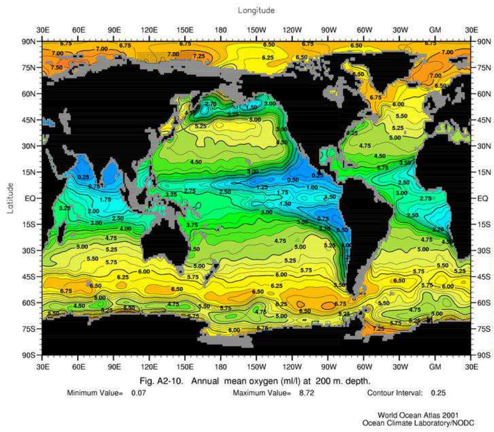
Regionale Ozeanographie

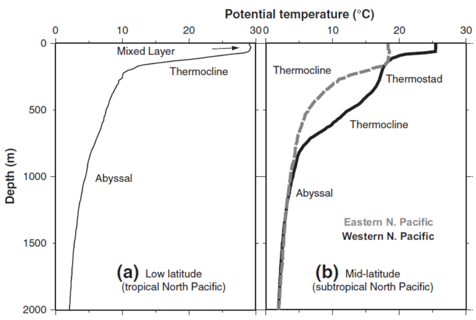
10 – Subduktion und Warmwassersphäre



Literatur:

Pedlosky, J. (1998) Ocean Circulation Theory. Springer, 453 pp.

Schichtung im Ozean



Temperaturschichtung

Talley et al., 2011

Deckschicht ist Schnittstelle zwischen Atmosphäre und Ozean

Fragen und Möglichkeiten

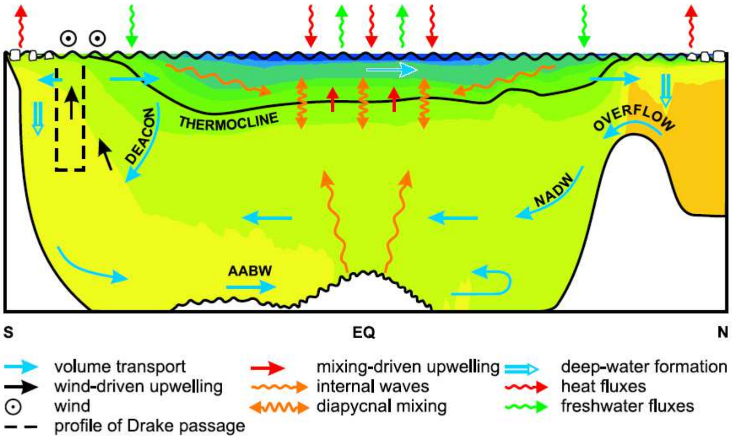
Wie werden die tiefen Schichten des Ozeans ventiliert/erneuert?

Tiefenkonvektion
Ekman Pumping

Welcher Prozess führt zur Ausbildung der Sprungschicht?

Auftrieb von kaltem Tiefenwasser
Vertikale Wärmediffusion
Advektion

Ventilation des Ozeans



Equations of motion

Auftrieb von Tiefenwasser -- vertikale Diffusion

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

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

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

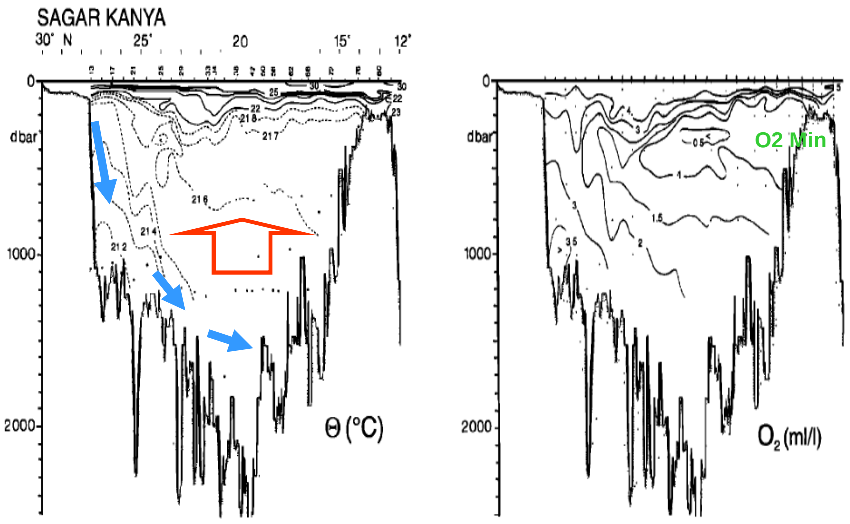
$$\text{continuity:}\quad \frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0,$$

