MOM6 Capabilities for Modeling Sea Level Rise

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with contributions from

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CESM Winter Workshop

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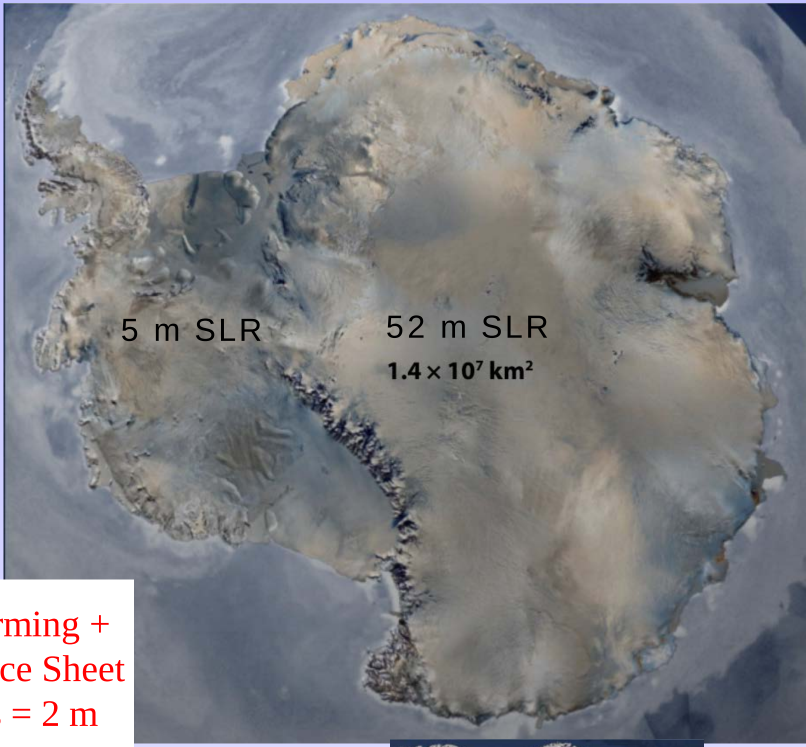
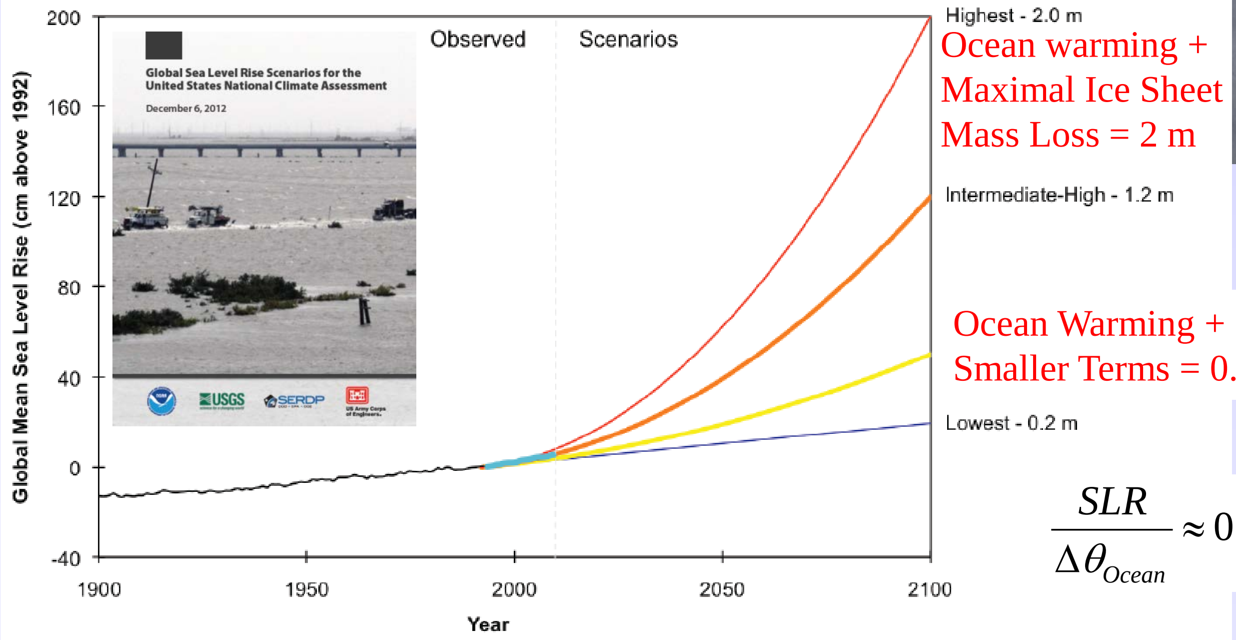
Projecting Sea Level Rise

- Sea levels are rising for a variety of reasons in oceans, mountain glaciers, ice-sheets & land
- Ocean expansion due to warming is currently the largest source of global sea level rise
- Ice sheet mass loss is the largest term and largest source of uncertainty in 21st century sea level rise projections.



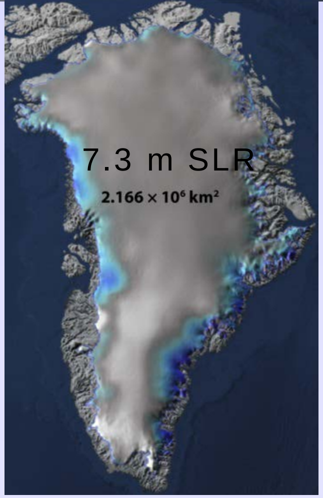
Sea Level Rise Scenarios from 2012 NOAA/CPO Report



Ocean warming + Maximal Ice Sheet Mass Loss = 2 m

Ocean Warming + Smaller Terms = 0.5 m

$$\frac{SLR}{\Delta\theta_{Ocean}} \approx 0.5\frac{m}{{}^{o}C}$$



3 Ocean Modeling Challenges for Predicting Sea Level Rise

- Controlling diapycnal diffusion in the ocean

  Numerical ocean models introduce spurious mixing.
  - Arbitrary Lagragian Eulerian (ALE) approach
  - Hybrid/Isopycnal coordinates

  Physically based (energetically constrained) mixing parameterizations need to regulate diapycnal mixing
- Dynamically interactive ice-sheets
  - Continuous evolution of the ice-ocean boundaries at the grounding line and within ice-shelf cavities
- Icebergs and ice-ocean coupled instabilities
  - (Full talk tomorrow)

The Ocean’s Role in Climate Change
Steric Sea Level Rise

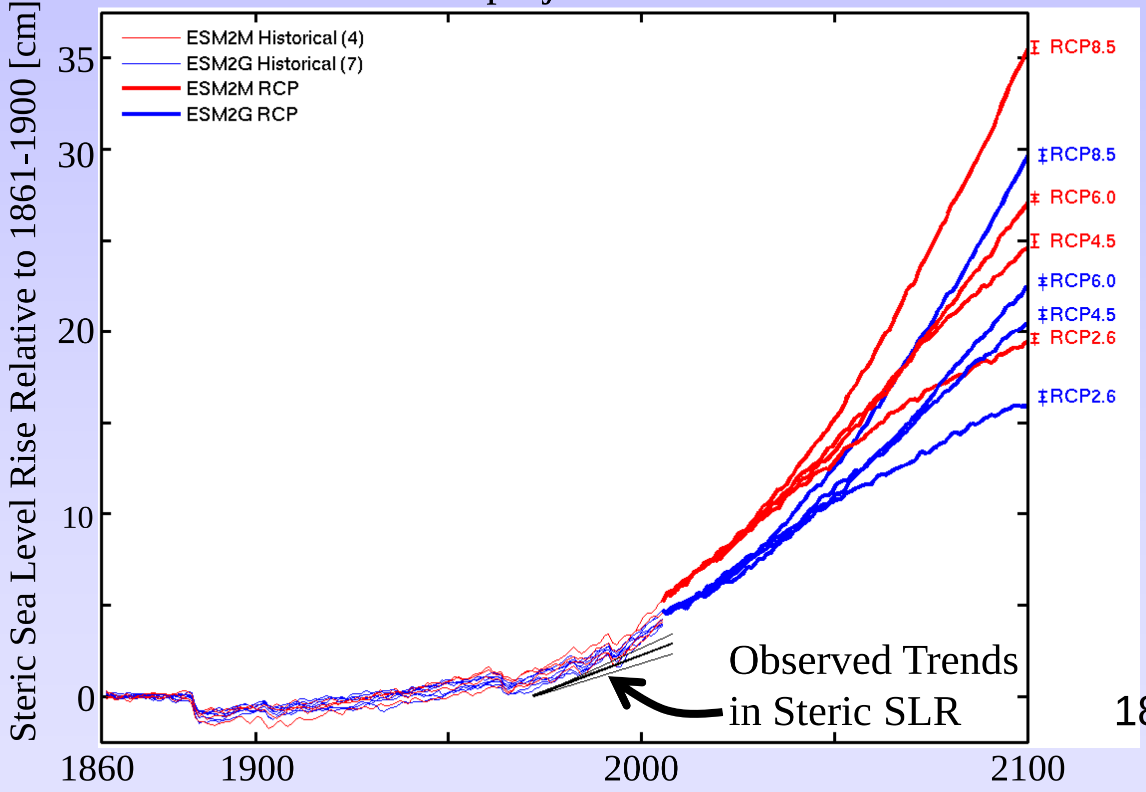
Exploring the dynamics of Sea Level Rise

ESM2M & **ESM2G** – same atmosphere & ecosystems, different ocean models.

