Equations of motion

x-momentum: $$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + \nu\frac{\partial^2 u}{\partial z^2},$$

y-momentum: $$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} + \nu\frac{\partial^2 v}{\partial z^2},$$

z-momentum: $$0 = -\frac{\partial p}{\partial z} - \rho g,$$

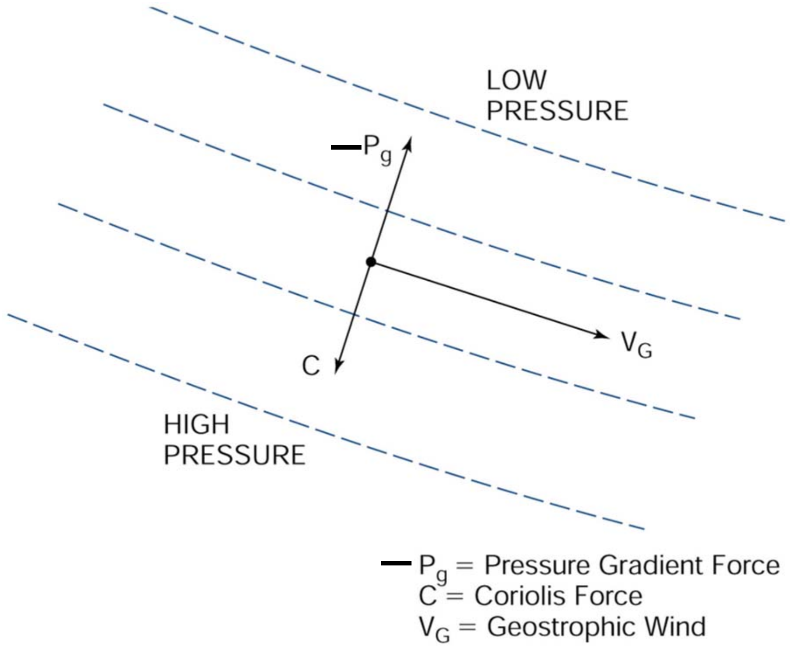
continuity: $$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0,$$

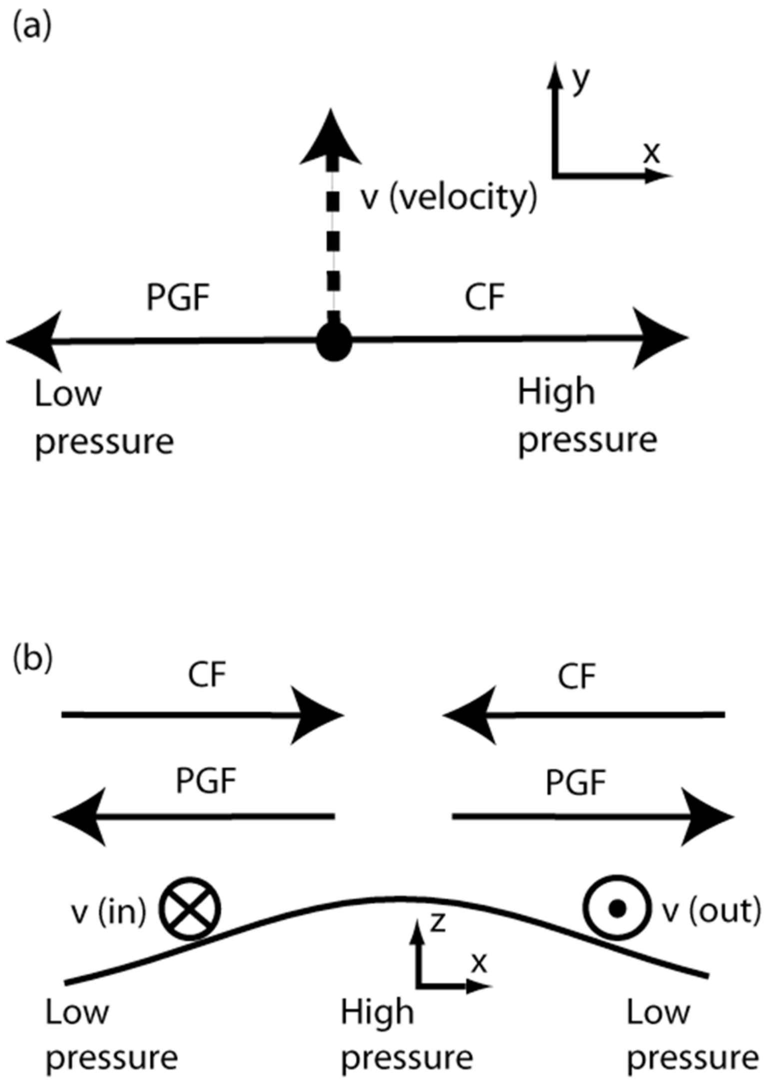
density: $$\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial x} + v\frac{\partial \rho}{\partial y} + w\frac{\partial \rho}{\partial z} = \kappa\frac{\partial^2 \rho}{\partial z^2},$$

Geostrophic balance R_o=0, $R_o > 0$

Cushman-Roisin, 1994

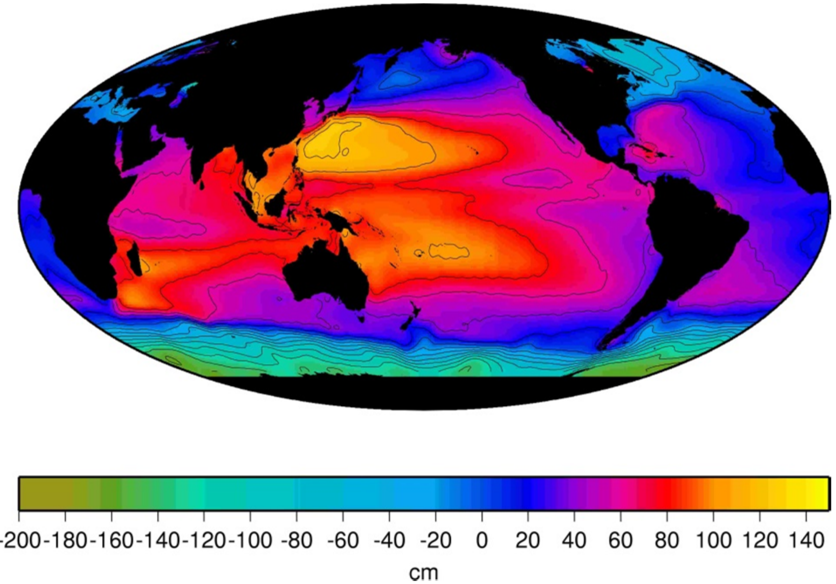
Geostrophy - interior ocean





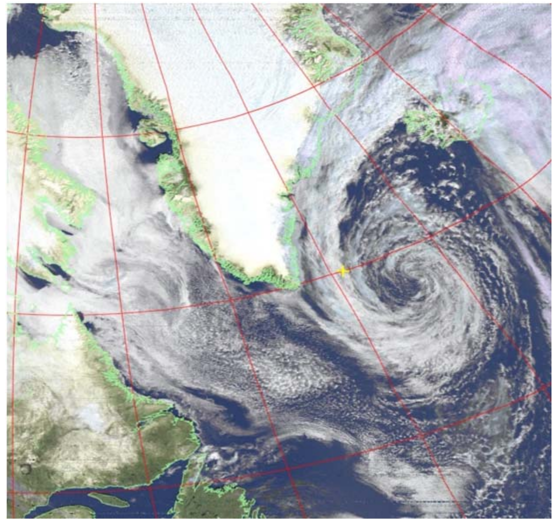
Talley, 2010

Geostrophy

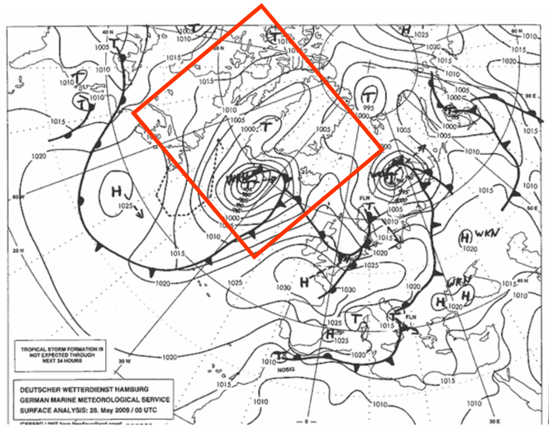


SSH from TOPEX

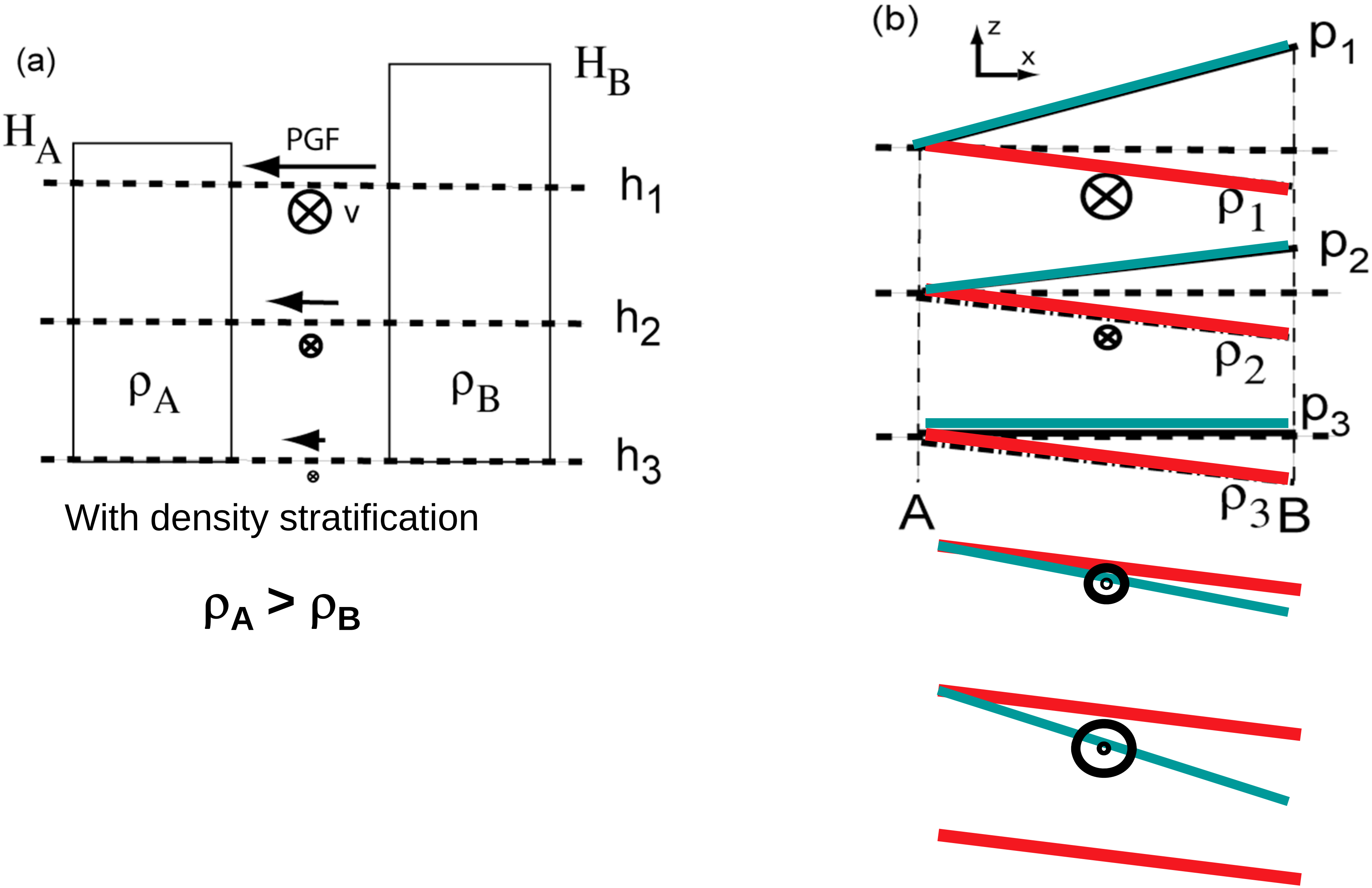
Steward, 2008



Satellite image for May 28th



Geostrophy



With density stratification

$\rho_A > \rho_B$

Talley, 2010

Geostrophy

Specific volume anomaly $\delta = \alpha - \alpha(35, 0°, p)$

where $\alpha = 1/\rho$ is specific volume.

