Antarctic Ocean-Ice Shelf Interactions in High-Resolution, Global Simulations Using the Accelerated Climate Model for Energy (ACME)

S. Price[1], M. Petersen[1], X. Asay-Davis[2], J. Fyke[1],
J. Wolfe[1], M. Hoffman[1], A. Turner[1], T. Ringler[1],
(and ACME and PISCEES project members)

[1]Los Alamos National Laboratory
[2]Potsdam Institute for Climate Impact Research (PIK)

Supported by DOE Office of Science BER & ASCR

Model simulations conducted on *Edison* & *Cori* at NERSC

U.S. DEPARTMENT OF ENERGY Office of Science

ACME Accelerated Climate Modeling for Energy

SciDAC Scientific Discovery through Advanced Computing

Background & Motivation

Model Components & Configurations

Simulation Results & Biases

Summary

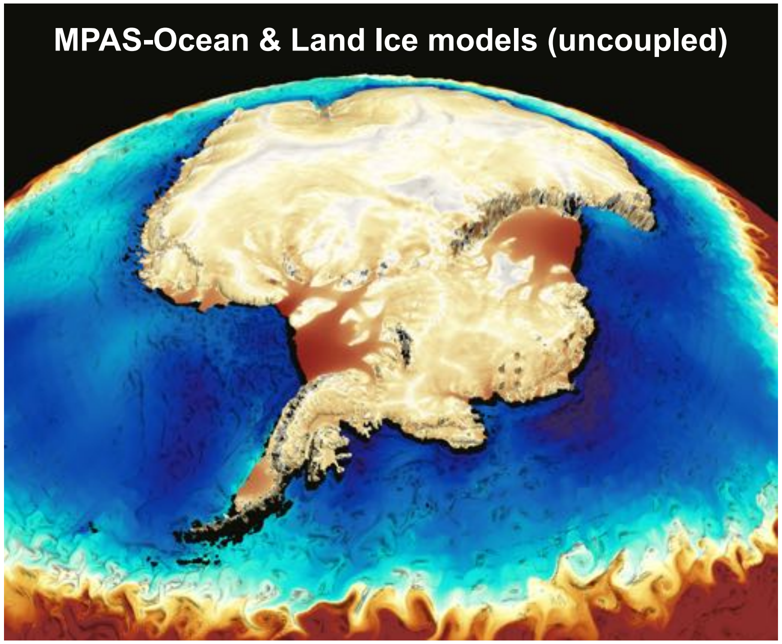
On-going & Future Work

Background / Motivation

DOE's *Accelerated Climate Model for Energy* (ACME) project:

- multi-lab effort to develop & apply ESM for DOE mission needs
- technical focus: high-and-resolution, next generation HPC
- science focus areas:
    1. How do the hydrological cycle and water resources interact with the climate on local to global scales?
    2. How do biogeochemical cycles interact with global climate change?
    3. ***How do rapid changes in cryosphere-ocean systems interact with the climate system?***
- timescale: 1970-2010 hindcast, 2010-2050 projection

ACME Cryosphere Focus

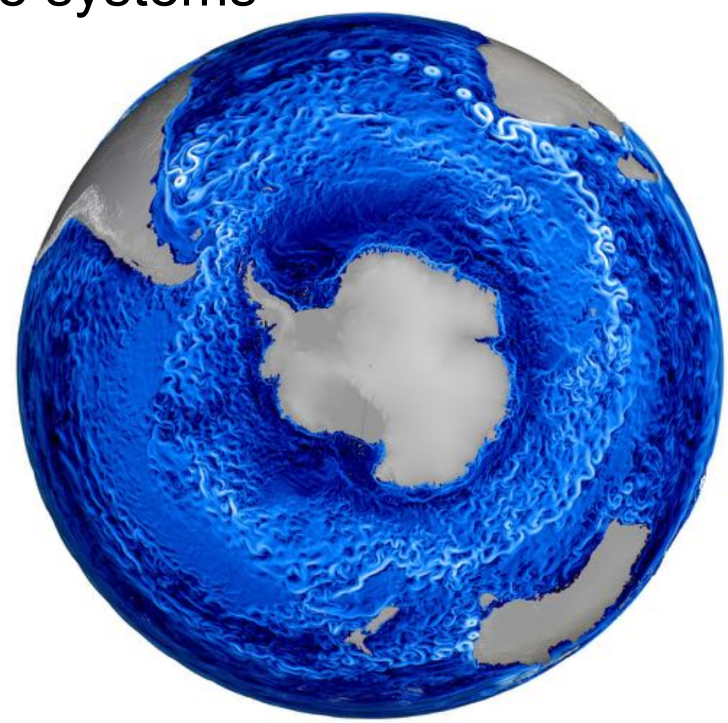


Explore likelihood of rapid sea-level rise on decadal to century timescales

Focus on Antarctica & Southern Ocean

Target simulations include dynamically-coupled, atmosphere, ocean, sea ice, and land ice systems

Challenges:
- <u>new ocean, sea ice, land ice models</u>
- spatial scales down to ~1 km
- ice sheet and ocean coupling
- sparse observations
- impact of long equilibrium timescales on coupled model initialization



Southern ocean eddy activity from global, high-resolution (18-6km) MPAS-Ocean simulation

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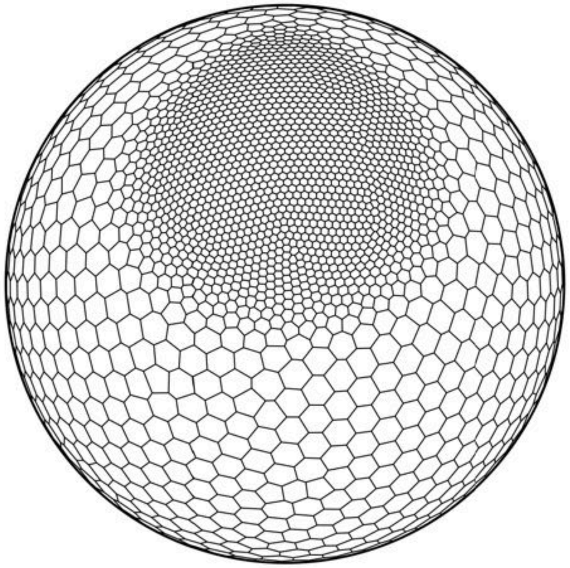
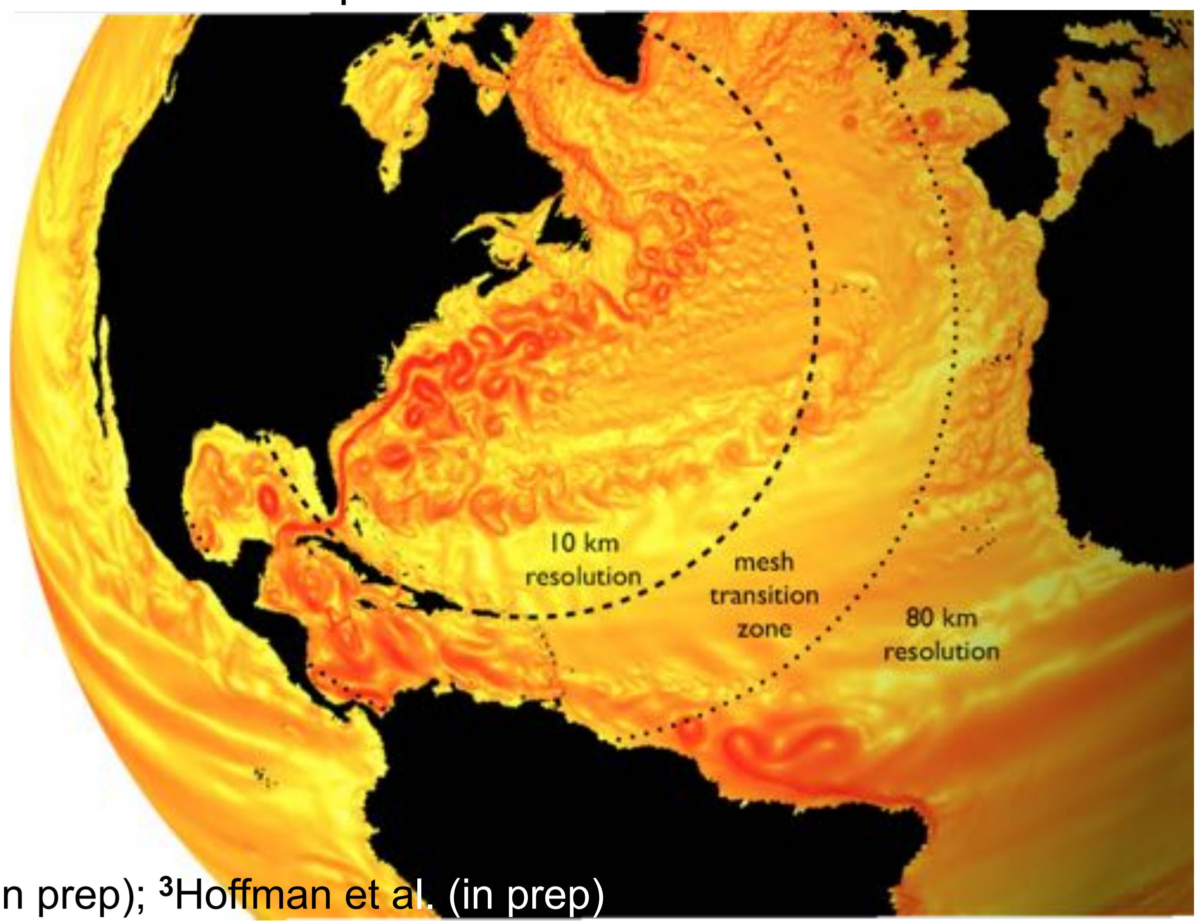
Models: MPAS-Ocean, Sea Ice, Land Ice



Model for Prediction Across Scales (MPAS): climate modeling framework built around SCVT* meshes (LANL + NCAR collaboration)

