Modeling pathways and processes of deep ocean ventilation

Henri Drake
Assistant Professor
UC Irvine, Earth System Science
This workshop is primarily concerned with how surface exchange fluxes are communicated to the deep ocean.

Modeling methods must adequately represent the ventilation processes involved for a given scientific problem.
Another interesting question is how deep (or benthic) fluxes are communicated to the interior ocean and, ultimately, the sea surface.

Modeling methods should be designed to address the specific question at hand; methods for the “surface-to-deep” problem are different from those for the “deep-to-surface” one!
Surface-to-deep pathways are strongly asymmetric: the pathways and timescales of tracer transport between two points can depend strongly on this directionality.
Overview of numerical model analysis methods

A) Eulerian tracer methods
B) Lagrangian particle methods
C) Semi-Lagrangian water mass transformation methods
A) Eulerian tracer methods

Evolution of tracer concentration $\lambda$: 
\[
\frac{D\lambda}{Dt} = \frac{\partial \lambda}{\partial t} + \mathbf{u} \cdot \nabla \lambda = \dot{\lambda} \quad \rightarrow \quad \frac{\partial \lambda}{\partial t} = -\mathbf{u} \cdot \nabla \lambda + \dot{\lambda}
\]

1. **Active tracers (which feedback on circulation)**
   - Temperature, salinity, and density

2. **Passive tracers (which do not affect the circulation)**
   - Chemically inert transient tracers (CFCs, SF6, etc.)
   - Radioactive tracers, sourced naturally (e.g. radiocarbon and actinium) and anthropogenically (radiocarbon, tritium)
   - Biogeochemically active tracers (DIC, DO, nutrients, etc.)
   - Hypothetical passive versions of active tracers (e.g. passive temperature; Armour et al. 2016, *Nature Geo.*)
   - Idealized tracers w/ custom forcing and initial and boundary conditions (e.g. ideal seawater age; England 1995, *JPO*)
Biogeochemically inert transient tracers

- Well-known atmospheric concentrations (as surface boundary condition)
  - CFCs: A multi-decadal pulse that peaks in 1980s
  - SF6: linearly increasing since the 1950s
- Approximately conserved in the ocean interior
- Simulated ventilation can be evaluated by comparing against sustained repeat hydrography

Example: results from GFDL’s CM4X global climate model at 1/8th resolution (Griffies et al, in prep)

Drake et al. (in prep); see also England (1995), GRL and Wang et al. (2021), PNAS
Custom tracers: ideal seawater age

Initial condition: \( a(x, t = t_0) = 0 \)

Age forcing: \( \frac{Da}{Dt} = 1 \) (waters get older by 1 second per 1 second of simulation time)

Boundary condition: \( a(x, y, z = 0, t) = 0 \) (waters are reborn when ventilated at the surface)

The equilibrium age distribution has a straightforward interpretation as “time since ventilated”.

However, we can not afford to run state-of-the-art models all the way to equilibrium (see Gokhan’s talk).
Custom tracers: ideal seawater age

Initial condition: \[ a(x, t = t_0) = 0 \]

Age forcing: \[ \frac{Da}{Dt} = 1 \] (waters get older by 1 second per 1 second of simulation time)

Boundary condition: \[ a(x, y, z = 0, t) = 0 \] (waters are reborn when ventilated at the surface)

Transient age deficit:

The age deficit is by definition bounded between \([0, 1]\), where:

- \( D = 1 \) for perfectly ventilated (young) waters
- \( D = 1 \) for unventilated (old) waters

Drake et al. (in prep); Griffies et al. (in prep)
B) Lagrangian particle methods

1. Mass/volume transport streamtubes
2. Tracers as probability distributions of stochastic Lagrangian particles

Antarctic Circumpolar Current flow speed (at 0.1°)

Drake et al. (2018), GRL

See our comprehensive review paper, still reasonably up-to-date.
Mass/volume transport streamtubes

\[ \frac{D (dV)}{Dt} = 0 \quad \text{along material parcel trajectories } X(t), \text{ found by integrating } u = \frac{DX}{Dt} \]