ESM2G – Isopycnal Coordinate Ocean

ESM2M – Z* Coordinate Ocean

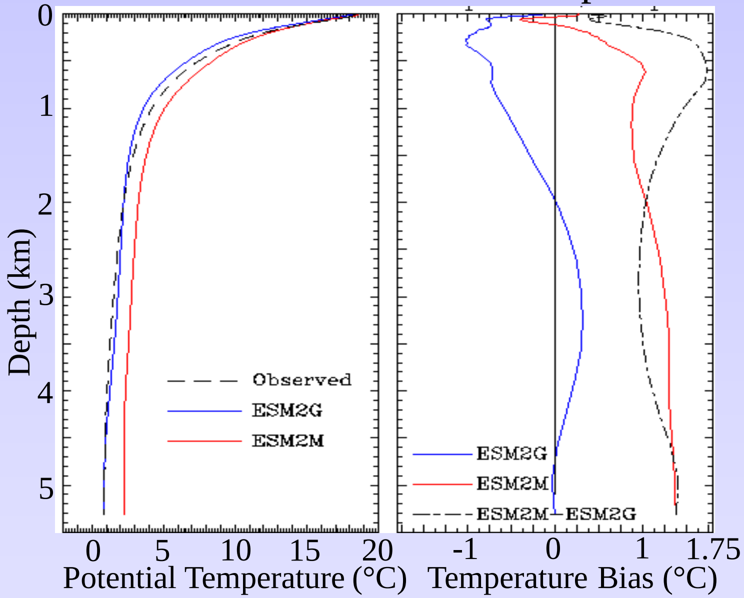
Historical & Scenario-projected Steric Sea Level Rise



Ref: Hallberg et al., 2013, *J. Climate*

ESM2G & **ESM2M** 1980-2000

Horizontal-Mean Ocean Temperature



18% larger steric SLR in ESM2M

9% due to more & deeper heat uptake

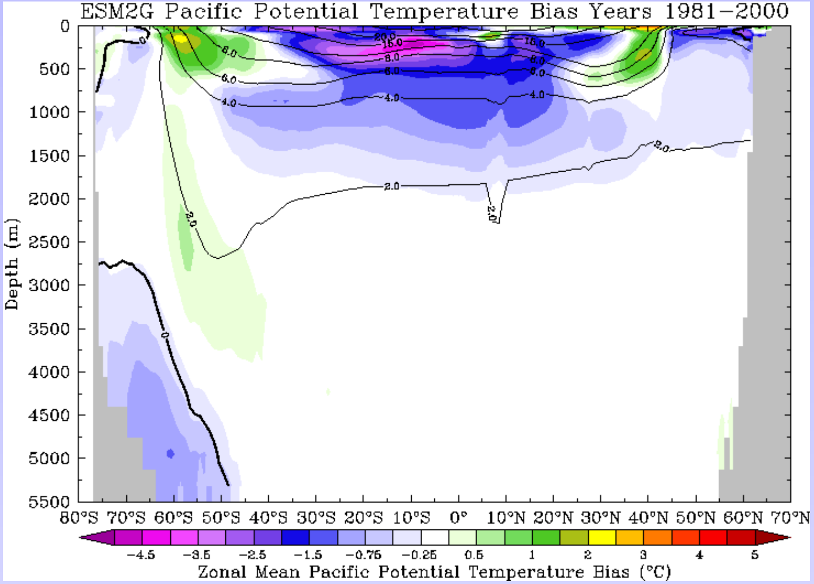
7% due to warmer spun-up ocean

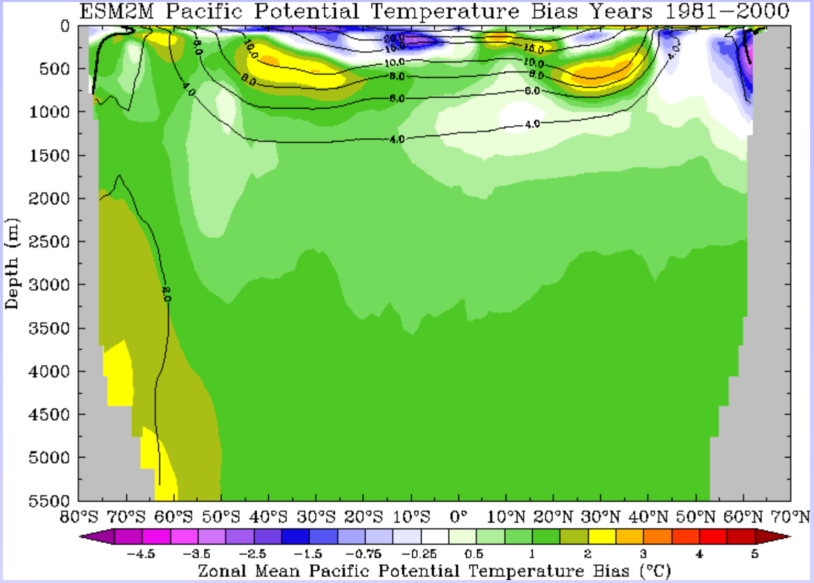
Pacific Ocean 1981-2000 Zonal-mean Biases

