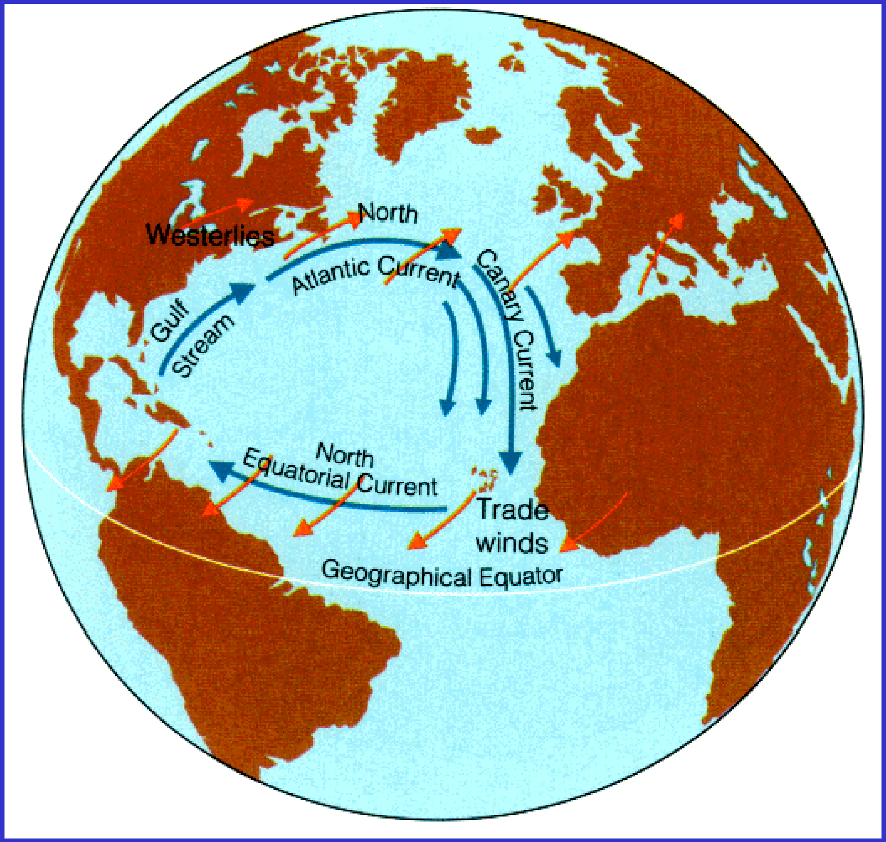
Lecture 10: Ocean Circulation



- ❑ Ekman Transport
- ❑ Ekman Pumping
- ❑ Wind-Driven Circulation

Basic Ocean Structures

Warm up by sunlight!

❑ Upper Ocean (~100 m)

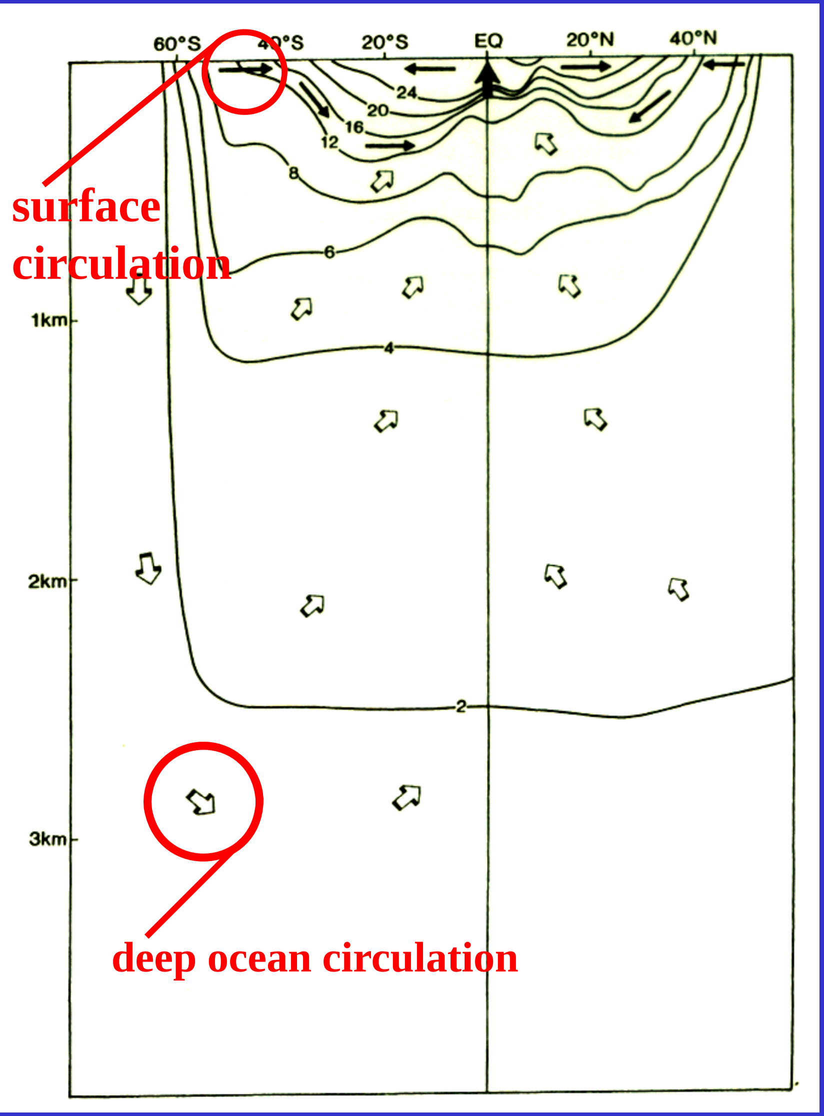
Shallow, warm upper layer where light is abundant and where most marine life can be found.

❑ Deep Ocean

Cold, dark, deep ocean where plenty supplies of nutrients and carbon exist.

No sunlight!

Basic Ocean Current Systems

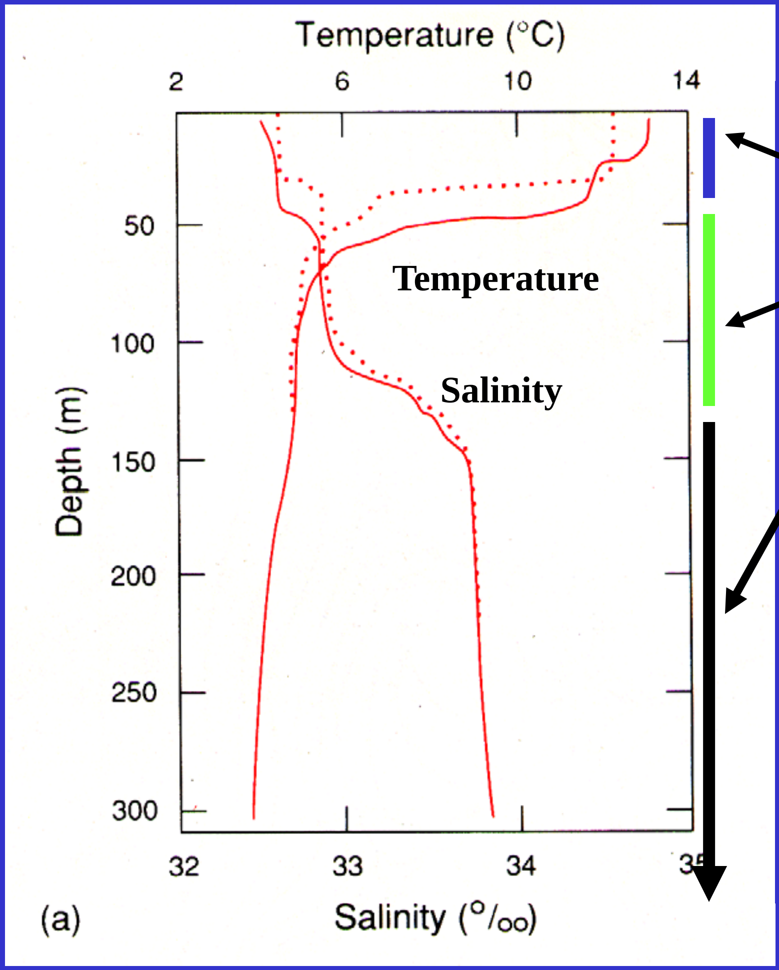


Upper Ocean

Deep Ocean

(from *"Is The Temperature Rising?"*)

Vertical Structure of Ocean



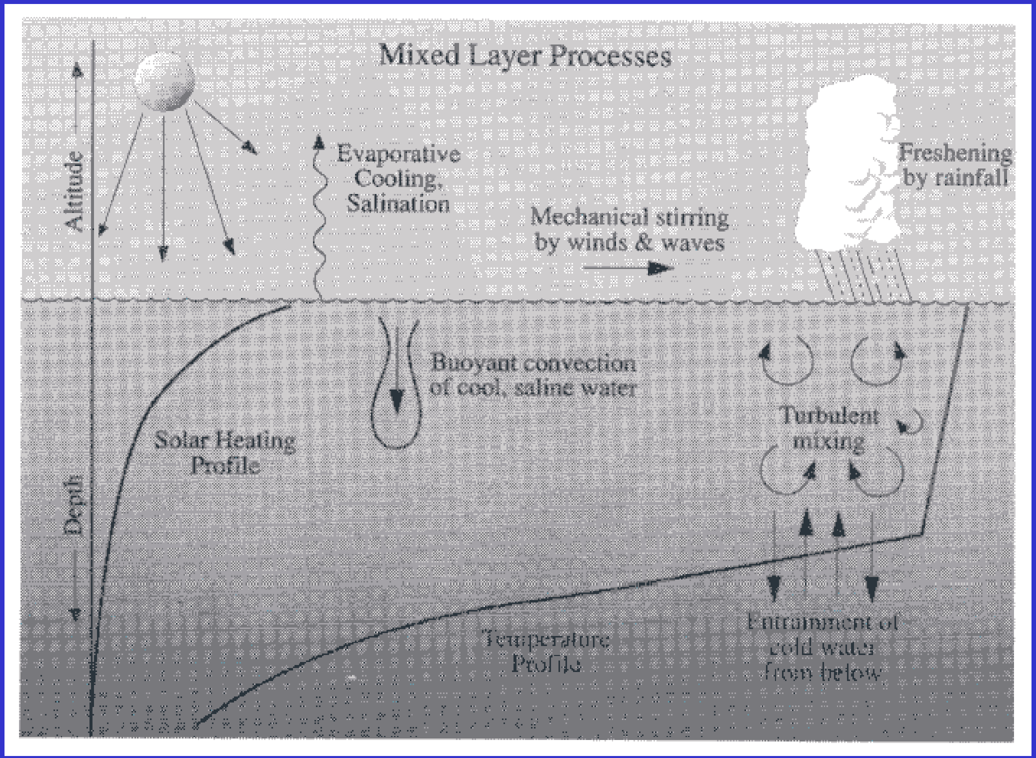
Mixed Layer: T and S well mixed by winds

Thermocline: large gradient of T and S

Deep Ocean: T and S independent of height
cold
salty
high nutrient level

(from *Climate System Modeling*)