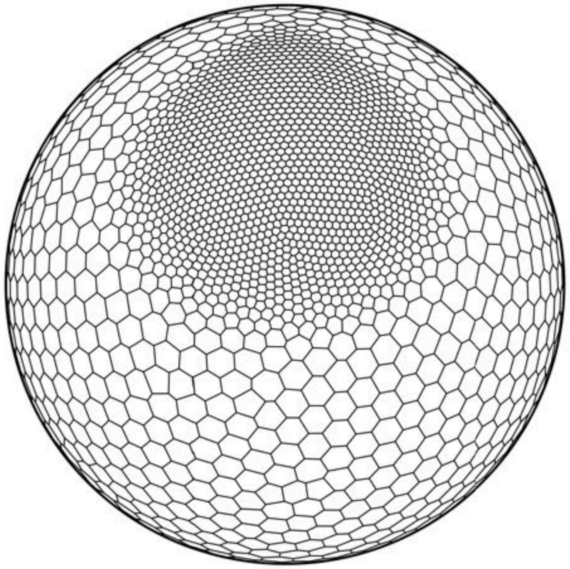
***SCVT** = Spherical Centroidal Voronoi Tesselations



- ocean[1], sea ice[2], and land ice[3] dynamical cores exist
- built using shared software framework
- new capabilities added to one core benefit all others

[1]Ringler et al., 2013; [2]Turner et al. (in prep); [3]Hoffman et al. (in prep)

Models: MPAS-Ocean, Sea Ice, Land Ice



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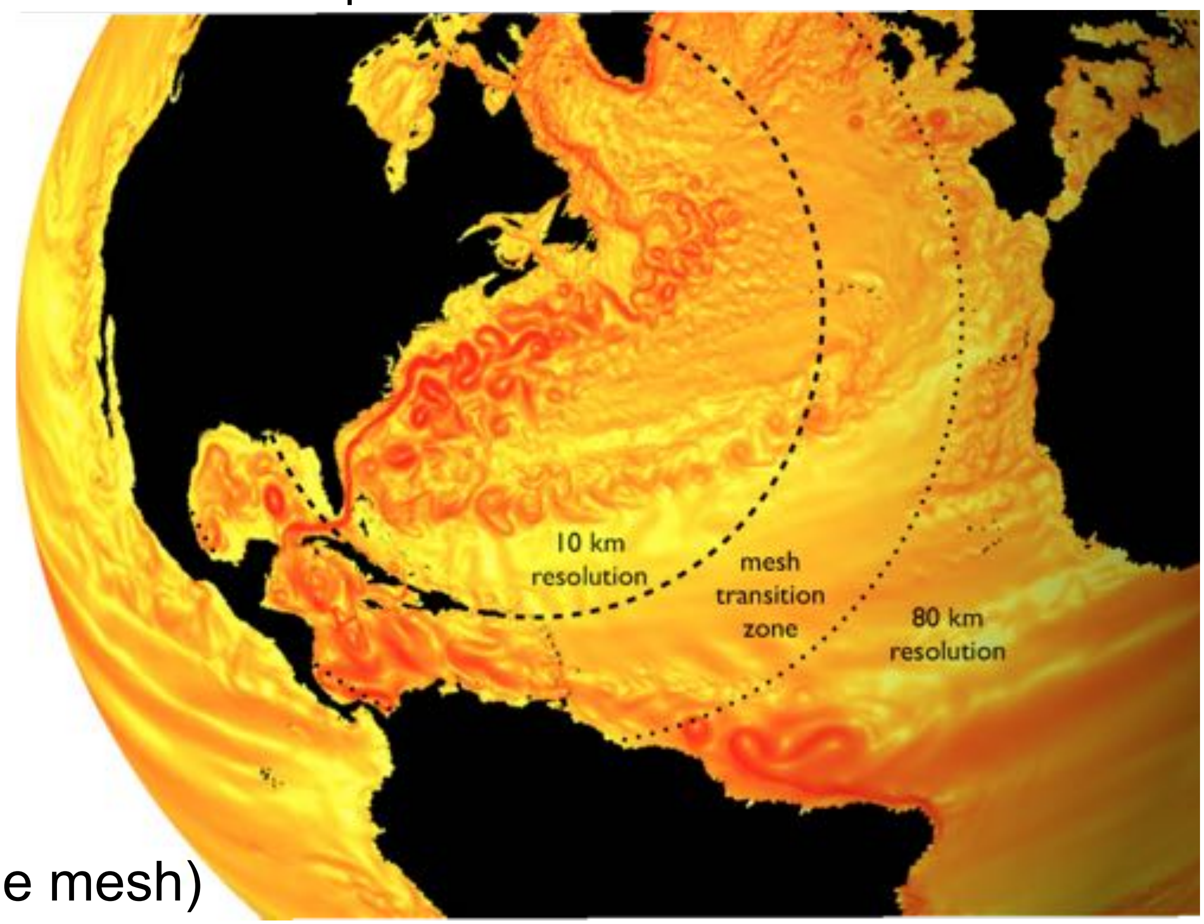


<u>low-res (1° POP)</u>
mid-lat: 60 km,
equator / poles: 30 km

<u>med-res (1/10th ° POP)</u>
equator: 30 km
poles: 10 km

<u>high-res</u>
equator: 18 km
poles: 6 km

(ocean and sea ice on same mesh)

Models: DOE PISCEES

- PISCEES: *Predicting Ice Sheet and Climate Evolution at Extreme Scales*
- Scientific Discovery through Advanced Computing (SciDAC) 5 year project (2012-2017)

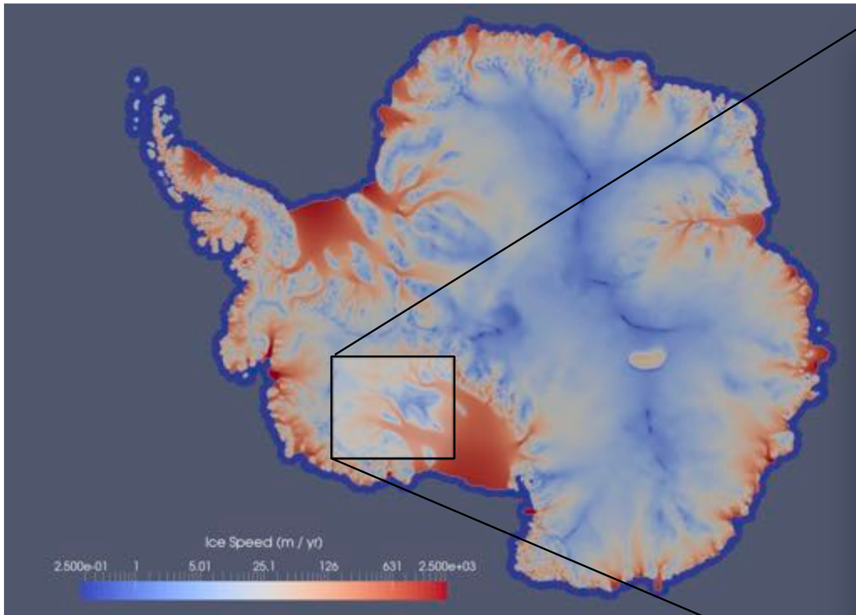
PISCEES Focus Areas:

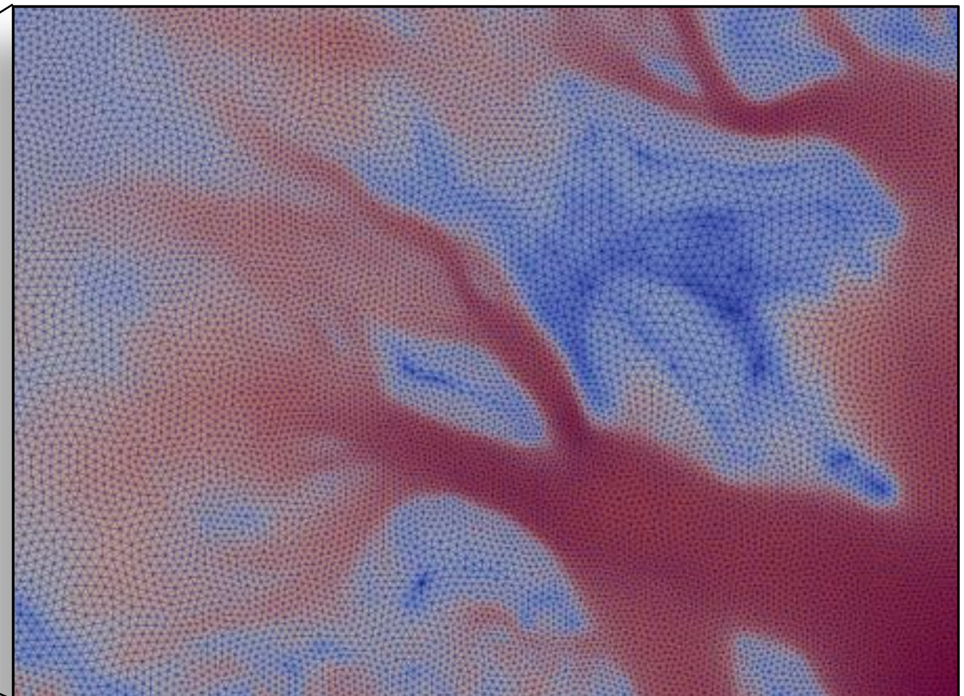
1) develop and apply robust, accurate, scalable computer codes for ice sheet modeling on structured and unstructured meshes with adaptive refinements

2) evaluate models using new tools and data sets for verification and validation and uncertainty quantification

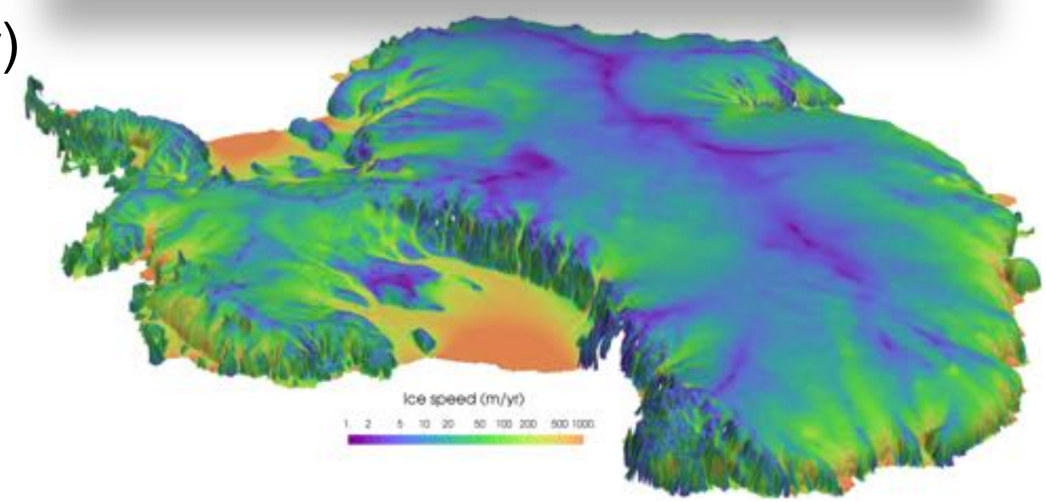
3) Integrate these models and tools into DOE Earth System Models