ESM2G

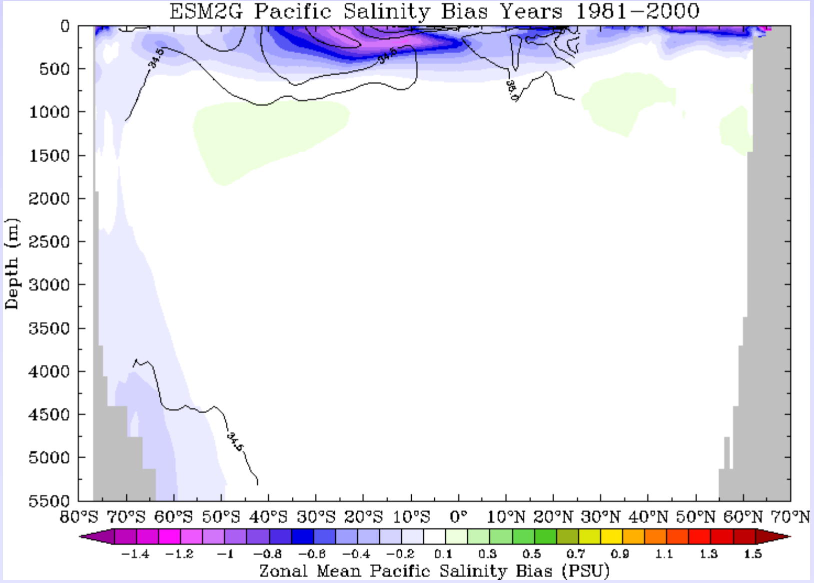
ESM2M

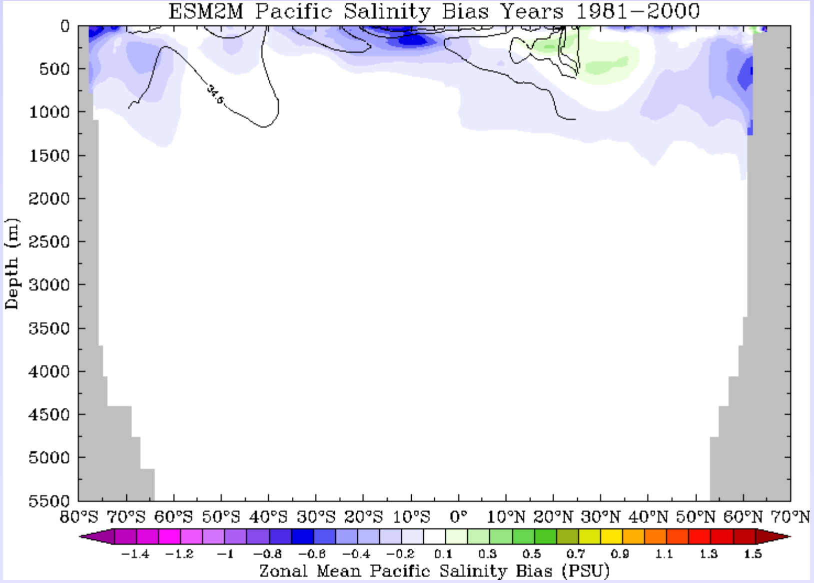
Potential Temperature


ESM2G Pacific Potential Temperature Bias Years 1981–2000


ESM2M Pacific Potential Temperature Bias Years 1981–2000

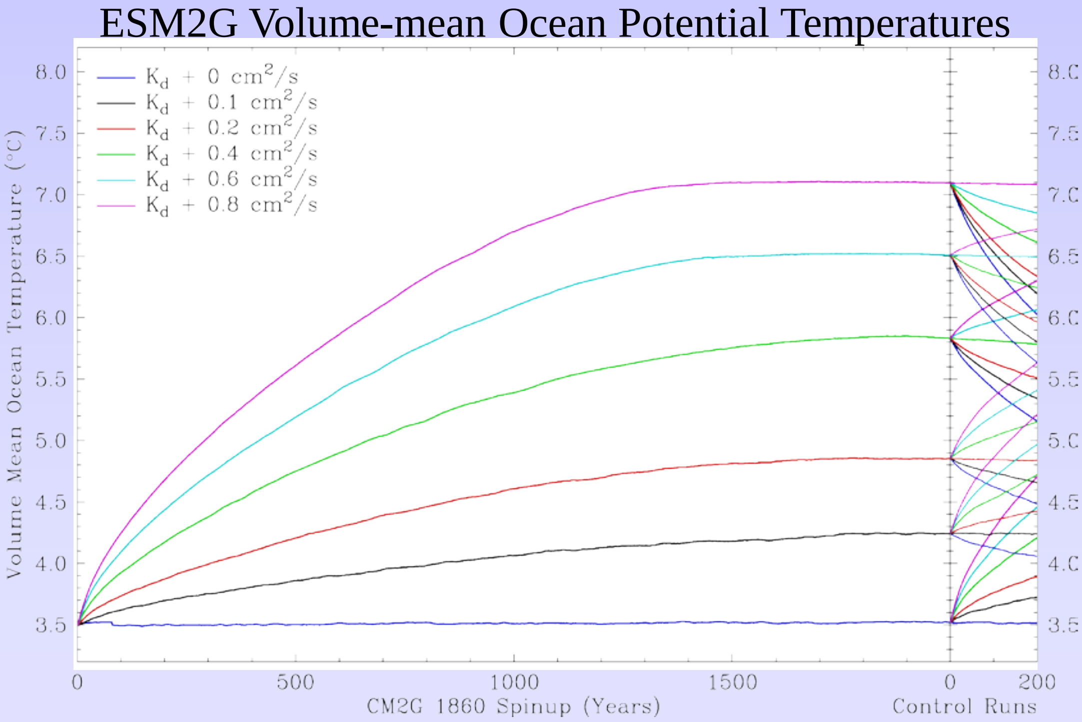
Salinity

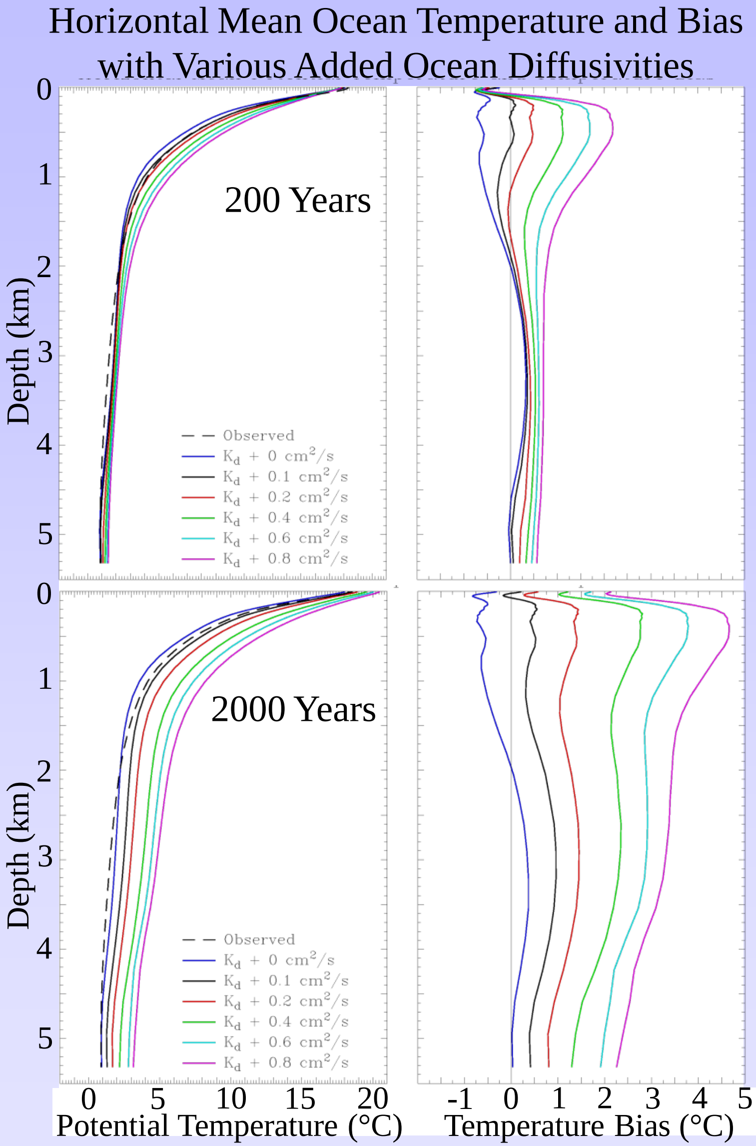

ESM2G Pacific Salinity Bias Years 1981–2000


ESM2M Pacific Salinity Bias Years 1981–2000

Sensitivity of the Ocean State and Steric Sea Level Rise to Diapycnal Mixing in the Ocean

Coupled model ocean drift and equilibrium bias are sensitive to the magnitude of diapycnal diffusion (mixing) in the ocean.


ESM2G Volume-mean Ocean Potential Temperatures

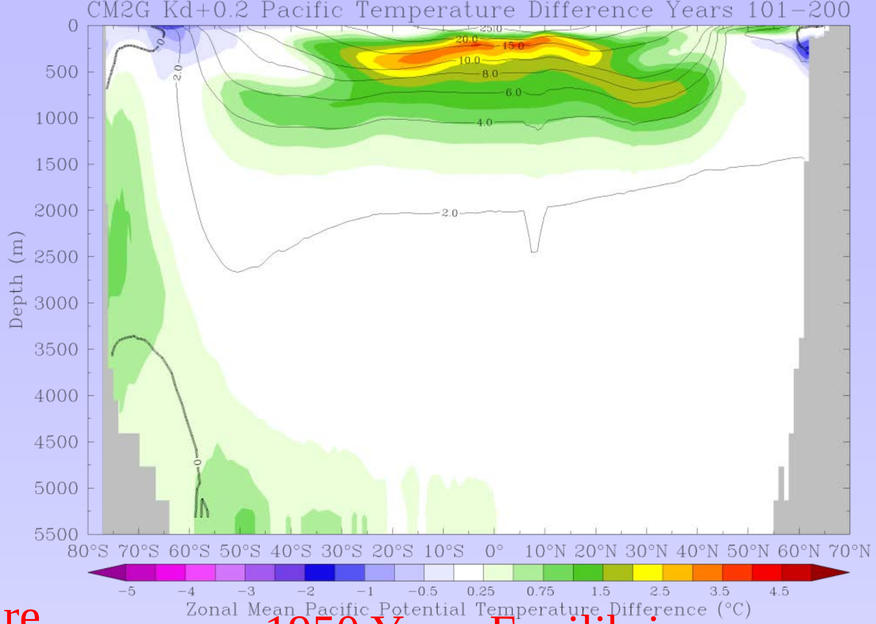

Horizontal Mean Ocean Temperature and Bias with Various Added Ocean Diffusivities

Ref: Hallberg, Melet & Samuels, 2018?

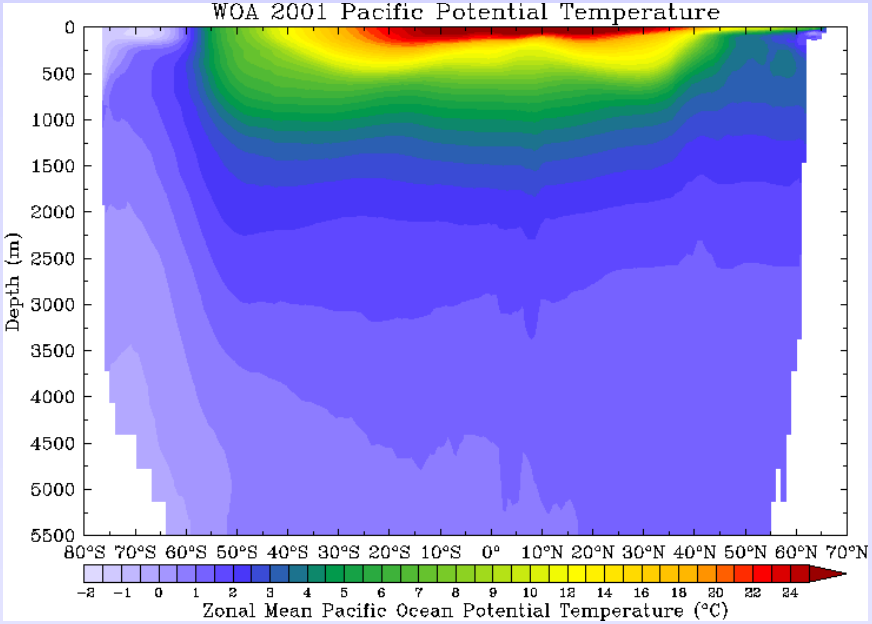
Pacific Temperature Response to Increased Diapycnal Diffusivity

- Increasing diffusivity warms the ocean
- Warming occurs first and most strongly in the main thermocline, but later throughout the ocean

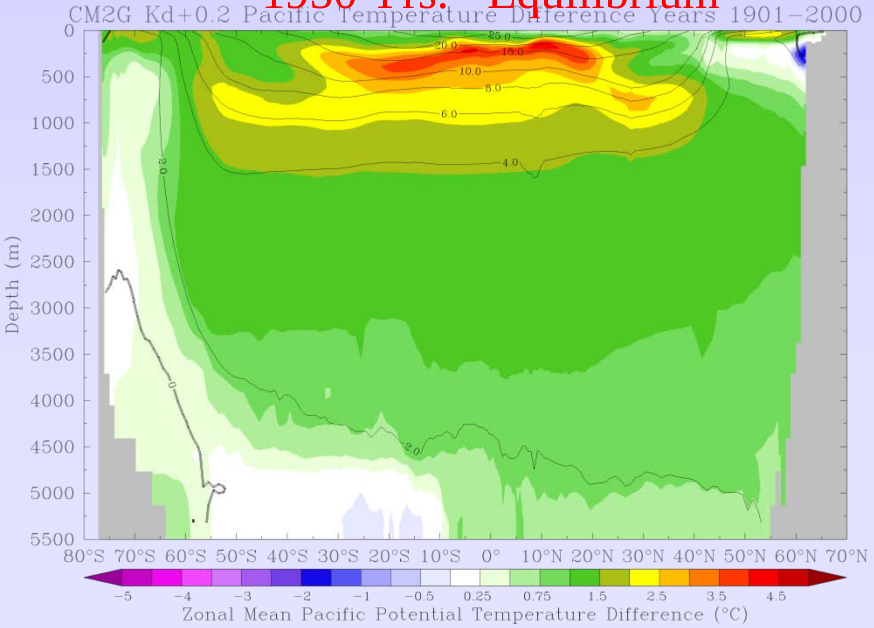
Effect of Increasing K_d $2x10^{-5}$, 150 Yrs.