Lagrangian decomposition of the AMOC by deep water source region

Mass/volume transport streamtubes

\[ \frac{D (dV)}{Dt} = 0 \] along material parcel trajectories \( X(t) \), found by integrating \( u \equiv \frac{DX}{Dt} \)

Pathways of upwelling in the Southern Ocean

Drake et al. (2018), GRL
Mass/volume transport streamtubes

\[ \frac{D (dV)}{Dt} = 0 \] along material parcel trajectories \( X(t) \), found by integrating \( u = \frac{DX}{Dt} \)

Pathways of upwelling in the Southern Ocean

Pathways and timescales of Southern Ocean upwelling are strongly resolution-dependent!

a) CM2-1deg-5day (1°) c) CM2.6-5day (0.1°)

Drake et al. (2018), GRL

Timescales of global overturning circulation cells

Rousselet, Cessi, and Forget (2021), Science Advances
Tracers as probability distributions of stochastic Lagrangian particles

\[(\partial_t + \mathbf{u} \cdot \nabla) C = \nabla \cdot (\mathbf{J} \nabla C)\]  \hspace{1cm} \text{(Fokker-Planck PDE for Eulerian tracer concentration)}

Mathematical equivalence via Itô (or Stratonovich) Calculus

\[dX^{(p)}_i(t) = u^{\text{drift}}(X^{(p)}, t) dt + \sigma_{ik}(X^{(p)}, t) dW_k(t)\]  \hspace{1cm} \text{(Stochastic diff. eq. for Lagrangian tracer trajectory)}

Spivakovskaya, Heemink, Deleersnijder (2007)
Tracers as probability distributions of stochastic Lagrangian particles

\[(\partial_t + \mathbf{u} \cdot \nabla) C = \nabla \cdot (\mathbf{J} \nabla C) \quad \text{(Fokker-Planck PDE for Eulerian tracer concentration)}\]

Mathematical equivalence via Itô (or Stratonovich) Calculus

\[dX^{(p)}_i(t) = u^{\text{drift}}(X^{(p)}, t)dt + \sigma_{ik}(X^{(p)}, t)dW_k(t) \quad \text{(Stochastic diff. eq. for Lagrangian tracer trajectory)}\]

**Modeling gap:** Virtually no Lagrangian ocean model analyses correctly implement these sub-gridscale turbulence effects!

Modelers instead either ignore tracer diffusion or implement ad-hoc Brownian motion schemes that are inconsistent with the underlying Eulerian model.
C) Semi-Lagrangian water mass transformation analysis

**Concept:** analyze the drivers of the size $\mathcal{M}$ of a water mass defined by a range of tracer concentrations $\lambda$ in a region $\mathcal{R}$.

**Schematic mass budget:** The mass of water shaded in red can change for three reasons:
1. **Surface volume/mass fluxes**
2. **Movement of the bounding tracer isosurface**
3. **Horizontal transport across the region’s lateral boundary**

Drake et al. (2024), *Submitted to JAMES* ([https://doi.org/10.22541/essoar.171284935.57181910/v1](https://doi.org/10.22541/essoar.171284935.57181910/v1))

See also review by Groeskamp et al. (2019), *Annual Reviews of Marine Science*
C) Semi-Lagrangian water mass transformation analysis

**Concept:** analyze the drivers of the size $\mathcal{M}$ of a water mass defined by a range of tracer concentrations $\lambda$ in a region $\mathcal{R}$.

Using the water mass transformation relationship, we can relate the movement of the bounding isosurface to the tracer fluxes due to various processes (including numerical model errors).

Drake et al. (2024), *Submitted to JAMES* ([https://doi.org/10.22541/essoar.171284935.57181910/v1](https://doi.org/10.22541/essoar.171284935.57181910/v1))

See also review by Groeskamp et al. (2019), *Annual Reviews of Marine Science*
Example application of water mass transformation analysis

Using Water Mass Transformation theory, we can decompose the drivers of the MOC:

$$\Psi(\sigma_2, \phi)$$

overturning

Drake, MacGilchrist, Tesdal, Turner, Krasting, and Griffies (in prep.)
See also Xu et al. (2018), JPO for the North Atlantic only
Example application of water mass transformation analysis

Using Water Mass Transformation theory, we can decompose the drivers of the MOC:

$$\Psi(\sigma_2, \phi)$$

overturning

We compute the mass budget for waters denser than $$\sigma_2 = \rho_2 - 1000$$ and south of latitude $$\phi$$.