$\Delta\Phi = -\int \delta \, dp$ geopotential anomaly

$f(v_2 - v_1) = -\partial \Delta\Phi/\partial x$ $f(u_2 - u_1) = \partial \Delta\Phi/\partial y$

OR

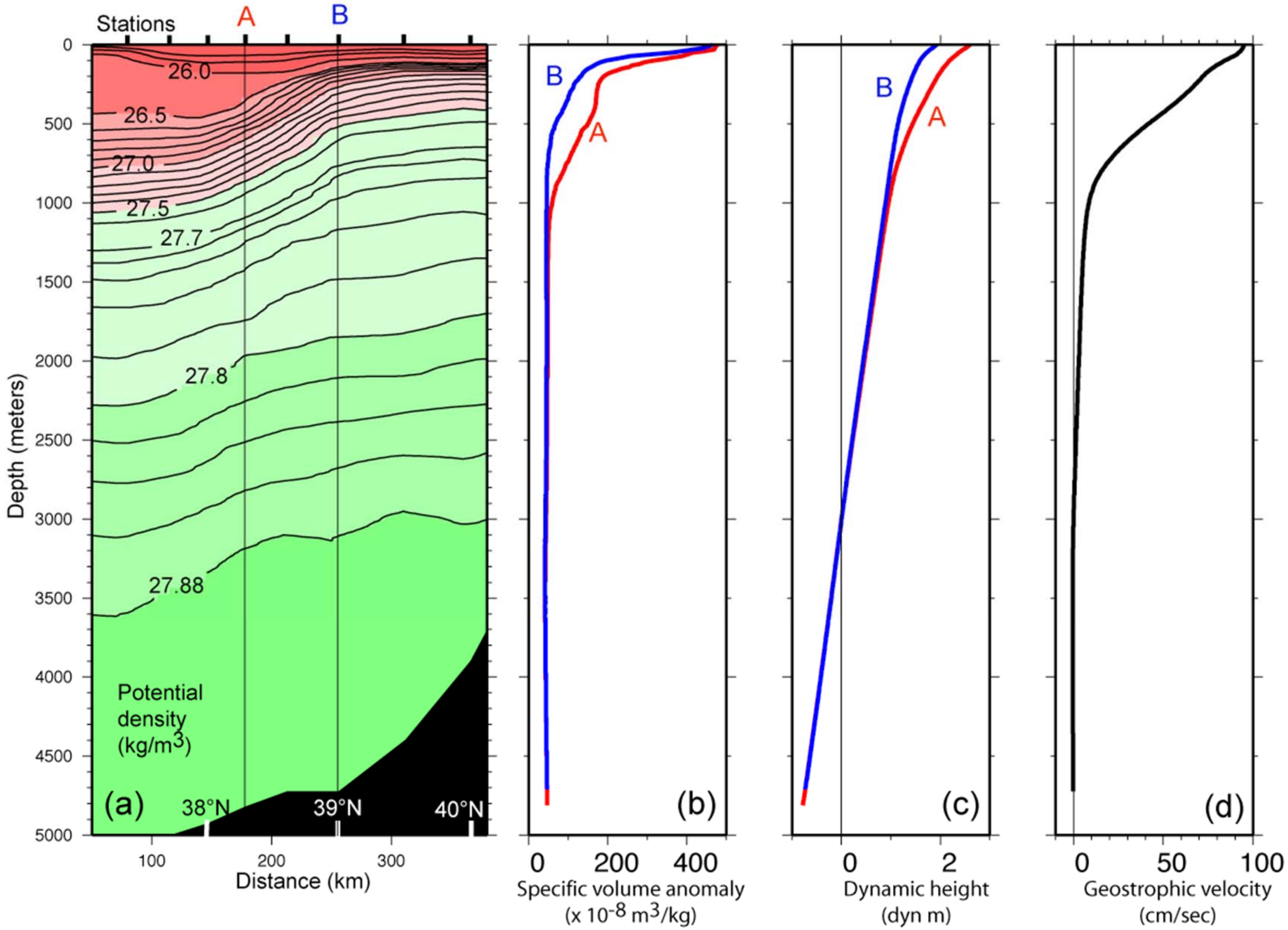
$\Delta D = -\Delta\Phi / 10 = -\int \delta \, dp \; /10$ dynamic height

1 dyn m = 10 m^2/sec^2

$f(v_2 - v_1) = 10 \, \partial \Delta D/\partial x$ $f(u_2 - u_1) = -10 \, \partial \Delta D/\partial y$

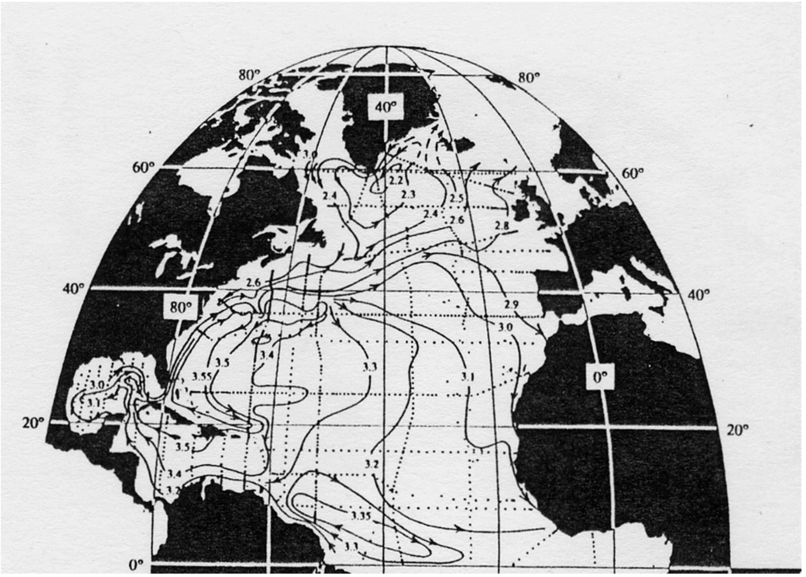
Talley, 2010

Geostrophy



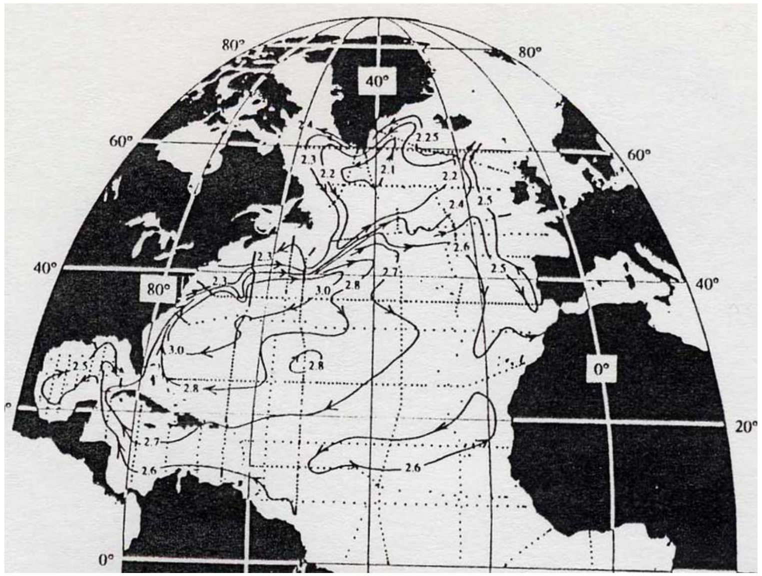
Talley, 2010

Geostrophy



Dynamic height

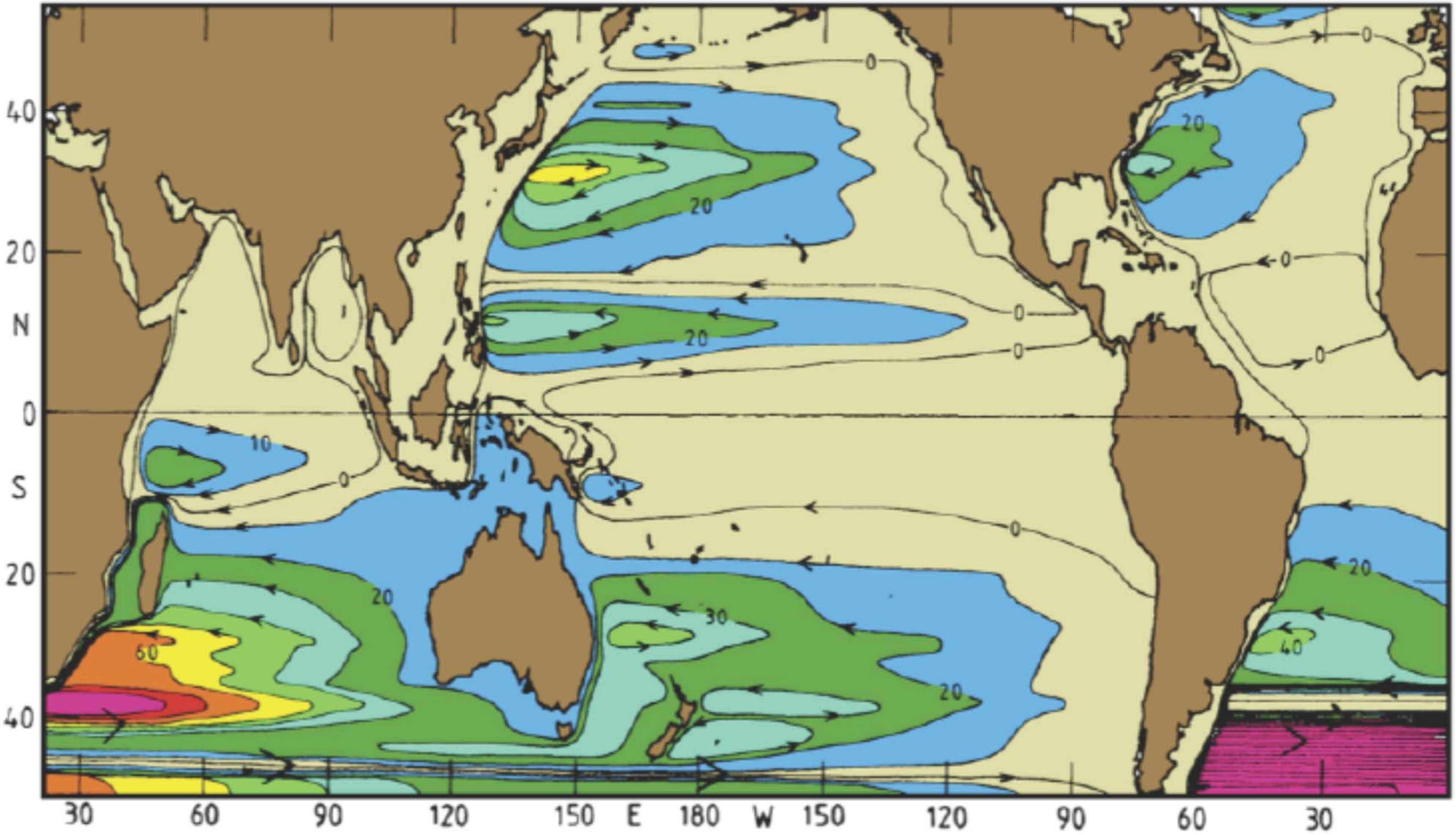
0/2000 dbar



250/2000 dbar

Reid, 1994

Global Sverdrup circulation



Tomczak and Godfrey, 2001

Ventilation

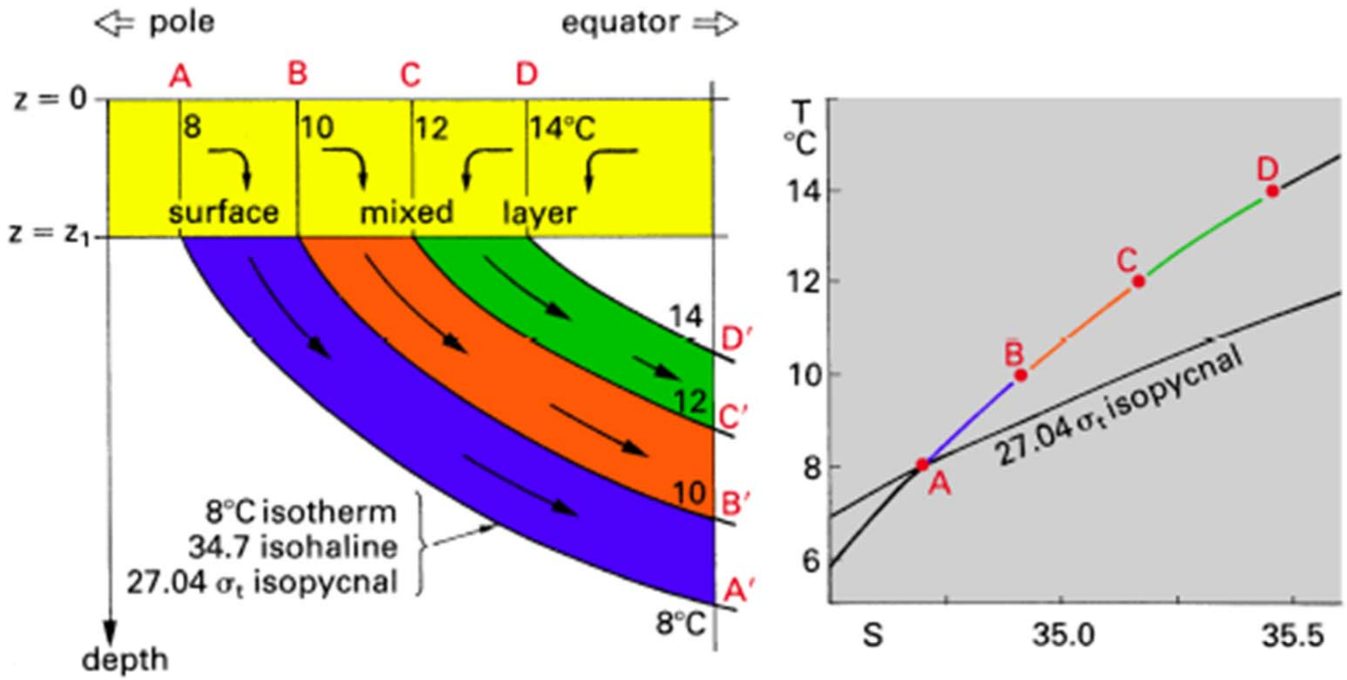
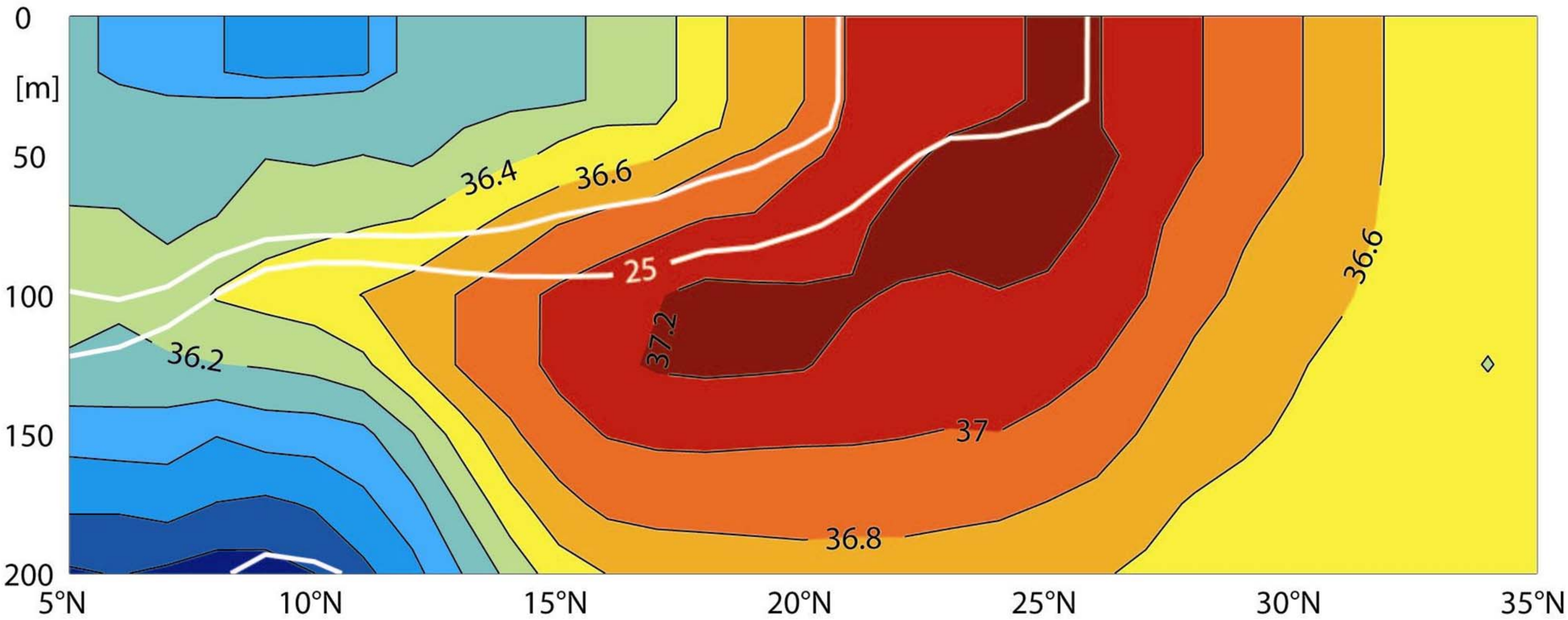


