Physical Modeling of the Deep Ocean: Challenges and Opportunities

JOINT US CLIVAR & OCB WORKSHOP

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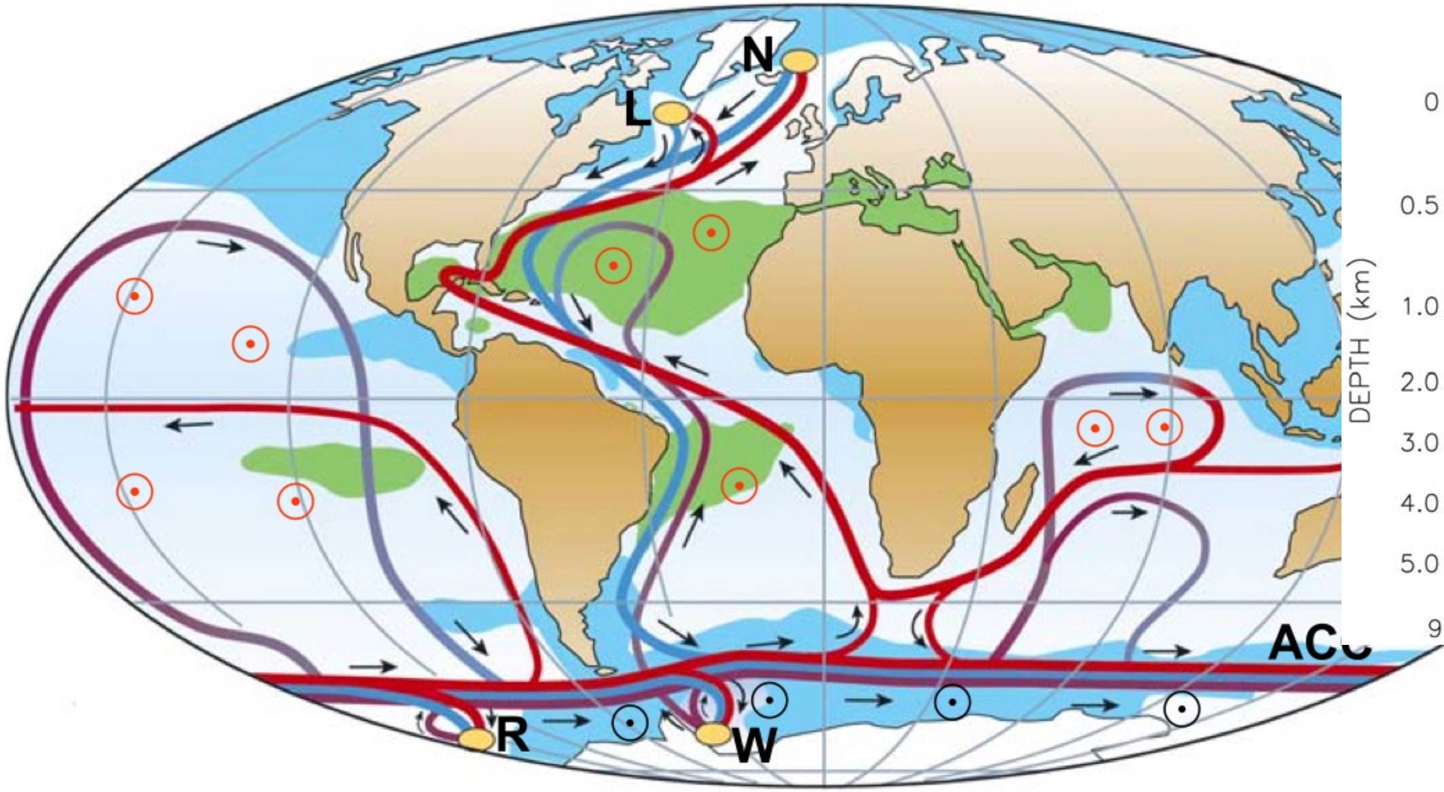
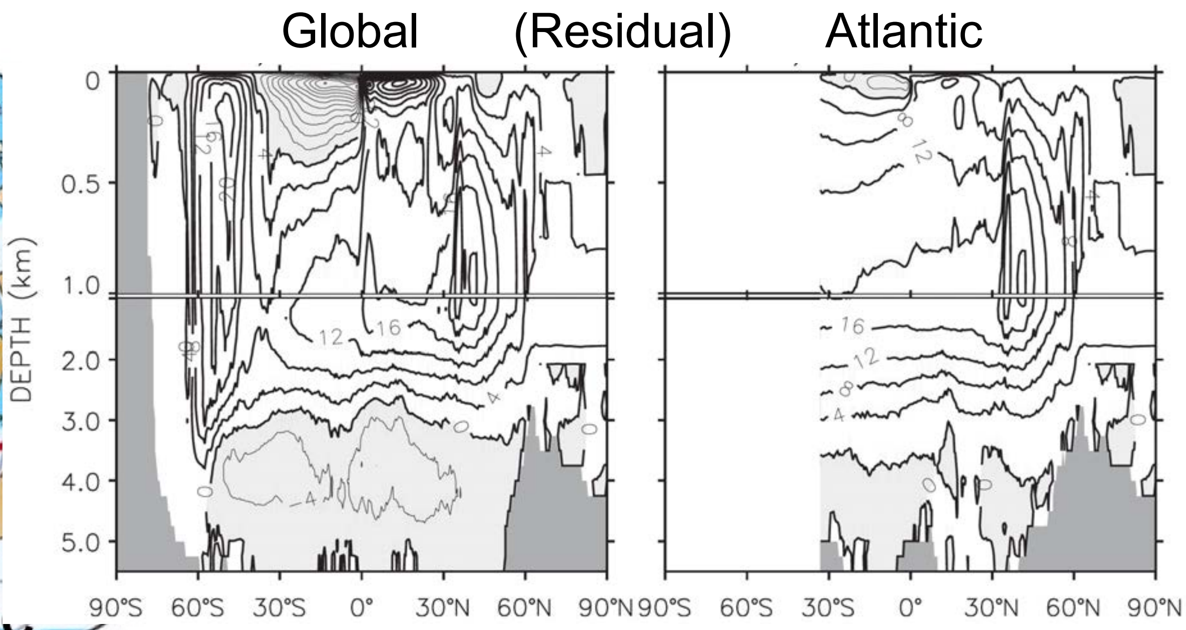
Outline

- Global overturning circulation
- Representation of bathymetry; overflows
- Equilibration timescale; approach to equilibrium; drift
- Mixed layer depths
- Use of passive tracers (Ideal Age, CFC-11, He isotopes)
- Opportunities