Models: MPAS-Land Ice (FELIX)





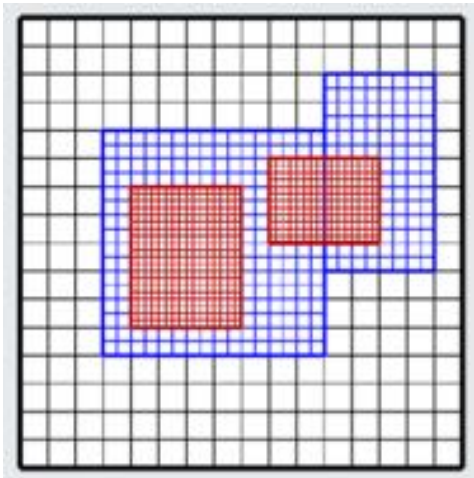
- low, med., and high, var. res. meshes (to focus computing pwr)
- finite element, higher-order, 3d dynamical core (first-order Stokes approx.)
- initial conditions optimized to match present-day observations
- coupled to ACME



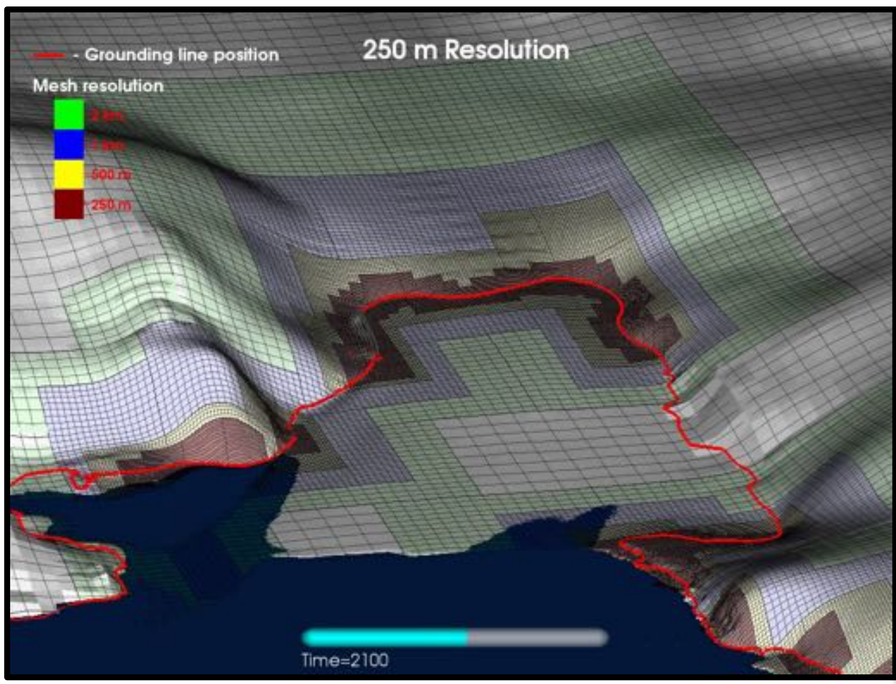
Initial velocities optimized to obs. of Rignot et al. (2011)

Models: BISICLES[1]

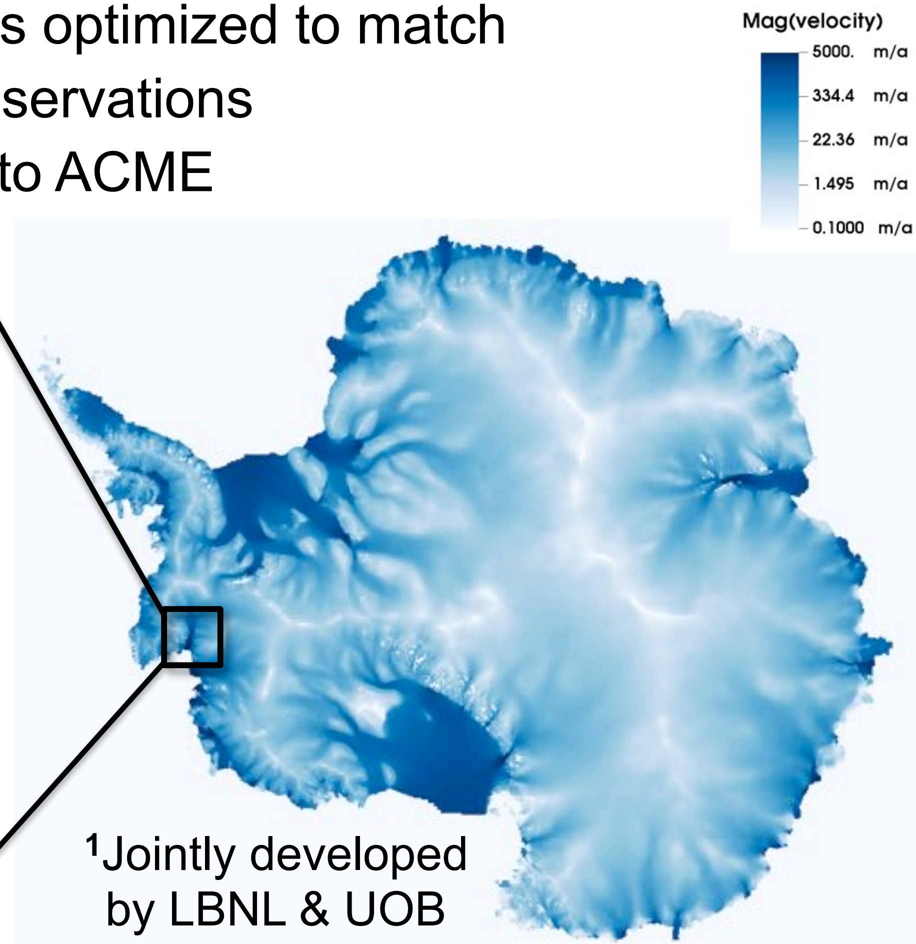
block structured AMR



- finite volume, higher-order, quasi-3d dynamical core (SSA*, L1L2)
- Block-structured AMR to focus resolution & computing power
- Initial conditions optimized to match present-day observations
- to be coupled to ACME



Grounding line of Pine Island Glacier, West Antarctica

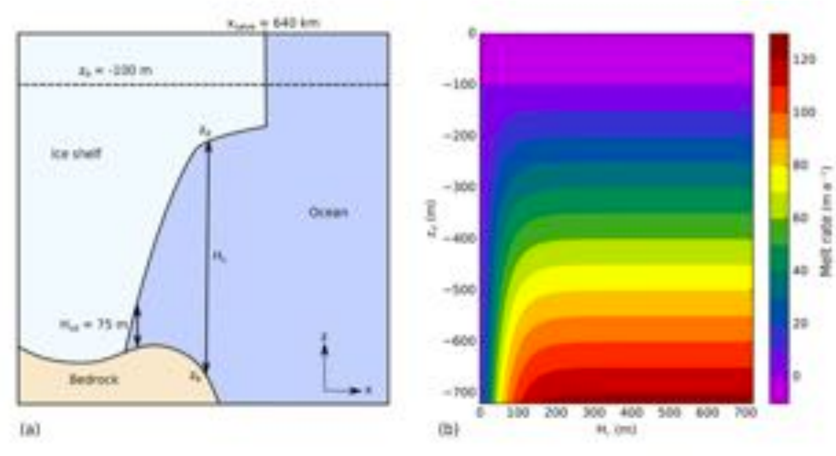


[1]Jointly developed by LBNL & UOB

Models: Coupled Ice Sheet & Ocean MIPS

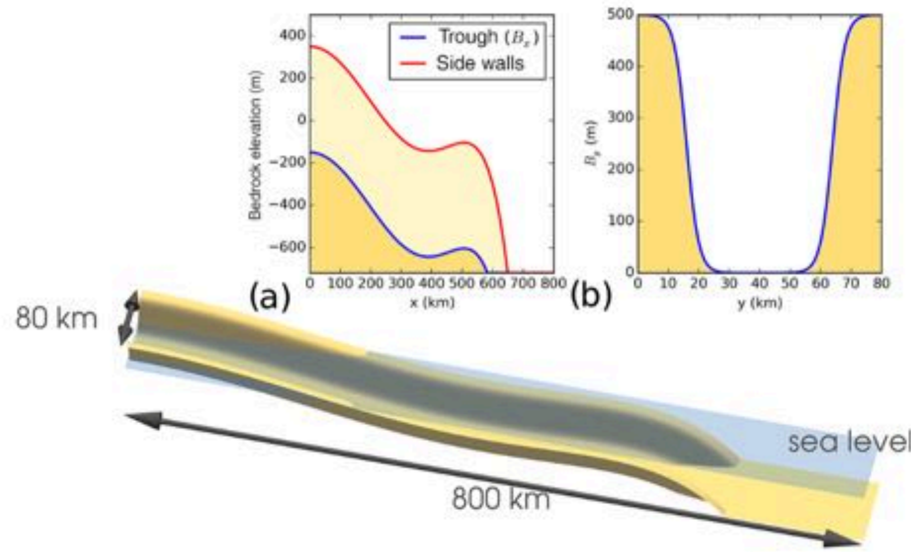
ISOMIP+

- ocean evolution in idealized, static ice shelf cavity with idealized forcing (melting; T,S restoring)



MISMIP+

- marine-ice sheet evolution with idealized submarine melt forcing (with retrograde bed and buttressing included)



