Inverse Estimate of Ocean Mixing from Observations

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1. Mixing in the ocean

The ocean, as we observe it (using ARGO, WOCE, etc), is the result of an interplay between advection and water-mass transformation. Here water-mass transformation refers to a change in a water-mass's Absolute Salinity (S_A) and Conservative Temperature (Θ). Water-mass transformation is caused by boundary (mainly air-sea) fluxes of S_A and Θ and mixing. Therefore, mixing has an important role in modifying the state of the ocean. Global observations of S_A and Θ are currently more accurate and readily available than that of velocity.

Here I present a technique that utilizes gridded climatologies based on observations of S_A and Θ distribution to estimate mixing and water-mass transformation, without using velocities.

2. The World Ocean in (S_A,Θ) coordinates

We study changes in the ocean's (S_A,Θ) distribution, by representing the ocean in (S_A,Θ) coordinates. All changes in the the ocean's volume distribution in (S_A,Θ) coordinates (Figs. 1 and 2), requires a water-mass transformation. For a water-mass transformation salt and heat fluxes are required. Note; advection may lead to a change in the position of a volume with a particular (S_A,Θ), but it does not change the (S_A,Θ) values itself and therefore its effect does not show up in (S_A,Θ) coordinates.

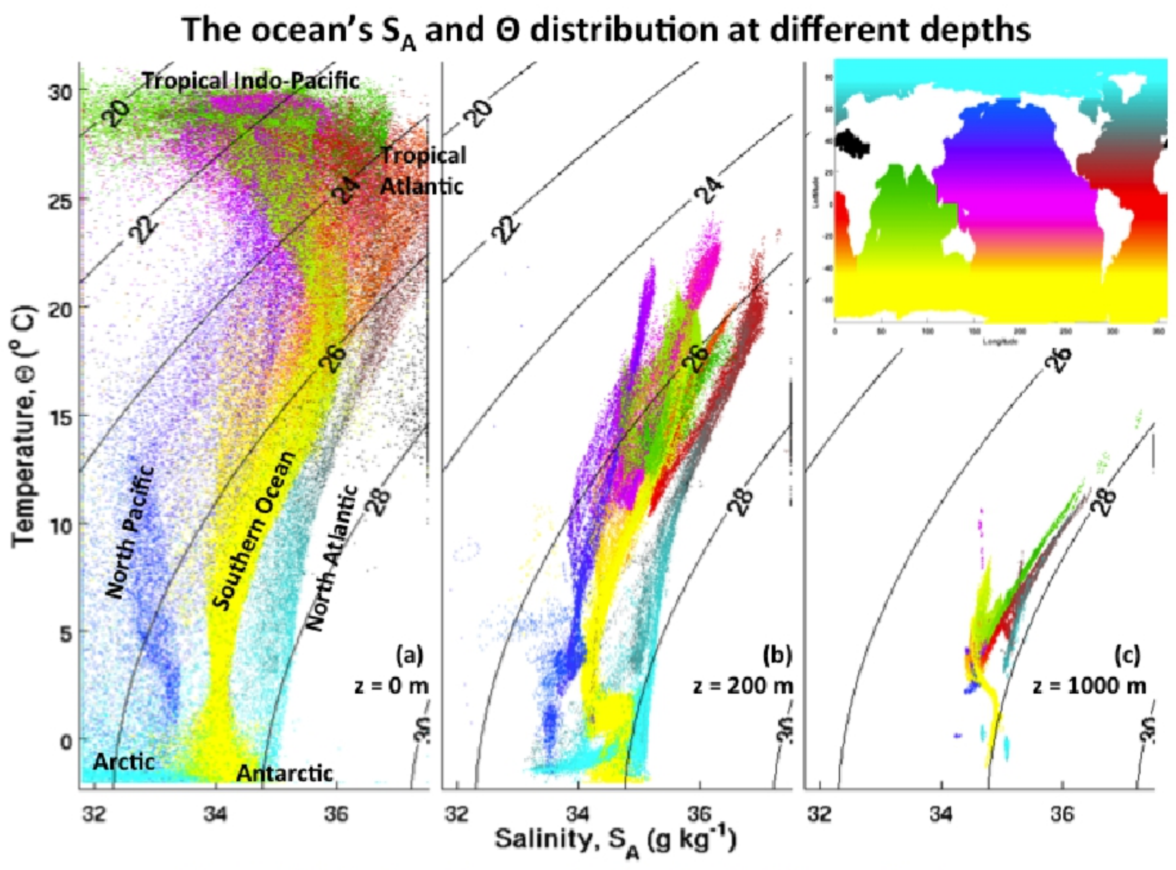

Fig. 1; Distribution of ocean basins in (S_A,Θ) coordinates.

