Winds, Ekman, and the Wind-Driven Circulation

AOS 660, Fall 2013

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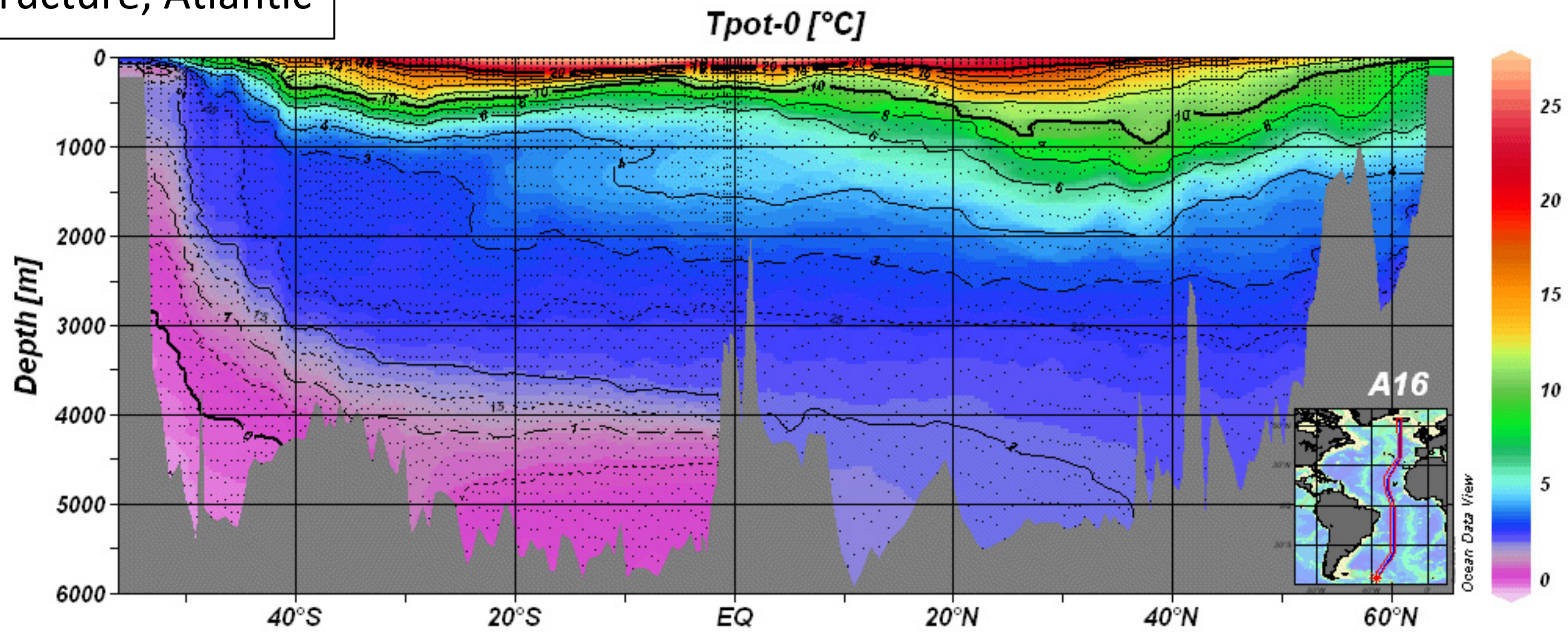
Ocean general circulation

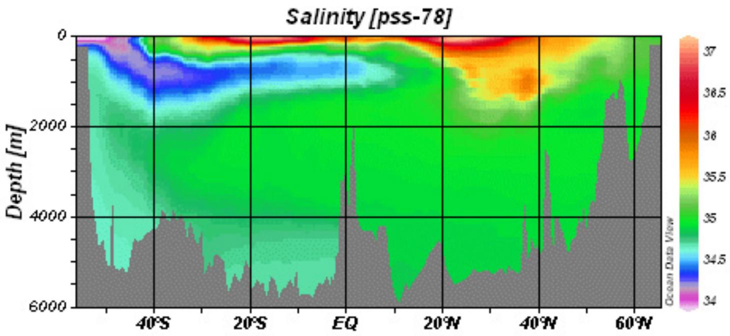
Ocean Circulation
Three key divisions in space and time

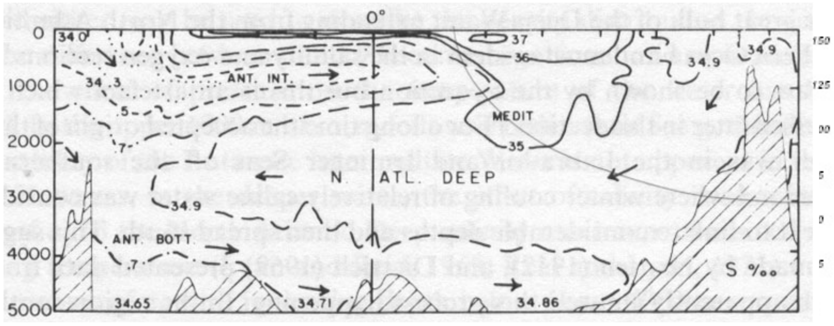
1. Ekman circulation / Surface
   - Short timescales (daily to seasonal)
   - Surface 50-200, dependent on strength of stratification
2. Wind-driven circulation / Thermocline
   - Intermediate timescales (decadal)
   - Surface to ~1000m
3. Thermohaline circulation / Abyss
   - Long timescales (1000 year)
     - Deep ocean, ~1000-4500m