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

Advektions-Diffusionsgleichung

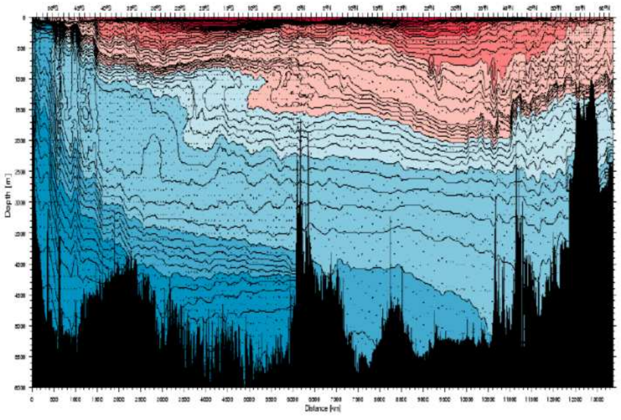
Cushman-Roisin, 1994

Ventilation im Roten Meer



Woelk & Quadfasel, 1996

Atlantic temperatures



Mixed layer
Seasonal thermocline

Main thermocline

Deep water

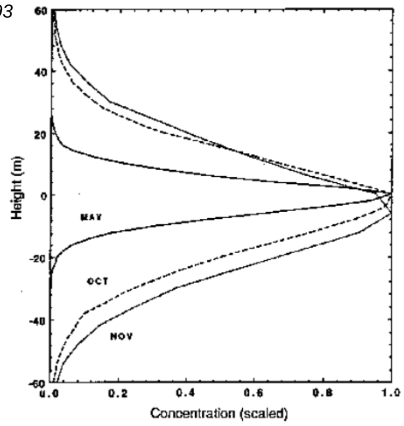
WOCE Atlas, 2001

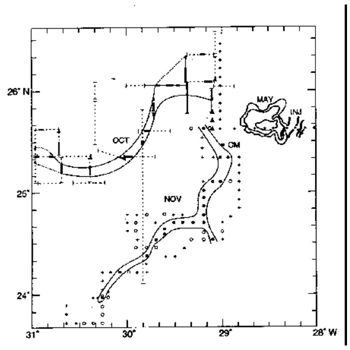
Tracer experiment - mixing estimates

Evidence for slow mixing across the pycnocline from an open-ocean tracer-release experiment

James R. Ledwell*, Andrew J. Watson† & Clifford S. Law†

Nature, 1993

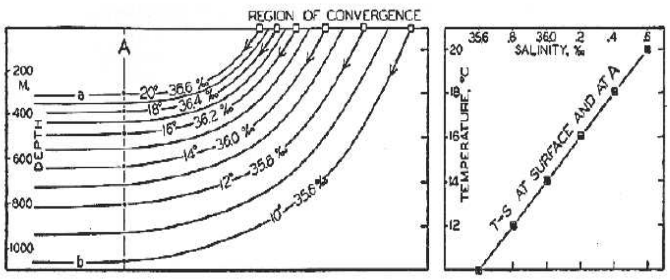




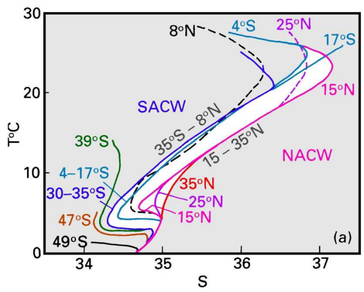
Diapycnal diffusivity

0.1 ± 0.02 cm^2/s

Subduction



Montgomery, 1938



Tomczak & Godfrey, 2004

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

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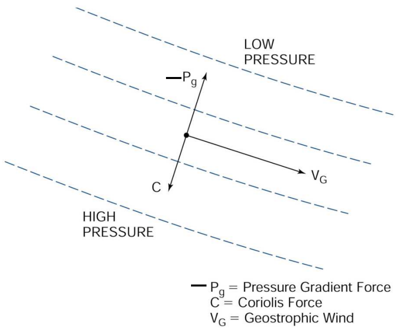
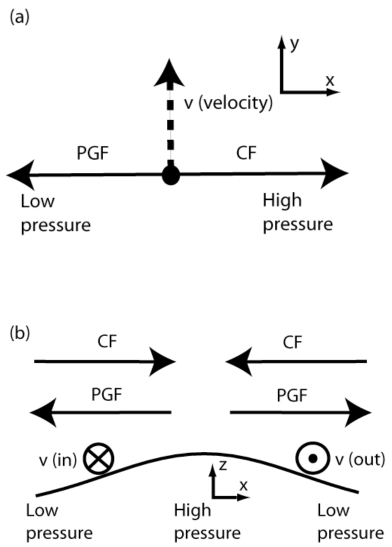
Geostrophic balance R_o=0, **$R_o > 0$**

