

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

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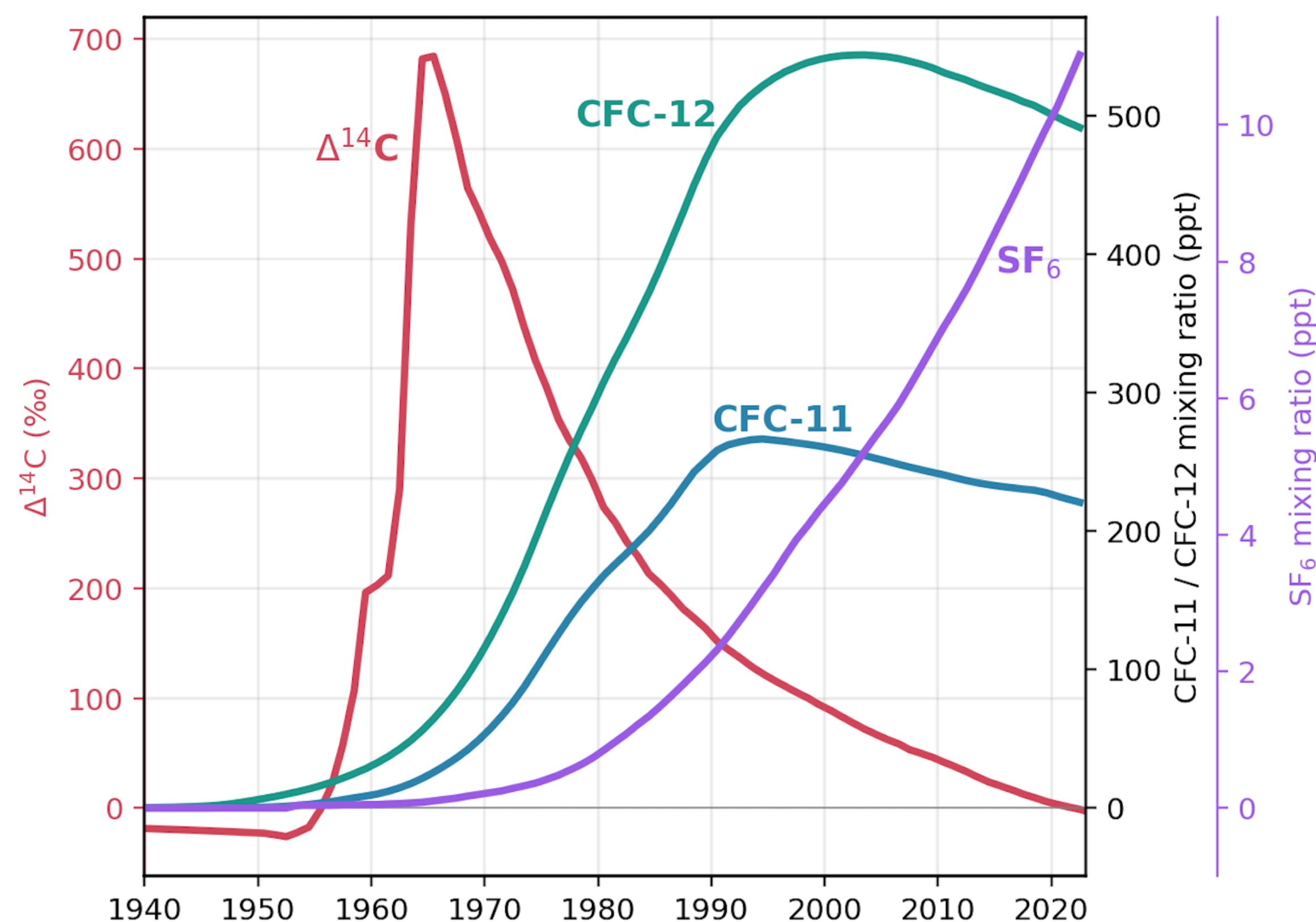
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Introduction

Ocean transport and ventilation remain a major uncertainty in carbon-cycle assessments and Earth system reanalyses.

