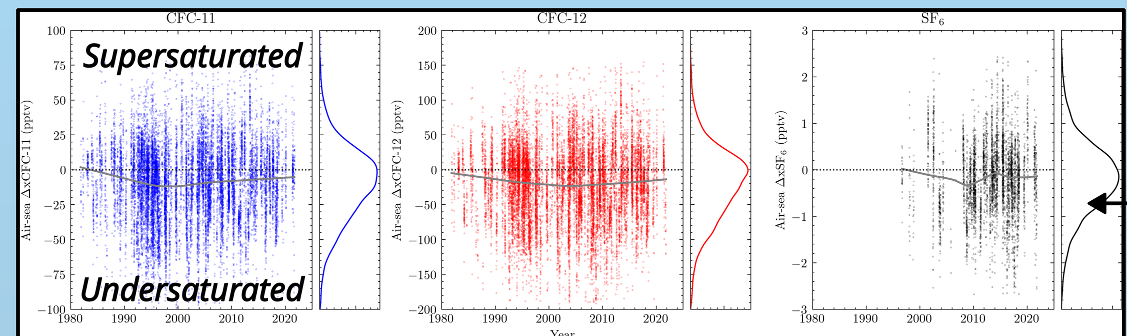
Deriving mixed layer boundary conditions from ocean transient tracer observations

Daniel E. Sandborn[1], Mark J. Warner[1], Brendan R. Carter[2,3], Zach K. Erickson[3] 1: University of Washington School of Oceanography, 2: Cooperative Institute for Climate, Ocean, & Ecosystem Studies, 3: NOAA Pacific Marine Environmental Laboratory

Why do mixed layer transient tracer concentrations lag behind their atmospheric histories? *And how does this inform tracer age modeling?*

Transient tracers (e.g. CFCs, SF_6) are anthropogenic conservative gases acting as "clocks" for ventilation and the ocean CO_2 sink, and their mixed layer saturation histories are the **single largest source of error** in transit time distribution (TTD) age models and carbon budgets.[1]



Mixed layer concentrations are generally **undersaturated** w.r.t. the atmosphere, yet this varies in space and time, and has been unevenly accounted for in previous tracer age models.

Fig. 1: MML transient tracer disequilibrium vs. atmosphere in GLODAPv2.2023 dataset. Grey line represents LOESS regression, negative values represent undersaturation.

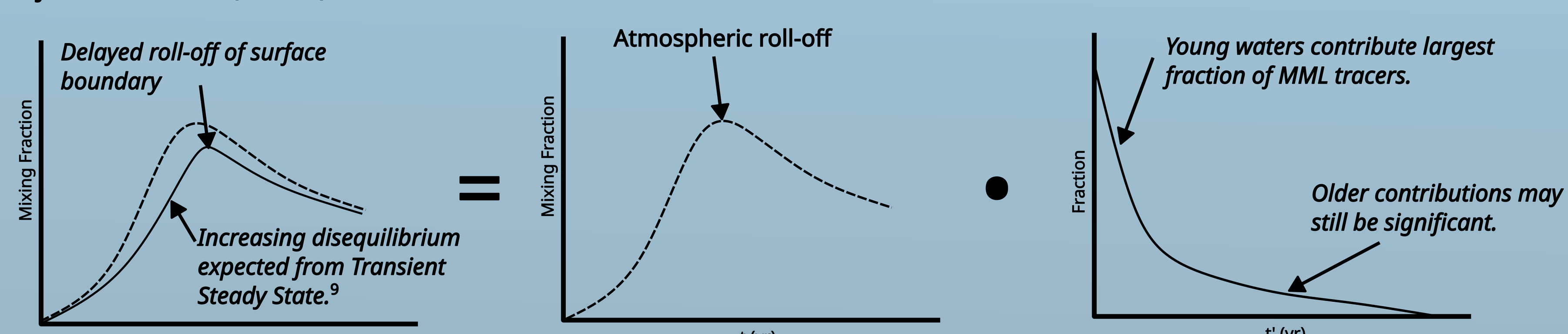
Accurate tracer age models require accurate surface boundary conditions,[2] which we derive empirically using Bayesian statistical inversion.

