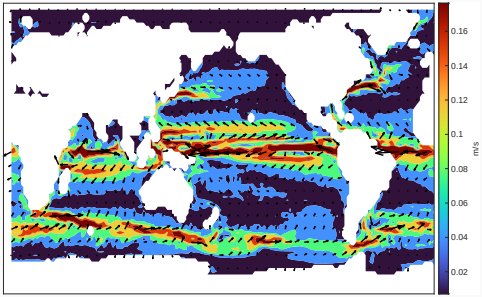
A Multi-Tracer Data Assimilation Framework for Constraining Global Ocean Transport and Mixing

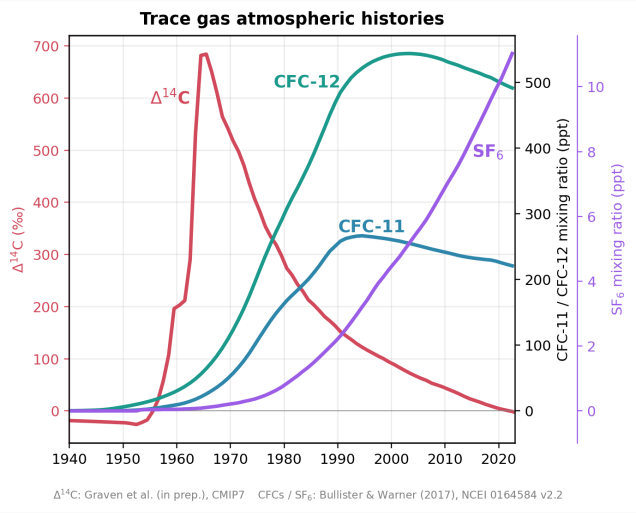
Nabir Mamnun[1], Nikita Tournebise[2],
Tim DeVries[2], Heather Graven[1]

[1]Imperial College London, UK
[2]University of California, Santa Barbara, USA

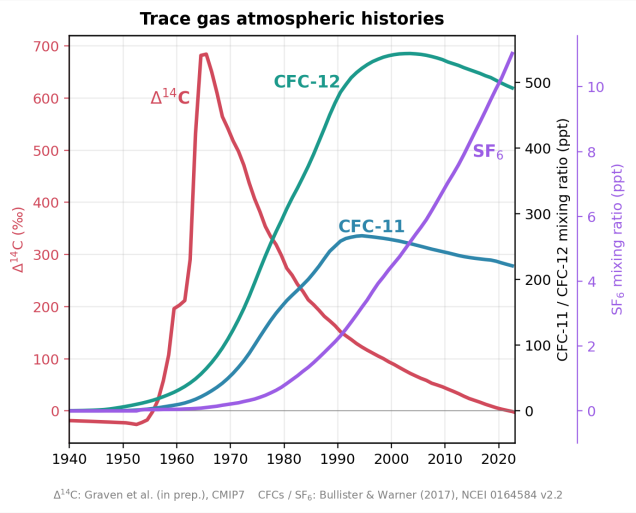
Thursday, 29 October 2026
Joint CP-TT/DA-TT Workshop at ECMWF, UK



Transient tracers constrain circulation and gas-transfer rates



Transient tracers constrain circulation and gas-transfer rates



- **Ventilation rate:** surface-to-interior transport.
- **Mixing:** isopycnal eddy diffusivities.
- **Gas-transfer:** the global air–sea gas-transfer velocity.

The Ocean Circulation Inverse Model (OCIM)

A data-assimilated, steady-state ocean transport operator. Tracer concentration C evolves under $\mathbf{T}(\boldsymbol{\theta})$:

$$\frac{\partial C}{\partial t} \;=\; -\,\mathbf{T}(\boldsymbol{\theta})\,C \;+\; J_{\mathsf{src/snk}}(C,t)$$

- $\boldsymbol{\theta}$: advection + isopycnal mixing parameters — optimized to best fit observations.

DeVries & Primeau (2011), *J. Phys. Oceanogr.* **41**, 2381–2401; Holzer, DeVries & de Lavergne (2021), *Nat. Commun.* **12**, 4348.