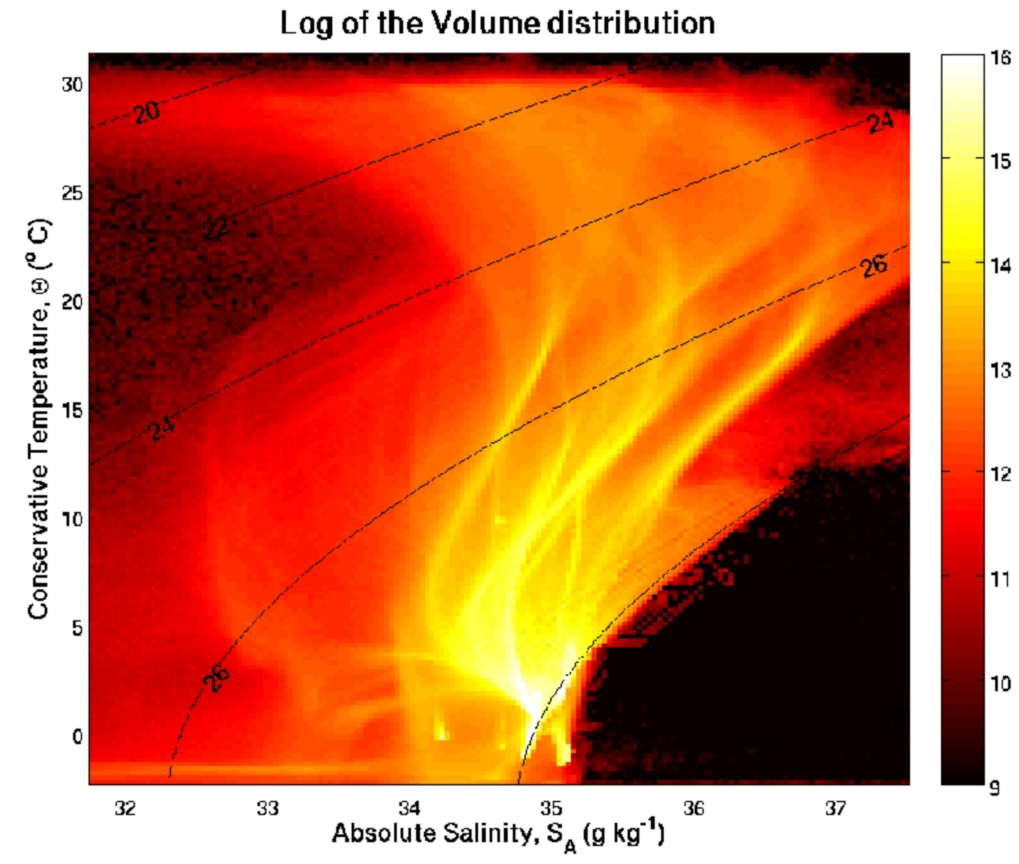

Fig. 2; The ^{10}Log of the world ocean volume distribution in (S_A,Θ) coordinates.

