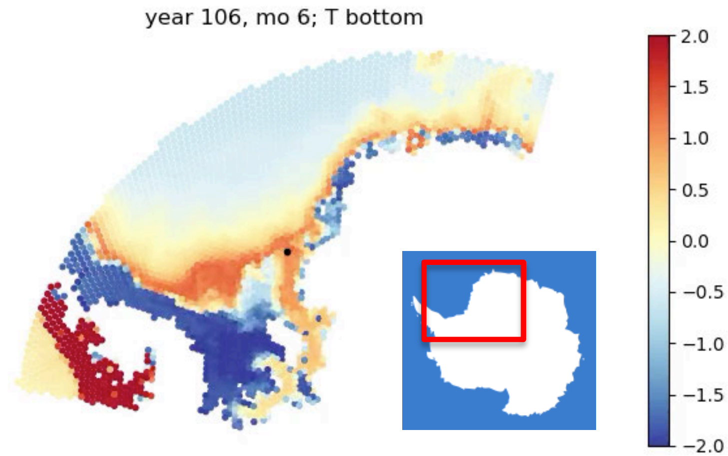
How will the atmosphere, ocean and sea-ice systems mediate sources of sea-level rise from the Antarctic ice sheet over the next 30 years? [using V2 model]

Science Questions (V1 model)

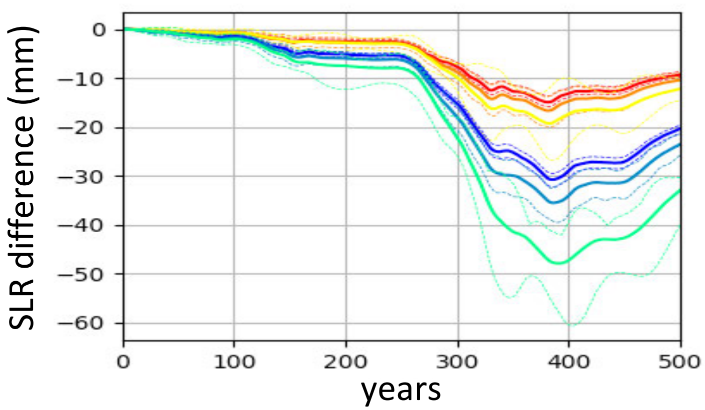
What are the impacts of ocean-ice shelf interactions on melting of the Antarctic Ice Sheet, the global climate, and sea level rise?



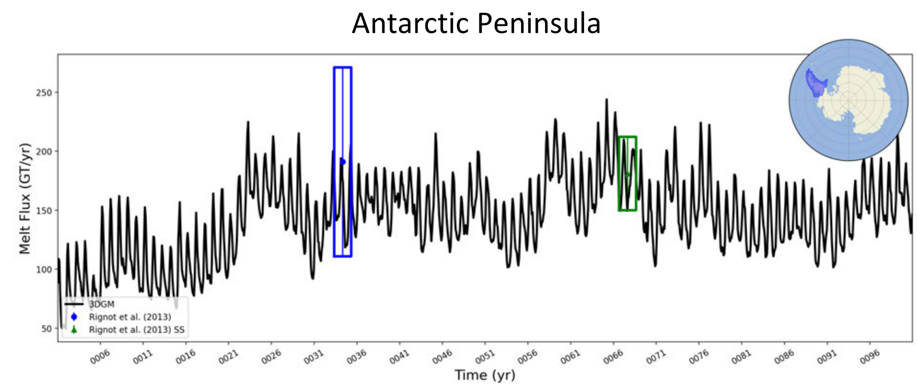
Impacts of explicit ice-shelf melt fluxes (Jeong et al., 2020)



Filchner-Ronne ice shelf instability and impacts (Hoffman et al., in prep.)



Sensitivity of SLR from Thwaites Glaicer, West Antarctica to internal ocean-forcing variability (Hoffman et al., 2019)



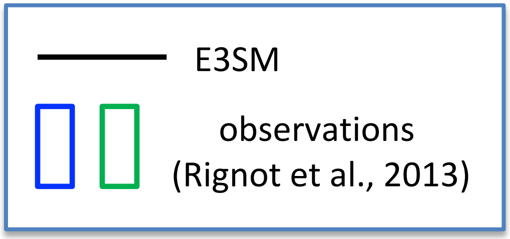
Realistic sub-ice shelf melt rates (Comeau et al., in prep.)

Science Questions (V1 model)

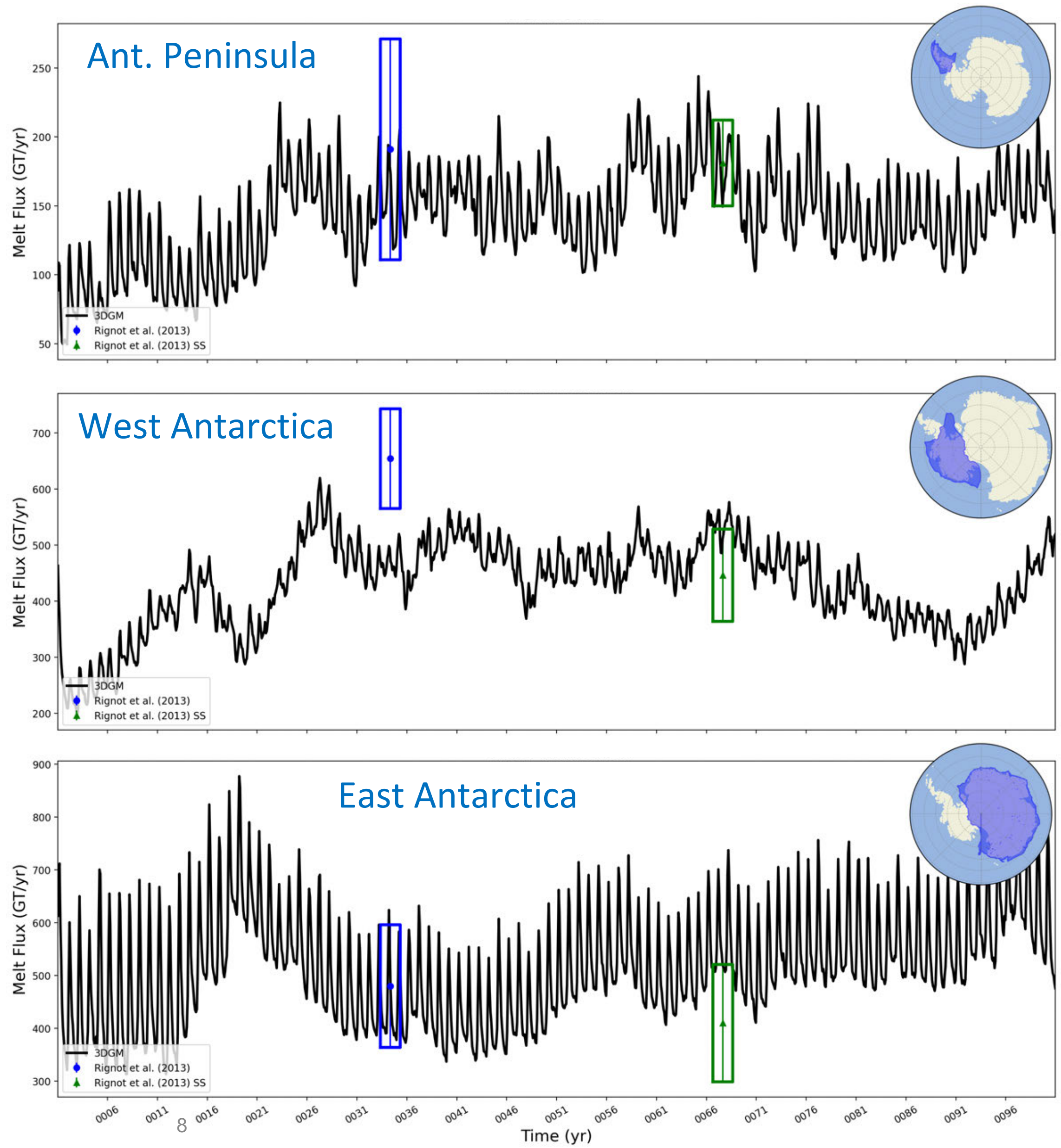
What are the impacts of ocean-ice shelf interactions on melting of the Antarctic Ice Sheet, the global climate, and sea level rise?