Cushman-Roisin, 1994

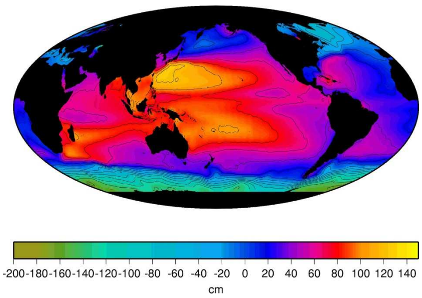
Geostrophy - interior ocean





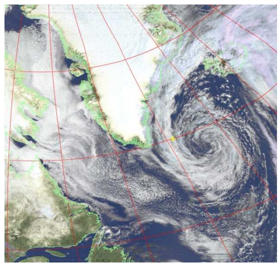
Talley, 2010

Geostrophy

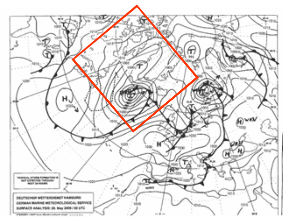


SSH from TOPEX

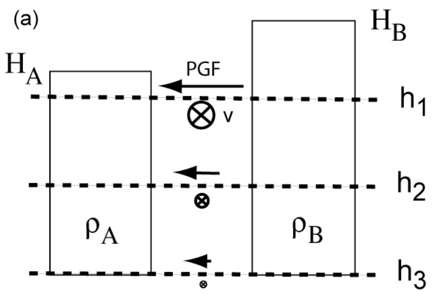
Steward, 2008



Satellite image for May 28th

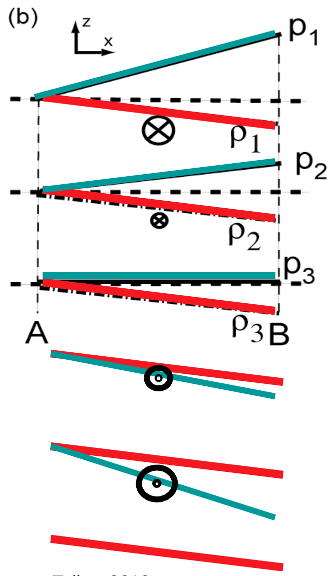


Geostrophy



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

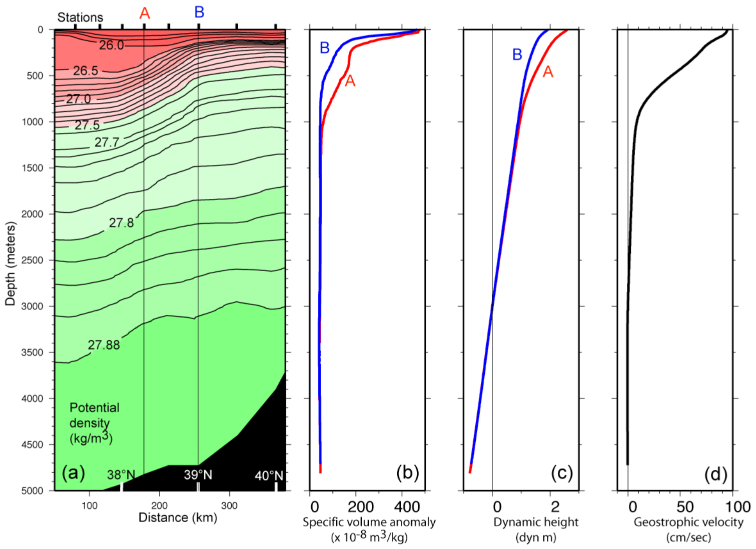
$\Delta D = -\Delta\Phi / 10 = - \int \delta \, dp \, /10$ dynamic height

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

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

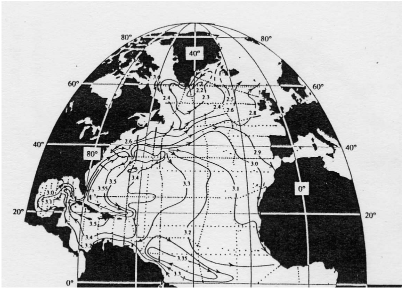
Talley, 2010

Geostrophy



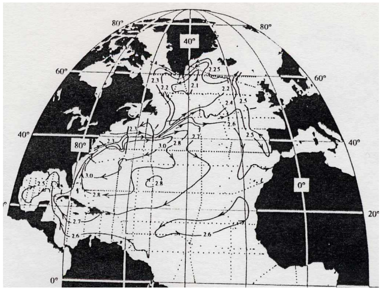
Talley, 2010

Geostrophy



Dynamic height

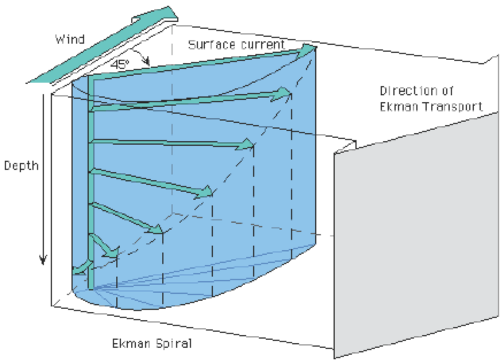
0/2000 dbar



250/2000 dbar

Reid, 1994

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.

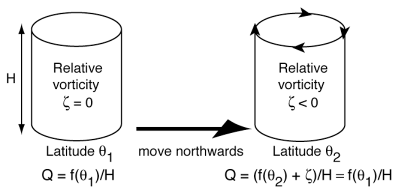
Therman, 1996

Conservation of potential vorticity

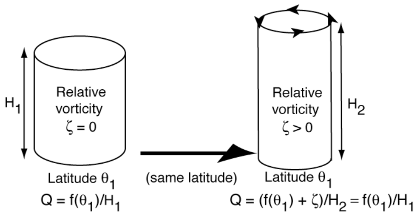
conservation of angular momentum,

Potential vorticity $Q = (f + \zeta)/H$

1. Vorticity ("relative vorticity" ζ) due to fluid circulation
2. Vorticity ("planetary vorticity" f) due to earth rotation, depends on local latitude when considering local vertical column
3. Stretching 1/H due to fluid column stretching or shrinking



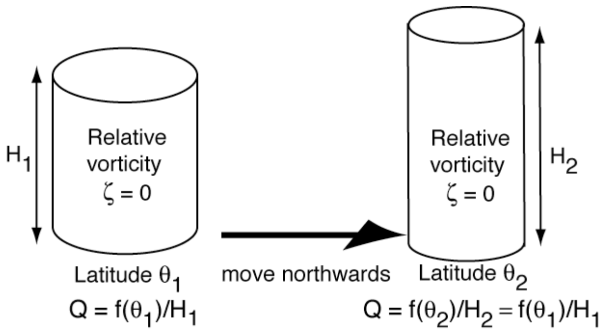
Conservation of potential vorticity Q in the absence of stretching (northern hemisphere): balance of planetary vorticity and relative vorticity



Conservation of potential vorticity Q in the absence of planetary vorticity change (northern hemisphere): balance of relative vorticity and stretching

Talley, 2010

Conservation of potential vorticity - Sverdrup circulation



Conservation of potential vorticity Q in the absence of relative vorticity (northern hemisphere): balance of planetary vorticity and stretching