Fig. 5.3. Sketch of water mass formation by subduction in the Subtropical Convergence. The T-S diagram shows both the meridional variation of temperature and salinity between stations *A* and *D*, and the vertical variation equatorward of station *D* from the surface down along the line *A'B'C'D'*. For more detail, see text.

Price, 2001

Subtropical underwater

Salinity along 50°W

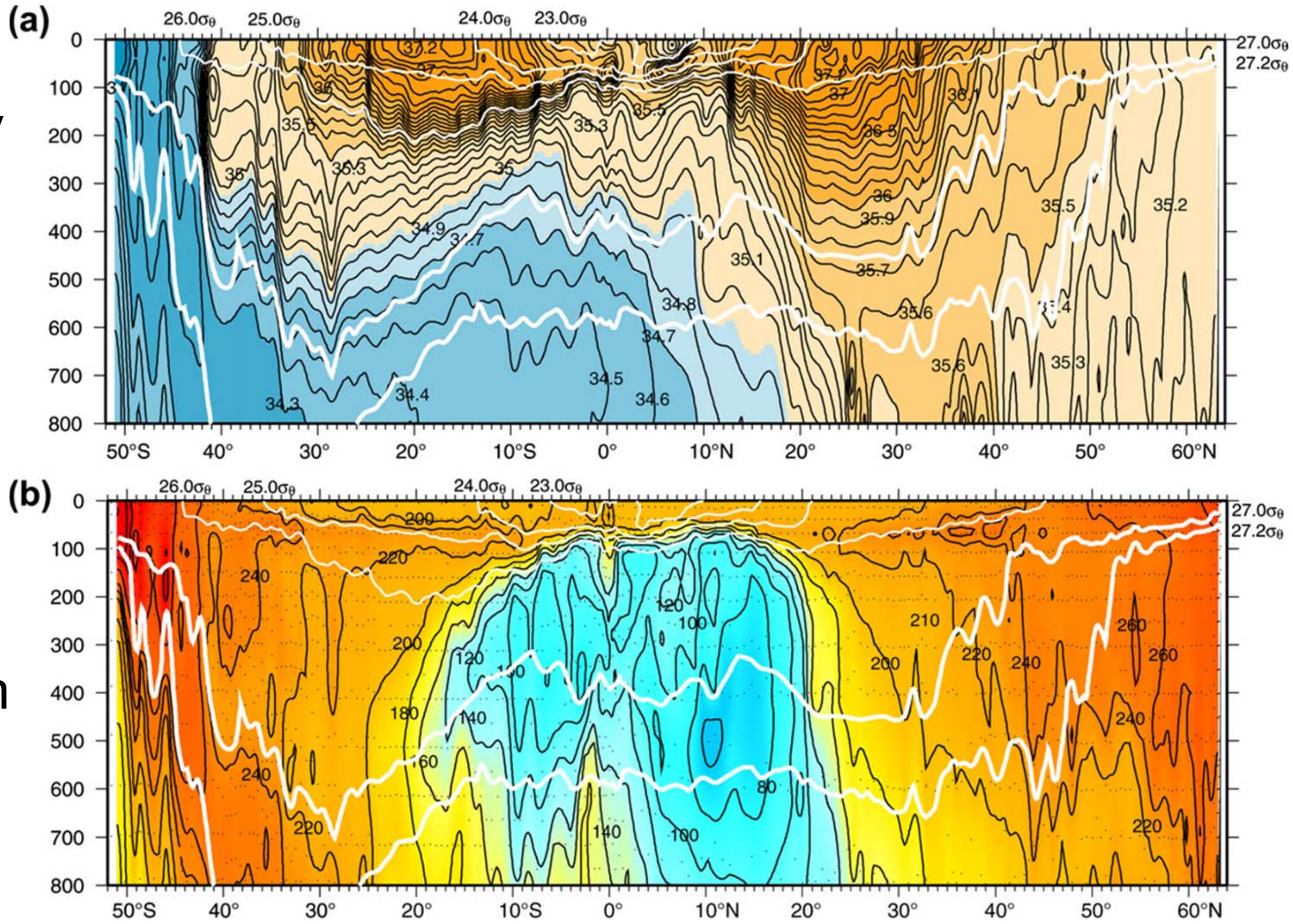


- **High-salinity waters in the subsurface layer of the subtropical gyre**
- **Generated in the high evaporation regions**
- **Subducts southward and forms a salinity maximum in the vertical.** *Karstensen, 2007*