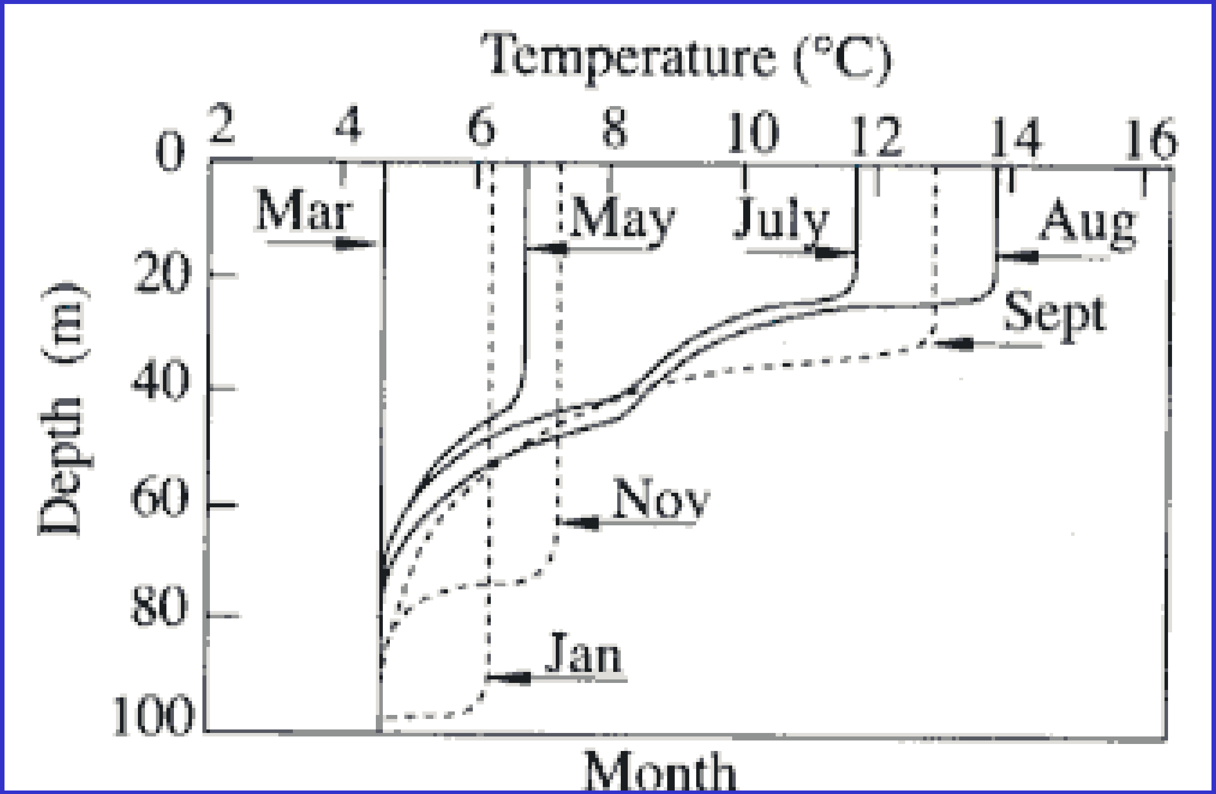
Mixed Layer Processes



(from *Global Physical Climatology*)

- ❑ The depth of the mixed layer is determined by (1) the rate of buoyancy generation and (2) the rate of kinetic energy supply.
- ❑ The atmosphere can affect the mixed layer through three processes: heating, wind forcing, and freshening (P-E).
- ❑ The global-average depth of the mixed layer is about 70 m.
- ❑ The heat capacity of the mixed layer is about 30 times the heat capacity of the atmosphere.

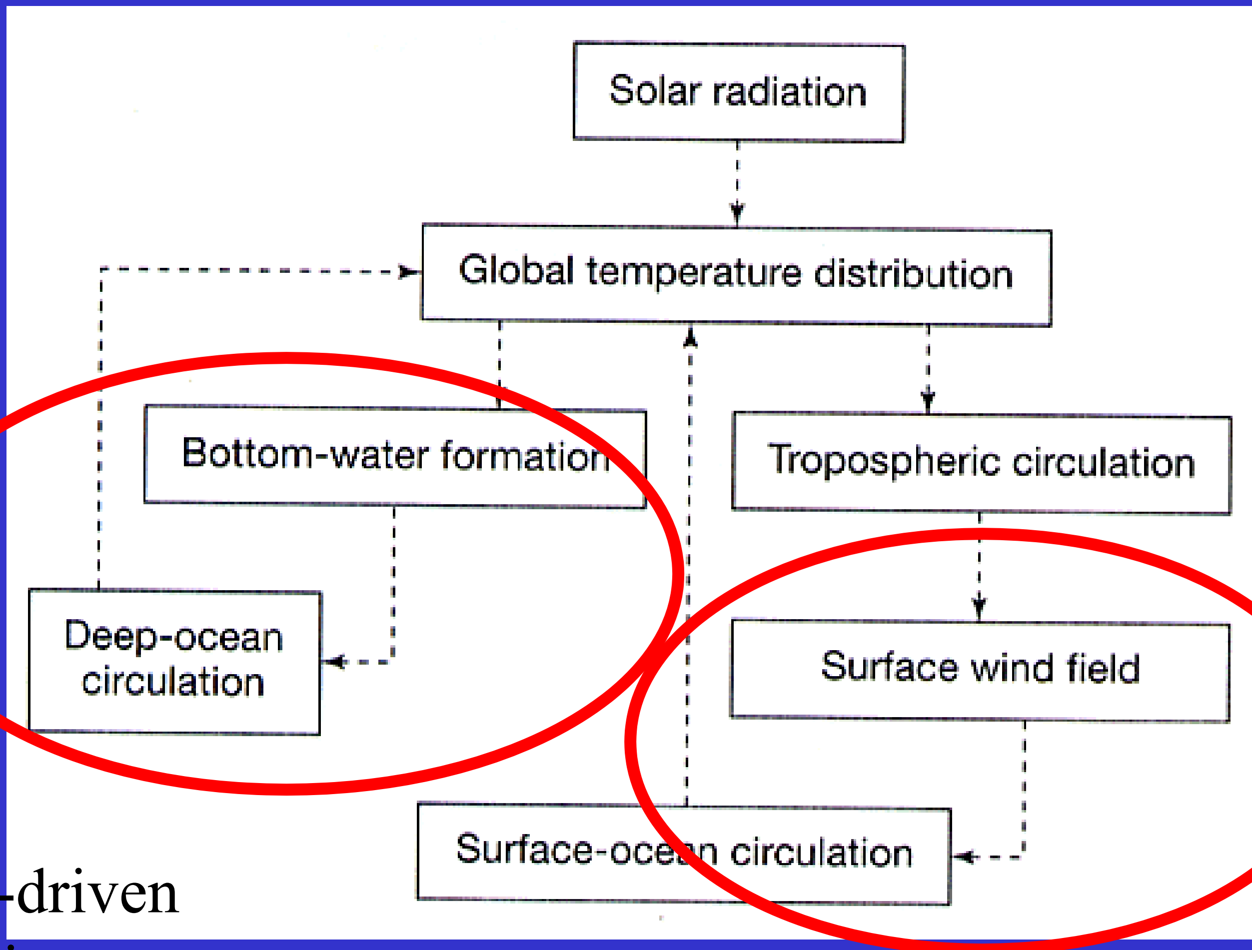
Seasonal Variation of Mixed Layer



(from *Global Physical Climatology*)

- Summer: warm and thin.
- Winter: cold and deep (several hundred meters).

Two Circulation Systems

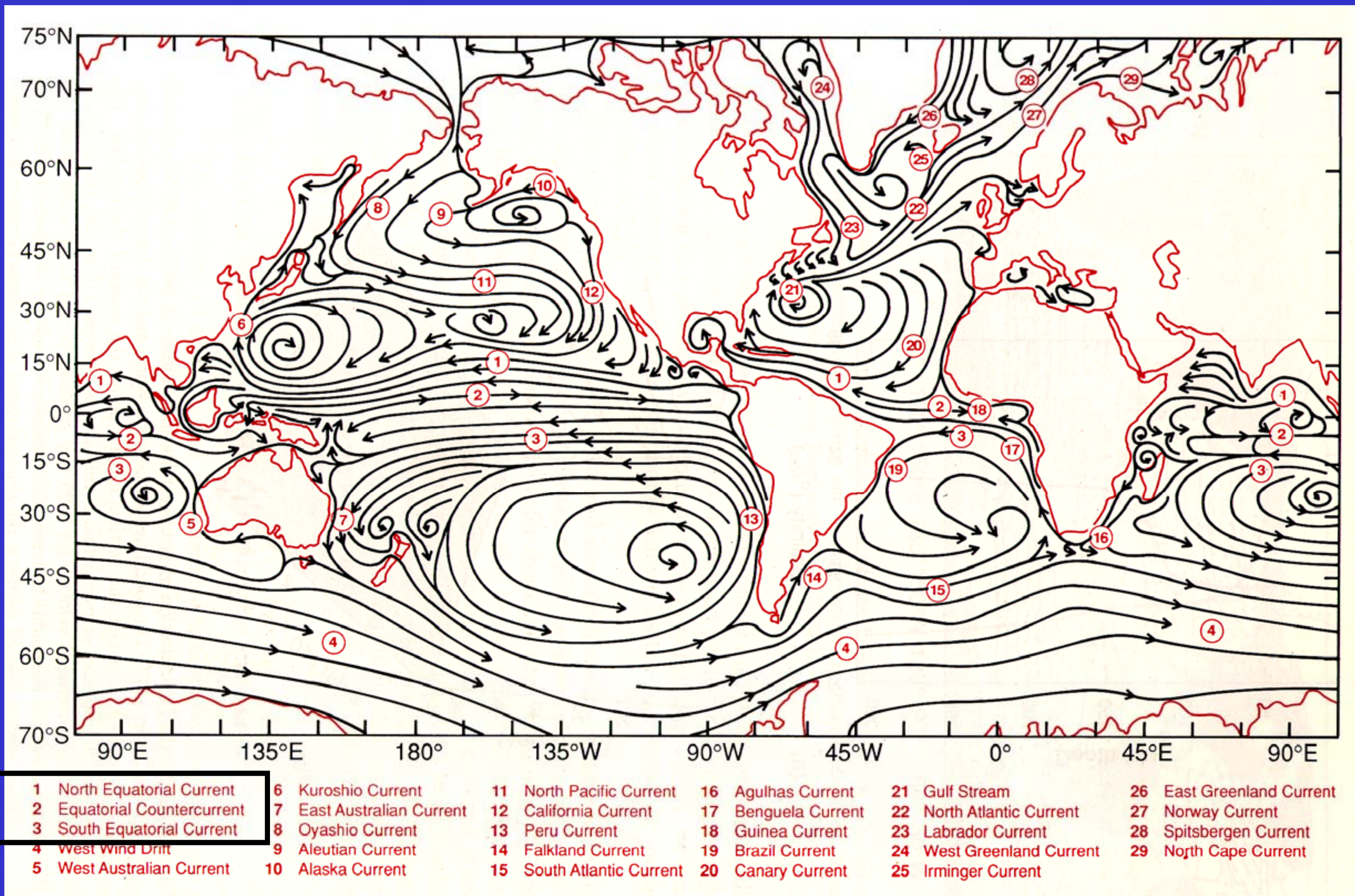


density-driven circulation

wind-driven circulation

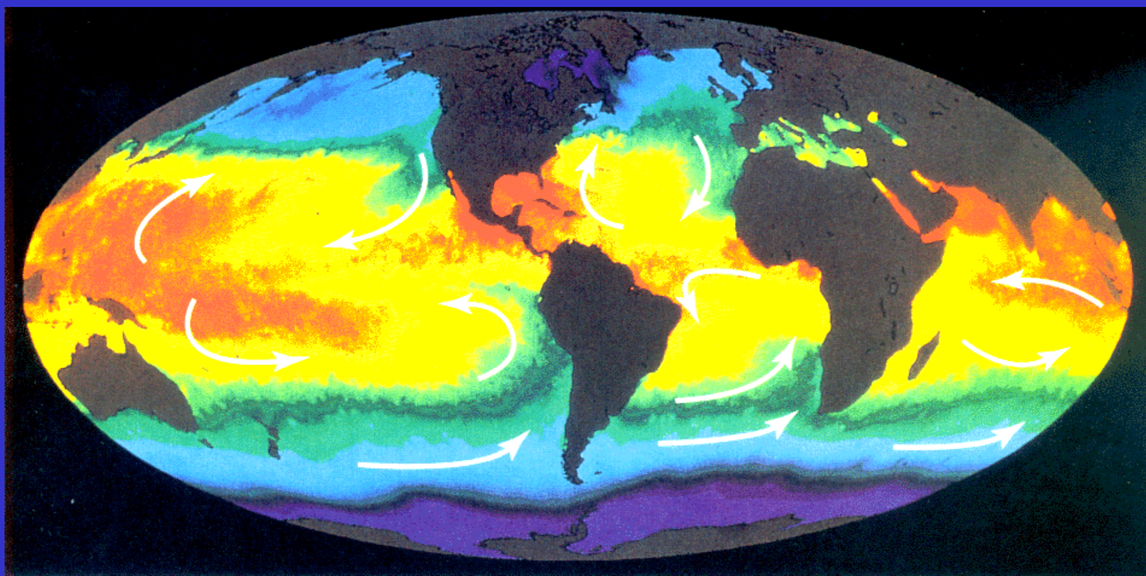
(Figure from *The Earth System*)

