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)

Kuhlbrodt et al. (2007, Rev. Geophys.)
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
Nordic Seas & Gravity Current Overflows

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

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

Coupled CMIP6 Simulations

Forced Ocean Simulations

Danabasoglu et al. (2014, Ocean Modelling)

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):

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

Tidal mixing can reduce this time scale in certain regions.

\[
k_v = k_{bg} + \frac{\Gamma \varepsilon}{N^2}
\]

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

Chang et al. (2020, JAMES)

Low resolution: $\sim 1^\circ$

High resolution: $0.1^\circ$
In model simulations, AMOC variability on (multi-) decadal time scales is strongly connected to the Labrador Sea mixed layer depth variability.
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 $^{3}$He 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

Where do deep waters re-emerge?

(Bianchi 2010)

Regionally Variable Adj RMSE=2.5

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)