Water mass subduction in the isopycnic coordinate

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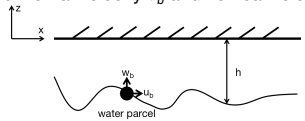
Introduction

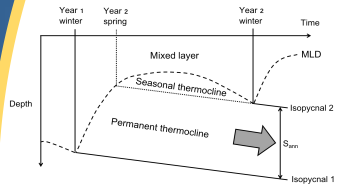
Considering either 1) the continuity of the entire surface mixed layer, or 2) the movement of a water parcel at the base of the mixed layer with horizontal velocity u_b and vertical velocity w_b, e.g.,



the classic theory of water mass subduction finds the rate to be associated with three components:

$$S = \frac{\partial h}{\partial t} + \boldsymbol{u}_b \cdot \nabla h + w_b$$

Temporal variation of the MLD | Lateral induction | Vertical velocity at the ML base



- Permanent subduction is linked to the water mass pumped into/from the permanent thermocline.
- Theory of Stommel's demon: the summer subducted water is later reentrained into the surface layer again and has thus been neglected.
- Obduction (upward transfer of fluid) occurs if the winter MLD is deeper than the previous winter.

Extensions to the theory

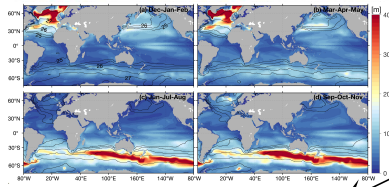


Figure: MLD in four seasons, overlapped by surface density contours (ECCO data).

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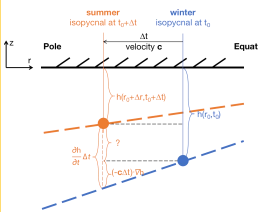
$$S = \underbrace{\frac{\partial h}{\partial t}} + \boldsymbol{u}_b \cdot \nabla h + w_b \quad (1)$$

switch the Eulerian coordinate to the coordinate associated with migrating isopycnals

$$\underbrace{\frac{\partial h}{\partial t}\Big|_\sigma} \Delta t = h(r_0 + \Delta r, t_0 + \Delta t) - h(r_0, t_0) = \frac{\partial h}{\partial t}\Big|_r \Delta t + (\boldsymbol{c}\Delta t) \cdot \nabla h \quad (2)$$

$$S = \frac{\partial h}{\partial t}\Big|_\sigma + \boldsymbol{u}_b\Big|_\sigma \cdot \nabla h + w_b = \underbrace{\frac{\partial h}{\partial t}\Big|_r} + \boldsymbol{c} \cdot \nabla h + (\boldsymbol{u}_b - \boldsymbol{c}) \cdot \nabla h + w_b \quad (3)$$



water parcel at (r_0, t_0)

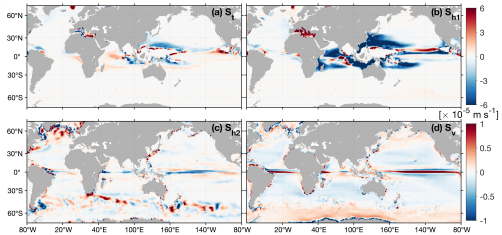
water parcel at $(r_0+\Delta r, t_0+\Delta t)$

new temporal term
lateral induction relative to isopycnal movement

vertical velocity

Results

1. Subduction estimated at the migrating isopycnal



$$S_t = \frac{\partial h}{\partial t}\Big|_\sigma,$$
$$S_h = S_{h1} + S_{h2} = -\boldsymbol{c} \cdot \nabla h + \boldsymbol{u}_b \cdot \nabla h,$$
$$S_v = w_b.$$

- Large scale is dominated by the vertical velocity at the ML base, i.e., Ekman pumping.
- Spatial patterns along the ACC and in the polar North Atlantic are controlled by lateral induction.
- Migration of isopycnals matters in the tropical and subtropical regions.
- The temporal term does not vanish to zero as assumed in the theory of Stommel's demon.

2. "Eddy" component of subduction

- The outcropping area is dependent on time and density.
- Nonlinearity leads to modifications of subduction rates at different isopycnals.

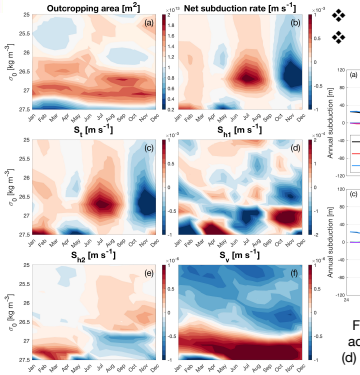


Figure: Annual subduction from (a) monthly accumulation; (b) daily accumulation. (c) and (d) further consider the modification of areas in terms of latitudes.

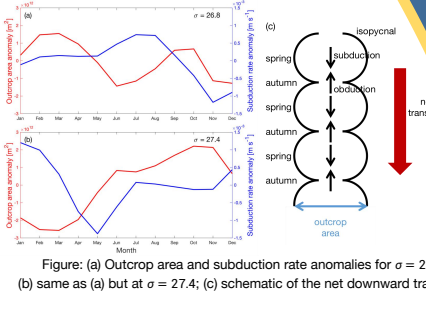


Figure: (a) Outcrop area and subduction rate anomalies for σ = 26.8; (b) same as (a) but at σ = 27.4; (c) schematic of the net downward transport.

Table: Densities of major upper-ocean water masses in the ECCO simulations and Argo observations.

Acronyms	*Full name*	*Density range (ECCO)*	*Density range (Argo)*
NPSTMW	North Pacific Subtropical Mode Water	$25.2 \le \sigma < 26.4$	$25.1 \le \sigma < 25.5$
NASTMW	North Atlantic Subtropical Mode Water	$25.2 \le \sigma < 26.4$	$26.4 \le \sigma < 26.6$
SHSTMW	Southern Hemisphere Subtropical Mode Water	$25.2 \le \sigma < 26.4$	$26.3 \le \sigma < 26.8$
SAMW	Subantarctic Mode Water	$26.4 \le \sigma < 27.1$	$26.8 \le \sigma < 27.2$
AAIW	Antarctic Intermediate Water	$27.1 \le \sigma < 27.6$	$26.8 \le \sigma < 27.4$

Main reference: Subduction of water masses in an eddying ocean. Marshall (1997).