Thermohaline / Overturning

Temperature, Salinity
Depth Structure, Atlantic

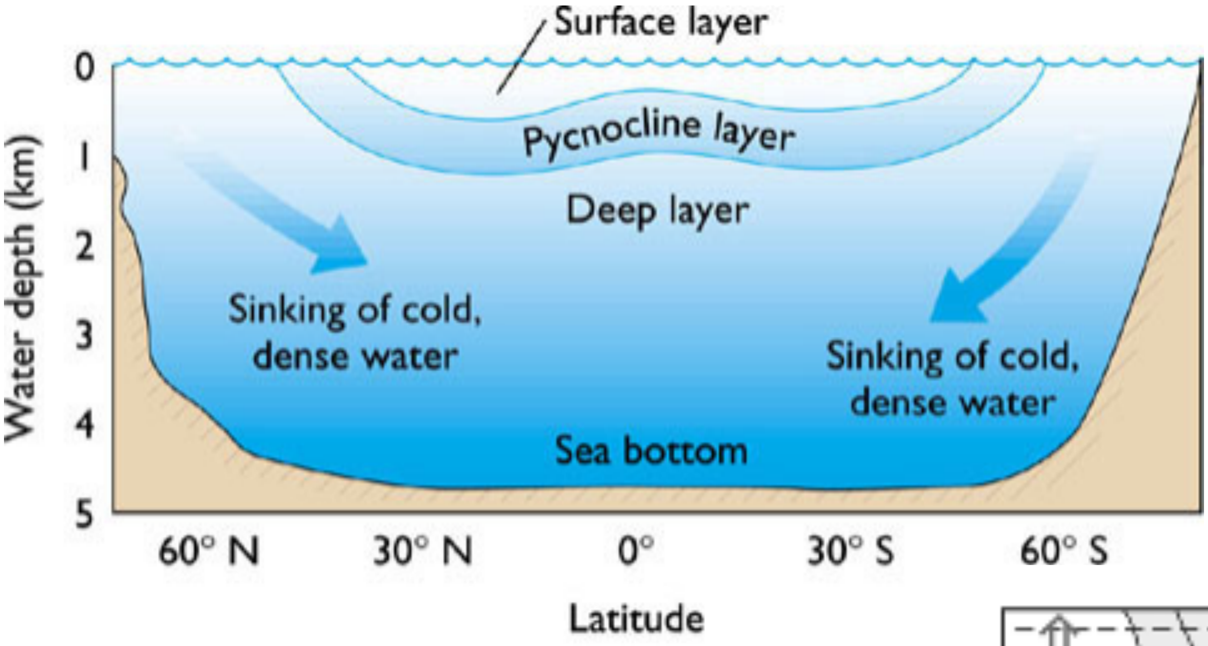




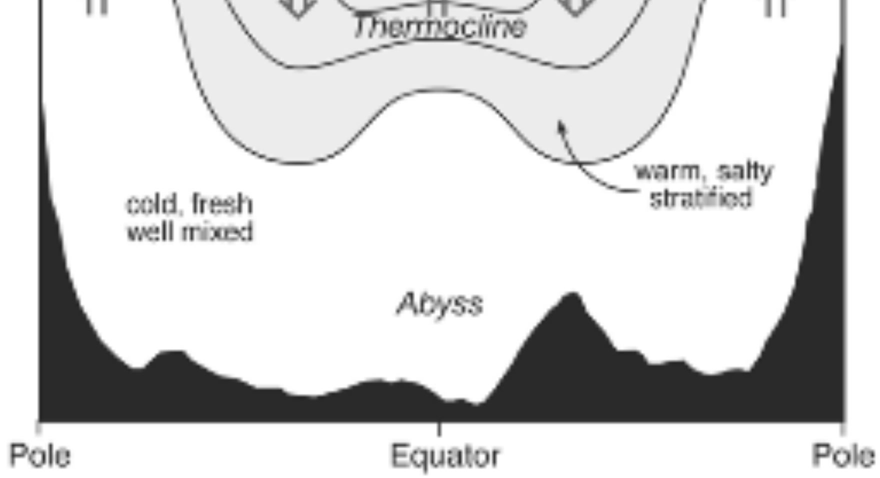


PE 7.15b

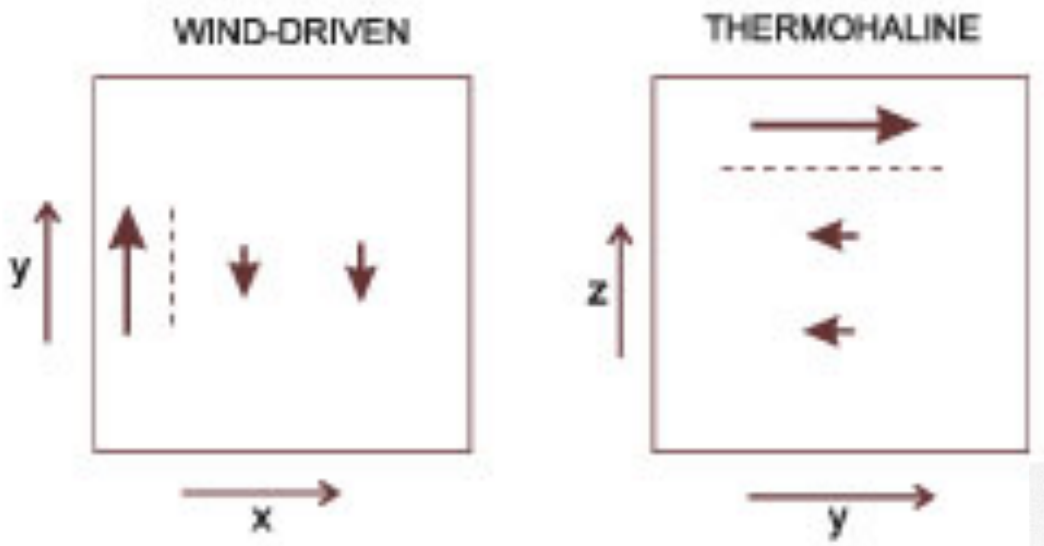
Density Cross-Section



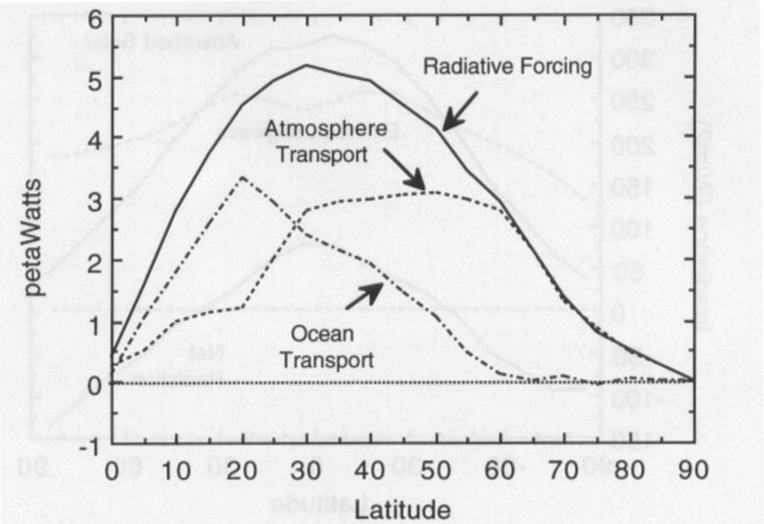
TAMU Oceanography



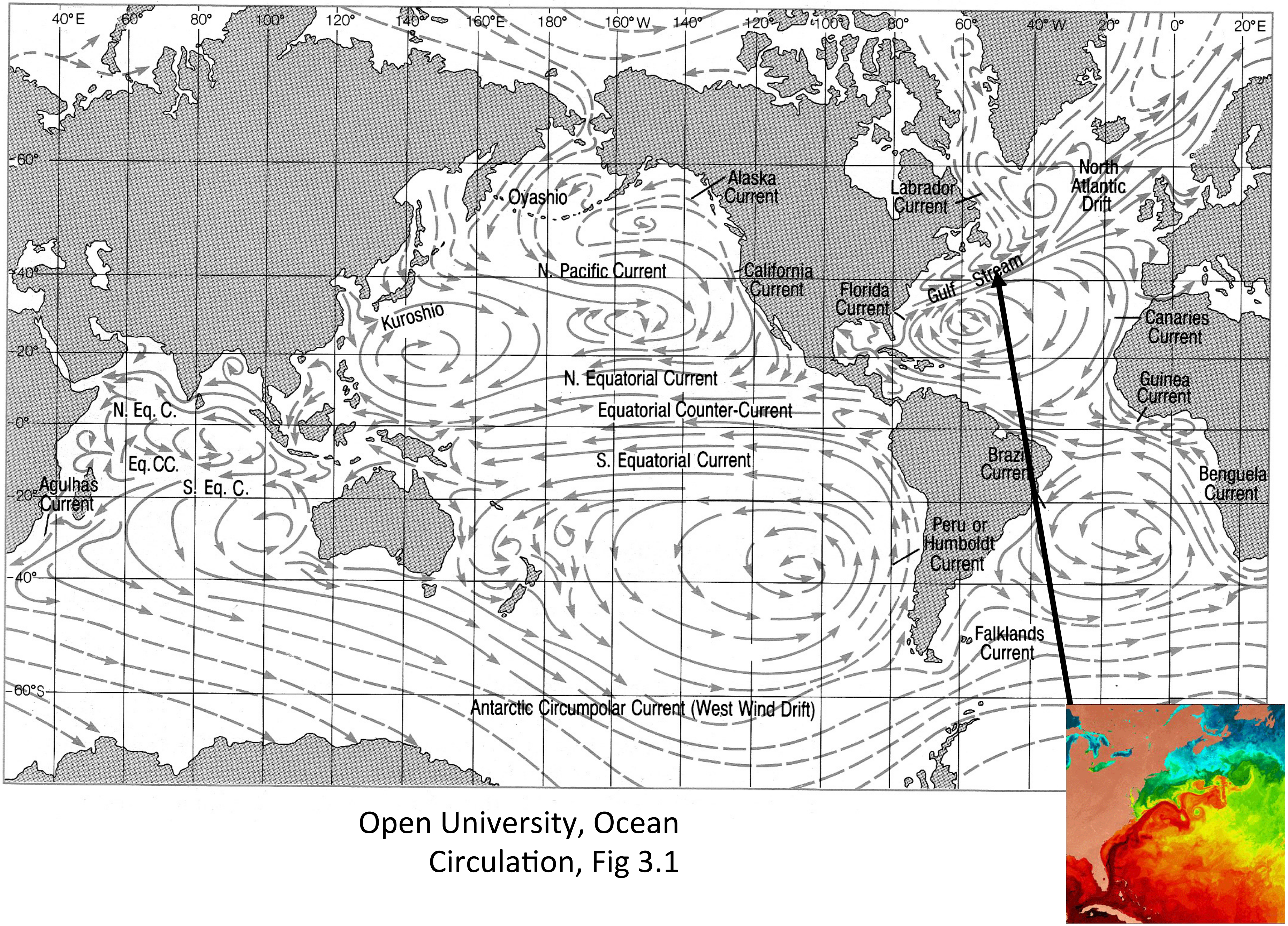
Heat Transport in Ocean



Marshall and Plumb, 2003

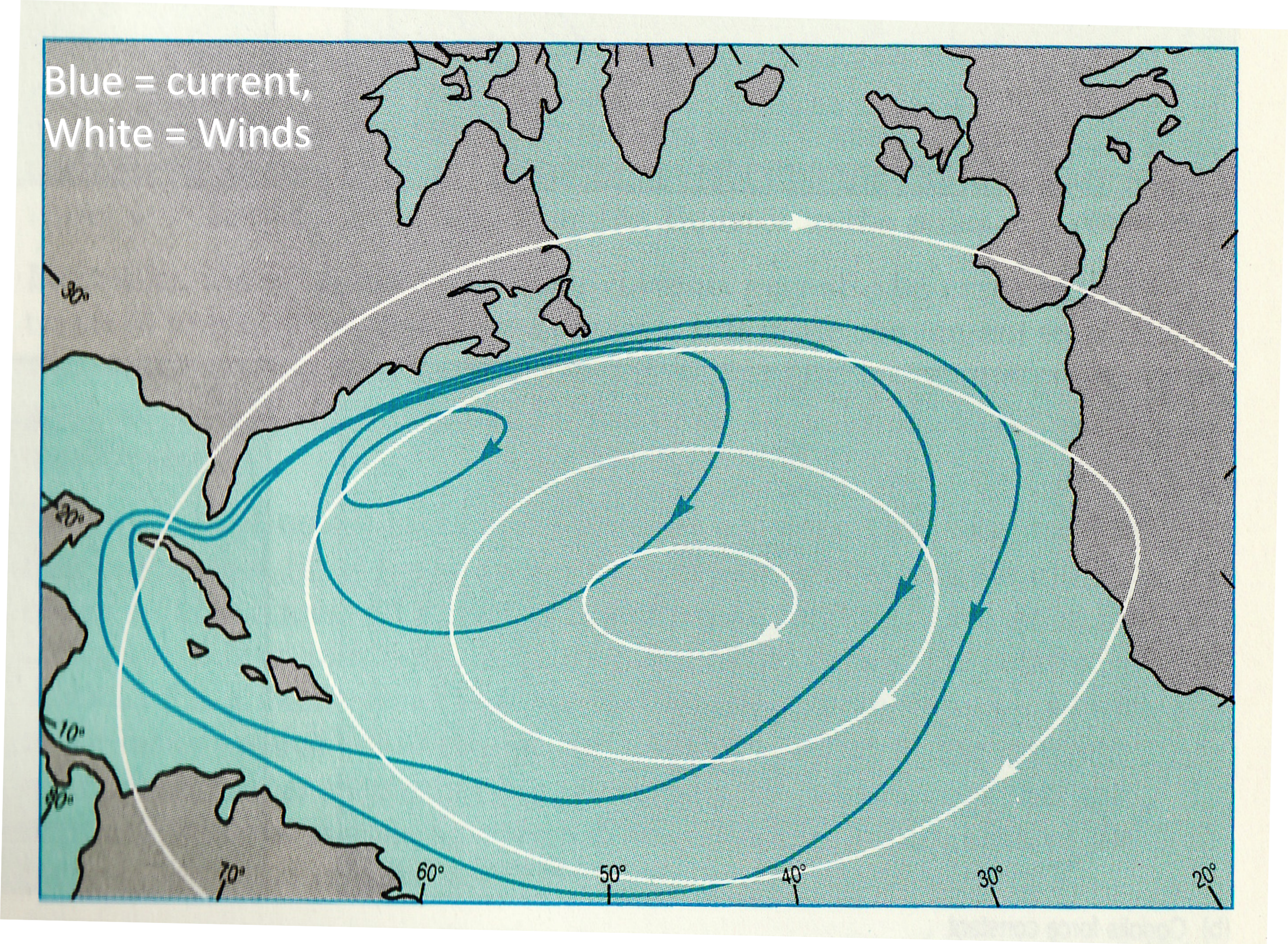


GPC fig 2.14



Open University, Ocean Circulation, Fig 3.1

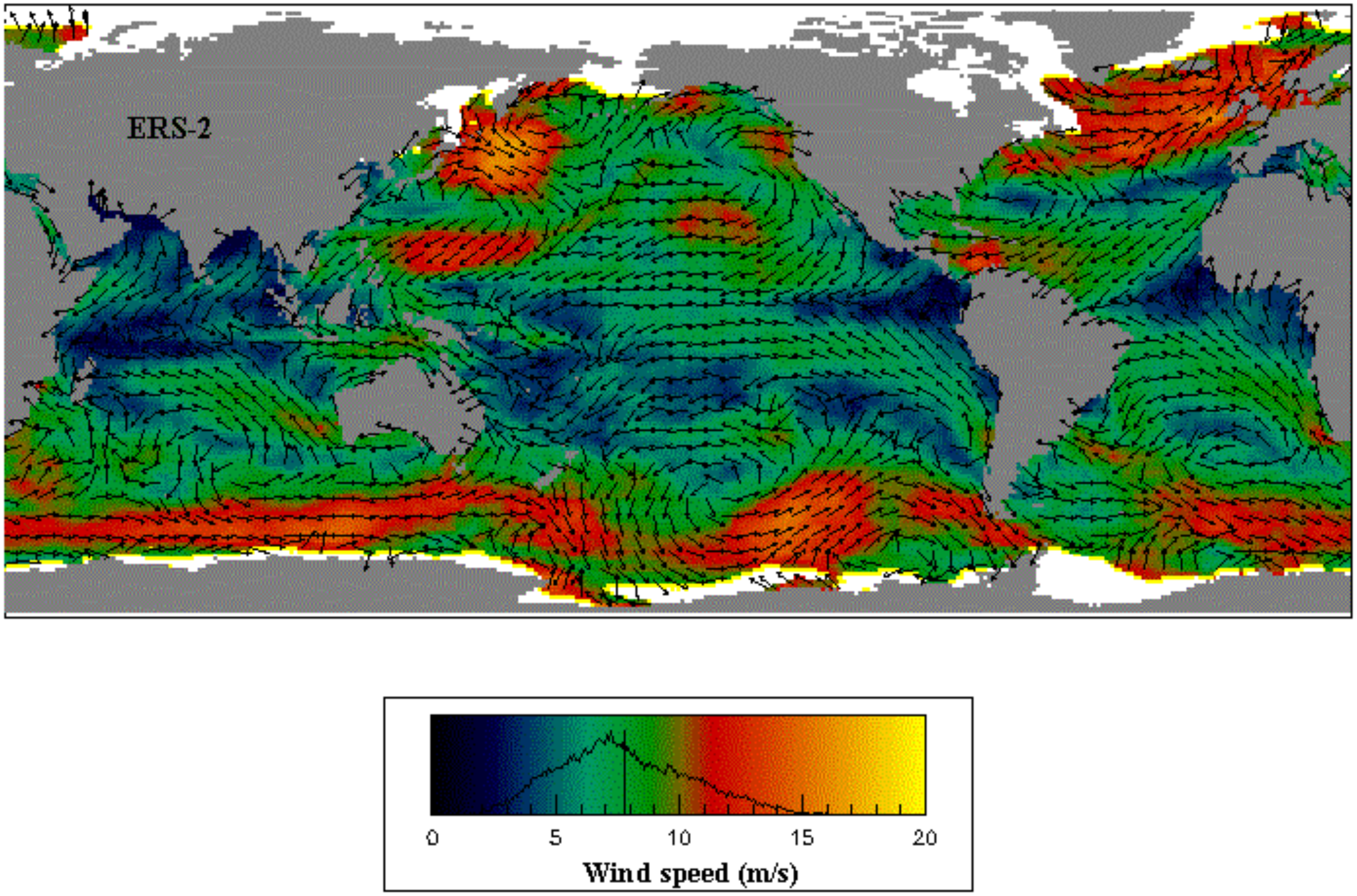
Atmospheric forcing is symmetric, but ocean response is asymmetric
i.e. why is there a Gulf Stream?


Blue = current,
White = Winds

Open University, Ocean Circulation, Fig 4.11

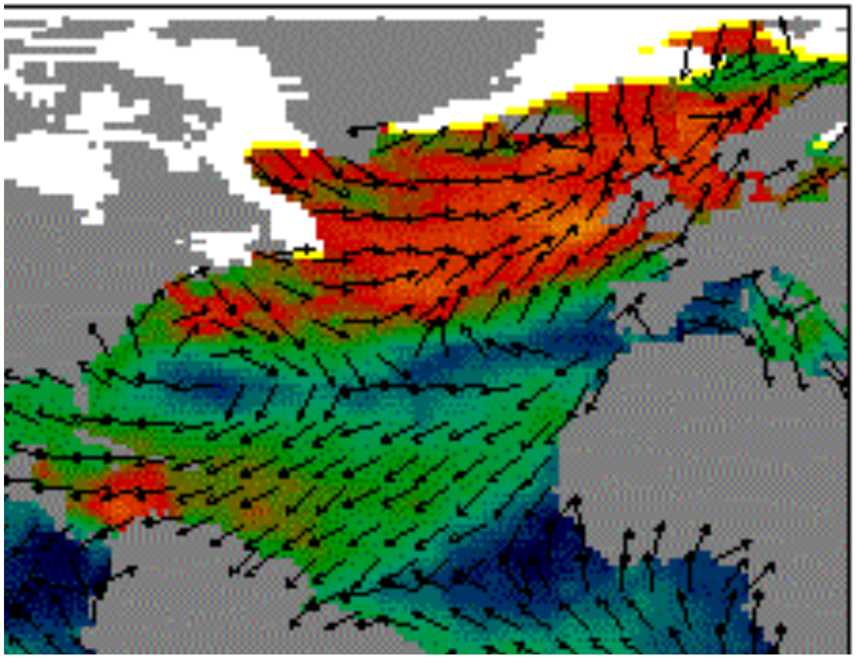
1. Friction from the winds -> surface Ekman Layer

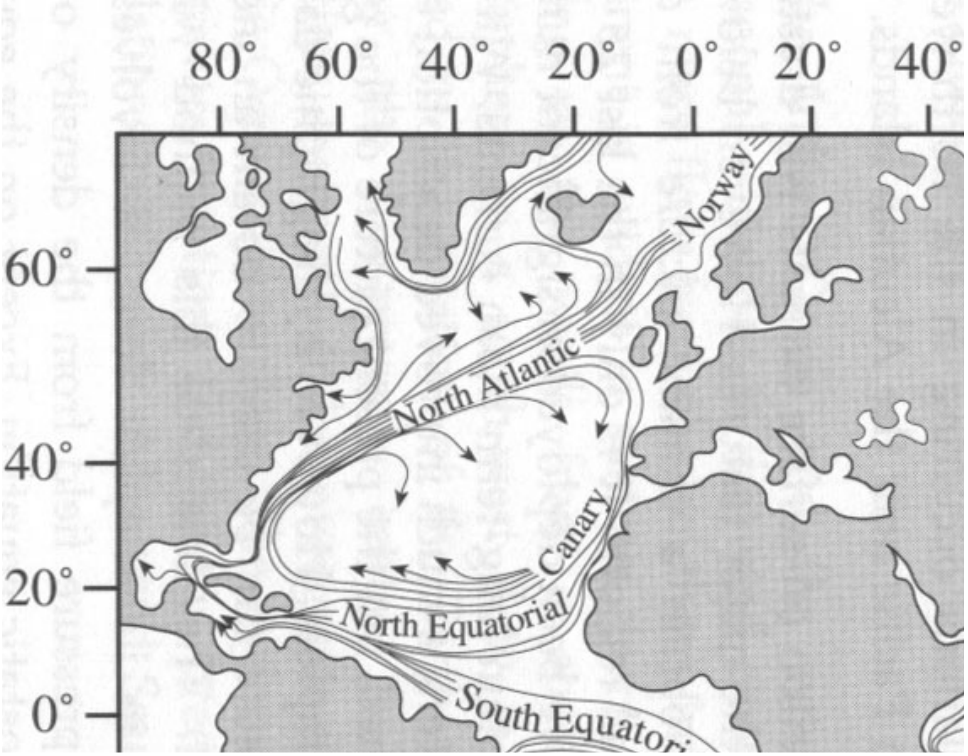
Wind stress



Vectors = Wind stress vectors (N/m^2)

North Atlantic:
Wind Stress and Currents





Friction in the horizontal components of the equations of motion

Ekman Number

- Compare Friction and CF forces

$$E_k = \frac{A_z}{fH^2}$$

How does the ocean respond to this frictional forcing?