Because mixed layer transient tracer concentrations reflect past atmospheric states…

The winter **maximum mixed layer (MML)** achieves incomplete equilibration with shifting atmospheric concentrations due to slow air-sea flux and entrainment of older water.[2,3]

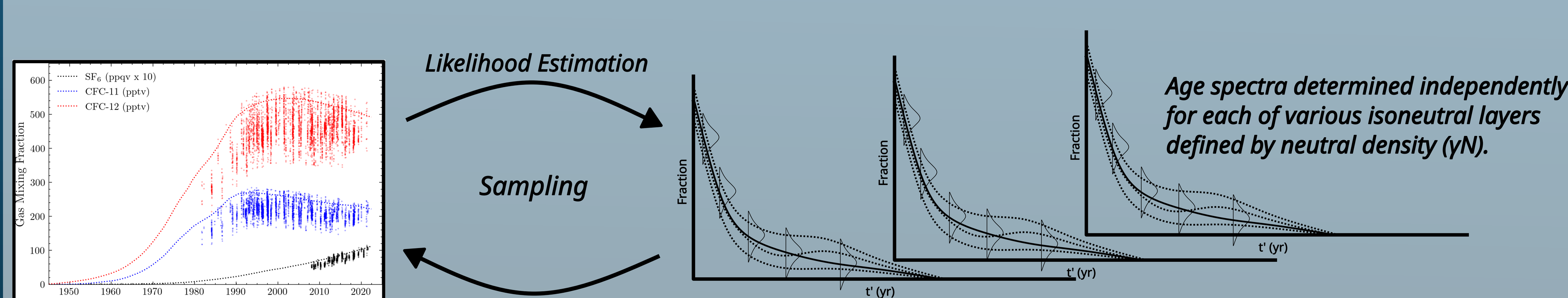
$$\chi_S(t) = \int_0^\infty \chi_{atm}(t')\,\mathcal{K}(t-t')\,dt'$$

The signal of atmospheric history is retained as a **surface age spectrum**, a Dirichlet boundary condition given by an Green's function *K*(t') for tracers subject to a Robin (mixed) condition.[2]



MML Tracer Concentration $\chi_s(t)$ = Atmospheric History $\chi_{atm}(t)$ • Surface Age Spectrum *K*(t')

… so surface age spectra were deconvoluted from hydrographic observations



Five decades' transient tracer observations in the GLODAP dataset[4] were selected to represent MML tracer concentrations (χ_s) within the climatological MML depth[5] by selecting each cast's greatest transient tracer observation and assuming it represented coldest water (highest solubility) during deep winter mixing.[6]

A Markov Chain Monte Carlo deconvolution inverted optimal *K*(t') and posterior uncertainties from observations of all three tracers on global and regional scales from a minimally-informative uniform prior.