- demonstrate century-scale, stable, realistic Antarctic ice shelf melt rates in global, fully coupled, low-res. configuration (Comeau et al., *in prep.*)
- exploration and demonstration of impacts of including explicit sub-shelf melt rates on S. Ocean climate (Jeong et al., *J. Climate*, 2020)
- identification / confirmation of "tipping points" in sub-shelf circulation and melting that would have significant impacts on Antarctic-sourced SLR and global climate (~10x increase in sub-shelf melt rates and S. Ocean freshwater flux; Hoffman et al., *in prep.*)
- exploration of the impacts of S. Ocean climate variability on sea-level rise from Thwaites Glacier (Hoffman et al., *JGR Earth Surf.*, 2019)
- analysis of V1 atmos. polar climate (Lee et al., *Earth Space Sci.*, 2019; *Clim. Dyn.*, 2020)
- S. Ocean climate improvements in high-res. E3SM v1 (Jeong et al., *J. Climate*, in review)
- identification of critical ocean param. improvements needed for obtaining reasonable S. Ocean climate in E3SM v1 (Comeau et al., *in prep.*)

Results: simulated sub-ice shelf melt rates



- modeled melt fluxes are within the range inferred from observations
- variability on a wide range of time scales (intra-annual, seasonal, decadal)

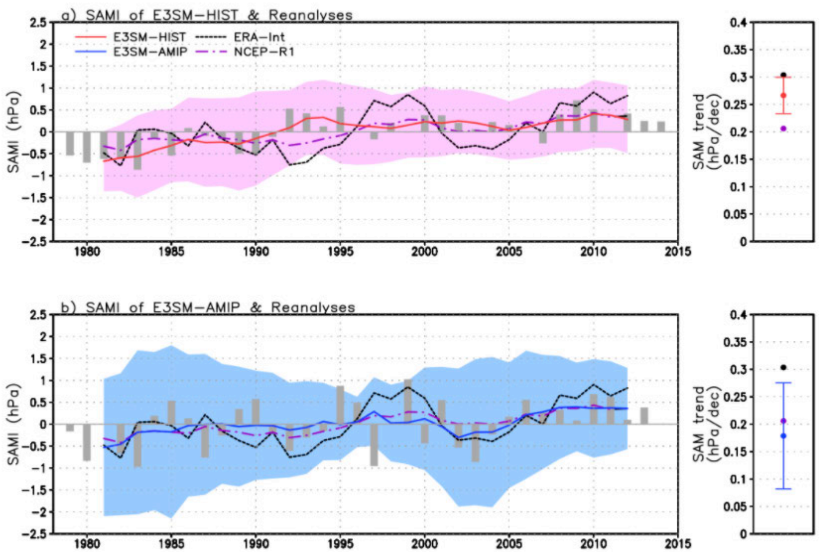


Comeau et al. (in prep.)

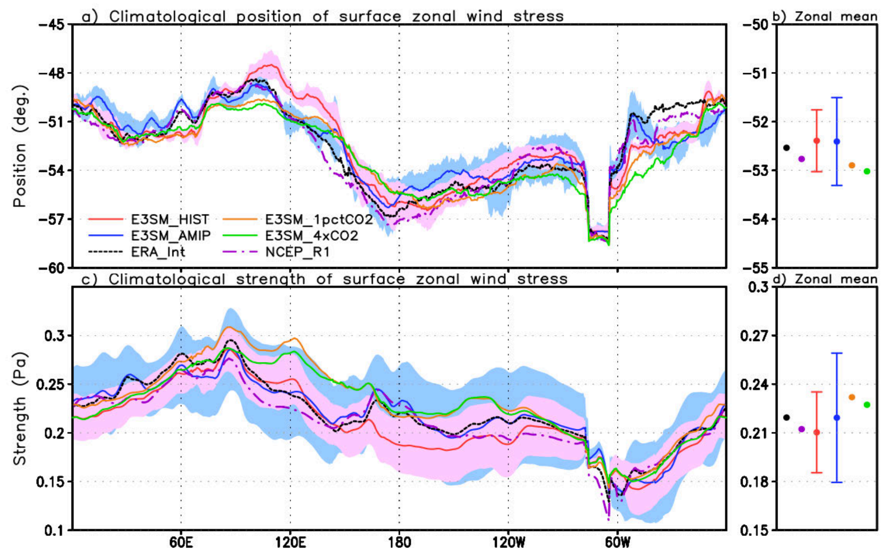
V1 Atmosphere in S. Hemisphere

- metrics developed to evaluate S. hemis. climatology, modes of variability, synoptic weather regimes, and cloud properties
- E3SMv1 ensemble captures SAM pattern and observed positive trend
- observed position and strength of max zonal mean wind stress – important for S. Ocean circulation – are within E3SM ensemble spread

Time series of SAM indices from E3SM ensemble historical (top) and AMIP (bottom) simulations



Climatological position (top) and strength (bottom) of max S. Ocean zonal wind stress in E3SM vs. reanalysis



Lee et al. (Earth Space Sci., 2019); *Lin et al.* (in prep.)

Science Questions (V2 model)

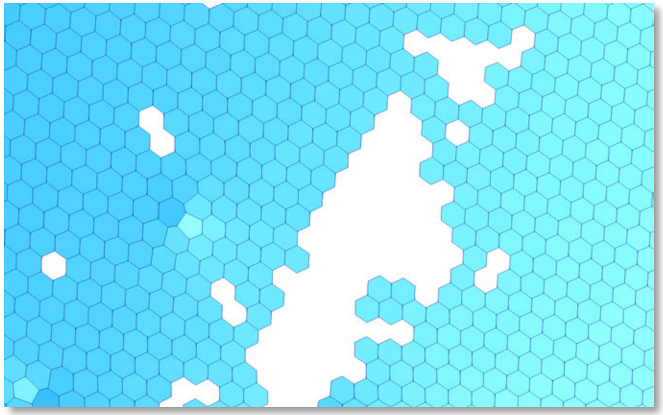
How will the atmosphere, ocean and sea-ice systems mediate sources of sea-level rise from the Antarctic ice sheet over the next 30 years?