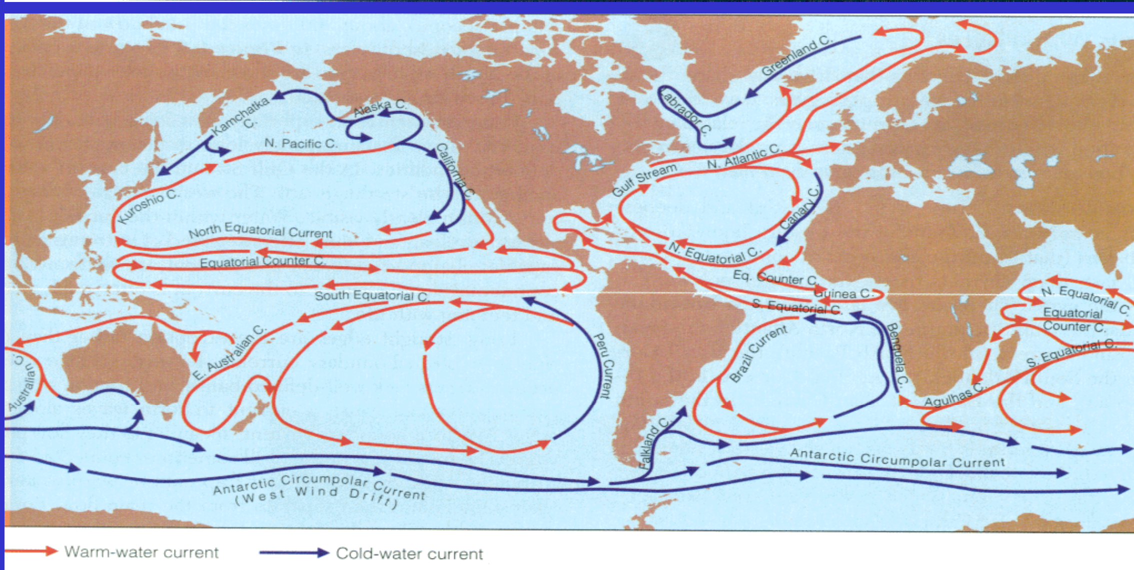
Global Surface Currents



(from *Climate System Modeling*)

Six Great Current Circuits in the World Ocean





- **5 of them are geostrophic gyres:**

  North Pacific Gyre

  South Pacific Gyre

  North Atlantic Gyre

  South Atlantic Gyre

  Indian Ocean Gyre

- **The 6th and the largest current:**

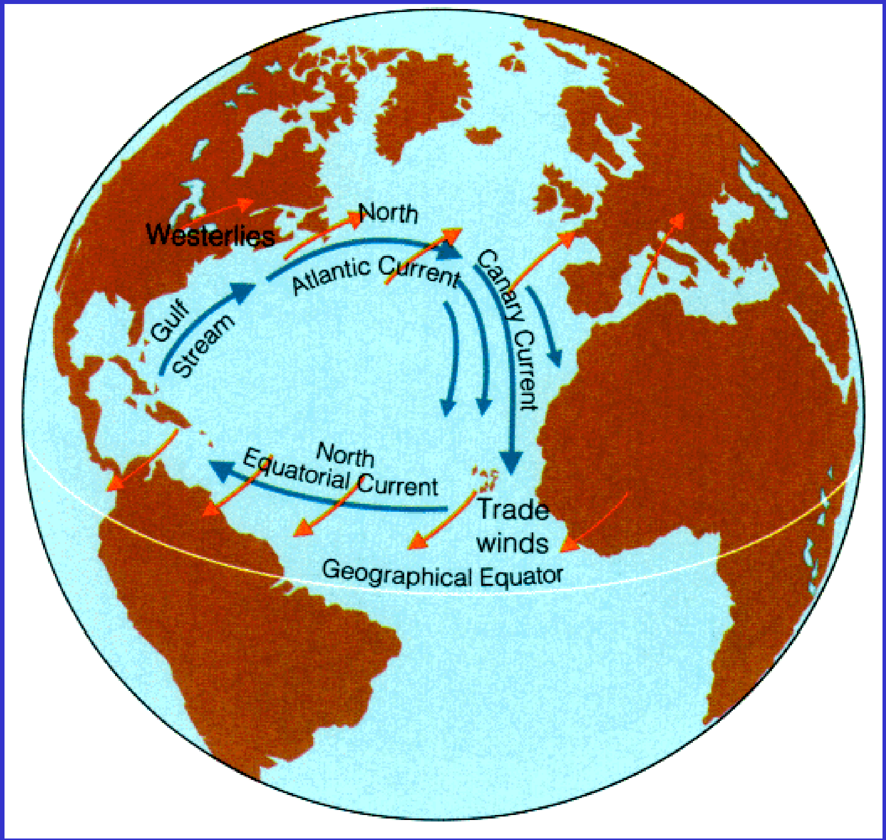
  Antarctic Circumpolr Current

  (also called West Wind Drift)

(Figure from *Oceanography* by Tom Garrison)

Characteristics of the Gyres

(Figure from *Oceanography* by Tom Garrison)



Volume transport unit:

1 sv = 1 Sverdrup = 1 million m^3/sec

(the Amazon river has a transport of ~0.17 Sv)

- **Currents are in geostropic balance**
- **Each gyre includes 4 current components:**

two boundary currents: western and eastern

two transverse currents: easteward and westward

Western boundary current (jet stream of ocean)

the fast, deep, and narrow current moves **warm** water polarward (transport ~50 Sv or greater)

Eastern boundary current

the slow, shallow, and broad current moves cold water equatorward (transport ~ 10-15 Sv)

Trade wind-driven current

the moderately shallow and broad westward current (transport ~ 30 Sv)

Westerly-driven current

the wider and slower (than the trade wind-driven current) eastward current

Major Current Names

- **Western Boundary Current**

  Gulf Stream (in the North Atlantic)
  Kuroshio Current (in the North Pacific)
  Brazil Current (in the South Atlantic)
  Eastern Australian Current (in the South Pacific)
  Agulhas Current (in the Indian Ocean)

- **Eastern Boundary Current**

  Canary Current (in the North Atlantic)
  California Current (in the North Pacific)
  Benguela Current (in the South Atlantic)
  Peru Current (in the South Pacific)
  Western Australian Current (in the Indian Ocean)

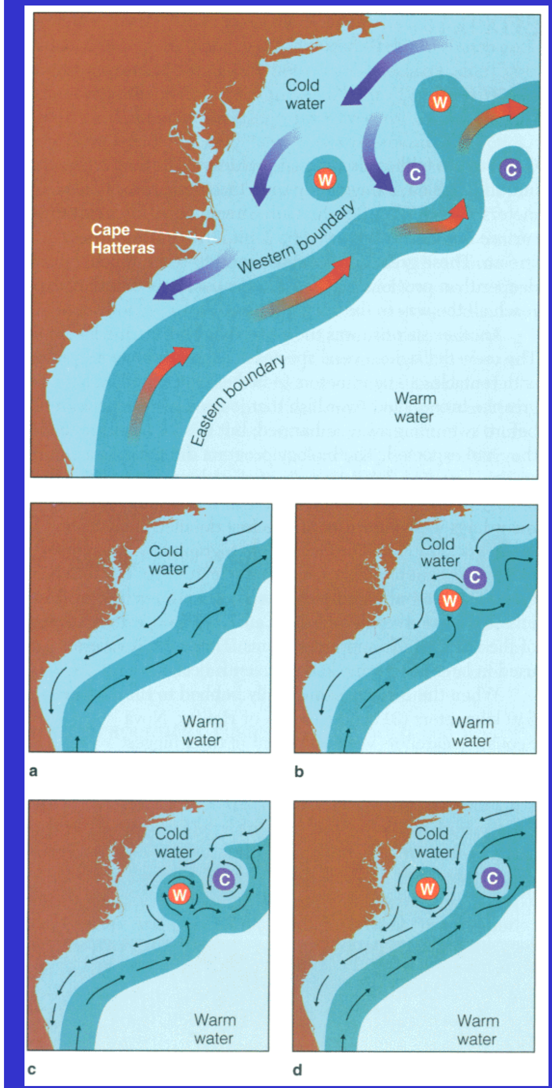
- **Trade Wind-Driven Current**

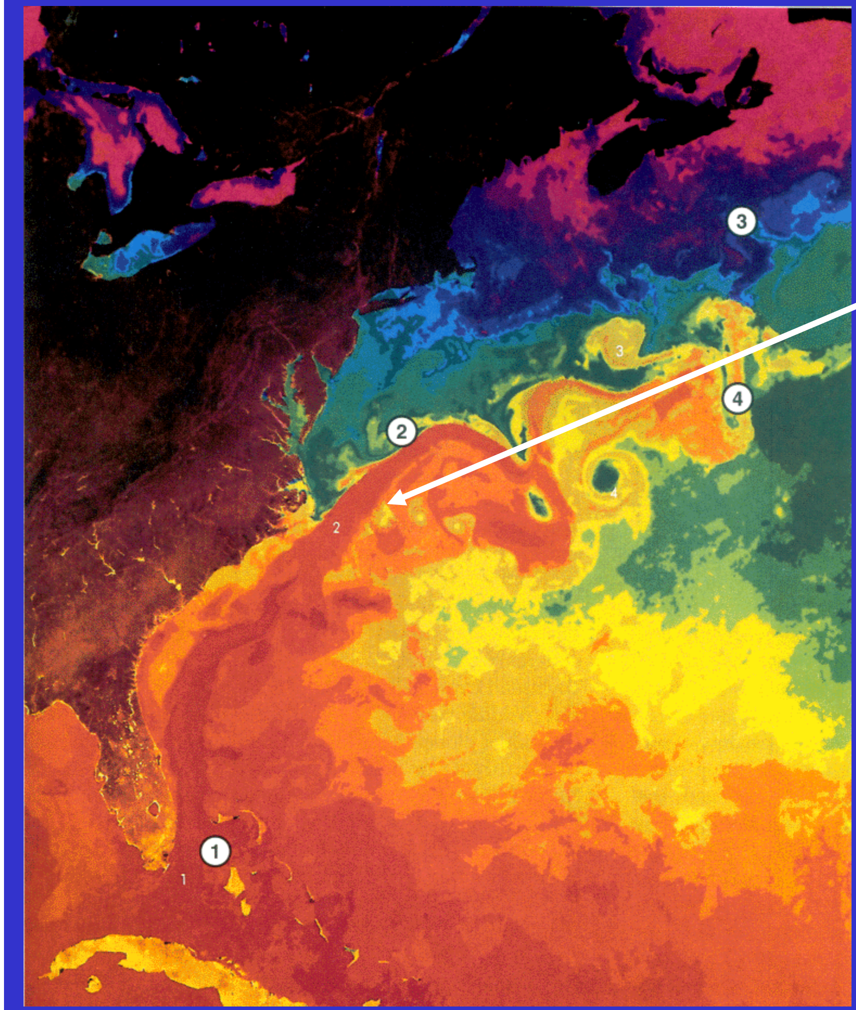
  North Equatorial Current
  South Equatorial Current

- **Westerly-Driven Current**

  North Atlantic Current (in the North Atlantic)
  North Pacific Current (in the North Pacific)

Gulf Stream





A river of current

Jet stream in the ocean

- Speed = 2 m/sec
- Depth = 450 m
- Width = 70 Km
- Color: clear and blue

(Figure from *Oceanography* by Tom Garrison)

Surface Current – Geostrophic Gyre

❑ Mixed Layer

Currents controlled by frictional force + Coriolis force

→ wind-driven circulation

→ Ekman transport (horizontal direction)

→ convergence/divergence

→ downwelling/upwelling at the bottom of mixed layer

❑ Thermocline

downwelling/upwelling in the mixed layer

→ pressure gradient force + Coriolis force

→ geostrophic current

→ Sverdrup transport (horizontal)

Step 1: Surface Winds

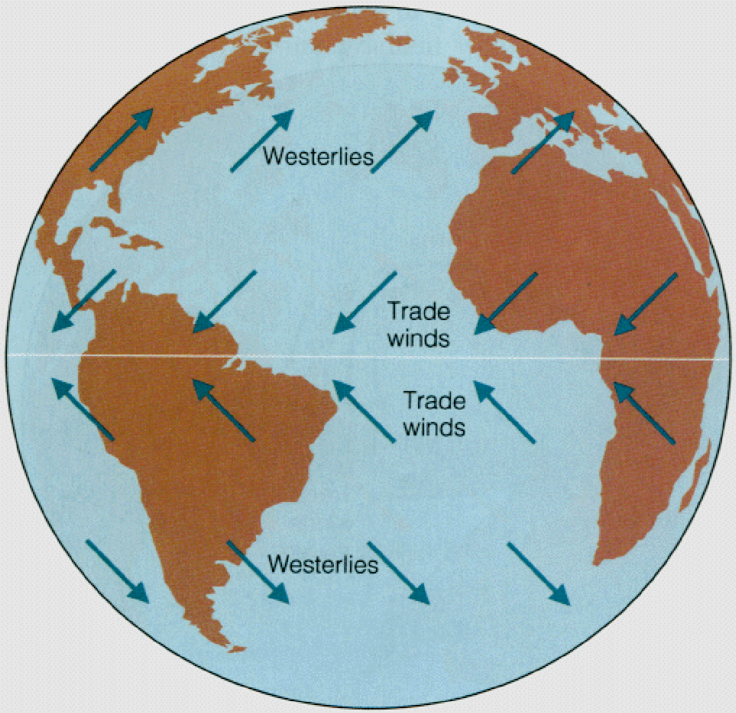


Figure 9.1 Winds, driven by uneven solar heating and Earth's spin, drive the movement of the ocean's surface currents. The prime movers are the powerful westerlies and the persistent trade winds (easterlies).