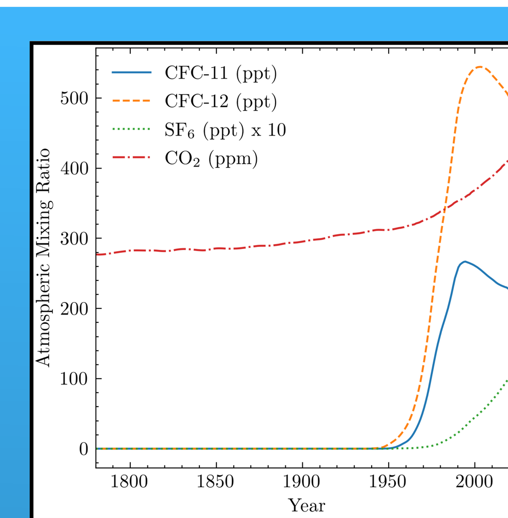
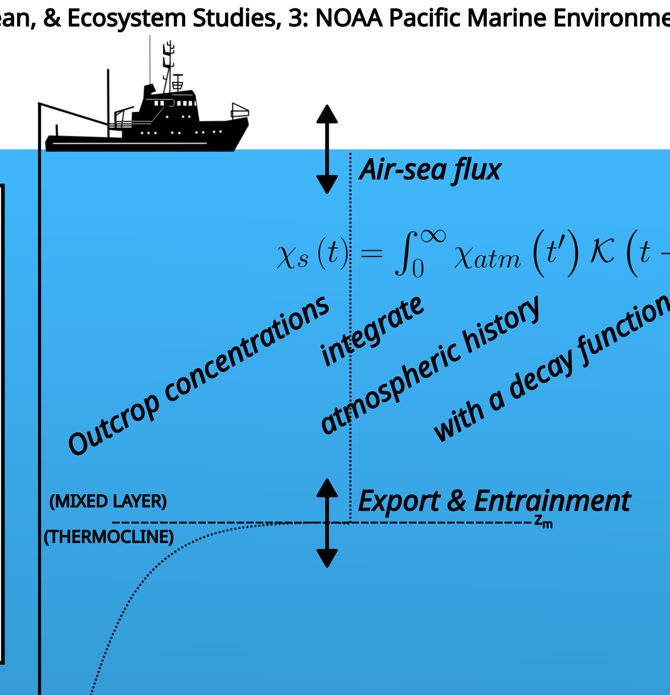


Fig. 2: Atmospheric histories of CFC-11, CFC-12, SF_6, and CO_2.[4,7]



$$\chi_S(t) = \int_0^\infty \chi_{atm}(t')\,\mathcal{K}(t-t')\,dt'$$

Transient Tracer Measurement
Water was collected on decadal hydrography transects using Bullister bottles. Gases were extracted over CFC/SF6-free gas, trapped, and quantified by ECD-GC against standards. QA/QC were performed in assembly of GLODAP.