- detailed analysis of S. Ocean climate & oceanography in *global, high-resolution* V1 simulation (*Jeong et al.,* J. Climate, in review); improvements in:
    - sea ice area & thickness
    - coastal and open ocean polynyas
    - deep water formation, currents, ocean temp., salinity, & density

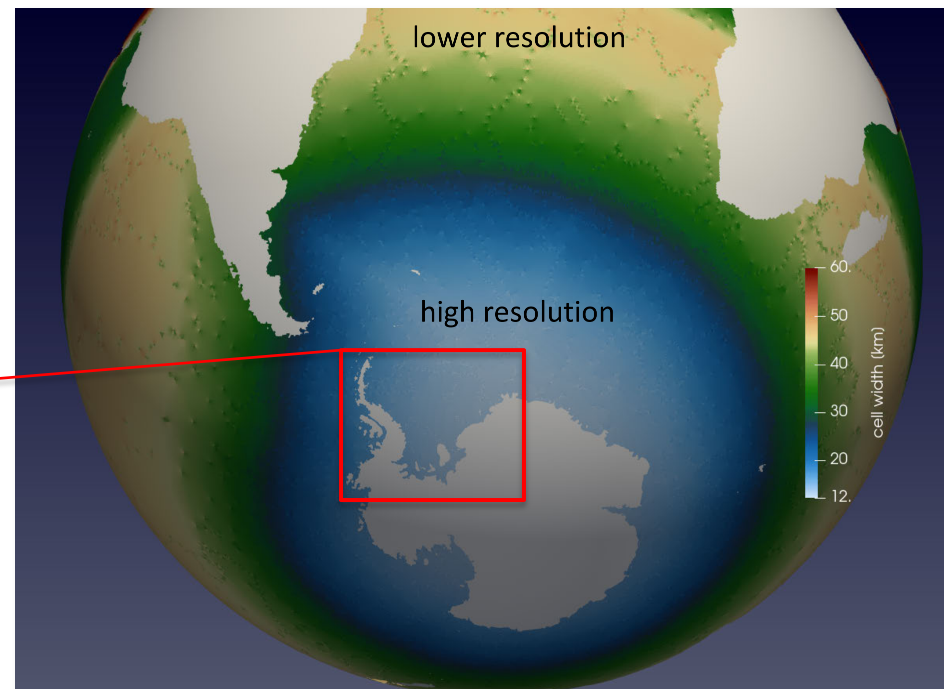
- analysis of simulations with Southern Ocean *regionally refined* mesh (SORRM):
    - realistic sub-ice shelf melt rates (improved for small ice shelves)
    - similar ocean improvements to global high res.
    - negates complications related to tuning of low-res. eddy-param.

- analysis of atmos. with regionally refined mesh (RRM) over Antarctica
    - RRM improvements over Antarctica are similar to global high res.
    - tuning allows for further regional improvements

V2 Results: variable resolution configuration

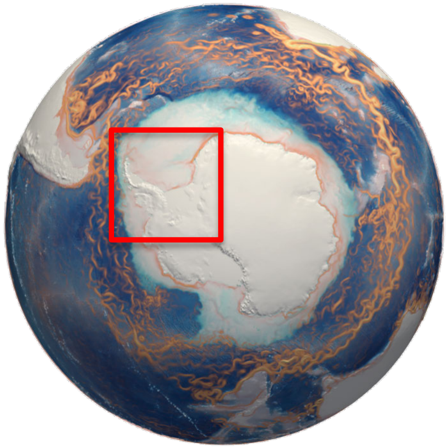


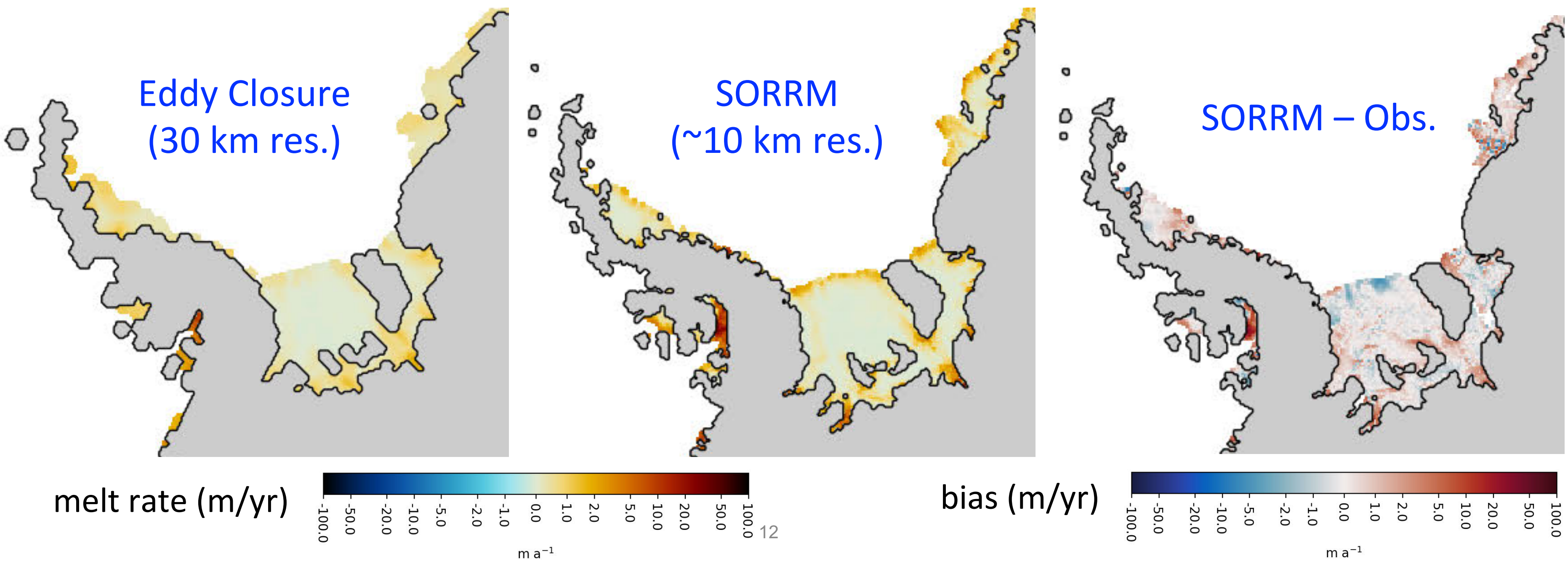
Resolution	Horizontal grid cells
EC60to30 (low)	0.2 million
SO60to10 (regionally refined)	0.42 million
RRS18to6 (high)	3.7 million



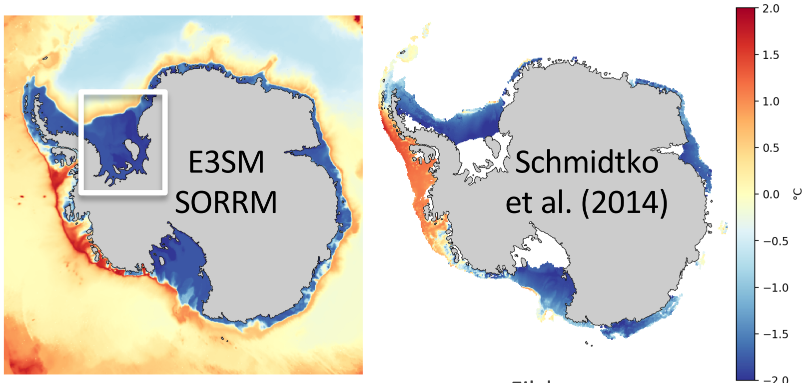
Results: variable resolution configuration