Prater, 2007

Ekman pumping

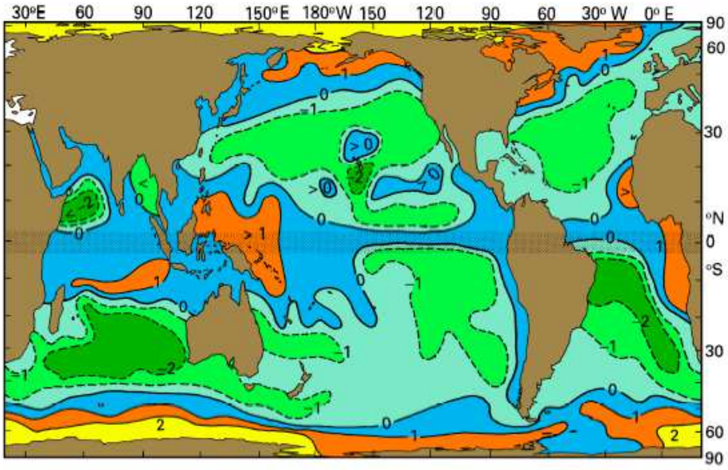
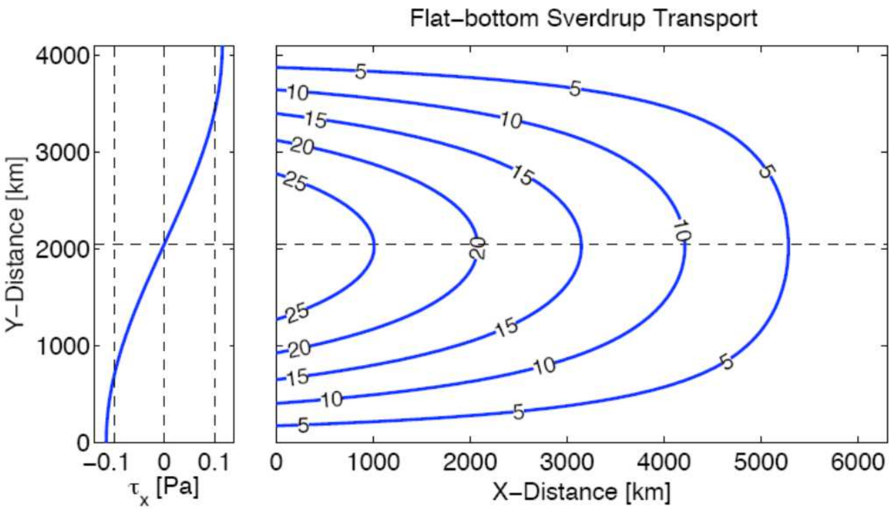


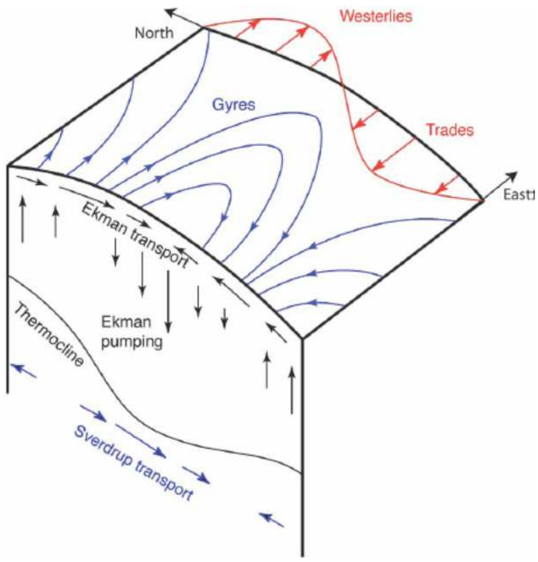
Fig. 4.3. Annual mean distribution of curl(τ/f), or Ekman pumping, calculated from the distribution of Fig. 1.4 (10^{-3} kg m^2 s^{-1}). Positive numbers indicate upwelling. In the equatorial region (2°N - 2°S, shaded) curl(τ/f) is not defined; the distribution in this region is inferred from the dynamical arguments of Fig. 4.1 and is not quantitative.

