Modeling pathways and processes of deep ocean ventilation

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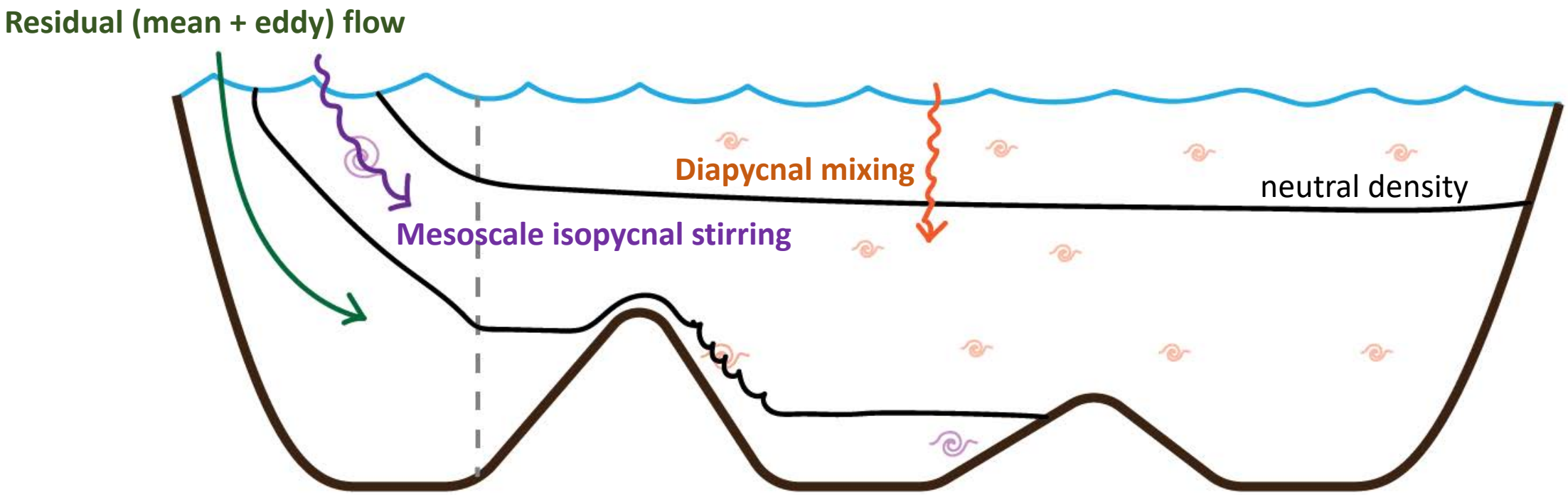
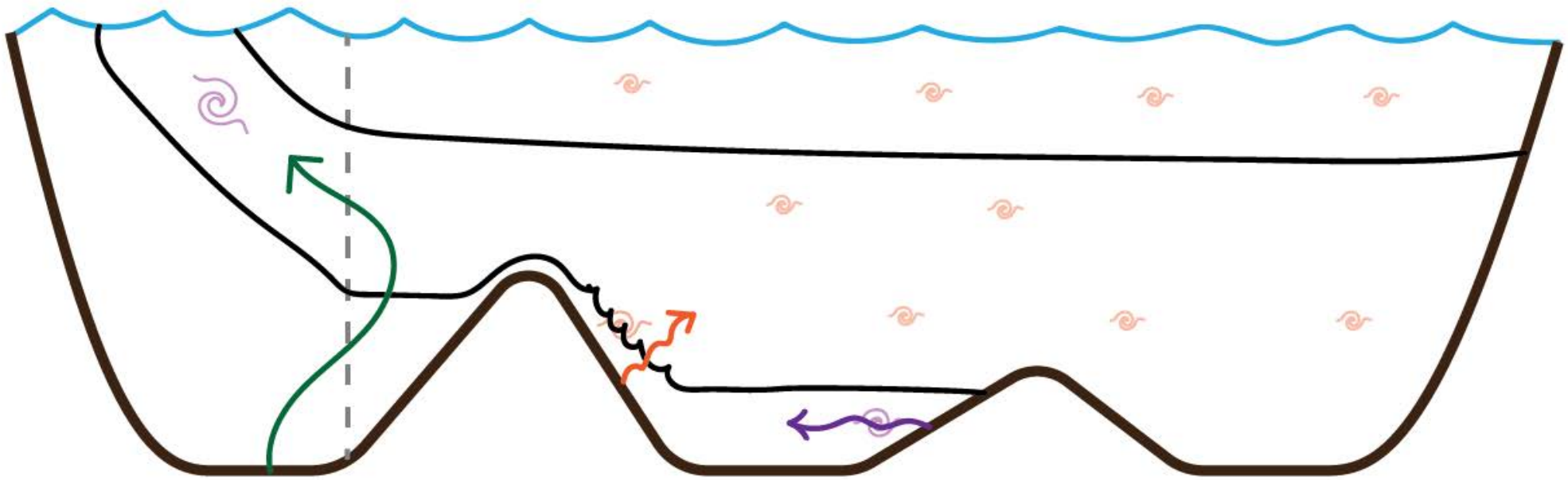
This workshop is primarily concerned with how surface exchange fluxes are communicated to the deep ocean.



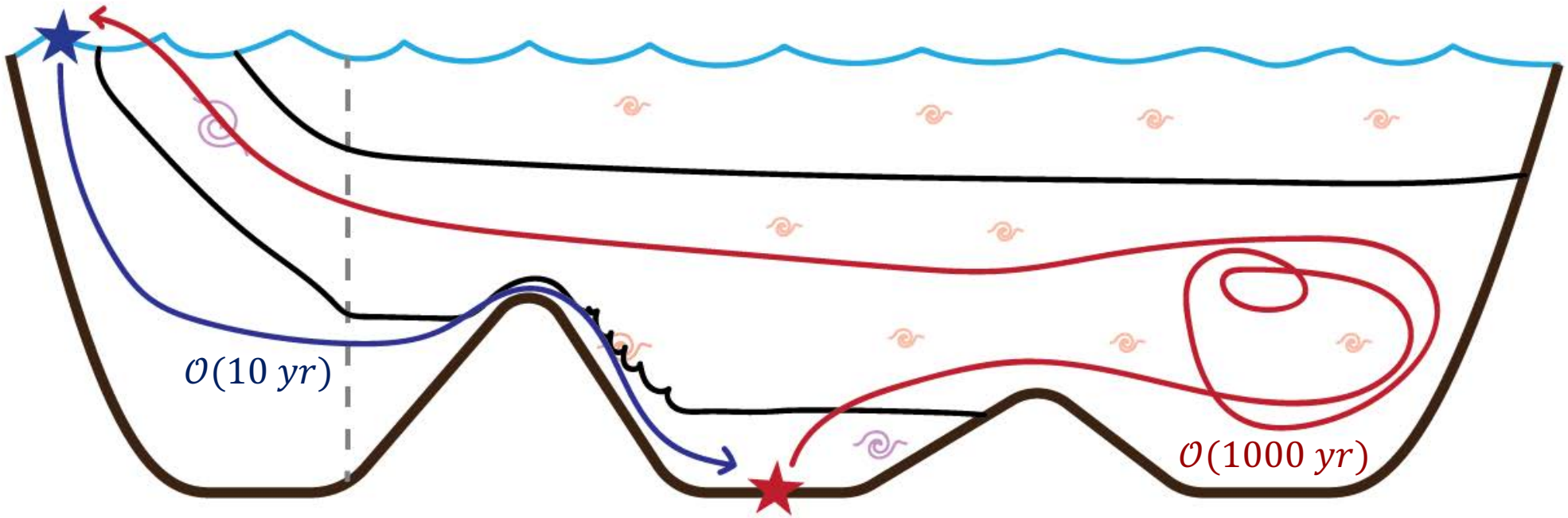
Modeling methods must adequately represent the ventilation processes involved for a given scientific problem.