Subtropical underwater

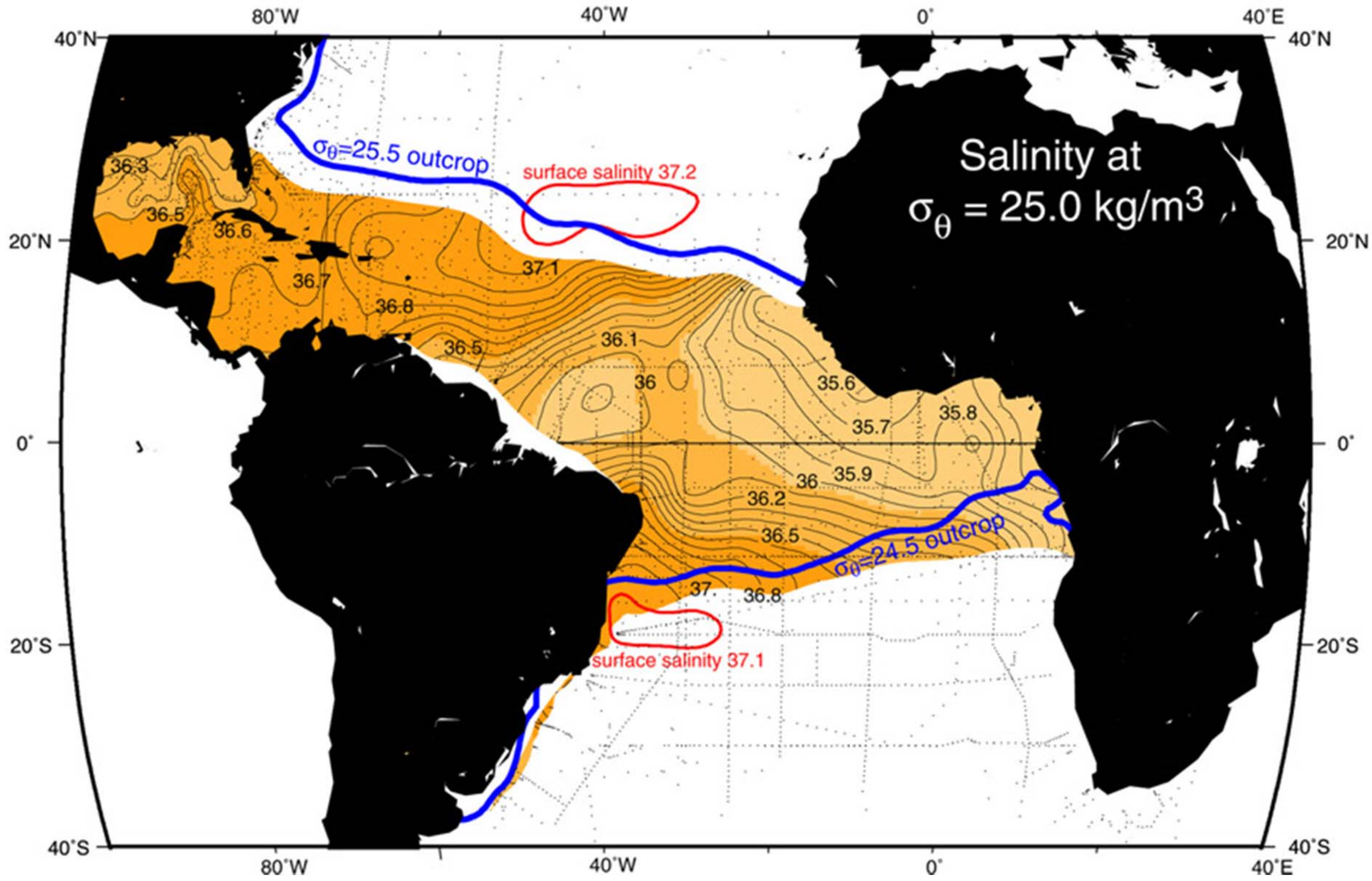
Salinity

Oxygen



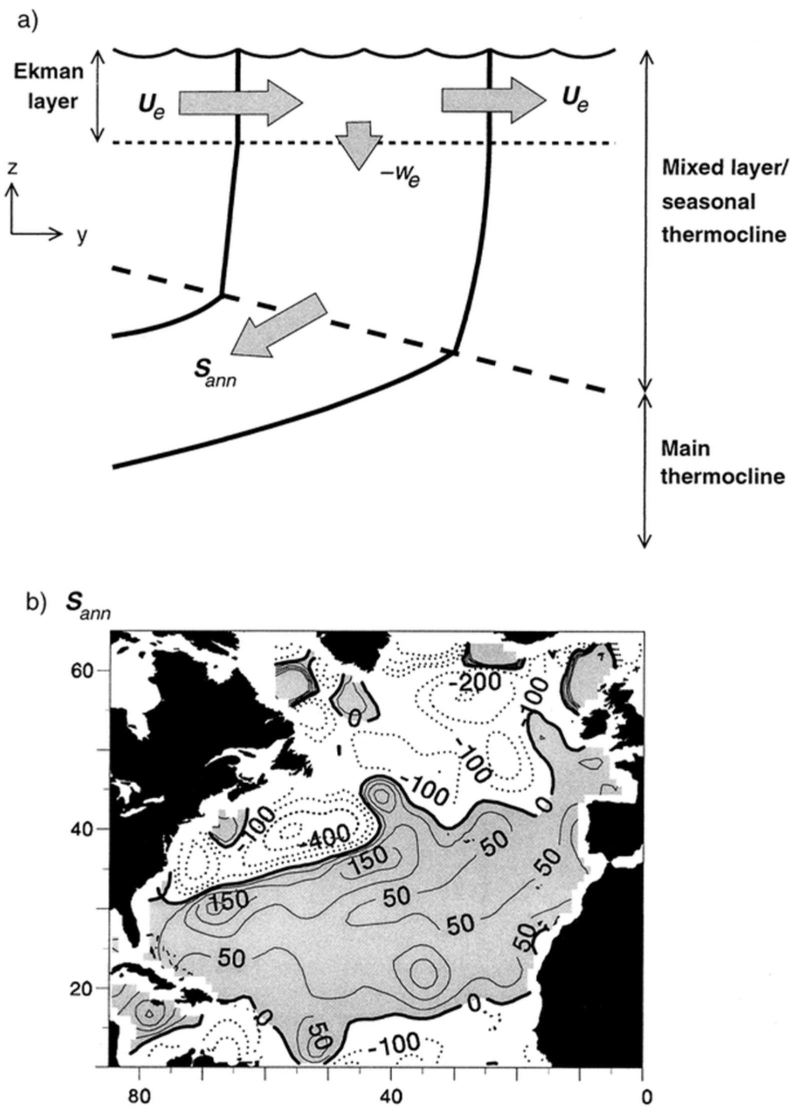
Aus Talley, 2011

Subtropical underwater



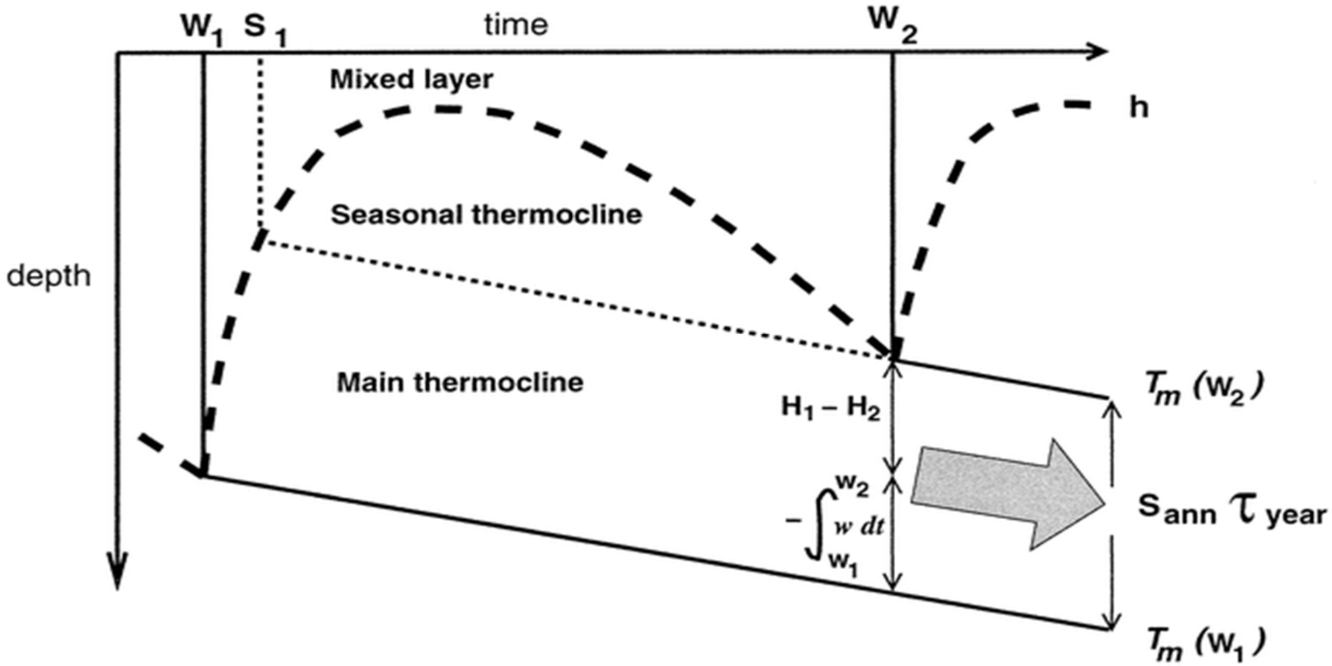
Aus Talley, 2011

Subduction



Marshall, 1986

Subduction

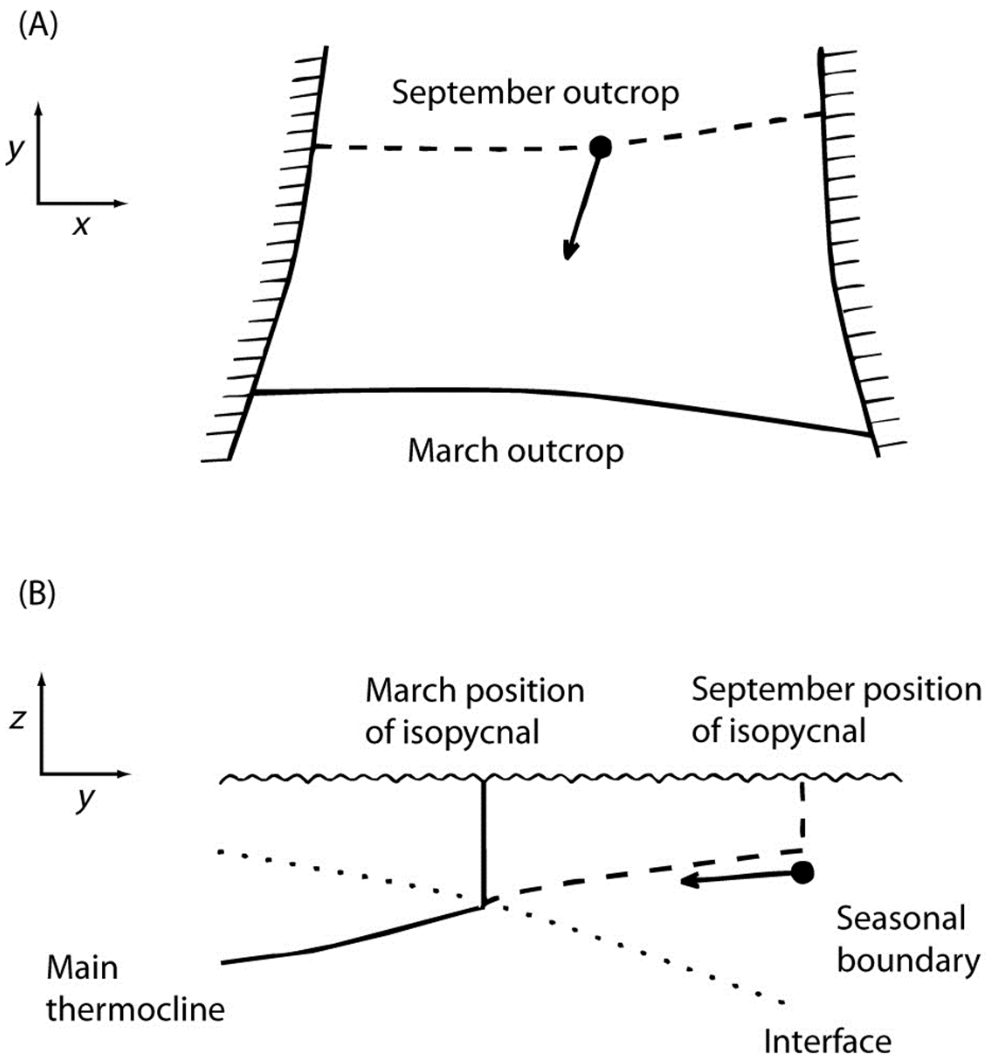


$$S_{ann} = -\overline{\left(w_{Ek} - \frac{\beta}{f}\int_{-h_m}^{0} v_m\, dz\right)} + \overline{\mathbf{u}_m \cdot \nabla h_m},$$

In this Lagrangian frame, the subduction rate into the main thermocline, S_{ann}, consists of a vertical pumping contribution and a lateral transfer due to the shoaling of the winter mixed layer. Isotherms subducted from the end of winter mixed layer are depicted by the thin full lines. The base of the seasonal thermocline is marked by the thin dashed line.

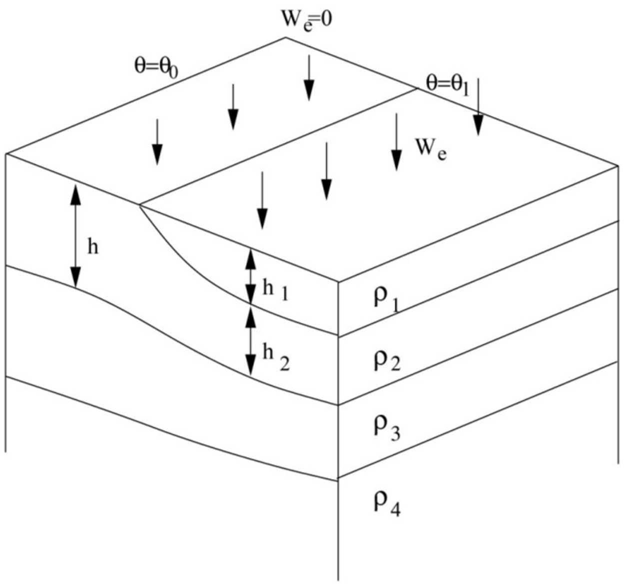
Williams et al., 1995

Stommel's demon



Williams et al., 1995

Ventilated thermocline

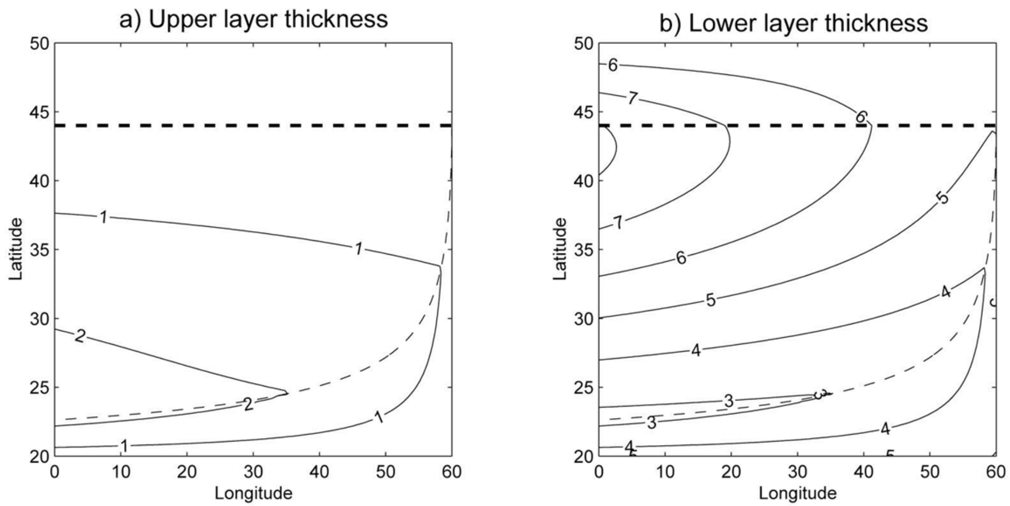


First Model by Luyten, Pedlosky, Stommel (1983)

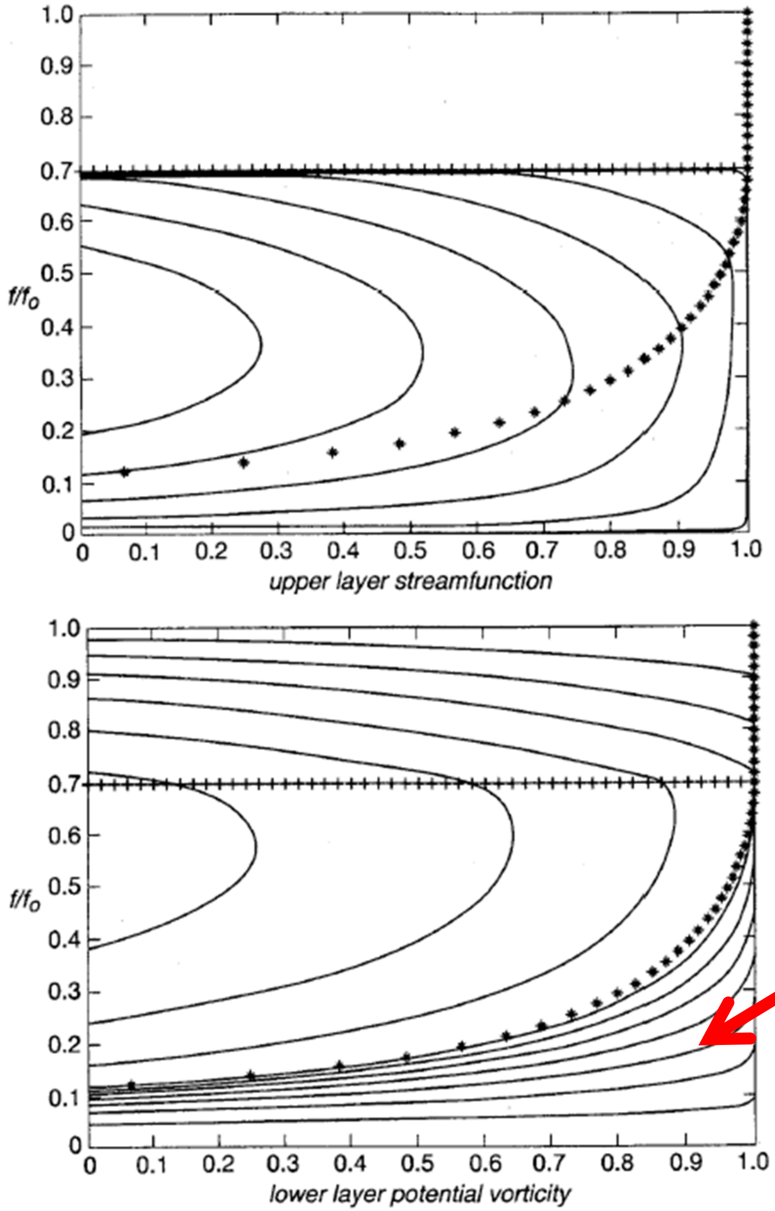
Assumptions made:

- ocean interior, excluding western boundary
- excluding Ekman layer, but Ekman pumping w_e
- geostrophy (potential vorticity conservation)
- no diapycnal mixing

- constant layer thickness at the eastern boundary
- increase of layer thickness toward west due to Ekman pumping
- eastern boundary no streamline – shadow zone