A Simplified Sketch of the Global Overturning Circulation System



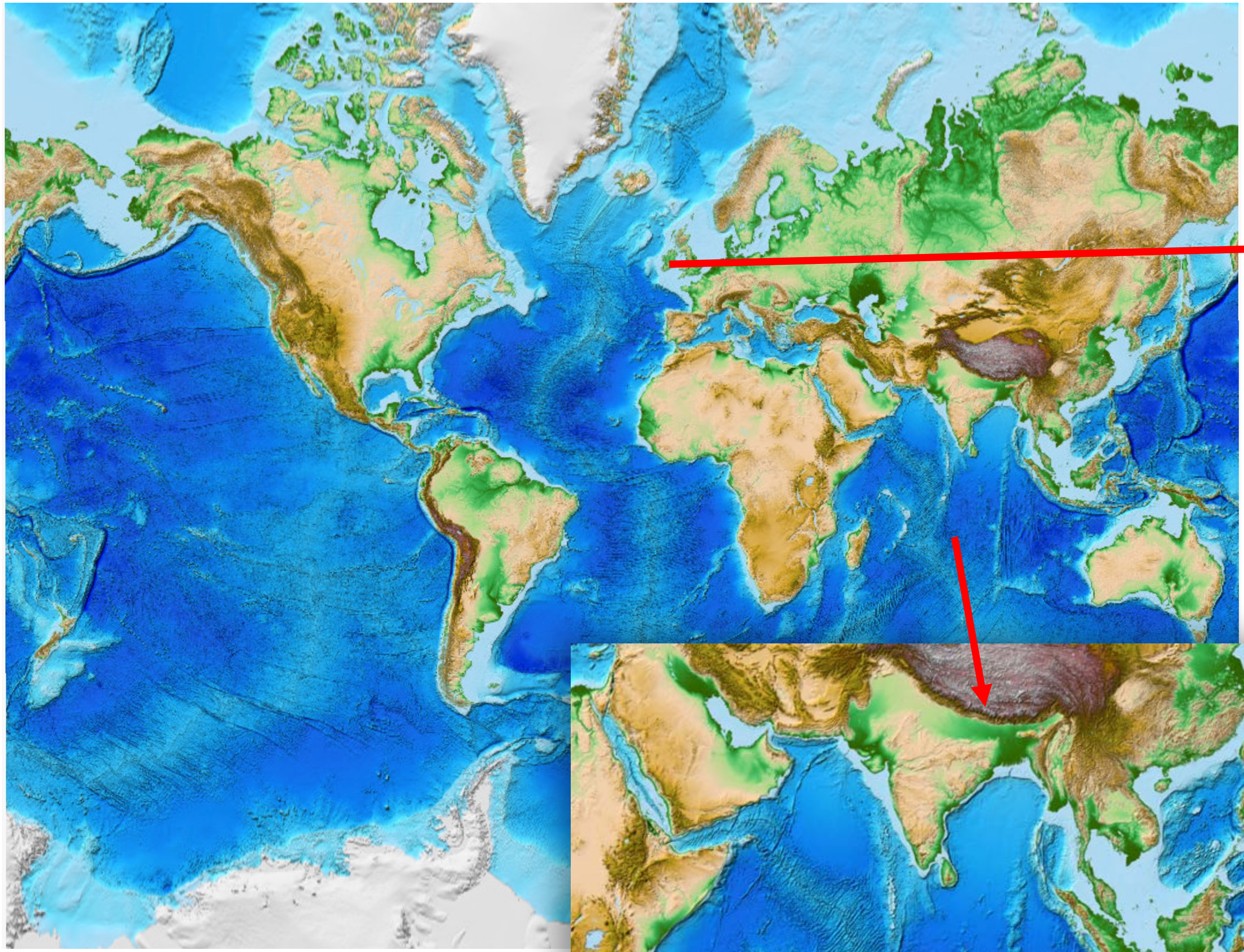


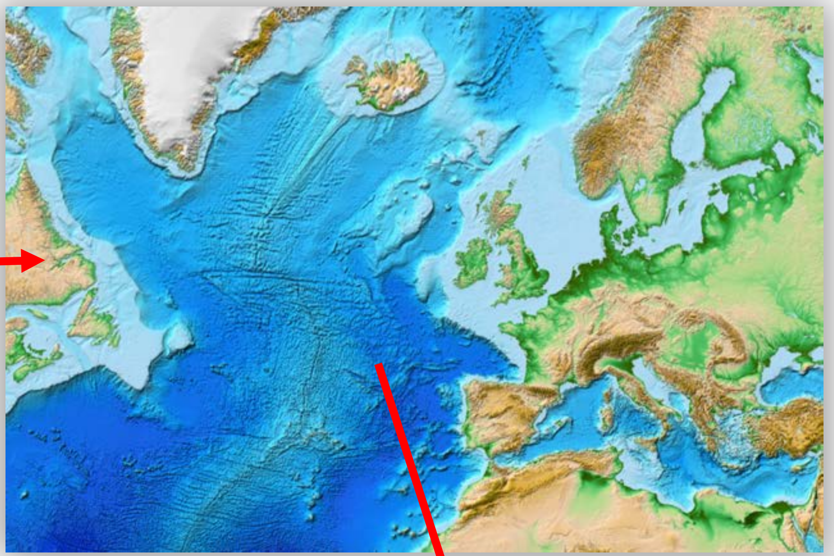
Danabasoglu et al. (2012, J. Climate)

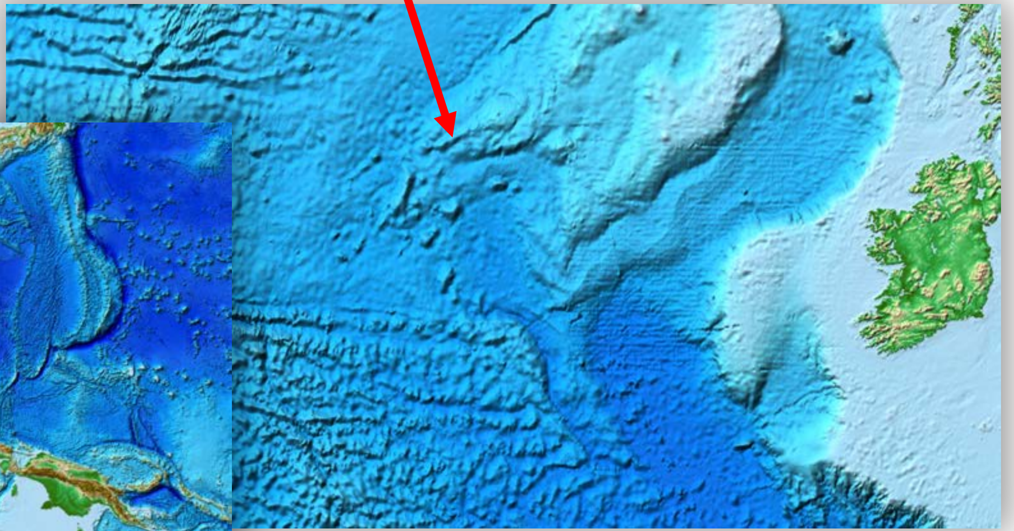
	Surface flow	⊙	Wind-driven upwelling	**L**	Labrador Sea
	Deep flow	⊙	Mixing-driven upwelling	**N**	Nordic Seas
	Bottom flow		Salinity > 36 ‰	**W**	Weddell Sea
	Deep Water Formation		Salinity < 34 ‰	**R**	Ross Sea

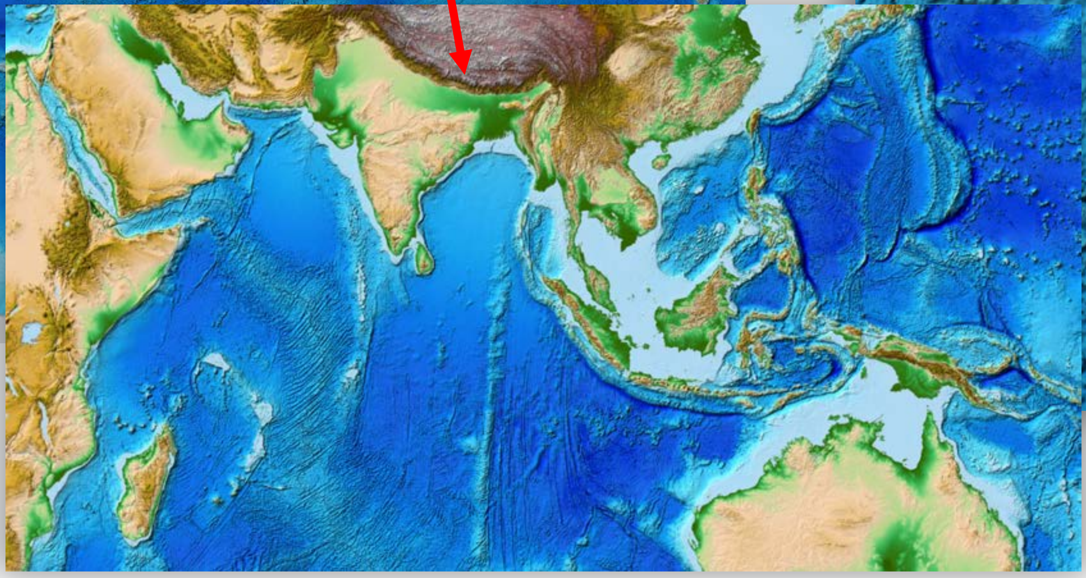
Kuhlbrodt et al. (2007, Rev. Geophys.)

Bathymetry

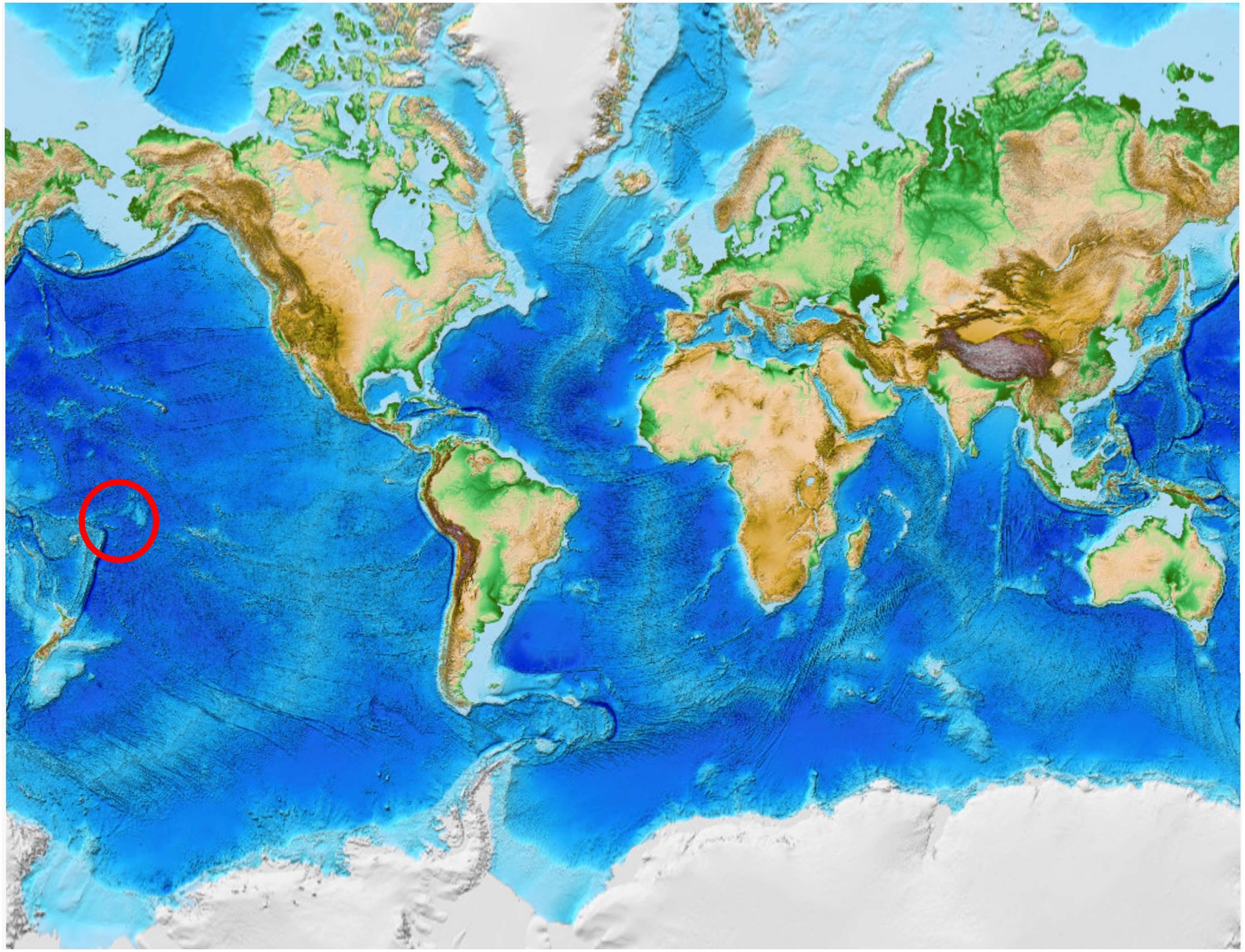








NOAA ETOPO1



Representation in the Ocean Models

Remains rather ad-hoc with each group / model applying their own method, that is, no accepted best practice

