Next generation ocean and ice models at GFDL: MOM6, SIS2, and icebergs

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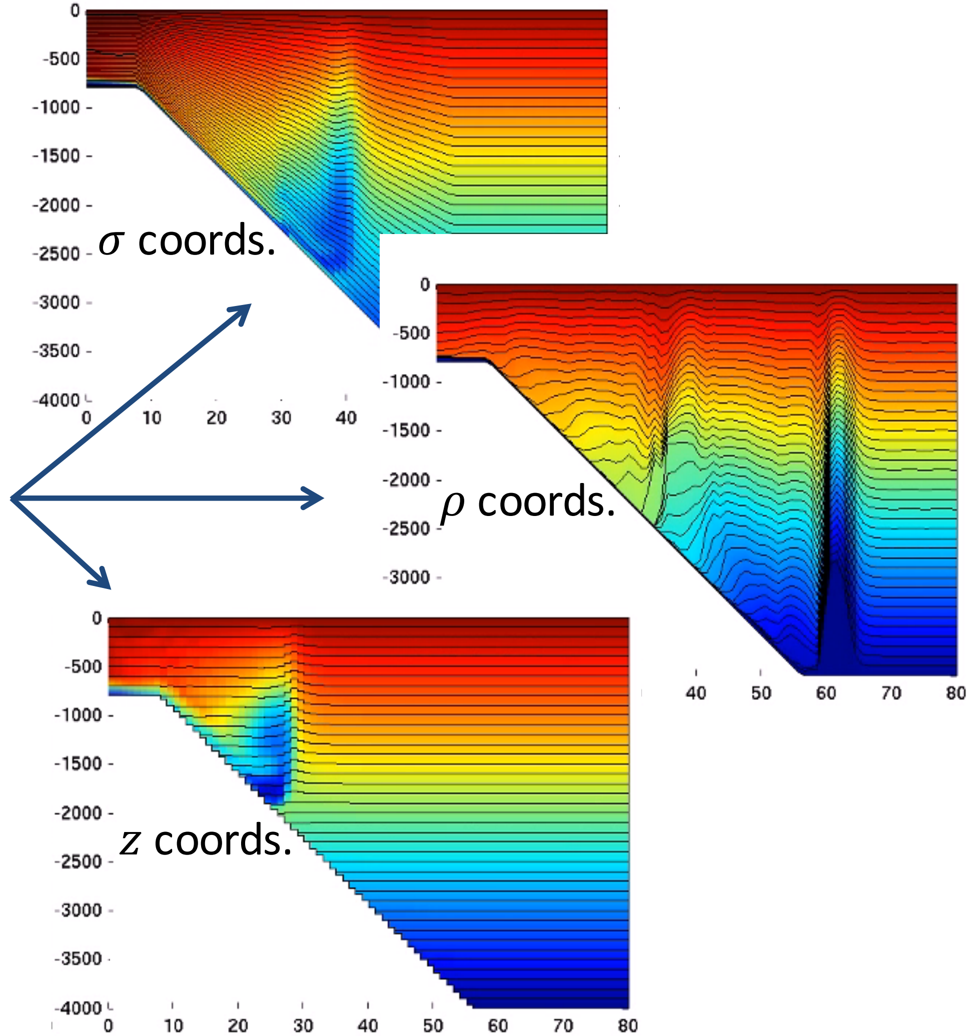
What is MOM6?

- The Modular Ocean Model traces origins to Cox, 1984.
  - Past versions of MOM have been foundation of other ocean models (POP, NEMO, …).
  - MOM is a comprehensive model of global ocean circulation and regional applications.
  - Traditionally a fixed vertical coordinate model.
- MOM6 represents new generation of model
  - Arbitrary-Lagrangian-Eulerian method used in the vertical direction
    - Allows adoption of any (arbitrary) vertical coordinate.

MOM6 development: Objectives

- Unification of production/ experimental dynamic cores
  – C-grid, Finite Volume
  – Wetting & drying, …
- Arbitrary Lagrangian Eulerian Method (ALE) *Bleck, 2002*
  - General vertical coordinates
  - Efficiencies - biogeochemistry
- Energetically consistent
  – More processes, physically based parameterizations
- Collaborations
  – CVMix, CORE/OMIP, CMIP6 / 4 x CPTs

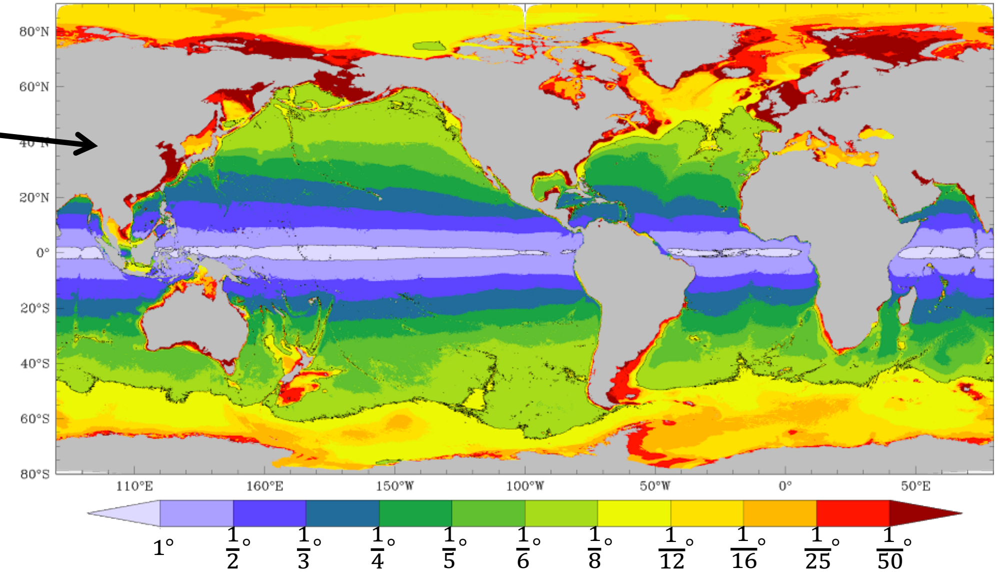
White et al., 2009

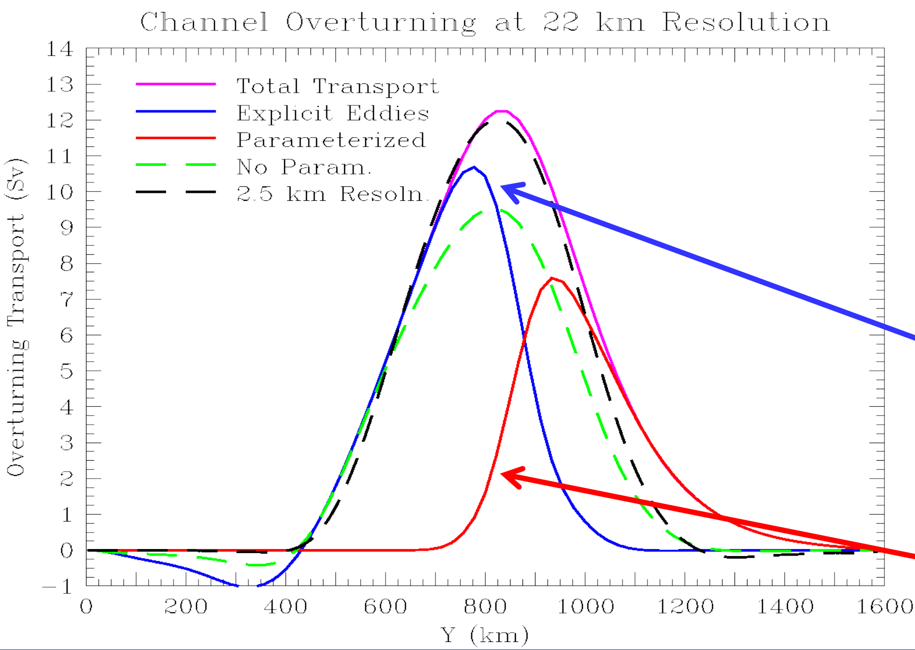


Eddy parameterization I

- Even "fine-resolution" ocean models cannot resolve first-mode eddies everywhere
- Adding a global eddy parameterization dampens resolvable eddies

Mercator resolution that resolves deformation radius





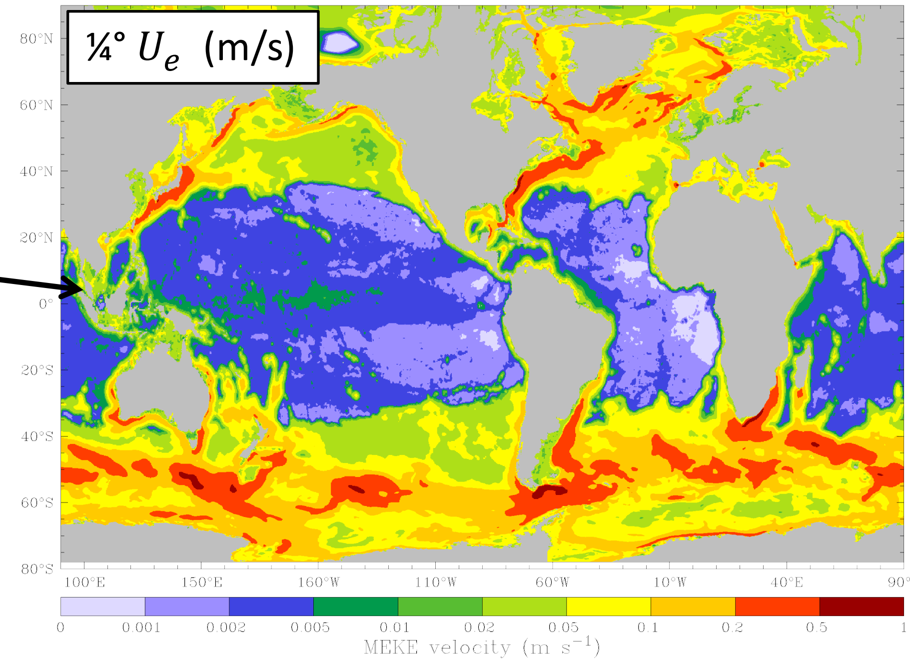
- Resolution-aware eddy parameterization
  - Allows baroclinic instability to proceed when resolution is sufficient
  - Parameterizes eddy fluxes otherwise