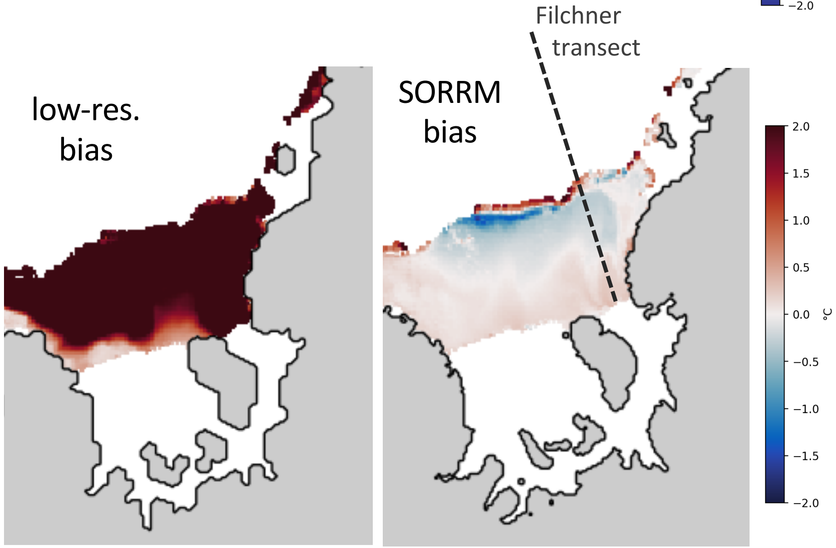
- Southern Ocean Regionally Refined Mesh (SORRM)
- 3x higher resolution under Antarctic ice shelves for 2x computational cost
- increased res. removes need for eddy-param.
- improved representation of coastline, critical passages, small ice shelves, & grounding lines





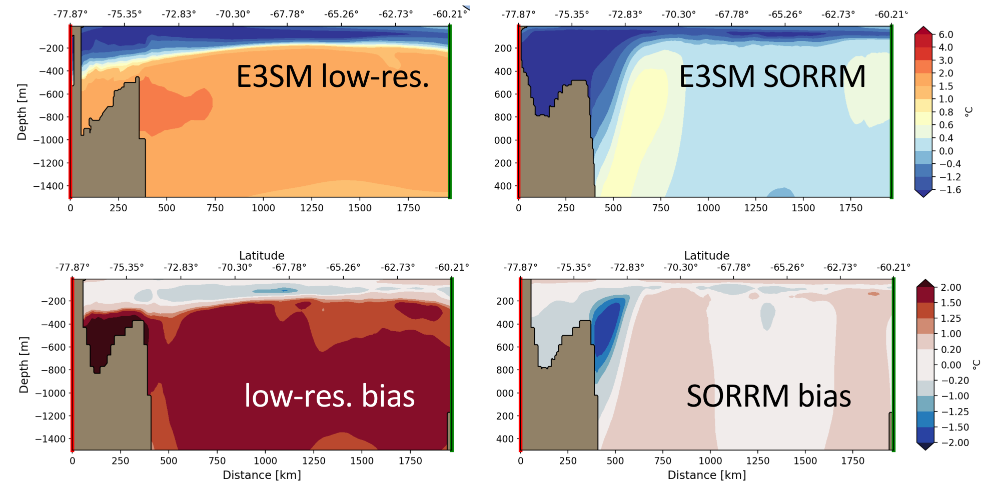
Results: variable resolution configuration



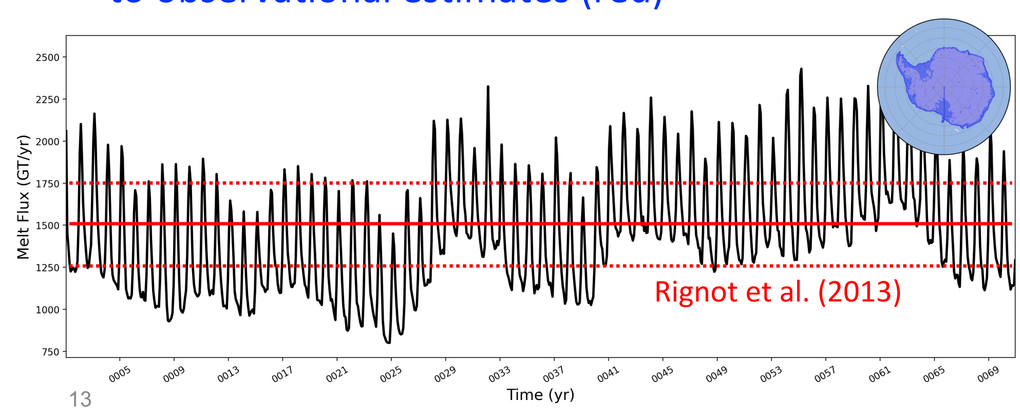


- Modeled vs. obs. seafloor temperatures (top)
- low-resolution (lower left) and SORRM (lower right) seafloor temperature bias

Ocean Temperature vs. Depth (Filchner transect)

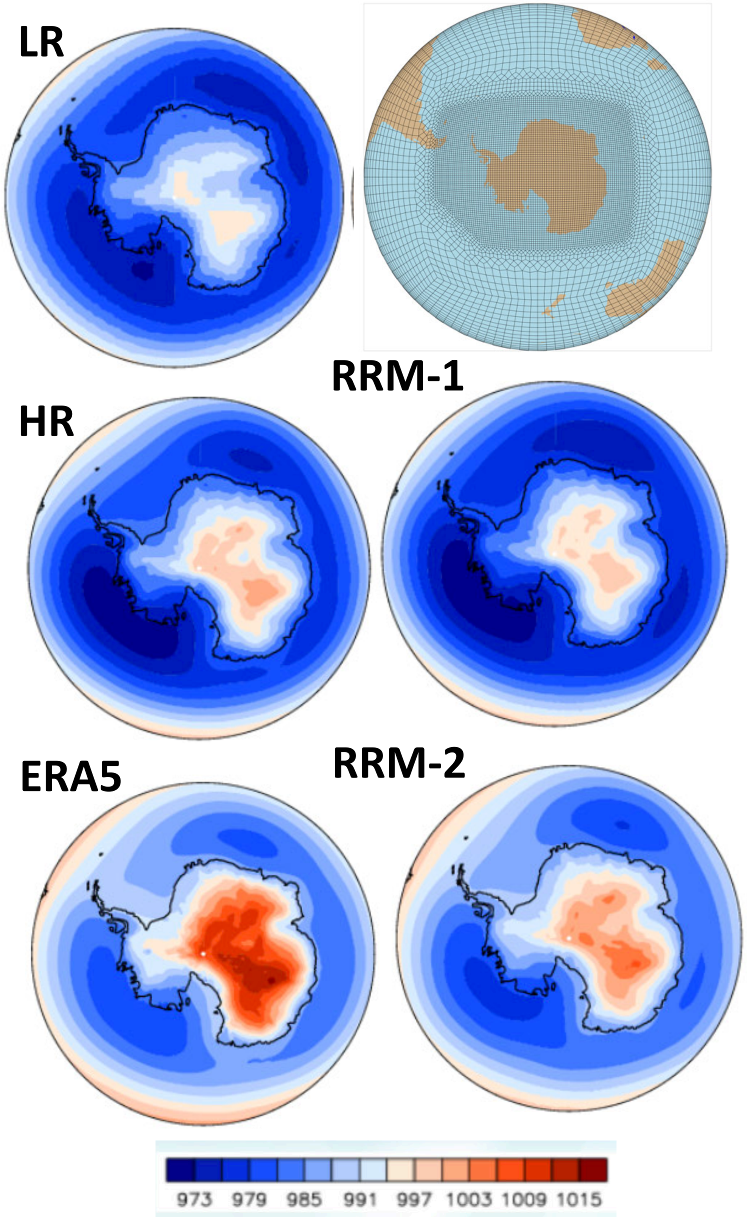


- Modeled ocean temperature (top) and bias (bottom) for low-res. (left column) and SORRM (right column)
- Whole Antarctic ice shelf melt flux (black) relative to observational estimates (red)



Progress in V2 Atmosphere over S. Ocean

- tracking S. hemis. and Antarctic climate metrics in v2 alpha WC simulations
- atmospheric forcing sensitive to both resolution and parameter changes
- higher resolution leads to improvements, which are broadly reproduced with RRM
- further improvements possible with atmos. tuning (part of WC finalization).