Processes are usually not (well) documented

Once created, usually used for many many years

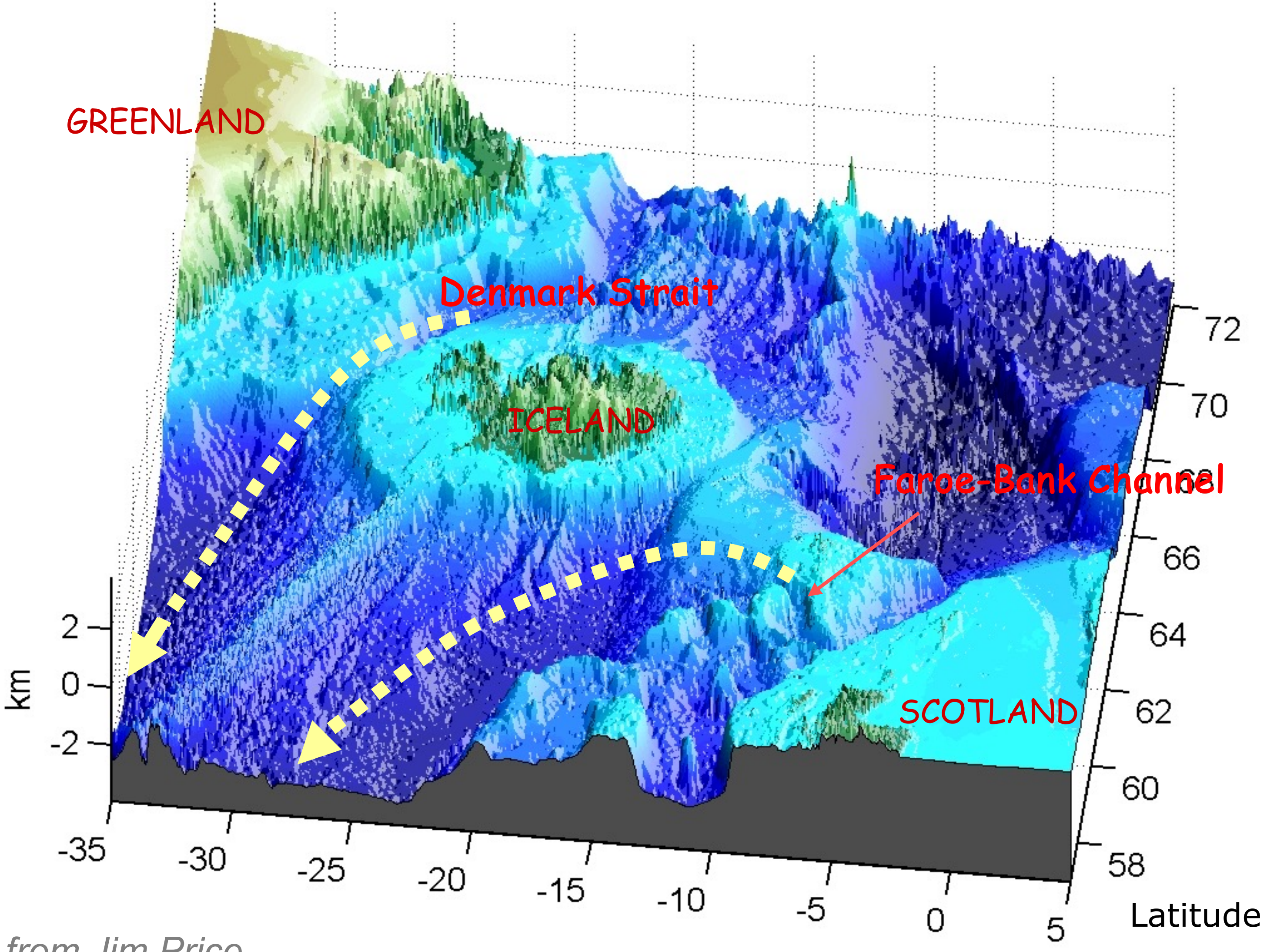
Involves quite a bit of trial-and-error to obtain reasonable transports across various channels, straits, etc.

Details matter

Bathymetry

NOAA ETOPO1

Nordic Seas & Gravity Current Overflows



from Jim Price

Methods Include:

Bulldozing

Terrain following coordinates

Partial / shaved cells (Adcroft et al. 1997, MWR)

Bottom boundary layer schemes

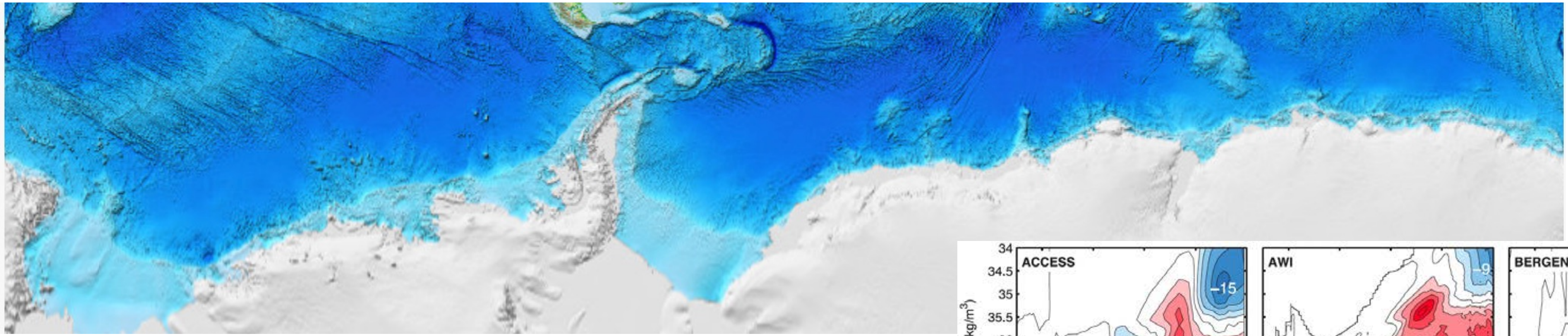
Overflow parameterization (Danabasoglu et al. 2010, JGR)

Regional grid refinement

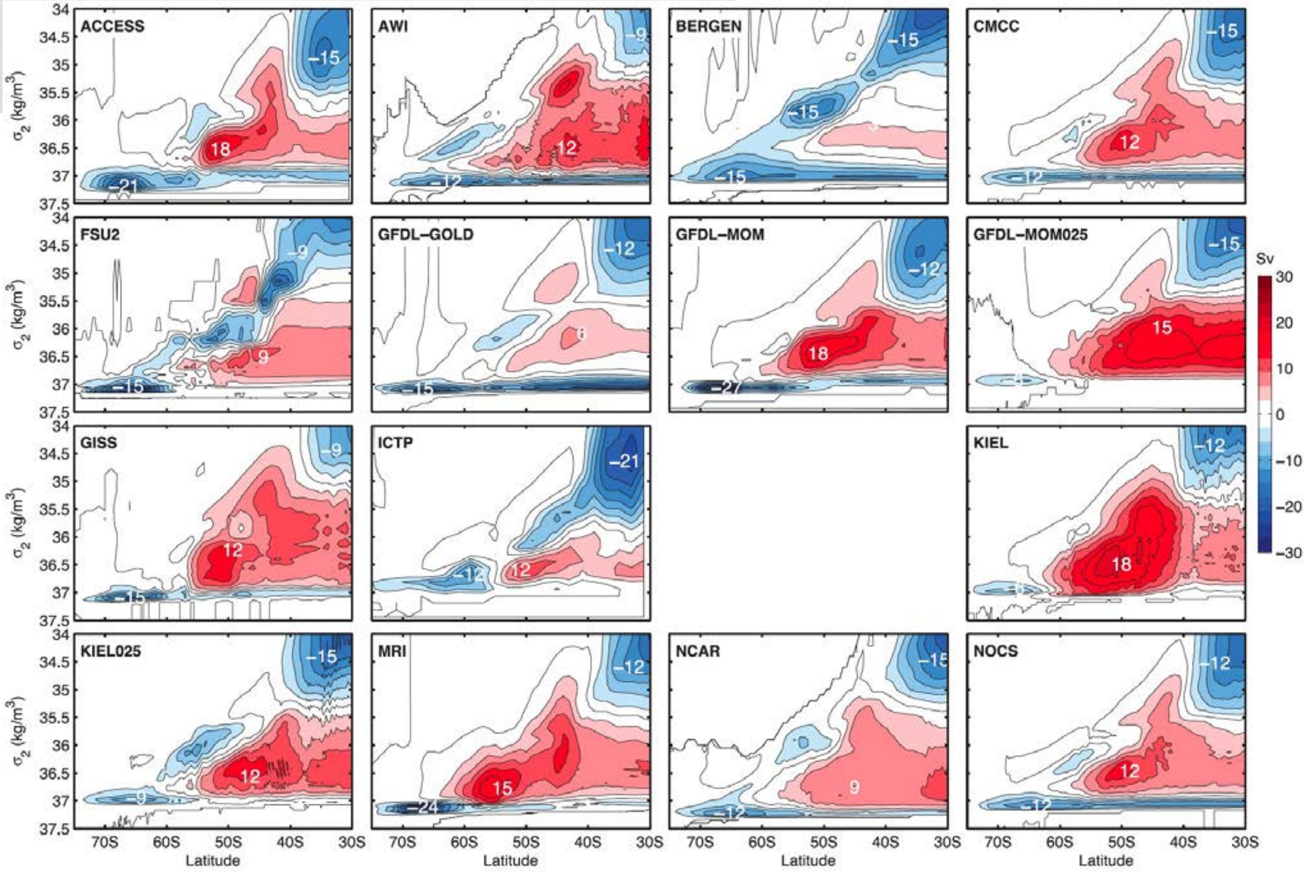
Correct source water properties depend on the realism of surface buoyancy fluxes

Entrainment strongly depends on the correctness / realism of the downstream ambient waters