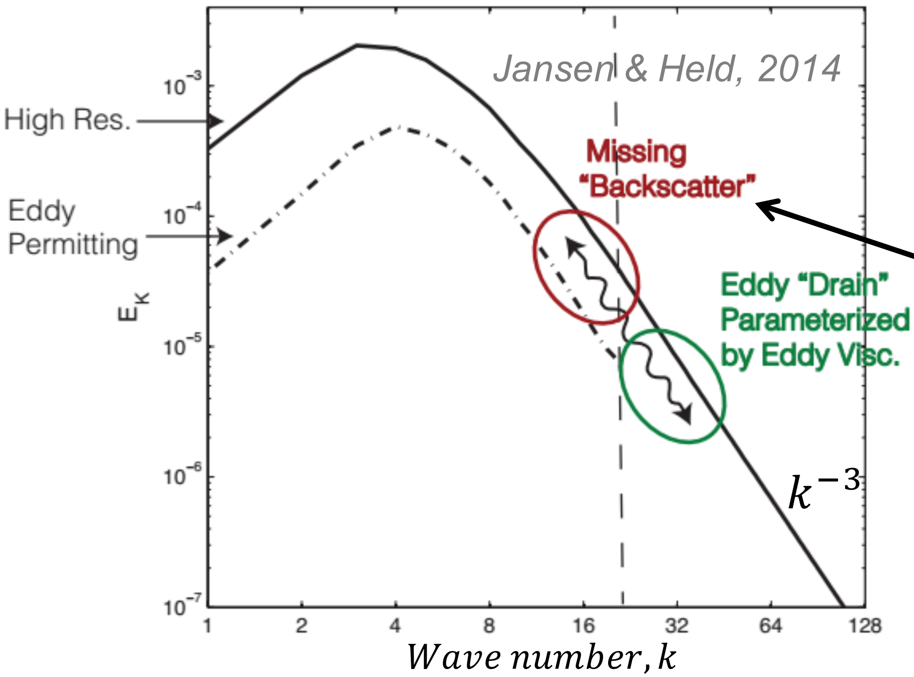
Hallberg, 2013

Eddy parameterization II

- Higher order closures
  - Predicts scales to use in eddy parameterization

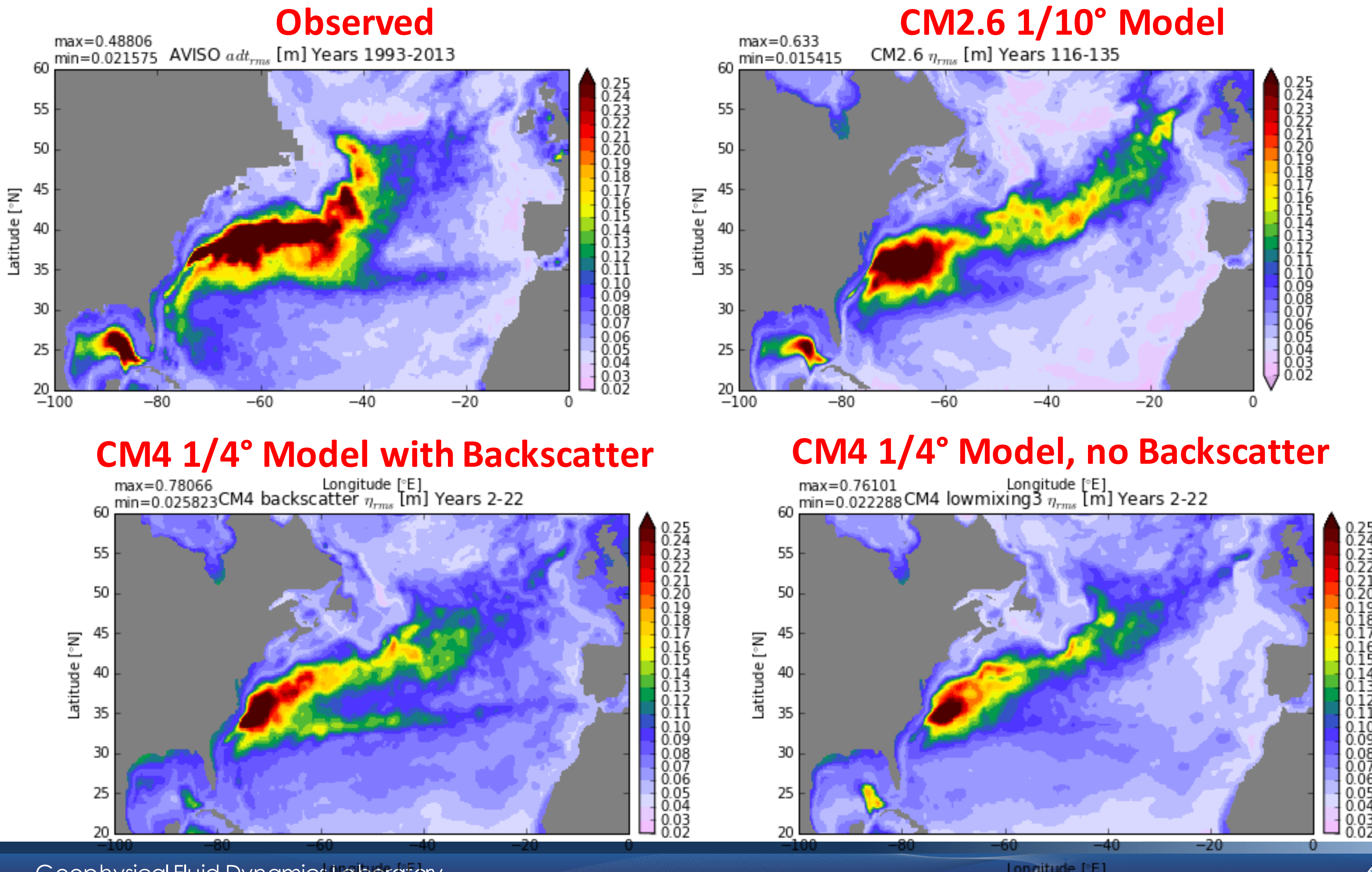
    e.g. $\kappa_h \propto U_e L_e$





- Influence of small scales on large scale
  - Backscatter of energy from unresolved scales to resolved scales

Sea Surface Height Variability with Improved "Backscatter" Eddy Mixing Parameterization

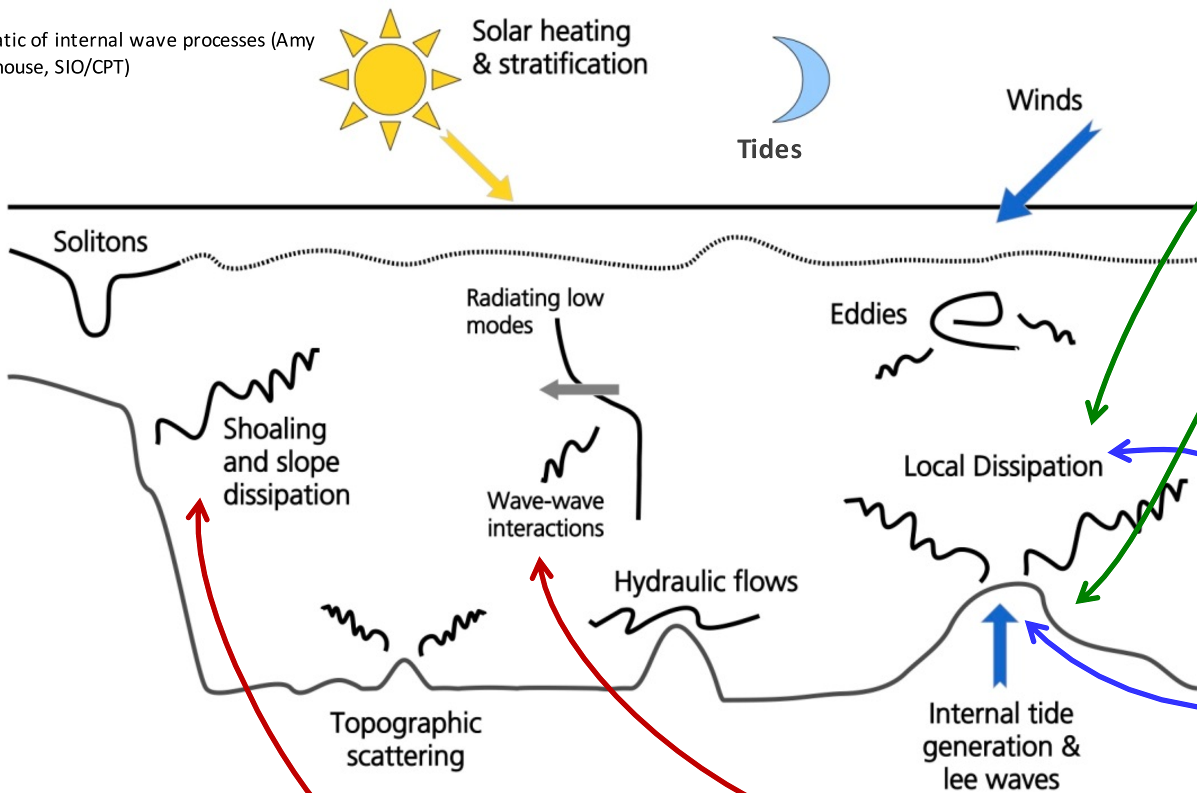


(Jansen and Held, 2014; Jansen et al., 2015)

Physically-based, energetically-consistent parameterizations of diapycnal mixing

As part of NOAA/NSF Internal Wave-Driven Mixing **C**limate **P**rocess **T**eam, we are developing and implementing parameterizations of sub-grid-scale mixing which allow mixing to vary spatially and **evolve in a changing climate**.