Nansen observed iceberg movements

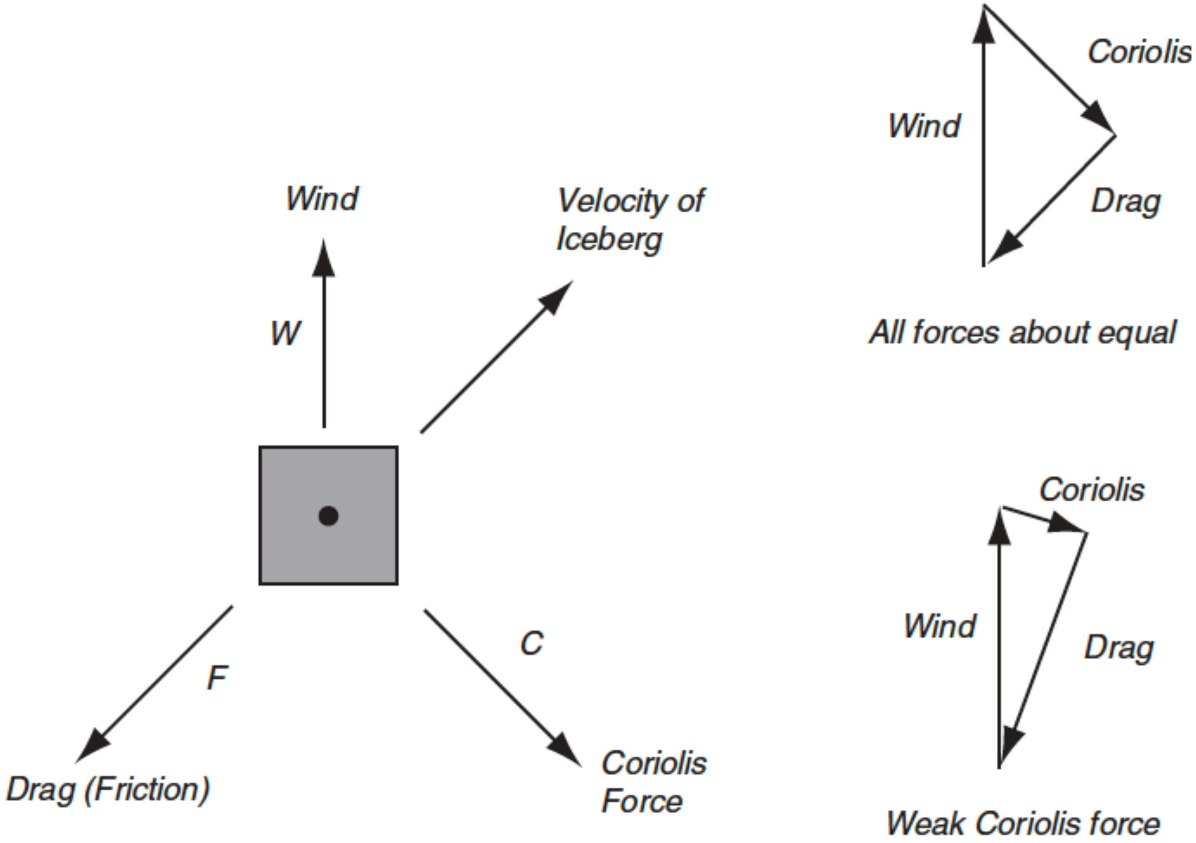
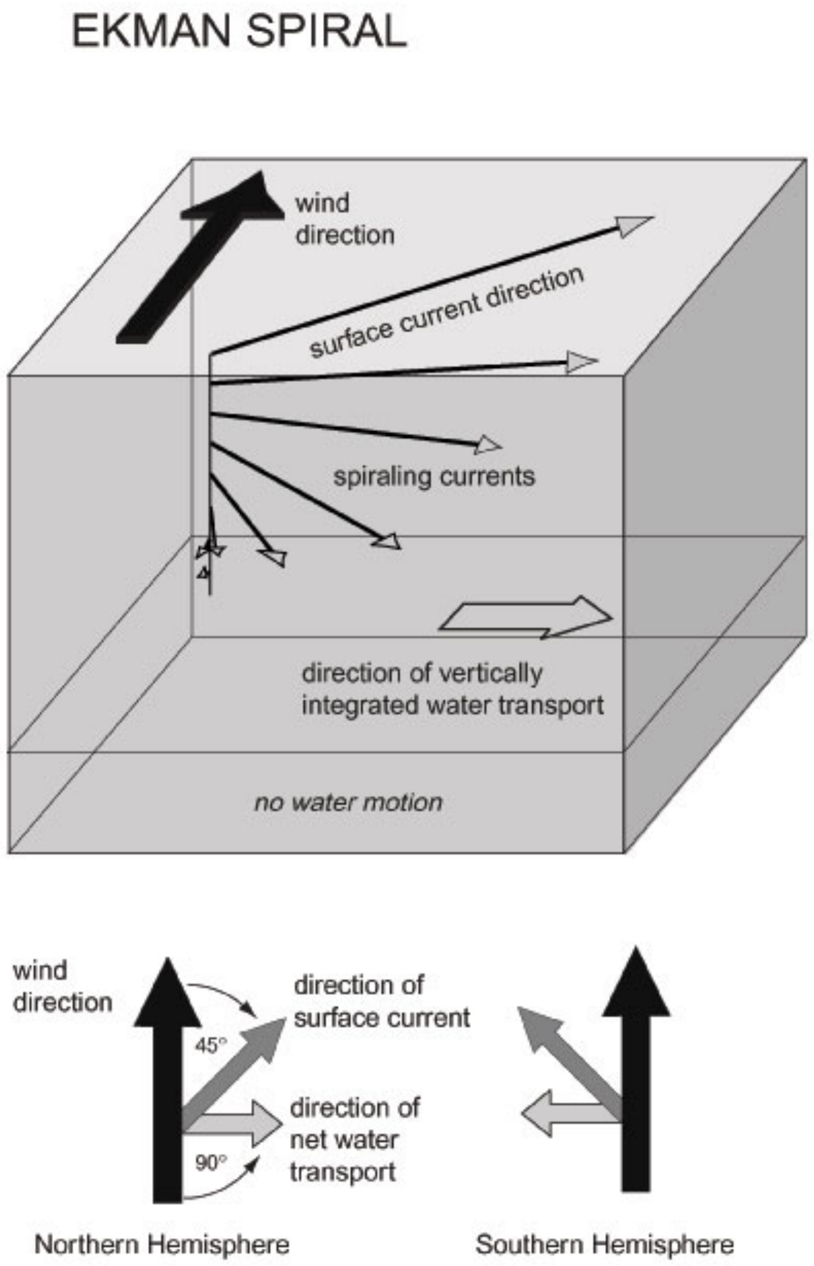


Figure 9.2 The balance of forces acting on an iceberg in a wind on a rotating Earth.

Ekman solution

- Steady, homogenous, horizontal flow with friction

- Constant vertical eddy viscosity A_z



Sarmiento and Gruber, 2004

Figure 2.2.3

Wind stress frictional force is communicated down into the water column

Important note

- The Ekman solution is only part of the TOTAL flow.
- At large scale, PGF = CF (geostrophy)
- At small scale, Friction = CF (Ekman)

$$u = u_g + u_e$$

$$v = v_g + v_e$$

How fast does the spiral decay?

- Arbitrary choice, since never exactly zero
- Choose to be where current velocity is 180 degrees from the surface
- Knowing the equations, solve for depth