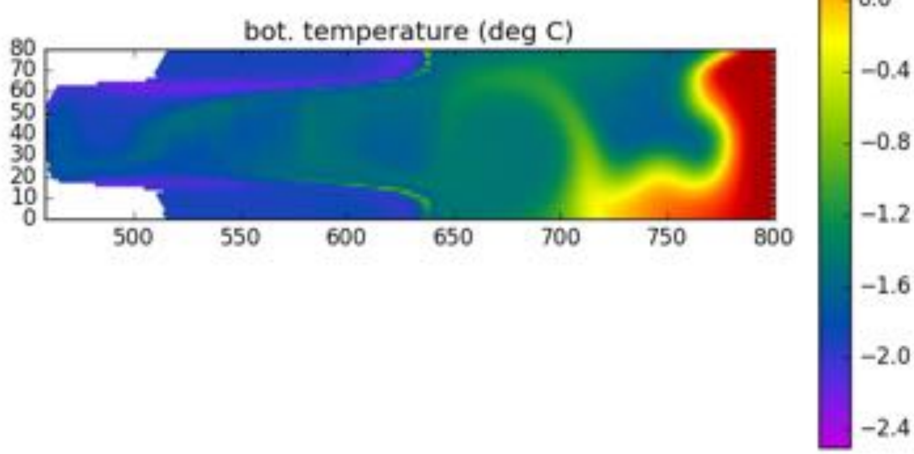
MISOMIP

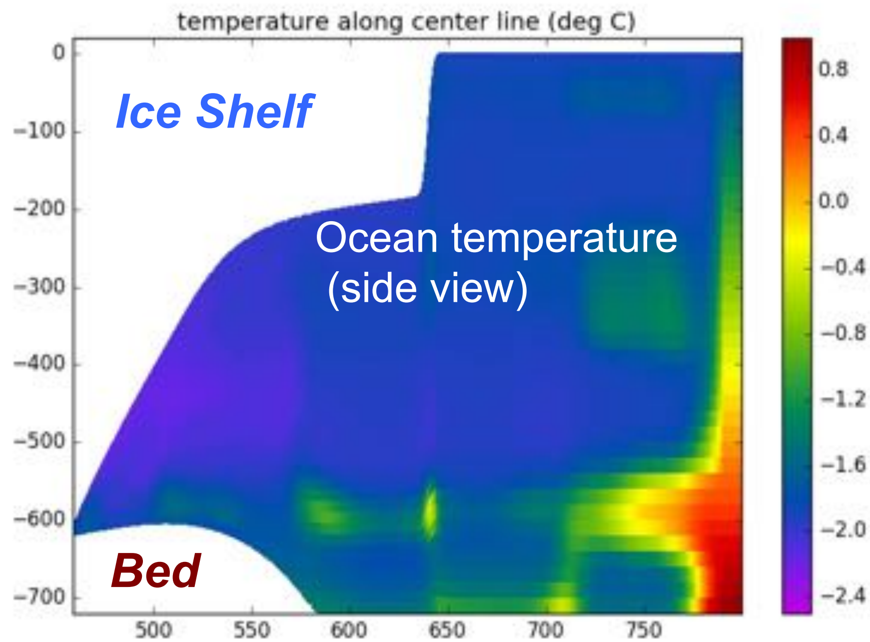
- Combine ISOMIP+ and MISMIP+ domains to simulate coupled ice sheet and ocean evolution

Asay-Davis et al., *GMD*, **9**, 2016

Models: Coupled Ice Sheet & Ocean MIPS

Ocean bottom temperature (plan view)

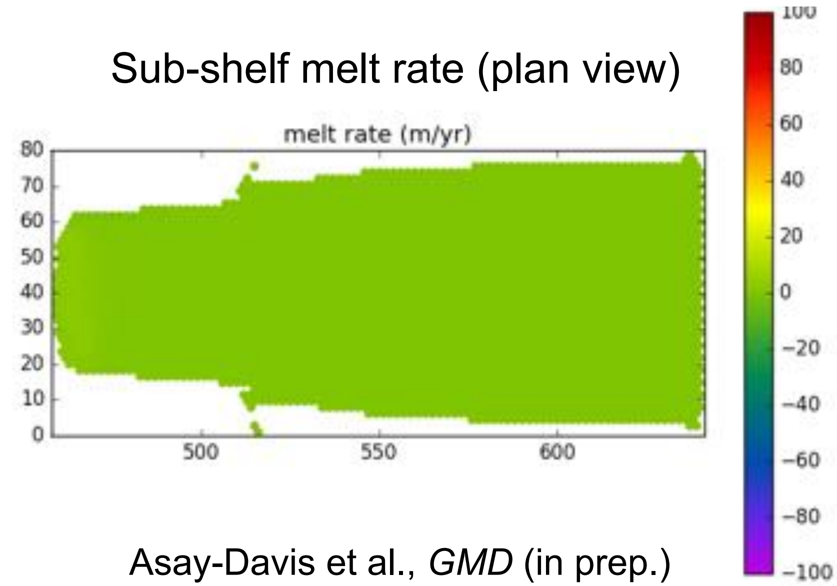




ISOMIP+ experiment with MPAS-O

- Experiment ”Ocean 1”:
  - Static ice shelf
  - Dynamic ocean
  - One-way coupling via oceanBL physics
- Ocean temperature & sub-shelf melt rate evolution shown over ~20 years

Sub-shelf melt rate (plan view)



Asay-Davis et al., *GMD* (in prep.)

Model Configurations *

	Ocean & Sea Ice	Ice Sheet
Low Resolution	EC 60-30 km	20 km
Med. Resolution	RRS 30-10 km	14-4 km
High Resolution	RRS 18-6 km	30-1 km

* Global, with ocean circulation in ice shelf cavities

EC = “Eddy Closure”

RRS = “Rossby Radius Scaling”

Model Configurations

	Ocean & Sea Ice	Ice Sheet
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Med. Resolution	RRS 30-10 km ✔	14-4 km ✔
High Resolution	RRS 18-6 km	30-1 km ✔

✔ = active ocean and sea ice + data atmosphere from CORE-1,2 (“G case”)
✔ = fully coupled 1850 (“B case”)
✔ for ice sheet = offline forced using G-case simulated sub-shelf melt rates

* Yeager and Large, *Clim. Dyn.* **33**, 2009; Griffies et al., *Ocean Mod.*, **26**, 2009)

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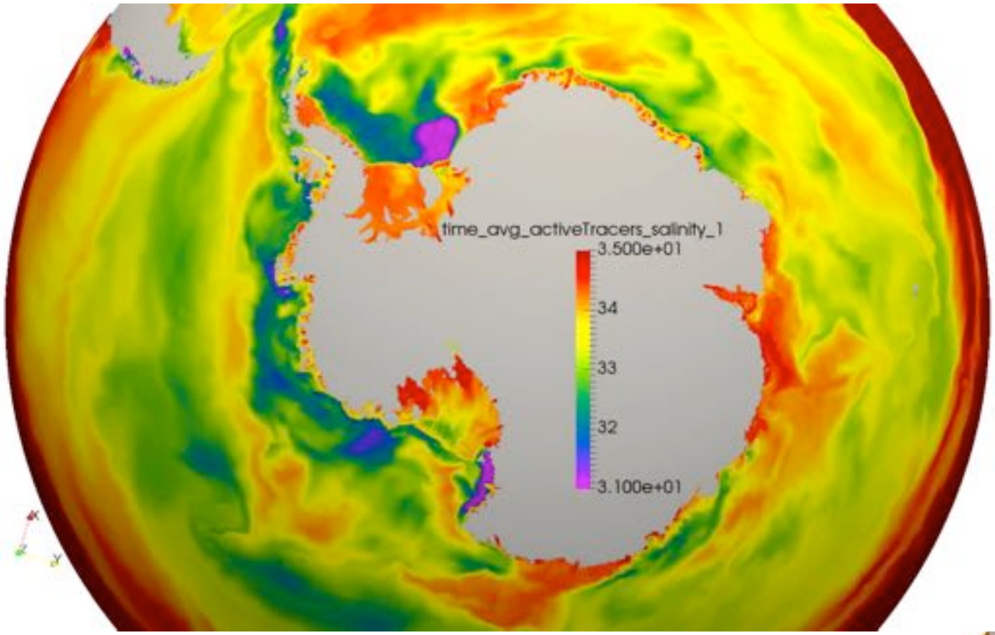
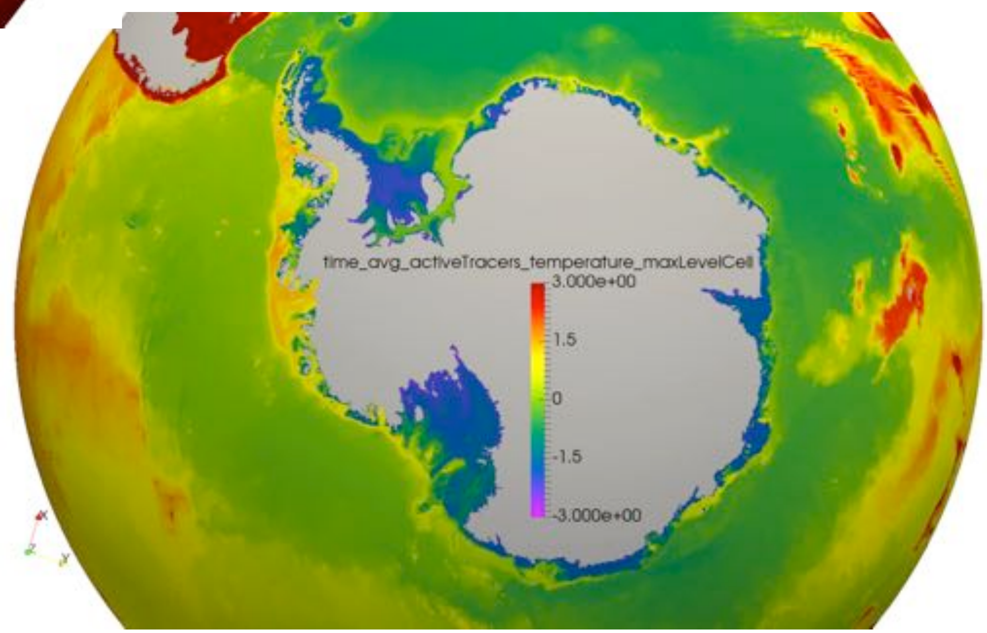
Circulation Beneath Antarctic Ice Shelves In ACME