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 λ: $$\frac{\mathrm{D}\lambda}{\mathrm{D}t} = \frac{\partial \lambda}{\partial t} + \boldsymbol{u} \cdot \boldsymbol{\nabla}\lambda = \dot{\lambda} \quad \rightarrow \quad \underbrace{\frac{\partial \lambda}{\partial t}}_{\text{time tendency in a model grid cell}} = -\overbrace{\boldsymbol{u}}^{\text{ocean model velocity}} \cdot \boldsymbol{\nabla}\lambda + \dot{\lambda}$$

1. Active tracers (which feedback on circulation) $$\frac{\partial \boldsymbol{u}}{\partial t} = \boldsymbol{F}(\lambda, \ldots)$$
   - Temperature, salinity, and density

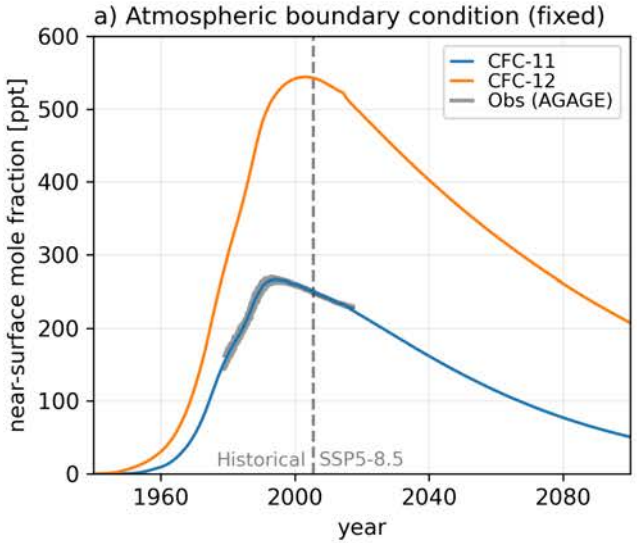
2. Passive tracers (which do not affect the circulation) $$\frac{\partial}{\partial \lambda}\left[\frac{\partial \boldsymbol{u}}{\partial t}\right] = 0$$
   - Chemically inert transient tracers (CFCs, SF6, etc.)
   - Radioactive tracers, sourced naturally (e.g. radiocarbon and actinium) and anthropogenically (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*)

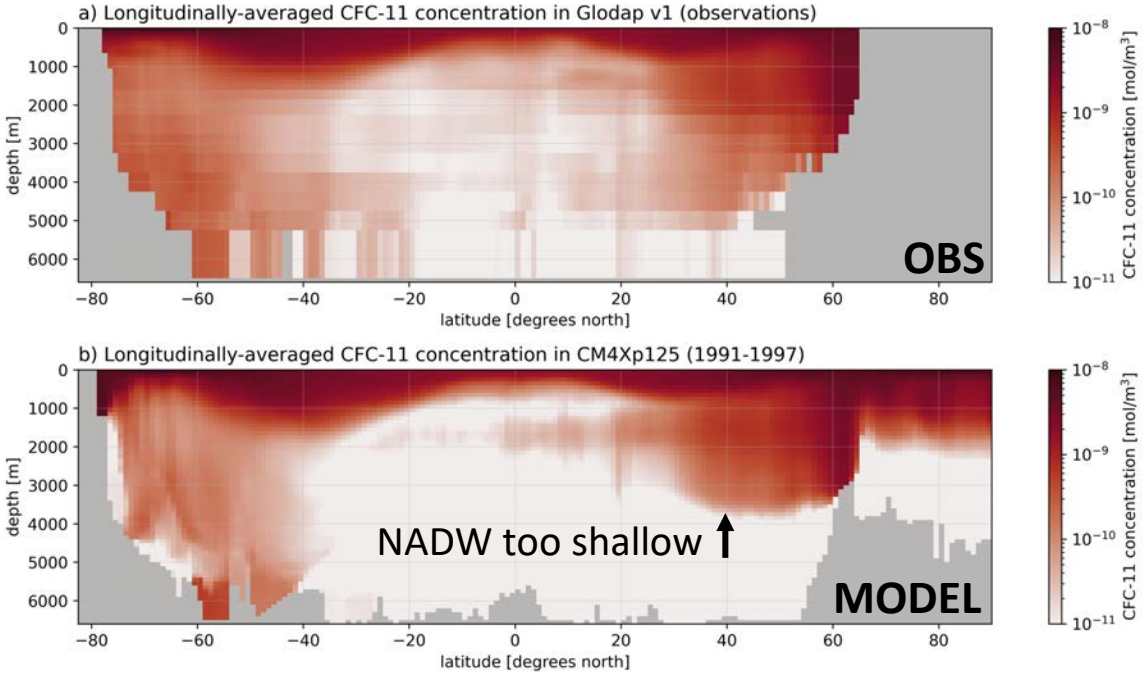
Chemically inert transient tracers: Chlorofluorocarbons (CFCs) and SF_6

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 1/8$^{th\underline{o}}$ resolution (Griffies et al, *in prep*)





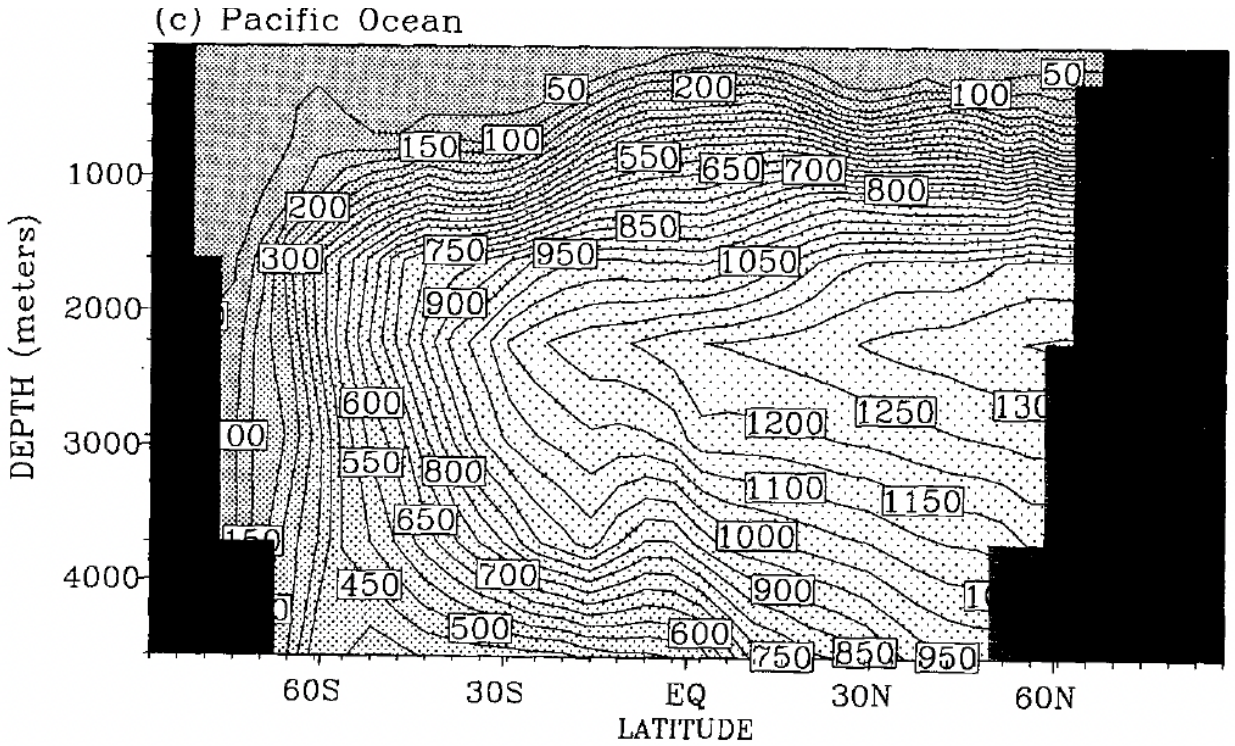
Drake et al. (*in prep*); see also England (1995), *GRL* and Wang et al. (2021), *PNAS*

Custom tracers: ideal seawater age

Initial condition: $a(\boldsymbol{x}, t = t_0) = 0$

Age forcing: $\dfrac{\mathrm{D}a}{\mathrm{D}t} = 1$ (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)



England (1995), *JPO*

The equilibrium age distribution has a straight-forward 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).