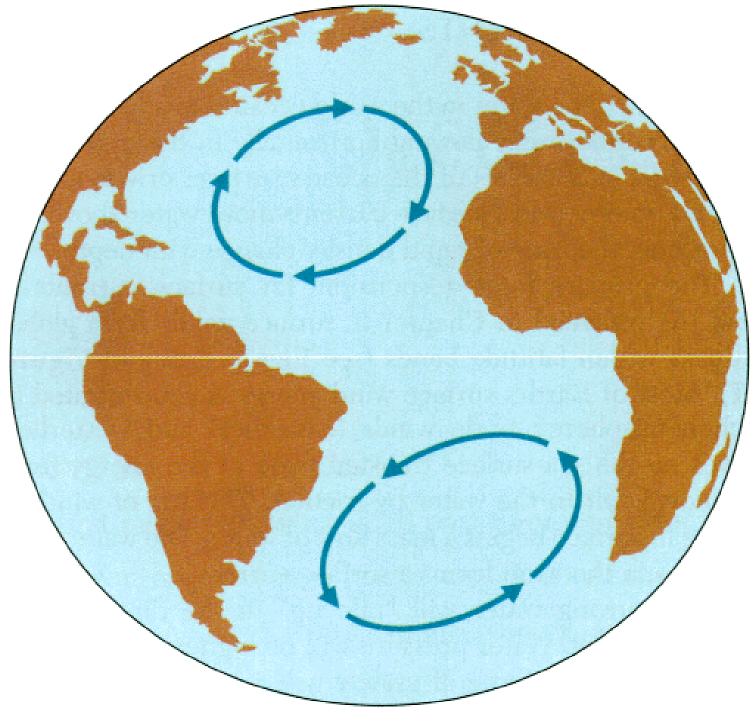
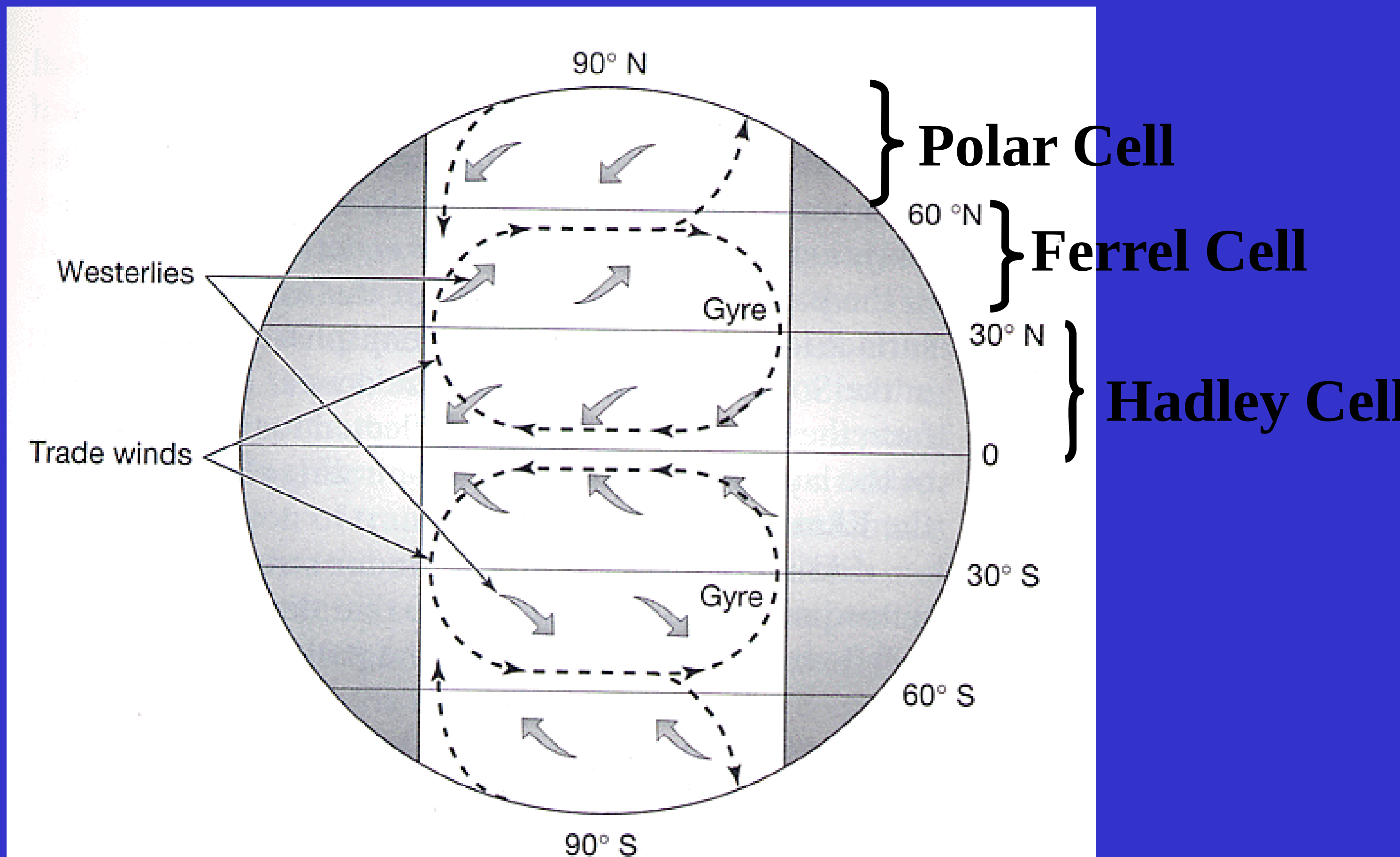


Figure 9.2 A combination of four forces—surface winds, the sun's heat, the Coriolis effect, and gravity—circulates the ocean surface clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere, forming gyres.

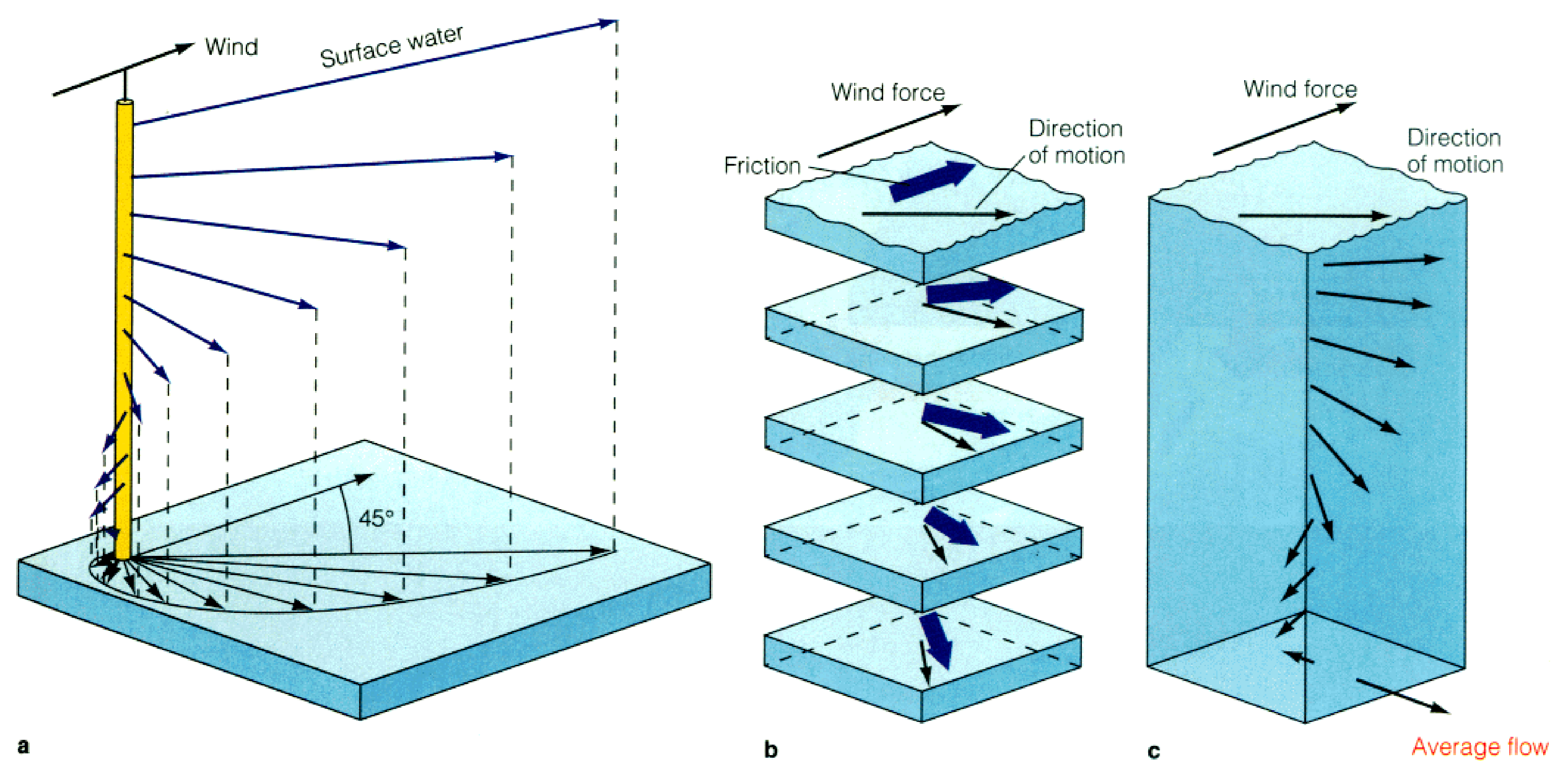
(Figure from *Oceanography* by Tom Garrison)

Winds and Surface Currents



(Figure from *The Earth System*)

Step 2: Ekman Layer
(frictional force + Coriolis Force)



(Figure from *Oceanography* by Tom Garrison)