Schematic of internal wave processes (Amy Waterhouse, SIO/CPT)



Implemented in MOM6:

Vertical profile of local dissipation. *Polzin, 2009; Melet et al, 2013a*

Parameterization of lee-waves. *Nikurashin and Ferrari, 2011; Melet et al, 2013b*

Developed:

Local dissipation at tall steep topography. *Klymak, Legg and Pinkel, 2010; Klymak et al, 2012*

Contribution to generation from abyssal hills. *Melet et al, 2013c*

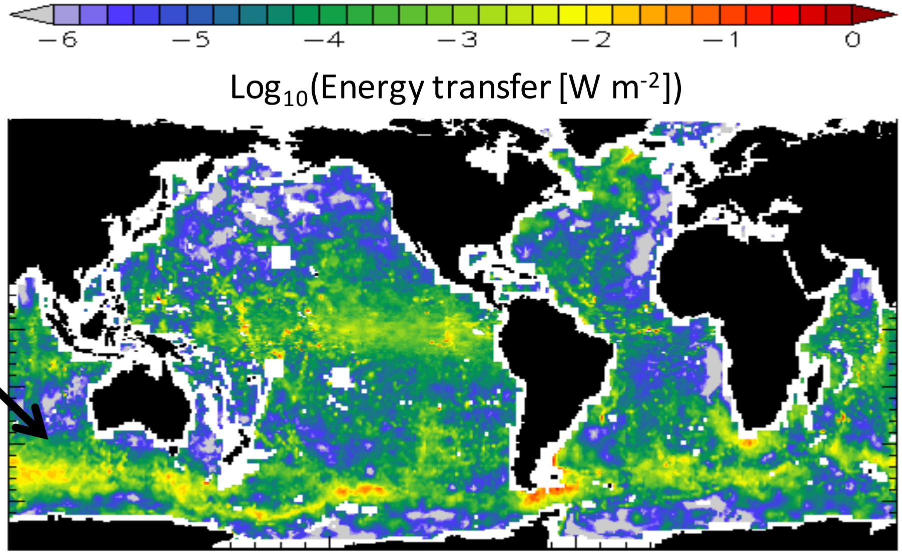
Under development:

Low-mode shoaling and reflection. *Legg, 2013*

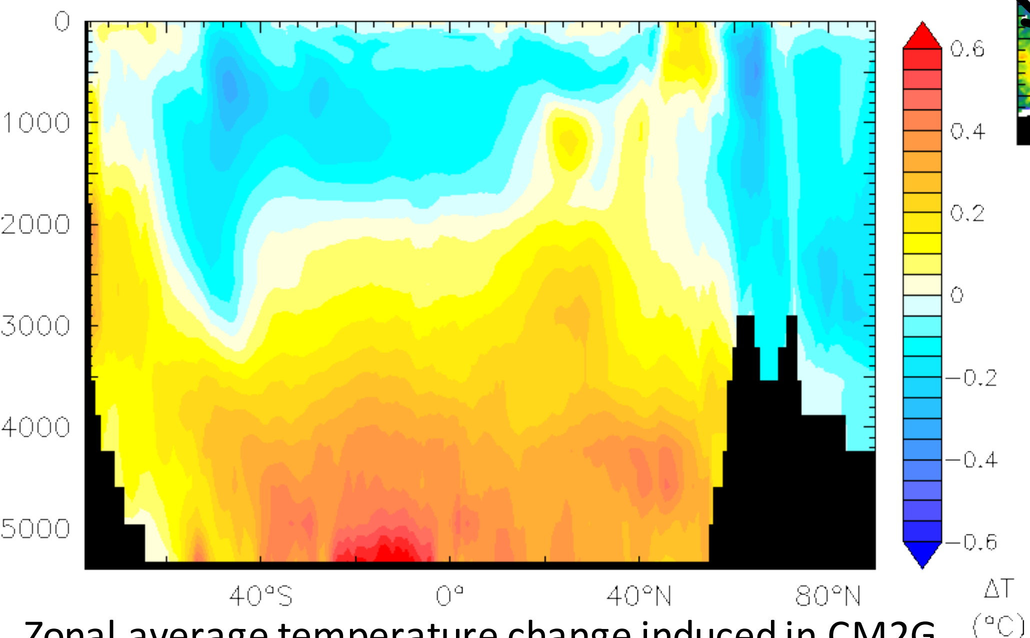
Latitudinal dependence of wave-wave interactions. *Nikurashin and Legg, 2011*

CPT: Impact of Lee-wave driven mixing

- Lee-wave energy is most significant in Southern Ocean



Nikurashin and Ferrari, 2011



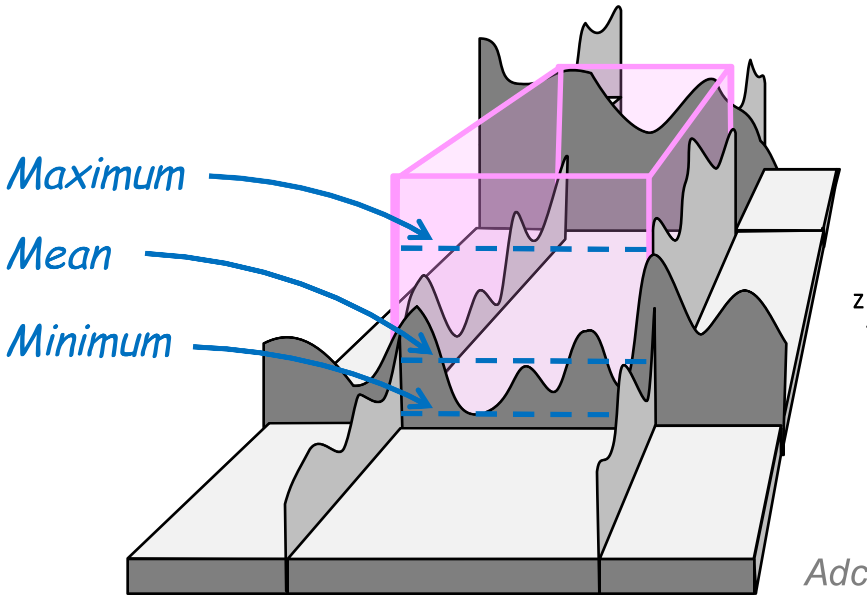
Zonal average temperature change induced in CM2G by extra source of energy for mixing

- Addition of lee-wave driven mixing parameterization systematically warms deep ocean & cools upper ocean
- Adding missing physics improves model credibility

Melet, Hallberg, Nikurashin and Legg, 2013

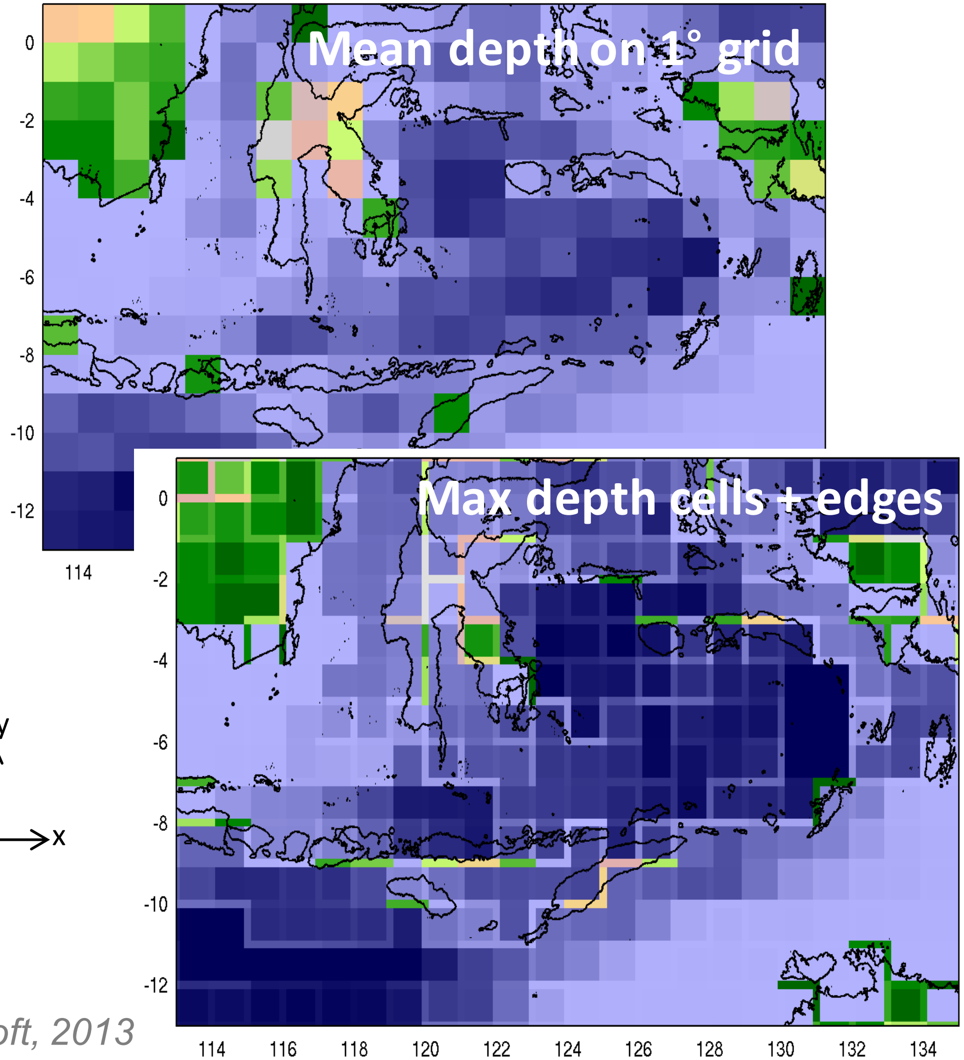
Porous barrier topography

- Use PDF of topography along edges (and within column)
- Real-world "actual" values:
  - areas/volumes
  - sill-depths/ridge-heights