Climatology of Zonal Mean Pacific Temperature

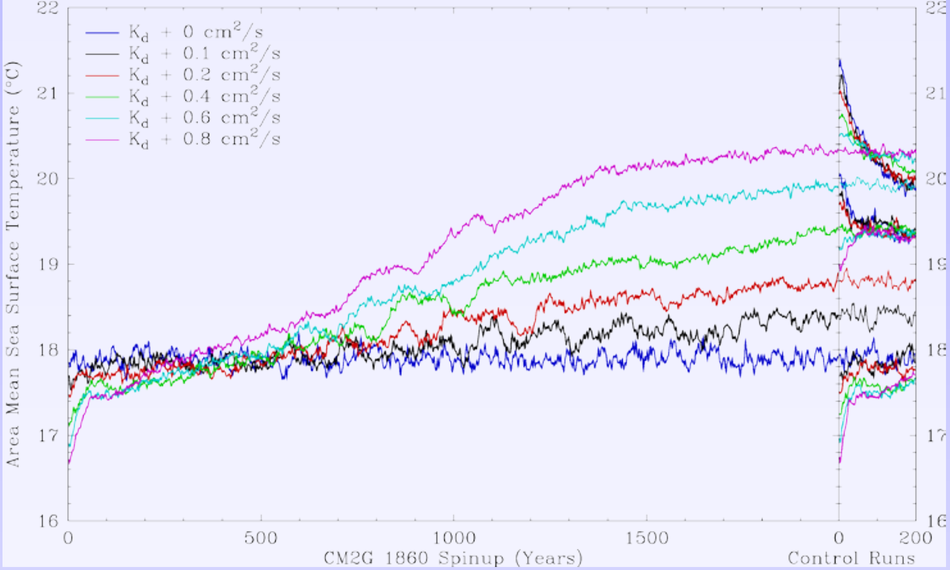


1950 Yrs. ~Equilibrium

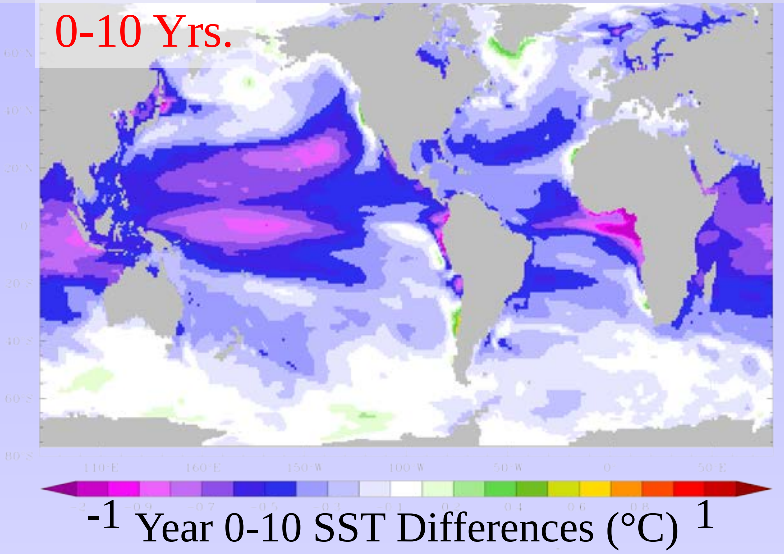


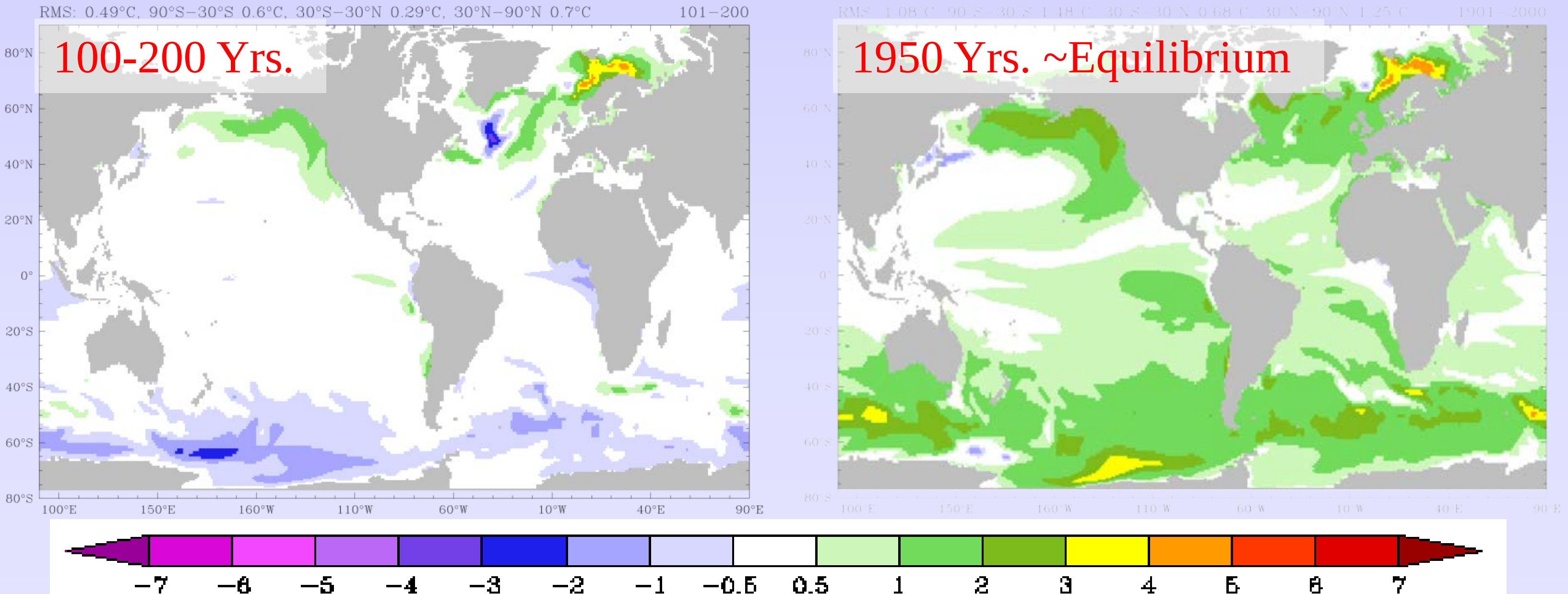
Diffusivity induced changes over time in Coupled Model Sea Surface Temperatures

Global Mean Sea Surface Temperature over Time



SST Change after Increasing K_d $2x10^{-5}$ m^2/s



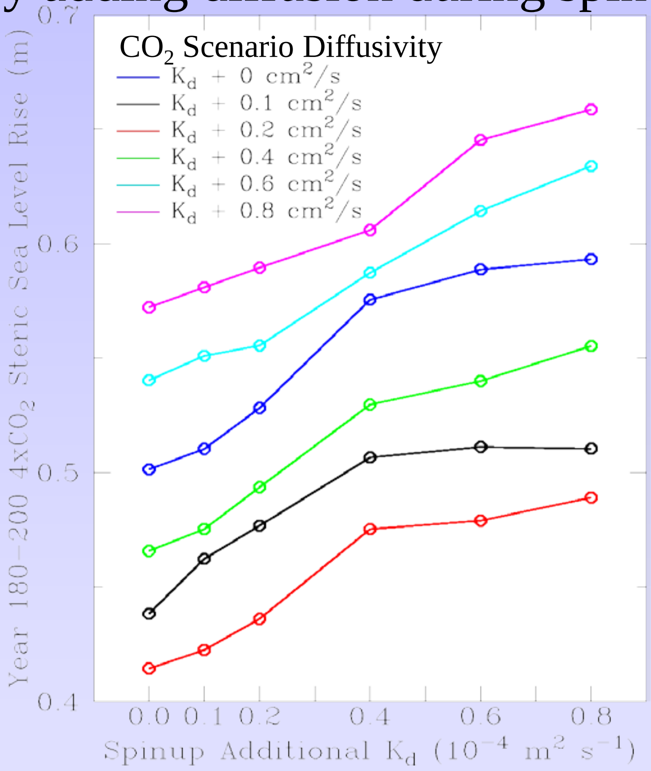


Sea Surface Temperature Differences (°C)

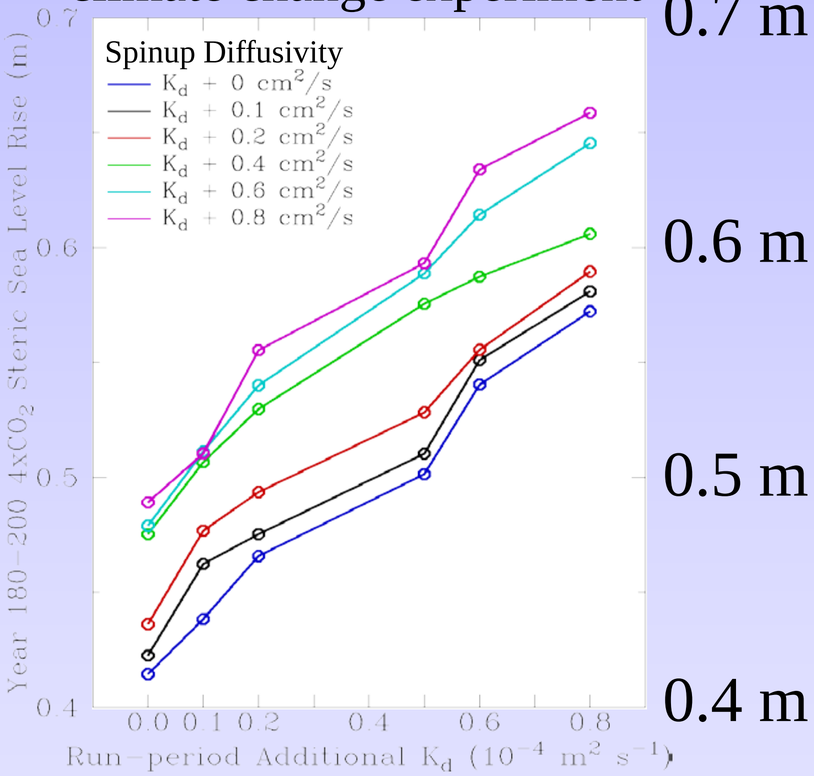
Sensitivity of Sea Level Rise to Ocean Diapycnal Mixing

Steric Sea-Level Rise after 200 Years in 1%/year to 4x CO_2 Run, Relative to Control