Ross Sea & Weddell Sea Overflows



Overturning in Density Space



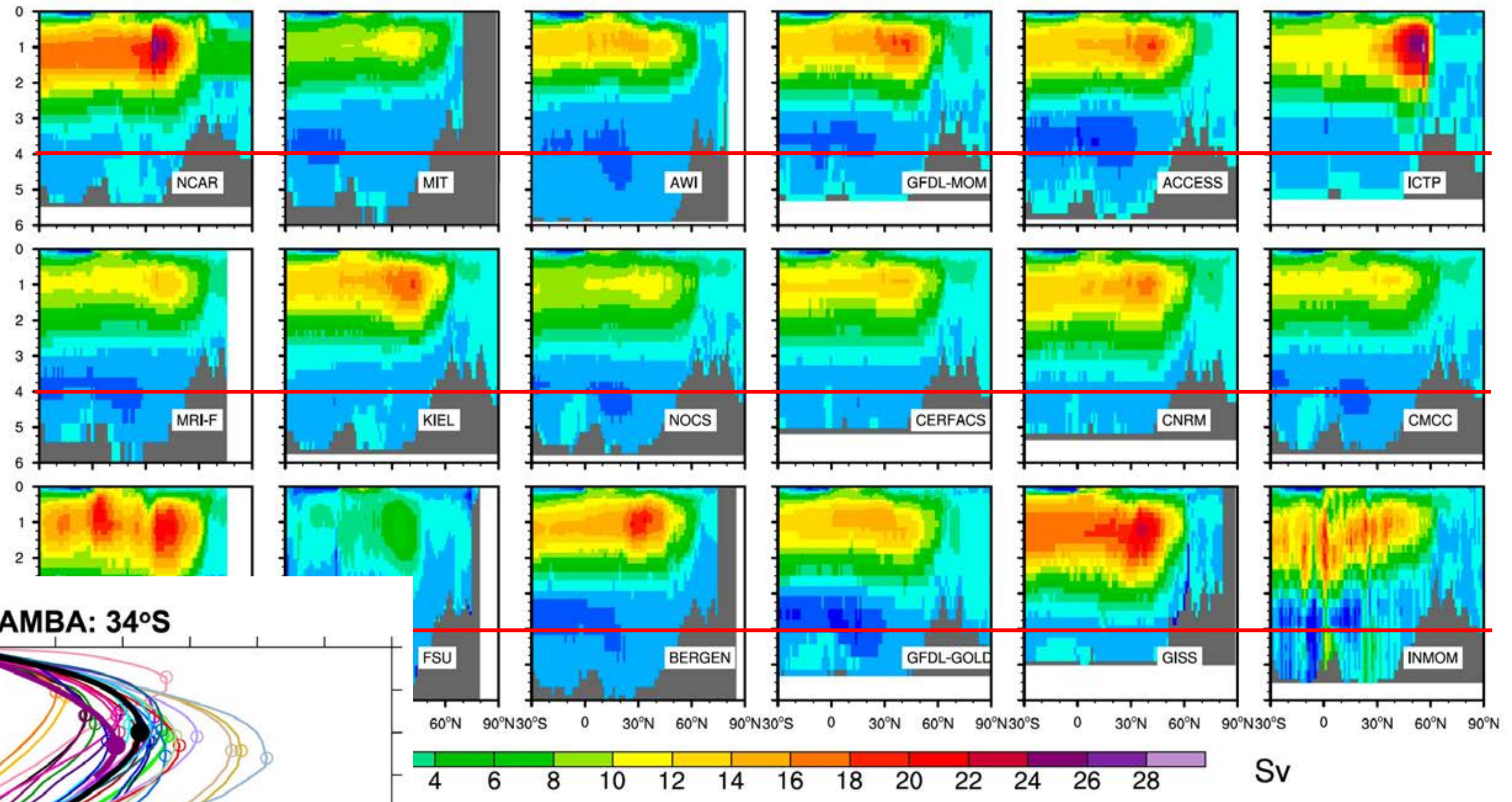
Different properties than their Northern Hemisphere counterparts: Shelf overflows; and entrainment dominates the source waters 4:1!

Ambient stratification is important along the latitudes of the Southern Ocean….. Bottom topography, surface momentum and buoyancy fluxes all matter.

Carbon and heat uptake implications

Farneti et al. (2015, Ocean Modelling)

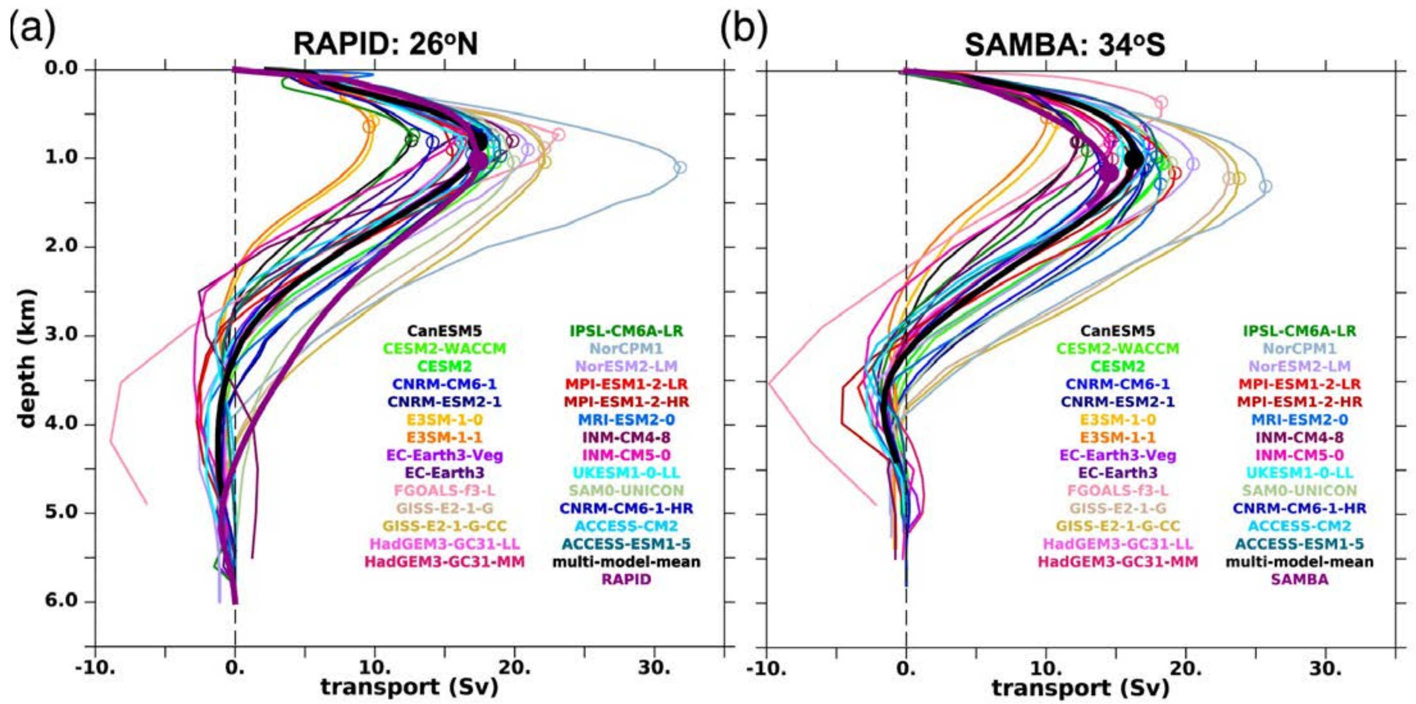
Shallow Penetration Depth of the North Atlantic Deep Water (NADW) Cell



Forced Ocean Simulations

Danabasoglu et al. (2014, Ocean Modelling)

Coupled CMIP6 Simulations



Weijer et al. (2020, GRL)

Equilibration Timescale

Mixing across density surfaces is extremely small once water masses are buried below the mixed layer base.

Scaling argument for deep adjustment time (**diffusive timescale**):

$H^2/\kappa = (3500\ \text{m})^2\ /\ (1 \times 10^{-4}\ \text{m}^2/\text{s}) =$ O (4,000) years

Tidal mixing can reduce this time scale in certain regions.

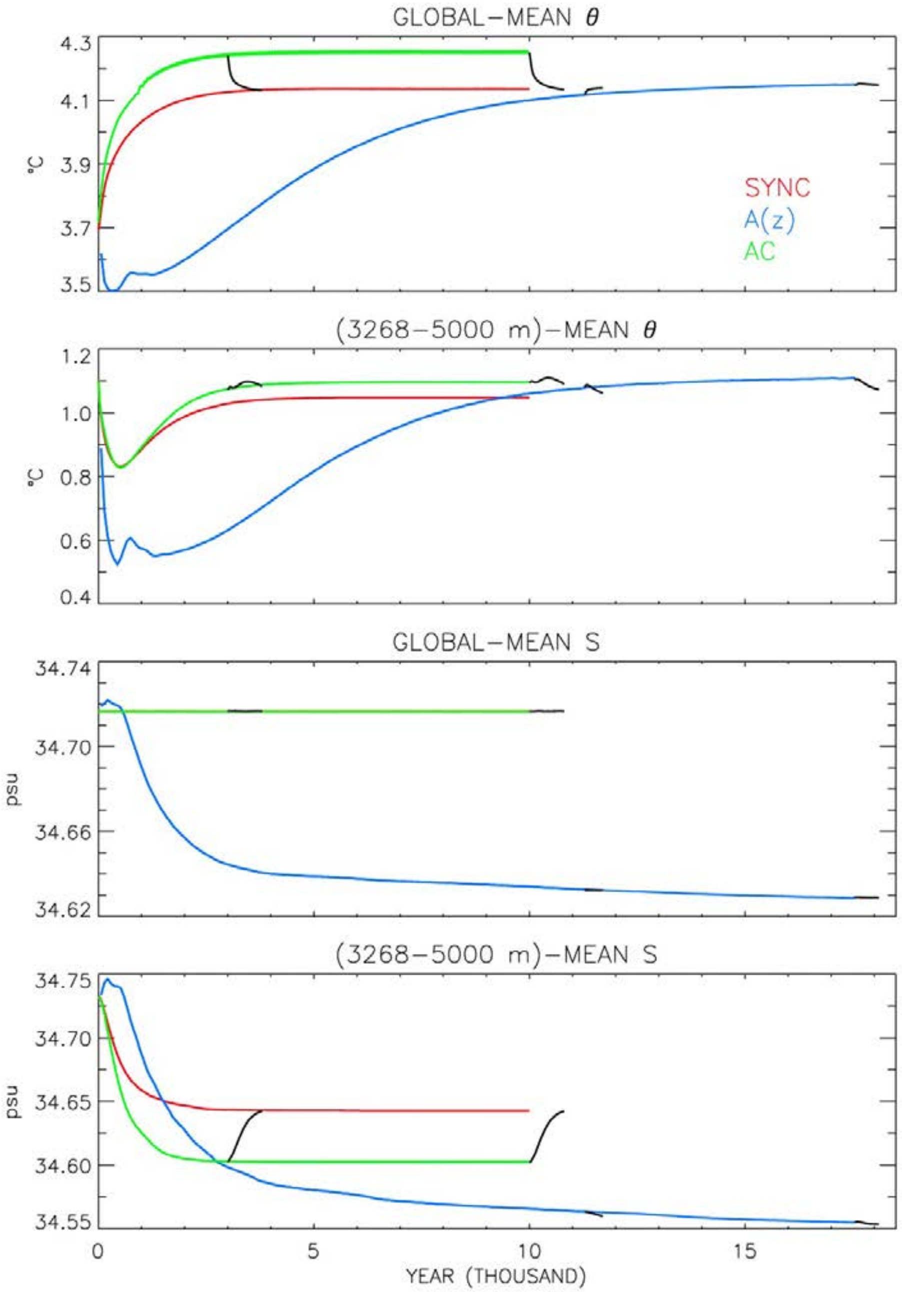
$$k_v = k_{\text{bg}} + \frac{\Gamma \varepsilon}{N^2}$$