Ventilated thermocline 2-layers



Schattenzone
Keine Ventilation

Luyten et al., 1983

Subduction Multi layer

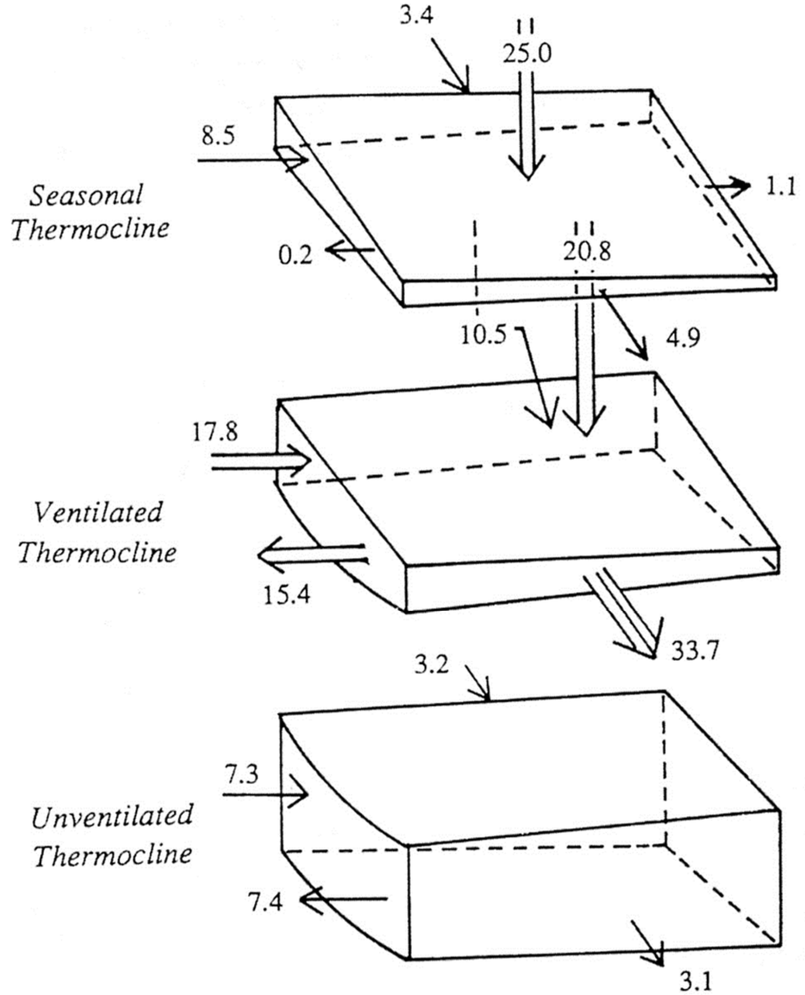
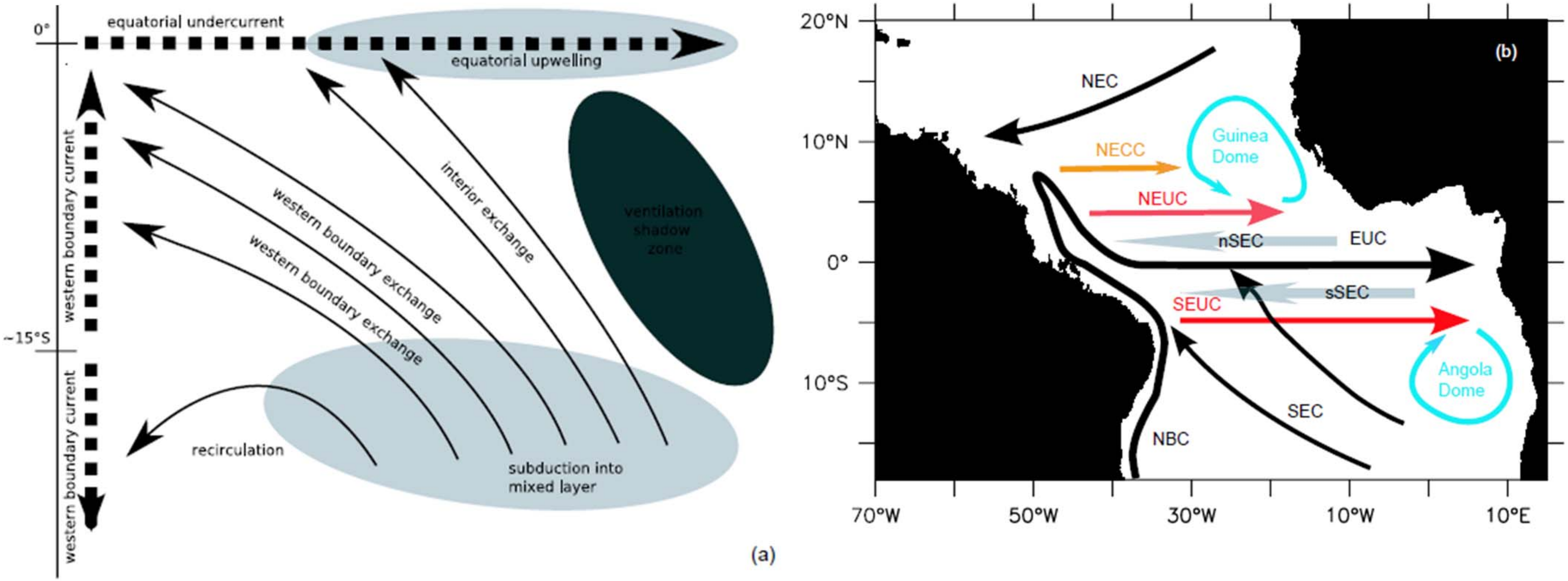


Fig. 5.3.4 Mass fluxes (units of Sverdups) between layers of the North Pacific thermocline indicated. The northern boundary is to the top, and the Ekman pumping is shown as the downward-directed double arrow. From Huang and Russell (1995), Fig. 12.

Huang & Russel, 1995

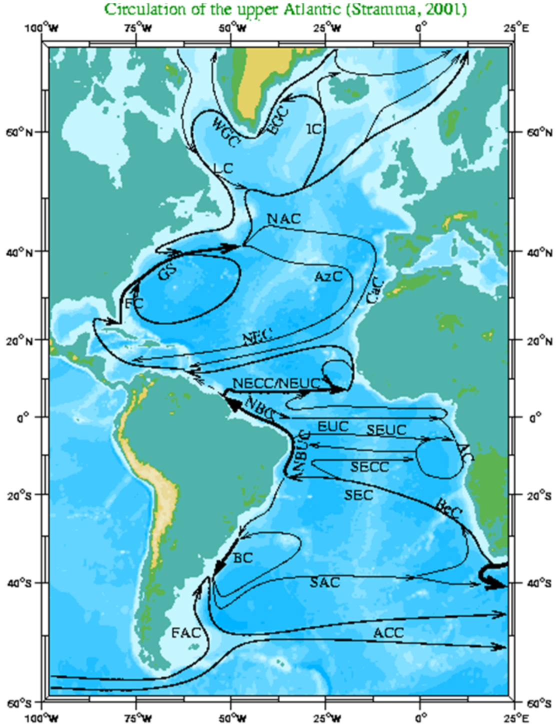
Shadow zones



Schematics of the a) thermocline ventilation windows and b) the subsurface equatorial current system including the doming circulations. From Hüttl, 2006.

Shadow zones - Oxygen 200 m

Circulation of the upper Atlantic (Stramma, 2001)



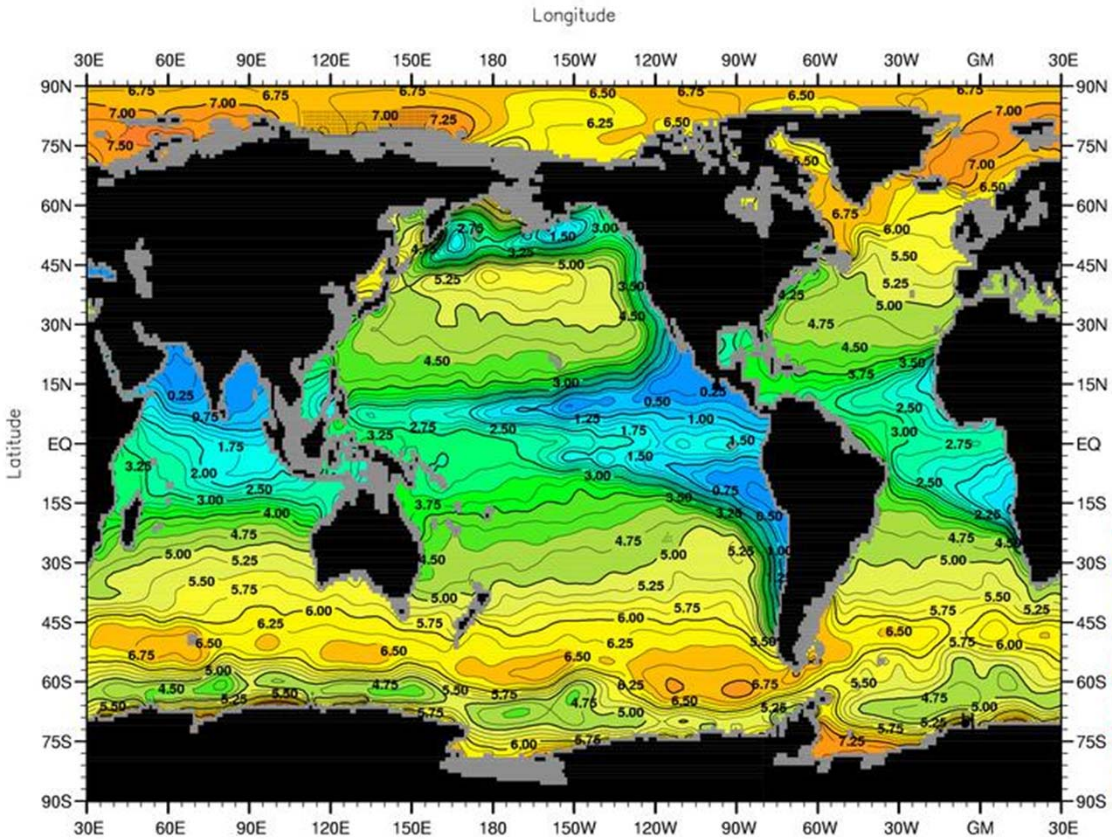


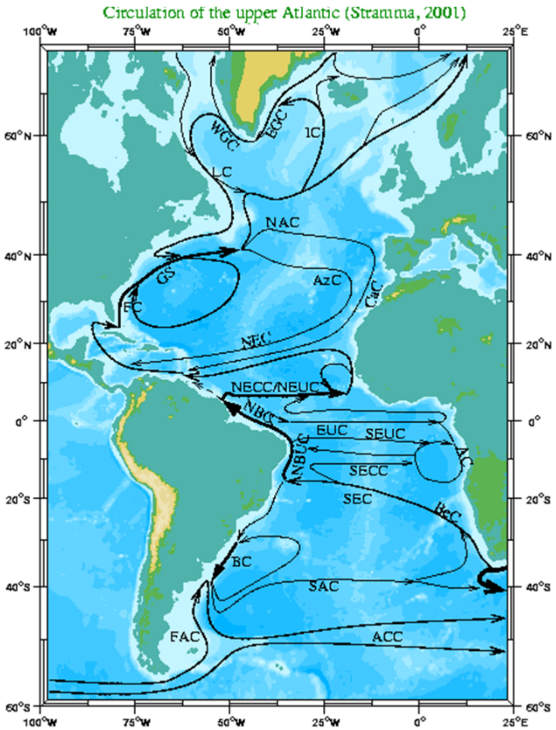
Fig. A2-10. Annual mean oxygen (ml/l) at 200 m. depth.

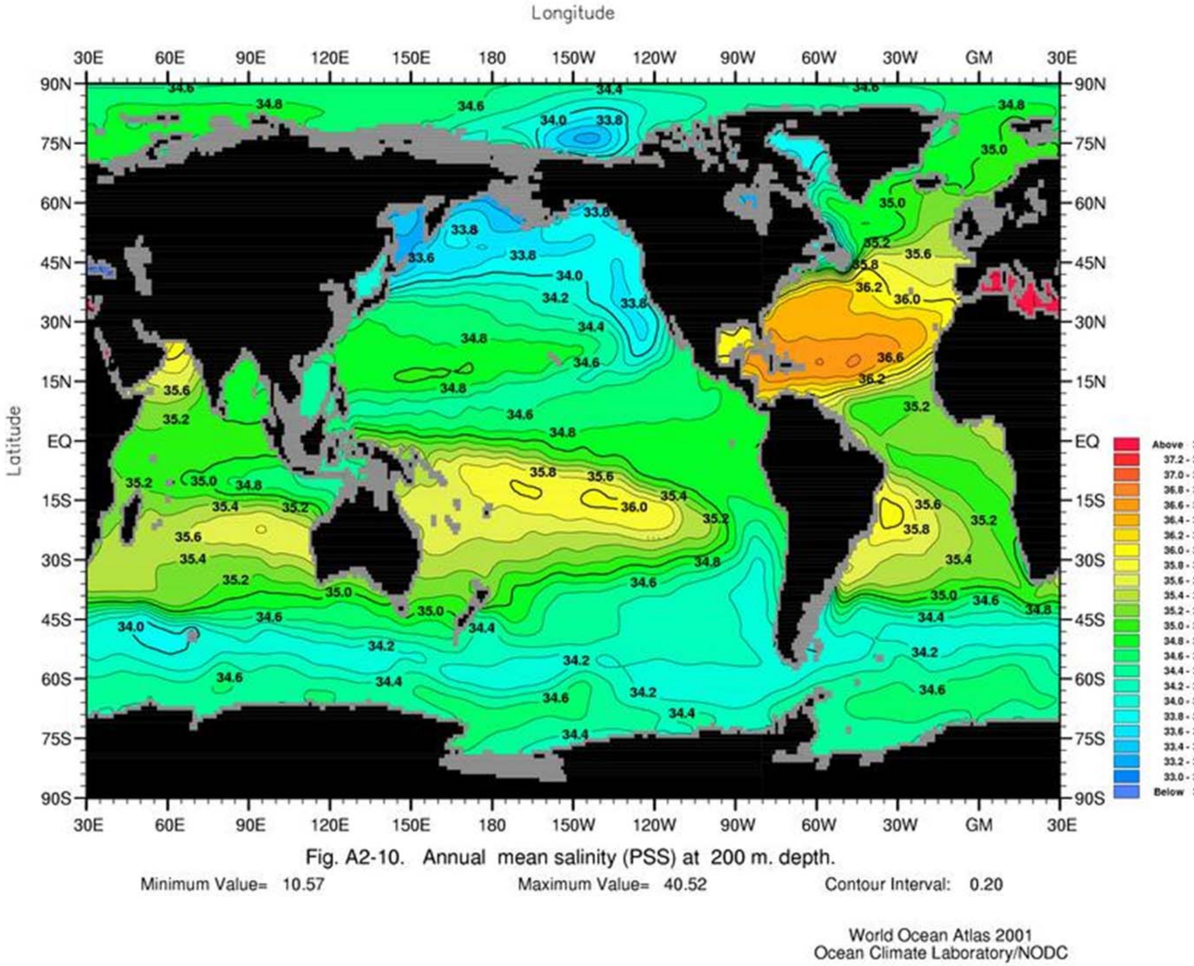
Minimum Value= 0.07 Maximum Value= 8.72 Contour Interval: 0.25