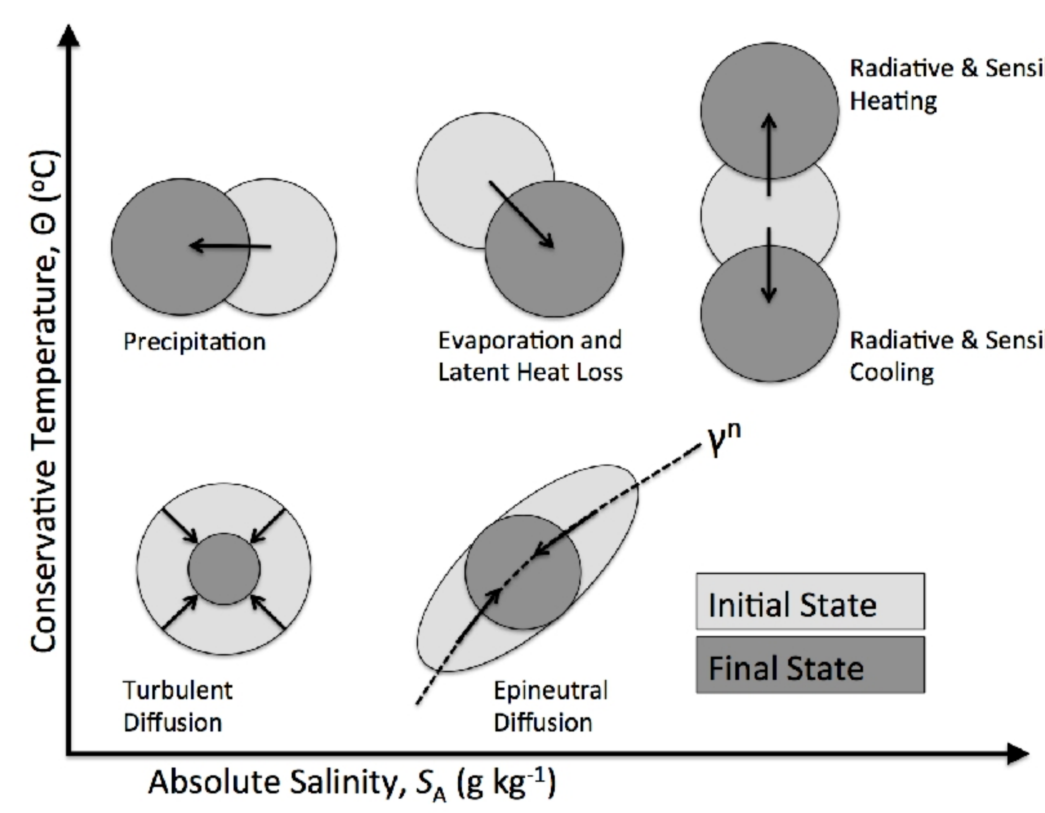

Fig. 3; Thermohaline forcing leading to displacement of fluid parcels in (S_A,Θ) coordinates.

3. Diathermohaline streamfunction

For a steady state ocean, the volume transport in (S_A,Θ) coordinates is non-divergent (trends can be corrected for). We can therefore represent the resulting 2-Dimensional non-divergent flow as the Diathermohaline Streamfunction in (S_A,Θ) coordinates. The Diathermohaline Streamfunction is directly forced by salt and heat fluxes due to air-sea fluxes and mixing (Fig. 4). The mixing term however, contains unknown diffusion coefficients. The (S_A,Θ) gradients upon which these diffusivities operate can be obtained from the climatology. We use of structure functions to represent the spatial variability of the mixing strengths*. A solution is obtained using a matrix inversion (least squares).

Thermohaline Inverse Method Applied to Observations

ΔΨ = Forcing + Mixing (4 per grid)

Rewrite as set of equations:

$$\Psi_1 - \Psi_2 - K_H c_{kH,S} f_{KH}(z) - K_I c_{kI,S} f_{KI}(z) - D c_{D,S} f_D(z) = b_{S_1}$$
$$\Psi_1 - \Psi_3 - K_H c_{kH,T} f_{KH}(z) - K_I c_{kI,T} f_{KI}(z) - D c_{D,T} f_D(z) = b_{T_1}$$

Etc...

- Here K_H, K_I are the horizontal and isopycnal mesoscale diffusivity.
- D small-scale turbulent diffusivity.
- b_{T1}, b_{S1}: heat and freshwater surface forcing.
- c-terms: salt and temperature gradients from climatology.
- f-terms: mixing structure functions.

Solution using weighted least squares:

$$\chi^2 = (x-x_0)^T W_c^{-2} (x-x_0) + (Ax-b)^T W_r^2 (Ax-b).$$

- $x = [\Psi_1, \Psi_2, \ldots, \Psi_n, K_H, K_I, D]$, are the unknowns.
- Here W_c and W_r are the column and row weights.
- x_0 is your best prior estimate of x.
- A = coefficients multiplying Ψ (1 or -1), K_H, K_I and D.
- Minimizing χ^2, (Least Squares) → Finds Ψ, K_H, K_I and D.