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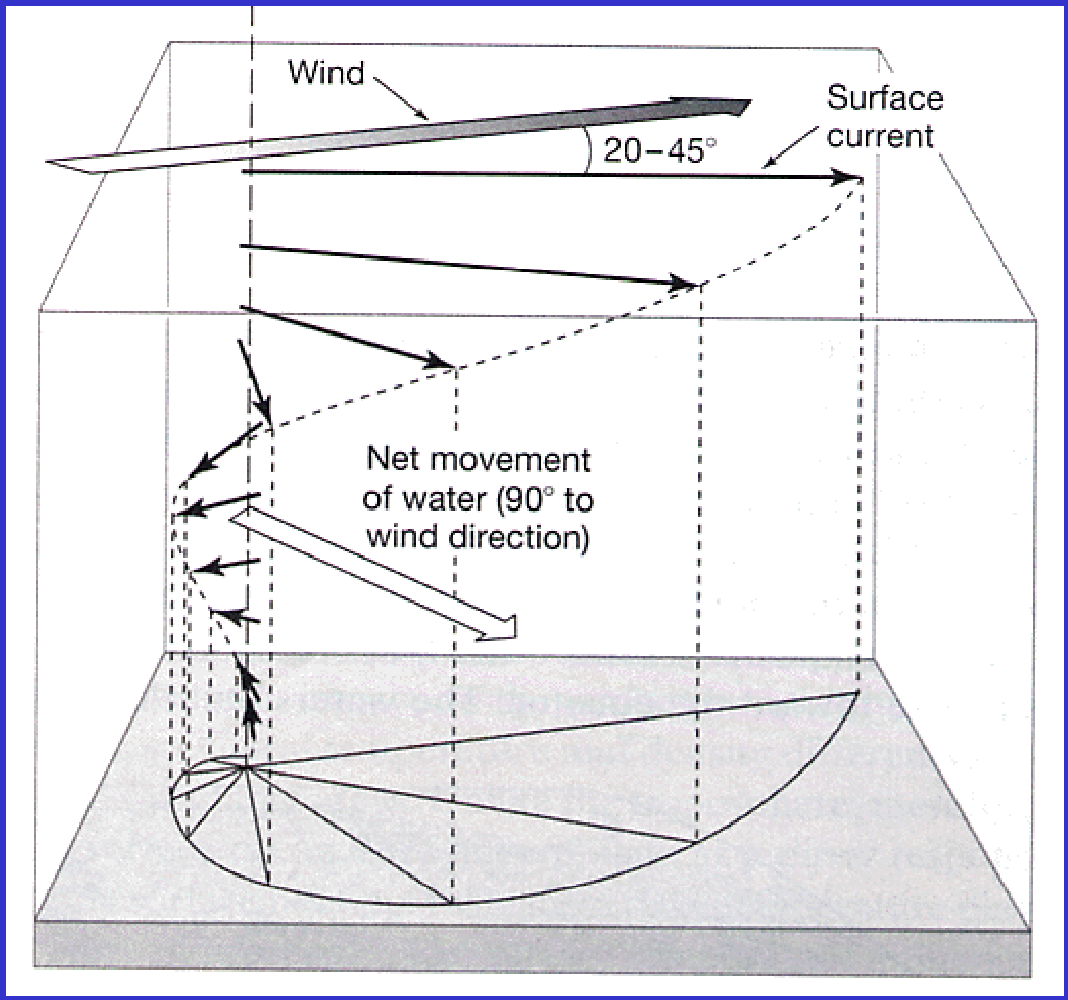
Ekman Spiral – A Result of Coriolis Force



(Figure from *The Earth System*)

Formula for Ekman Transport

$$U_E = \int_{-\infty}^{0} u_E \; dz = \frac{\tau_y}{\rho_o f}; \qquad V_E = \int_{-\infty}^{0} \upsilon_E \; dz = -\frac{\tau_x}{\rho_o f}$$

How Deep is the Ekman Layer?

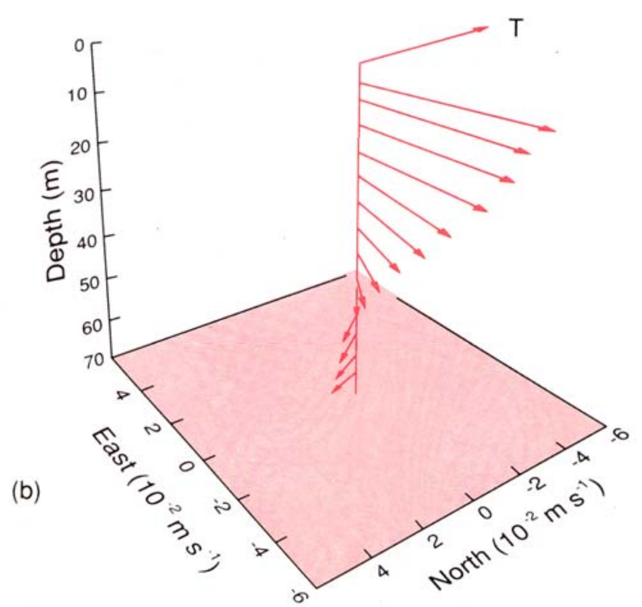


Fig. 4.4 (a) Vertical distribution of temperature and salinity at 50°N., 145°W. in early September, 1977. The solid lines are before a storm and the dotted lines are after a storm, which depict the vertical mixing above the seasonal thermocline. The main thermocline, or pycnocline in this area is between 110 m and 160 m depth. (b) Time-averaged velocity for a 25 day summer period at an open ocean site southwest of Bermuda. Current meter measured velocity is referenced to 70 m. The topmost dashed vector is the time-averaged wind stress (Price et al., 1986).

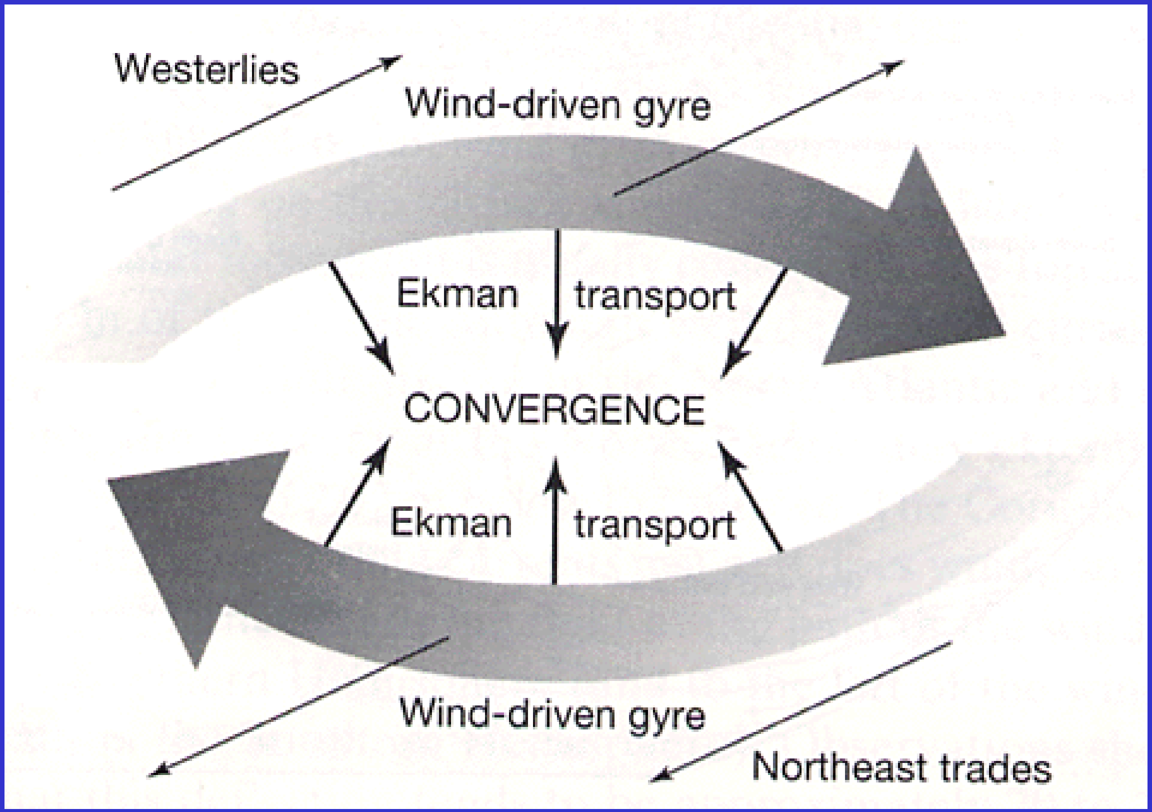
(from *Climate System Modeling*)

- $D \propto (\nu/f)^{1/2}$

ν = vertical diffusivity of momentum

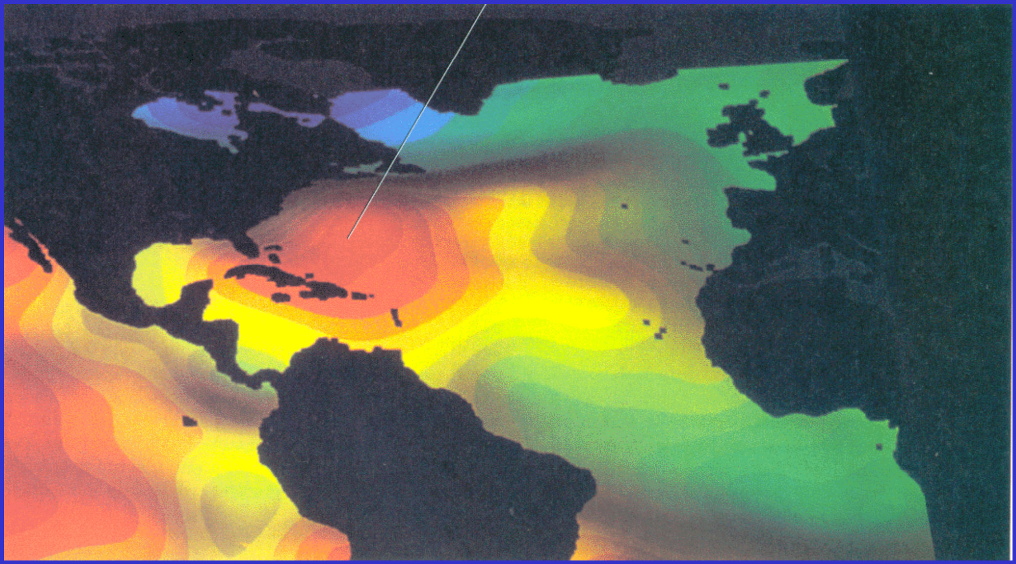
f = Coriolis parameter = $2\Omega\sin\phi$

Ekman Transport

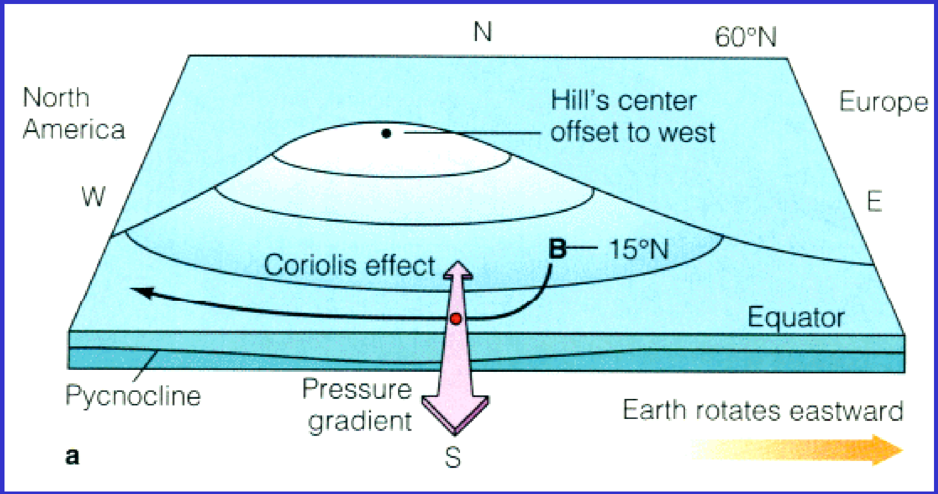


(Figure from *The Earth System*)

Step 3: Geostrophic Current
(Pressure Gradient Force + Corioils Foce)