Subtropical Sverdrup gyre



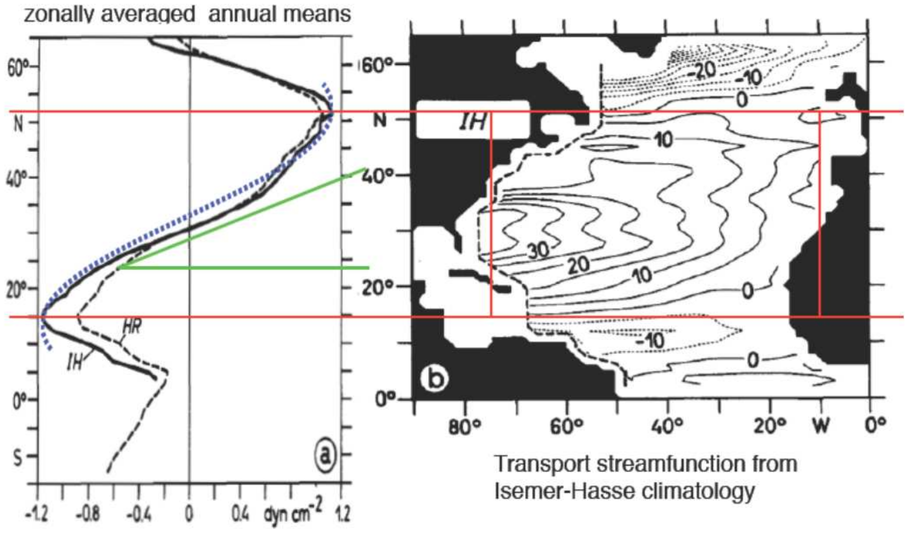
Prater, 2007

Ekman pumping and Sverdrup circulation



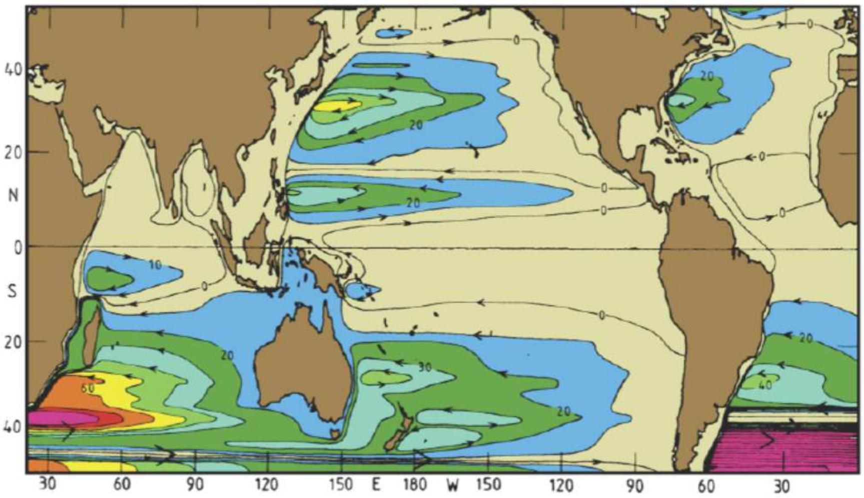
Prater, 2007

North Atlantic Sverdrup gyre



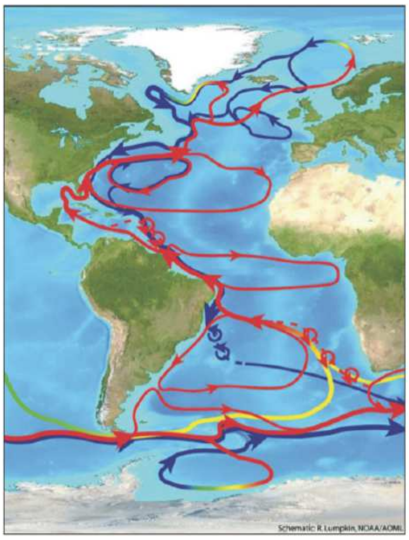
Prater, 2007

Global Sverdrup circulation



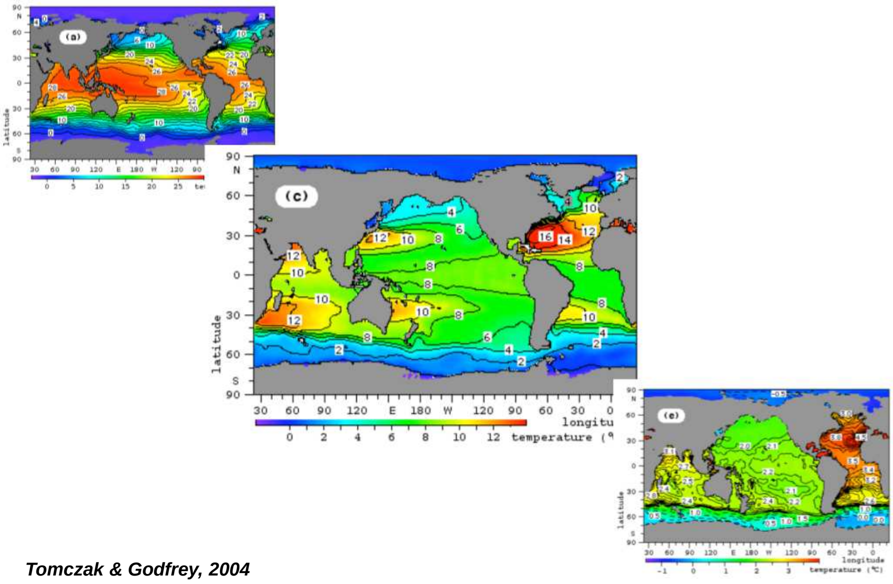
Tomczak and Godfrey, 2001

Atlantic upper ocean circulation



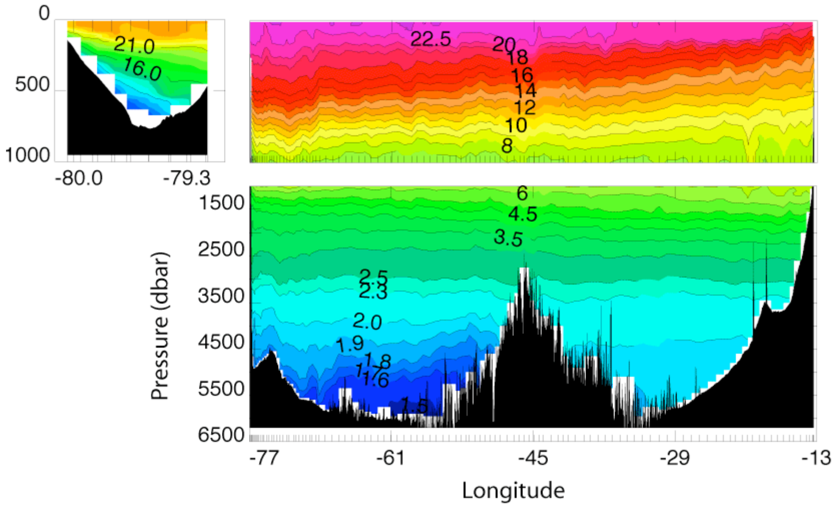
Schmitz and McCartney

Temperature at surface, 500 and 2000 m



Tomczak & Godfrey, 2004

E-W Section at 25° N



UK Rapid RRS Discovery cruise D279, 2004

Ventilation

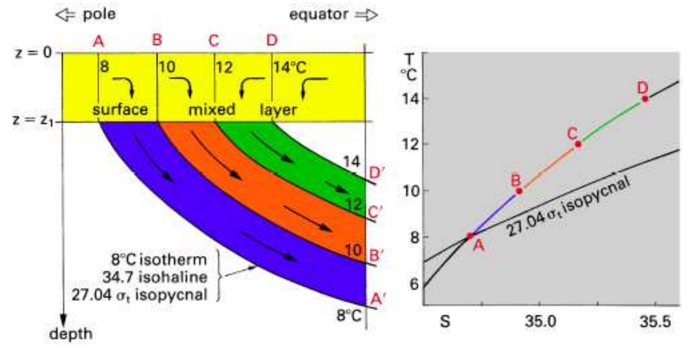
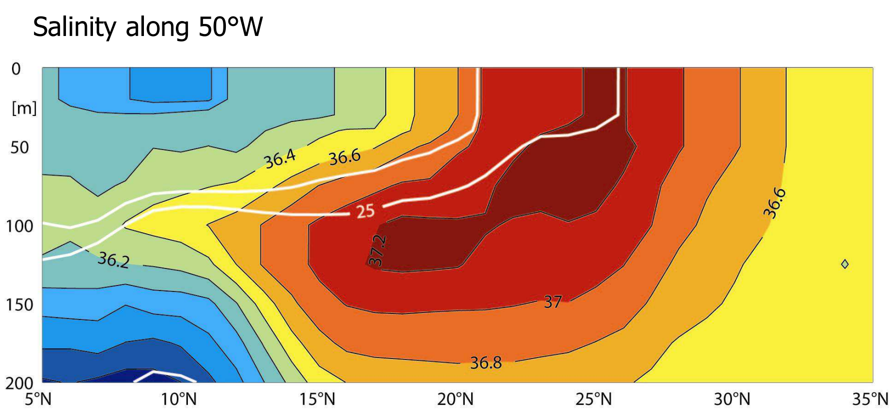