Fig. 4; Some of the mathematical details of the Thermohaline Inverse Method (THIM).

4. The results

The obtained water-mass transformations (Fig. 5) and resulting Diathermohaline Streamfunction (Fig. 6) are realistic and comparable to previous studies*. The small-scale turbulent mixing (D) and horizontal mesoscale mixing (K_H in the mixed layer) are comparable to other modeled and observed studies (Table 1). However, the mesoscale isopycnal mixing (K_I in the interior layer) is a first of a kind estimate which is up to 2 orders of magnitude smaller than that used in models.

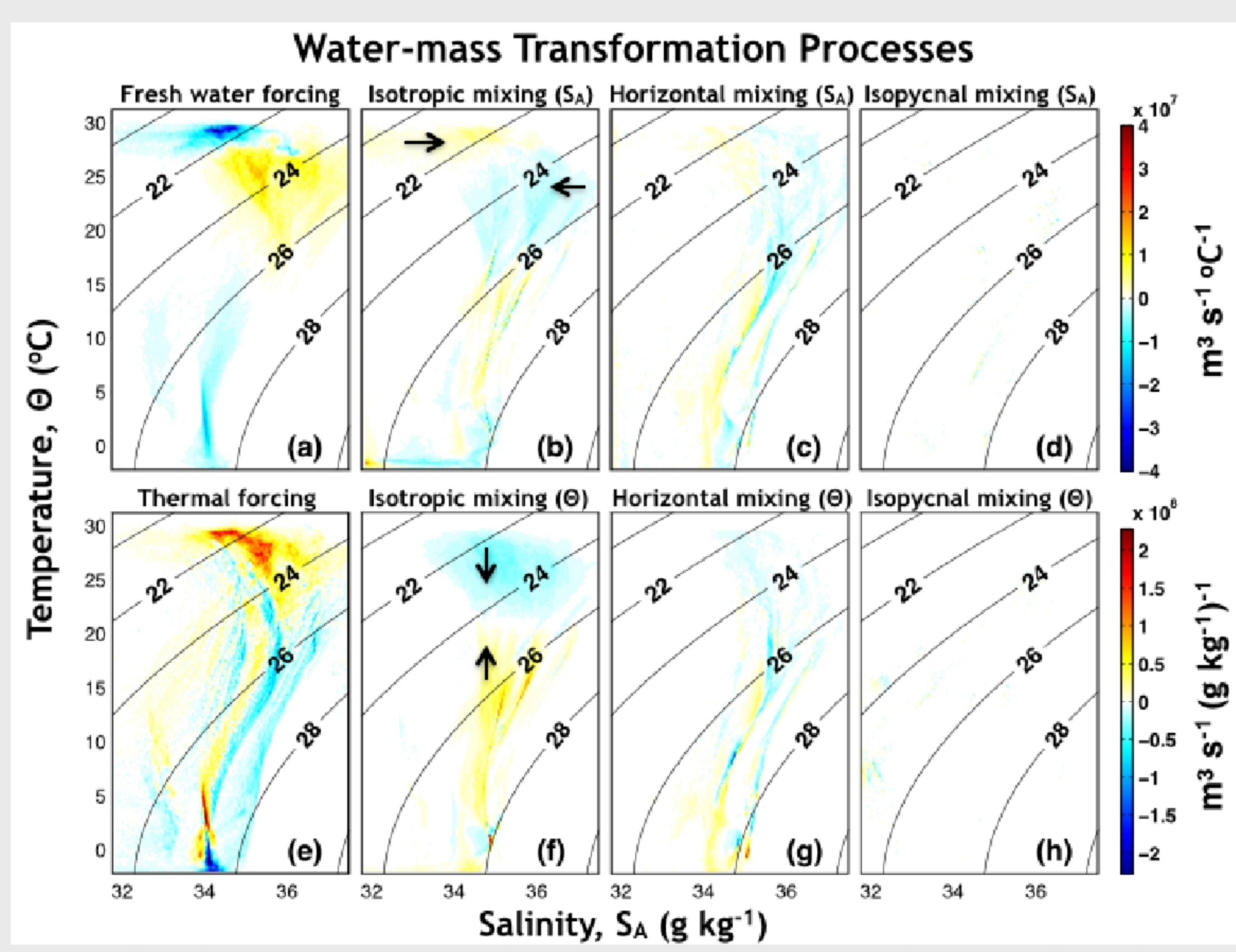

Fig. 5; Water-Mass Transformations due to heat fluxes (top) and salt fluxes (bottom) for surface forcing and mixing. These processes drive the circulation in (S_A,Θ) coordinates. The arrows indicate direction of flow.