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- 3-D global grid: $2^\circ \times 2^\circ$, 48 vertical levels.
- OCIM assimilates T, S, SSH, $\Delta^{14}\mathrm{C}$, CFC-11, CFC-12 (SF_6 in progress).
- Provides an offline, computationally efficient circulation for biogeochemical and tracer studies.

DeVries & Primeau (2011), *J. Phys. Oceanogr.* **41**, 2381–2401; Holzer, DeVries & de Lavergne (2021), *Nat. Commun.* **12**, 4348.

OCIM solves a regularized weighted least-squares inverse problem

$$\mathcal{J}(\boldsymbol{\theta}) \;=\; \sum_k w_k \left\| C_k^{\mathrm{mod}}(\boldsymbol{\theta}) - C_k^{\mathrm{obs}} \right\|^2_{\mathbf{R}_k^{-1}} \;+\; \left\| \boldsymbol{\theta} - \boldsymbol{\theta}_0 \right\|^2_{\mathbf{B}^{-1}}$$

Tracers k: T, S, SSH, $\Delta^{14}\mathrm{C}$, CFC-11, CFC-12, SF_6 (in progress)

Control vector $\boldsymbol{\theta}$

- Geostrophic momentum-balance corrections.
- Isopycnal eddy-diffusivity $\kappa_{\|}$.
- Gas-transfer (piston) velocity.

Solver

- $\nabla_{\boldsymbol{\theta}} \mathcal{J}$ via the *adjoint* of $\mathbf{T}(\boldsymbol{\theta})$.
- Quasi-Newton minimisation.

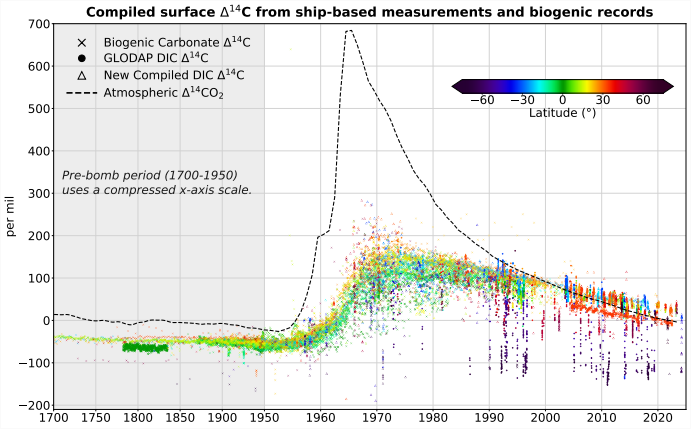
Joint constraint: complementary tracer timescales constrain *advection* and *mixing*.

DeVries & Primeau (2011), *J. Phys. Oceanogr.* **41**, 2381–2401; Holzer, DeVries & de Lavergne (2021), *Nat. Commun.* **12**, 4348.

A new global ocean radiocarbon ($\Delta^{14}C$) data set (1700–2024)

Ship-based measurements (GLODAP, recent GO-SHIP cruises and peer-reviewed studies)
+ **biogenic records** (corals, mollusk shells, sclerosponges).

Coverage from the pre-industrial period through the bomb-^{14}C peak to recent years.

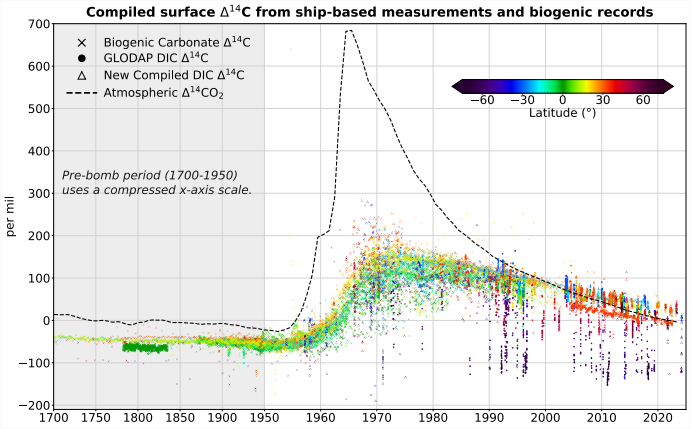


Data: Mamnun et al. (2026)