Bottom line for climate ……

- Performing long "equilibrium" simulations are not practical, particularly at eddy-resolving / permitting resolutions
- Must live with deep / abyssal ocean not being at equilibrium in most simulations

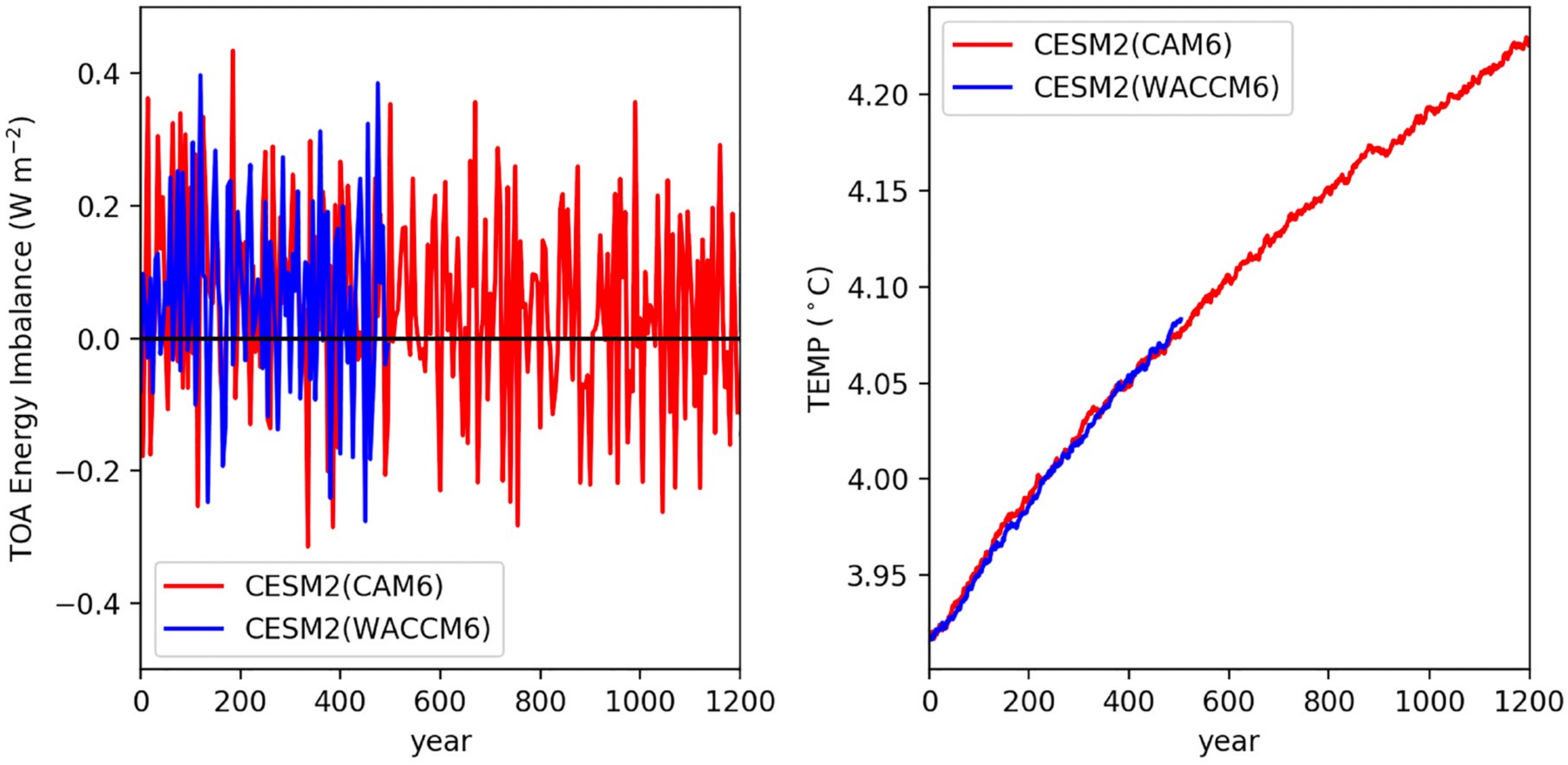
Potential Temperature and Salinity Time Series

Forced ocean simulation at nominal 3° resolution run for 10 000 years (Red Line)



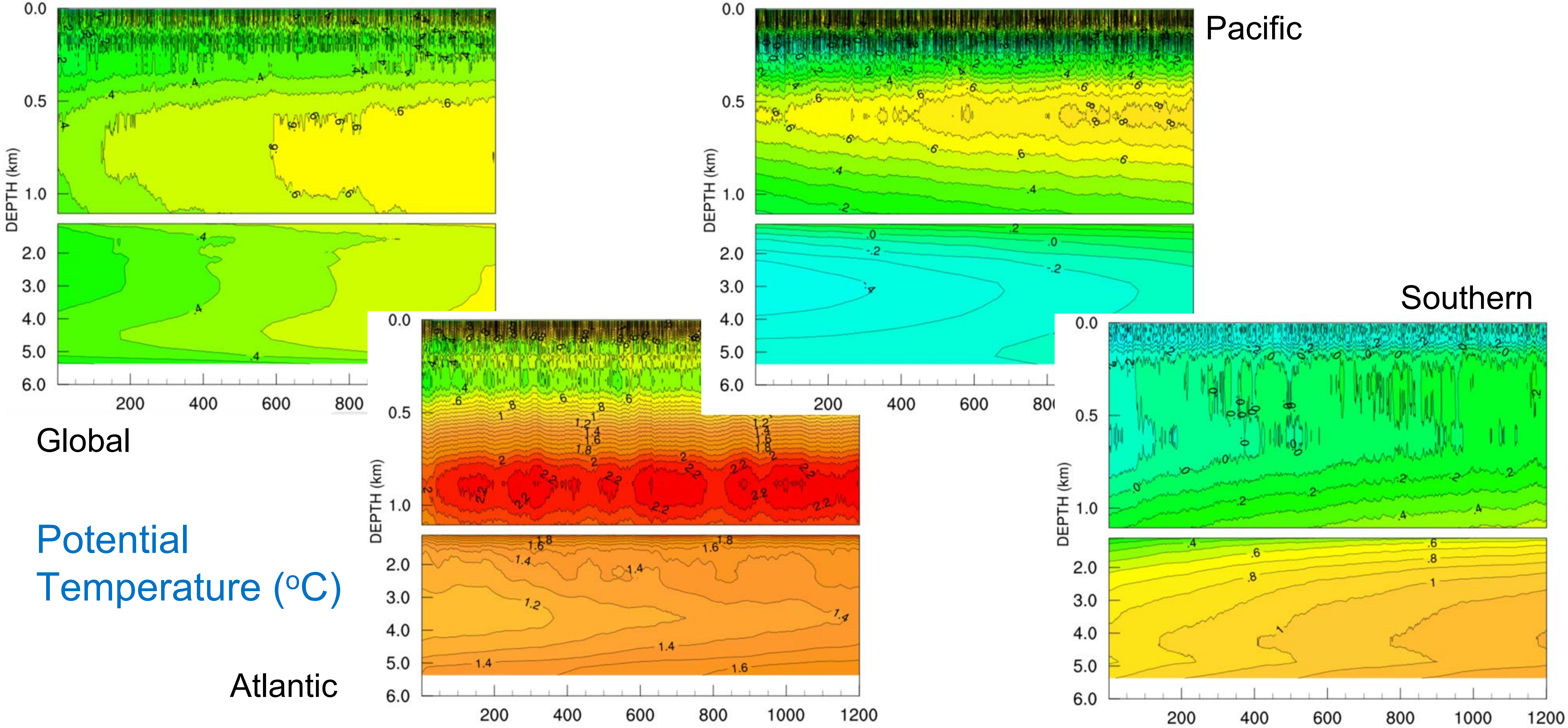
Danabasoglu (2004, Ocean Modelling)

Approach to Equilibrium in CESM2 Fully-Coupled Simulations



Top-of-atmosphere imbalances: +0.03 W m^{-2} during 701-1200 for CESM2(CAM6)
+0.06 W m^{-2} during 301-500 for CESM2(WACCM6)