Changing initial conditions by adding diffusion during spinup



Adding diffusion during the climate change experiment

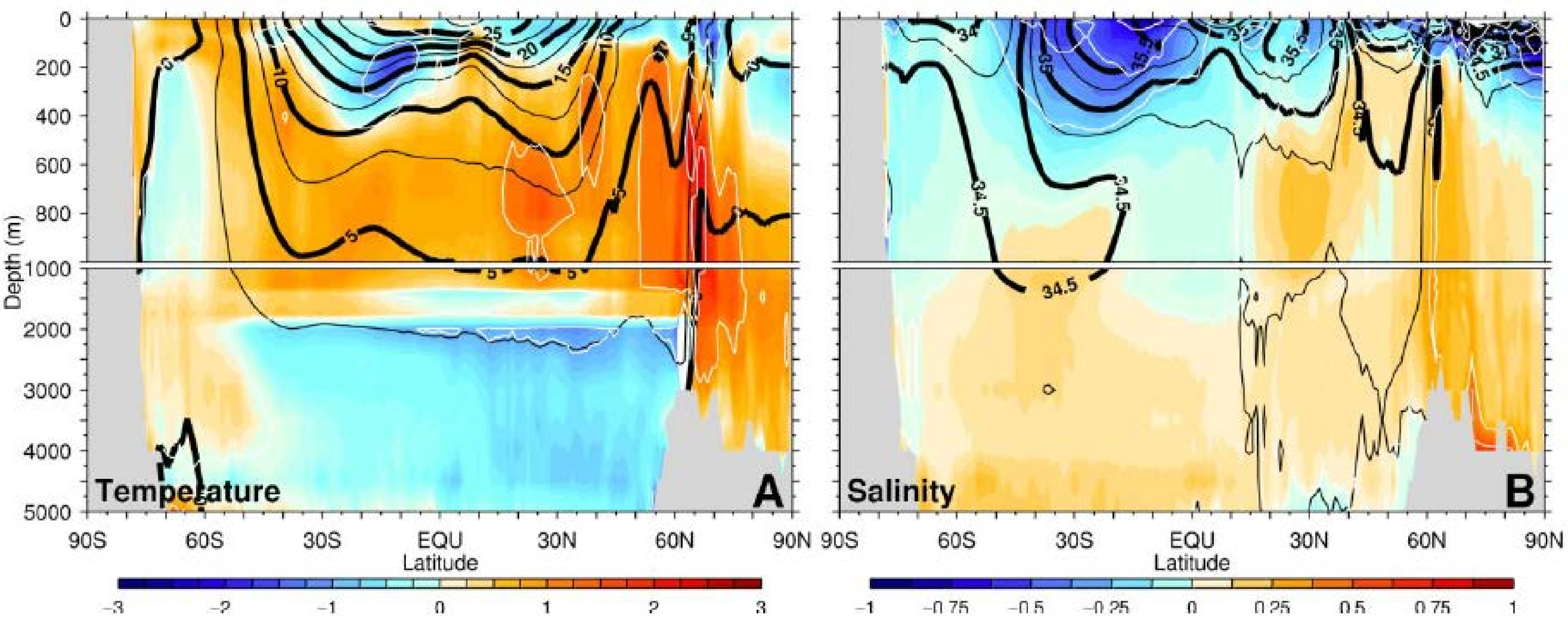


Adding diapycnal diffusion increases steric sea level rise both by increasing heat uptake and by warming the ocean (warmer water expands more when heated).

Both the initial conditions and mixing during the run contribute significantly.

CMIP5 Ensemble mean biases

Zonal Mean Ocean Temperature and Salinity Biases
in Ensemble Mean of CMIP5 Coupled Models



IPCC AR5 WG-I Fig. 9.13

- The majority of CMIP5 Coupled Climate Models have an overly broad and warm lower main thermocline.
- This is broadly consistent with excessive (numerical?) diapycnal diffusion.

The Arbitrary Lagrangian Eulerian method

Solve equations in 2 phases:

- a **Lagrangian** dynamic update (shallow water eqns.)
- Vertical remapping to an arbitrary (**Eulerian**?) coordinate

Momentum eqn.:

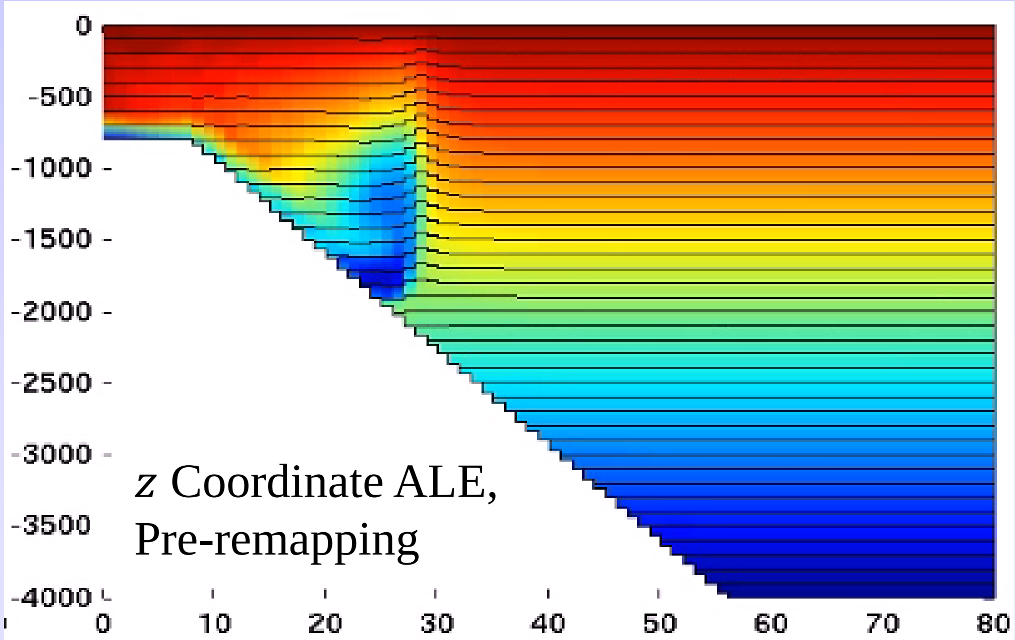
$$\underline{\underline{\frac{\partial \vec{u}}{\partial t}} + \dot{s}\frac{\partial \vec{u}}{\partial s}} + \underline{\left(f + \nabla_s \times \vec{u}\right)\hat{k} \times \vec{u} = -\frac{1}{\rho}\nabla_s p - \nabla_s\left(\phi + \tfrac{1}{2}\left\|\vec{u}\right\|^2\right) + \frac{1}{\rho}\nabla \cdot \tilde{\tilde{\tau}}}$$

Continuity eqn.:

$$\underline{\underline{\left.\frac{\partial}{\partial t}\right|_s \left(\frac{\partial p}{\partial s}\right)} + \nabla_s \cdot \left(\vec{u}\frac{\partial p}{\partial s}\right)} + \underline{\frac{\partial}{\partial s}\left[\dot{s}\frac{\partial p}{\partial s}\right]} = 0$$

Tracer eqn.:

$$\underline{\underline{\left.\frac{\partial}{\partial t}\right|_s \left(\frac{\partial p}{\partial s}\theta\right)} + \nabla_s \cdot \left(\vec{u}\frac{\partial p}{\partial s}\theta\right)} + \underline{\frac{\partial}{\partial s}\left[\dot{s}\frac{\partial p}{\partial s}\theta\right]} = \underline{Q\frac{\partial p}{\partial s}}$$



z Coordinate ALE,
Pre-remapping

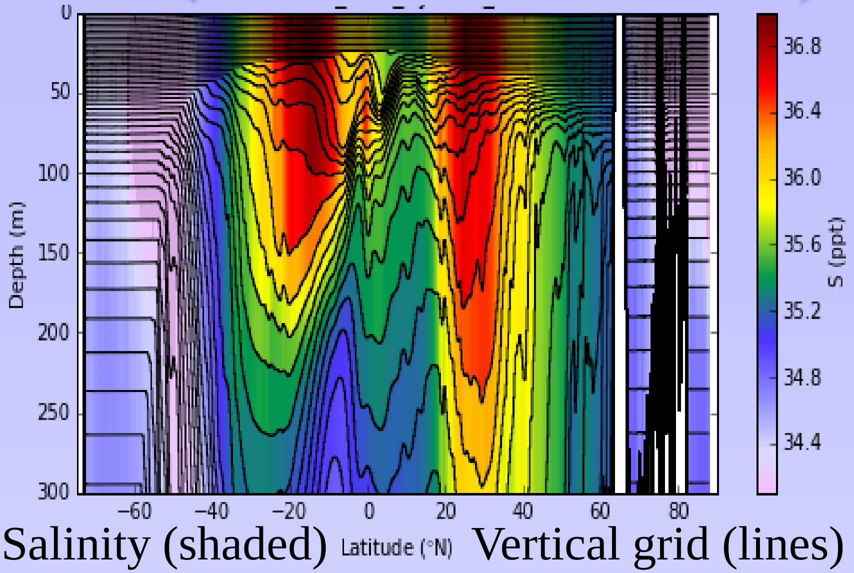
ALE advantages:

- Flexible vertical coordinates
- Remapping imposes no vertical CFL limit on timesteps
- Tracer advection not required to represent gravity waves

Role of vertical coordinate (¼° ocean in CM4)

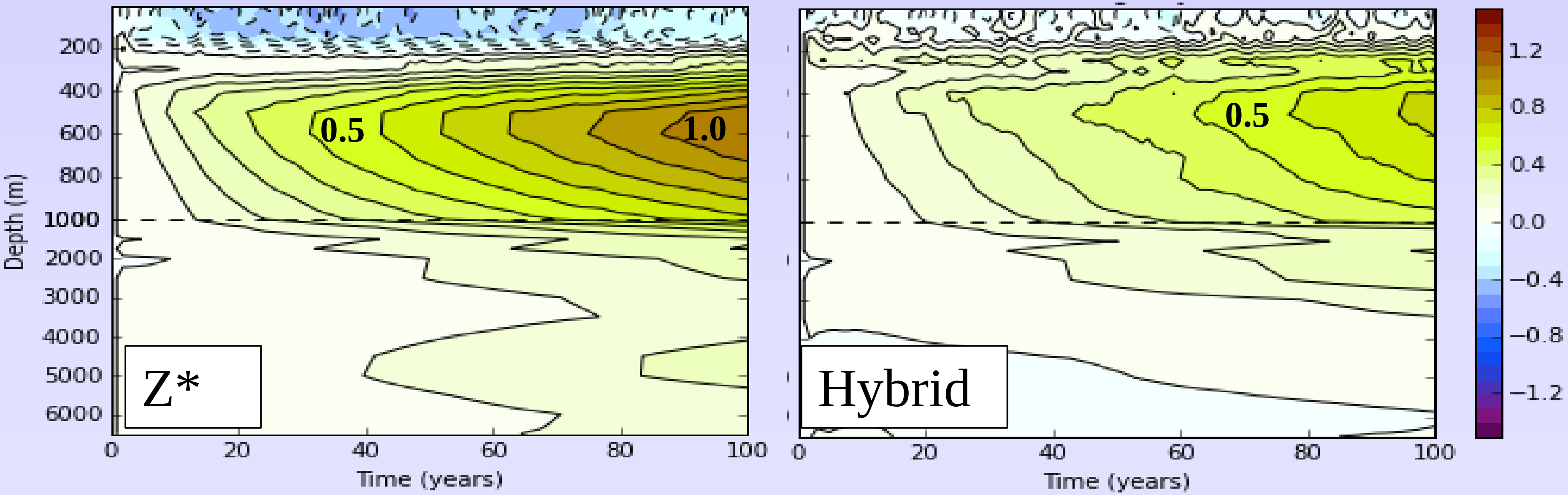
Changing vertical coordinate alone

- z^* to hybrid z^*/ρ_2 (a.k.a. HYCOM)
- Identical parameterizations and atmospheric models
- Reduced heat uptake by 0.27 Wm^{-2}