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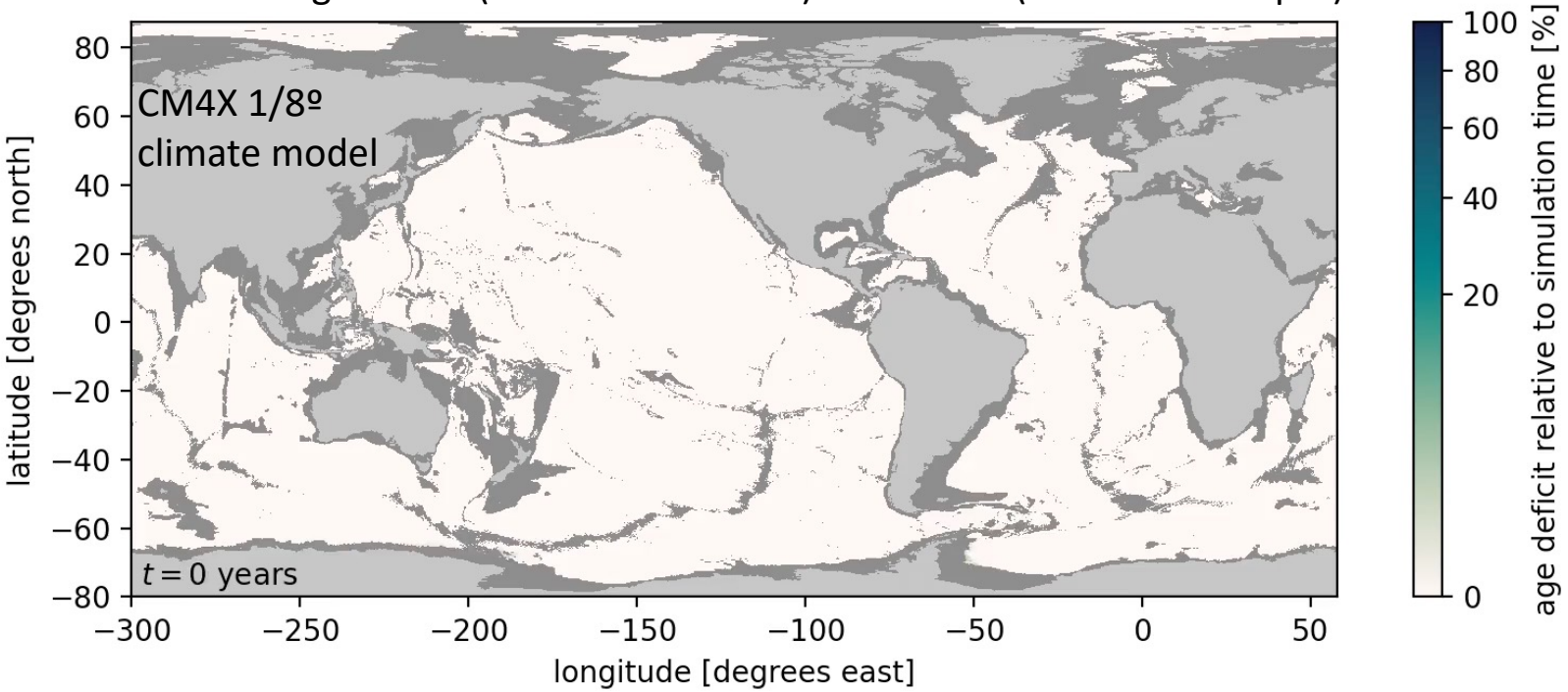
Transient age deficit (ventilated fraction) at seafloor (3000 m or deeper)



Transient age deficit : $\mathcal{D} \equiv \dfrac{(t - t_0) - a}{t - t_0}$

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

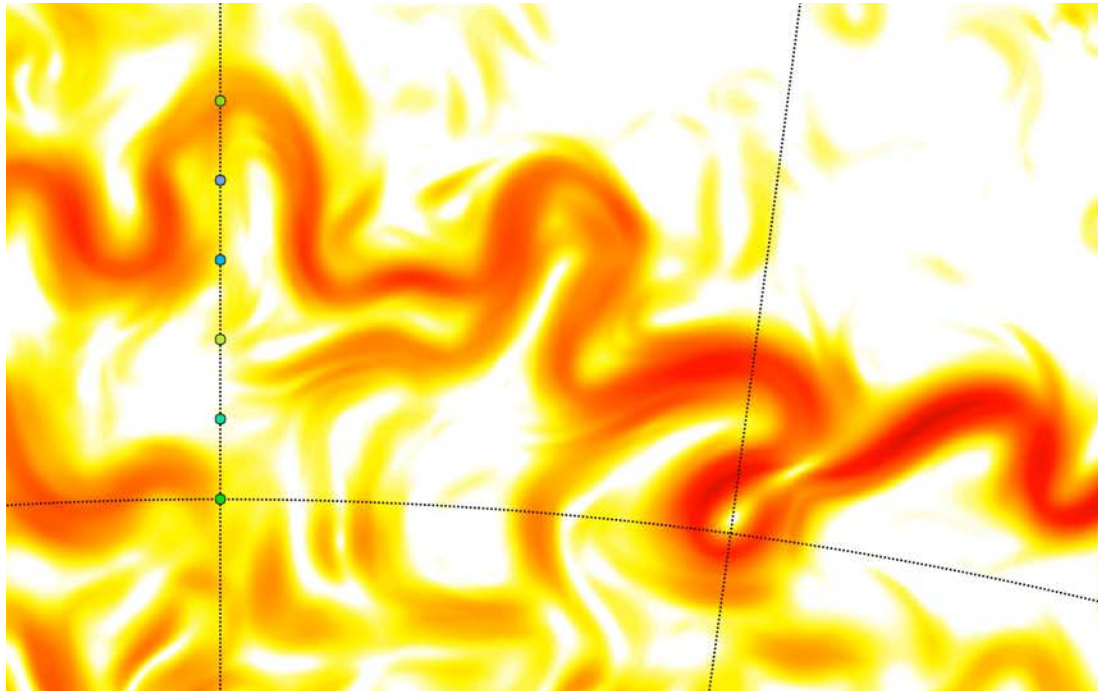
- $D = 1$ for perfectly ventilated (young) waters
- $D = 1$ for unventilated (old) waters