$$D_e = \sqrt{\frac{2\pi^2 A_z}{f}}$$

Both wind and latitude are important

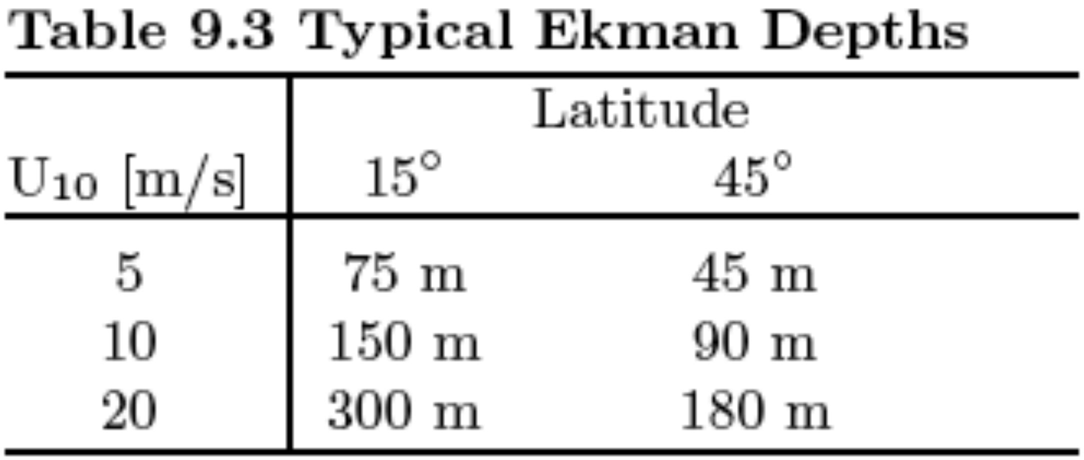


Table 9.3 Typical Ekman Depths

	Latitude	
U_{10} [m/s]	15°	45°
5	75 m	45 m
10	150 m	90 m
20	300 m	180 m

EKMAN SPIRAL

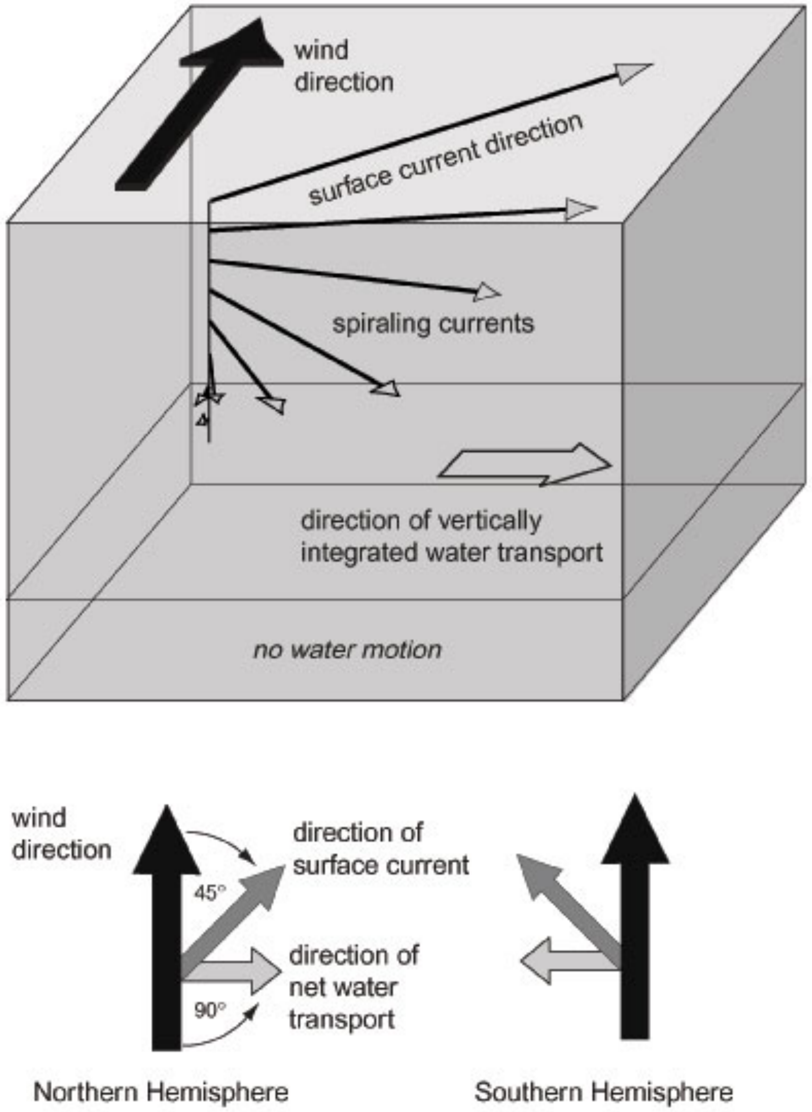
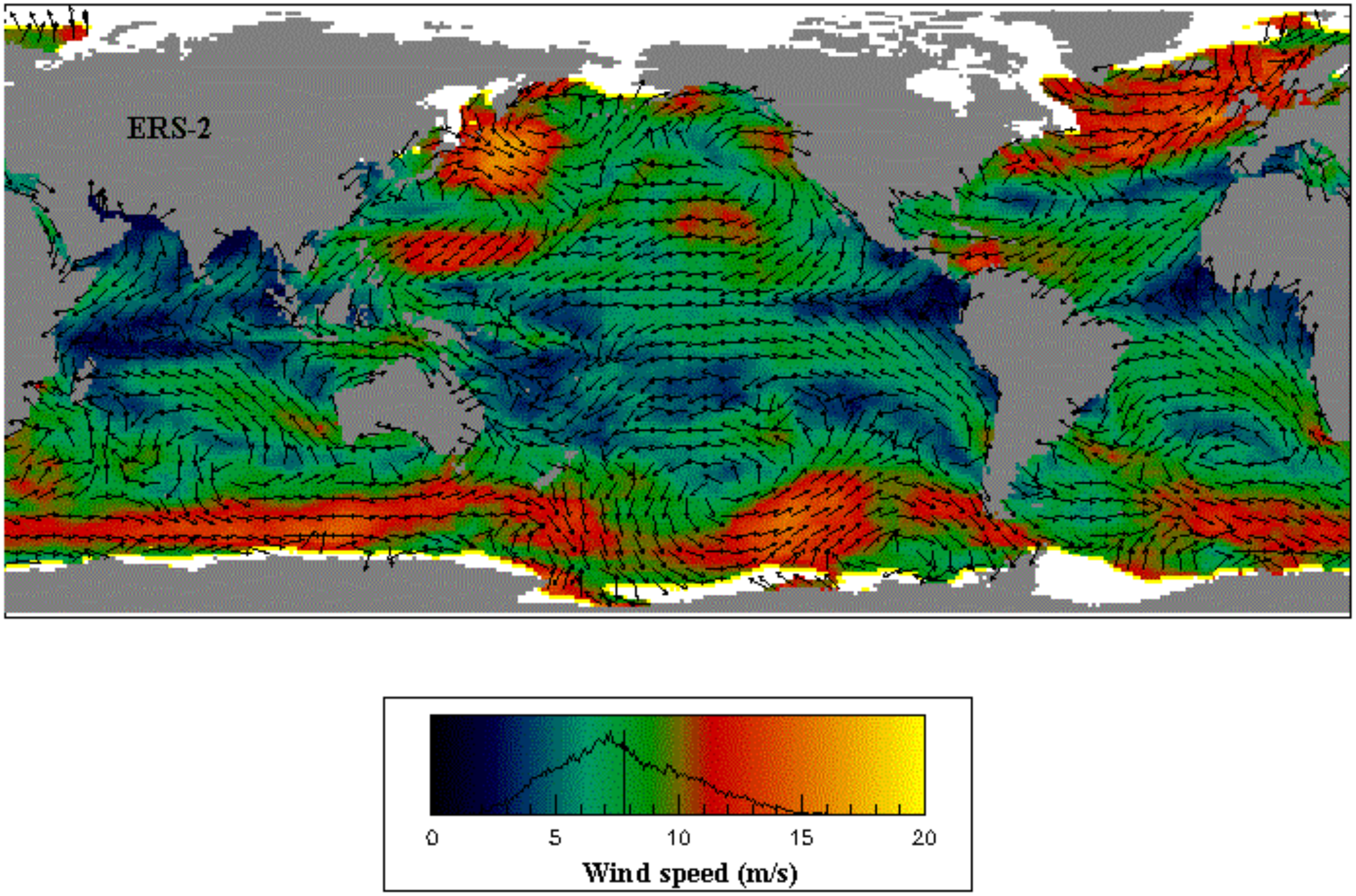


Figure 2.2.3 Sarmiento and Gruber, 2004

Ekman velocity in terms of wind stress



Vectors = Wind stress vectors (N/m^2)

Color = Wind speed (m/s)

Parameterization of Windstress

- Relates the surface stress to the square of the wind speed at 10m (u_{wind}, v_{wind})
- Force / unit area (N/m^2)

$$(\tau_x, \tau_y) = \rho_a C_d \sqrt{u_{wind}^2 + v_{wind}^2}\,(u_{wind}, v_{wind})$$

$$\tau = \rho_a C_d U_{wind}^2$$

Drag Coefficient for wind stress

- Typical values Cd ~ 1 - 1.5 x 10^{-3}
- Can try to improve this by accounting for additional drag at high windspeed
  - Due to increasing waves, change to the surface structure of the ocean

Various C_d estimates

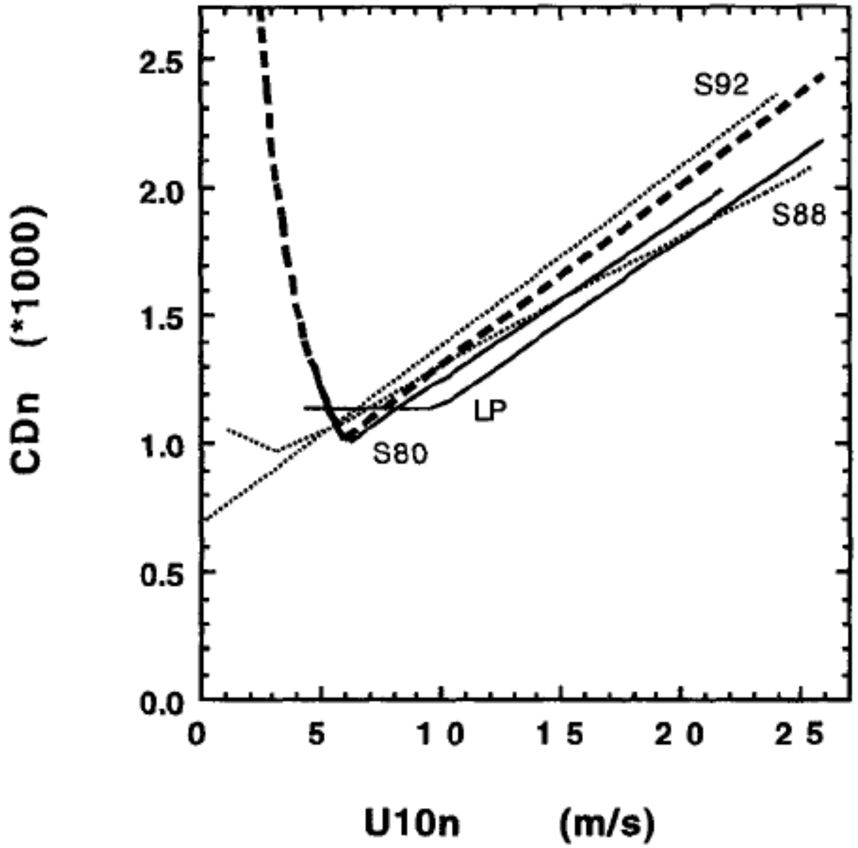


FIG. 12. (a) Comparison of drag coefficient relationships: results from this study (dashed line), Smith et al. 1992 (upper dotted), Smith 1980 (upper solid), Large and Pond 1981/82 (lower solid), and Smith 1988 (lower dotted).

Yelland and Taylor 1996

Lack of low wind speed data, so they throw out below 3 m/s…

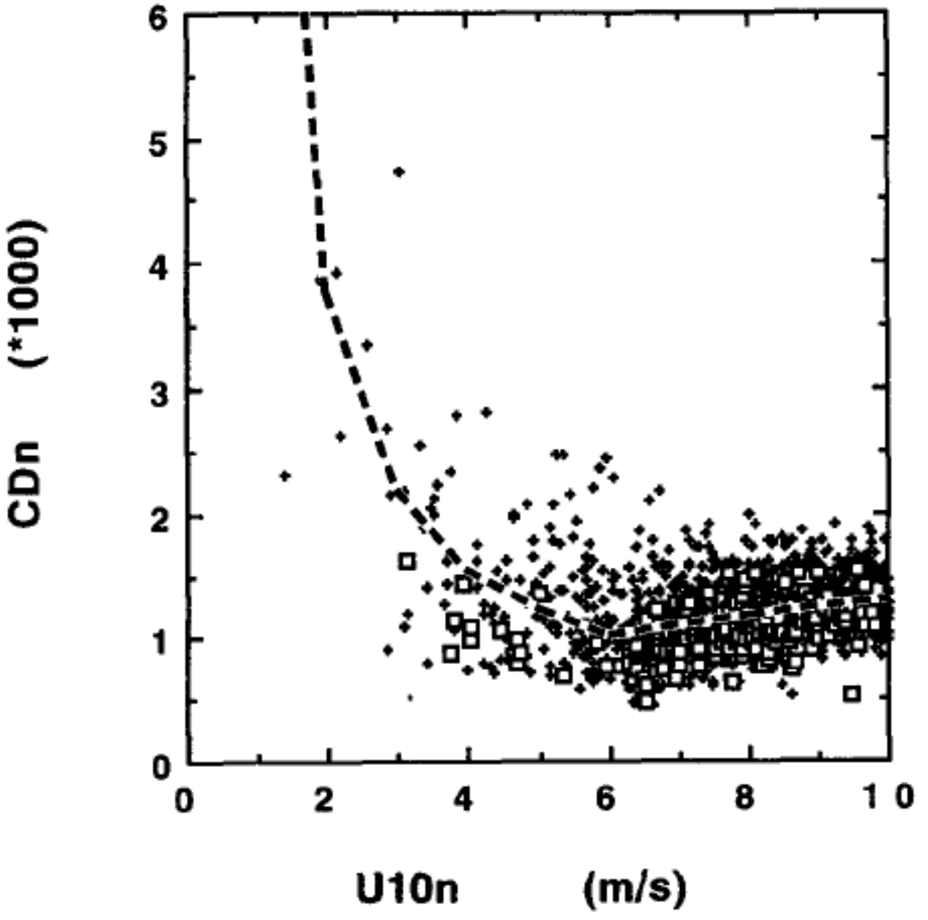
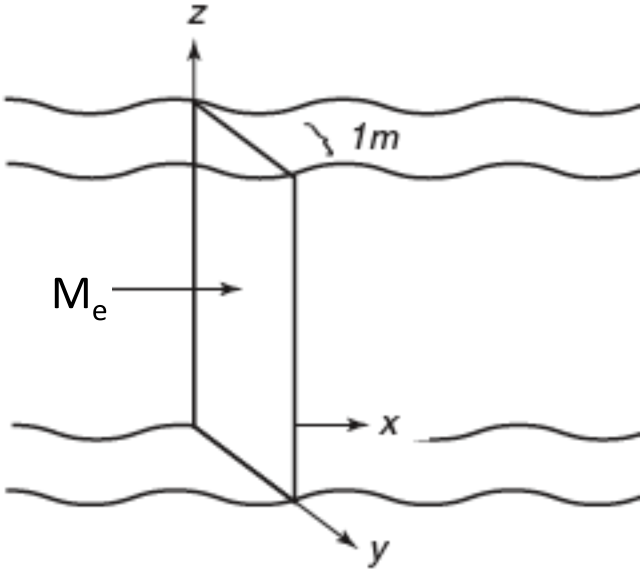


FIG. 10. (b) As Fig. 10a but individual low wind speed data points from the *Discovery* (crosses), and *Le Suroit* (squares). The dashed line indicates the relationship of Eq. (20b).

Details of the Ekman spiral are NOT critical to large-scale ocean circulation.