World Ocean Atlas 2001
Ocean Climate Laboratory/NODC

Karstensen, 2007

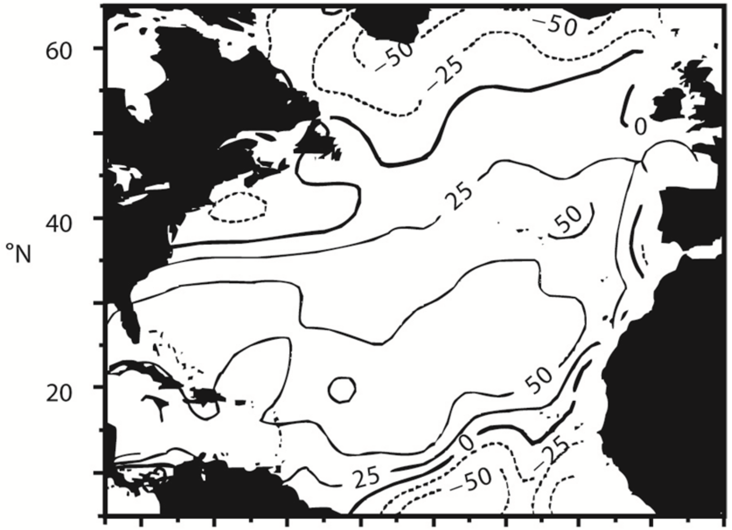
Shadow zones - Salinity 200 m





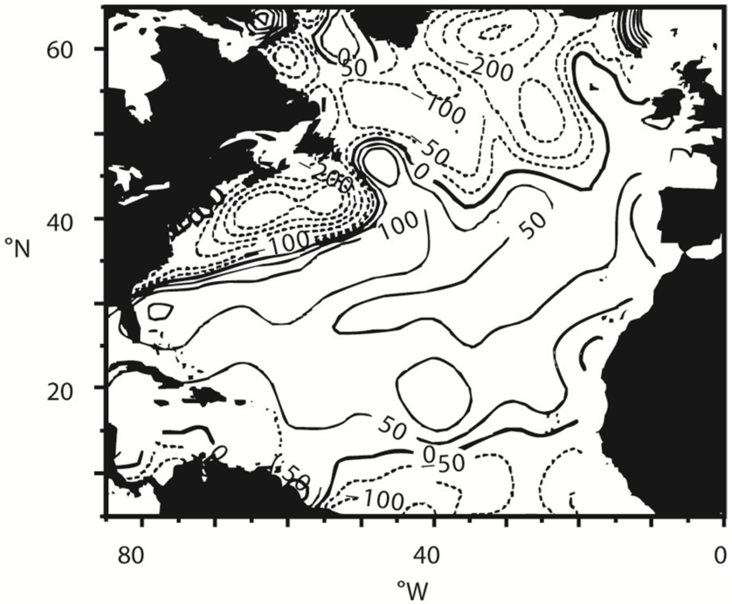
Karstensen, 2007

Subduction rates



Annual mean Ekman pumping (m/yr)

$$S_{\text{ann}} = -\overline{\left(w_{\text{Ek}} - \frac{\beta}{f}\int_{-h_m}^{0} v_m \, dz\right)} + \overline{\mathbf{u}_m \cdot \nabla h_m},$$



Annual subduction rates (m/yr)

Marshall et al., 1993

Globale Subduktionsraten

$$S_{ann} = -\overline{\left(w_{Ek} - \frac{\beta}{f}\int_{-h_m}^{0} v_m \, dz\right)} + \overline{\mathbf{u}_m \cdot \nabla h_m},$$

Ekman Pumping

Sverdruptransport
in der Deckschicht

Lateraler Eintrag durch
geneigt Bodenfläche
der Deckschicht

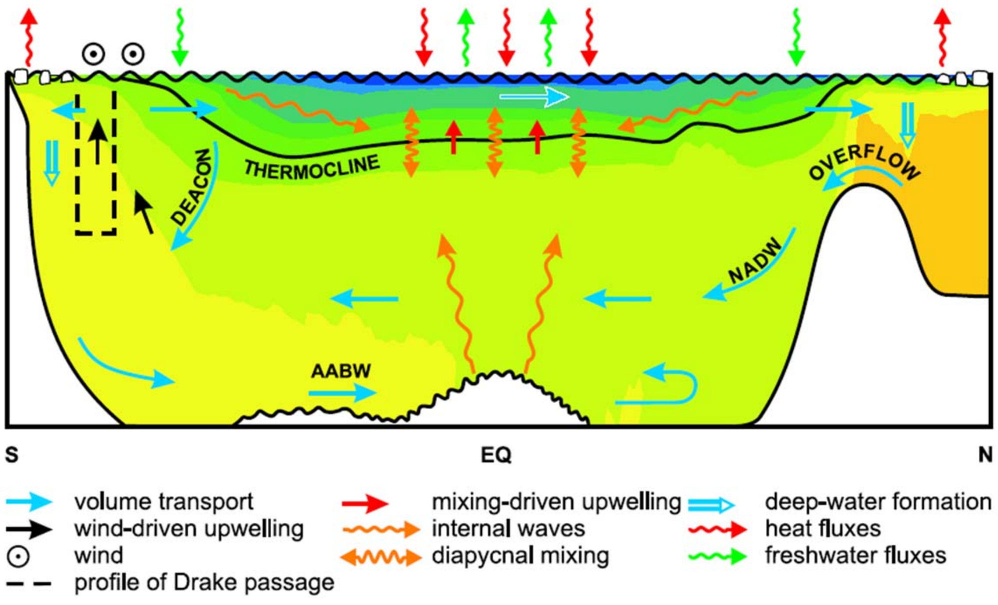
Nordatlantik:	~ 20 Sv
Südatlantik:	~ 20 Sv
Südl. Indischer Ozean	~ 35 Sv
Nordpazifik	~ 30 Sv
Südpazifik	~ 45 Sv
gesamt	~150 Sv

Davon jeweils etwa die
Hälfte durch
Vertikaltransporte und
durch laterale Einträge

Transfer aus der Deckschicht in die Thermokline

Karstensen & Quadfasel, 2002

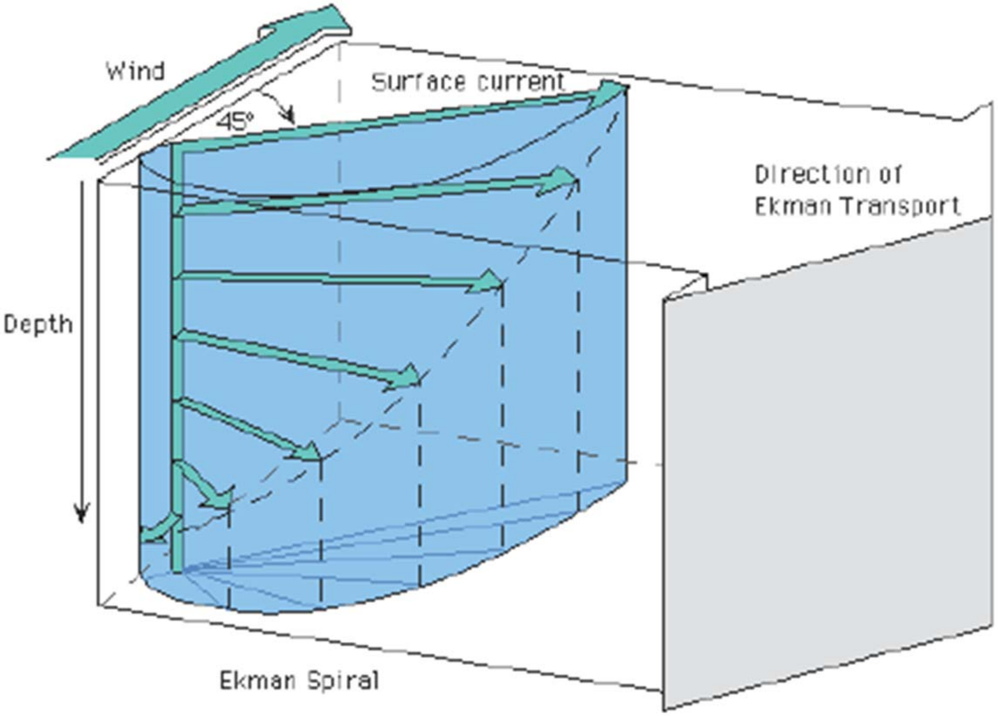
Auftrieb



Wie kommt das subduzierte Wasser wieder zurück in die Deckschicht?

Küstenauftrieb und äquatorialer Auftrieb

Ekman currents



Adapted from Thurman, Harold V. **Essentials of Oceanography, 5th ed.** Prentice-Hall, Inc., 1996.

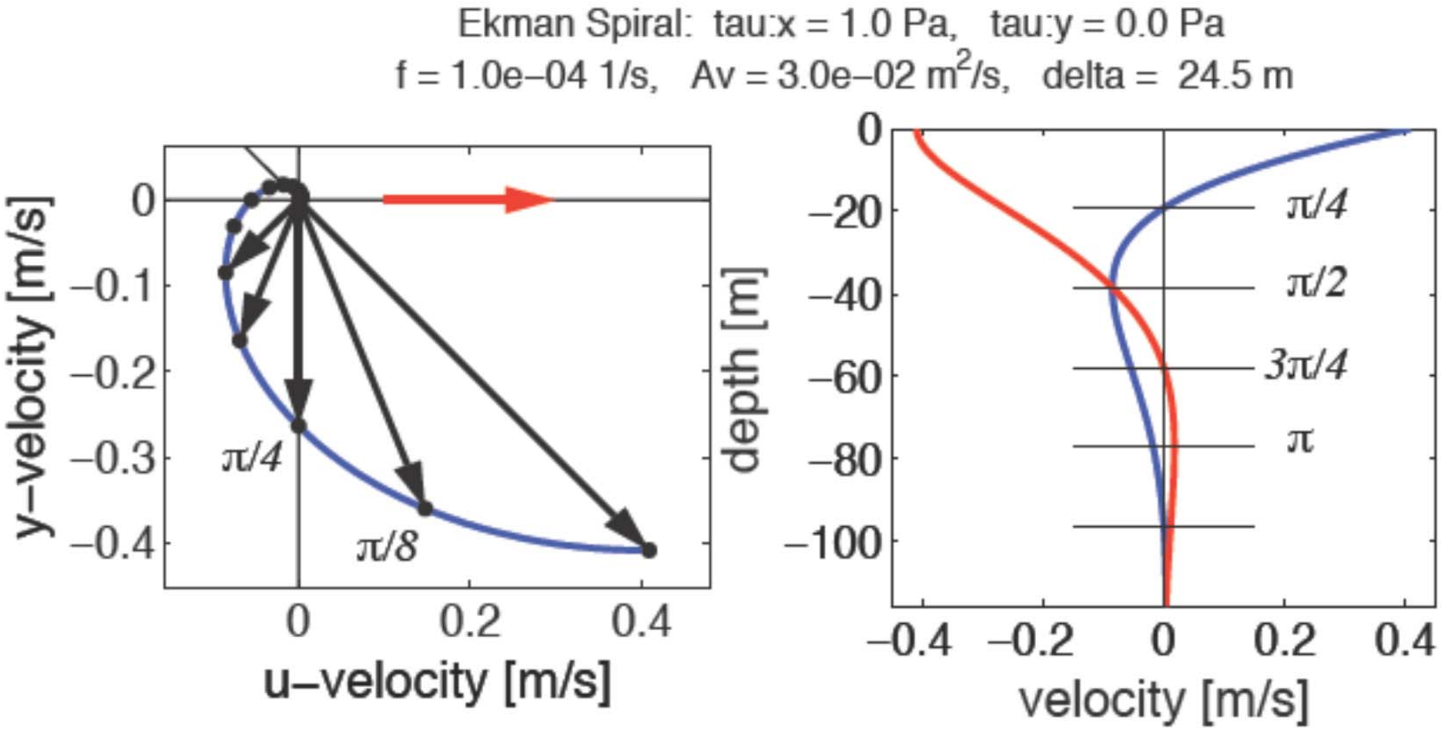
The total transport is the vertical integral of the velocities...

$$U_e = \int_{-\infty}^{0} u_e \, dz = \frac{1}{\rho f} \tau^y \qquad V_e = \int_{-\infty}^{0} v_e \, dz = -\frac{1}{\rho f} \tau^x$$

which is exactly 90 deg to the right of the wind vector.