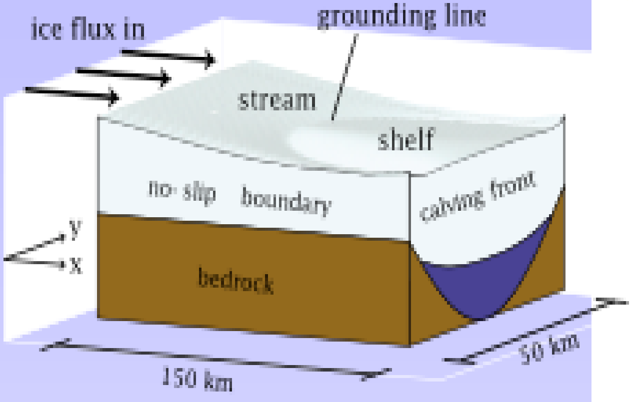
Salinity (shaded) Vertical grid (lines)

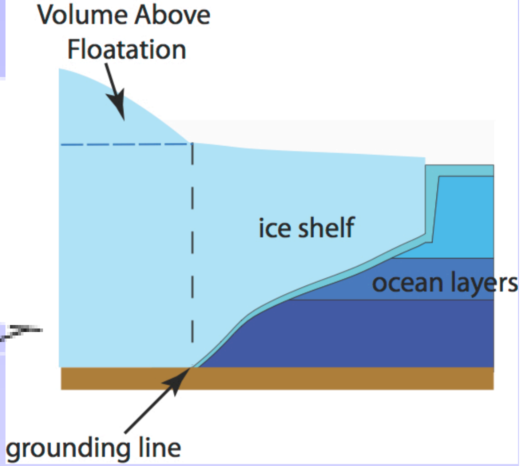
Horizontal Mean Temperature Drift



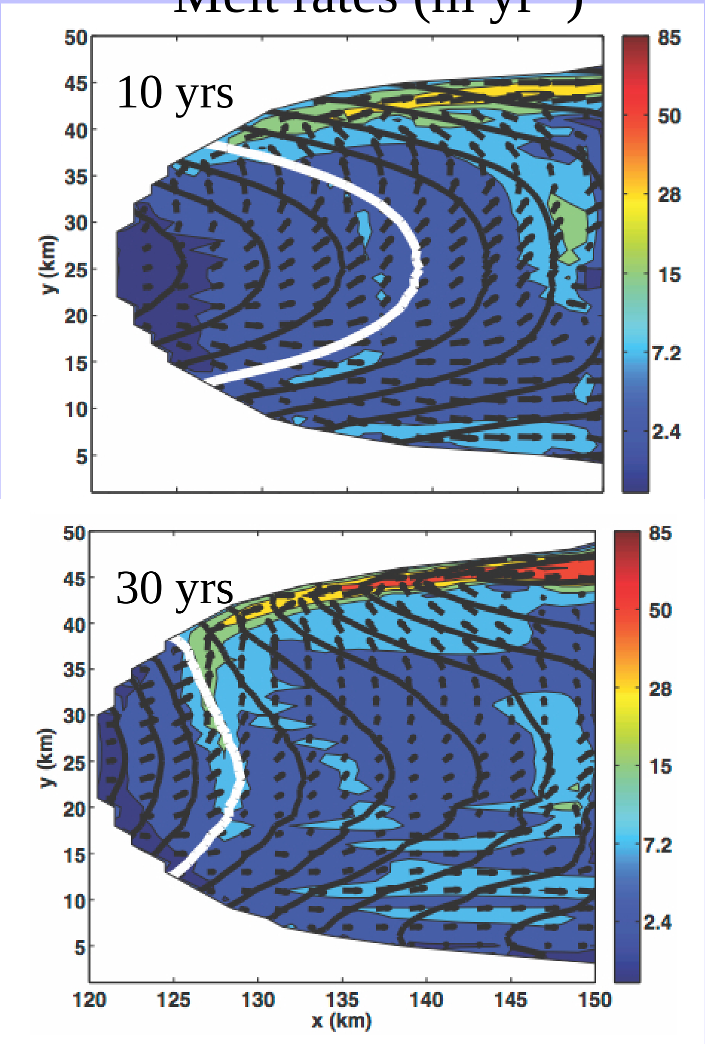
Chassignet et al., 2003; Megann et al., 2010; Ilicak et al., 2012

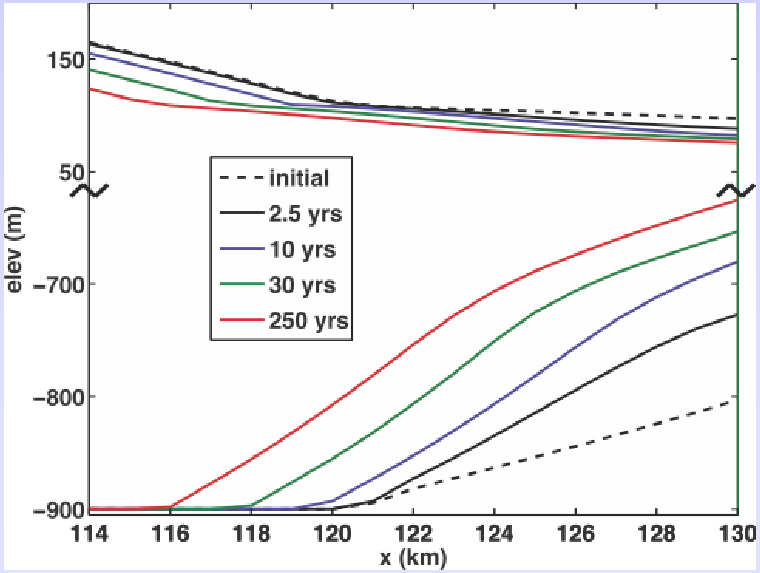
Dynamic Ice-shelf-ocean Interactions





Melt rates (m yr^{-1})





Goldberg et al., *JGR* (2012)

Dynamically Evolving Ice Shelf Cavities

- Melt-driven flow in ice shelf cavities simulated with evolving ice shelf model coupled to ocean
  - Moving upper boundary
  - Moving grounding line
- Note ocean squashed between shelf and bottom
- Preparing ⅛° coupled ocean-ice-shelf global simulations

Study by Gustavo Marques (2017)

MOM6 changes to permit dynamically evolving ice-shelf cavities and moving ground lines

- Do not approximate total ocean thickness by bottom depth
- Nonlinear barotropic continuity solver, including a local linearization about the transports from the layers and appropriate limits for strong flows

$$\eta \equiv \sum_k h_k - H_{Bottom} \qquad \frac{\partial h_k}{\partial t} + \nabla_s \cdot \left(u h_k \right) = 0 \qquad u h_k = \frac{1}{\Delta t} \int_{-u_k \Delta t}^{0} h(x)\, dx$$

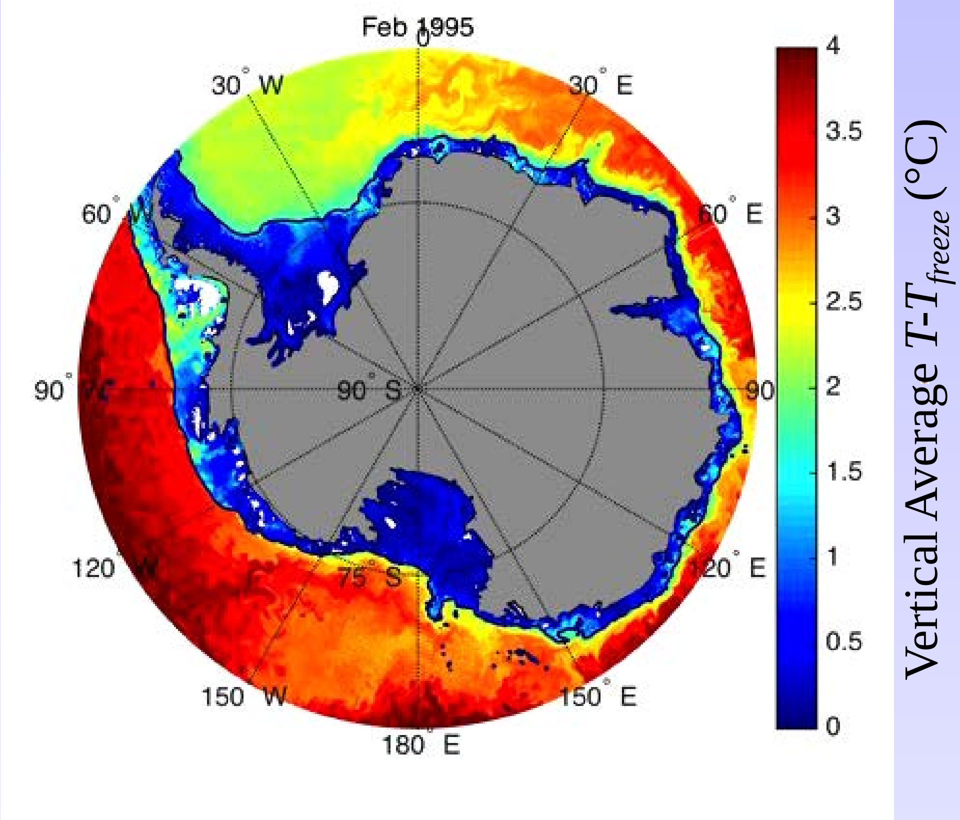
$$\frac{\partial \eta}{\partial t} + \nabla_s \cdot \left(\sum_k u h_k \right) = 0 \qquad U(\overline{u}) = \sum_k u^0 h_k + \left(\sum_k \frac{\partial u h_k}{\partial u_k} \right) \left(\overline{u} - \overline{u}^0 \right)$$

$$\frac{\partial \eta}{\partial t} + \nabla_s \cdot U(\overline{u}) = 0 \qquad \frac{\partial \overline{u}}{\partial t} + f\hat{k} \times \left(\overline{u} - \overline{u}^0 \right) = -g \nabla \left(\eta - \eta^0 \right) + \left(\sum_k h_k \frac{\partial u_k}{\partial t} \Big/ \sum_k h_k \right)$$