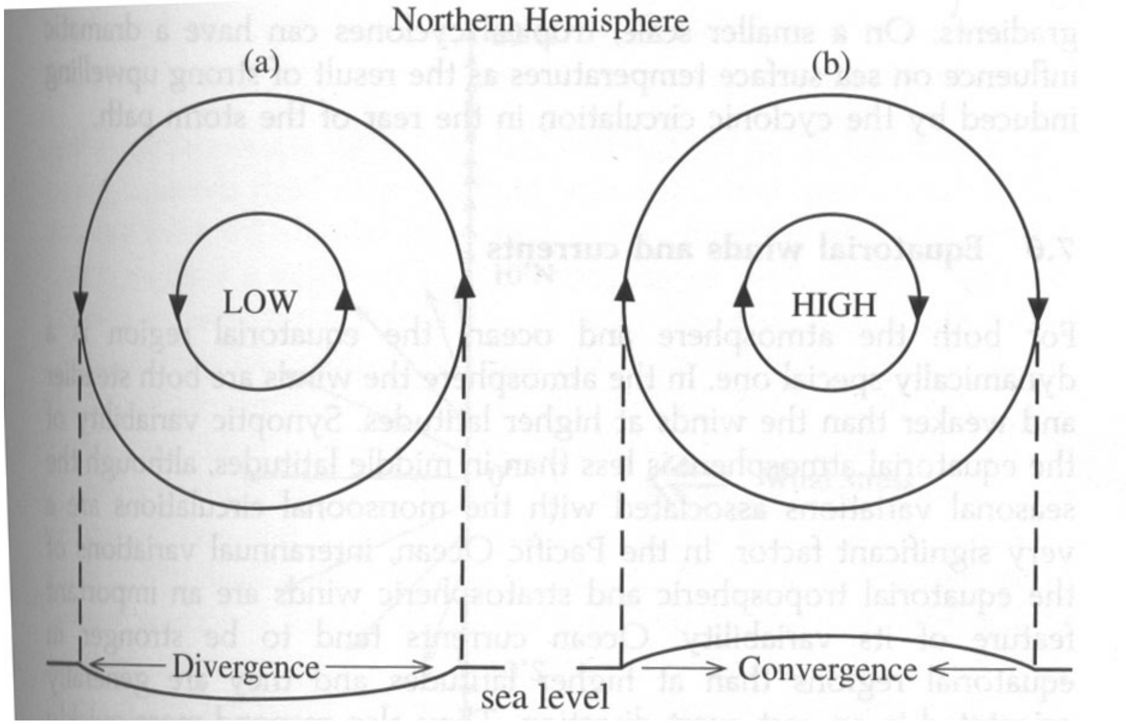
But, its effect integrated over the surface layer / Ekman depth is.

The integrated effect is a Mass Transport (Me) 90^o to the right (left in SH) of wind stress



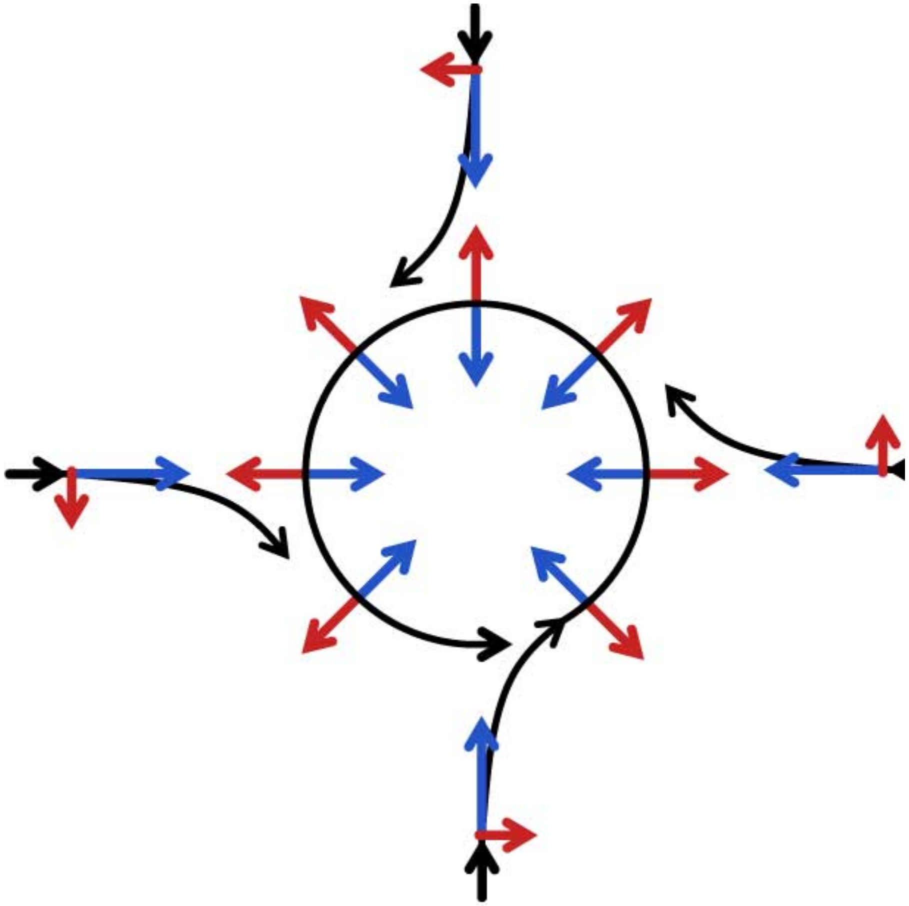
$$M_e = \frac{1}{f}\boldsymbol{\tau}_o \times \hat{k}$$

Net convergence or divergence



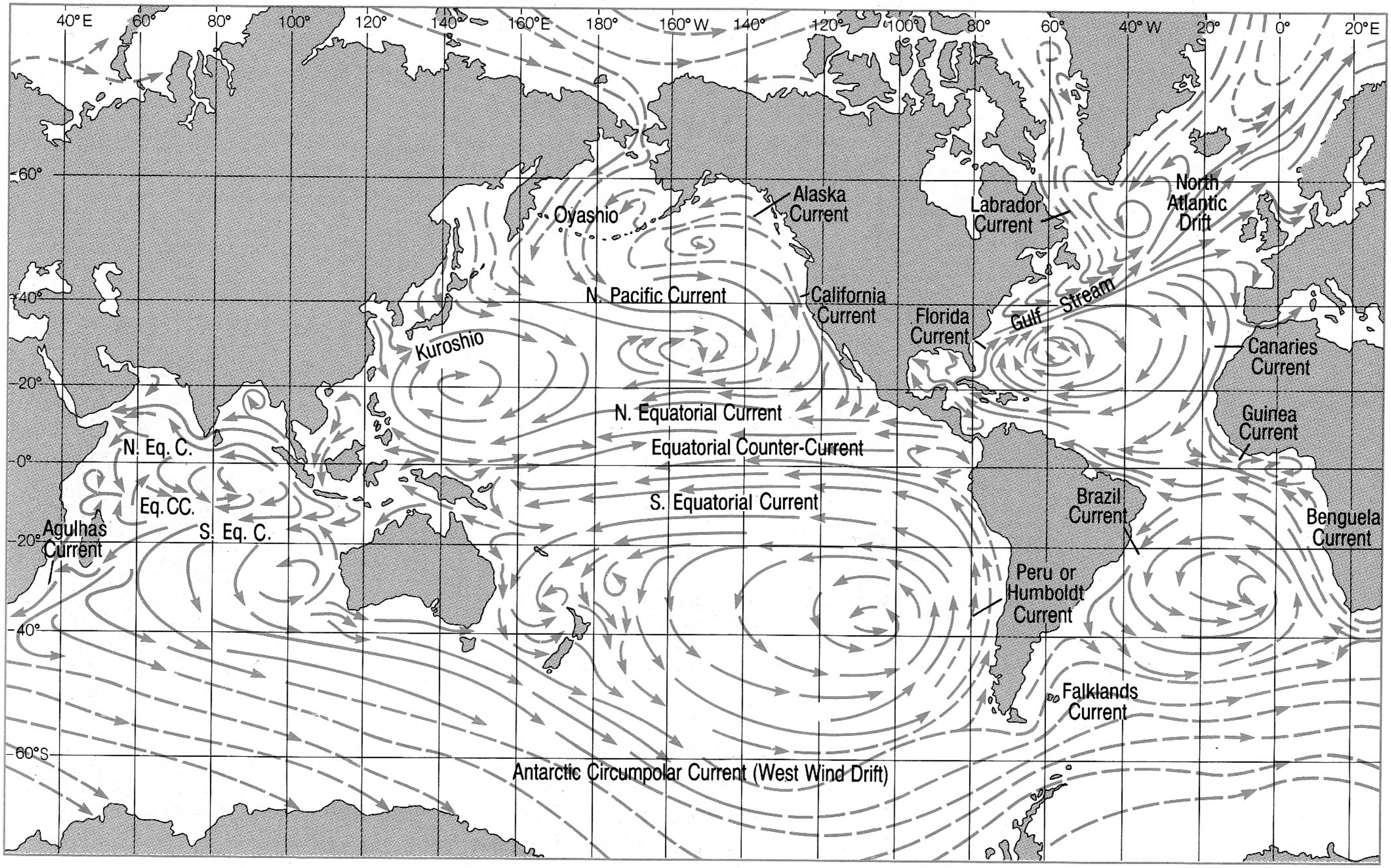
Wells (1998) Fig 7.16

Balanced flow: Geostrophy
PGF = CF
"Flow around the hill"



Inward flow due to PGF (blue force arrows) balance CF (red arrows) to create cyclonic flow (black arrows)

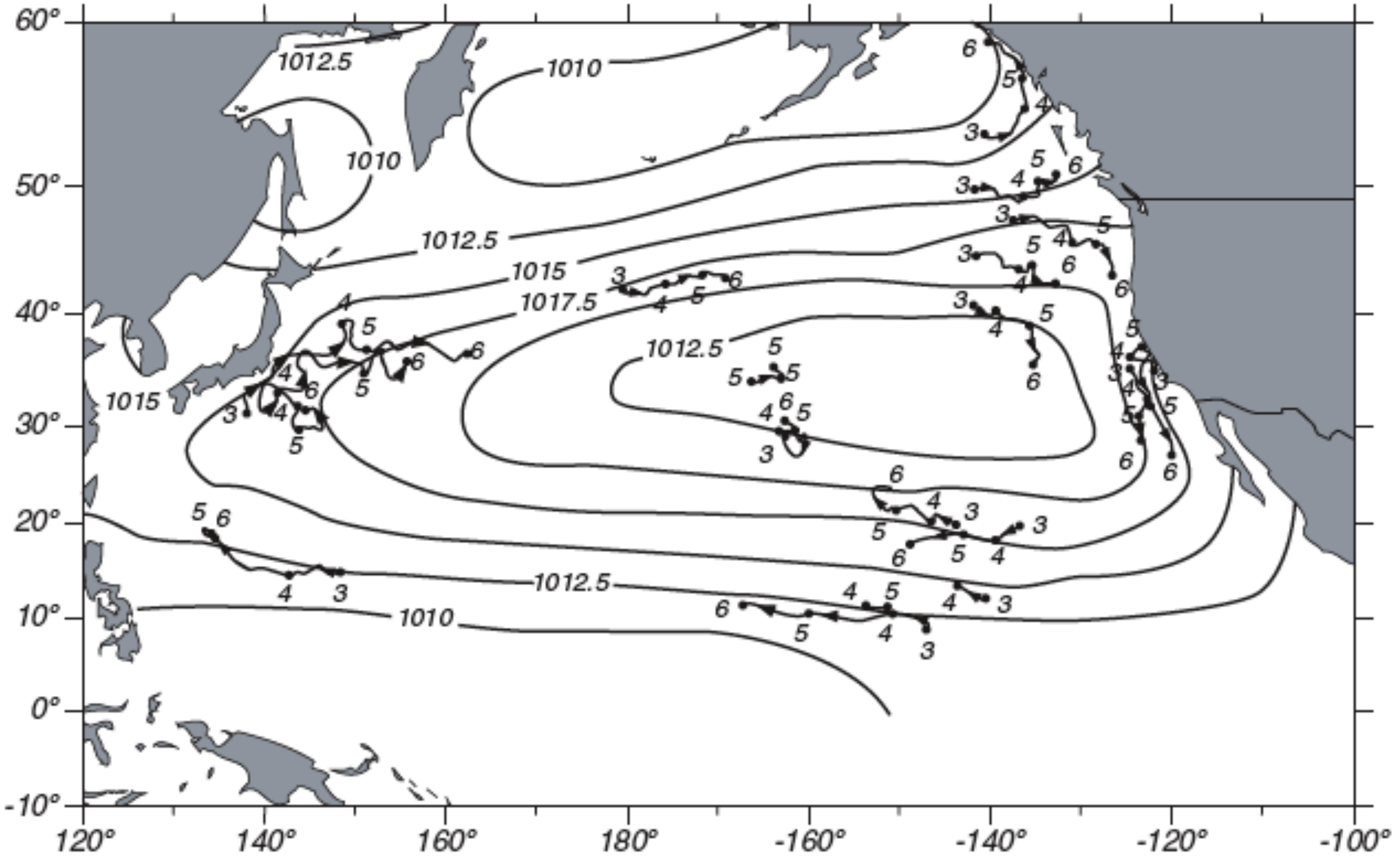
Northern Hemisphere Cyclone



Open University, Ocean Circulation, Fig 3.1

Comparison to Observations

Data indicate aloft wind and surface flow are parallel



Mean Sea Level Pressure in April 1978 (mb)

Comparison to Observations

- Ekman's predictions are surprisingly good when compared to recent data with current meters and drifters
- This suggests our initial assumptions (regarding steady flow, horizontal homogeneity) are realistic