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*

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Review

Lagrangian ocean analysis: Fundamentals and practices

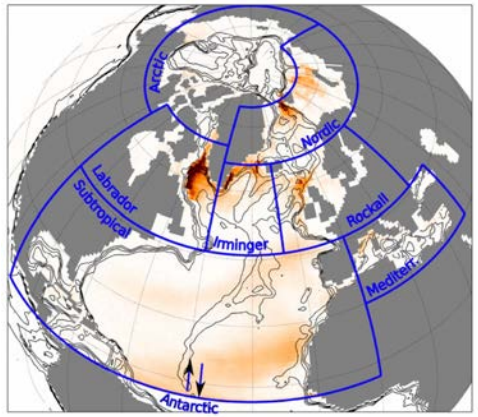
Erik van Sebille[*,a,b], Stephen M. Griffies[c], Ryan Abernathey[d], Thomas P. Adams[e], Pavel Berloff[f], Arne Biastoch[g], Bruno Blanke[h], Eric P. Chassignet[i], Yu Cheng[j], Colin J. Cotter[f], Eric Deleersnijder[k,l], Kristofer Döös[n], Henri F. Drake[o,p], Sybren Drijfhout[q], Stefan F. Gary[e], Arnold W. Heemink[l], Joakim Kjellsson[r,t], Inga Monika Koszalka[g,aa], Michael Lange[a,s], Camille Lique[h], Graeme A. MacGilchrist[u], Robert Marsh[q], C. Gabriela Mayorga Adame[v], Ronan McAdam[a], Francesco Nencioli[w], Claire B. Paris[j], Matthew D. Piggott[s], Jeff A. Polton[v], Siren Rühs[g], Syed H.A.M. Shah[m,l], Matthew D. Thomas[x], Jinbo Wang[y], Phillip J. Wolfram[z], Laure Zanna[t], Jan D. Zika[a,bb]

See our comprehensive review paper, still reasonably up-to-date.

Mass/volume transport streamtubes

$$\frac{\mathrm{D}\,(\mathrm{d}V)}{\mathrm{D}t} = 0 \quad \text{along material parcel trajectories } \boldsymbol{X}(t)\text{, found by integrating } \boldsymbol{u} \equiv \frac{\mathrm{D}\boldsymbol{X}}{\mathrm{D}t}$$

Lagrangian decomposition of the AMOC by deep water source region



Thomas et al. (2015) *J. Clim.*, applying a method pioneered by Döos et al. (1995) *JGR* and Blanke and Raynaud (1997) *JPO*

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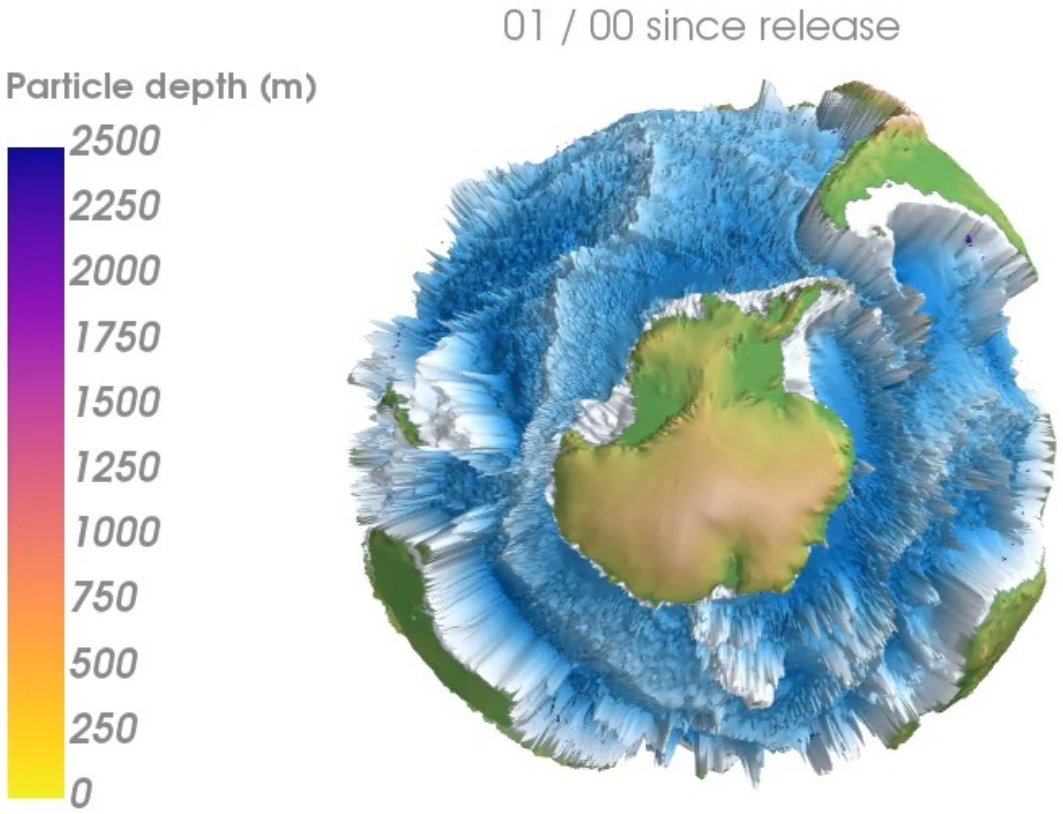
Pathways of upwelling in the Southern Ocean



Drake et al. (2018), *GRL*
Tamsitt, Drake, et al. (2017), *Nature Comms.*

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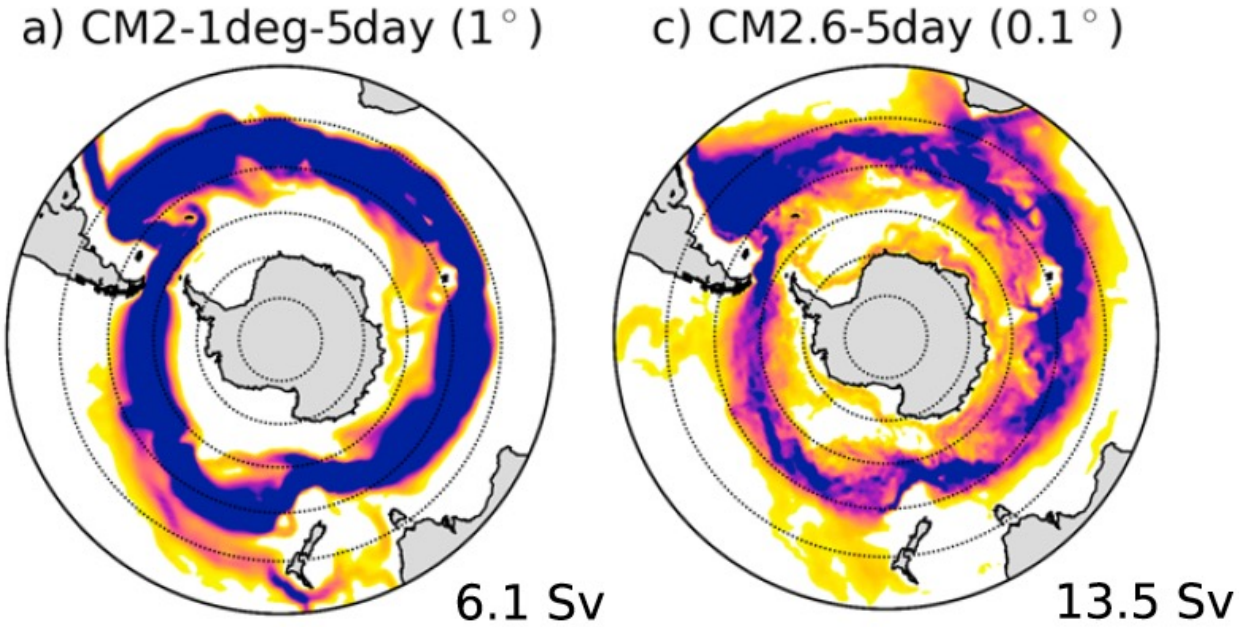
Pathways of upwelling in the Southern Ocean