- Invert layers' piecewise parabolic method continuity solvers to find the barotropic velocity correction with the summed transport determined by the barotropic solver
- Add damping of external gravity waves by ice-shelf rigidity

Coupled Ice-shelf-ocean Interaction

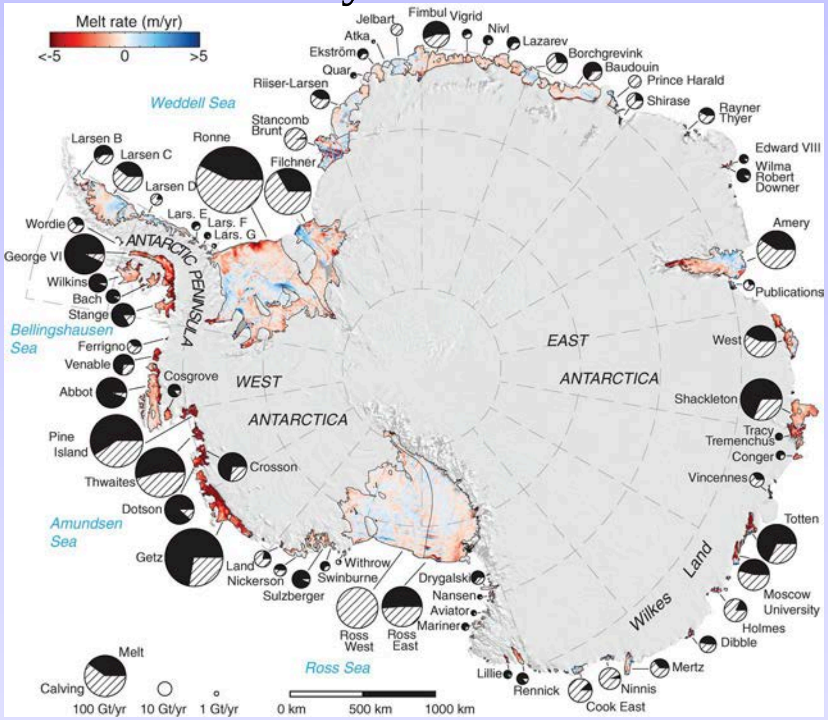
MOM6 ⅛° **Global** Ocean Model
Coupled with Ice-Shelf/Sheet Model



Vertically Averaged Ocean Temperature above the in-situ Freezing Point

Sergienko, Harrison and Hallberg (2018?)

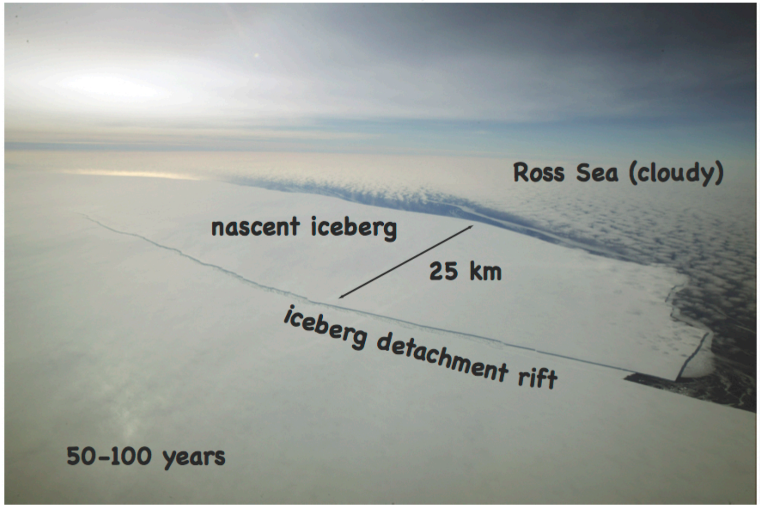
Observationally Inferred Mass Loss



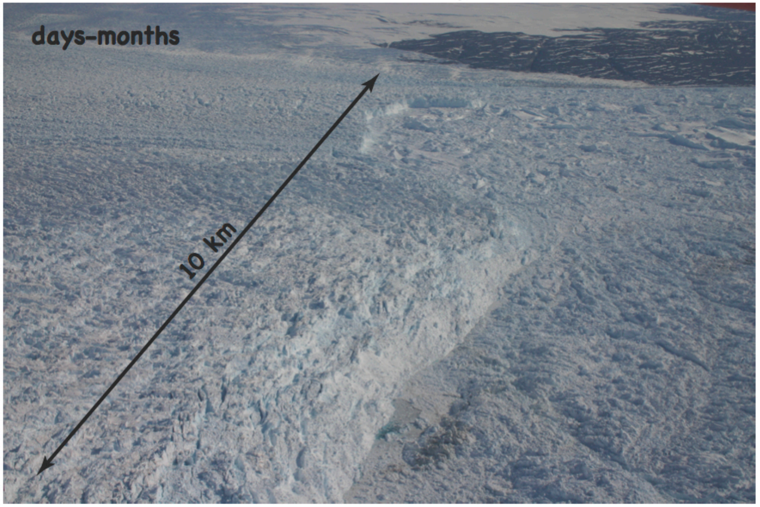
Rignot et al. (2013)