Approach to Equilibrium in CESM2 Fully-Coupled Simulations

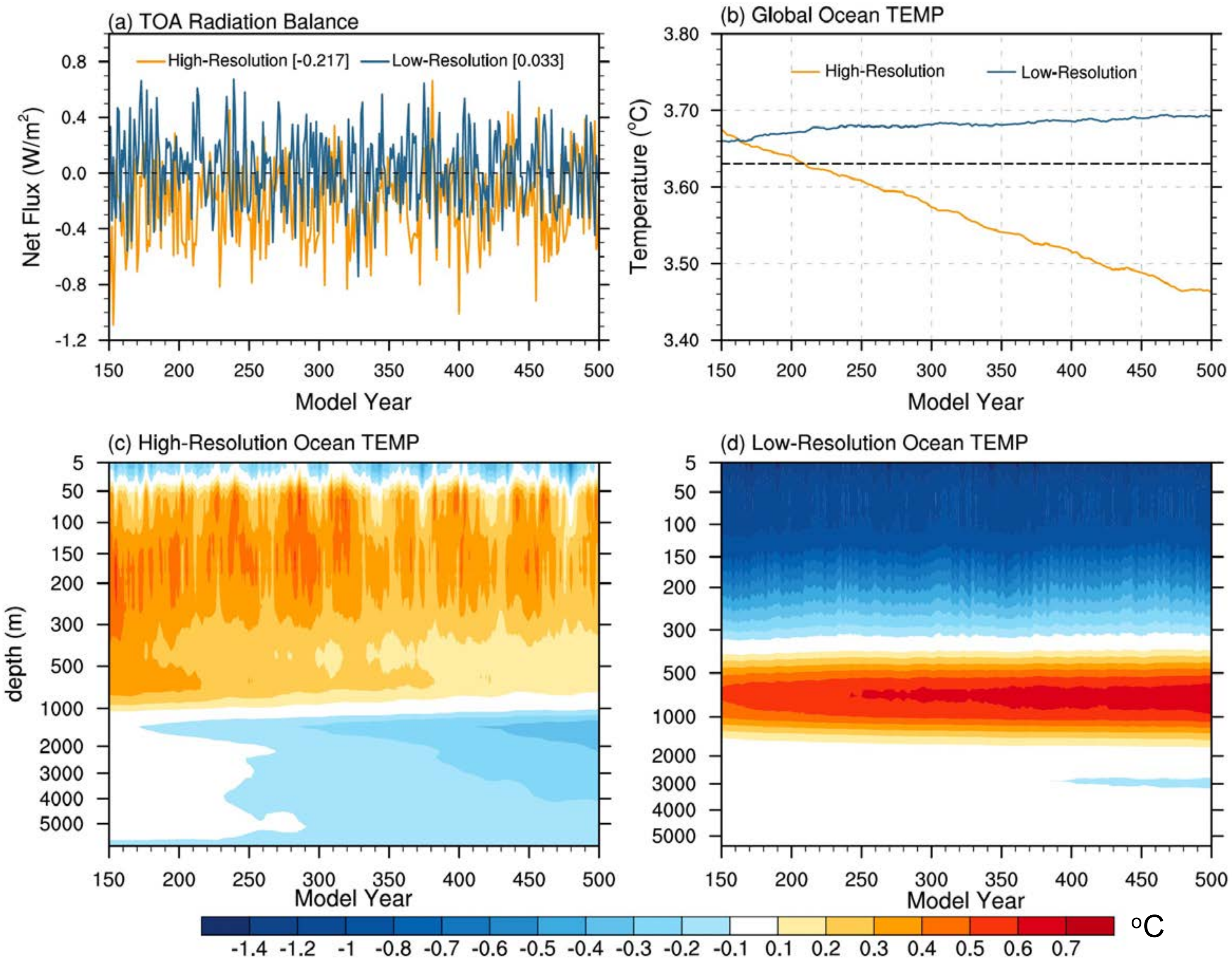


Potential Temperature (°C)

Low- vs High-Resolution Approach to Equilibrium

Low resolution: ~1°

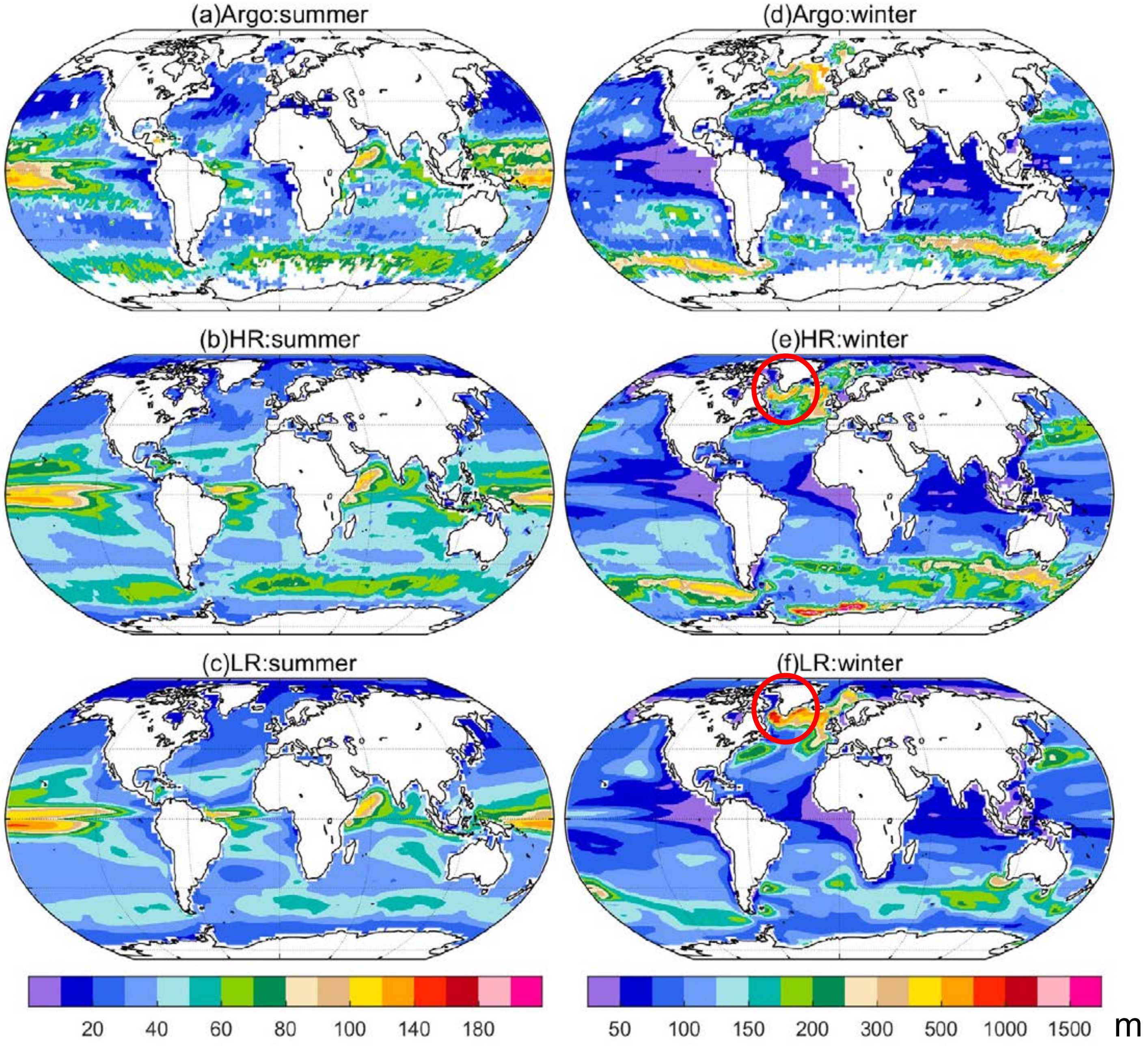
High resolution: 0.1°



Chang et al. (2020, JAMES)

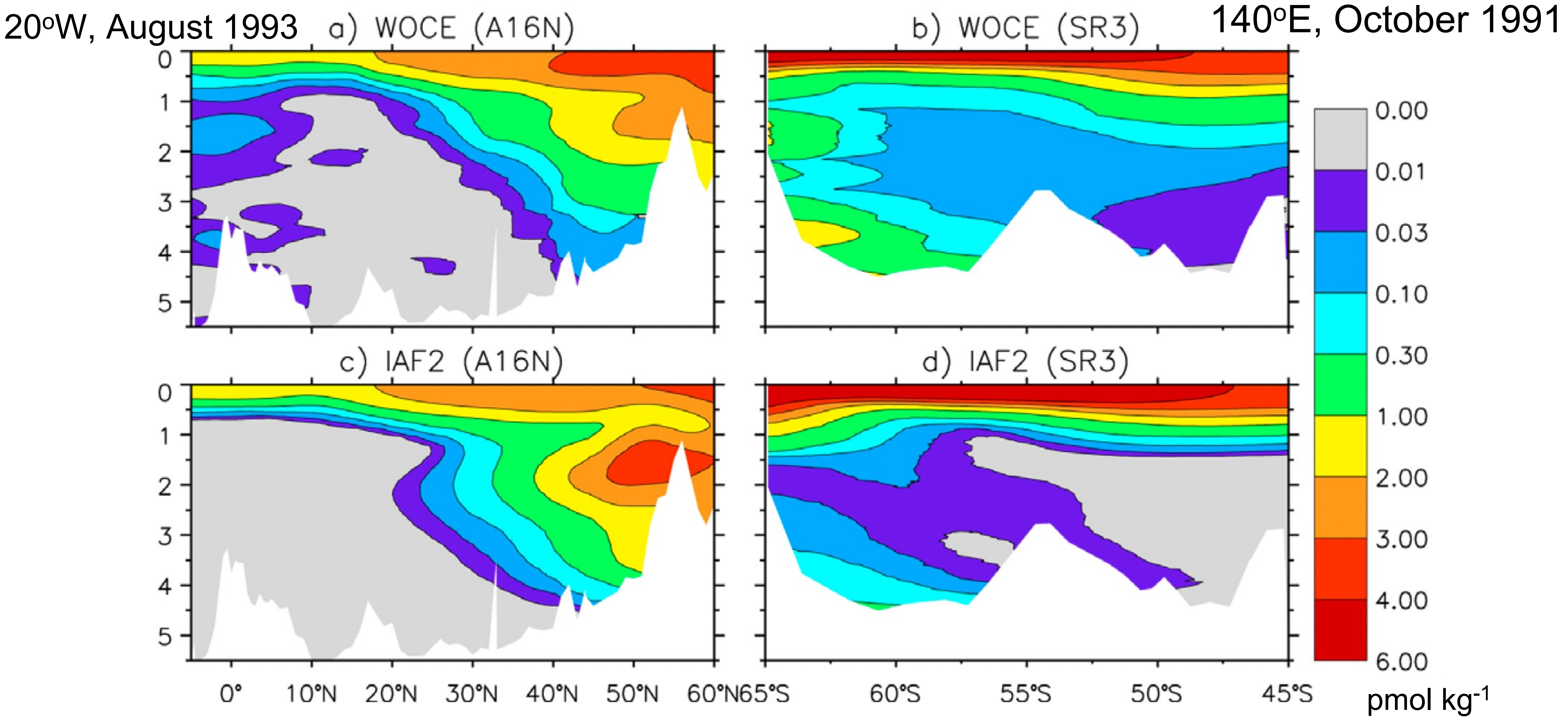
Mixed Layer Depth

In model simulations, AMOC variability on (multi-) decadal time scales is strongly connected to the Labrador Sea mixed layer depth variability.