Sea Surface Salinity

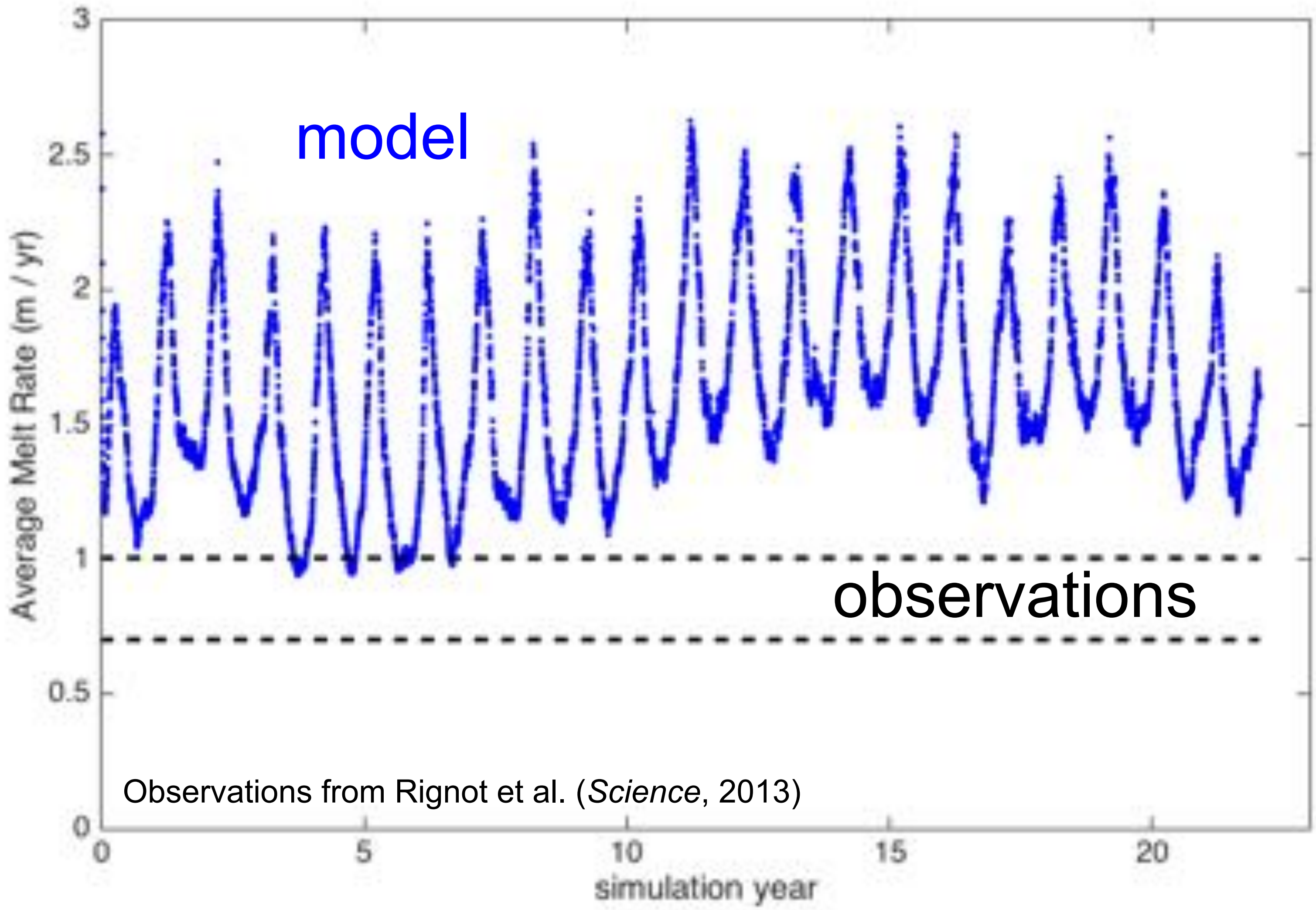
Price, Petersen, Asay-Davis, Fyke et al. (*AGU*, 2017)



Ocean Bottom Temperature

- RRS30to10km mesh (eddy permitting)
- CORE-NY forcing
- Shown: sea-surface salinity (top) and ocean bottom temperature (right) over ~7 yrs

Biases: sub-shelf melt rates

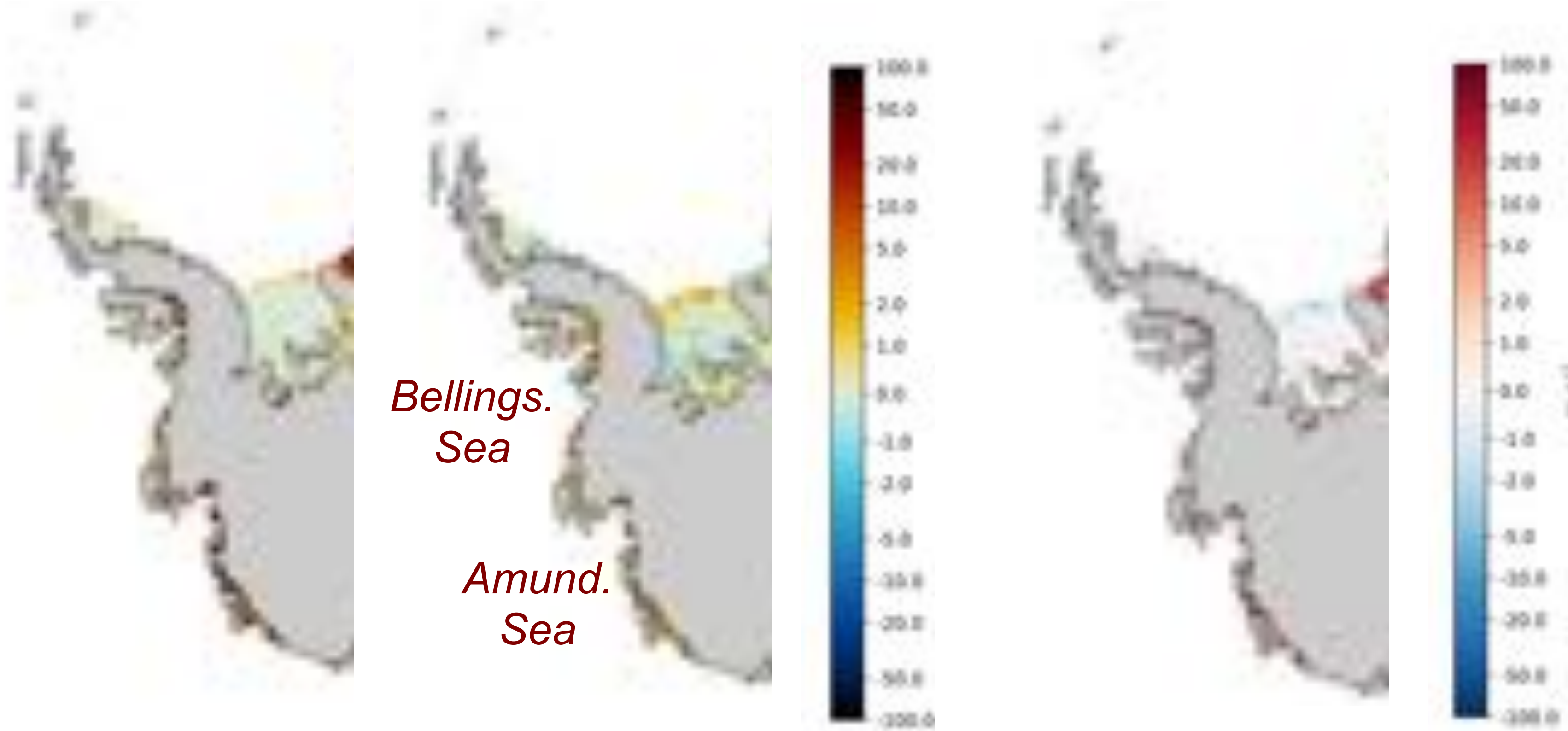


- integrated melt rates biased >2x too high
- no obvious trend

Biases: sub-shelf melt rates

(RRS30to10km resolution)

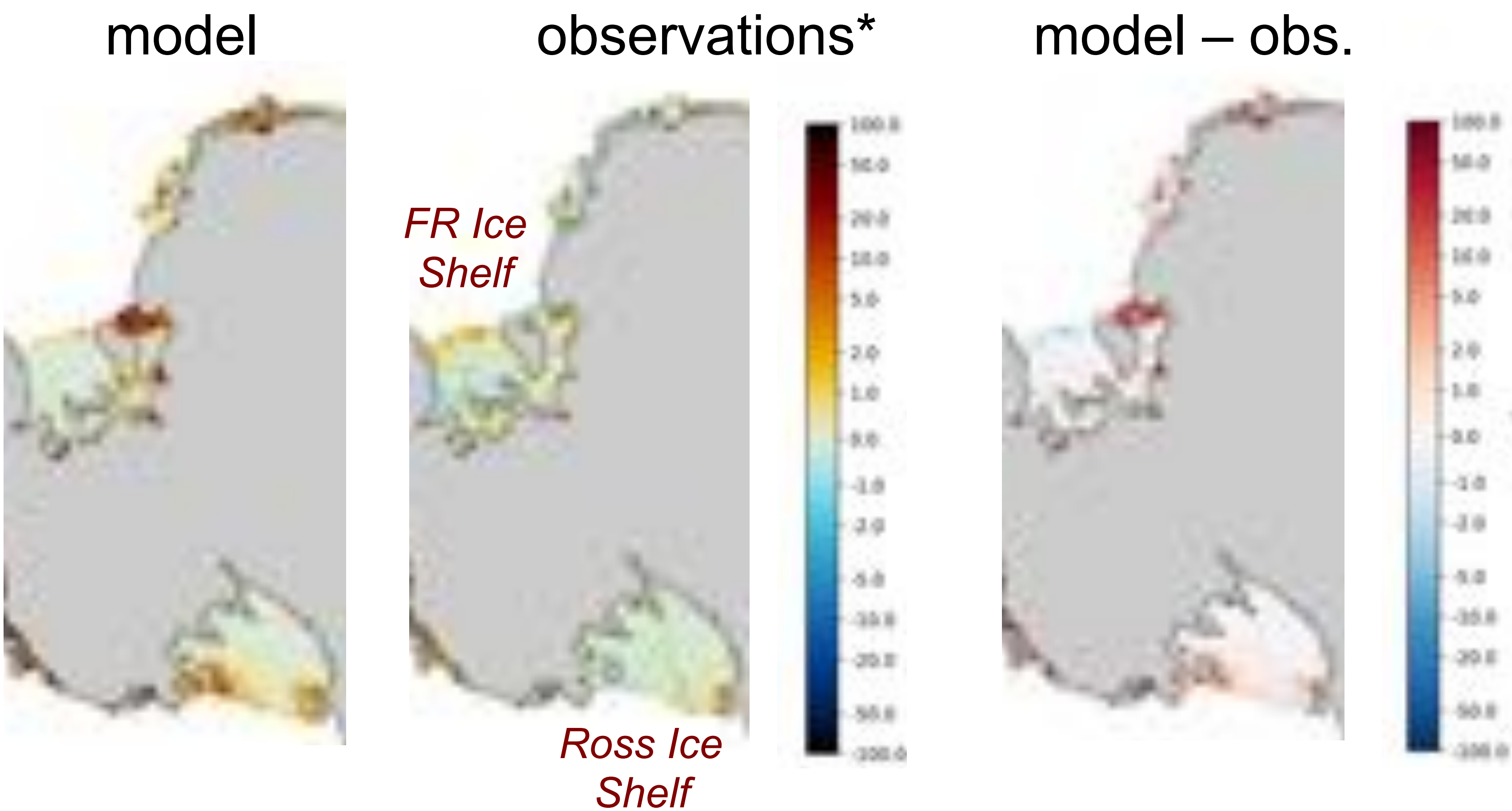
model | observations* | model – obs.