Right: 2010-2012 mean annual sea level pressure from EAM v2 alpha using low-res. (LR), high-res. (HR), and RRM (upper right) configurations. LR, HR and RRM-1 use identical tuning while RRM-2 uses an improved tuning.

V2 Water Cycle and Cryosphere Coordination

- Lab. Sea bias (broadly – vert. & horiz. ocean mixing improvements)
- Improved (variable vs. uniform) eddy-param. for low-res. configs.
- Unification of low-res. WC & Cryo ocean/ice meshes (towards unified WC and Cryo low-res. simulation campaigns)
- Improved mesh generation process & QC for var. res. ocean/ice meshes
- Coordination of ongoing v2 atmos. tuning (WC vs. Cryo configs.)
- Improved ocean bathymetry, coastlines, and critical passages
- Data MPAS sea ice model (for use with atmos. only configs.)
- Sea ice model improvements (bug fixes; unified snow radiation phys.)
- Consistent atmos. RRM generation process (N. Am. vs. S. Ocean focus)
- Analysis of high-lat. climate in high-res., v1 WC config.
- Development & support for MPAS-Analysis, E3SM-unified

Coordination with other efforts

SciDAC *ProSPect*: ice sheet model development, testing, E3SM integration (AIS & GIS); snowpack model devel; dataset support; V&V for ice sheet models and SMB; ice sheet model optimization for E3SM [ongoing during phase 2]

InterFACE: improved polar climate (ocean mixing, runoff flux); sea ice model improvements (landfast ice, wave-ice interactions); improved Arctic mesh design & QC (coastlines, critical passages) [starting]

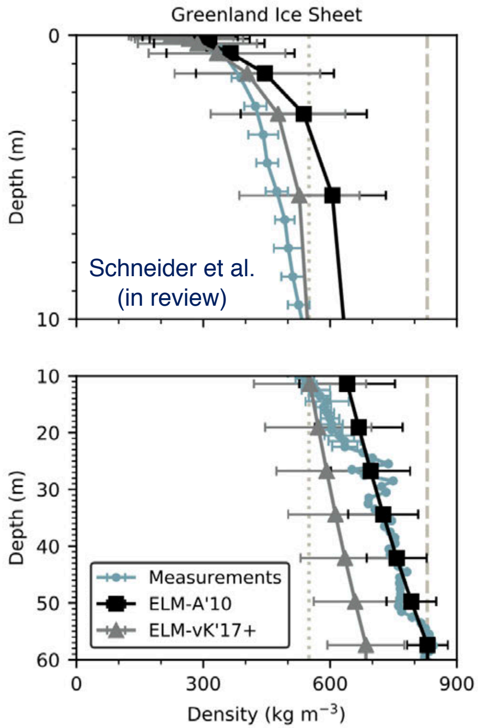
ICoM: tides (global impacts of cavities; tidal impacts on ice shelf melt); high-res. coastal ocean mesh development [starting]

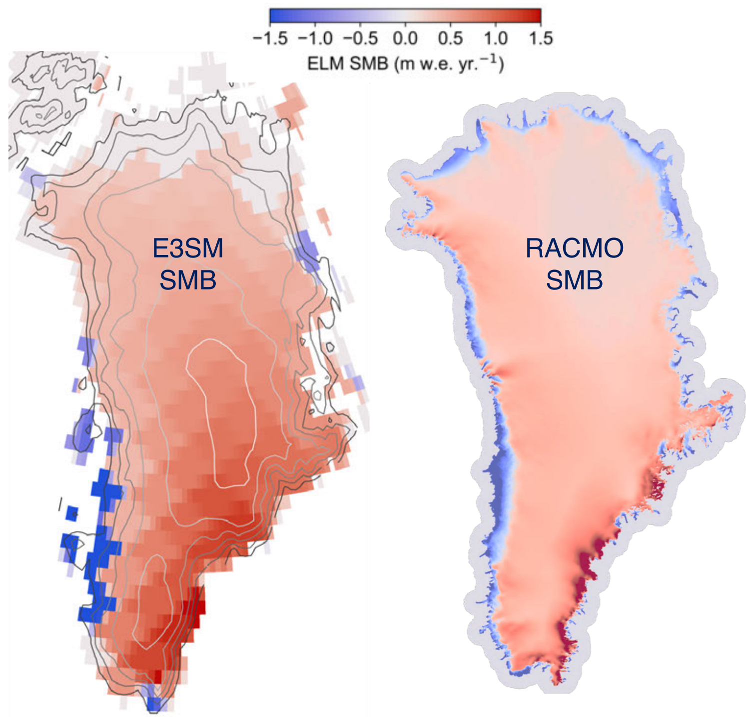
DOE Early Career: regional-scale sea level rise capability in E3SM [starting]

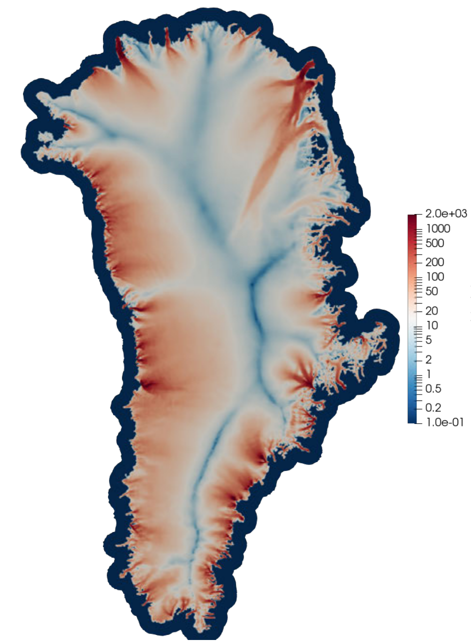
E3SM Univ. funded / other:

- U. of Mich. – atmos. & sfc. radiation coupling (including cryo model components)
- Johns Hopkins U. – parameterizing impacts of mesoscale eddies in E3SM
- ISMIP6 / CMIP6: ice sheet model projections of SLR; parameterization of climate model forcing; climate model selection for ice sheet forcing

Dynamic Greenland Ice Sheet





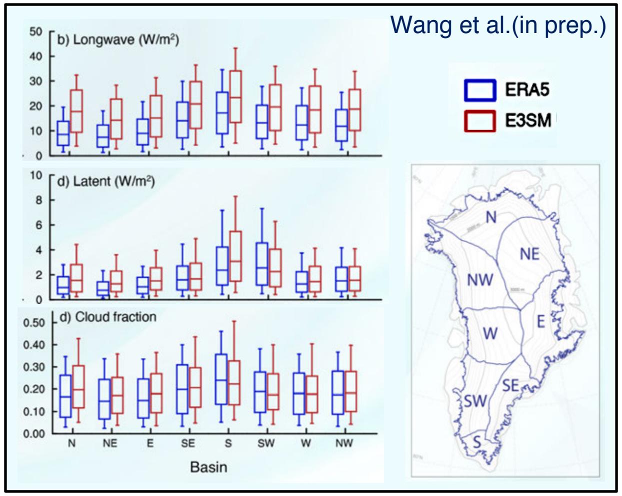


ELM snowpack model improvements (above left)

Greenland surface mass balance (SMB) spun-up in E3SM and compared to RACMO (above middle)

Greenland ice sheet surface speed from optimized MALI initial condition in E3SM (above right)

Factors controlling Greenland surface melting in E3SM (right)