Drake, MacGilchrist, Tesdal, Turner, Krasting, and Griffies (in prep.)
See also Xu et al. (2018), JPO for the North Atlantic only
Example application of water mass transformation analysis

Using Water Mass Transformation theory, we can decompose the drivers of the MOC:

\[ \Psi(\sigma_2, \phi) \]

overturning

We repeat this calculation for many combinations of latitudes and density surfaces.

Drake, MacGilchrist, Tesdal, Turner, Krasting, and Griffies (in prep.)
See also Xu et al. (2018), JPO for the North Atlantic only
Example application of water mass transformation analysis

Using Water Mass Transformation theory, we can decompose the drivers of the MOC:

$$\Psi(\sigma_2, \phi)$$

overturning

---

Drake, MacGilchrist, Tesdal, Turner, Krasting, and Griffies (in prep.)
See also Xu et al. (2018), JPO for the North Atlantic only
Example application of water mass transformation analysis

Using Water Mass Transformation theory, we can decompose the drivers of the MOC:

$$\Psi(\sigma_2, \phi) = g^{(\text{Surface})} + g^{(\text{Seafloor})} + g^{(\text{Mix})} + g^{(\text{Spurious})} + S + \partial_t M$$

---

Drake, MacGilchrist, Tesdal, Turner, Krasting, and Griffies (in prep.)
See also Xu et al. (2018), JPO for the North Atlantic only
The upper cell is primarily adiabatic, driven by surface buoyancy loss in the North Atlantic and closed by buoyancy gain in the Southern Ocean.

Drake, MacGilchrist, Tesdal, Turner, Krasting, and Griffies (in prep.)
See also Xu et al. (2018), JPO for the North Atlantic only
Example application of water mass transformation analysis

Using Water Mass Transformation theory, we can decompose the drivers of the MOC:

$$
\Psi (\sigma_2, \phi) = G^{\text{Surface}} + G^{\text{Seafloor}} + G^{\text{Mix}} + G^{\text{Spurious}} + S + \partial_t M
$$

The lower cell is driven by surface buoyancy loss around Antarctica but closed by widely-distributed turbulent mixing.

Drake, MacGilchrist, Tesdal, Turner, Krasting, and Griffies (in prep.)
See also Xu et al. (2018), JPO for the North Atlantic only
Summary of numerical model analysis methods

A) Eulerian tracer methods (observable vs. custom tracers)
   • Most direct method but scales poorly for large numbers of tracers
   • Custom-designed tracers can complement observable ones

B) Lagrangian particle methods (streamtubes vs. stochastic tracers)
   • Can conditionally average trajectories to separate distinct transport pathways
   • Trajectories can be computed using archived velocity fields, making analysis more accessible
   • Often used to qualitatively trace pathways, but quantitative/conservative methods are available

C) Semi-Lagrangian water mass transformation methods
   • Allows process-based attribution and detection of water mass and circulation changes
   • Requires either dedicated online diagnostics or archiving of enormous quantities of model output
**Challenges:**

1. Interpreting the results from each of these methods is much more challenging when both circulation and tracers are rapidly changing.

2. How can we control for model drift or correct for model biases (mean state and sensitivity)?

**Opportunities:**

1. With several decades of ocean modeling experience, these methods are mature: best practices are established and many open-source tools are available to the community.

2. With CMIP7 efforts underway, now is the time to advocate for the design of model experiments and diagnostics required to evaluate these pathways.

3. Observational counterparts to evaluate these model diagnostics:
   a) Eulerian tracers: Repeat hydrography, Deep Argo profiles, Tracer Release Experiments, etc.
   b) Lagrangian trajectories: RAFOS floats, Deep Argo drift
   c) Water mass budgets: moored arrays / hydrography + satellite surface fluxes + deep Argo