A water mass-based state estimate of the changing ocean

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Motivation

- Quantifying ocean uptake of heat, carbon, fresh water and other tracers is critical to understanding climate.
- The geography of these fluxes is highly uncertain.
- We are developing a method to infer fluxes based on water mass and tracer transport theory.

Concept

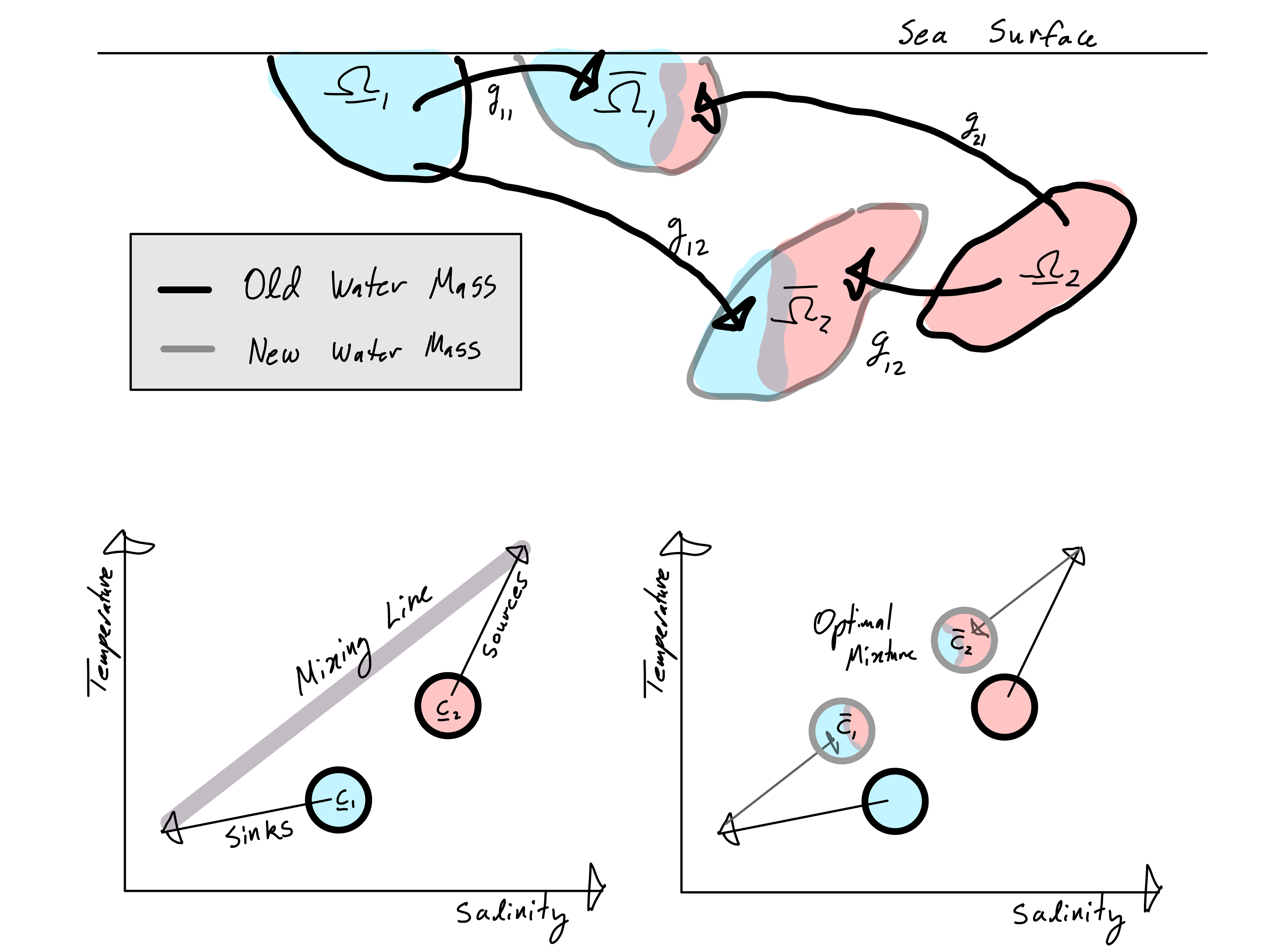

Figure 1: Top: Two old water masses (black lines) ($\underline{\Omega}_1$ - tagged with blue dye and $\underline{\Omega}_2$ - tagged with red dye) circulate and mix to form two new water masses (grey lines; Ω_1 and Ω_2). Left: The properties of the two old water masses are first augmented by sources and sinks. The new water masses must then be on a straight line in the property-property diagram. Right: Our method helps us estimate the necessary sources, sinks, and optimal circulation and mixing that explain the changing water masses

Theory

Consider a set of N modern-day water masses each with the same mass. The jth water mass is distinguished by its geographical location ($\overline{\Omega_j}$) and conserved thermodynamic and chemical properties $\overline{\mathbf{C}}_j = [\overline{T}_j, \overline{S}_j, \overline{CFC}_j, \ldots]$.

Going back to some earlier time, we can consider a set of N old water masses with the ith old water mass having location $\underline{\Omega_i}$ and properties $\underline{\mathbf{C}}_i = [\underline{T}_i, \underline{S}_i, \underline{CFC}_i, \ldots]$.