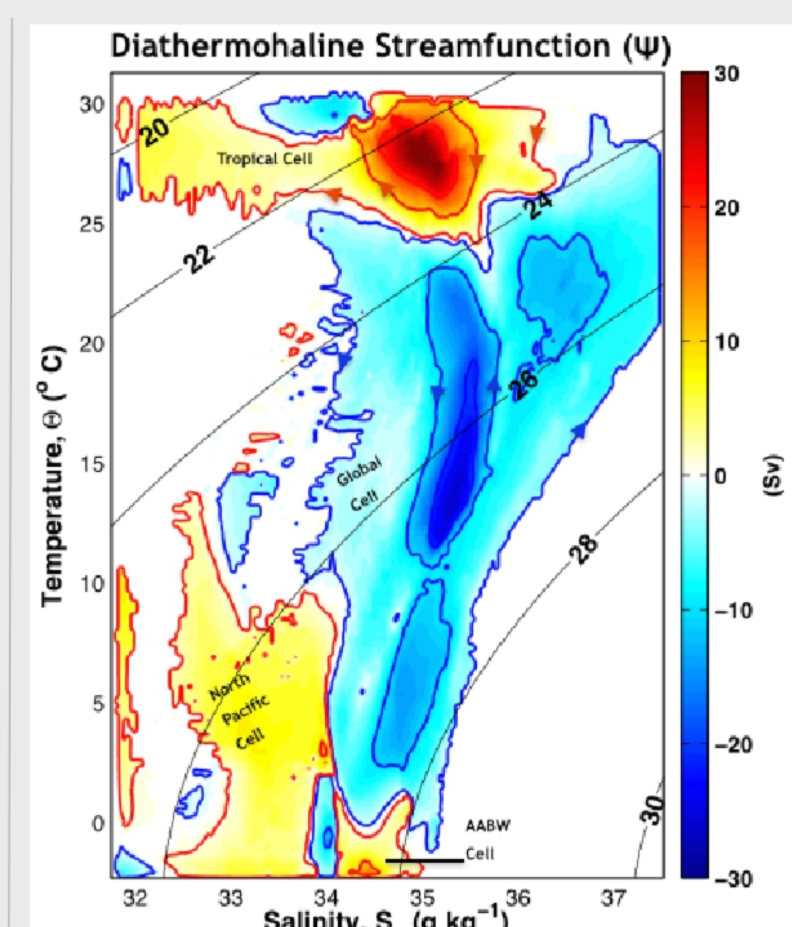

Fig. 6; The Diathermohaline Streamfunction representing ocean circulation in (S_A,Θ) coordinates.

Table 1; Diffusivities.

D	= (6.18 ± 0.04) x 10^{-5} m^{2}s^{-1}
K_H	= 20900 ± 200 m^{2}s^{-1}
K_I	= 200 ± 20 m^{2}s^{-1}
mean(K_H)	= 1800 m^{2}s^{-1}
mean(K_I)	= 8 m^{2}s^{-1} (surprise)
mean(D)	= 5.2 x 10^{-5} m^{2}s^{-1}

5. Can Isopycnal mixing be so small?

Errors are due to averaging processes, irregular and limited spatial and temporal resolution and imperfect mixing structure functions. Effects of solar penetration depth, geothermal heating or Brine rejection are not included, and the choices of column and row weighting influence the results. In our opinion it is unlikely that improvements can increase K_I by a factor 100. K_I is well constrained in (S_A,Θ) Coordinates, and such an increase will lead to unrealistic water-mass transformation (Fig. 5d and 5h).

Therefore we conclude that the interior small scale diffusion is much smaller than currently thought and applied in models. Future work should focus on improve the mixing estimates* and on understanding the impact of a small isopycnal mixing, for ocean modeling.

*Not discussed on poster. Discuss with presenter.