Progress Towards Metrics: short term

Ice sheet freshwater flux to ocean

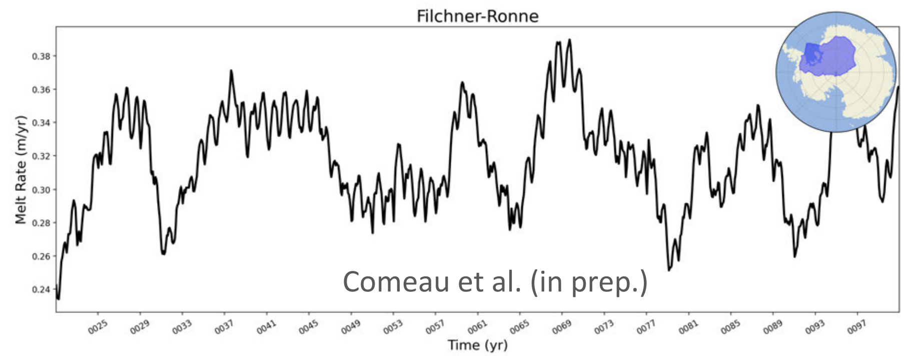
1. variability in sub-ice shelf melt rates
2. variability in ice sheet surface mass balance
3. trends in (1) and (2) as a function of radiative forcing

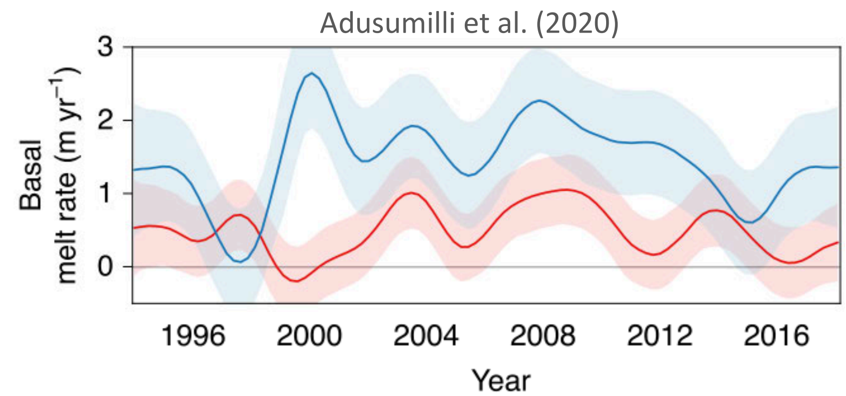
Progress:

1. century-scale simulations of (1) at the granularity of individual ice shelves; validation against long-term obs. means

2. new snowpack model in ELM; new E3SM configurations supporting calculation of ice sheet surface mass balance

Modeled (top) vs. recently published (bottom) melt rate variability for the Filchner-Ronne ice shelf





Progress Towards Metrics: short term

Antarctic atmospheric forcing

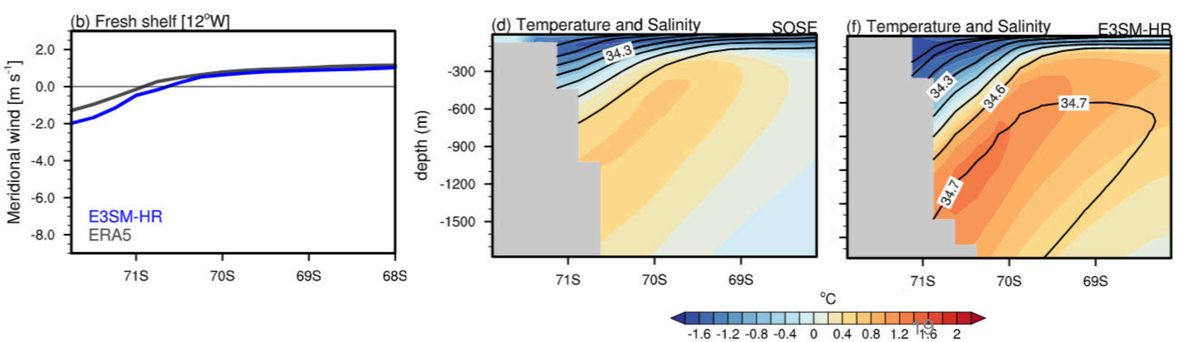
1. variability in S. Ocean surface winds, precipitation, radiation, and their relationship to the SAM
2. relative contributions of atmos., sea ice, ocean variability in forcing of surface and submarine melting of the Antarctic ice sheet

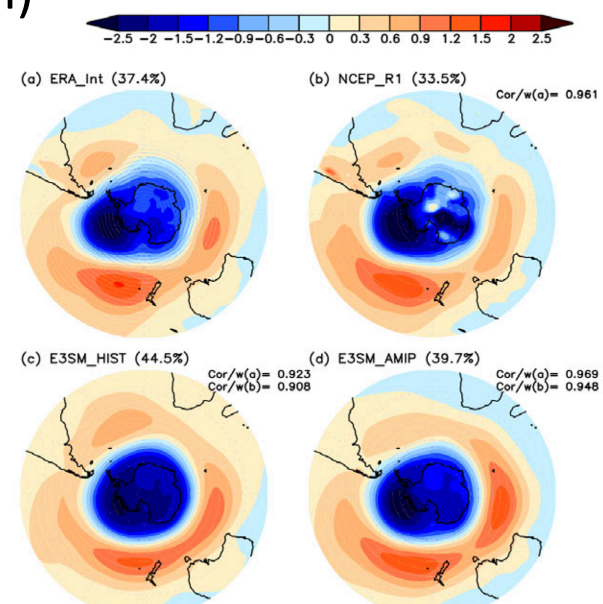
Progress:

1. characterized (1) for the E3SM v1; starting on similar for v2
2. initial S. Ocean characterization of (2) using high-res., v1 Water Cycle simulation (as proxy for v2, SORRM configuration)

Below: S. Ocean winds and ocean T&S structure for high-res. E3SM vs. reanalysis products (Jeong et al., in review)

Right: spatial pattern of leading EOF (SAM) on sea level pressure (Lee et al., 2019)



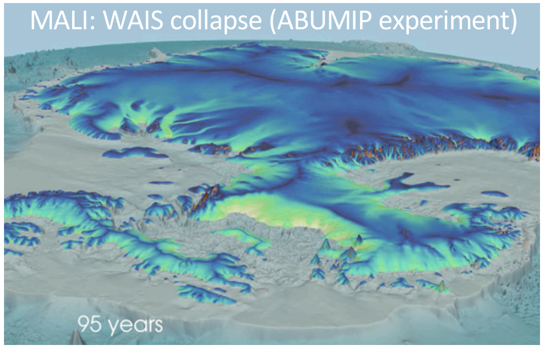


Progress Towards Metrics: long term

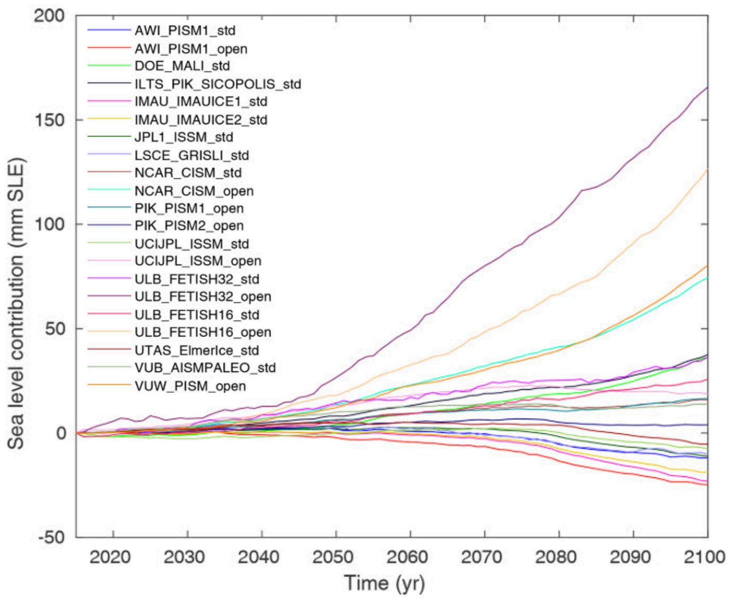
Contribution of land ice to global and regional sea level