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



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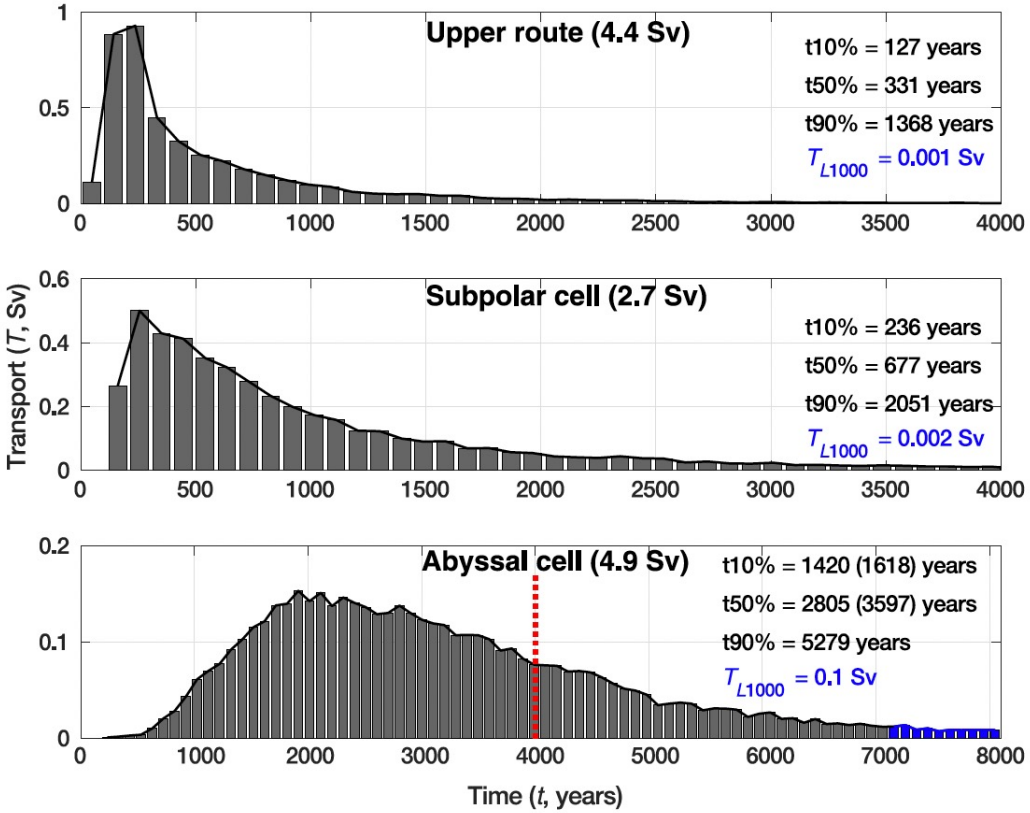
Timescales of global overturning circulation cells



Rousselet, Cessi, and Forget (2021), *Science Advances*

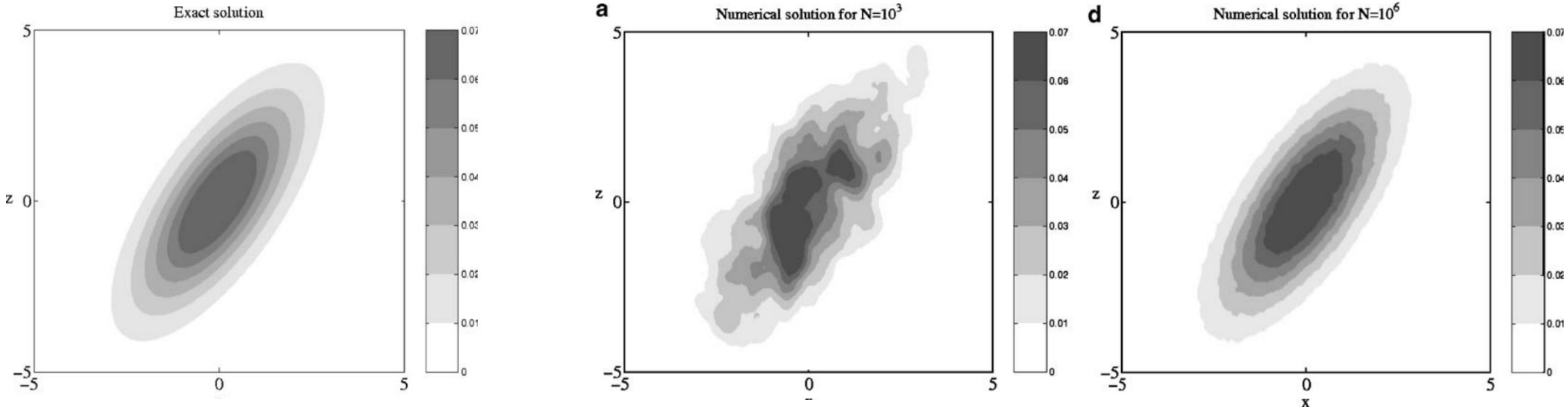
Tracers as probability distributions of stochastic Lagrangian particles

$$(\partial_t + \mathbf{u}\cdot\nabla)\,C = \nabla\cdot(\mathbf{J}\nabla C) \qquad \text{(Fokker-Planck PDE for Eulerian tracer concentration)}$$

Mathematical equivalence via Itô (or Stratonovich) Calculus

$$\mathrm{d}X_i^{(p)}(t) = \mathbf{u}^{\mathrm{drift}}(\mathbf{X}^{(p)},t)\mathrm{d}t + \sigma_{ik}(\mathbf{X}^{(p)},t)\mathrm{d}W_k(t) \qquad \text{(Stochastic diff. eq. for Lagrangian tracer trajectory)}$$

Eulerian "truth" model ⟷ **Lagrangian reconstructions from *N* particle trajectories**



Spivakovskaya, Heemink, Deleersnijder (2007)

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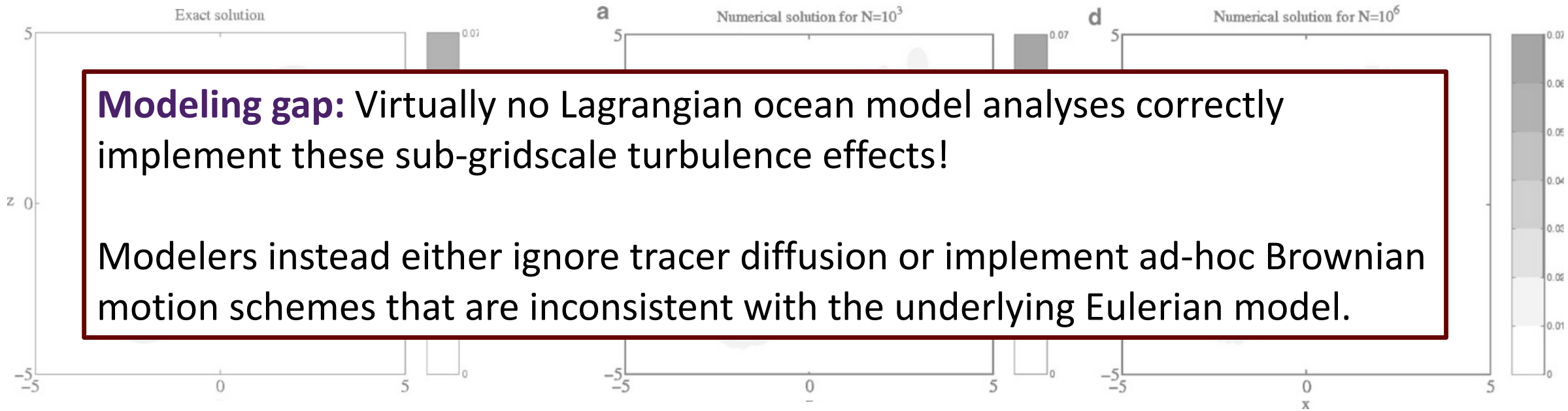


Modeling gap: Virtually no Lagrangian ocean model analyses correctly implement these sub-gridscale turbulence effects!