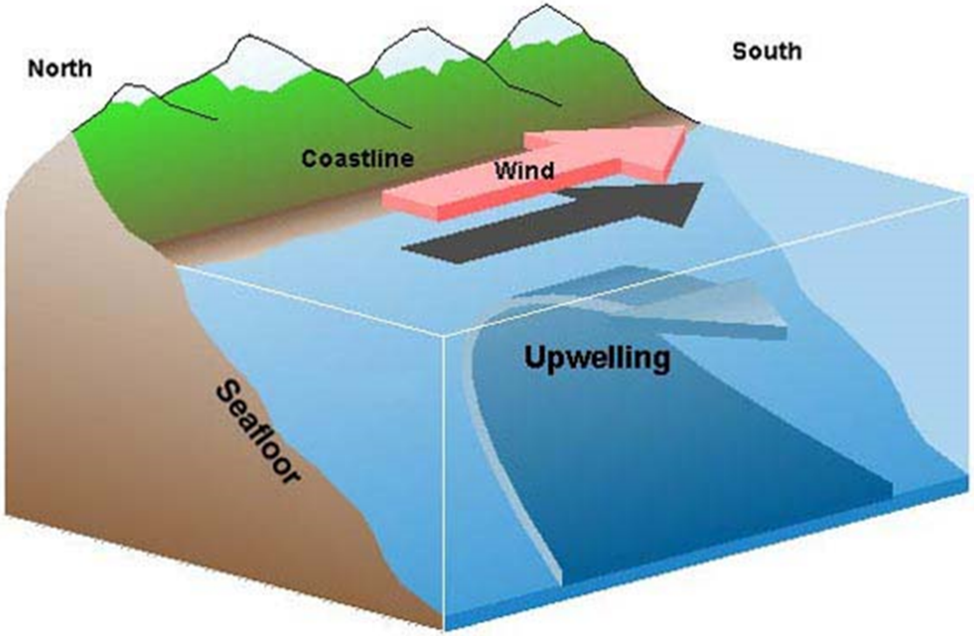
Therman, 1996

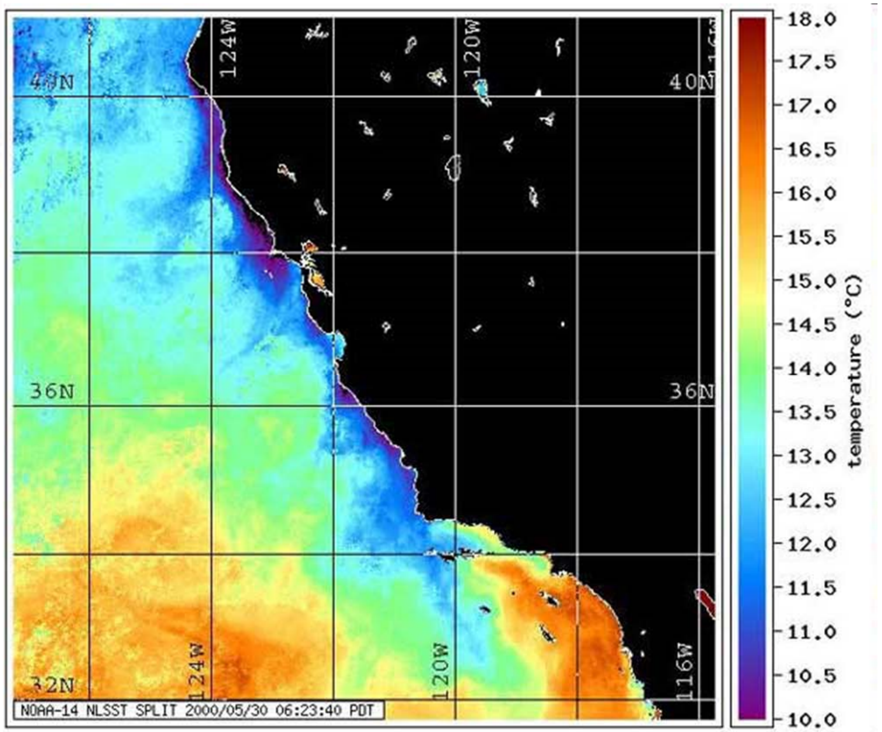
Ekman currents



Prater, 2007

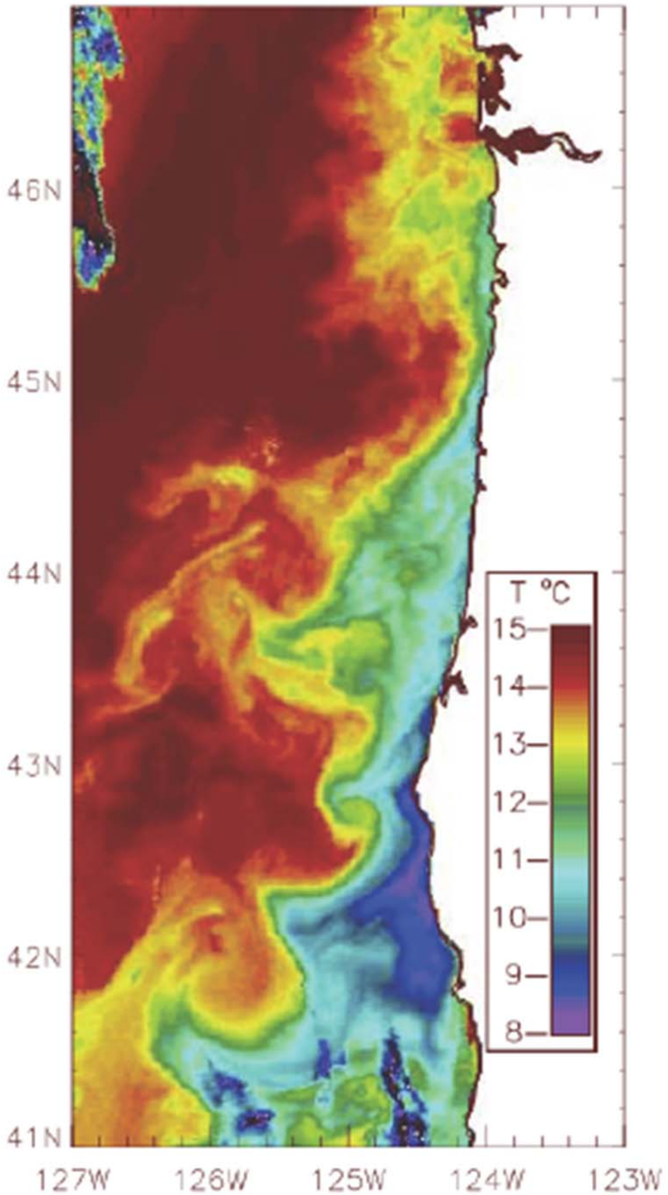
Coastal upwelling

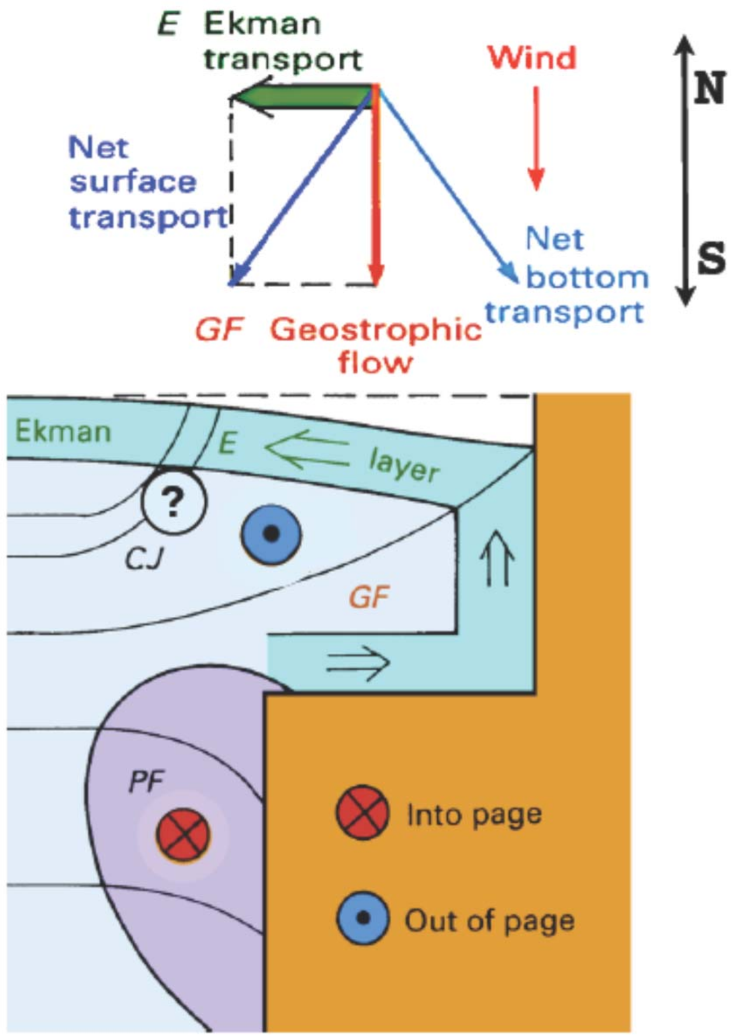




http://oceanexplorer.noaa.gov/

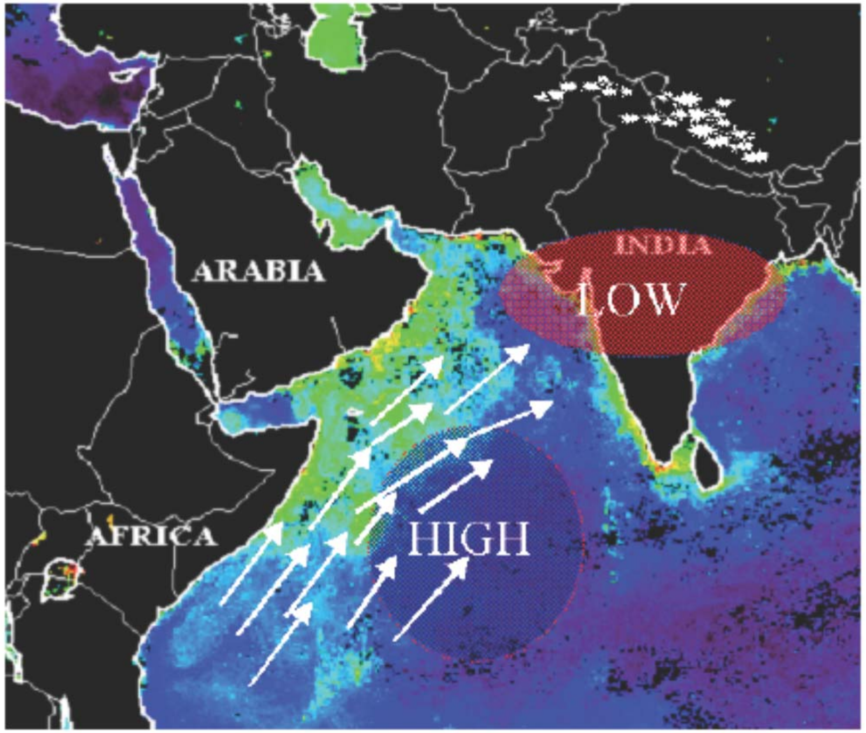
Coastal upwelling



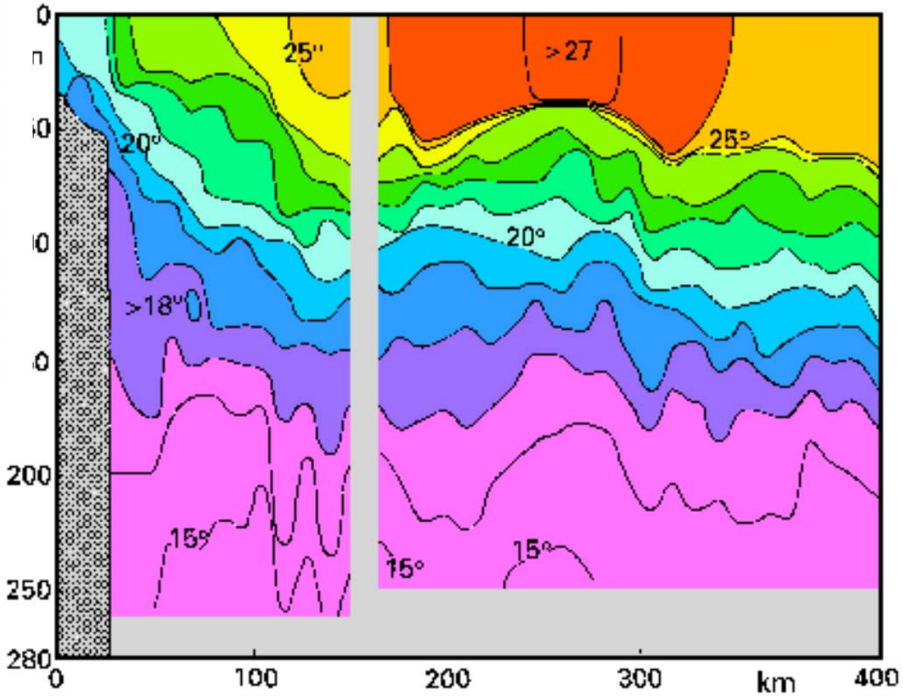


Prater, 2007

Monsoon upwelling

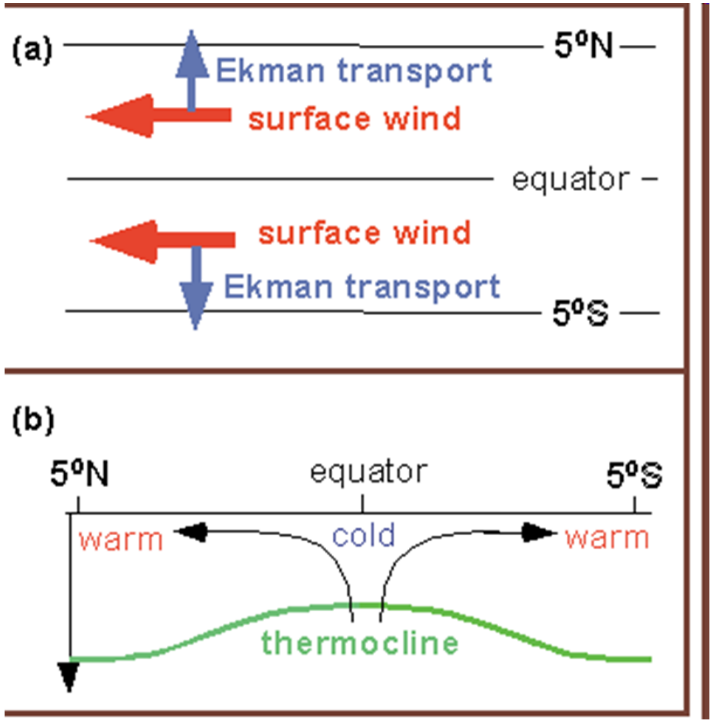


Price, 2001

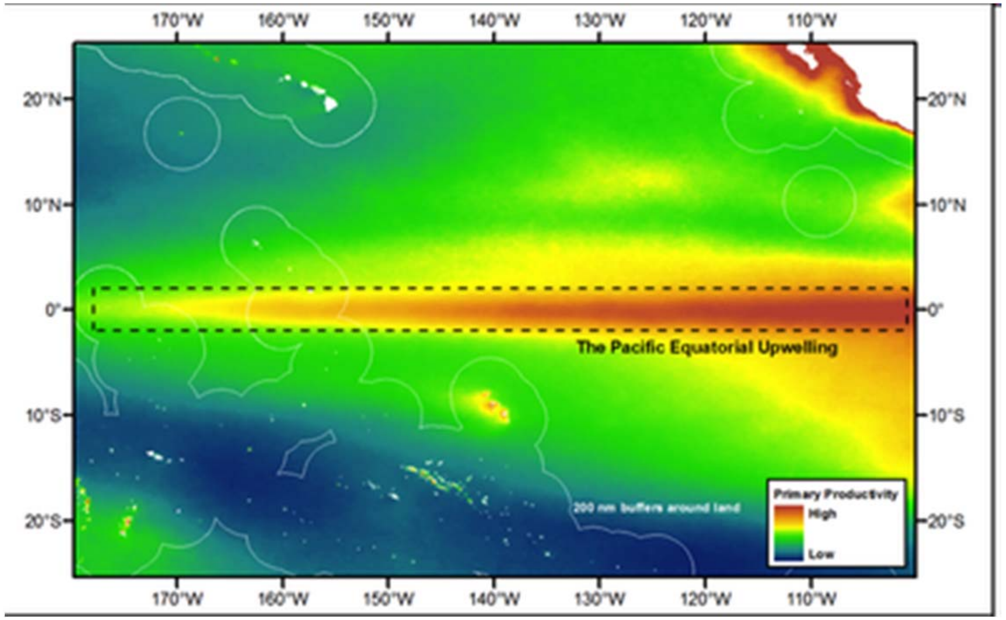


Tomczak & Godfrey, 2004

Equatorial upwelling

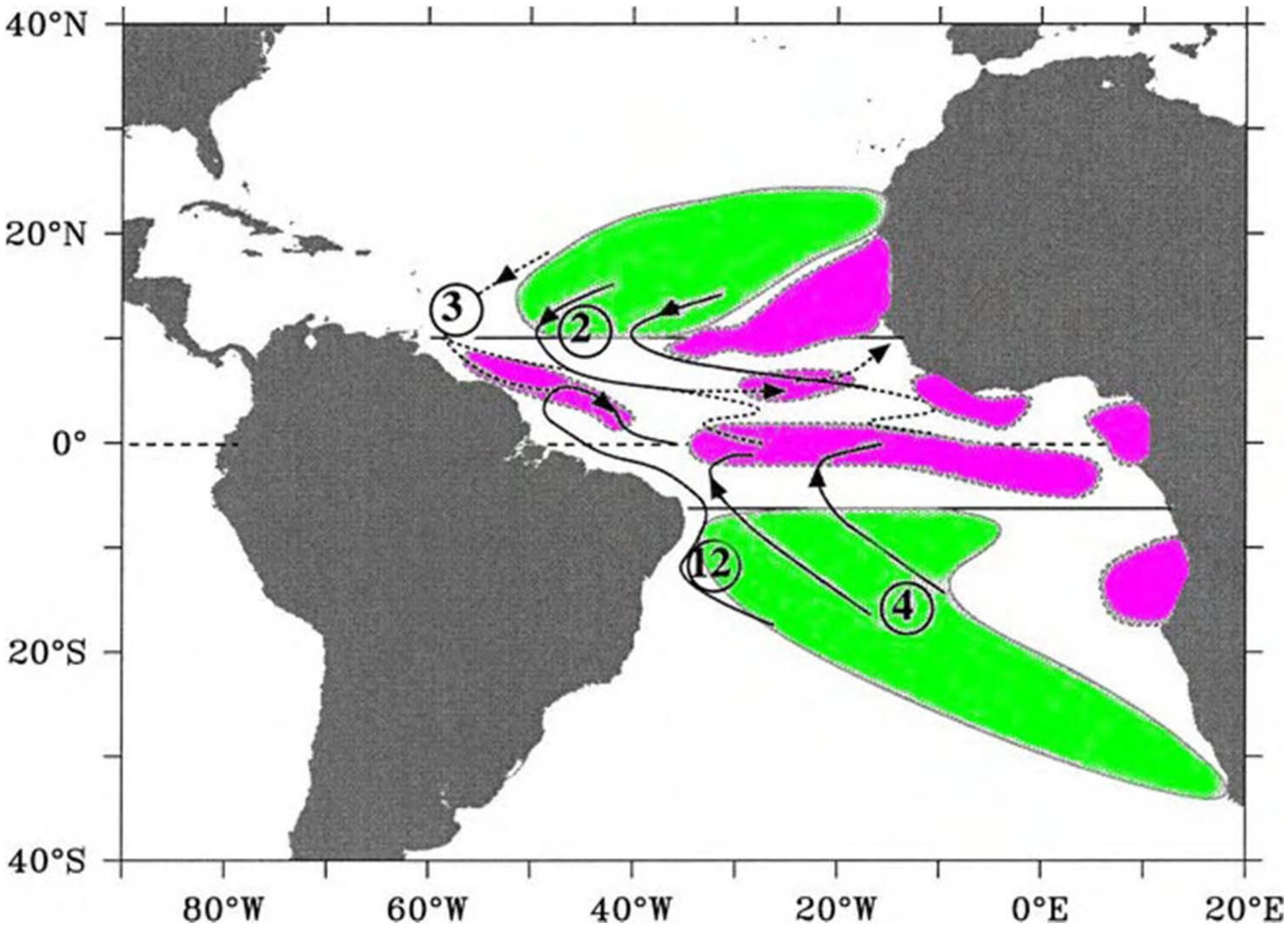


Geerts and E. Linacre , 1998



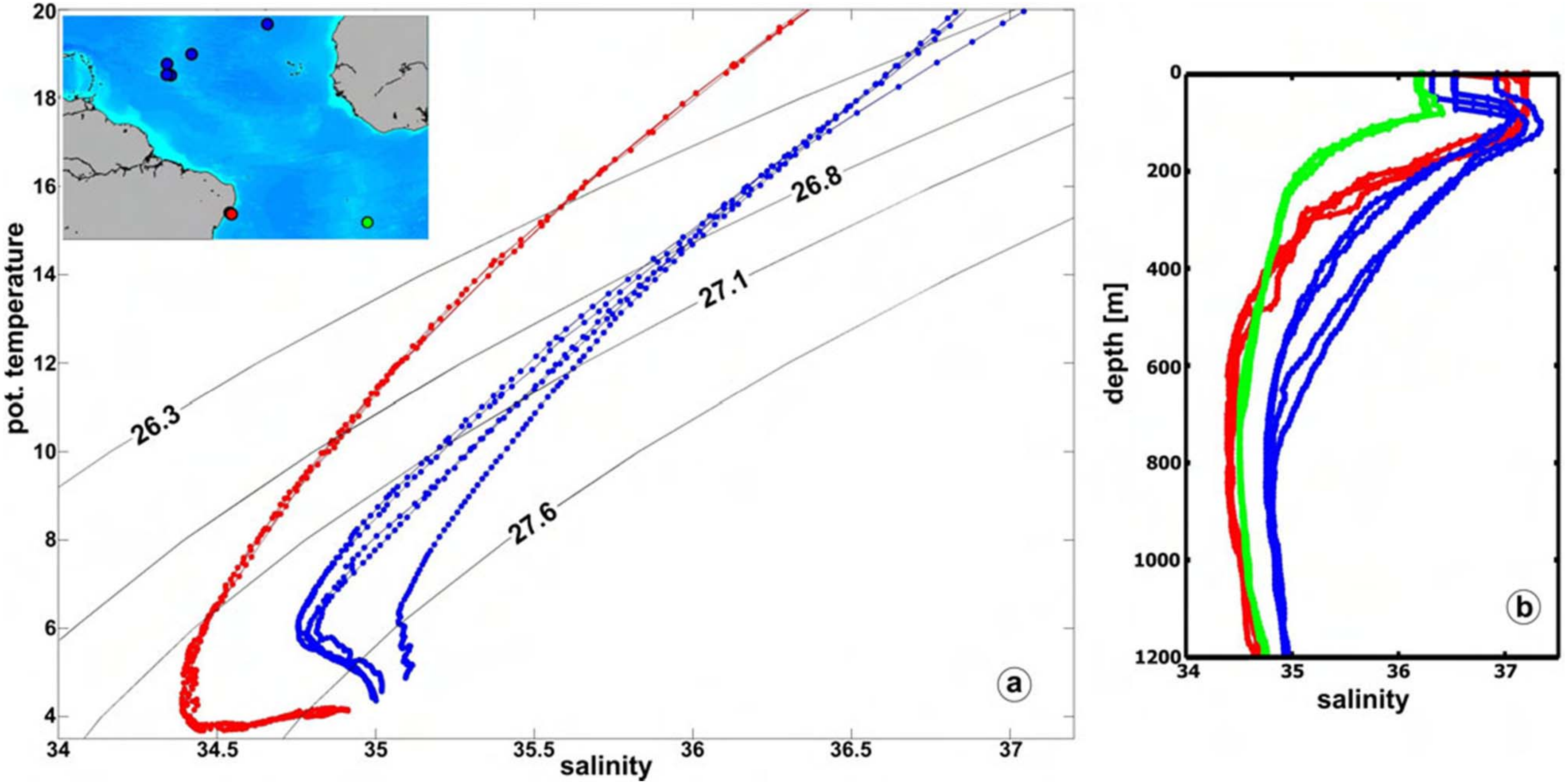
Roberts, http://openoceansdeepseas.org

STC – subtropical-tropical cell



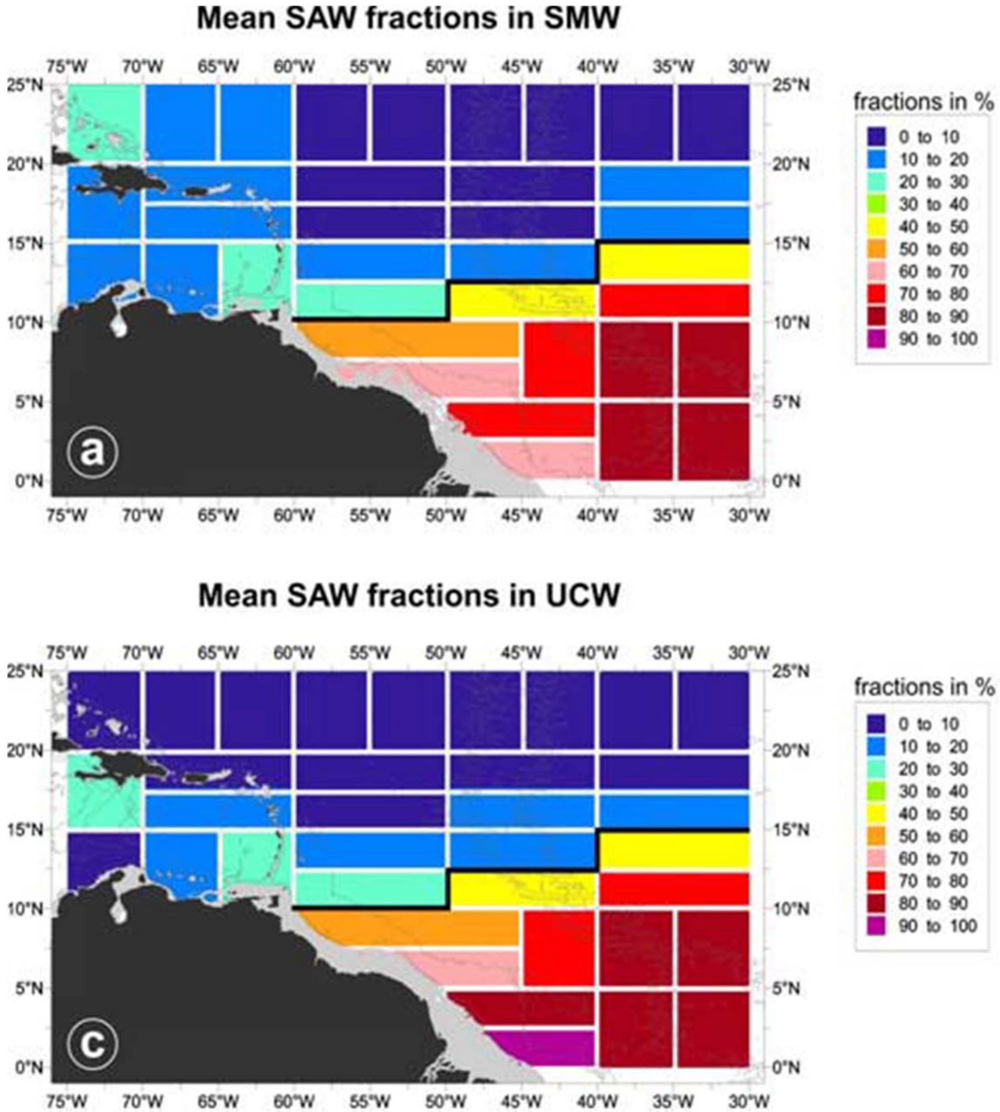
Schematic of the pathways and transports (Sv) of equatorward pycnocline flow from Zhang et al. (2003). Green: subduction areas and potential pathways towards the equator; pink: upwelling regions.

STC – subtropical-tropical cell



a: Examples for temperature and salinity relationships from the North and South Atlantic in 200-1100 m depth (CW and IW), with locations. b: Corresponding salinity profiles, the southern fresher SMW source has been added (green). The profile locations are indicated on the map in a.

STC – subtropical-tropical cell



Mean South Atlantic Water distribution (percent) in the western tropical North Atlantic. (a) SAW distribution in SMW, (c) SAW distribution in UCW. The shelf shallower than 100 m / 200 m is shaded in gray. The black lines indicate the strongest meridional decrease of SAW at the transition region from SAW to NAW. From Kirchner et al., 2009.