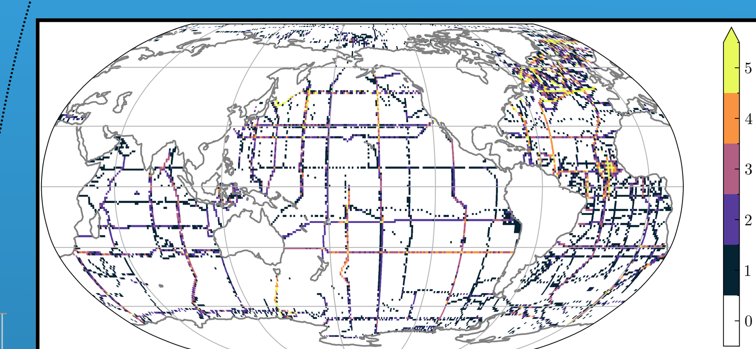
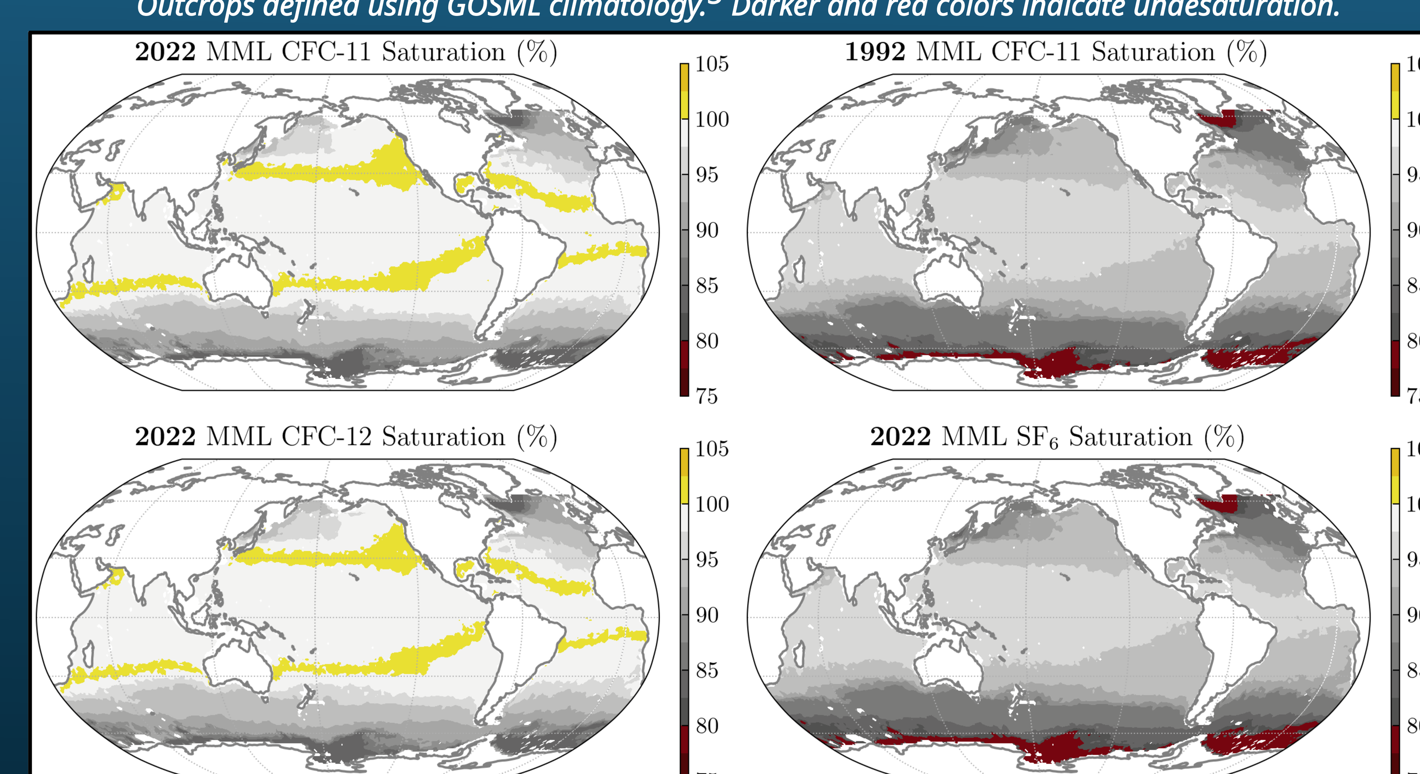


Fig. 3: Station locations in GLODAPv2.2023 dataset, shaded by number of reoccupations.

Ocean transient tracer surface saturations depend sensitively on their atmospheric histories, and studies of ventilation and C_{anth} uptake may benefit from an improved understanding.

We derive mixed layer age spectra from five decades of CFC and SF_6 observations using a Markov Chain Monte Carlo inversion method. The resulting reconstruction of transient tracers is an improved observational constraint for surface ocean circulation and carbon sink investigation.

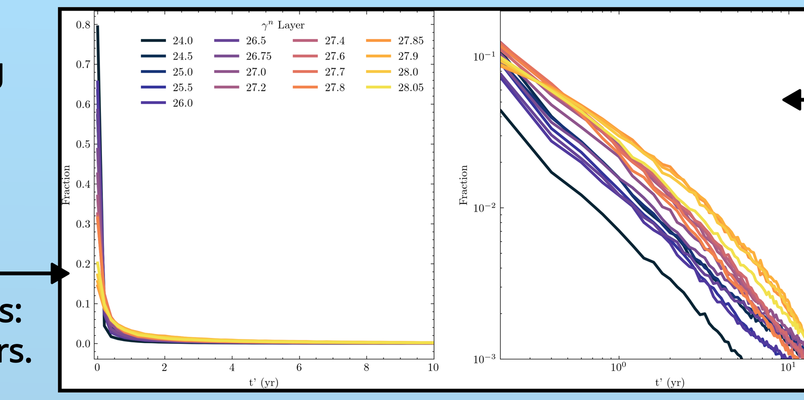
Fig. 4: Reconstructed winter MML isoneutral layer outcrop saturations of transient tracers at indicated years. Outcrops defined using GOSML climatology.[5] Darker and red colors indicate undesaturation.