Chang et al. (2020, JAMES)

Observed and Simulated CFC-11 Distributions

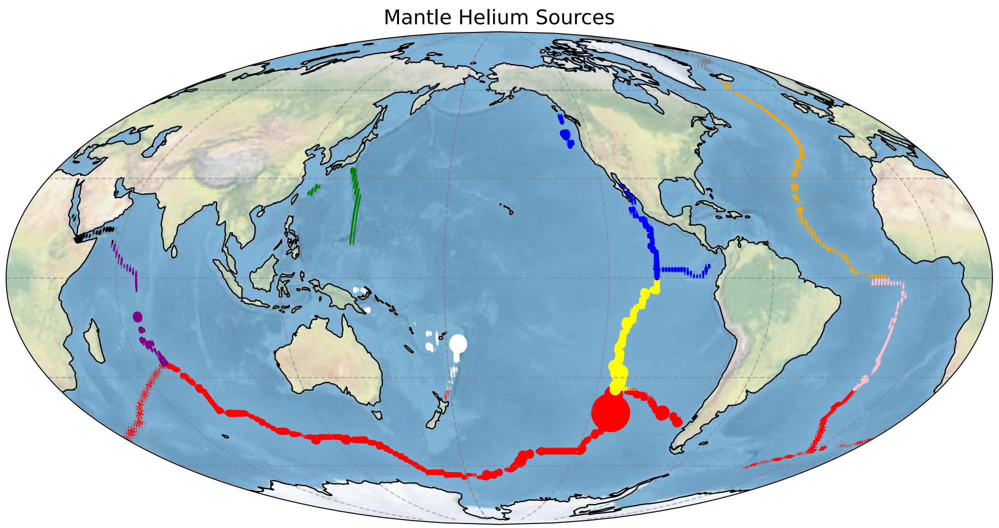


Ideal Age is another useful tracer!

Danabasoglu et al. (2009, Ocean Modelling)

Helium Isotopes as Tracers of Deep and Intermediate Waters

- Helium isotopes captured in the mantle and core during the Earth's formation are discharged to the deep ocean as new oceanic crust forms at mid-ocean ridges.
- The discharged helium is enriched in ^3He relative to ambient atmospheric values providing an isotopic signature of water mass contact with the ridge crest.



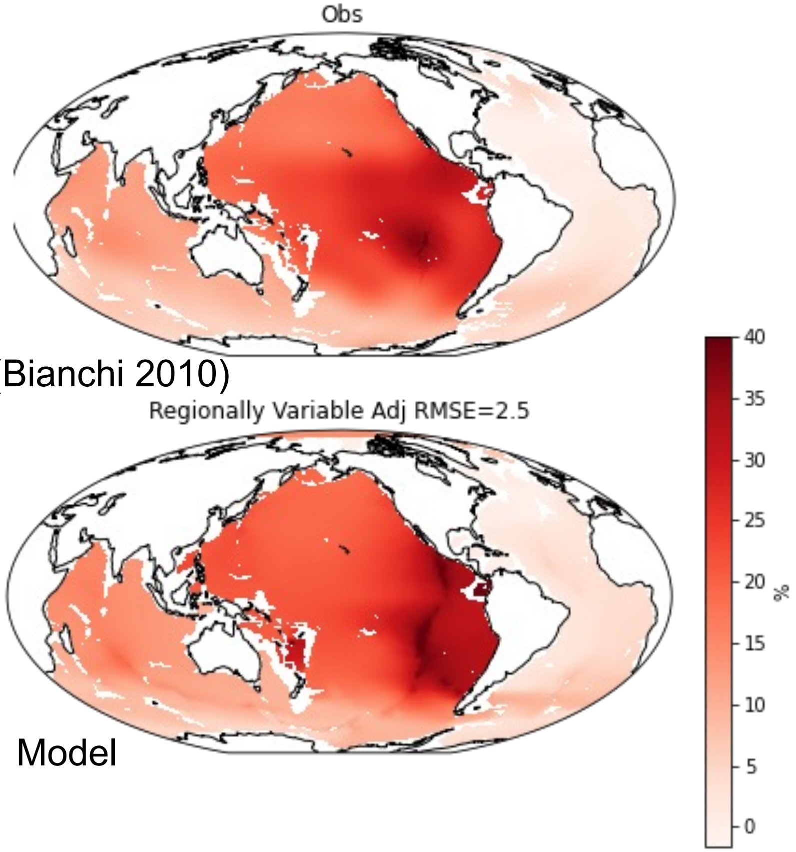
- The helium isotopic ratio $\delta^3 He$ therefore can serve as tracer of bottom water transport and re-emergence that is complimentary to surface sourced tracers.

Frank Bryan, Keith Lindsay, Daisuke Tsumune, & Kazuhiro Misumi

Helium Isotopes as Tracers of Deep and Intermediate Waters

Newton-Krylov Fast Iterative Solver

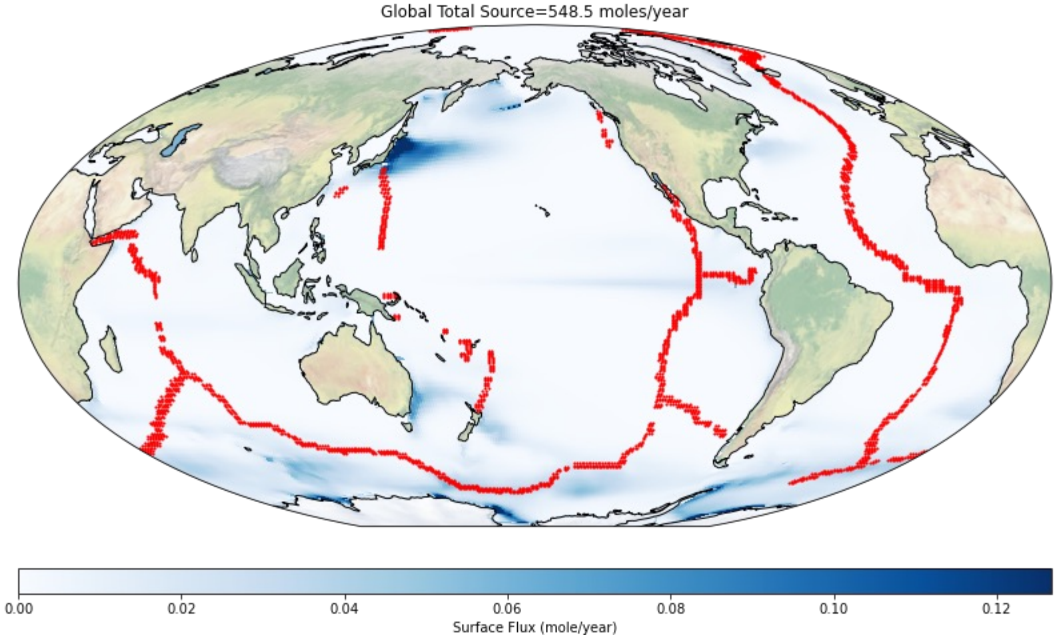
2500-m Depth

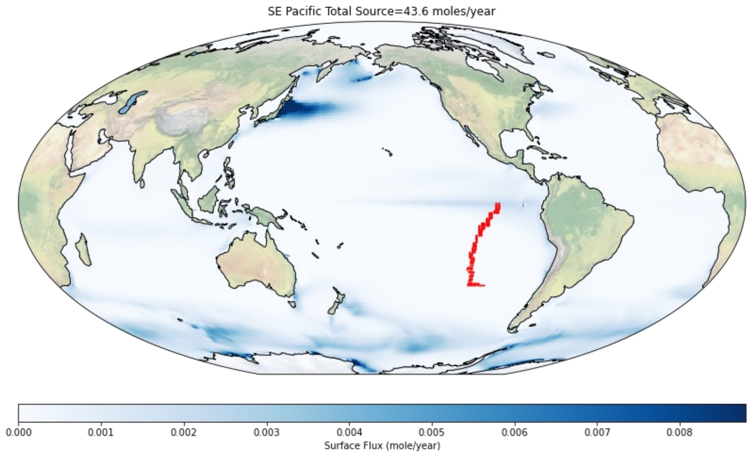


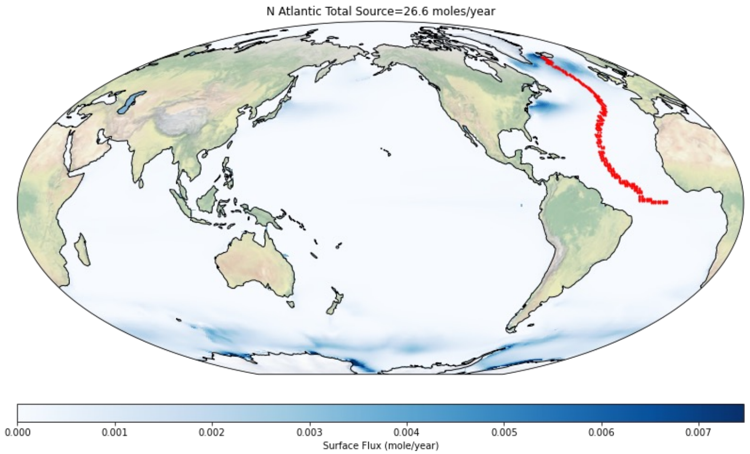
(Bianchi 2010)

Model

Where do deep waters re-emerge?