Adcroft, 2013

e.g. **Indonesian Through Flow**



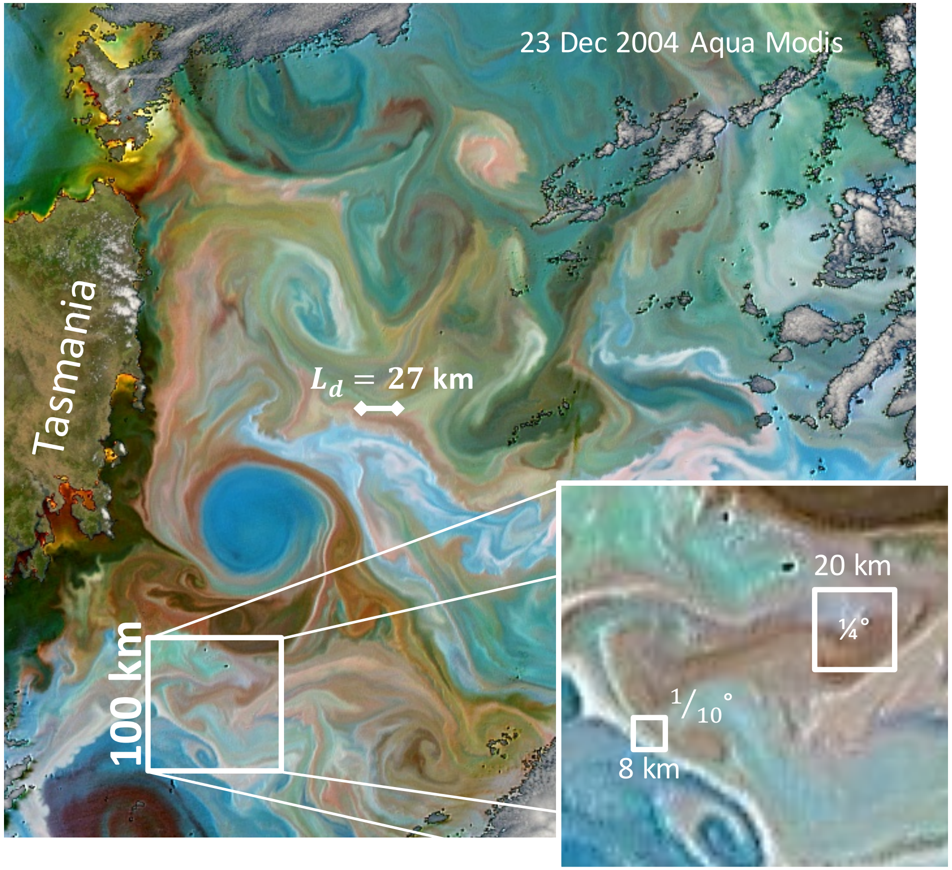
MOM6/SIS2 fact sheet

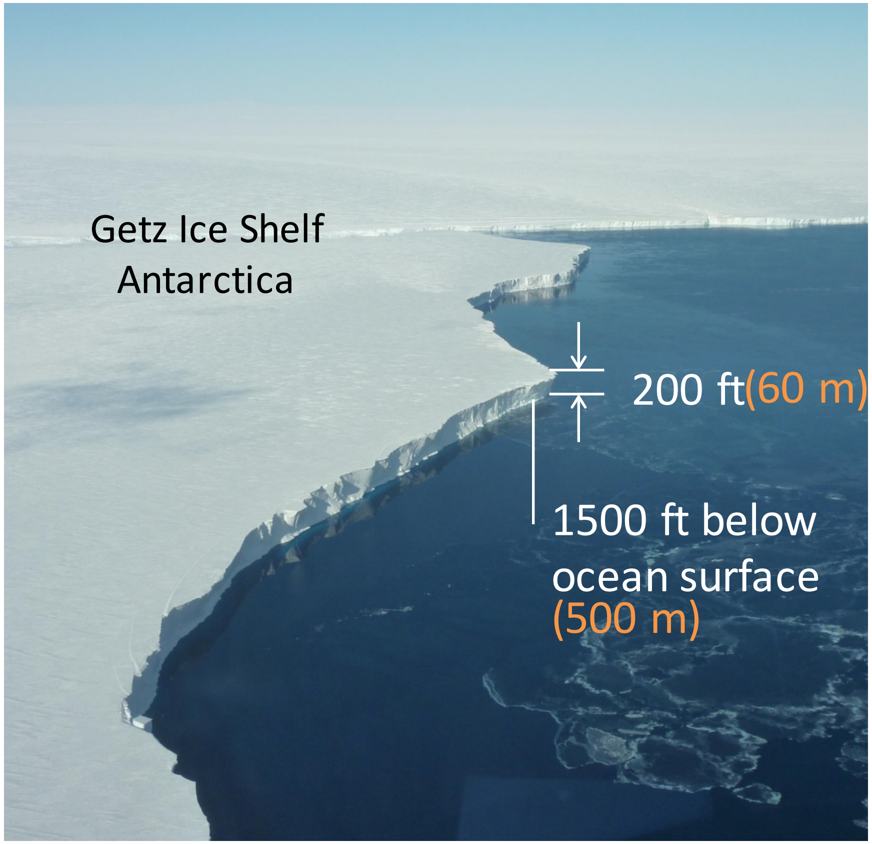
- MOM6 unifies GFDL's ocean modeling efforts - best of MOM5 and GOLD
- SIS2 modernizes our sea-ice model
- Key personnel are all active participants
  - Adcroft, Griffies, Hallberg, Harrison, Krasting, Liang, Rosati, Winton, Zadeh, …
- Scalable on large parallel computers
- C-grid discretization (replaces B-grid)
  - No "Checkerboard" null mode
  - Less smoothing of forcing required
- Better representation of topography and narrow channels
  - No need for "Cross-land mixing"
- MOM6 and SIS2 are basis of OM4 ocean/ice component of CM4
- Open development model (MOM6+SIS2)
  - All activity visible via *GitHub*
- Lagrangian Vertical Dynamics
  - Arbitrary Lagrangian-Eulerian method (ALE)
  - Tracer advection is not required for gravity wave dynamics
  - Able to use a wide range of vertical coordinates
- Implicit remapping replaces vertical advection
  - No vertical CFL limit on time steps
  - Ultra-fine vertical resolution possible
- Permits sub-cycled gravity-wave dynamics vs. tracer advection
  - Reduces cost to add tracers.
- Handles wetting and drying, and evolving geometry conservatively

  e.g., moving ice-shelf grounding line

Frontiers in ocean/ice-sheet model development

- Role of ocean eddies in climate/earth system
- Sea-level rise and ice-sheet/ocean interaction





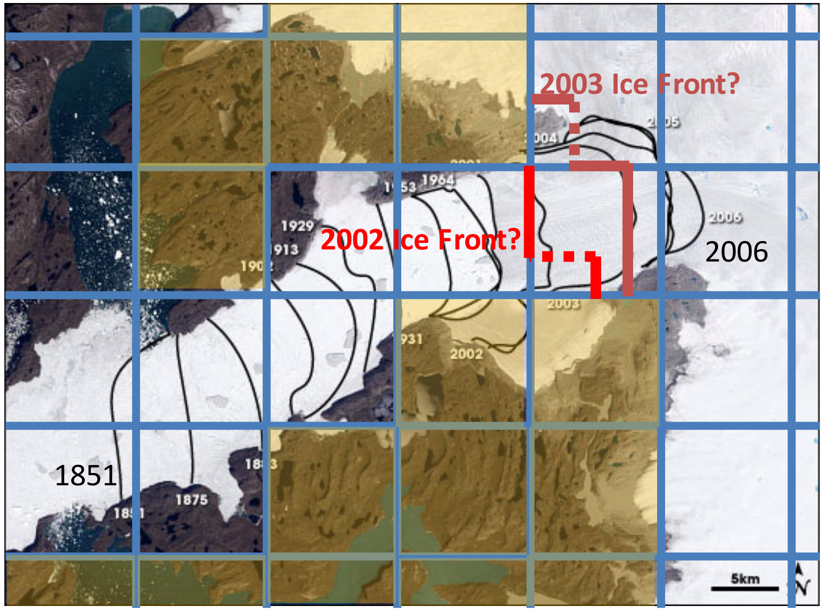
Credit: NASA/Dick Ewers

Ocean Working Group: Objectives

- **Eddying-resolution** (¼°) ocean component
  - Admit **large eddies** and **internal ocean variability**
  - Better **resolve boundary regimes**, e.g. Labrador Sea boundary currents
  - Allow interactive dynamic **sub-ice shelf cavities**
  - Strategy:
    - z*-coordinate first
    - Hybrid coordinates later