Modelers instead either ignore tracer diffusion or implement ad-hoc Brownian motion schemes that are inconsistent with the underlying Eulerian model.

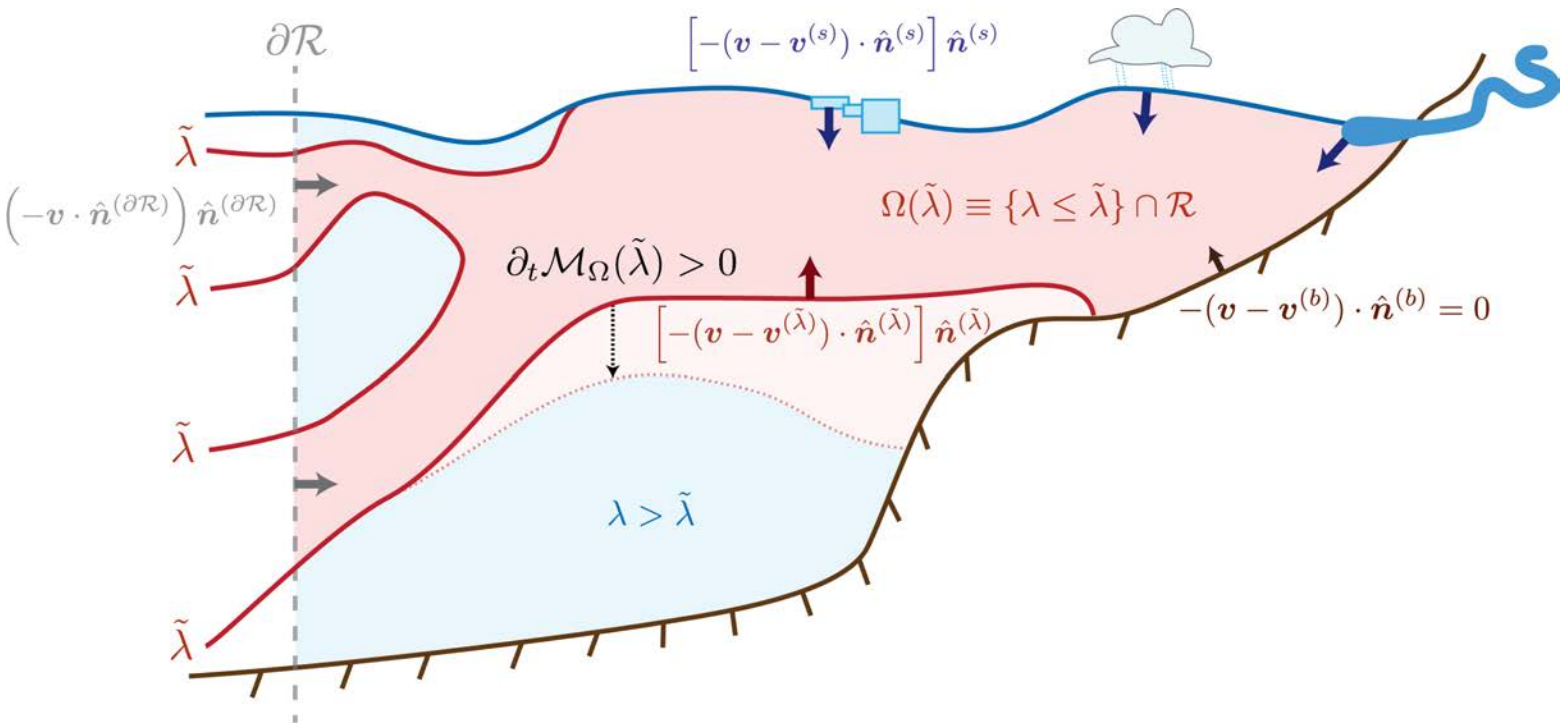
Spivakovskaya, Heemink, Deleersnijder (2007)

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 λ 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)
See also review by Groeskamp et al. (2019), *Annual Reviews of Marine Science*

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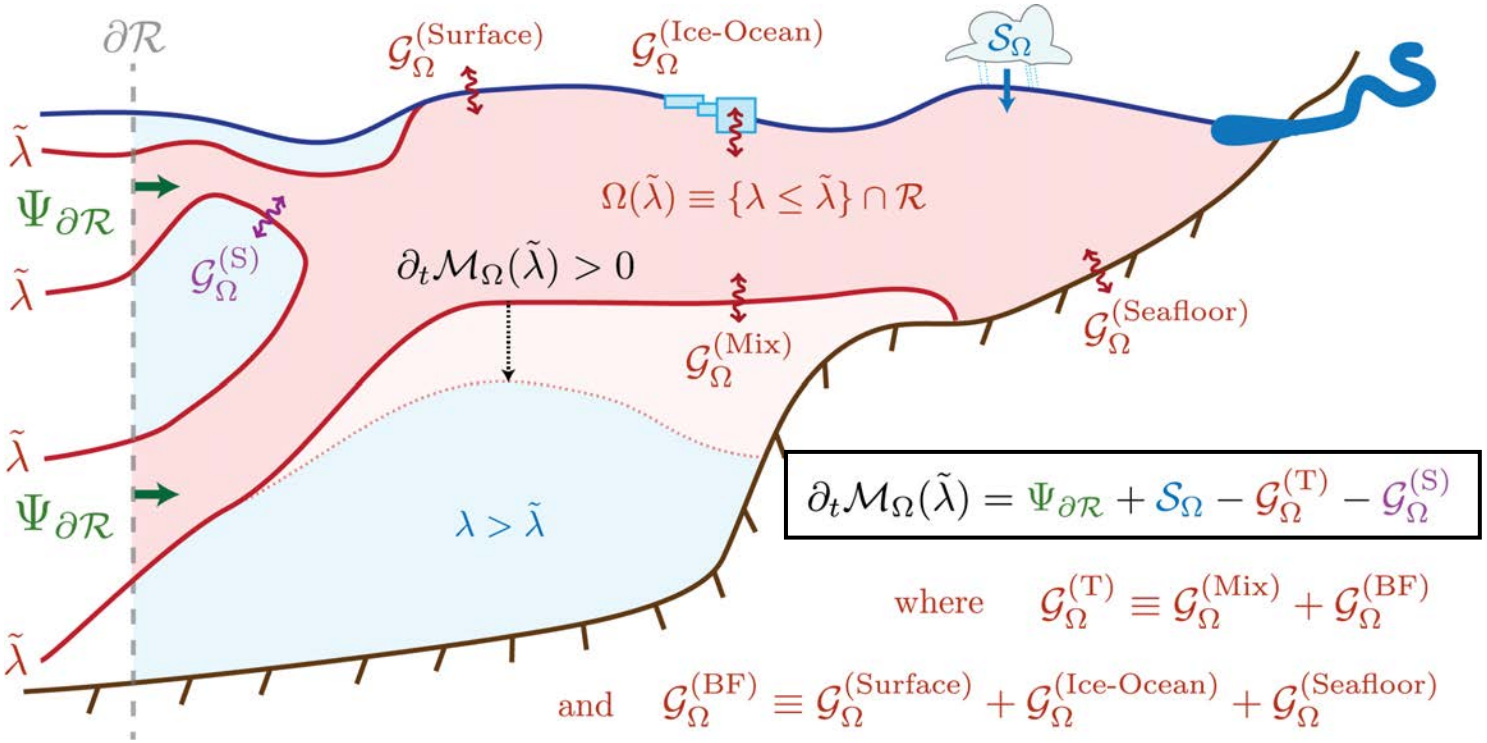
Using the water mass transformation relationship, we can relate the movement of the bounding isosurface to the tracer fluxes due to various processes (including numerical model errors).