Frank Bryan, Keith Lindsay, Daisuke Tsumune, & Kazuhiro Misumi

Opportunities

Continue model development / improvement efforts (not just in the ocean models) as challenges present opportunities

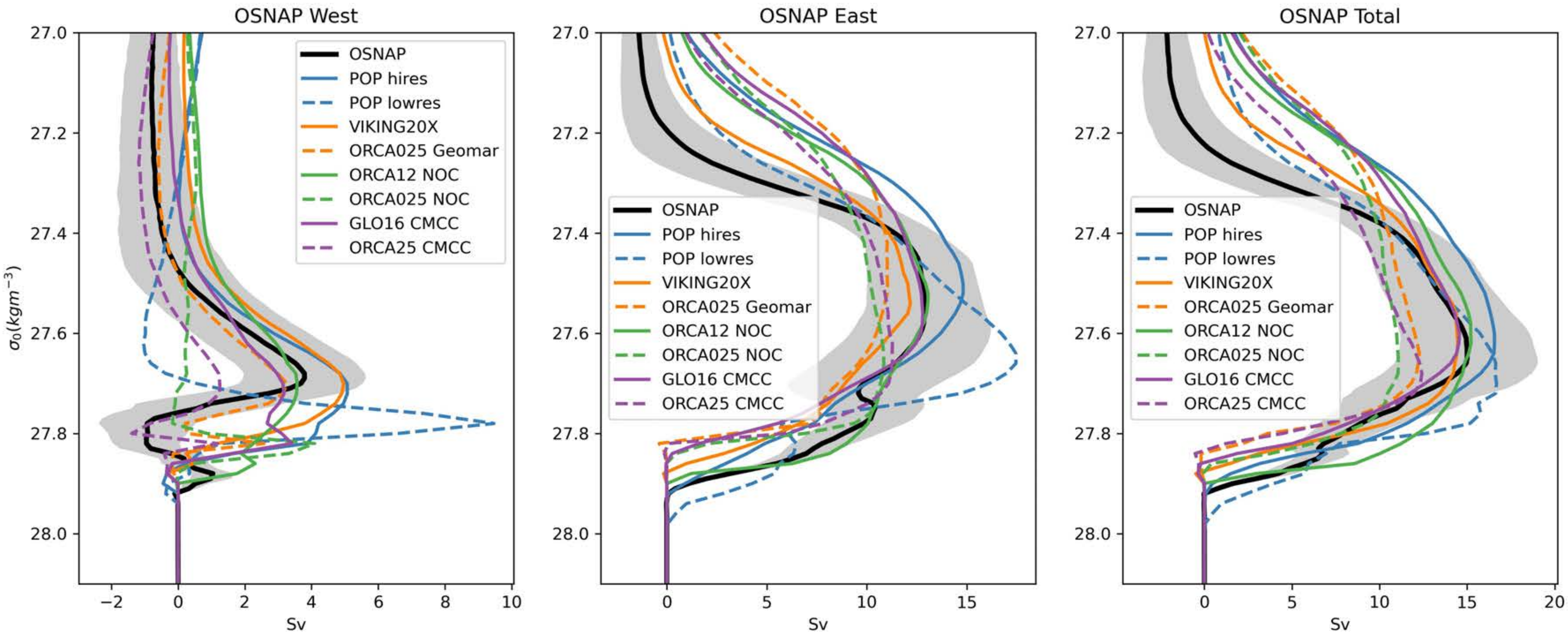
Expand Deep Argo (with BGC)

Use AI / ML techniques to accelerate approach to equilibrium and to reduce drift / expedite redistribution (?)

Further enhance collaborations / communications between modelers and observationalists as well as across disciplines

Thank you!

Time-Mean Transports Across OSNAP Sections

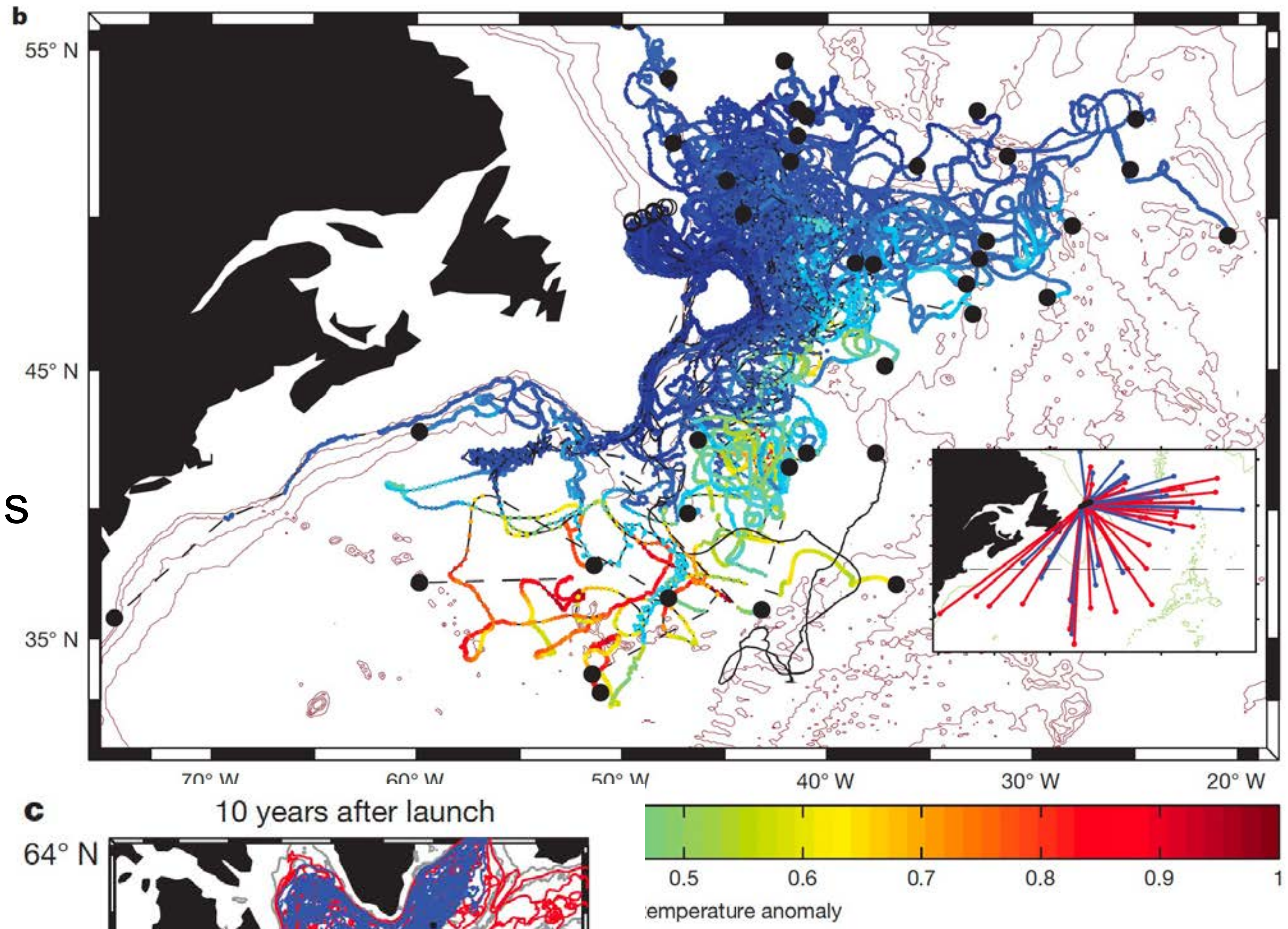


Danabasoglu et al. (2025)

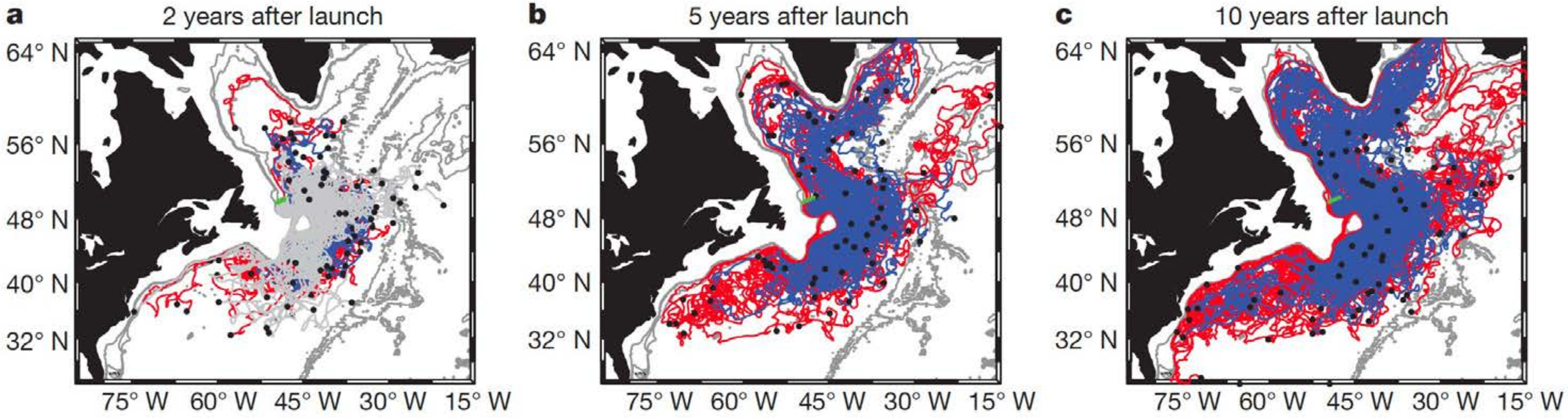
OSNAP: Overturning in the Subpolar North Atlantic Program

Interior Pathways in the North Atlantic Ocean

Observations



Simulations



Bower et al. (2009, Nature)