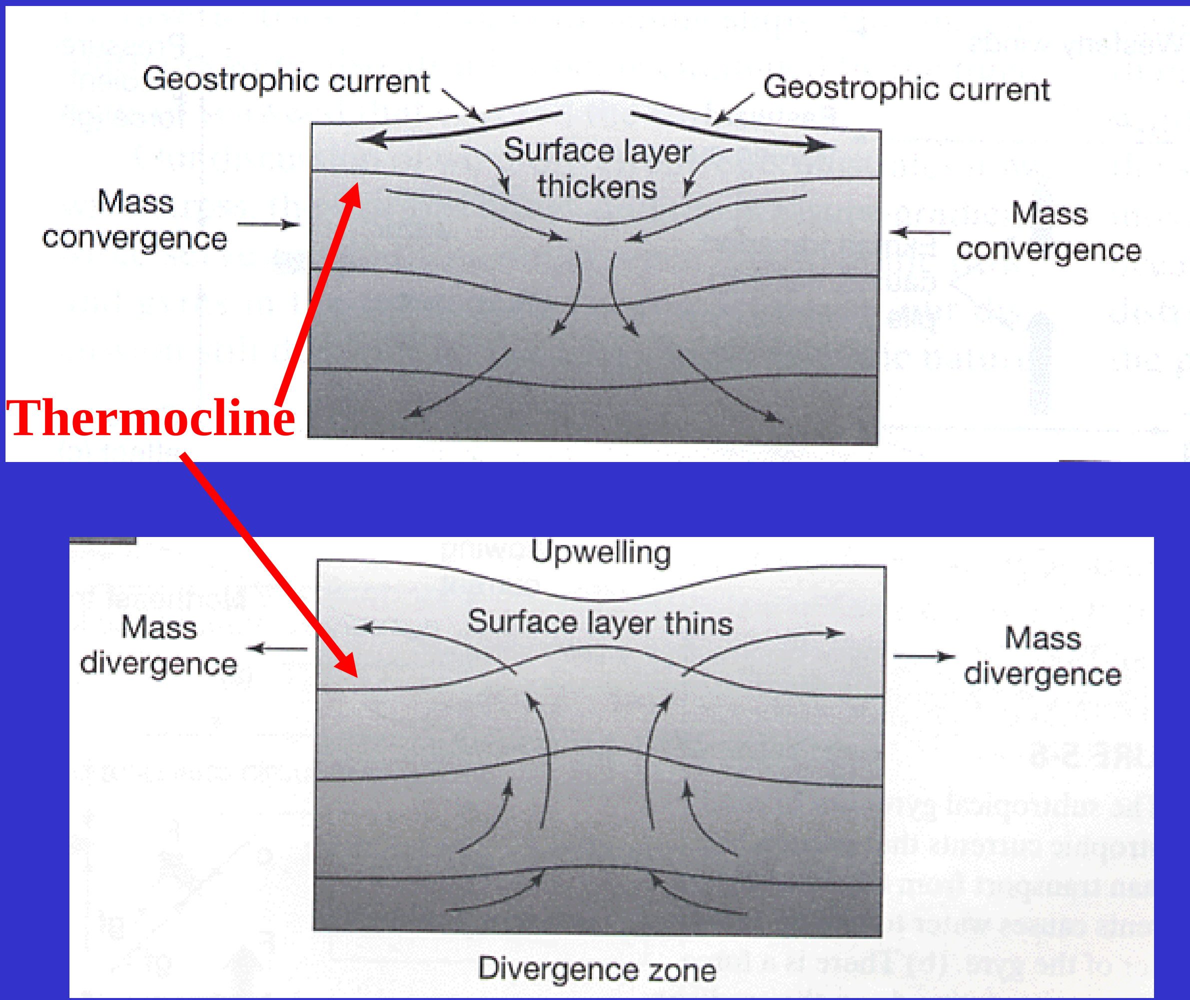
NASA-TOPEX Observations of Sea-Level Hight



(from *Oceanography* by Tom Garrison)

Ekman Transport → Convergence/Divergence

(Figure from *The Earth System*)



Surface wind + Coriolis Force

↓

Ekman Transport

↓

Convergence/divergence (in the center of the gyre)

↓

Pressure Gradient Force

↓

Geostrophic Currents

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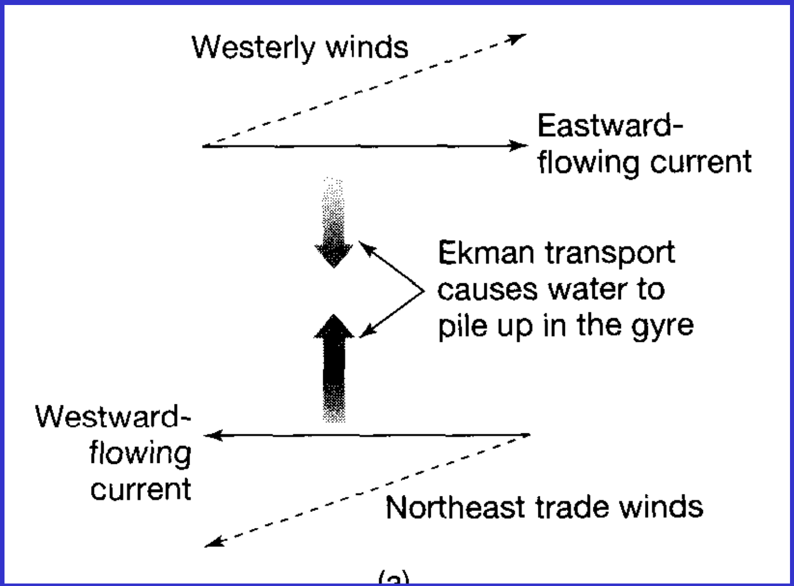
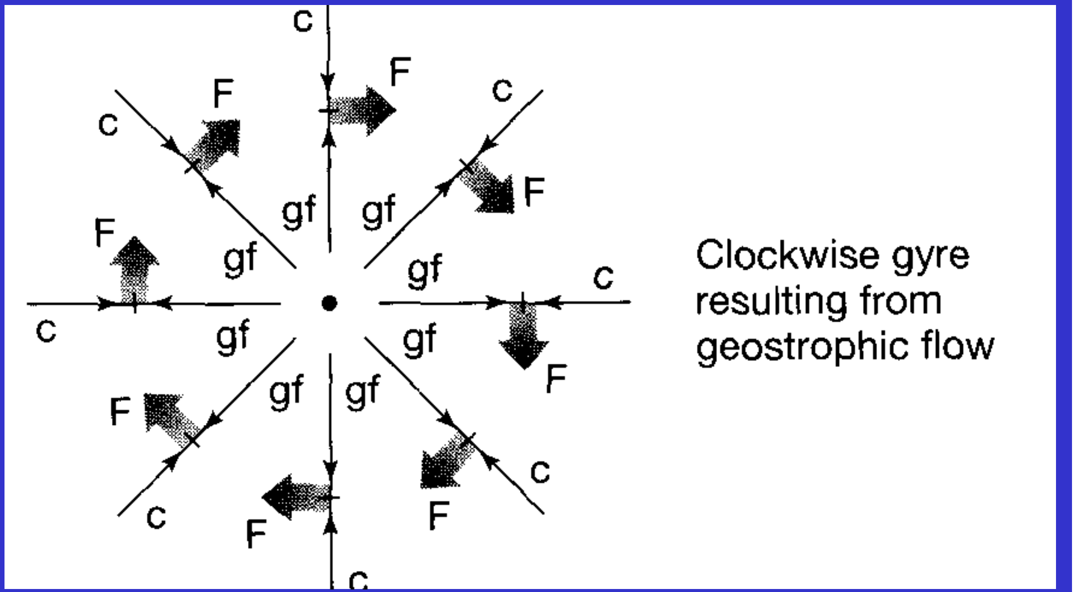
Geostrophic Current

Forces



Geostrophic Gyre Currents



(Figure from *The Earth System*)

Sverdrup Transport

$$V = \hat{\mathbf{k}} \cdot \frac{\nabla \times \tau}{\beta}.$$

- Continuity equation for an incompressible flow:

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

- Assume the horizontal flows are geostrophic:

$$\frac{\partial u_g}{\partial x} + \frac{\partial v_g}{\partial x} + \frac{\partial w}{\partial z} = 0$$

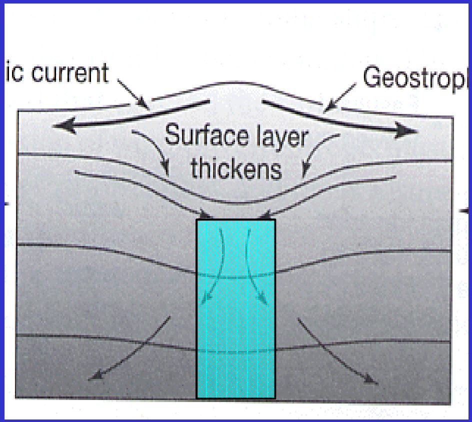
- Replace the geostrophic flow pressure gradients:

$$fu_g = -\frac{1}{\rho}\frac{\partial P}{\partial y}$$

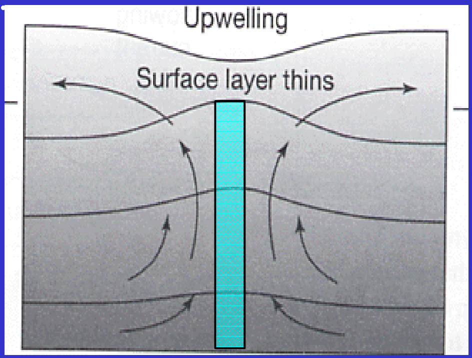
$$fv_g = \frac{1}{\rho}\frac{\partial P}{\partial y}$$

- The continuity equation becomes:

$$\frac{-\beta}{f} v_g + \frac{\partial w}{\partial z} = 0 \Rightarrow \boxed{\beta v_g = f\frac{\partial w}{\partial z}}$$



Ekman layer pumping
➔ vertical depth decreases
➔ move equatorward to conserve absolute vorticity.



Ekman layer suction
➔ vertical depth increases
➔ move poleward to conserve absolute vorticity.

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Sverdrup Transport

$$V = \hat{\mathbf{k}} \cdot \frac{\nabla \times \tau}{\beta}.$$

- Continuity equation for an incompressible flow:

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

- Assume the horizontal flows are geostrophic:

$$\frac{\partial u_g}{\partial x} + \frac{\partial v_g}{\partial x} + \frac{\partial w}{\partial z} = 0$$

- Replace the geostrophic flow pressure gradients:

$$fu_g = -\frac{1}{\rho}\frac{\partial P}{\partial y}$$

$$fv_g = \frac{1}{\rho}\frac{\partial P}{\partial y}$$

- The continuity equation becomes:

$$\frac{-\beta}{f} v_g + \frac{\partial w}{\partial z} = 0$$

- Integrate the equation from the bottom of the upper ocean (D_w) to the bottom of the Ekman layer (D_E):

$$\beta \int_{z=-D_W}^{z=-D_E} v \partial z = f\left[w_E - \cancel{w(-D_W)}\right]$$

assume zero

- Ekman pumping (w_E) is related to the convergence of the Ekman transport:

$$w(-D_E) = \frac{\partial}{\partial x}\left(\frac{\tau^y}{\rho f}\right) - \frac{\partial}{\partial y}\left(\frac{\tau^x}{\rho f}\right)$$

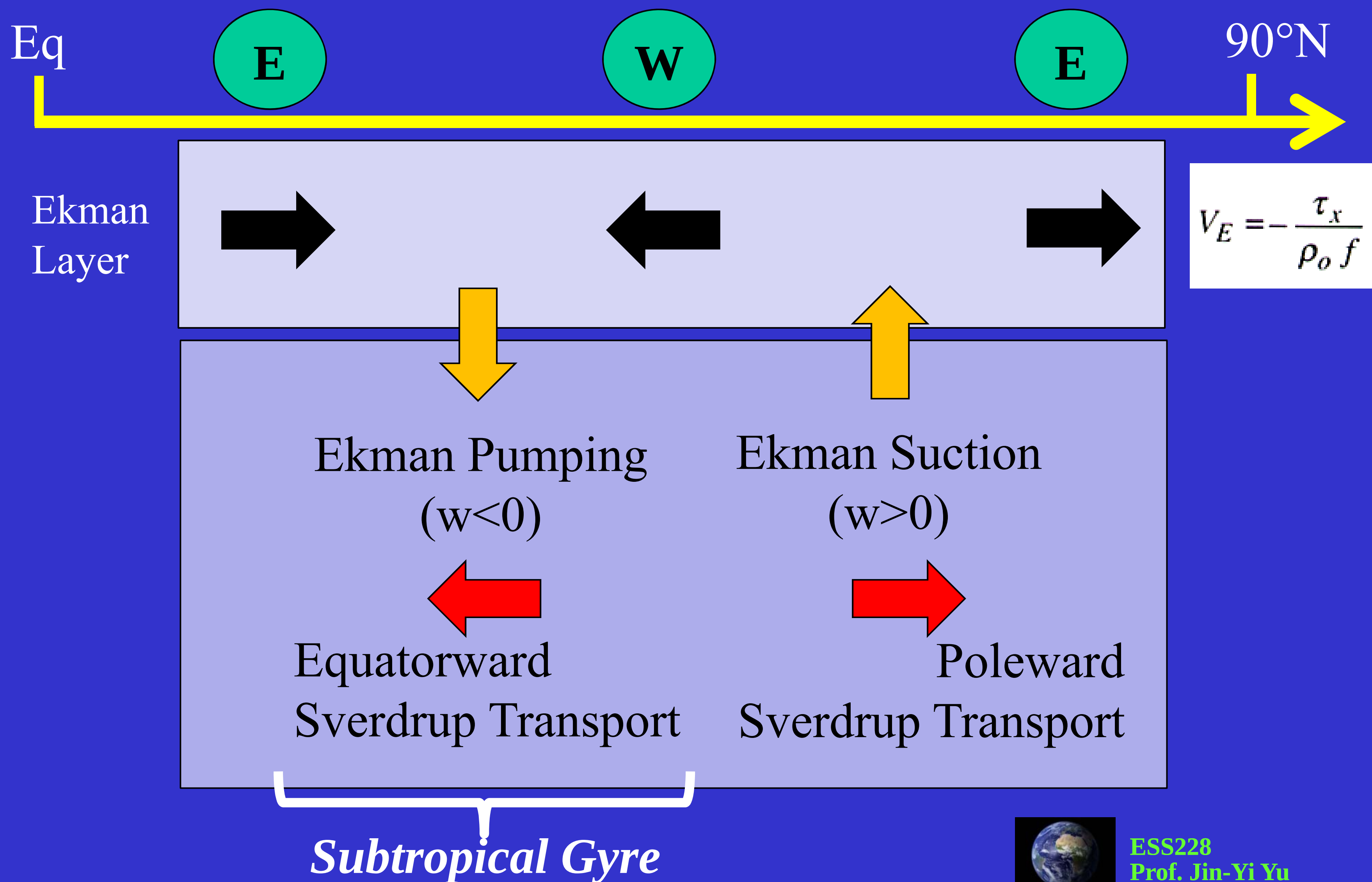
- Therefore, we obtain:

$$\underbrace{\int_{z=-D_W}^{z=-D_E} v \partial z}_{\text{geostrophic transport}} = \underbrace{\frac{1}{\rho\beta}\left(\frac{\partial \tau_W^y}{\partial x} - \frac{\partial \tau_W^x}{\partial y}\right)}_{\text{Sverdrup transport}} + \underbrace{\frac{1}{\rho f}\tau_W^x}_{\text{- (Ekman Transport)}}$$

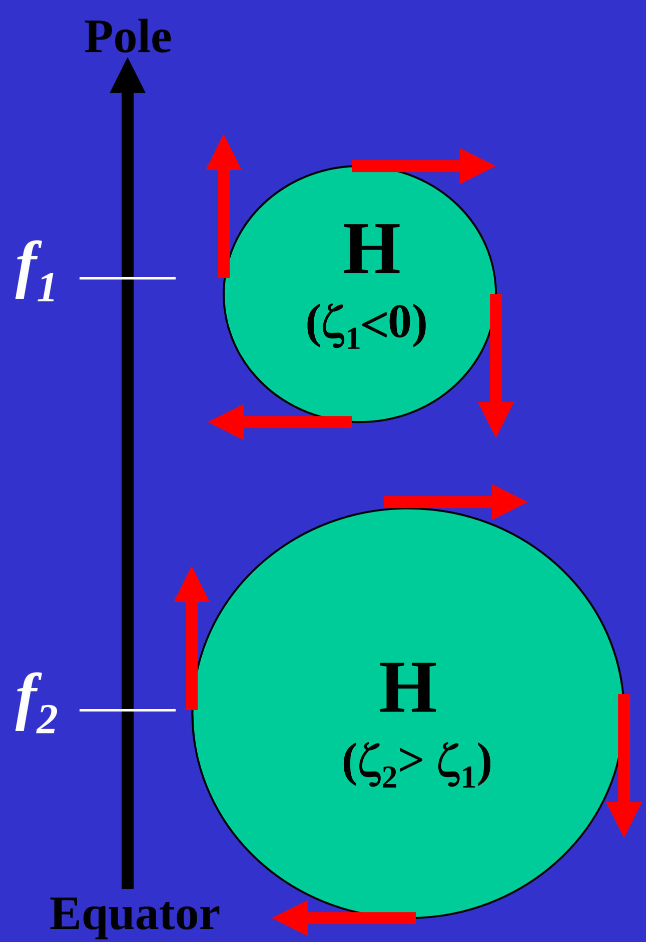
- Therefore,

Sverdrup transport = Geostrophic transport + Ekman transport

Ekman and Sverdrup Transports



Conservation of Potential Vorticity



- Potential Vorticity

  $PV = f + \zeta$

  f = planetary vorticity = $2\Omega\sin\phi$

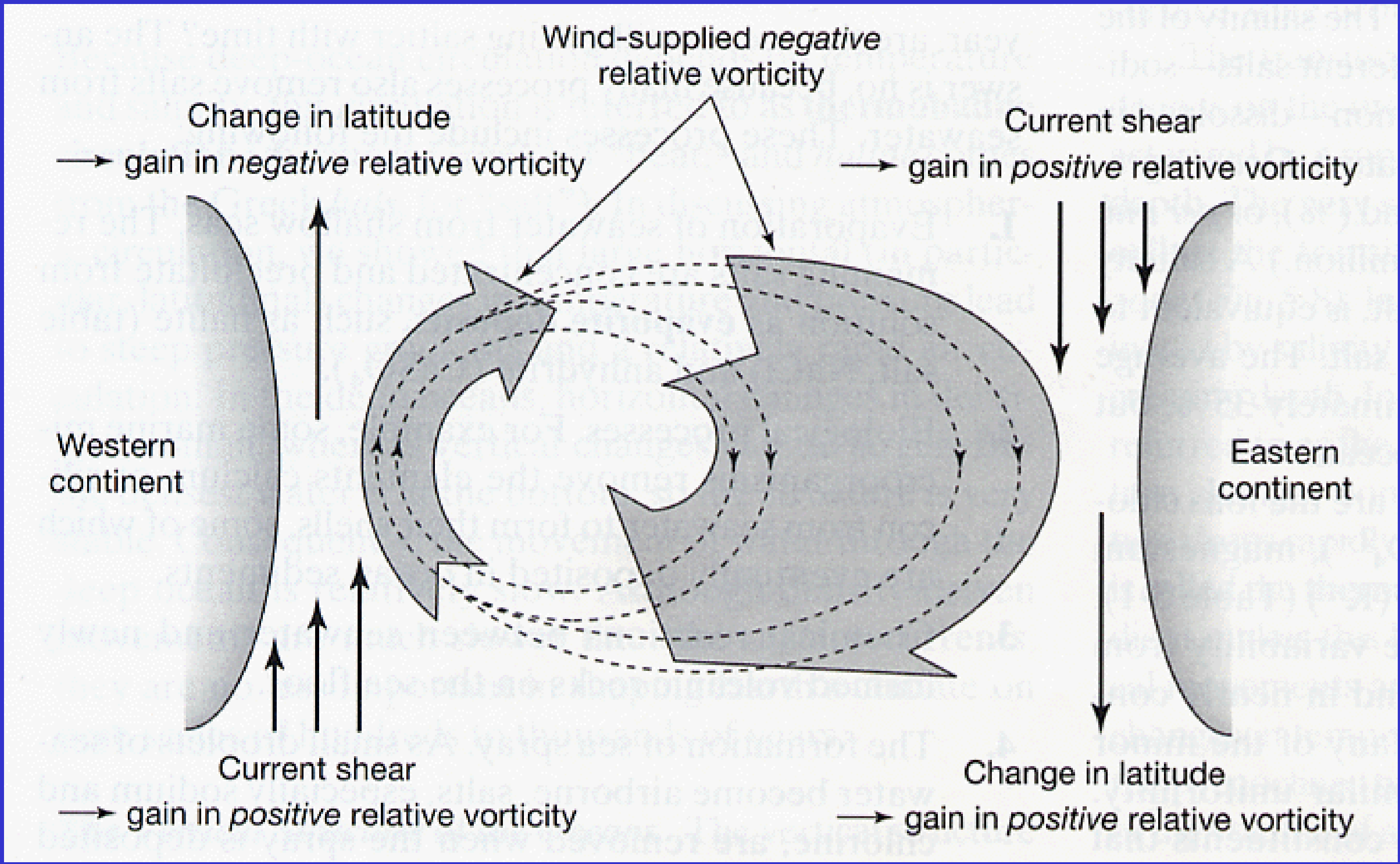
  ζ = relative vorticity = $\partial v/\partial x - \partial u/\partial y$

- $f_1 + \zeta_1 = f_2 + \zeta_2$

  since $f_1 > f_2 \rightarrow \zeta_1 < \zeta_2$

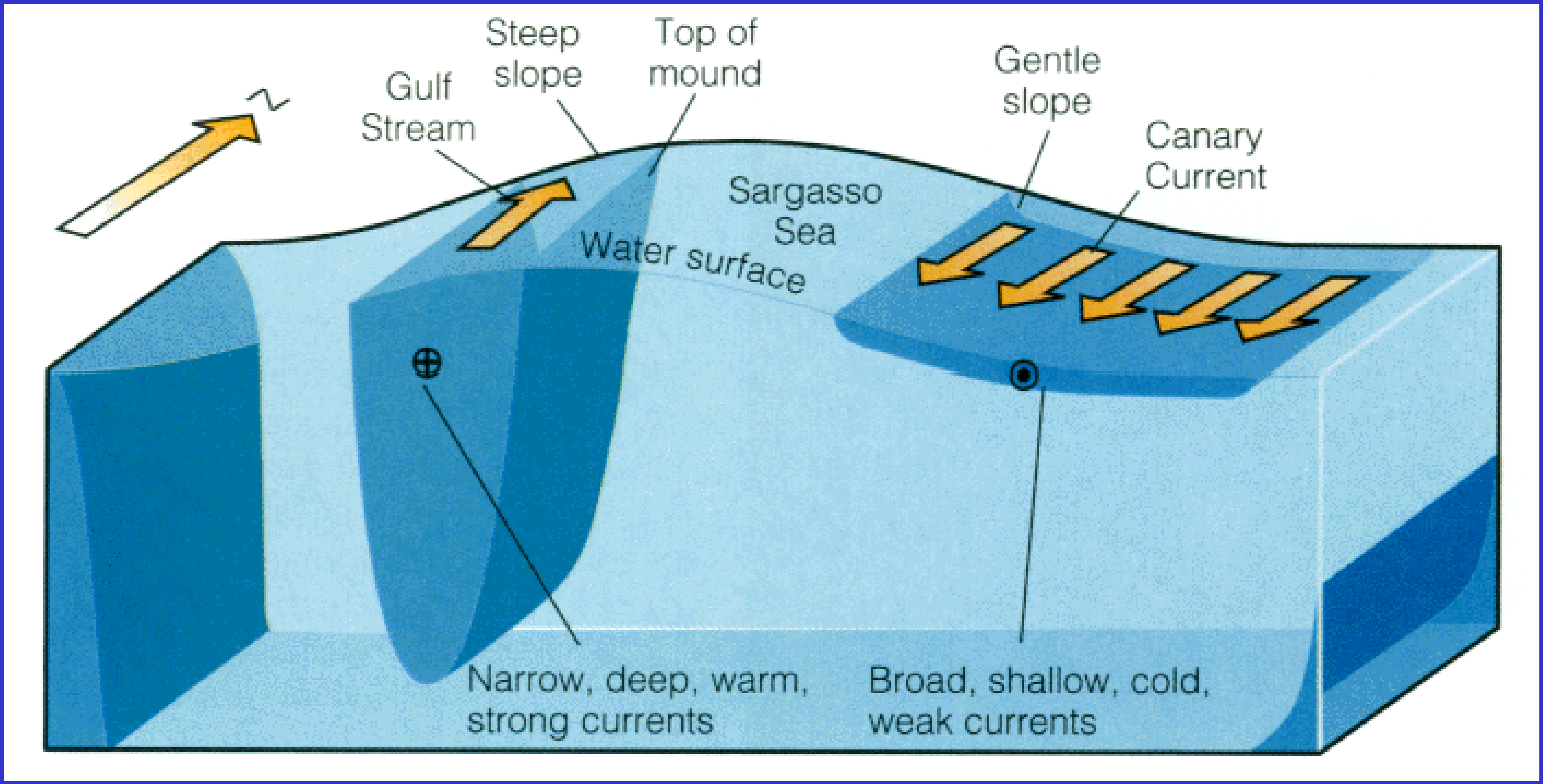
- If $\zeta < 0$, the vortex decreases rotation when moves toward lower latitudes and increases rotation when moves toward higher latitudes.