Atmospheric histories of the tracers used here [1, 2]



Transient tracers—gases and isotopes whose atmospheric concentrations have changed strongly over recent decades to centuries—enter at the surface and are carried into the interior, recording when that water last contacted the atmosphere. Joint assimilation exploits these complementary timescales to constrain ocean ventilation, mixing and gas-transfer rates.

Ocean Circulation Inverse Model (OCIM)

A data-assimilated, steady-state transport operator ($2^\circ \times 2^\circ$, 48 levels) [3, 4]. Tracer C evolves under $\mathbf{T}(\boldsymbol{\theta})$:

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

Advection and mixing parameters $\boldsymbol{\theta}$ are estimated by adjoint minimisation of a regularised least-squares cost:

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

k : T , S , SSH, ^{39}Ar , CFC-11, CFC-12, $\Delta^{14}\text{C}$; SF_6 forthcoming.

$\boldsymbol{\theta}$: geostrophic momentum corrections, T/S restoring, $\kappa_{\parallel}$, piston velocity. Solver: adjoint of $\mathbf{T}(\boldsymbol{\theta})$, transient surface BCs, quasi-Newton minimisation. Complementary timescales separate *ventilation* from *gas-transfer velocity*.

Observations

Hydrography, altimetry, and transient tracers jointly constrain $\boldsymbol{\theta}$.

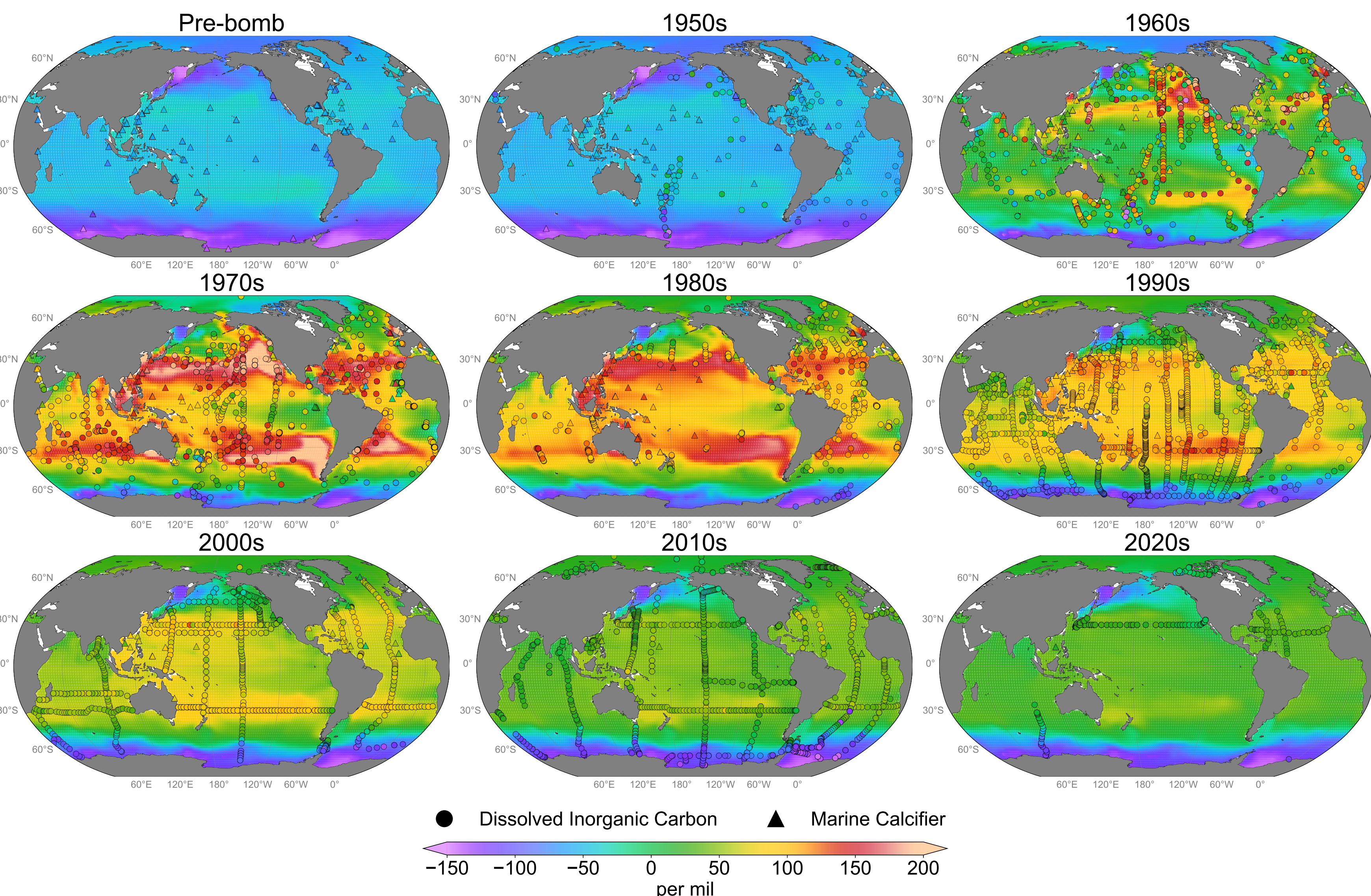
- T , S : World Ocean Atlas (WOA13).
- SSH: AVISO mean dynamic topography.
- ^{39}Ar : centennial-scale deep ventilation.
- $\Delta^{14}\text{C}$: newly compiled global dataset (1700–2024) of ship-based DIC and marine carbonate archives (corals, bivalves, gastropods, sclerosponges) [5].
- CFC-11, CFC-12: GLODAPv2.2023; a new quality-controlled compilation is planned.
- SF_6 : GLODAP; implementation in progress.