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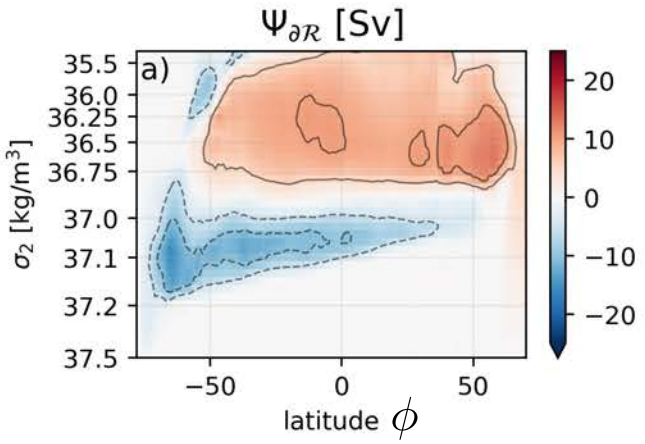
Example application of water mass transformation analysis

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

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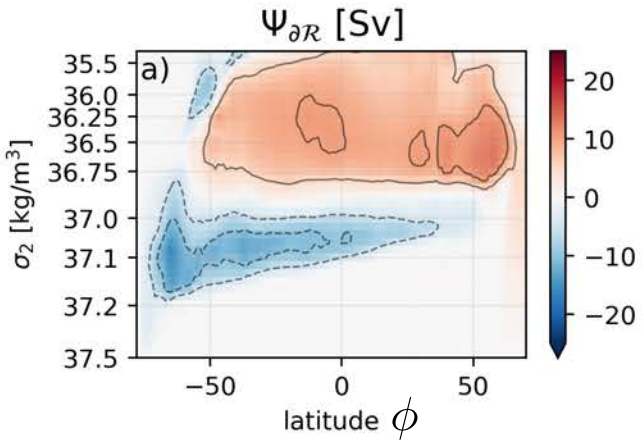

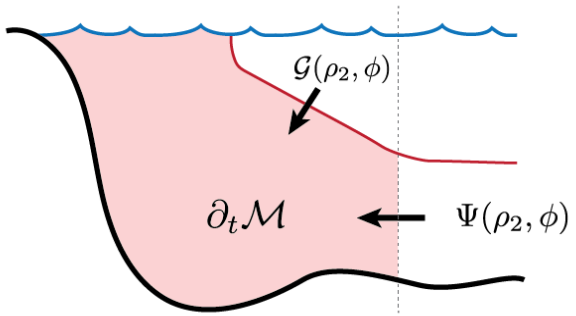

We compute the mass budget for waters denser than $\sigma_2 = \rho_2 - 1000$ and south of latitude ϕ.

Drake, MacGilchrist, Tesdal, Turner, Krasting, and Griffies (*in prep.*)
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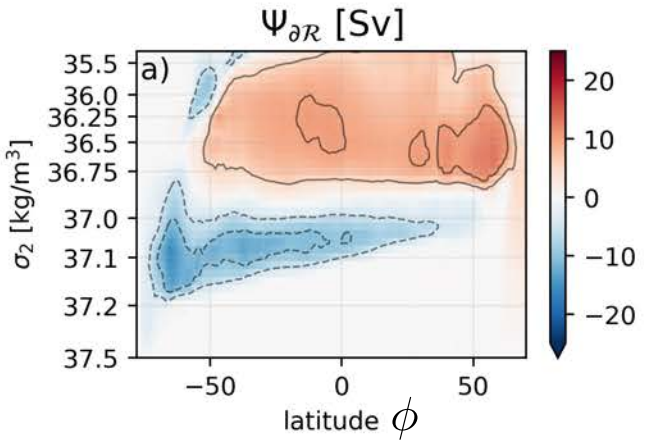

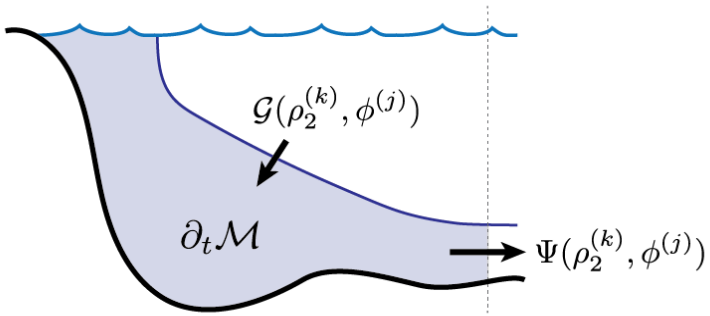

We repeat this calculation for many combinations of latitudes and density surfaces.

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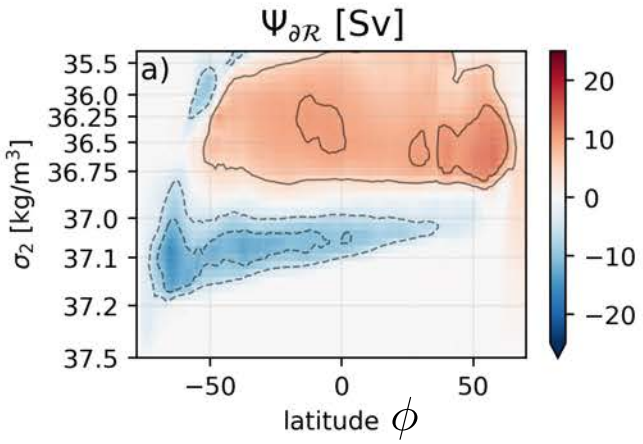

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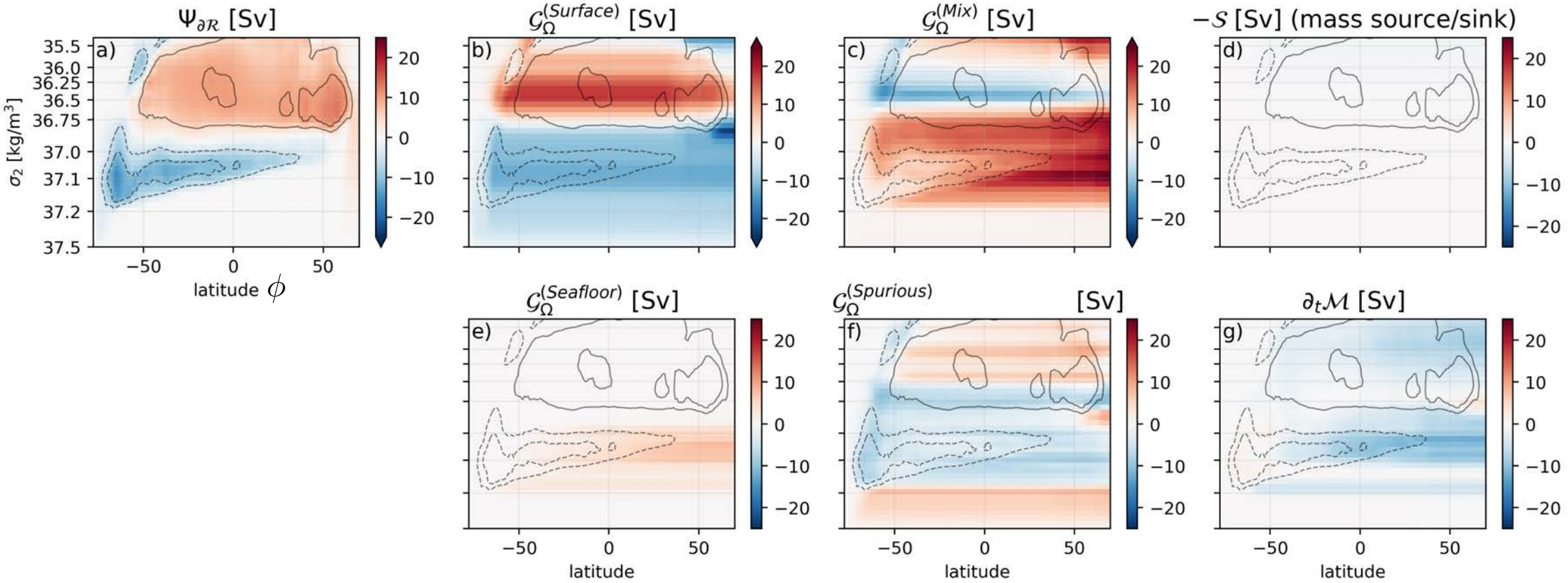
$$\Psi(\sigma_2, \phi) = \underbrace{\mathcal{G}^{(\mathrm{Surface})} + \mathcal{G}^{(\mathrm{Seafloor})} + \mathcal{G}^{(\mathrm{Mix})} + \mathcal{G}^{(\mathrm{Spurious})}}_{\text{transformations}} + \overbrace{\mathcal{S}}^{\text{mass flux}} + \partial_t \mathcal{M}$$