- **Address biases** of previous models
  - **Heat uptake/sea level**
  - Processes/coupled interact^{ns}: **overflows, cryosphere**

Jakobshavn & ¼° Mercator grid



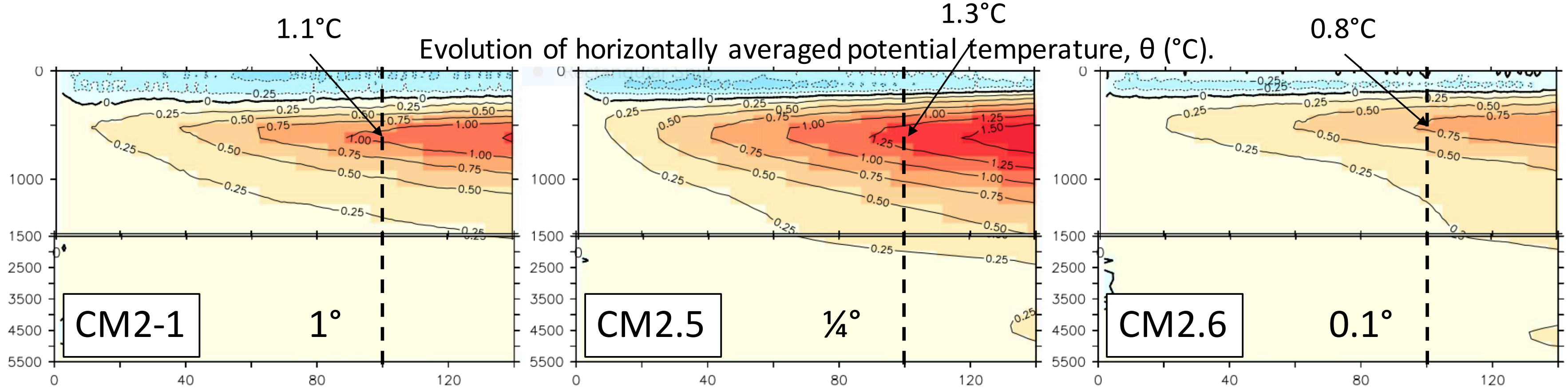
OM4 fact sheet

- ¼° x ¼° x 75 levels
  - Eddy permitting in low latitudes
  - Admits internal variability
  - Better resolves boundary current regimes
  - 2m near-surface resolution
- More representative land-sea mask
  - ITF, Queen Eliz. Islands, Inlets,…
- Hybrid vertical coordinates
  - Use ALE method
  - Initially developed with z*
  - HyCOM-like hybrid coordinate
- SIS2 on same horizontal grid
  - Conservative thermodynamics
  - Includes interactive icebergs
- All latest "physics"
  - Energetically based diffusive boundary layer
  - Internal wave driven mixing
  - Tidally driven mixing
  - Mesoscale stirring
  - High-latitude energy-based mesoscale eddy parameterization
  - …
- Variant with sub-ice-shelf cavities

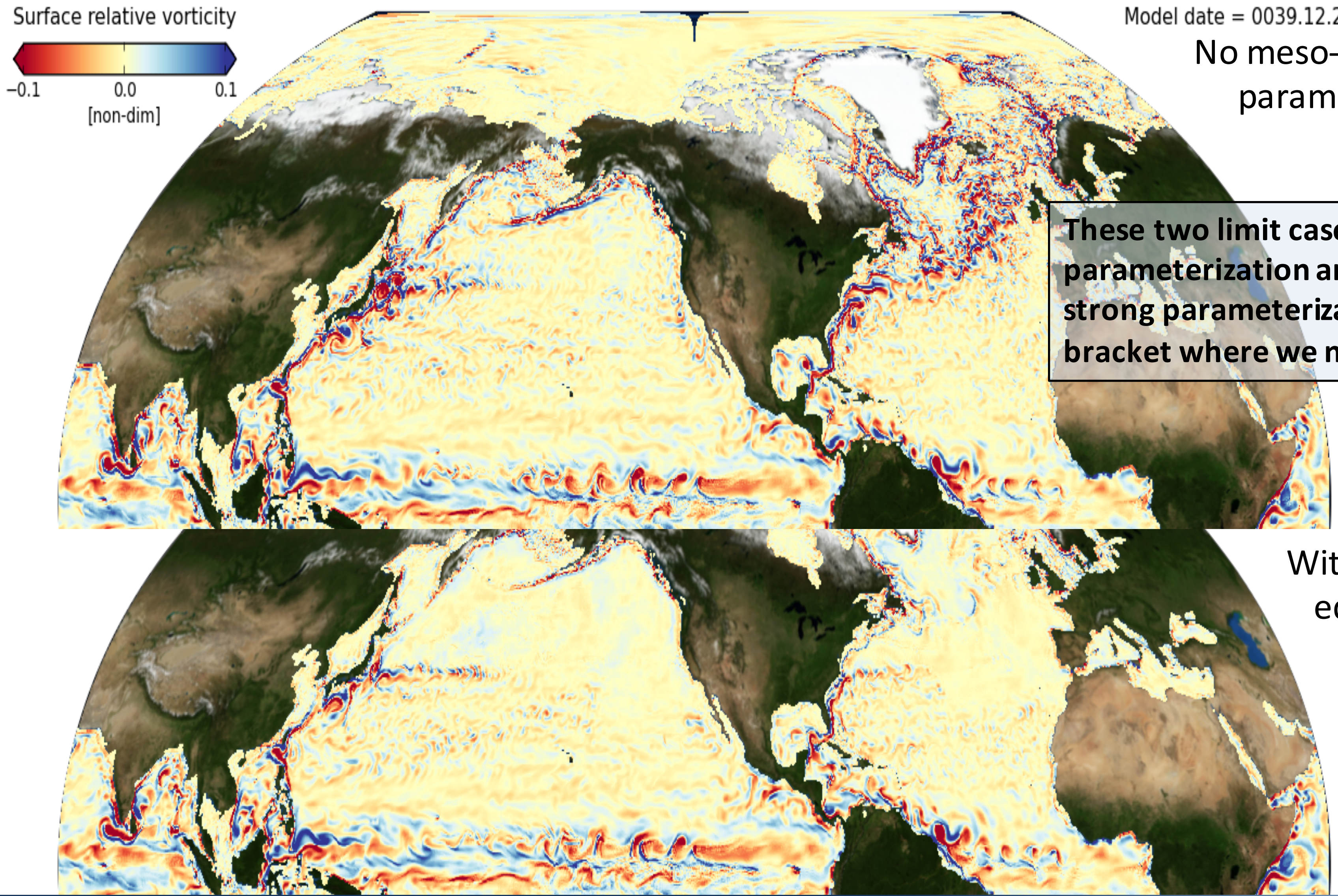
Can we do with 1/10th at 1/4th?

High-resolution coupled models at GFDL

- Delworth at el., 2012 coupled model series (CM2.1, CM2.5, CM2.6):
  - 200km, 100km, 50 km atmosphere
  - 1°, ¼° and 0.1° ocean
- Griffies et al., 2015, show that transient eddies in a 0.1° ocean transport heat upwards
  - Least heat uptake of CM2.x series
- For CMIP6, we can afford ¼° ocean



Parameterizing eddies in an eddying model



No meso-scale eddy parameterization

These two limit cases, of no parameterization and overly strong parameterization, bracket where we need to be