* Rignot et al., *Science*, 2013

Biases: sub-shelf melt rates

(RRS30to10km resolution)

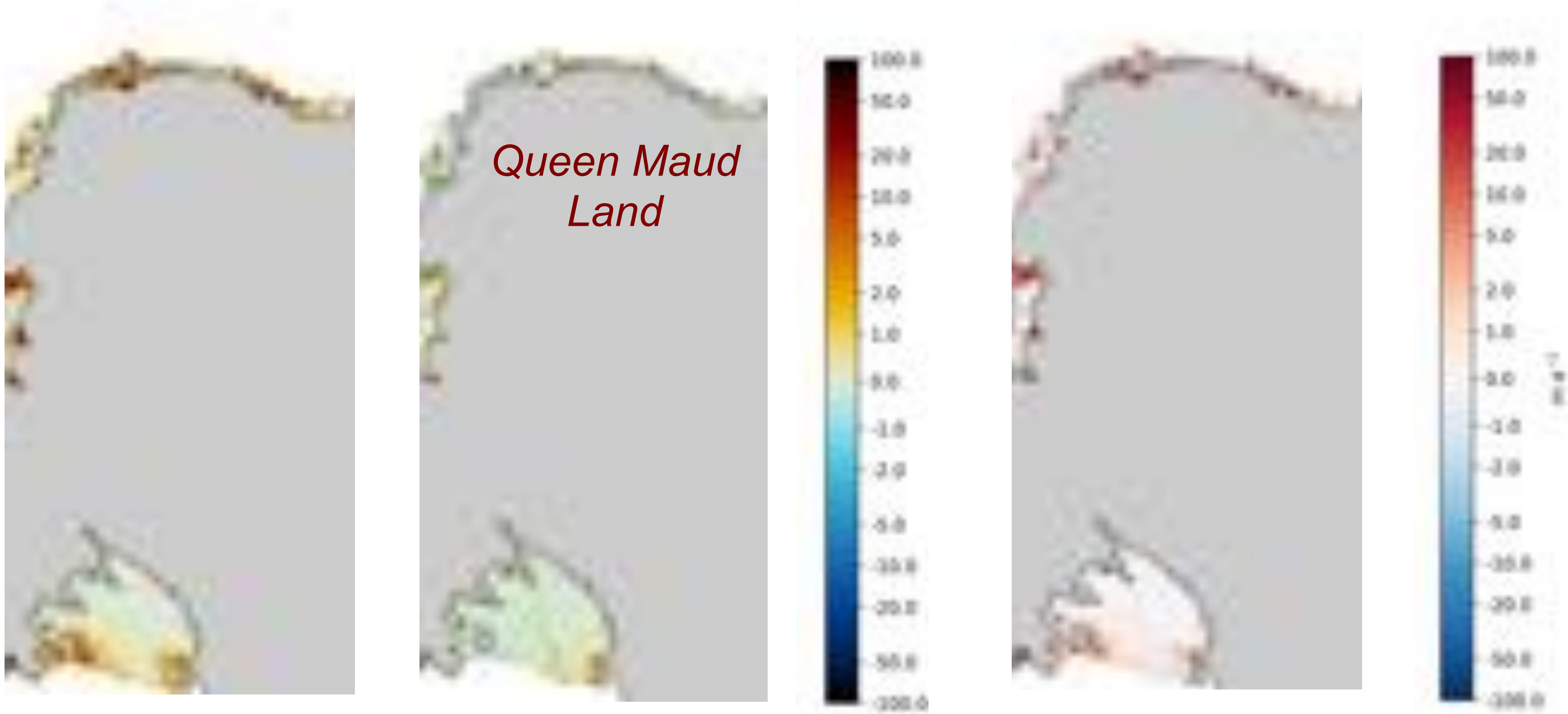


* Rignot et al., *Science*, 2013

Biases: sub-shelf melt rates

(RRS30to10km resolution)

model | observations* | model – obs.



- melt rates overall biased too high
- spatially variable (reasonable in some areas)

* Rignot et al., *Science*, 2013

Simulations Biases

Why are melt rates too high?

- turbulent boundary layer (BL) coefficients?
- ice-sheet proximal water mass properties?
- mixed layer properties / vertical mixing?
- circulation?

Biases are broadly consistent across …

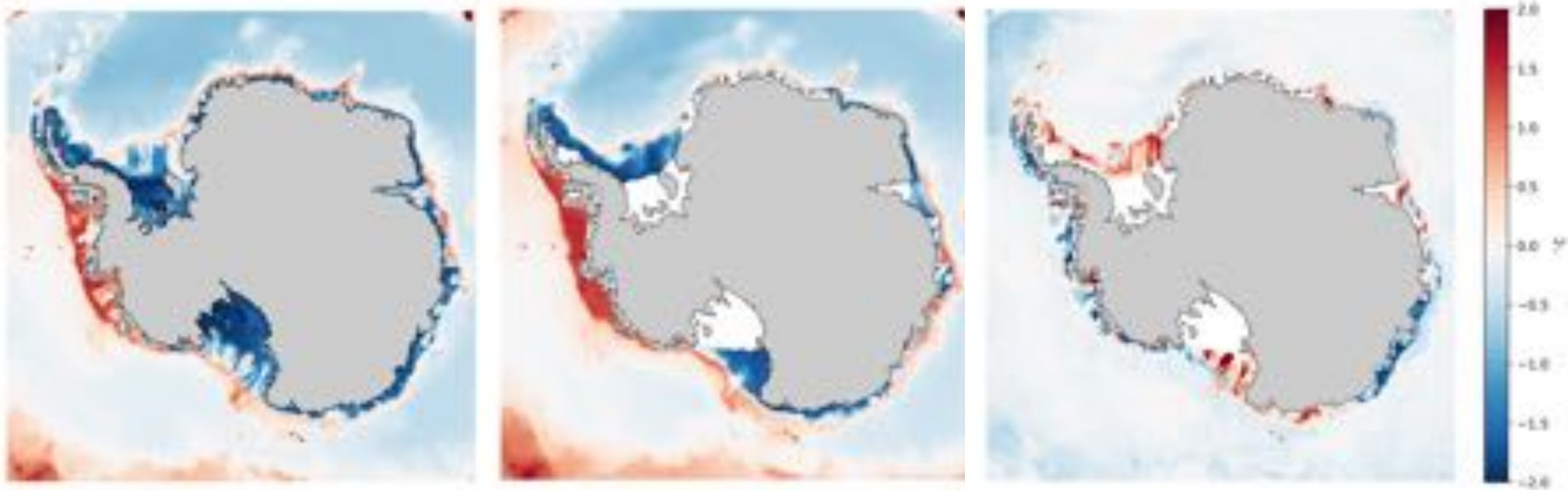
- range of forcings (CORE-NY, -IAF, fully coupled)
- range of resolutions (low and med res.)

Note: Some "observations" are model-data products (so uncertain & also possibly contributing to biases)

Biases: ocean T & S at depth

(RRS30to10km resolution)

model	observations	model – obs.
(MPAS-Ocean)	(SOSE* - MITgcm state est.)	

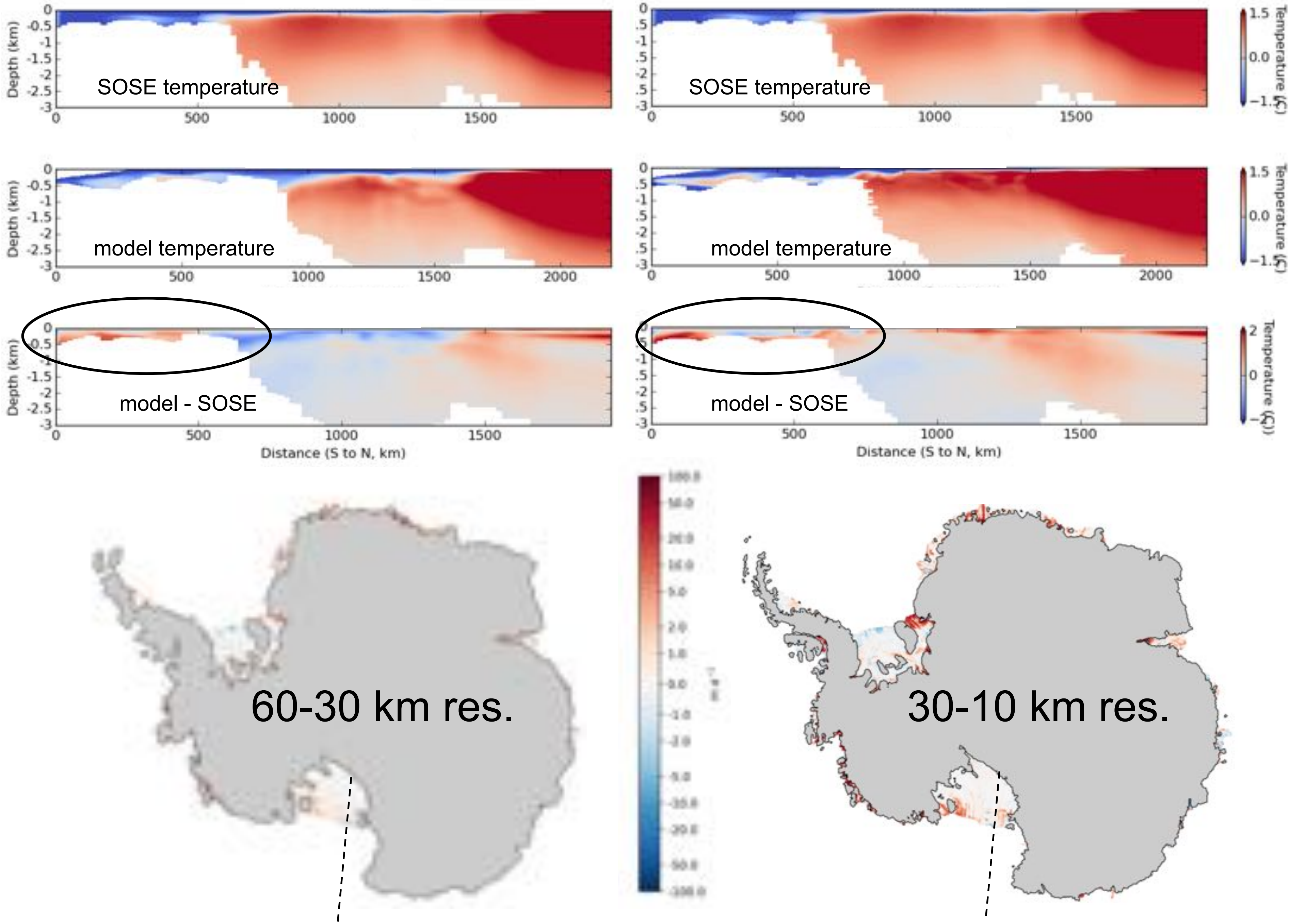


(bottom temperature shown)