Fig. 5.3. Sketch of water mass formation by subduction in the Subtropical Convergence. The T-S diagram shows both the meridional variation of temperature and salinity between stations *A* and *D*, and the vertical variation equatorward of station *D* from the surface down along the line *A'B'C'D'*. For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

Price, 2001

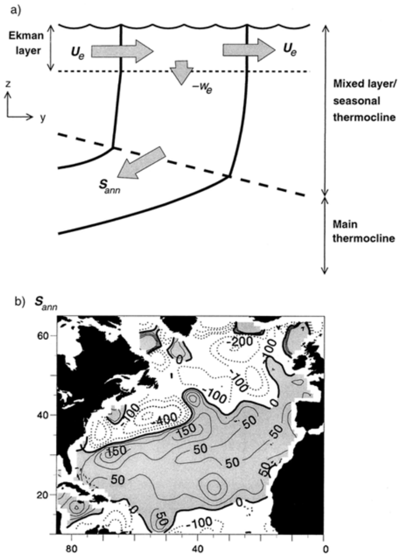
Subtropical underwater



- **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.**

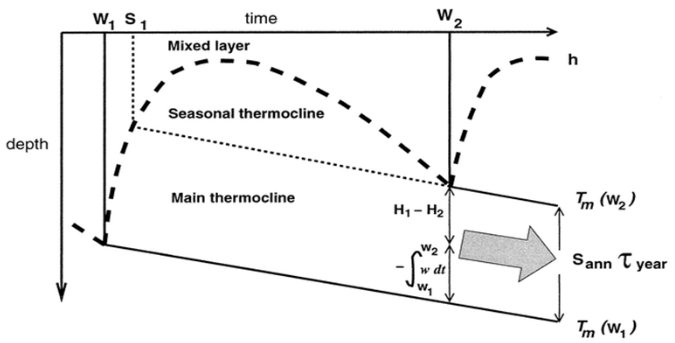
Karstensen, 2007

Subduction



Marshall, 1986

Subduction

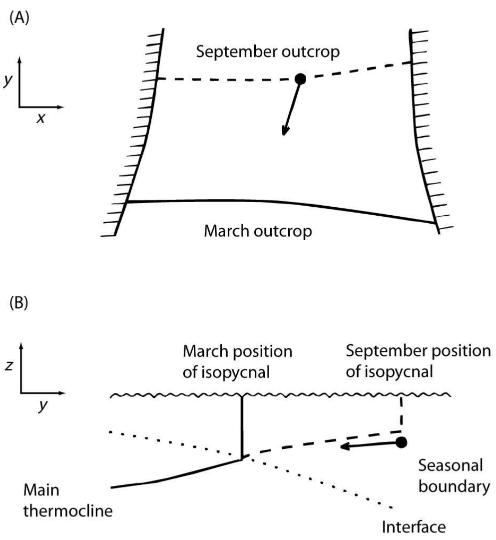


$$S_{ann} = -\overline{\left(w_{Ek} - \frac{\beta}{f}\int_{-h_m}^{0} v_m\, dz\right)} + \overline{\mathbf{u}_m \cdot \nabla h_m},$$

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.

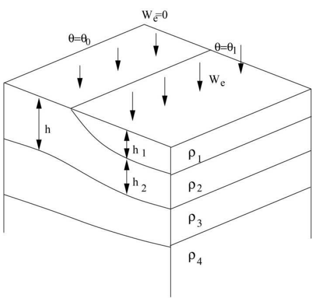
Williams et al., 1995

Stommel's demon



Williams et al., 1995

Ventilated thermocline

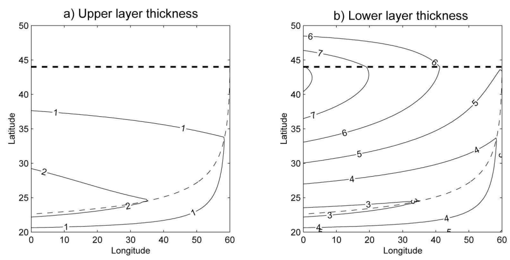


First Model by Luyten, Pedlosky, Stommel (1983)

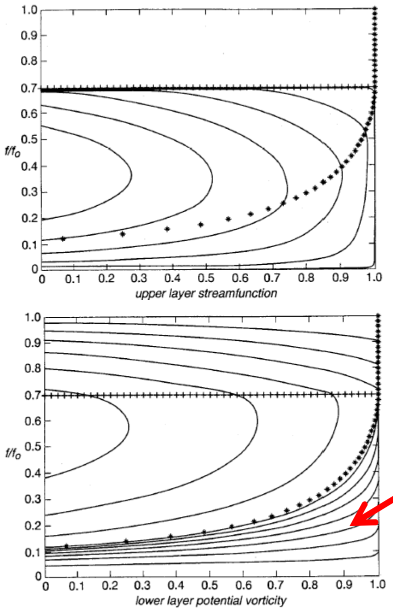
Assumptions made:

- 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

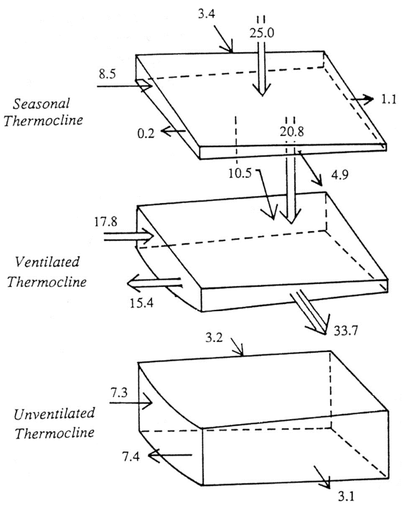
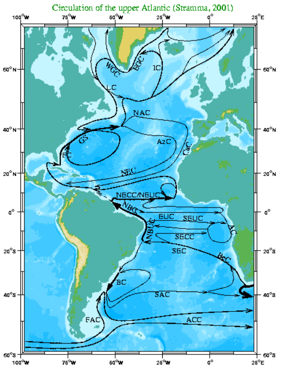
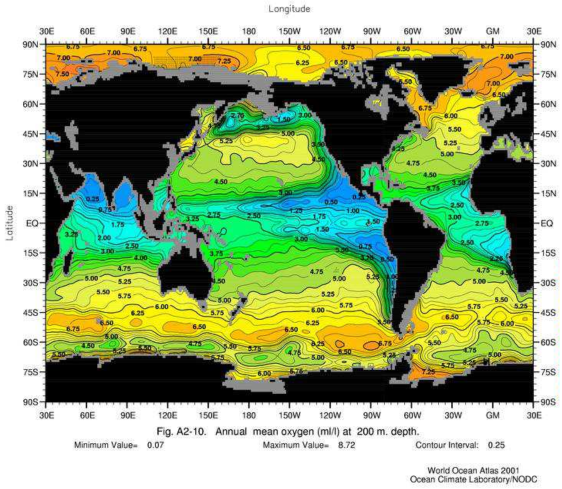


Fig. 5.3.4 Mass fluxes (units of Sverdups) between layers of the North Pacific thermocline indicated. The northern boundary is to the top, and the Ekman pumping is shown as the downward-directed double arrow. From Huang and Russell (1995), Fig. 12.

Huang & Russel, 1995

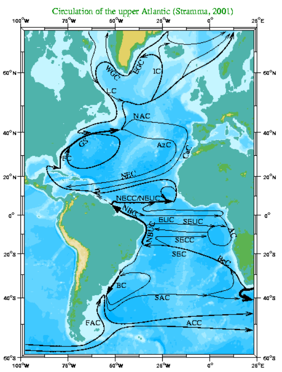
Shadow zones - Oxygen 200 m

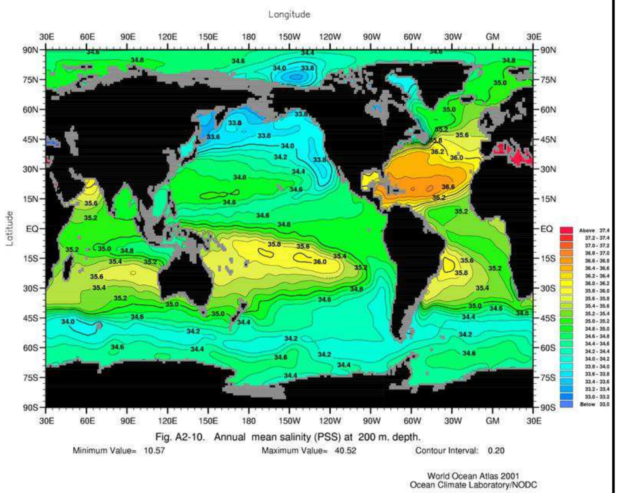




Karstensen, 2007

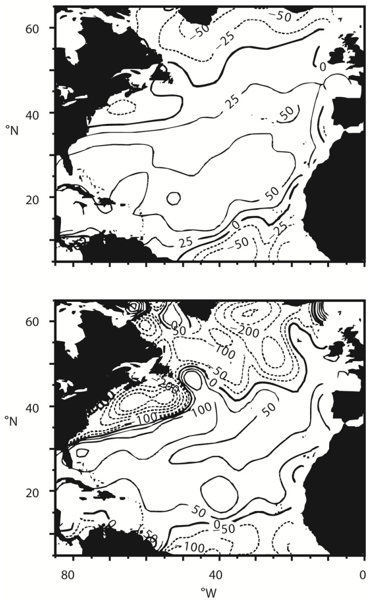
Shadow zones - Salinity 200 m





Karstensen, 2007

Subduction rates



Mixed layer depth April

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

Annual subduction rates

Marshall et al., 1993

Globale Subduktionsraten

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

Ekman Pumping

Sverdruptransport
in der Deckschicht

Lateraler Eintrag durch
geneigt Bodenfläche
der Deckschicht

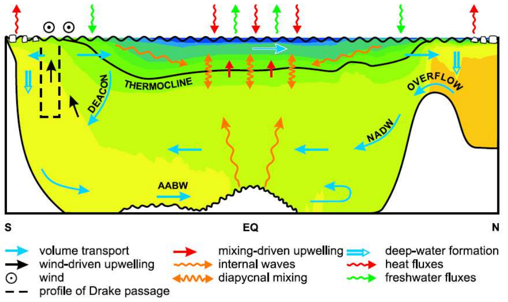
Nordatlantik:	~ 20 Sv
Südatlantik:	~ 20 Sv
Südl. Indischer Ozean	~ 35 Sv
Nordpazifik	~ 30 Sv
Südpazifik	~ 45 Sv
gesamt	~150 Sv

Davon jeweils etwa die Hälfte durch Vertikaltransporte und durch laterale Einträge

Transfer aus der Deckschicht in die Thermokline

Karstensen & Quadfasel, 2002

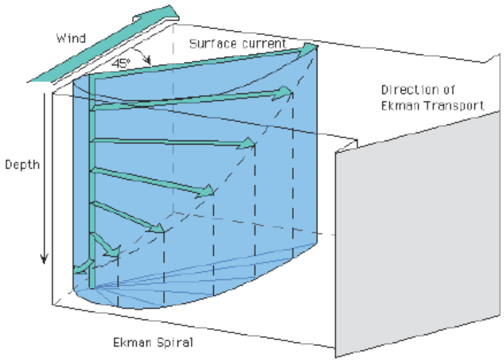
Auftrieb



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.