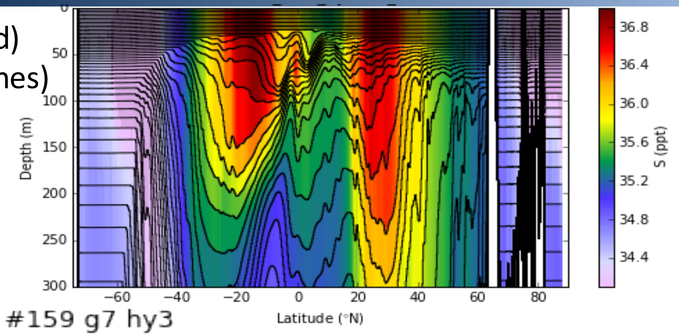
With "strong" eddy energy closure

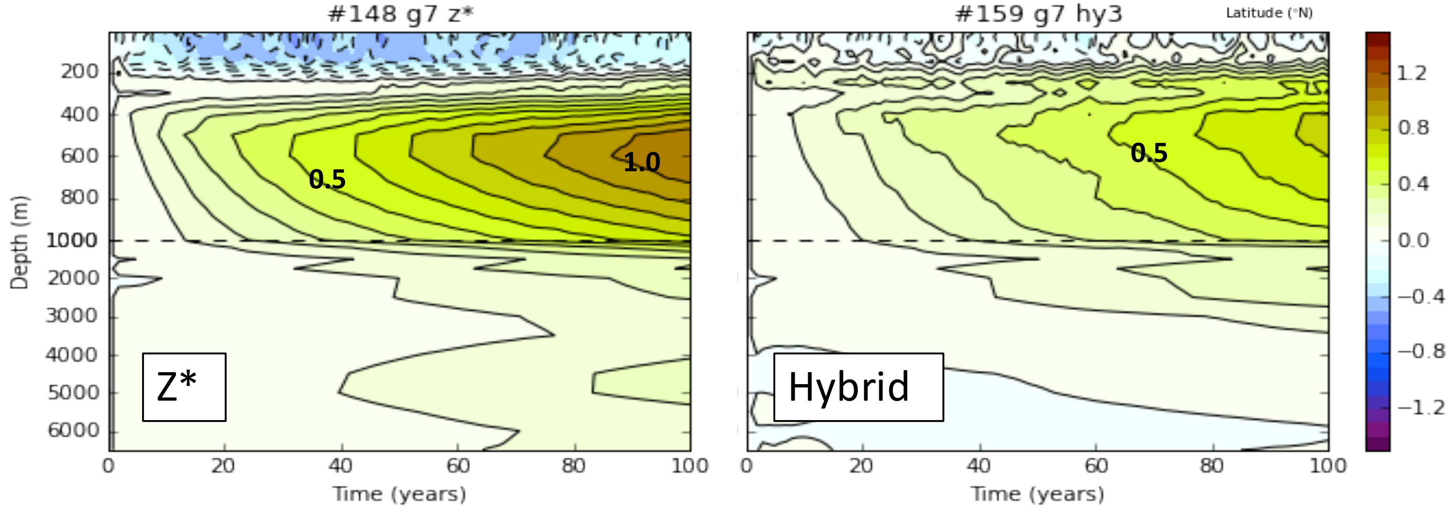
Vertical coordinates and drift

Role of vertical coordinate (¼° ocean in CM4)

- Changing vertical coordinate alone
  - z* to hybrid z*/ρ_2 (aka HYCOM)
  - Identical parameterization/atmos
  - Reduced heat uptake by 0.27 Wm^{-2}

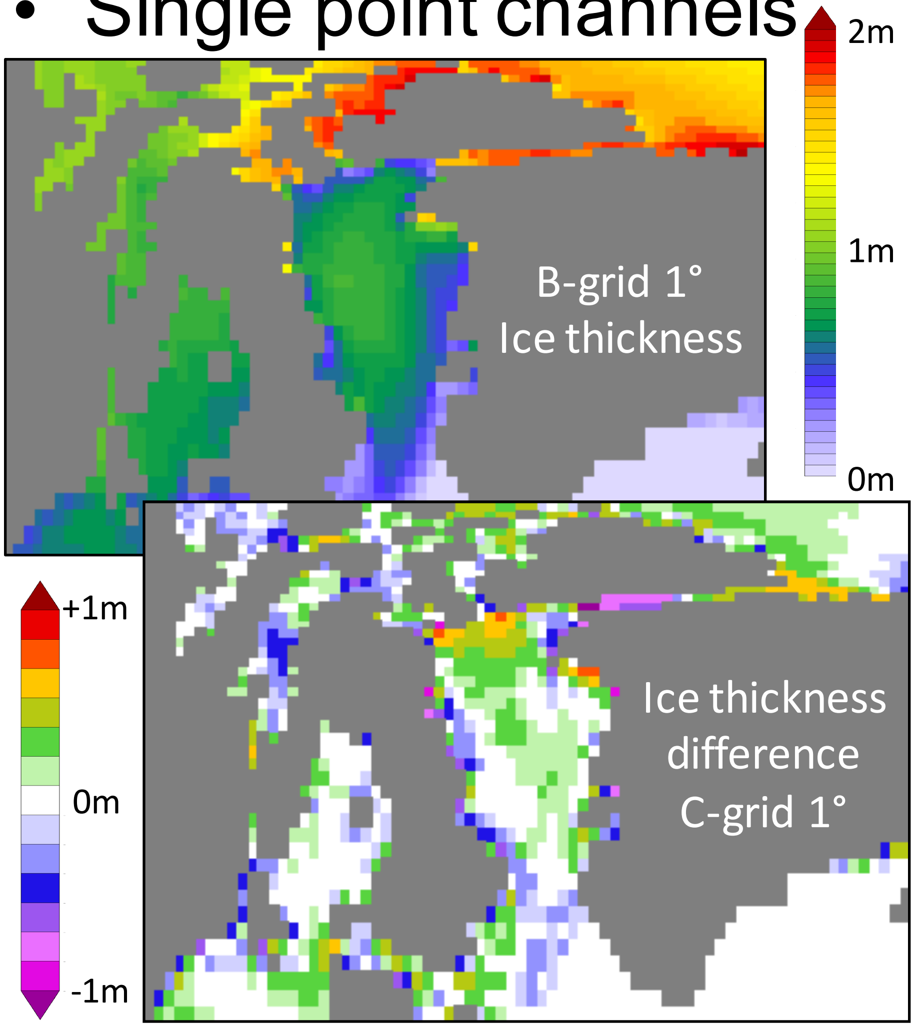
Salinity (shaded)
Vertical grid (lines)



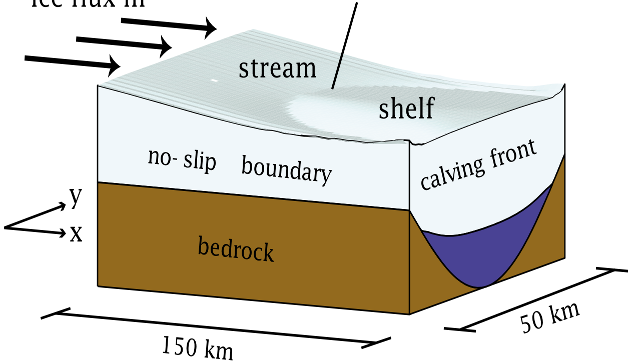


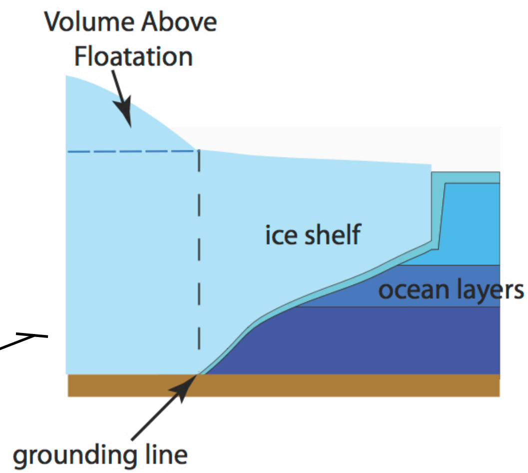
Revised sea-ice model: SIS2

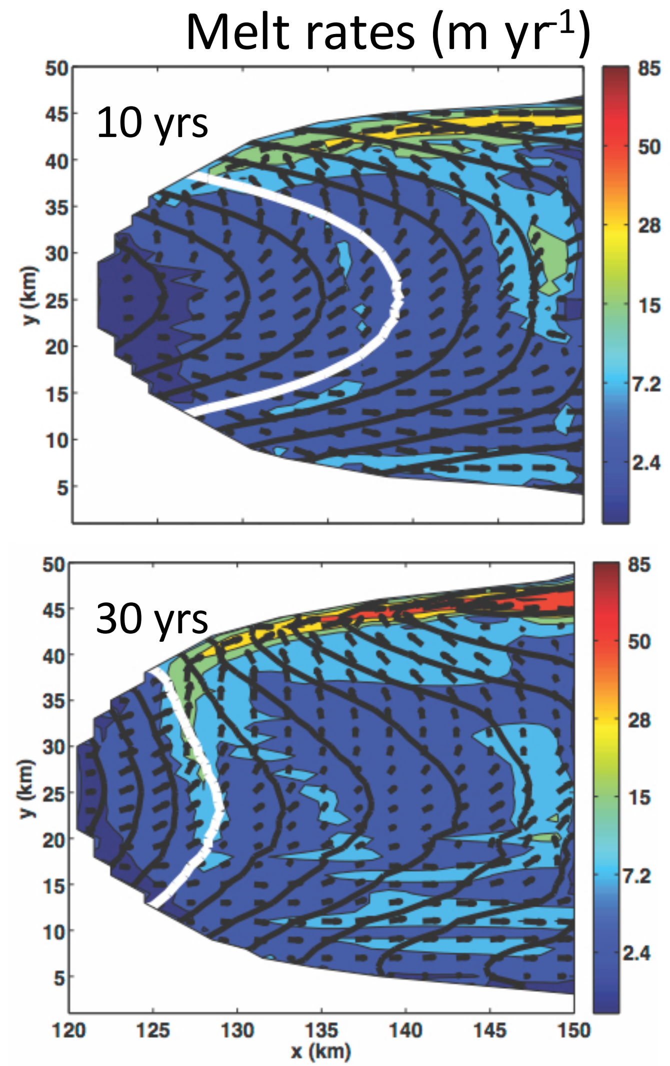
- Compatible with MOM6
  - C-grid; moving “coasts”
  - Multi-layer ice and snow; variable salinity
  - Delta-Eddington radiation (from CICE)
- Avoid high-resolution coupling instabilities
  - Dynamics part of ocean
- Collaborations
  - MIT, LANL (CICE physics)
- Single point channels