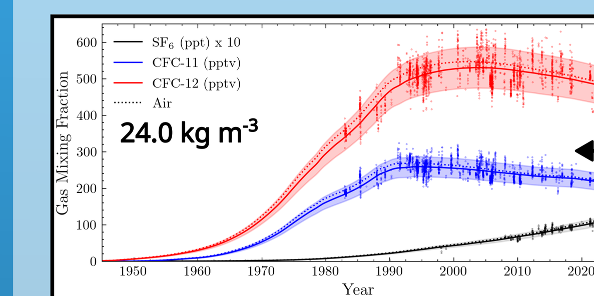
Surface age spectra explain lag in air-sea transient tracer equilibration

Heavy-tailed *K*(t') explained lagging equilibration: 40±10% of GLODAP average MML transient tracer reservoir was older than 1 year.

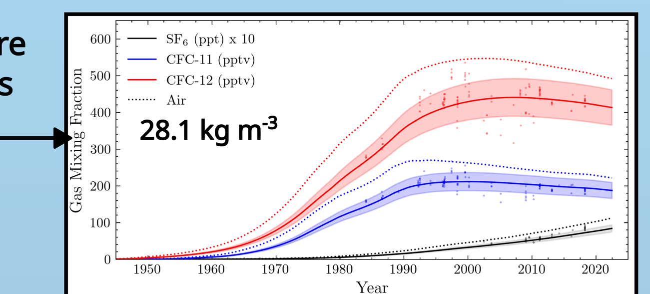
High-γ^N outcrops integrated larger fractions of older atmospheric states: less-efficient turnover of MML tracers.



An apparent power law relationship was evident from linearity of a log-log transform of K(t'): **surface age decayed faster than exponential.**