Coastal Upwelling

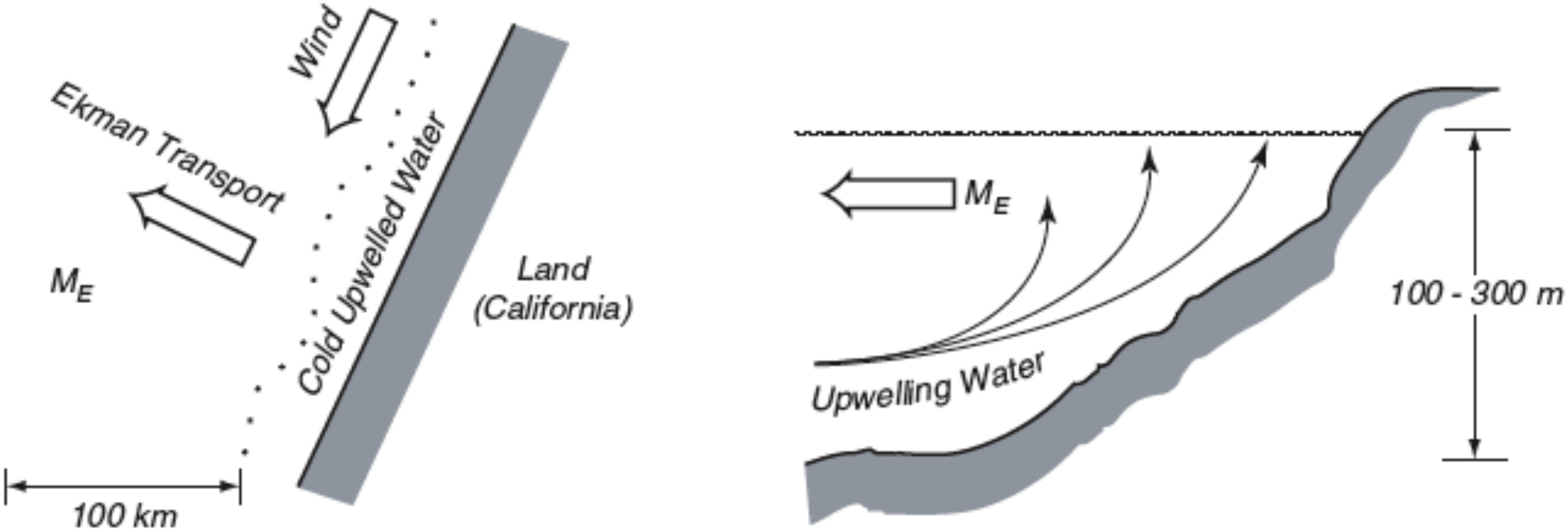
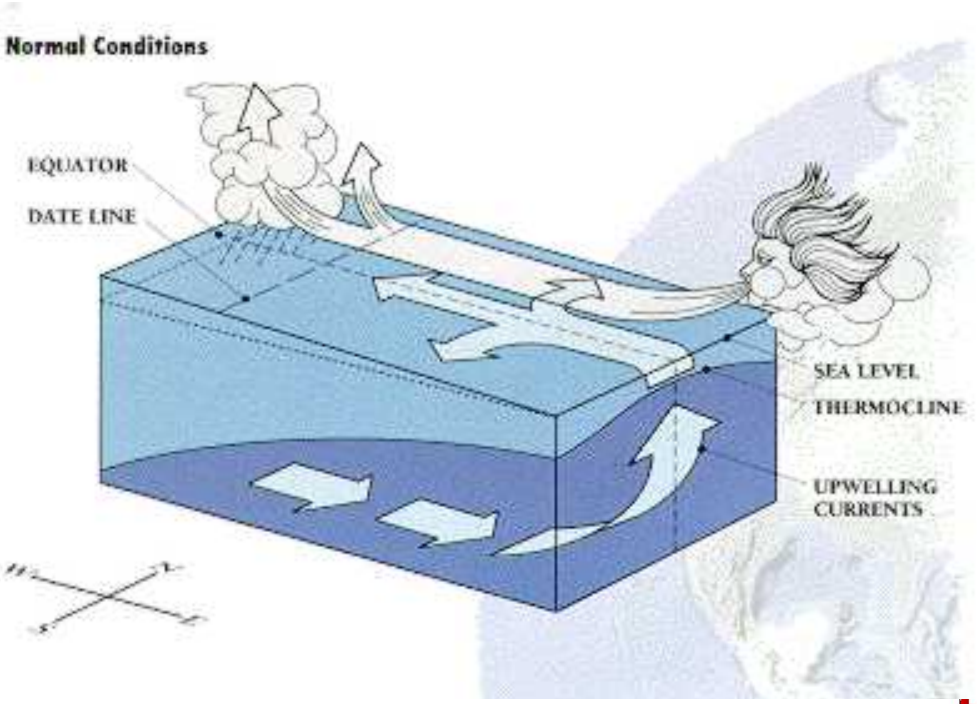
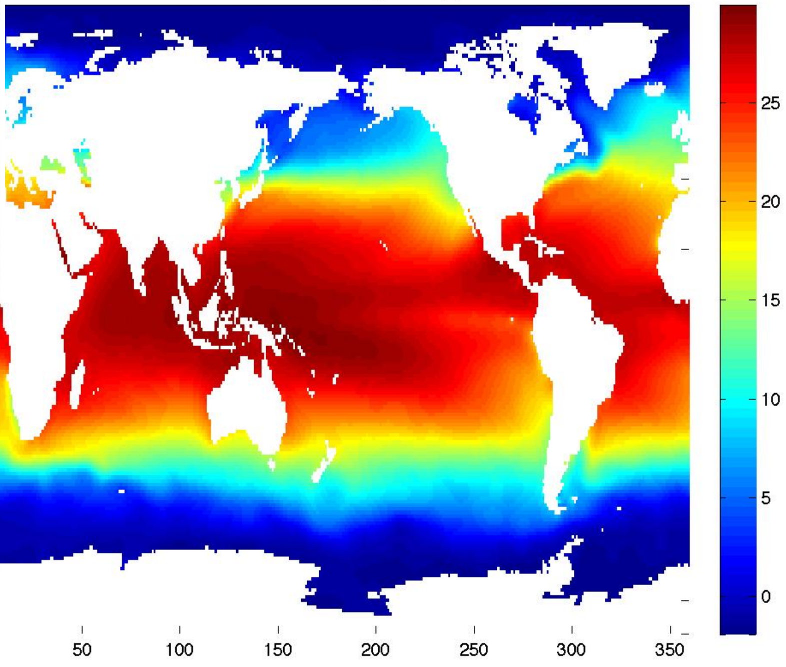


Figure 9.8 Sketch of Ekman transport along a coast leading to upwelling of cold water along the coast. **Left:** Cross section. The water transported offshore must be replaced by water upwelling from below the mixed layer. **Right:** Plan view. North winds along a west coast in the northern hemisphere cause Ekman transports away from the shore.

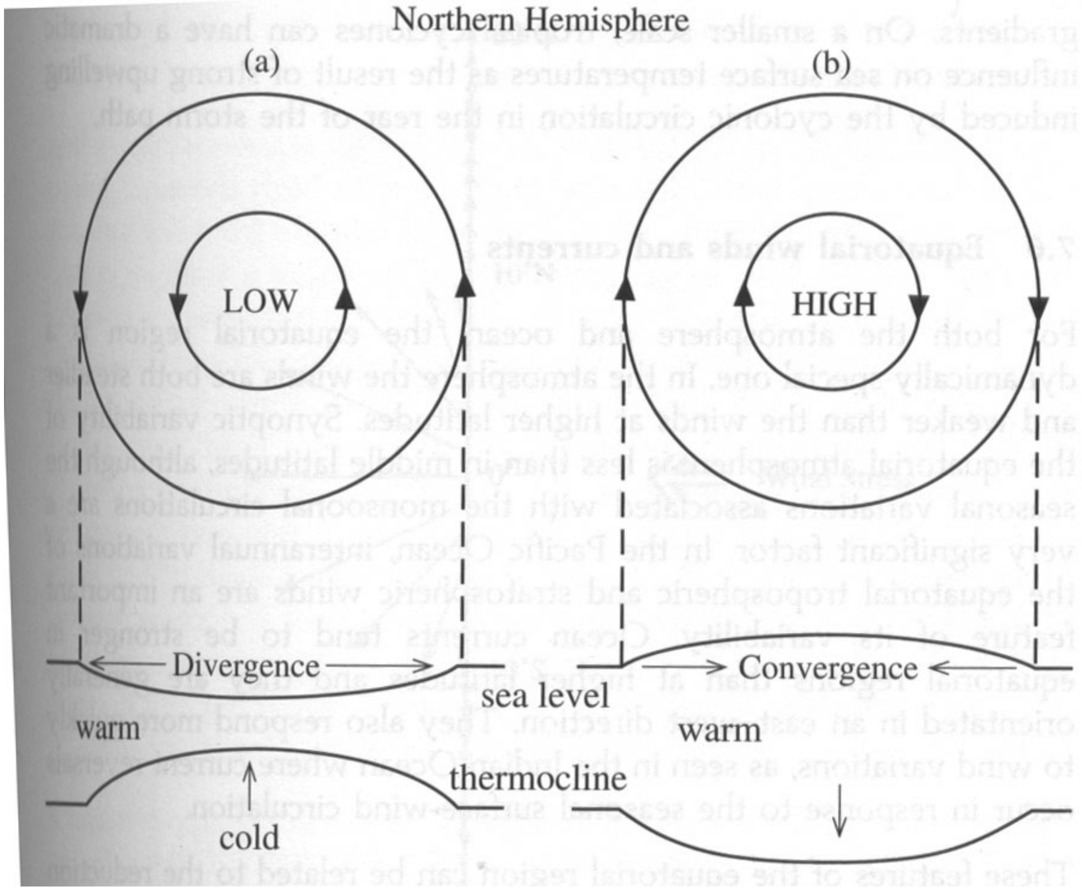
Equatorial Upwelling





Convergence / Divergence implies Vertical Motion in Gyres as well

Ekman pumping/suction also results from divergence or convergence

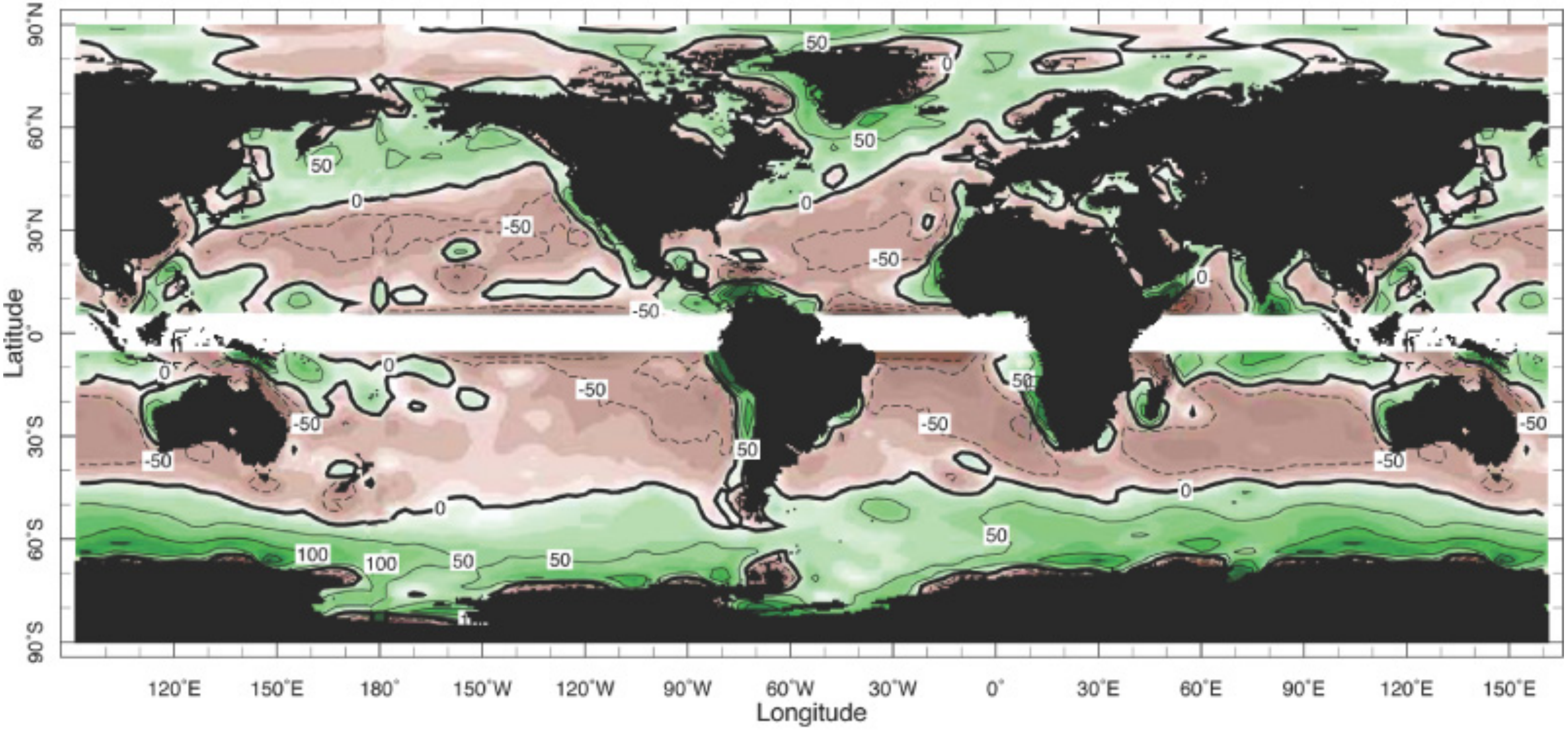


Wells (1998) Fig 7.16

Ekman Pumping / Suction

$$w_e = \frac{1}{\rho}\hat{k} \bullet \nabla \times \left(\frac{\boldsymbol{\tau}_o}{f} \right)$$