Boundary Currents



(Figure from *The Earth System*)

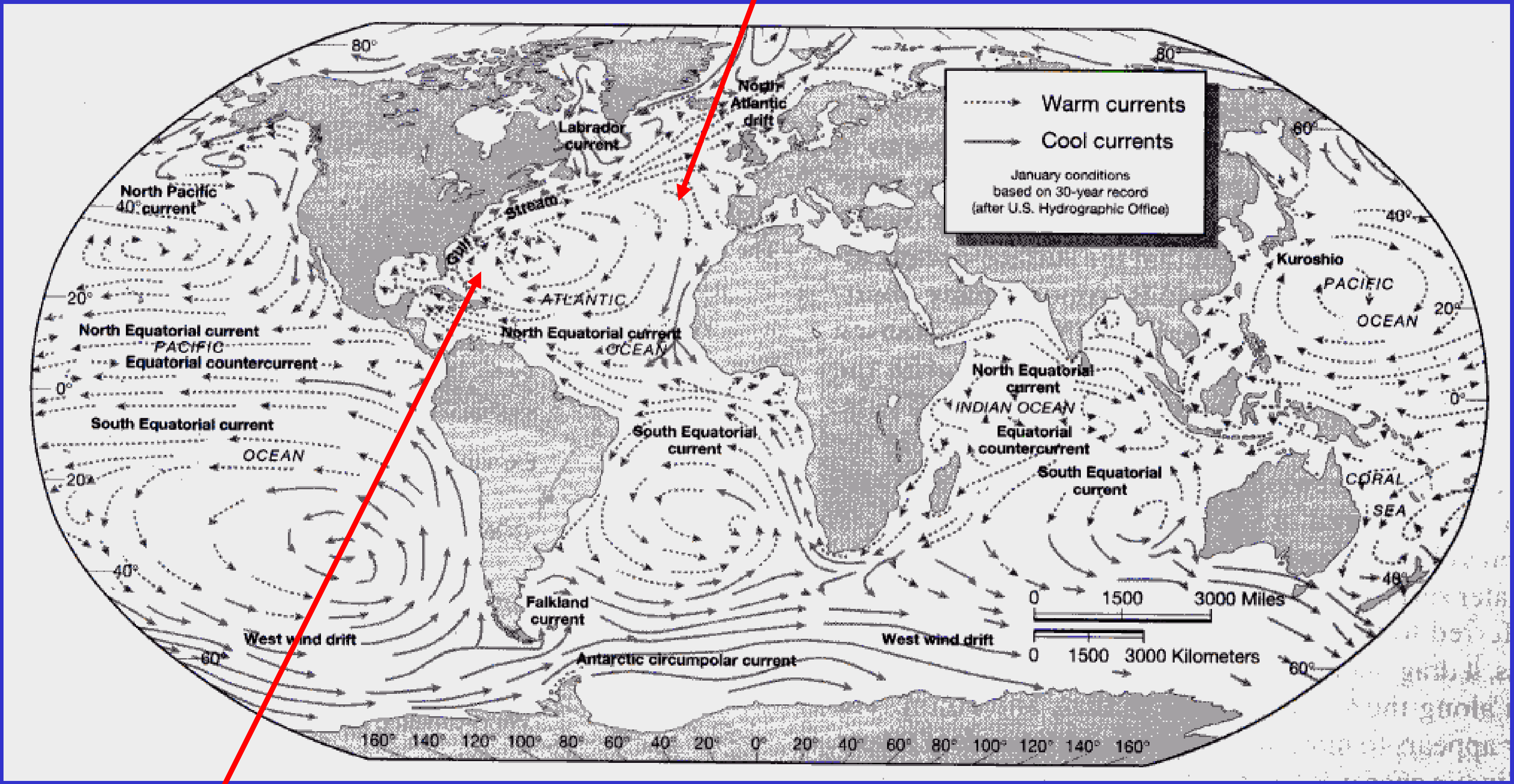
Step 4: Boundary Currents



(Figure from *Oceanography* by Tom Garrison)

Boundary Currents

Eastern boundary currents: broad and weak



Western boundary currents: narrow and strong

Eastern Boundary Current

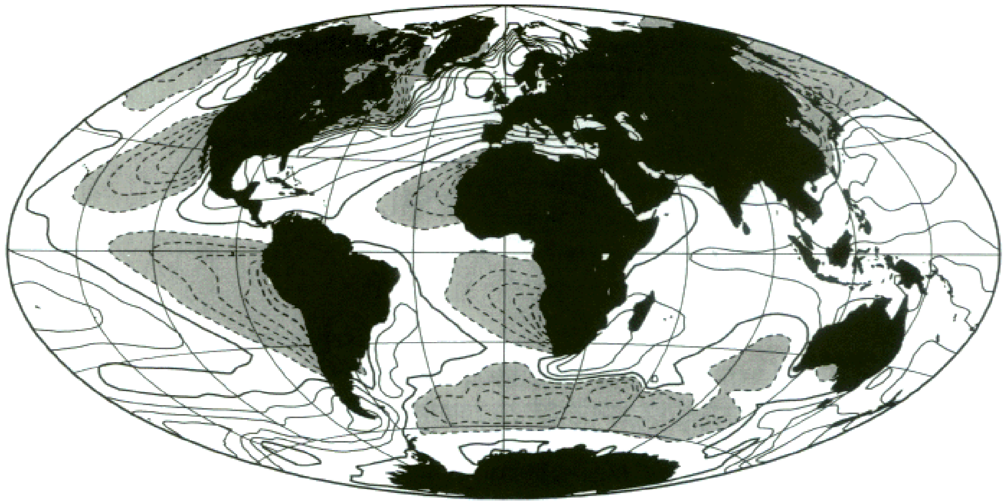
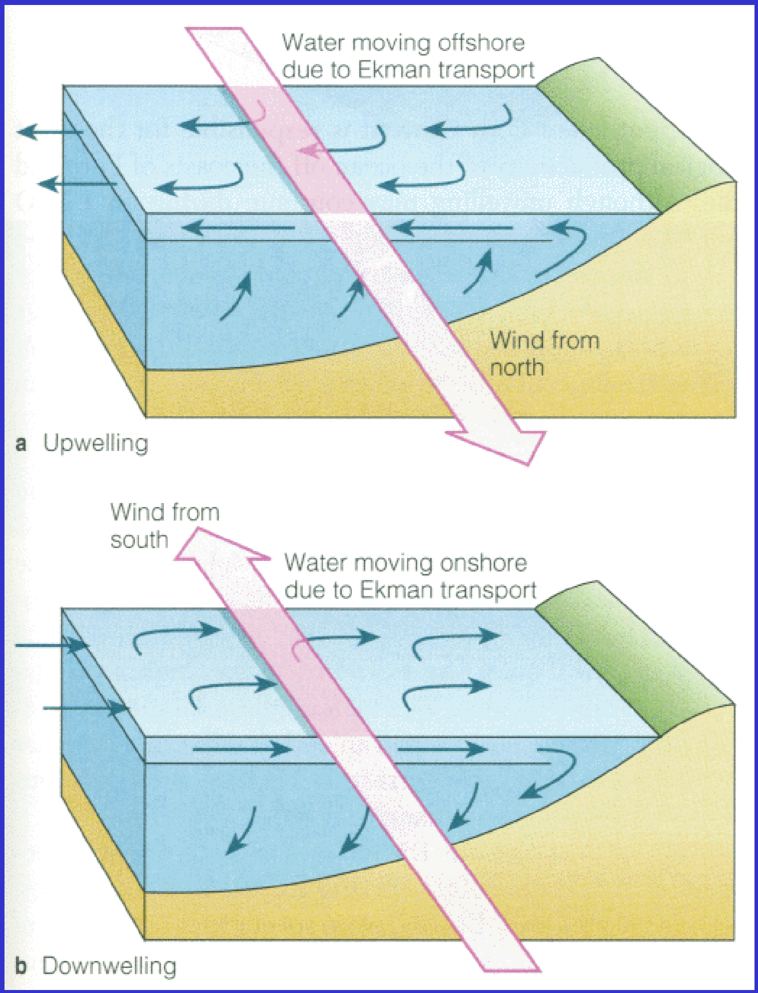


Fig. 7.11 The deviation of the July sea surface temperature from its zonal average at each latitude. Contour interval is 1°C, and values less than –1°C are shaded.

(from *Global Physical Climatology*)

- ❑ Cold water from higher latitude ocean.
- ❑ Costal upwelling associated with subtropical high pressure system.
- ❑ Atmospheric subsidence produce persistent stratiform clouds, which further cool down SSTs by blocking solar radiation.

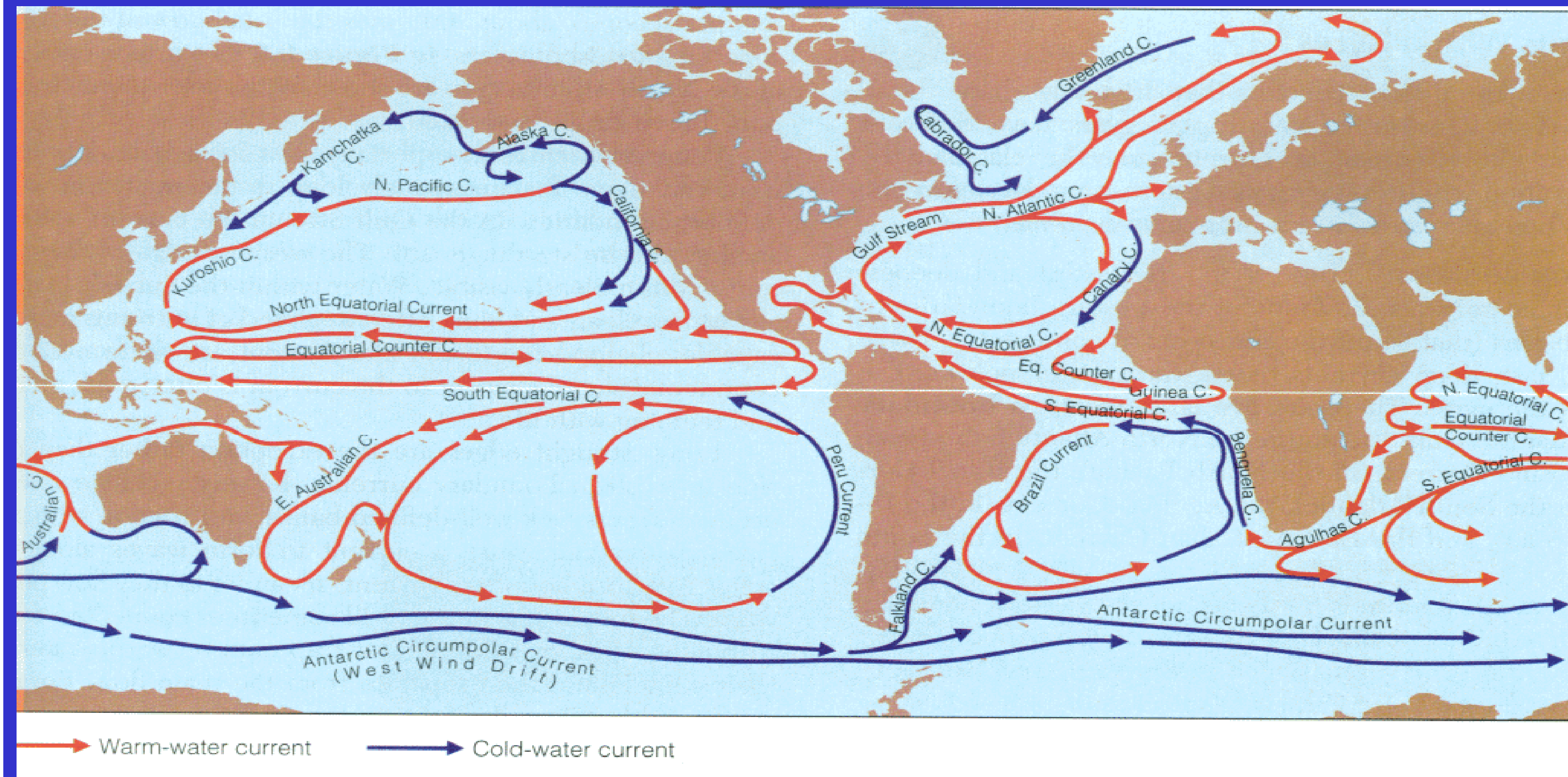
Costal Upwelling/Downwelling



- A result of Ekman transport and mass continuity.

(Figure from *Oceanography* by Tom Garrison)

Global Surface Currents



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