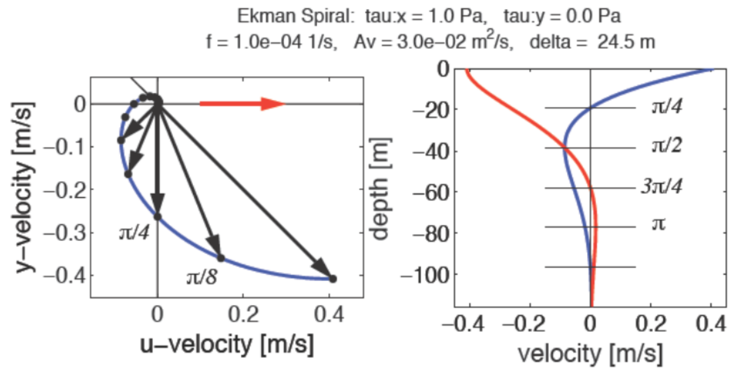
The total transport is the vertical integral of the velocities...

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

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

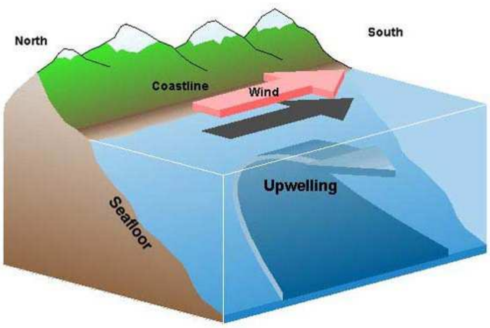
Therman, 1996

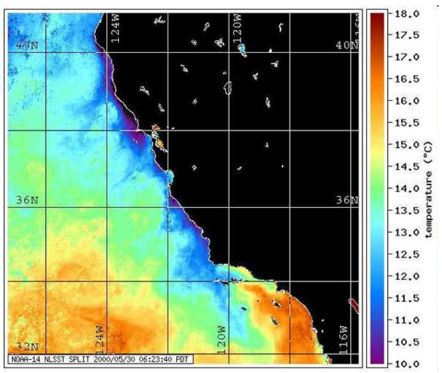
Ekman currents



Prater, 2007

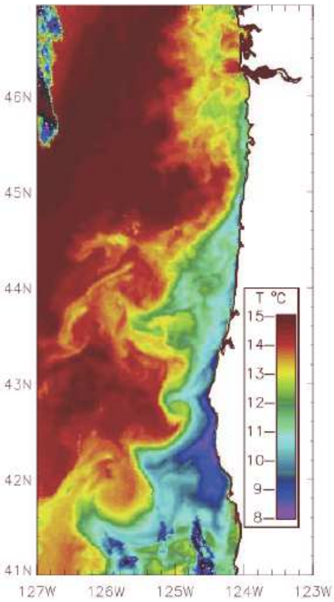
Coastal upwelling

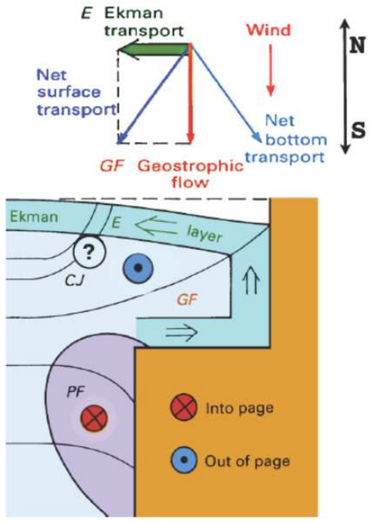




http://oceanexplorer.noaa.gov/

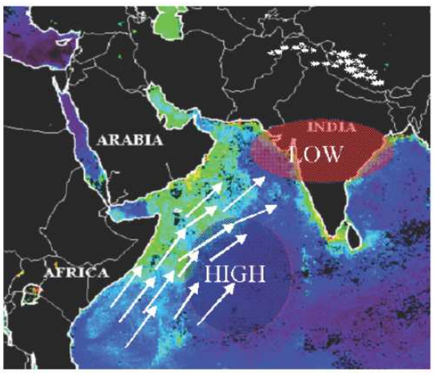
Coastal upwelling



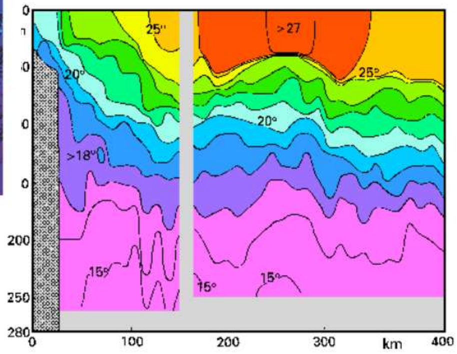


Prater, 2007

Monsoon upwelling

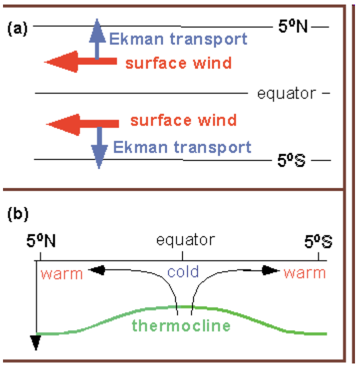


Price, 2001

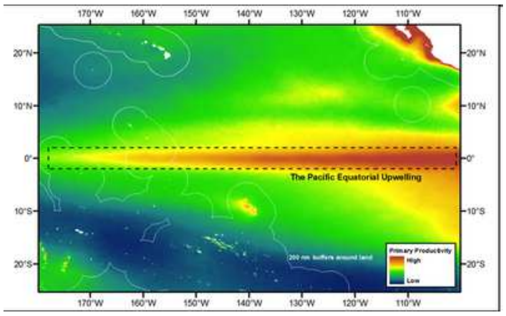


Tomczak & Godfrey, 2004

Equatorial upwelling



Geerts and E. Linacre , 1998



Roberts, http://openoceansdeepseas.org