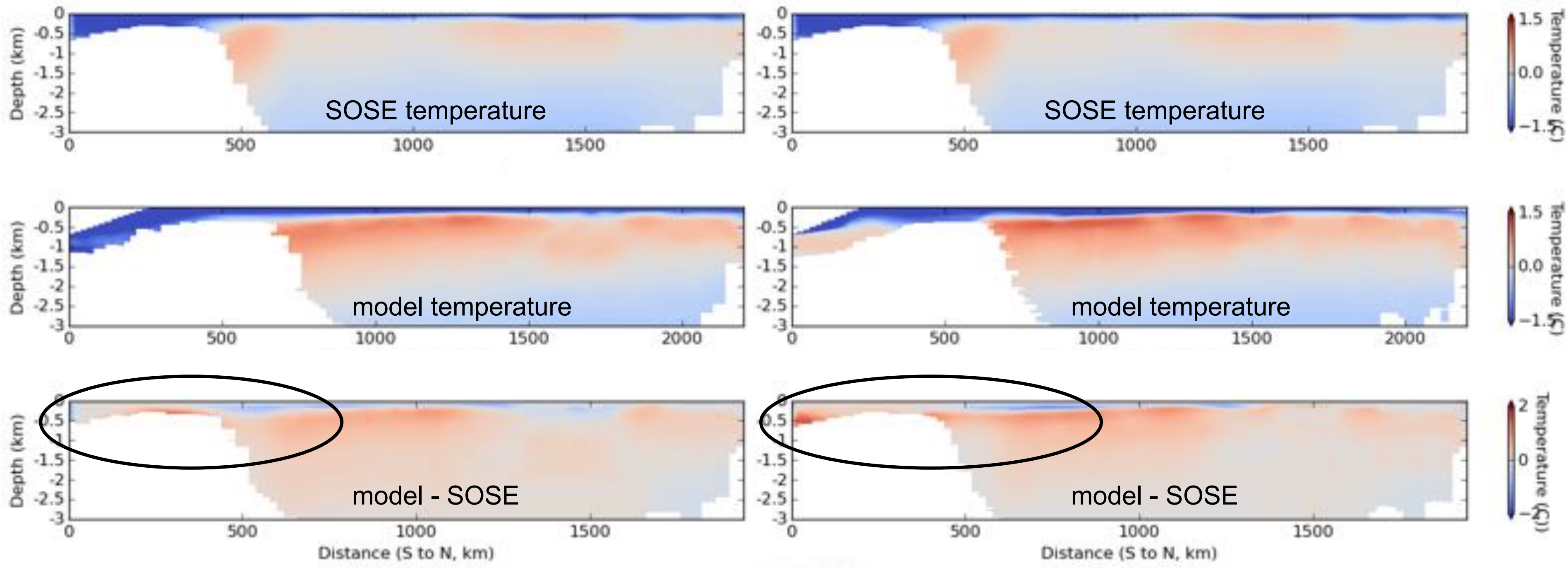
ocean temperatures at depth:

- too warm near near large ice shelves
- (regionally) too warm near *some* smaller shelves
- good correlation between too warm / too much melt

* SOSE: Mazloff et al., 2010



SOSE temperature
SOSE temperature
model temperature
model temperature
model - SOSE
model - SOSE
Depth (km)
Distance (S to N, km)
Temperature (C)
60-30 km res.
30-10 km res.



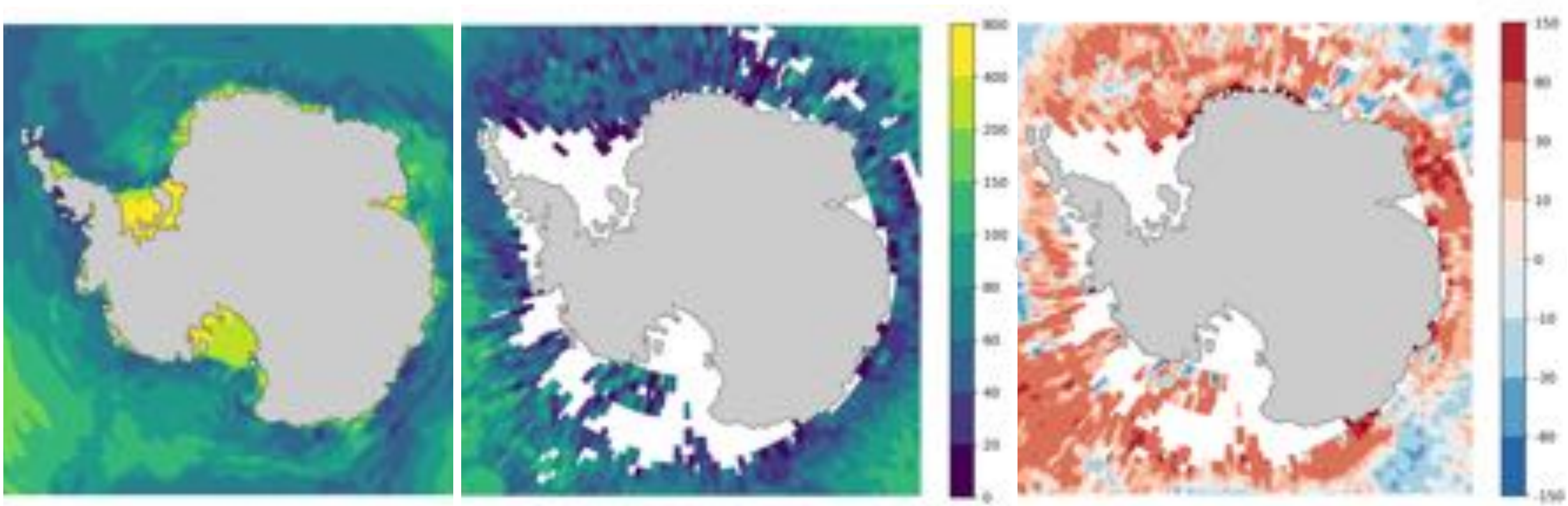
ocean temperature biases:

- ice-sheet proximal ocean too warm and/or …
- … too much warm water on cont. shelf / in cavity
- broadly similar biases for both low and med. res.

Why too warm on cont. shelves?

Biases: mixed-layer depth

model observations* model – obs. (m)



(annually-averaged mixed layer depth shown)

- mixed layer is too deep, especially in winter
- consistent with bias towards too much sea ice formation