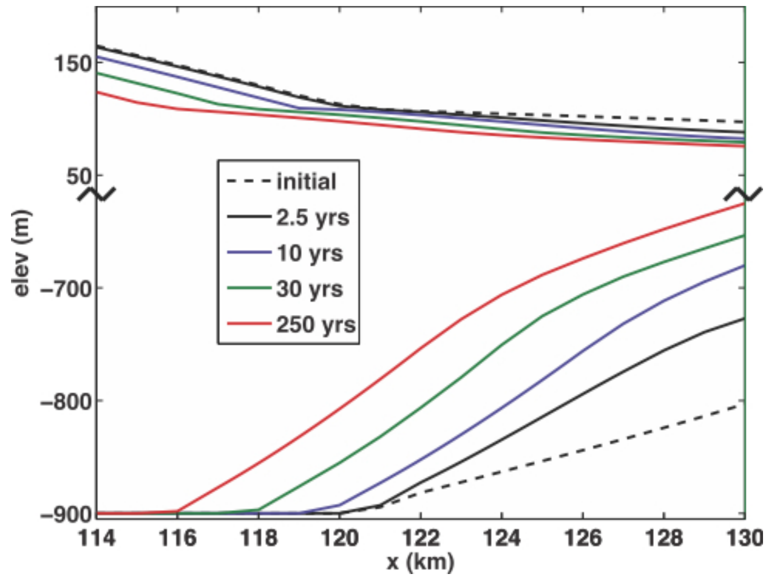


Dynamic Ice-shelf-ocean Interaction





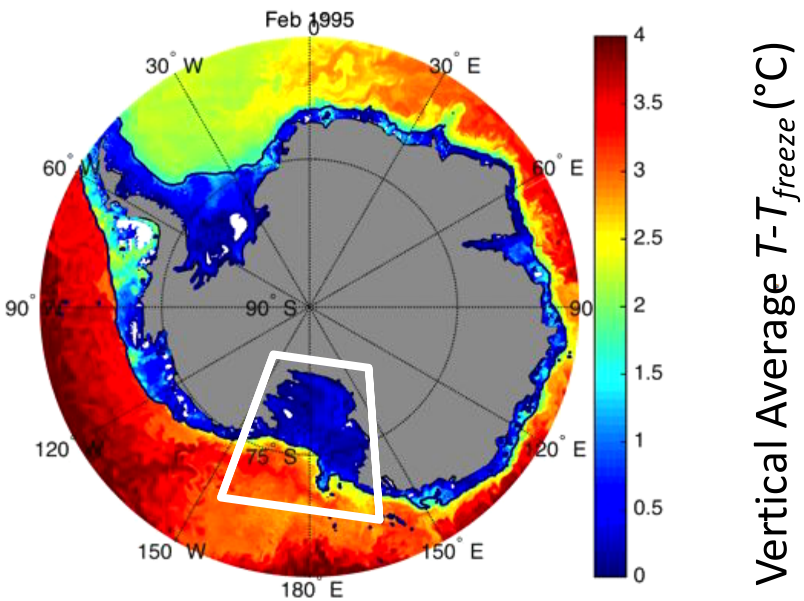




Goldberg et al., *JGR* (2012)

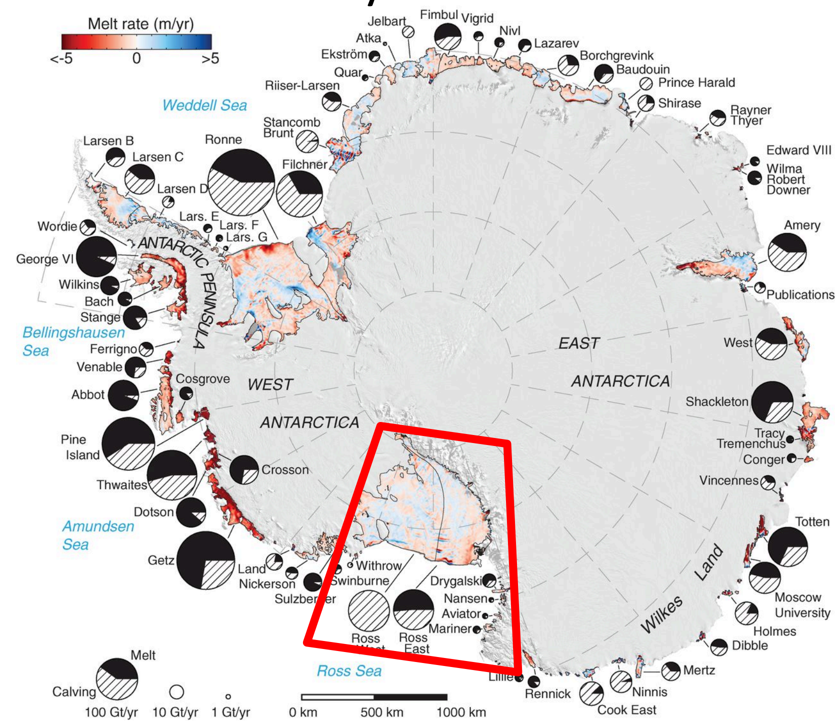
Coupled Ice-shelf-ocean Interaction

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



Vertically Averaged Ocean Temperature above the in-situ Freezing Point

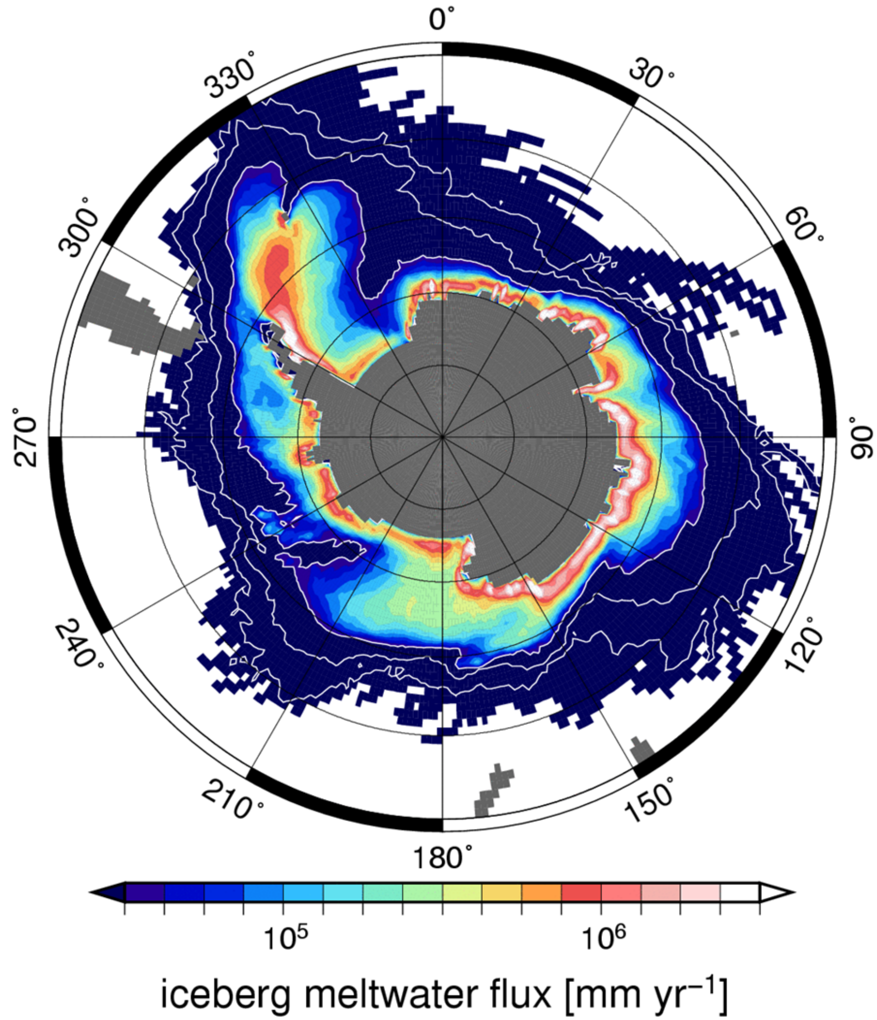
Observationally Inferred Mass Loss

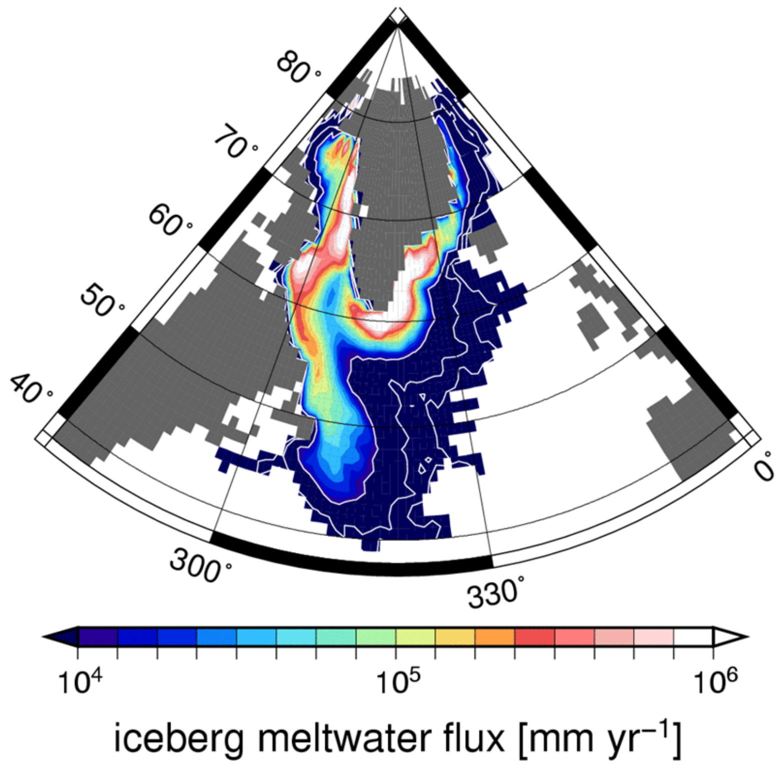


Rignot et al. (2013)