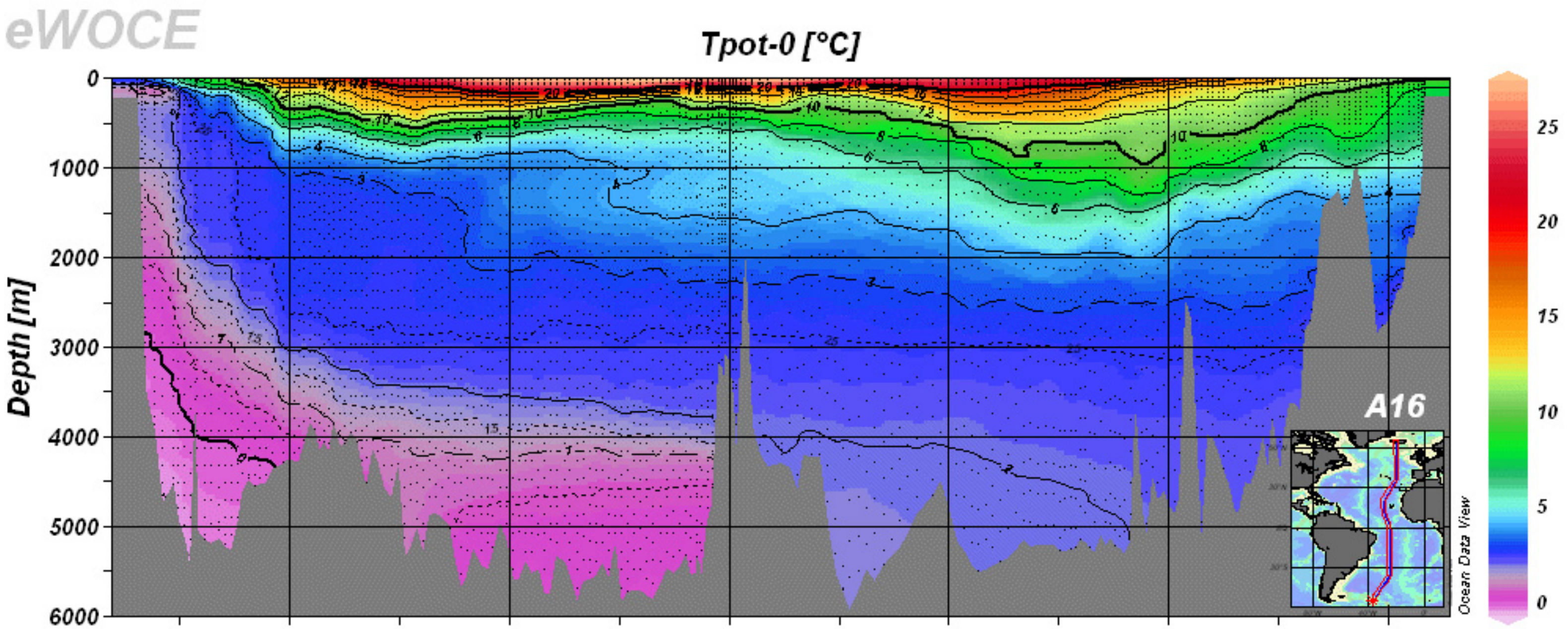
Ekman Pumping (m/y)

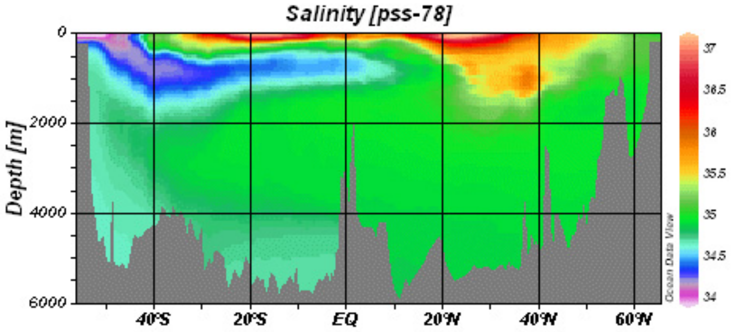


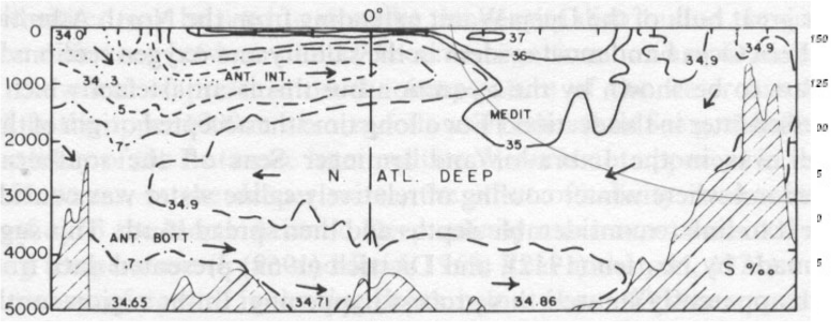
Ekman Suction in Rotating Tank

http://www-paoc.mit.edu/labweb/lab12/gfd12.htm

Temperature, Salinity
Depth Structure, Atlantic

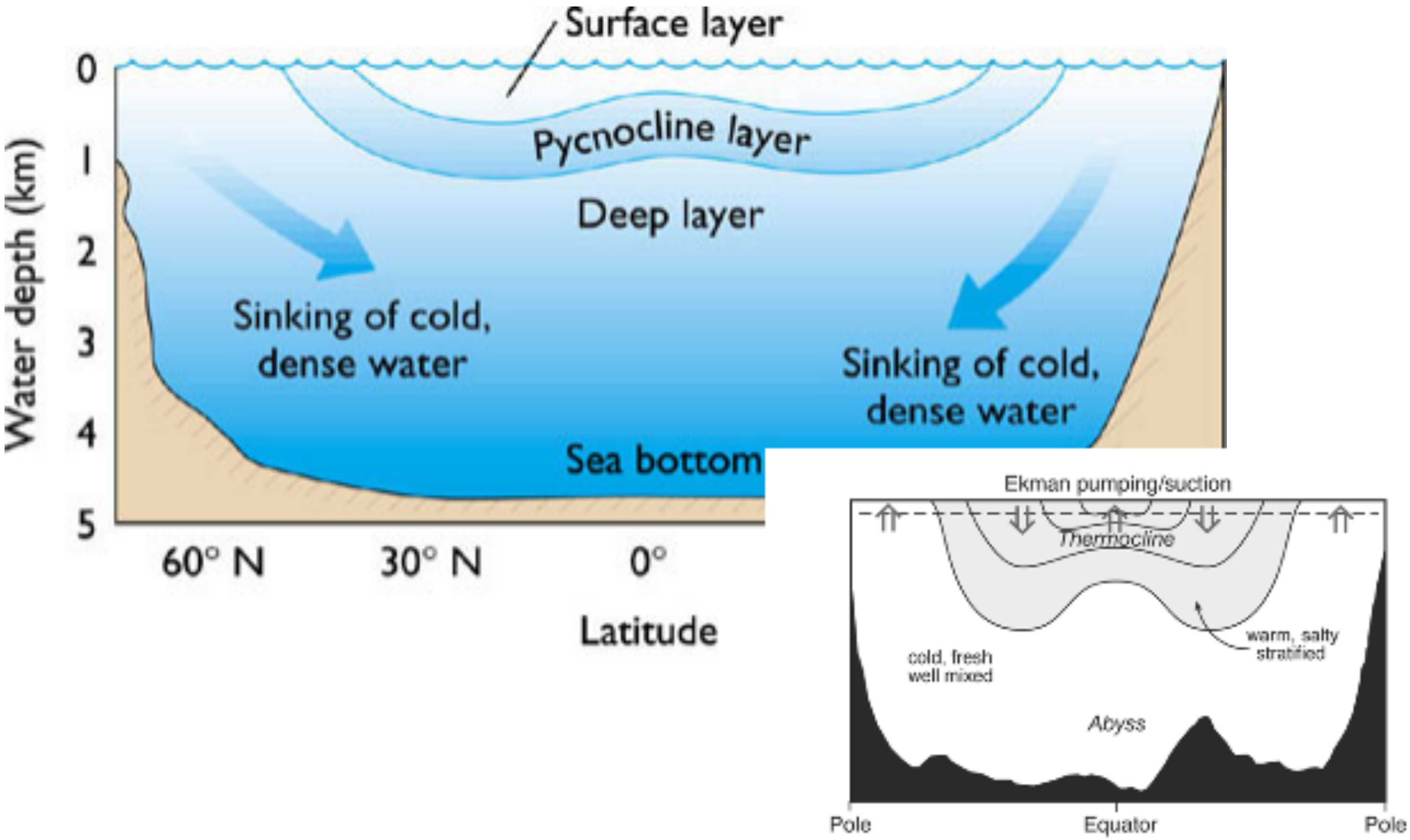






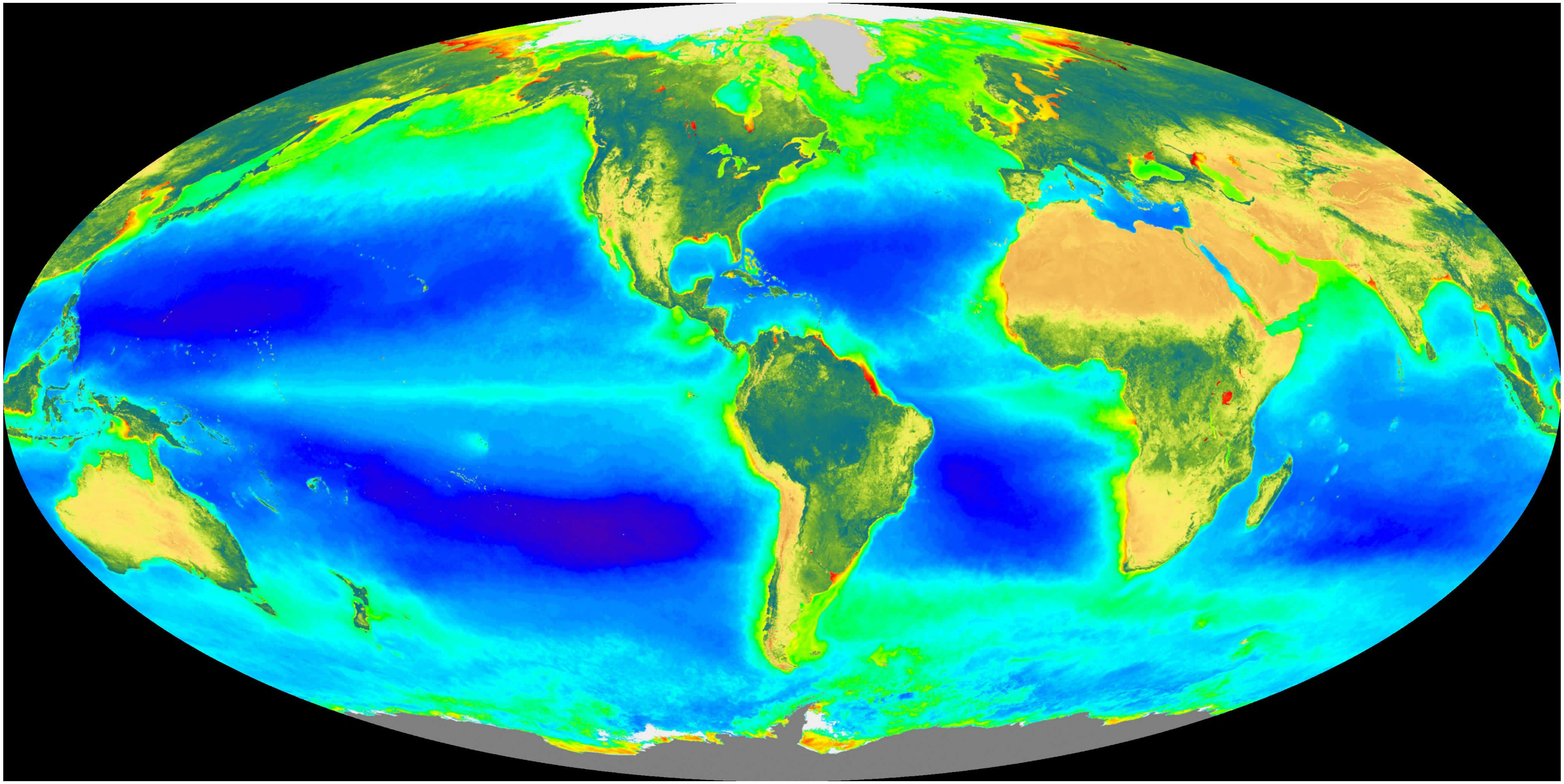
PE 7.15b

Ekman pumping / suction has strong influence on upper ocean (0 to ~1000m) circulation