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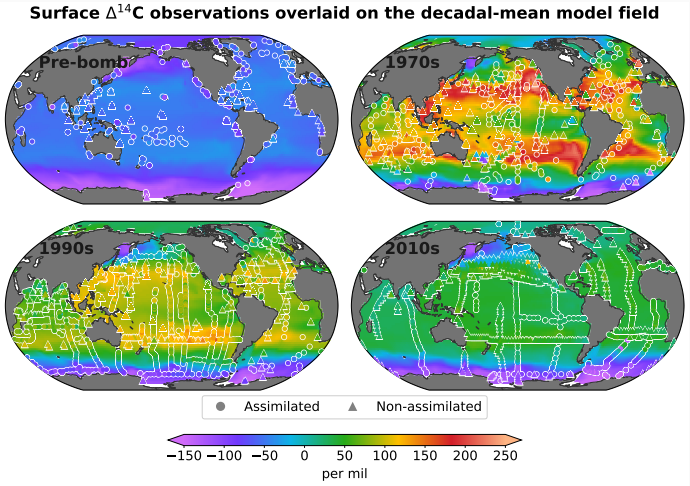
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Preprint: https://doi.org/10.5194/essd-2026-691; Data: https://doi.org/10.5281/zenodo.22100029

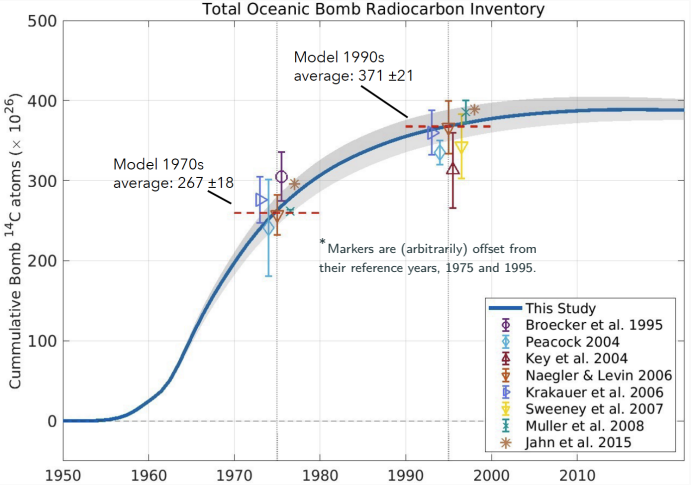
Model provides a realistic distribution of oceanic $\Delta^{14}C$



The model reproduces the observations well, capturing both the pre-bomb distribution and the bomb signal.

Agreement across basins supports **realistic air–sea exchange** and upper-ocean transport.

Model bomb-^{14}C inventory agrees with previous estimates



Most bomb ^{14}C entered the ocean by the 1990s, after which uptake levelled off.

How fast the ocean took it up constrains the global **gas-transfer velocity**.

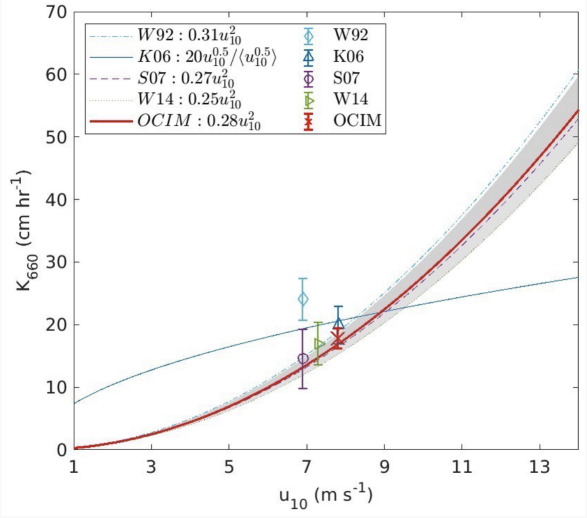
Bomb ^{14}C narrows the uncertainty in global gas-transfer velocity