Since no water is created or destroyed, each new water mass must be made of a mixture of the old water masses. The fraction of water 'transported' from old i to new j is g_{ij} such that

$$\sum_{i=1}^{N} g_{ij} = 1 = \sum_{j=1}^{N} g_{ij} \text{ and } 0 \leq g_{ij} \leq 1. \quad (1)$$

Here g_{ij} is basically a 'Green's function' linking the region $\underline{\Omega_i}$ to the region $\overline{\Omega_j}$ for a specific time interval (Haine and Hall 2002). Since the properties are conserved under mixing, $\overline{\mathbf{C}}_j$ is simply the average of all the $\underline{\mathbf{C}}_i$ values it came from, as in classical water mass analysis (Tomczak 1981), plus any sources and sinks on the path from i to j.

$$\overline{\mathbf{C}}_j = \sum_{i=1}^{N} g_{ij}\underline{\mathbf{C}}_i + \textbf{sources and sinks}. \quad (2)$$

We have prior estimates of the sources and sinks (air-sea fluxes) into the old water mass ($\mathbf{Q}_i^{Prior}$). We thin find the g_{ij} that satisfies (1) and minimises

$$[\text{Cost}] = \sum_{j=1}^{N} \left\| \left(\sum_{i=1}^{N} g_{ij} \left(\underline{\mathbf{C}}_i + \mathbf{Q}_i^{Prior} \right) - \overline{\mathbf{C}}_j \right) \right\|^2 . \quad (3)$$

This gives us the smallest possible (root mean squared) adjustments to the air sea fluxes necessary to define a consistent model of the changing ocean.

Additional constraints are imposed relating to how far water can travel geographically.

Preliminary results

- Conservative temperature and absolute salinity from EN4 (metoffice.gov.uk/hadobs/en4/).
- Air sea heat and fresh water fluxes from ERA5 (ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5).
- 'Old' period 1979-1988 and 'new' period 2006-2015.
- Ocean partitioned into 9 regions as in Zika et al. (2021) and then water masses are defined using Binary Space Partitioning (Sohail et al. 2022).
- Solution found using a constrained linear optimiser (CVXPY + MOSEC).

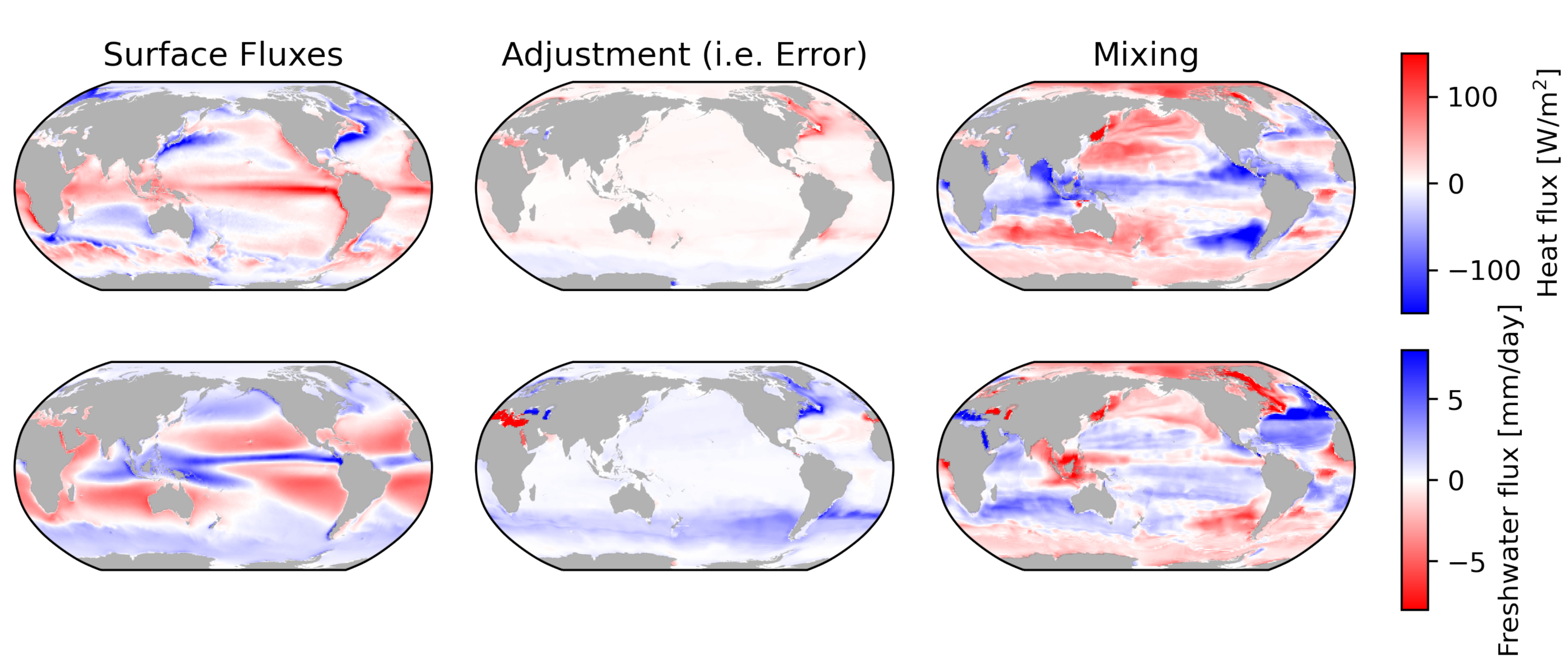

Figure 2: Prior air-sea fluxes (left), implied adjustment to fluxes (middle), inferred mixing rates(right)

Ongoing work

- So far, results are encouraging for mixing, circulation and air sea flux adjustments.
- We are currently validating the method with the ACCESS-CM2 historical simulation.
- We hope to present new insights into uptake and transport of heat, fresh water and carbon soon.
- Thoughts and feedback very welcome!

References

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