1. evolution of the Greenland and Antarctic ice sheets
2. surface and submarine melt rates of the ice sheet
3. uncertainty in land ice contributions to global sea level

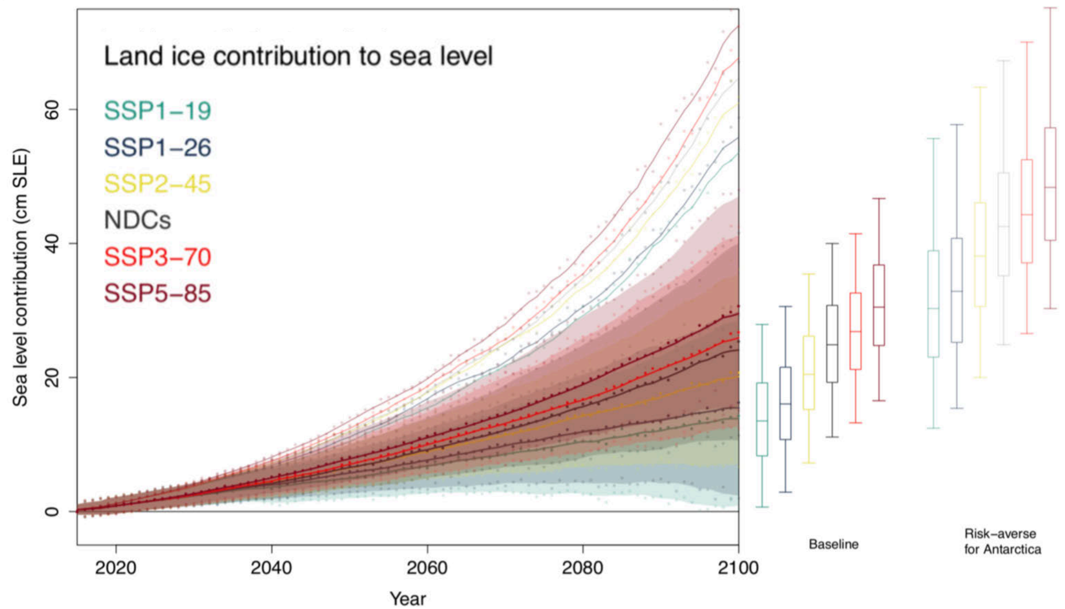
Progress: SciDAC efforts towards (1) via stand-alone ice sheet simulations (>10 publications towards IPCC AR6 as part of ISMIP6 effort)



visualization by ***RAPIDS*** (N. Woods, J. Patchet; LANL)



ISMIP6 ensemble of sea-level rise projections from Antarctic ice sheet models (Seroussi et al., 2020)



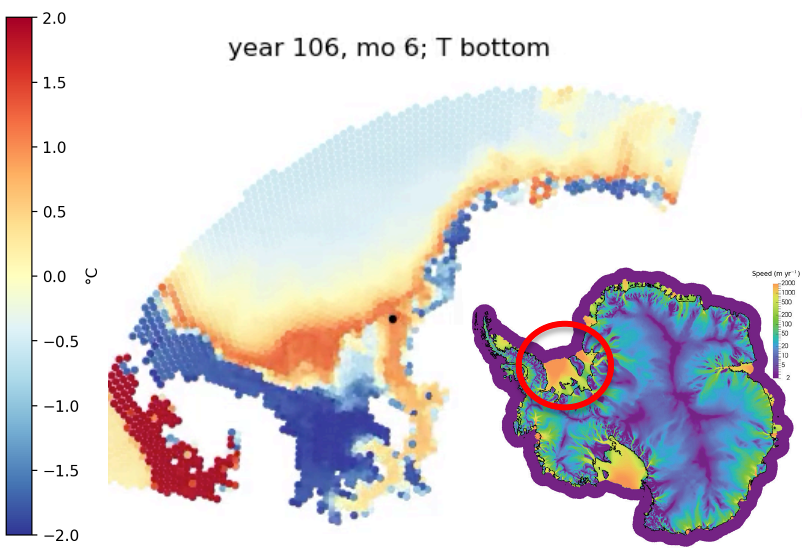
PDF of scenario dependent sea-level rise sea level rise from ISMIP6 land ice model emulation (Edwards et al., in review)

Progress Towards Metrics: long term

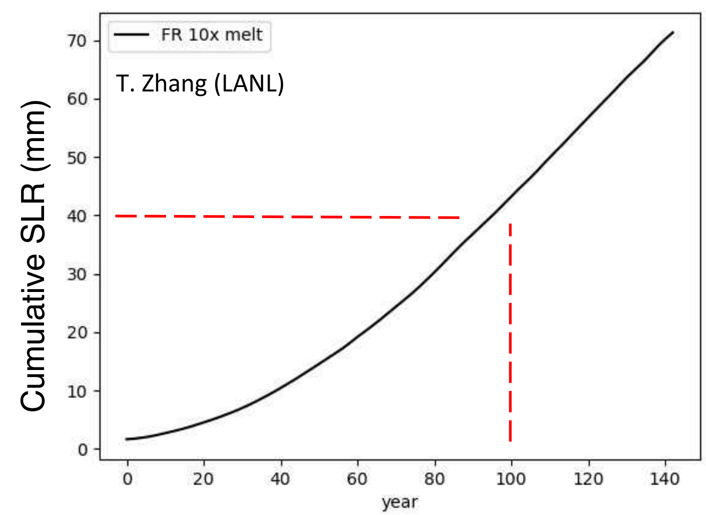
Contribution of land ice to global and regional sea level

1. evolution of the Greenland and Antarctic ice sheets
2. surface and submarine melt rates of the ice sheet
3. uncertainty in land ice contributions to global sea level

Progress: ongoing efforts towards (2) (as discussed above) including under-standing sub-ice shelf melt instabilities that could lead to significant, unexpected increases in sea-level rise from Antarctica



+10x in melting = ~40 mm sea level rise in 100 years = ~1/2 Greenland’s contribution at 2100

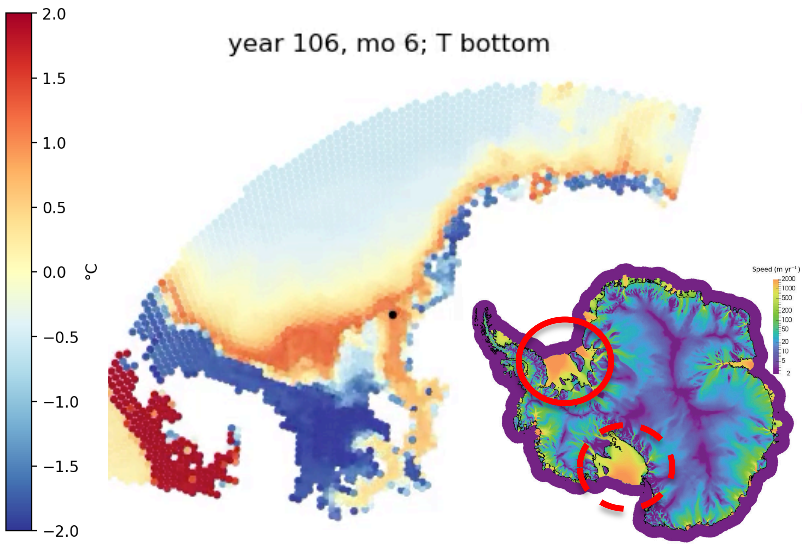


Progress Towards Metrics: long term

Contribution of land ice to global and regional sea level

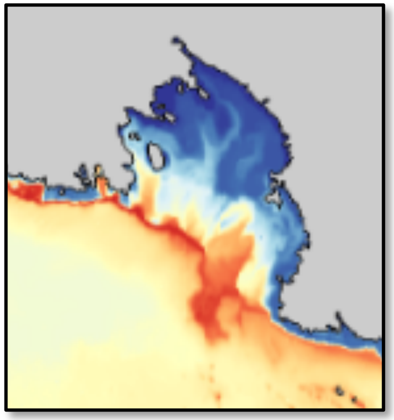
1. evolution of the Greenland and Antarctic ice sheets
2. surface and submarine melt rates of the ice sheet
3. uncertainty in land ice contributions to global sea level