Conclusion

- Joint assimilation of $\Delta^{14}\text{C}$ and CFCs constrains ventilation, mixing, and air–sea gas transfer across complementary timescales.
- A new global $\Delta^{14}\text{C}$ compilation (1700–2024) captures pre-bomb baselines through the bomb pulse [5].
- Bomb- $\Delta^{14}\text{C}$ assimilation weakens deep ventilation: the interior is older, especially along Southern Ocean pathways and in abyssal renewal.
- Transport and the Wanninkhof coefficient a are optimised together against natural and bomb $\Delta^{14}\text{C}$.
- Next: assimilate SF_6 and apply the circulation to anthropogenic carbon and heat uptake.

Modeled $\Delta^{14}\text{C}$ matches modern observations

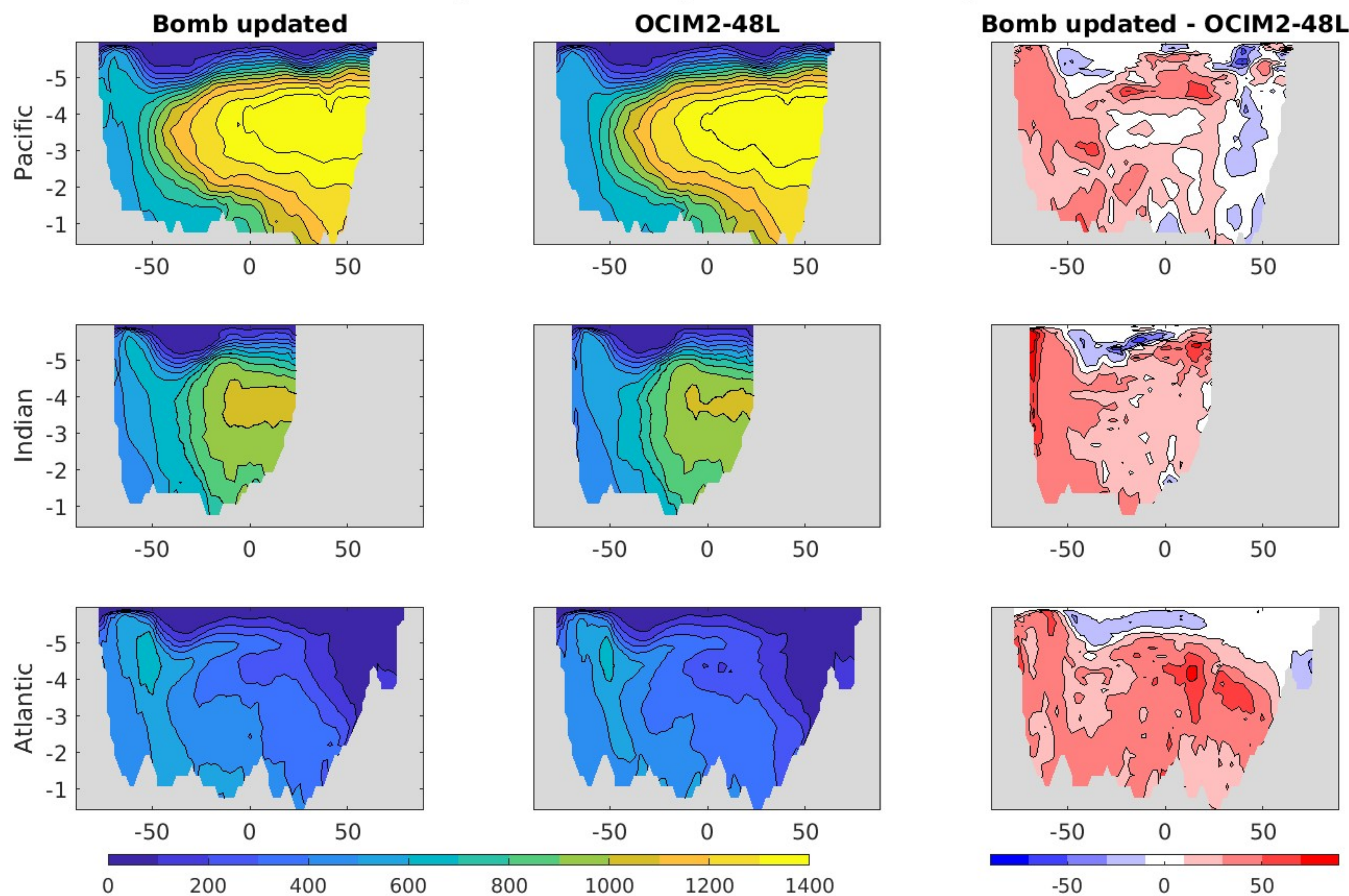
Surface $\Delta^{14}\text{C}$ (depth ≤ 54 m) overlaid by observations



Panels are decadal means of modelled surface $\Delta^{14}\text{C}$; pre-bomb is the 1750–1950 mean. Observations (circles: DIC; triangles: marine calcifiers) are from the new global compilation [5]. The model captures the timing and spread of the bomb pulse, but large positive biases remain in the Southern Ocean and major upwelling regions (northwest Pacific and northwest Indian Oceans), consistent with weak Antarctic Bottom Water formation and insufficient ventilation of low- $\Delta^{14}\text{C}$ deep waters to the surface. Negative biases in the subtropical gyres indicate too little bomb ^{14}C accumulation, pointing to upper-ocean transport, mixing, and air–sea gas exchange.

Bomb-radiocarbon assimilation implies slower deep-ocean renewal

Zonally basin-averaged ideal mean age



Rows are the Pacific, Indian, and Atlantic; columns are the bomb- $\Delta^{14}\text{C}$ -updated OCIM, the original solution, and their difference (updated minus original). The bomb constraint weakens deep ventilation, so the interior is older, with the largest increases along Southern Ocean pathways and in abyssal renewal, where deep waters are formed and exported. Longer interior residence times imply more time for carbon and heat to accumulate at depth, and they alter how tightly transient tracers can constrain air–sea gas exchange.

References

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