Calving of Icebergs

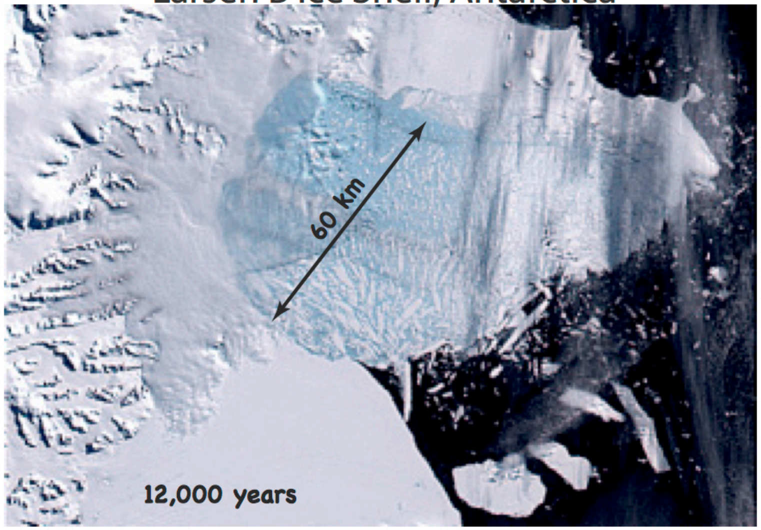
Ross Ice Shelf, Antarctica



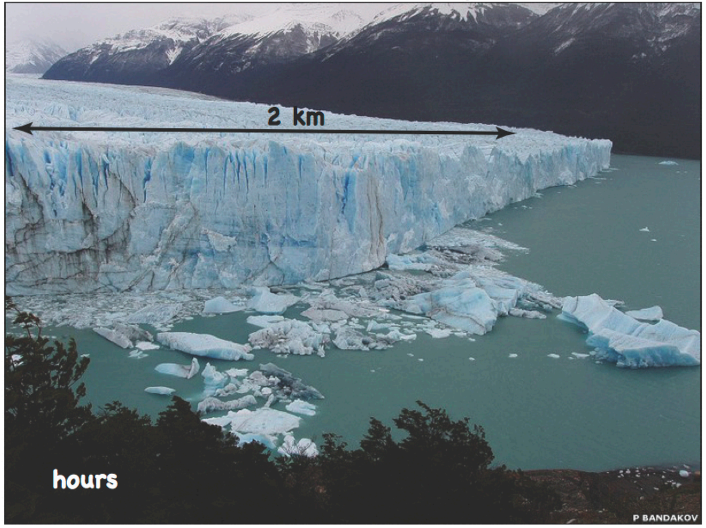
Jakovshavn Isbræ, Greenland



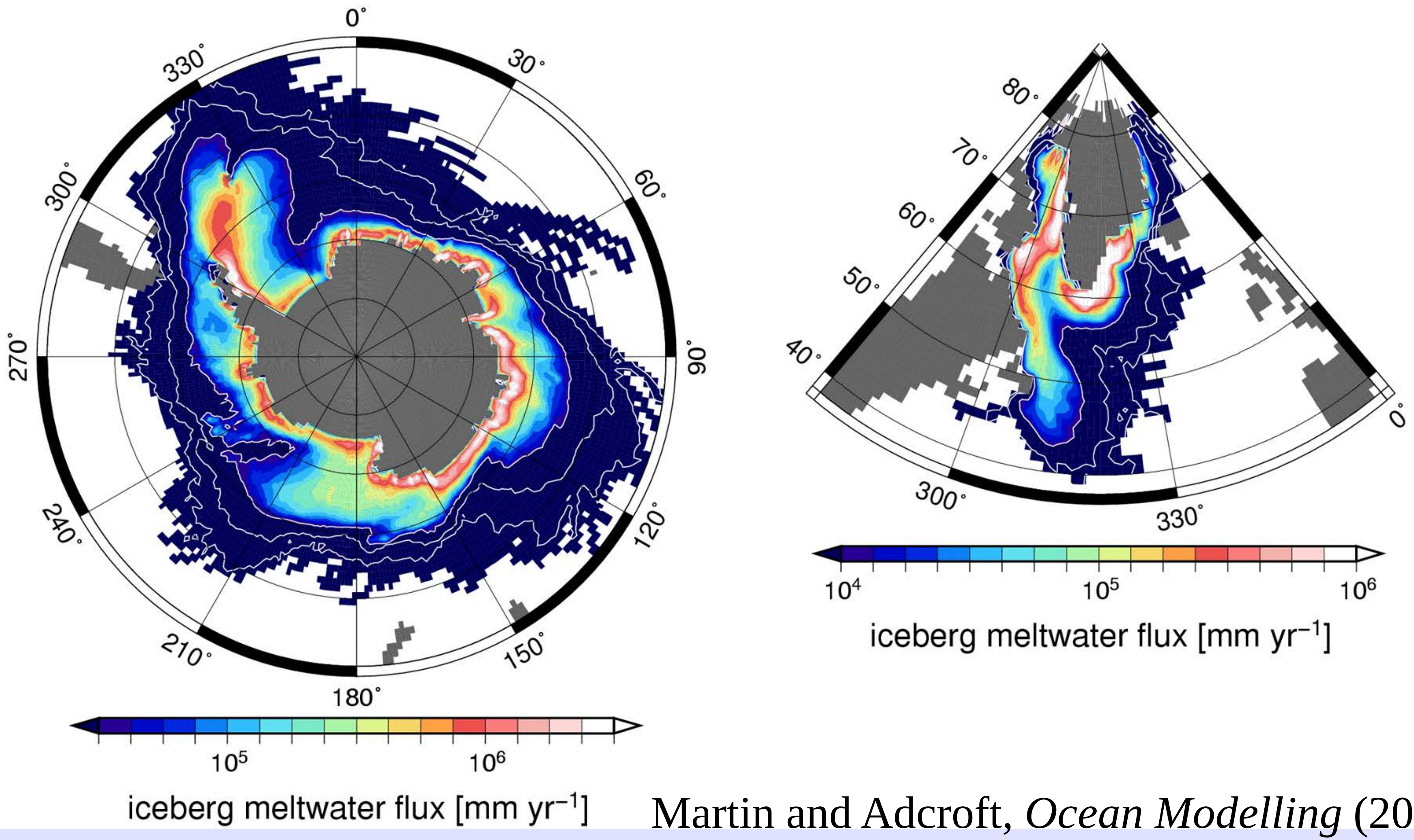
Larsen B Ice Shelf, Antarctica



Columbia Glacier, Alaska



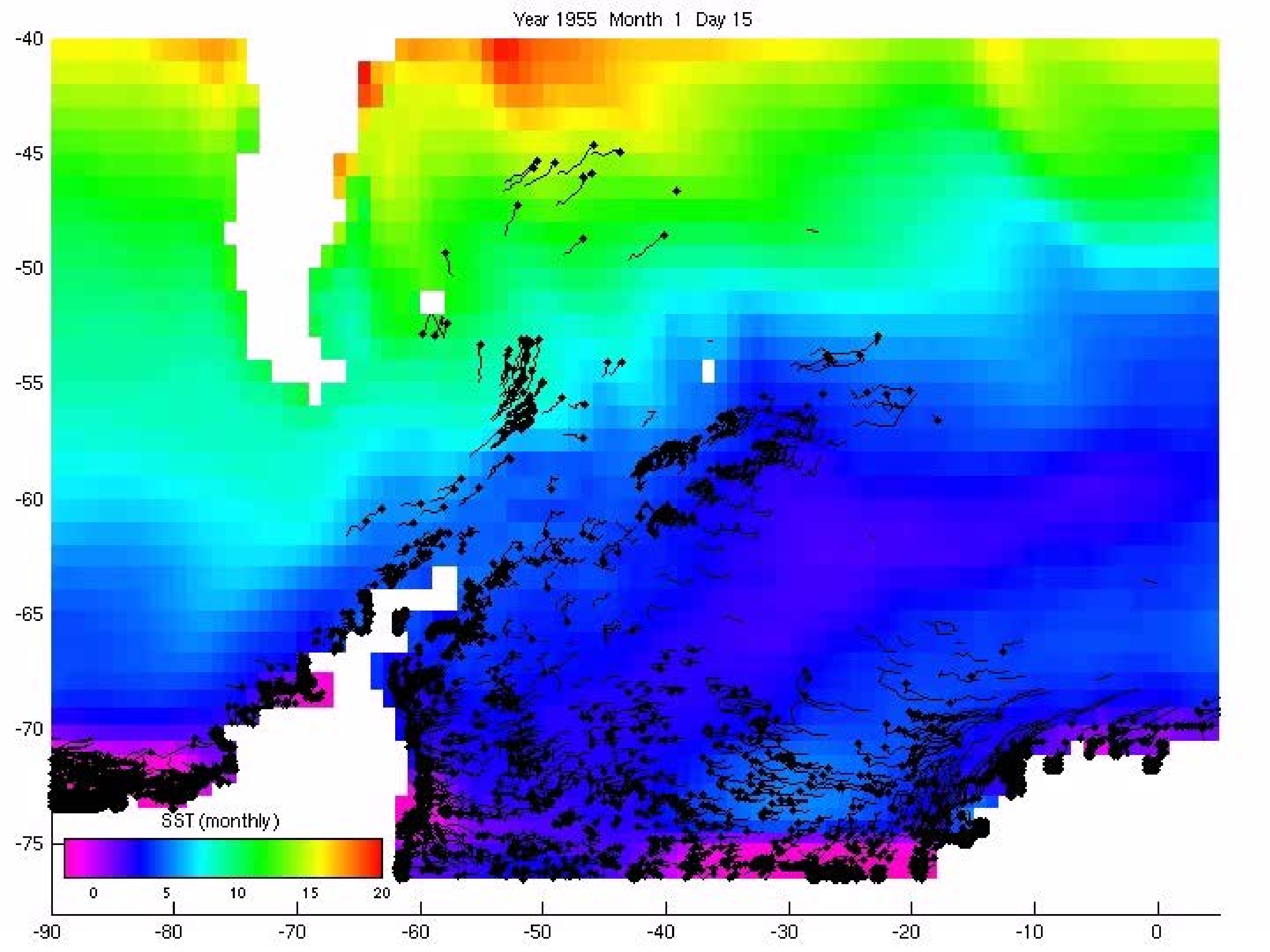
Iceberg Fresh Water Fluxes



Martin and Adcroft, *Ocean Modelling* (2010)

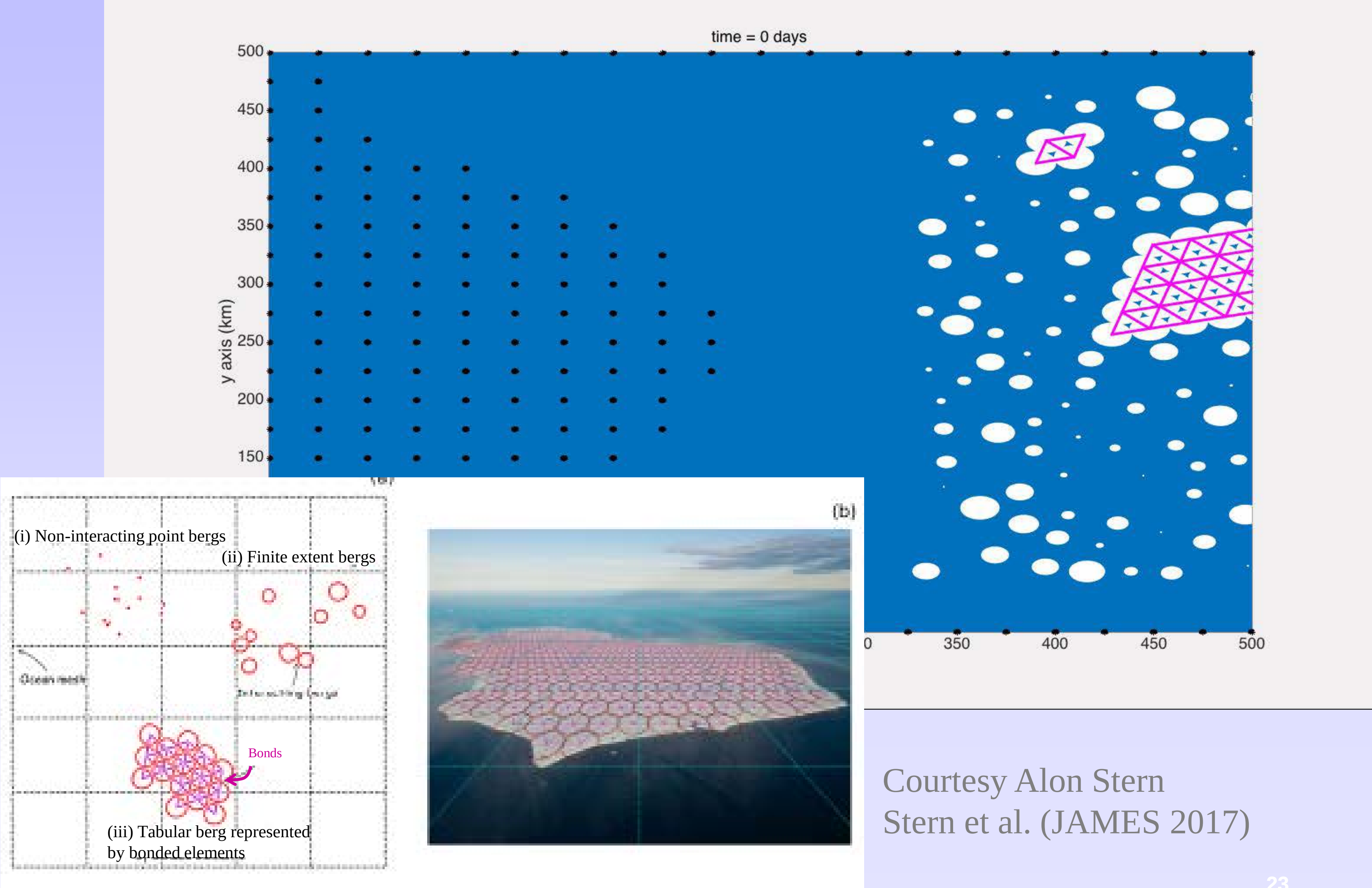
Objective is to replace current point-iceberg representation in GFDL climate models with extensive icebergs and calving induced changes in ice-shelf extent.

Point-Particle Model of Icebergs



Martin and Adcroft, *Ocean Modelling* (2010)

Tabular Icebergs as Bonded Particles



Courtesy Alon Stern
Stern et al. (JAMES 2017)

Iceshelf cavities and interactions with icebergs

- Iceshelf simulated by tabular iceberg model coupled to ocean

Top View

Side View
(Along Dashed Line)

Alon Stern &
Gustavo Marques

Take-Home Messages

MOM6 is eliminating unphysical assumptions and behavior to improve its ability to answer questions about sea level rise

- MOM6 works in configurations that limit numerically induced mixing
- MOM6 offers lots of physical mixing parameterization options
- MOM6 numerics are robust to continual and large changes in ocean geometry

Progress is toward more physically consistent interactions of marine ice (icebergs and sea ice) with the ocean

MOM6 code is freely available and welcomes contributions to shared development