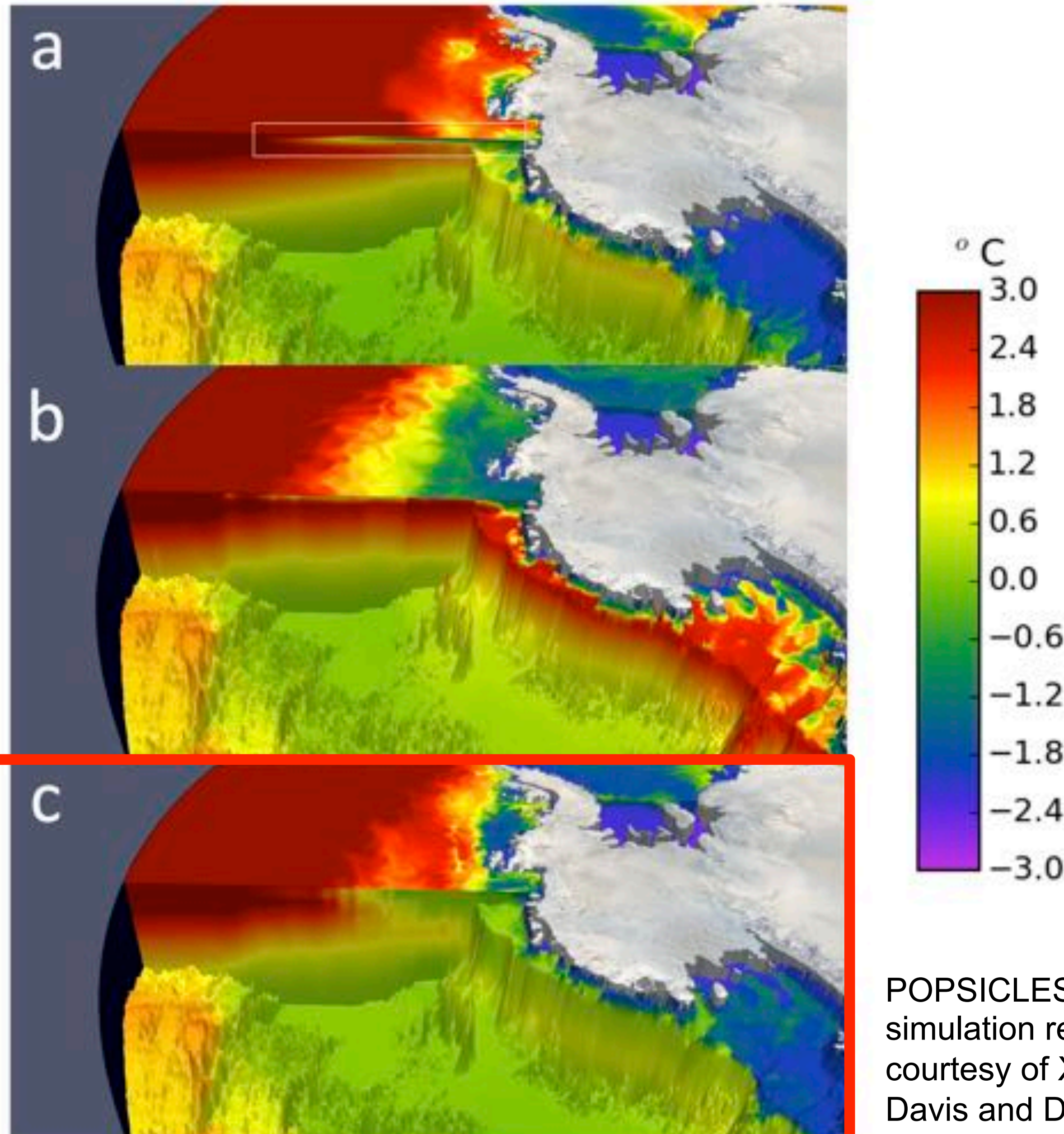
* Holte Talley density threshold MLD

Biases: mixed-layer (ML) depth

- normal ML

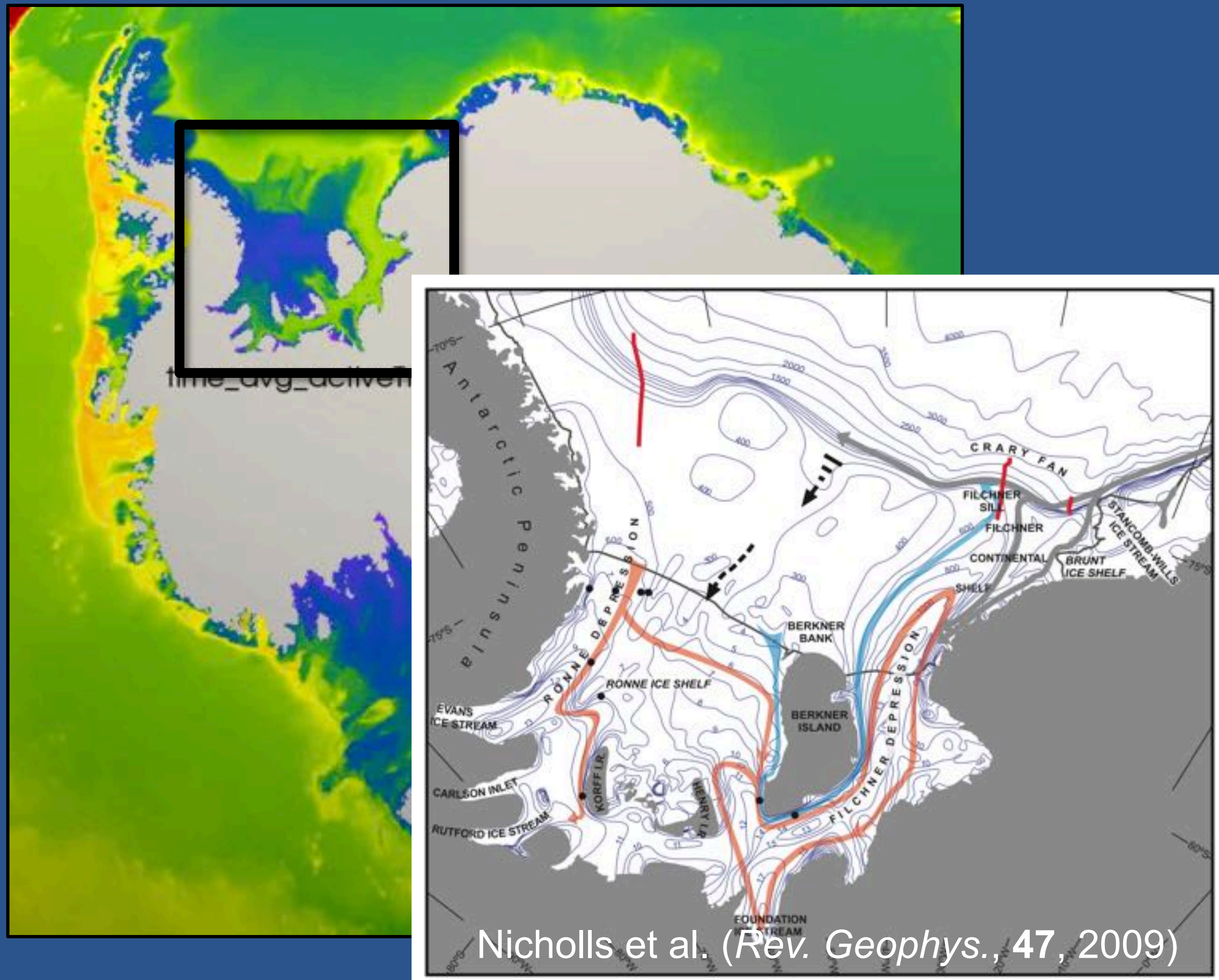
- ML shoals
- easy CDW access
- too much melting

- ML too deep
- CDW blocked
- too little melting



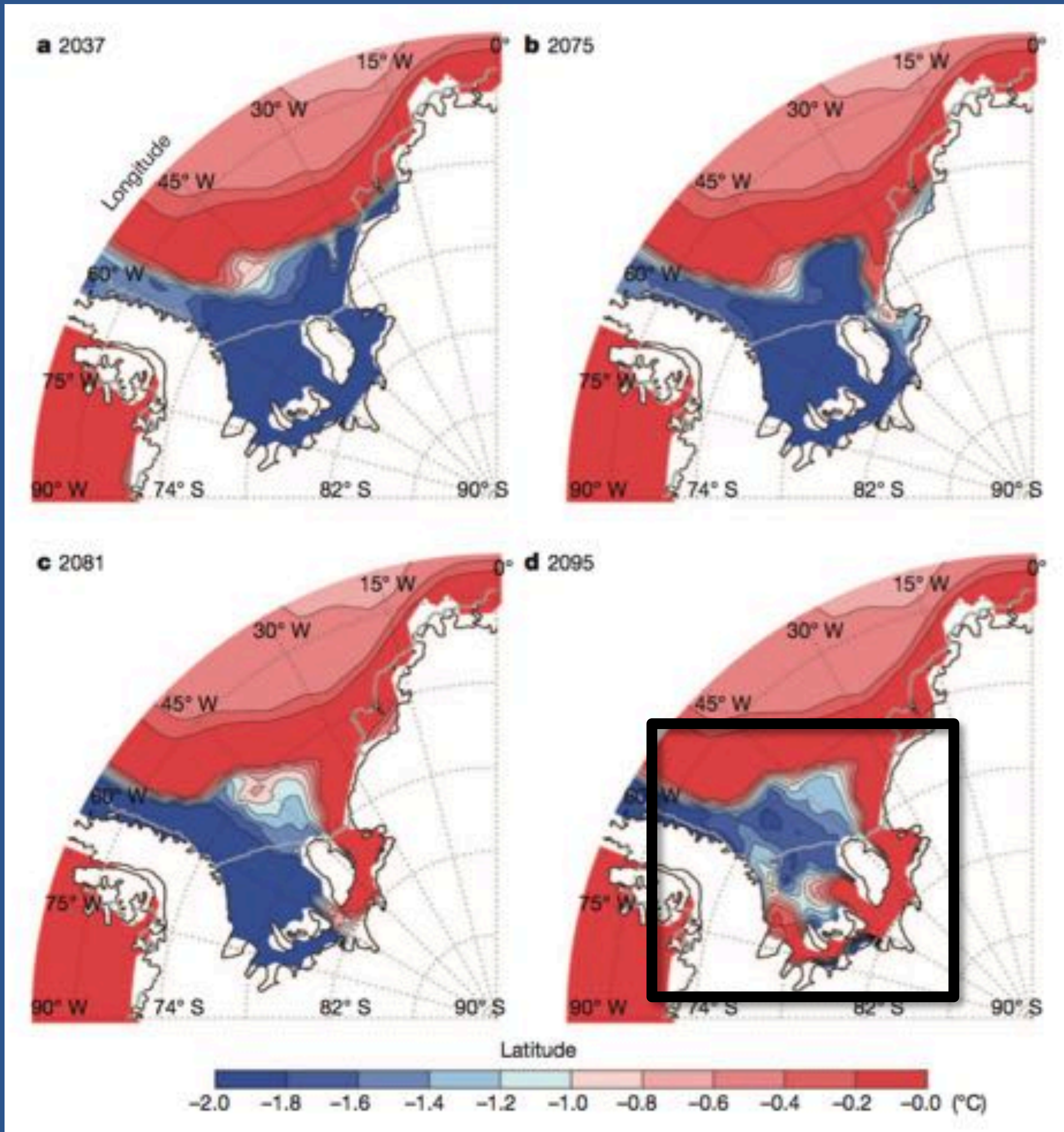
POPSICLES simulation results courtesy of X. Asay Davis and D. Martin

Large Ice Shelf Circulation Bias



Nicholls et al. (*Rev. Geophys.*, **47**, 2009)

Large Ice Shelf Circulation Bias



Modeled circulation beneath FRIS is akin to that reported by Hellmer et al. (*Nature*, **485**, 2012)

Allows CDW access to shelf cavity via Filchner trough with result of rapid sub-shelf melting

Attributed to changes in surface wind-stress and redirecting of coastal current

Summary

ACME has a robust capability for global, coupled simulations of ice shelf & ocean interactions (across a range of resolutions & configurations)

High-resolution land ice models appropriate for marine-ice sheet simulations are mature & partially coupled to ACME

Marine ice sheet & ocean focused MIPS are being used to gain community acceptance of new models & couplings

Melt rate biases due to warm water flooding of shelf cavities:

- Resolution? (coastal current; slope front; IS front)
- Improved initialization? (Ross, FR “cold”; others “warm”)
- Vertical mixing biases? Sea ice formation biases?
- Other coupled model biases?

On-going & Future Work

Continue bias identification & reduction:

- idealized configuration (e.g., G. Marques talk)
- understand biases in context of 3 “modes” of melting
- catalog & understand biases regionally

Perturbed wind experiments (e.g., S. Griffies talk)

New DOE HPC computing award focused on ice-ocean interactions (87 M cpu hours spread across 3 centers)

New 5 yr SciDAC project (pending) focused on furthering ACME sea-level projection capabilities:

- dynamic ice sheet & ESM coupling
- ice sheet & ocean model physics (e.g. non-Boussin.)
- solid earth & gravitational effects (eustatic -> regional)