Progress: ongoing efforts towards (2) (as discussed above) including under-standing sub-ice shelf melt instabilities that could lead to significant, unexpected increases in sea-level rise from Antarctica



Potential for similar instabilities beneath the Ross ice shelf?

warm water incursions beneath the Ross ice shelf in SORRM sims.



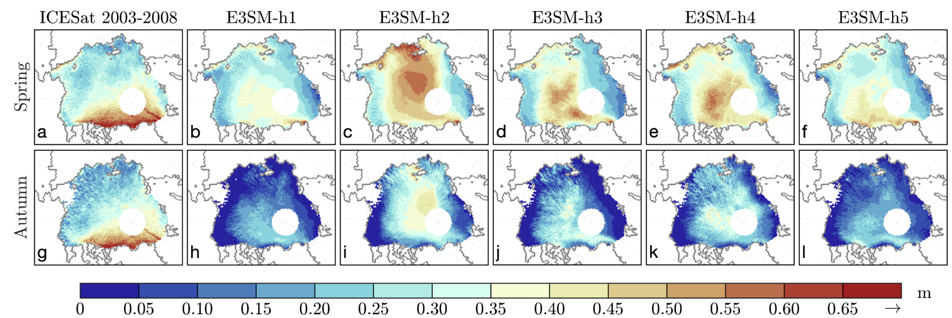
Progress Towards Metrics: long term

Decadal trends in sea ice cover

1. variability in sea ice over from seasonal to decadal time scales
2. decadal trends in sea ice since 1979
3. scenario dependent projections of sea ice cover

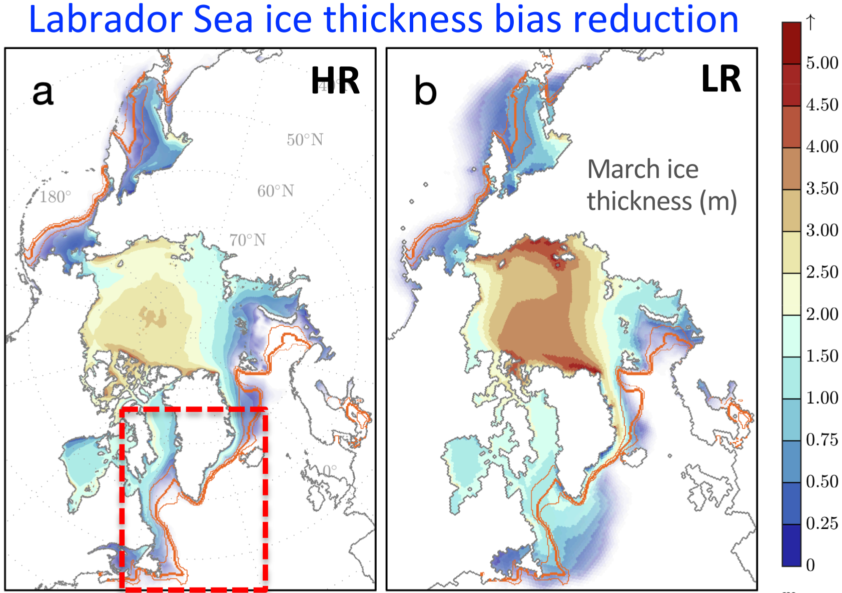
Progress: improvements in seasonal sea ice extent and thickness; satellite emulator for accurate thickness assessment & skill scores

sea ice thickness bias using ICESat emulator

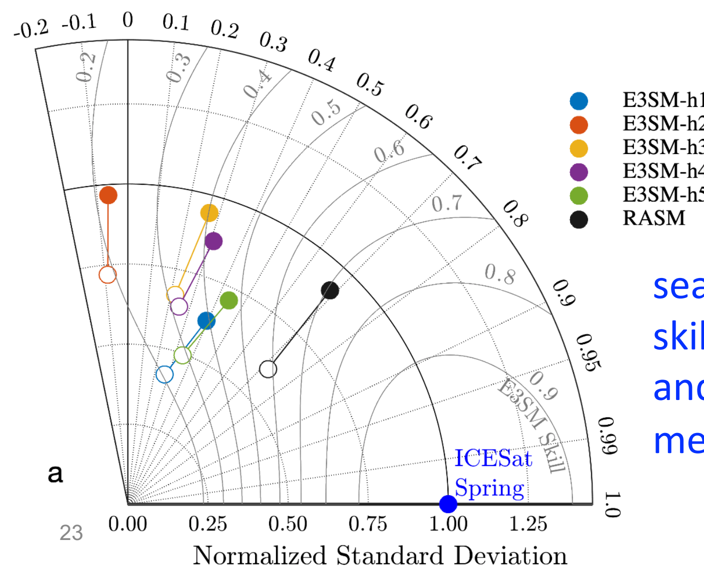


Figs. from Andrew Roberts

Labrador Sea ice thickness bias reduction



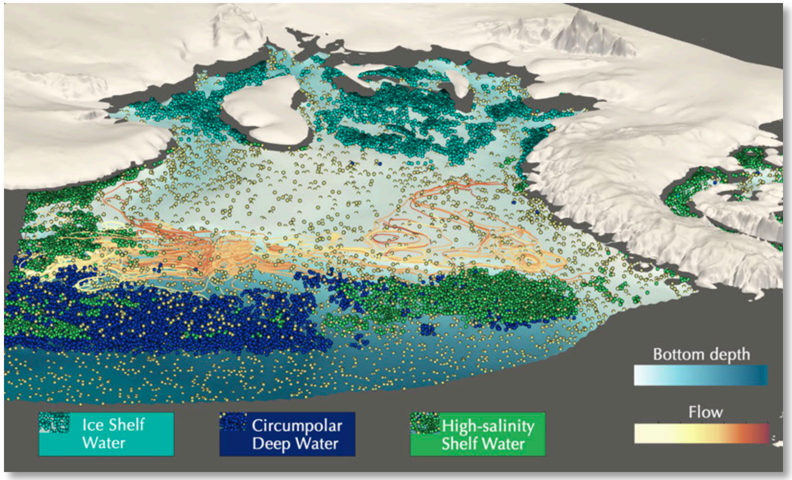
Caldwell et al. (2019)



sea ice thickness skill scores (ICESat and E3SM ensemble members)

Summary

- E3SM has the new & unique capability of explicitly simulating sub-ice shelf heat & freshwater fluxes in a global, coupled ESM
- Provides realistic, stable melt rates in century-scale simulations for both low- and variable-resolution configurations
- Will allow for the assessment of global climate impacts on Antarctic ice sheet evolution and vice versa
- Necessary first step for understanding and quantifying Antarctic-sourced sea level rise in a coupled Earth system model



ocean water mass analysis near and beneath Filchner-Ronne ice shelf, West Antarctica (Abrams et al., submitted)