Sergienko et al., 2015, submitted to *JGR*

Iceberg Fresh Water Fluxes



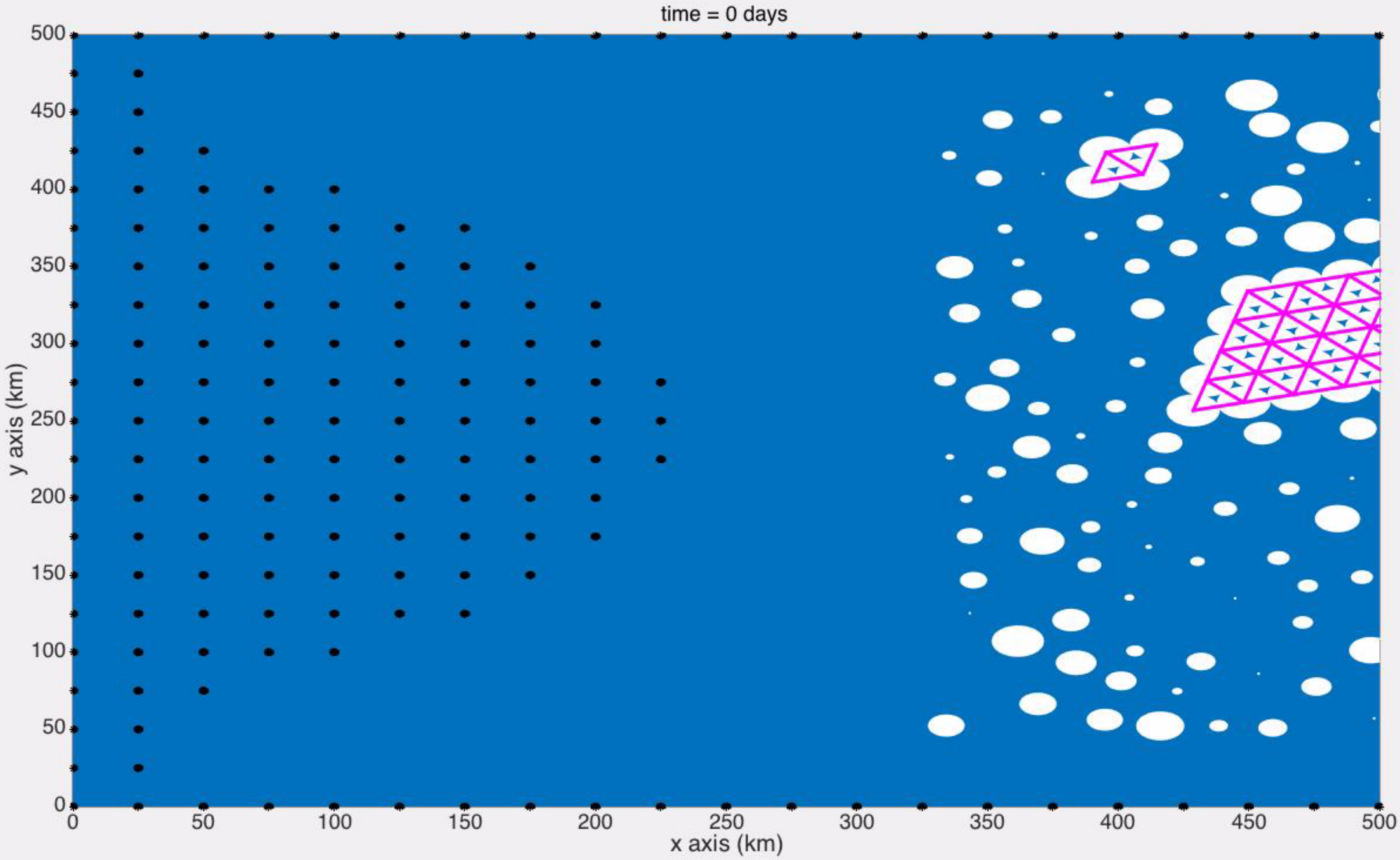


- Icebergs distribute cold fresh water (and minerals) across ocean

Martin and Adcroft, *Ocean Modelling*, 2010

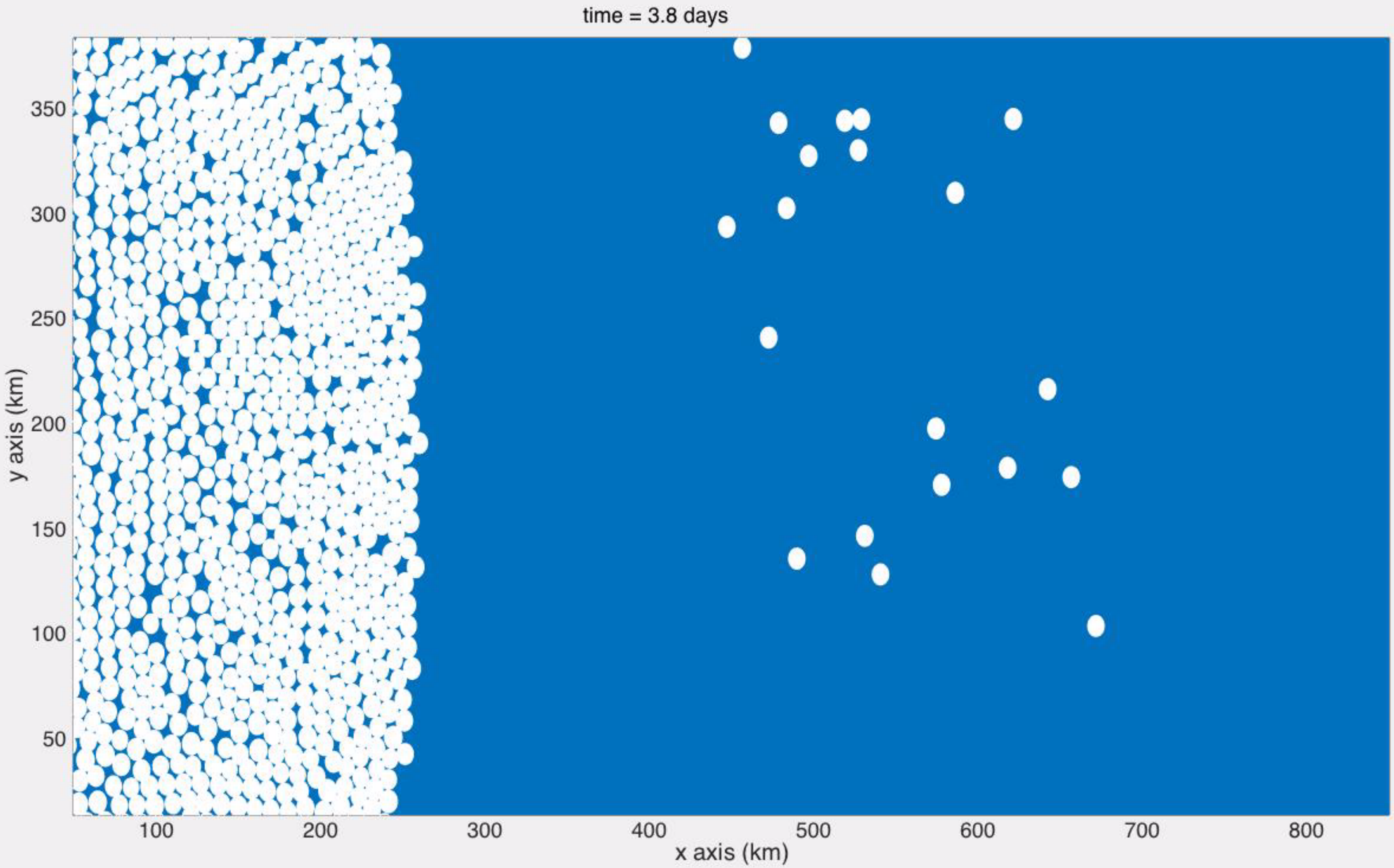
Tabular icebergs as bonded particles

Alon Stern and Alistair Adcroft



Simulating ice-shelf breakup

Alon Stern and Alistair Adcroft



Projects impacting development

- GFDL and Princeton Uni
  - CMIP6, seasonal forecasting, data assimilation, process models
  - Cryosphere coupling (sea ice, ice-shelf, ice bergs)
  - analysis tools: budgets, Lagrangian particles, water masses
- COSIMA
  - process models, regional/global, analysis methods
- Curchitser's team (Rutgers Uni)
  - regional/coastal configs (open boundaries, downscaling)
- NCEP
  - Seasonal forecasting CFSv3
  - Data assimilation (Steve Penny)
  - Coupling to Wavewatch (GFDL post-doc, NCEP engineer)

Potential projects impacting future development

- NCAR / CESM
  - CESM is switching to new ocean model.
  - Have expressed interest in MOM6.
- US Navy
  - HYCOM and MOM6 share many methods.
  - HYCOM needs a path for sustainability.

For COSIMA discussion

MOM6 is less mature than MOM5, but…

- Very active development, both deep and broad
- Existing MOM6 global configurations are better than earlier MOM5 configs; e.g., MOM5-025 vs MOM6-025

There are few ocean (and cryosphere) model development projects with more resources devoted to pushing envelope on science applications, numerical algorithms, analysis methods, and software engineering. NEMO is more mature, but unsure how they would work with an active open source community.

GFDL (from hands-on scientists/engineers to managers) considers COSIMA scientists and engineers as front line collaborators and friends.

Note: any projection for timelines from should be scaled up:
week→month; month→few months; year→few years.
This point is relevant for any path taken by COSIMA.