$$K_w = a\,\langle u_{10}^2 \rangle \left(\frac{Sc}{660}\right)^{-1/2}$$

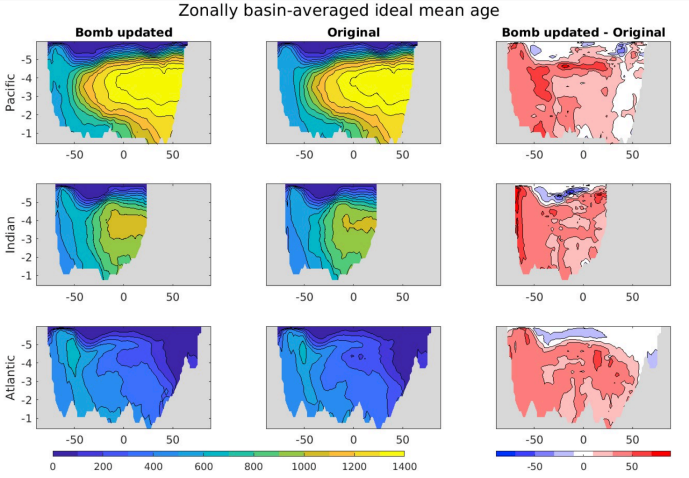
Optimising circulation and gas exchange together gives $a = 0.28 \pm 0.03$, within the range of previous estimates.

Its uncertainty is about 10%, compared with 20–30% in earlier studies.

Gas transfer velocity normalized to a Schmidt number of 660



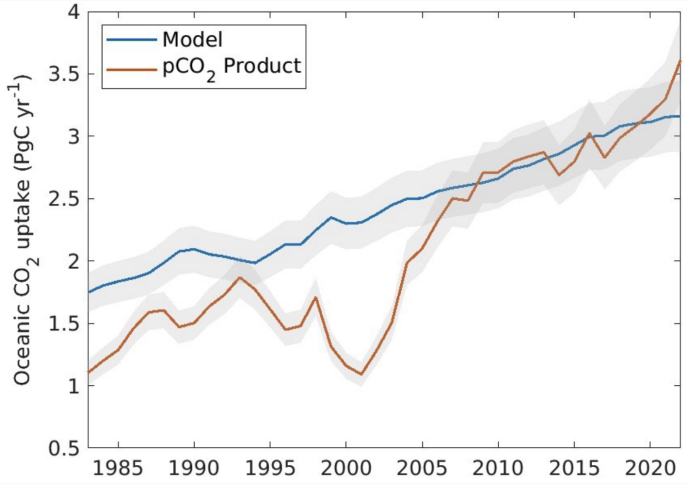
Bomb-radiocarbon assimilation implies slower deep-ocean renewal



Assimilating bomb $\Delta^{14}\mathrm{C}$ weakens deep ventilation, so the interior becomes older. The **largest changes** are in Southern Ocean pathways and abyssal renewal.

Longer interior residence times imply more time for carbon and heat to accumulate in the ocean.

Modelled anthropogenic CO_2 uptake is consistent with a pCO_2-based estimate



The model is close to one pCO_2-based product, from Jersild & Landschützer (2024), for 2010–2020, but does not capture year-to-year variability.

Jersild & Landschützer (2024), A spatially explicit uncertainty analysis of the air–sea CO_2 flux from observations, *Geophys. Res. Lett.* **51**, e2023GL106636.

Summary

- We assimilate $\Delta^{14}\mathrm{C}$ and CFCs into OCIM (SF_6 in progress). Their complementary timescales help constrain advection and mixing.
- Model reproduces observed $\Delta^{14}\mathrm{C}$ and the bomb-$^{14}\mathrm{C}$ inventory, and narrows the gas-transfer velocity uncertainty to $\sim$10%.
- Bomb-$\Delta^{14}\mathrm{C}$ assimilation implies slower deep-ocean renewal.
- Modelled anthropogenic CO_2 uptake is consistent with a pCO_2-based estimate.

Summary

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Thank you!

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