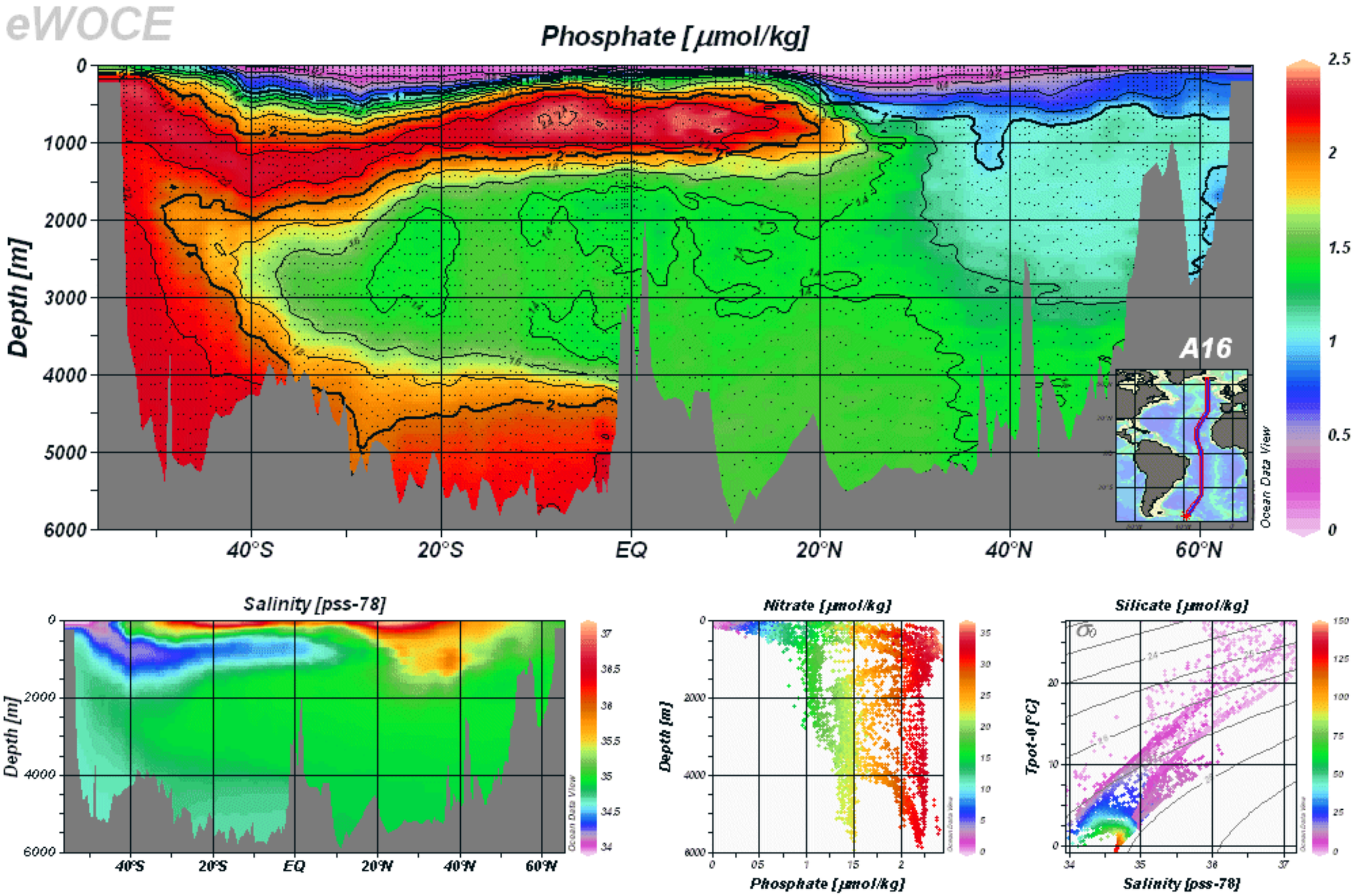


Gyre upwelling and downwelling key to distribution of productivity

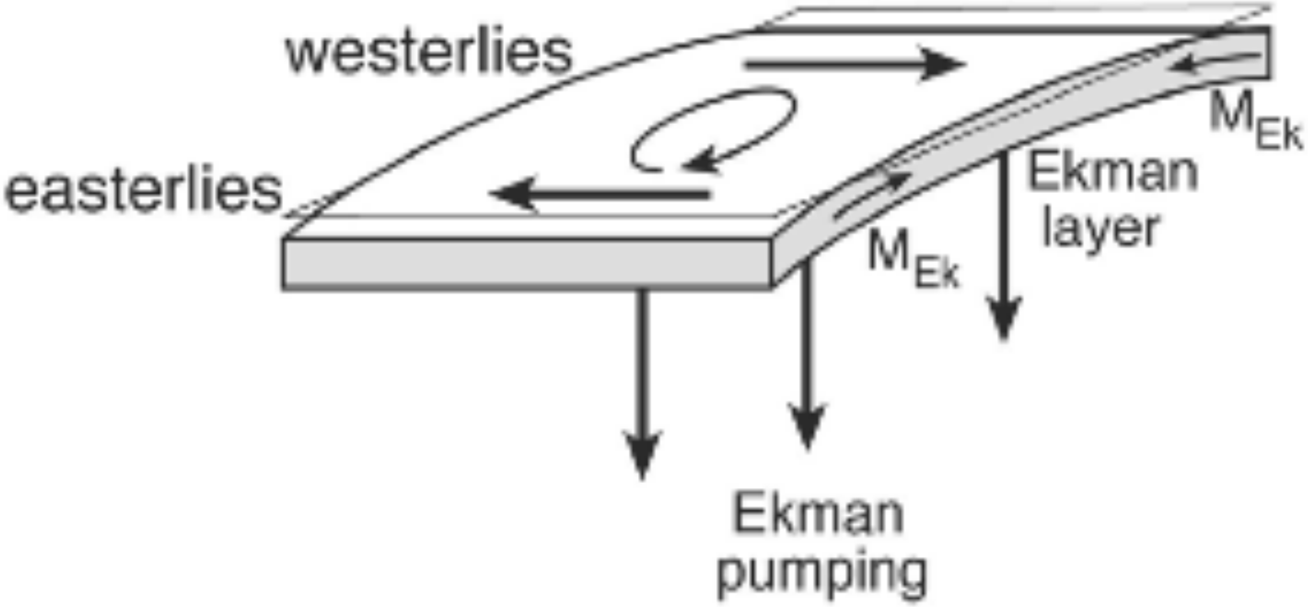
Satellite Ocean Surface Chlorophyll, average 1998-2006, NASA



Essential nutrients are at depth



Wind driven circulation, summary



What happens below the surface layer where winds drive mass convergence/ divergence, which in turn drives downwelling/upwelling….

Remember that away from surface and boundaries, ocean is very geostrophic ($R_o << 1$)

$$fv = \frac{1}{\rho_o}\frac{\partial p}{\partial x}; fu = -\frac{1}{\rho_o}\frac{\partial p}{\partial y}$$

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

How does the wind-driven interior respond to $w_e<0$ in the subtropical gyres?

- Beneath the Ekman layer, flow is geostrophic
- Continuity
  - Because concerned with w_e, can no longer assume horizontally non-divergent
  - Now:

$$\nabla_h \cdot u_g + \frac{\partial w}{\partial z} = 0$$

- Also note that over the large spatial scales, cannot assume that f is constant

Sverdrup Balance

$$\beta v_g = f \frac{\partial w}{\partial z}$$

Sverdrup Balance

- Geostrophic
- But, allow vertical motion to be non-zero
- Also, keep the latitudinal variation in the Coriolis parameter (i.e. $\beta = df/dy \neq 0$)
- To derive:
  - Plug in geostrophy to continuity

Depth-integrated flow, function of wind stress curl

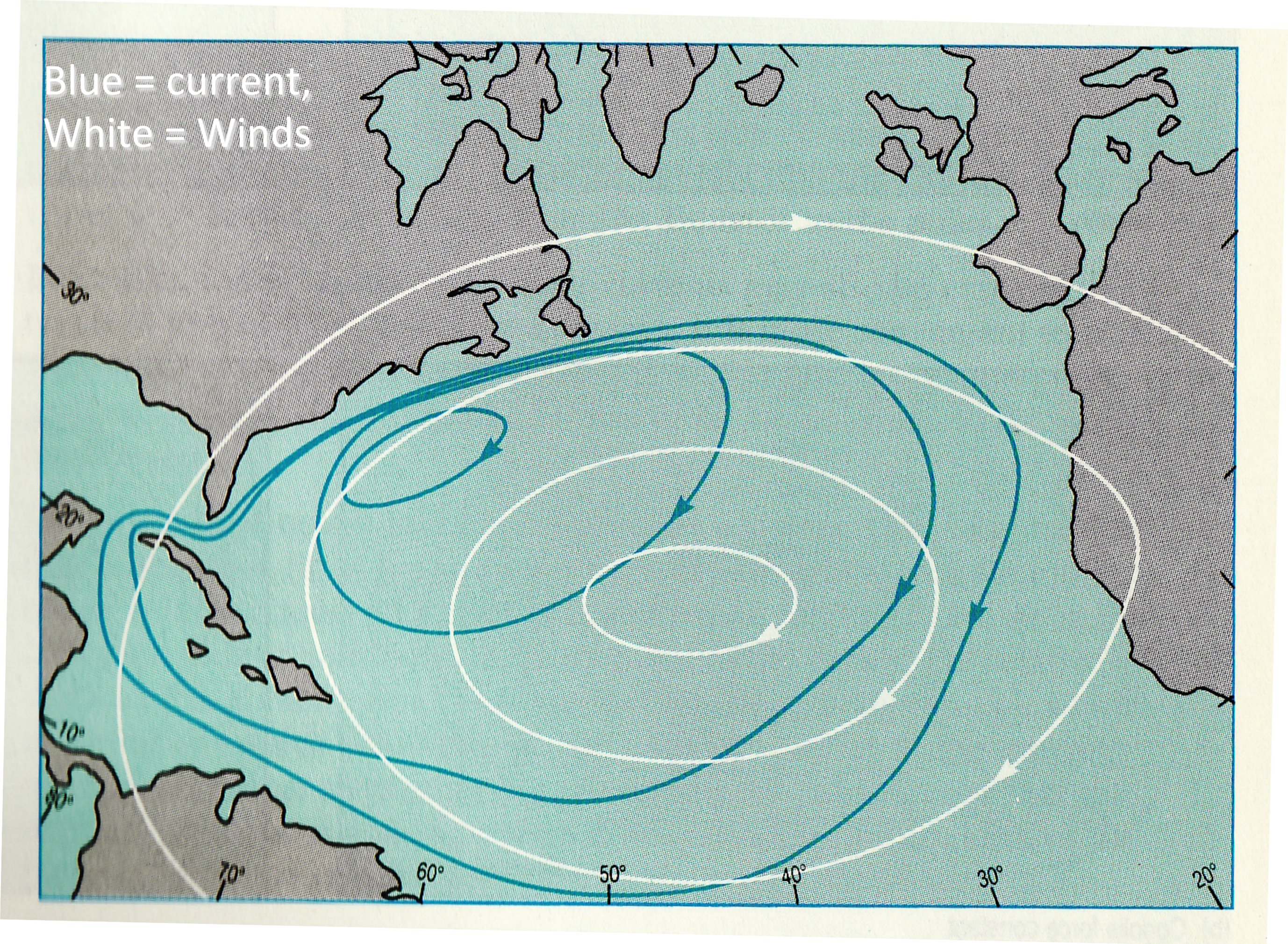
$$\beta V = \frac{1}{\rho_o}\left(\frac{\partial \boldsymbol{\tau}_{oy}}{\partial x} - \frac{\partial \boldsymbol{\tau}_{ox}}{\partial y}\right) \cong f w_e$$

Last approximation holds with $f \sim f_o$

Rotating Tank:
The Wind Driven Gyre

http://www-paoc.mit.edu/labweb/lab13/gfdxiii.htm

Wind drives the ocean, but why is there a Gulf Stream?



Open University, Ocean Circulation, Fig 4.11

Observed Gyres

- “Westward Intensification”

=> By mass conservation, can’t have flow continually to the South

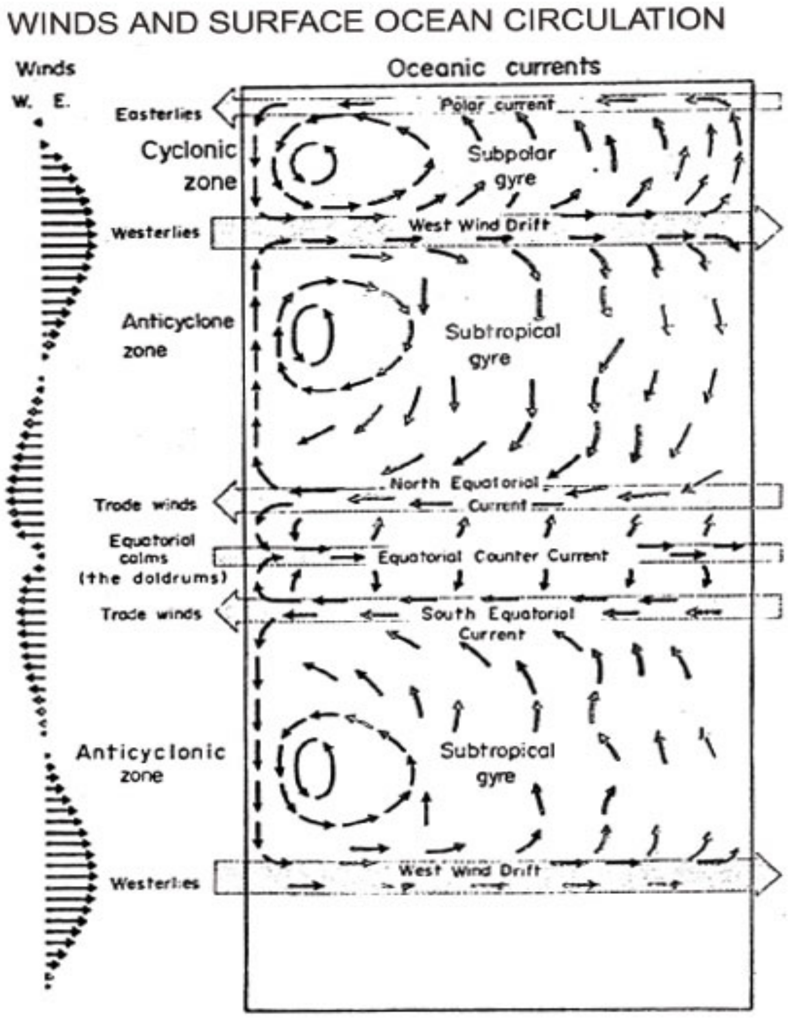


Figure 2.2.9

Sarmiento and Gruber, 2004