overturning

water mass change



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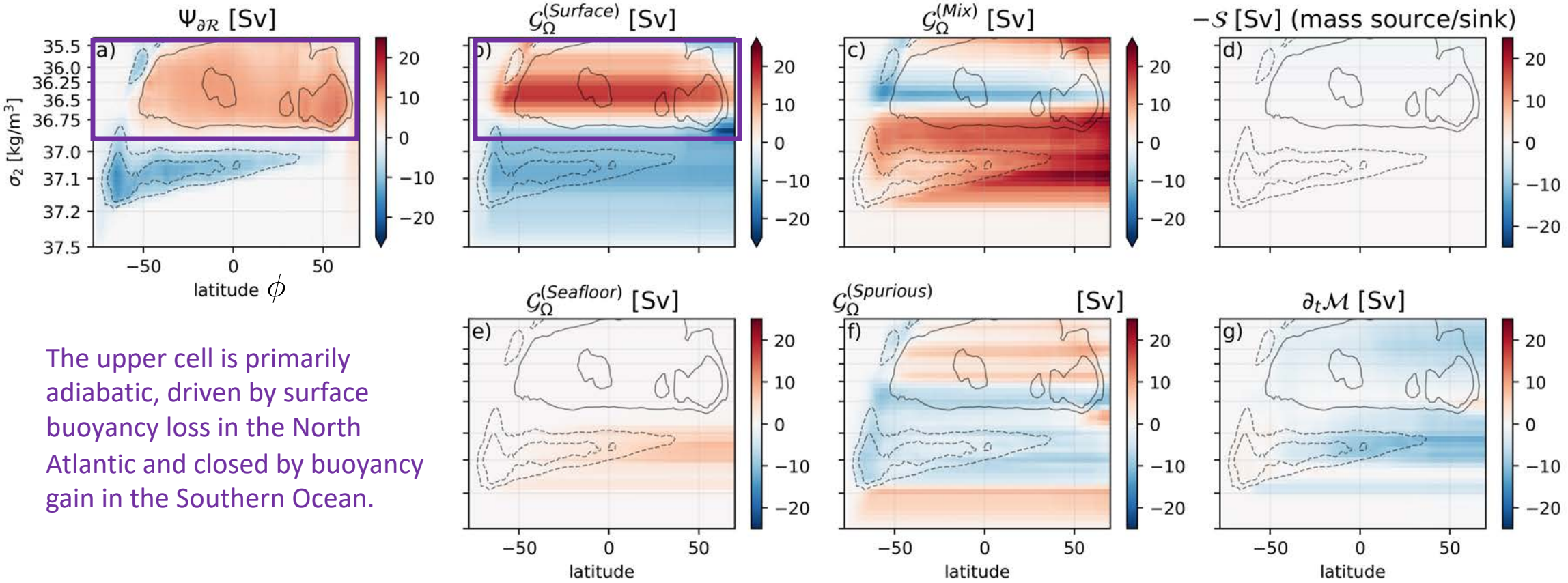

The upper cell is primarily adiabatic, driven by surface buoyancy loss in the North Atlantic and closed by buoyancy gain in the Southern Ocean.

Drake, MacGilchrist, Tesdal, Turner, Krasting, and Griffies (*in prep.*)
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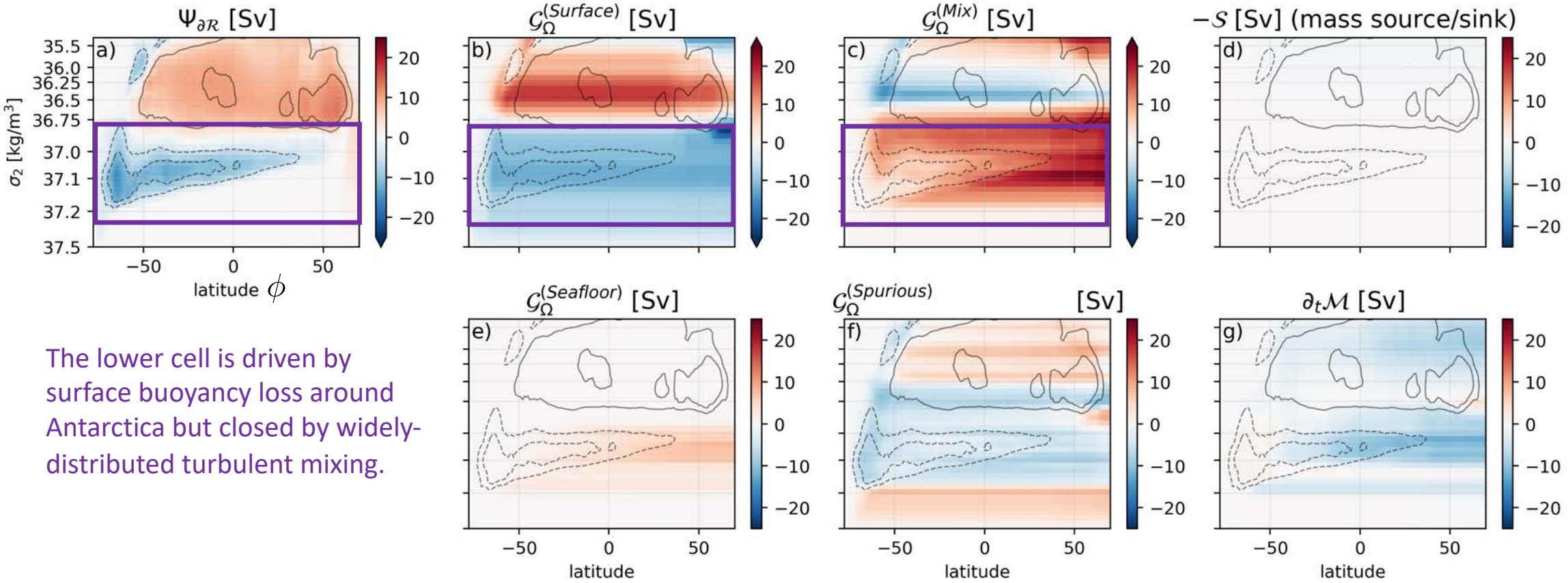

The lower cell is driven by surface buoyancy loss around Antarctica but closed by widely-distributed turbulent mixing.

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