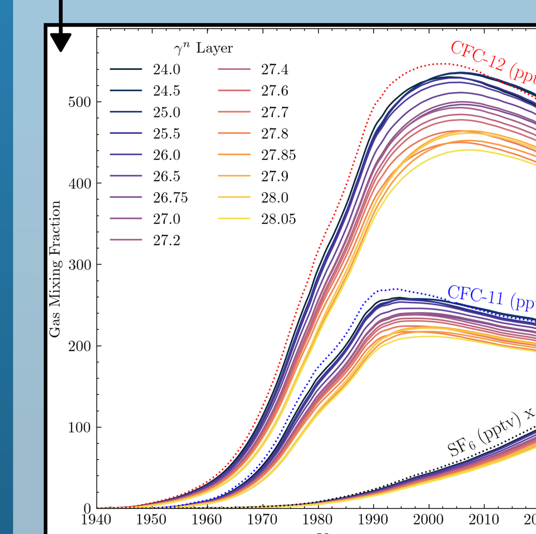


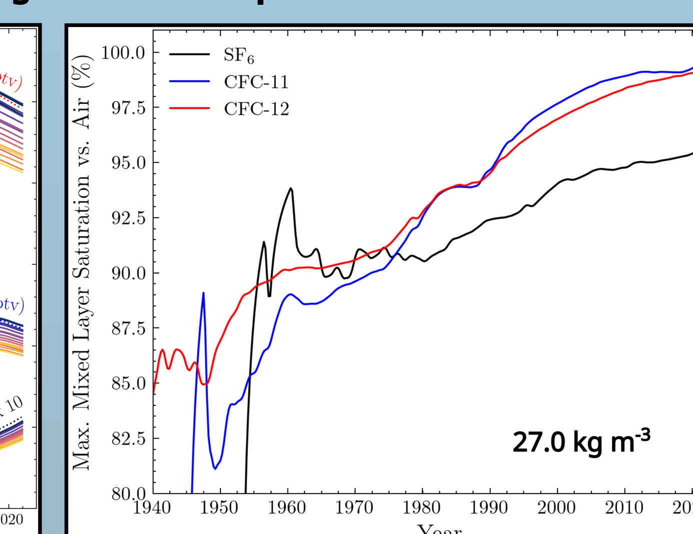
Reconstructed surface boundaries capture magnitude and variability of observations (1980-present) across outcrops with sufficient constraining data (γ^N: 24.0-28.1 kg m^{-3}). Error was propagated via Monte Carlo analysis.



We produce empirical CFC and SF_6 surface boundaries throughout the industrial era

Atmospheric transient tracer histories[7,8] were convolved with *K*(t') for each isoneutral layer, yielding a spectrum of CFC/SF_6 surface boundaries. **Decreasing saturation in poleward waters derived from incomplete equilibration** defined by *K*(t').





MML air-sea saturation was calculated as $\chi_S / \chi_{atm} \times 100\%$

Saturation time series displayed nearly identical behavior compared to previous GCM-based work[9,10] despite widely diverging methods, replicating saturation at indicated outcrop within 3-5% post-1970.

Global maps of winter isoneutral slab outcrop tracer saturations were produced by interpolating surface age spectra for climatological winter γ^N outcrops at 1° x 1° resolution. Comparison to similar work[1] indicates skill in reconstruction of positions and magnitudes of large-scale saturation phenomena.

Conclusions, applications, next steps

We derive space- and time-varying surface boundary conditions from transient tracer observations with a Bayesian inversion. Surface age spectra *K*(t') are concise expressions of physicochemical drivers of saturation, and their implied surface boundaries address the largest source of uncertainty in TTD-based studies. Our future work considers:

TTD age models

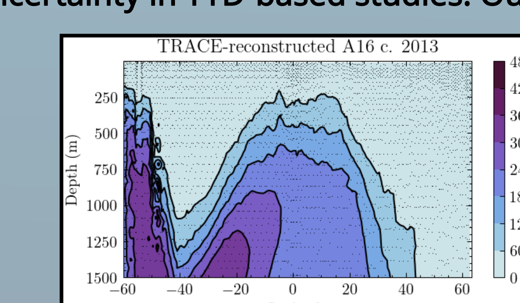
Our surface boundaries are directly applicable to single-source TTD analyses by substituting the surface boundary vector χ_s

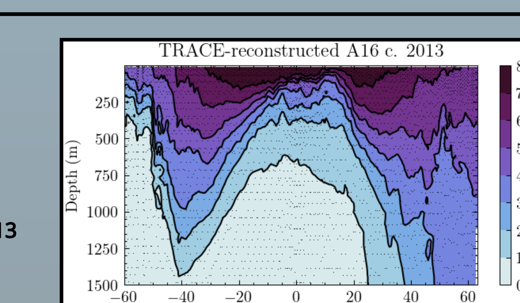
$$\chi(t) = \int_0^\infty \chi_s(t')\,\mathcal{G}(t-t')\,dt'$$

and inverting for the TTD *G*.[11]

C_{anth} estimation

Refining age models used to estimate C_{anth} (and the C_{anth} boundary condition) may improve present TTD-based Canth inventories. We use the "Tracer-based Rapid Anthropogenic Carbon Estimation" (**TRACE**)[12,13] software product to investigate these hypotheses.





Changing circulation

Our inversion and the TTD method assume steady state circulation. Studies seeking to observe circulation variability benefit from this surface boundary product resolving circulation variability from boundary variability. **Continuing repeat hydrographic measurement of transient tracers is essential for these studies.**

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Detailed methods, citations, &t.
https://d-sandborn.github.io/other