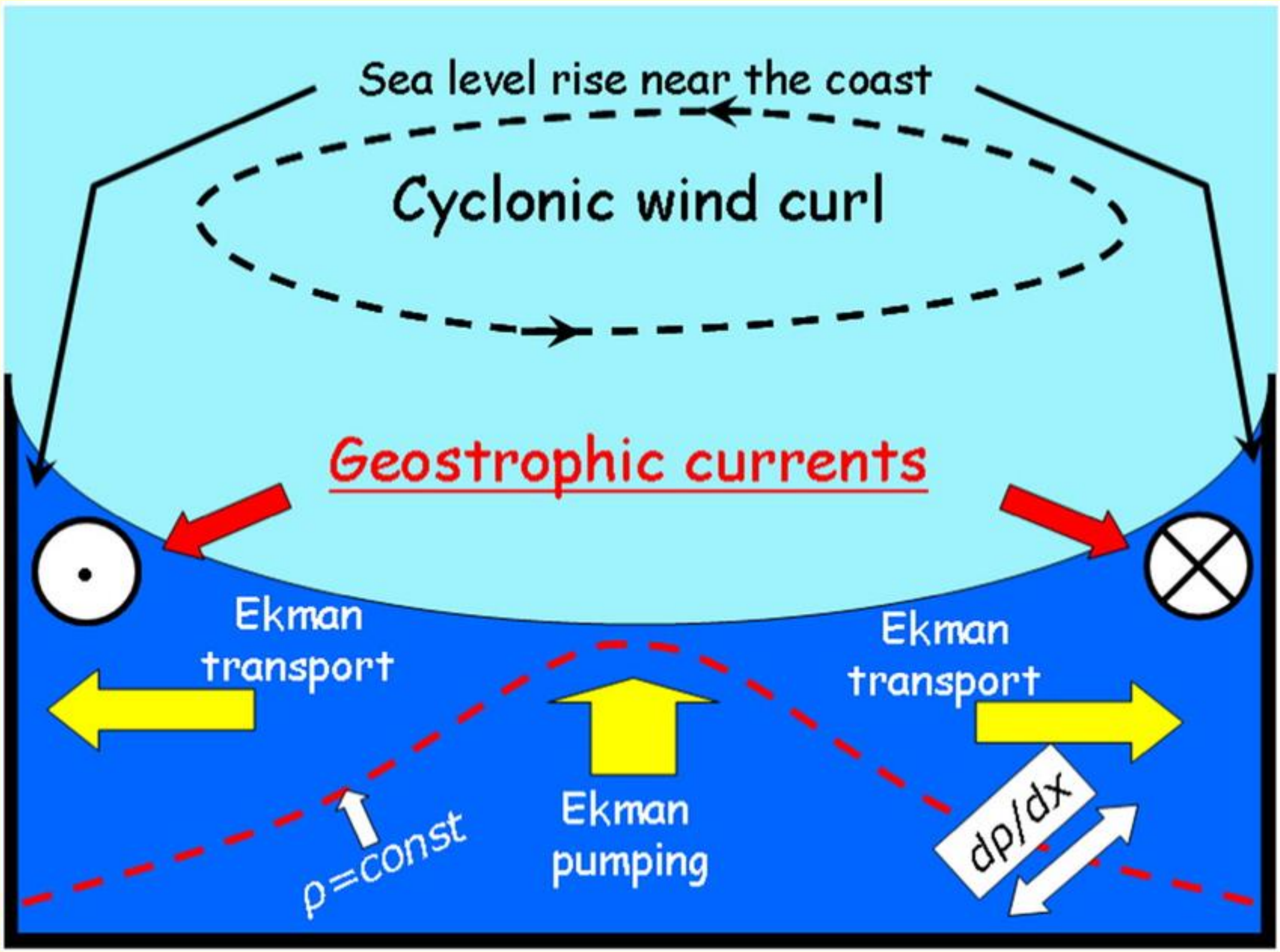
Ekman Transport & Wind Stress Curl



Learning Objectives

- Know the simplifying assumptions used to derive Ekman theory
- Understand the Ekman spiral and how its characteristics vary with latitude
- Know equation to compute Ekman transport from wind stress
- Understand concept of wind stress curl and resultant vertical flow in the sea

Remember

given a constant $tau_{(wind)}$ across latitude

- Ekman layer depth decreases with latitude
- Surface current decreases with latitude
- Mean current decreases with latitude

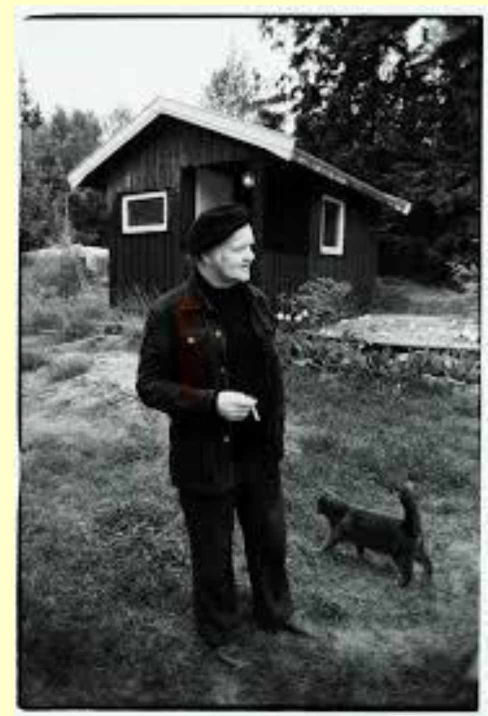
- Therefore:

  Ekman transport decreases with latitude

Ekman Flow Characterized as Mass or Volume Transport

- Mass transport – transport of kg of water
- Volume transport - transport of m^3 of water

- However, standard unit of volume transport:
  Sverdrup SV =
  $1*10^6$ m^3/sec

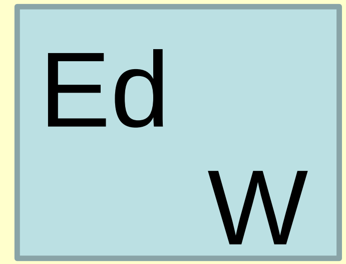


Ekman-Generated Transport (mass and volume)

- Strong latitudinal component
- Mean Ekman surface current decreases with increasing latitude
- Ekman depth decreases with increasing latitude
- Therefore Ekman transport decrease dramatically with increasing latitude

Estimating Ekman Transport (mass and volume)

- Volume transport (Vt)
  - mean Ekman current * E_d * width
  - m/sec * m * m = m^3/sec



- Mass transport (Mt)
  - $Mt_{(x)} = Tau_{(y)} / f$
    (where Tau is wind stress and f is coriolis parameter)
  - Units Tau = kg / (m sec^{-2}) & f = 1/sec
  - Thus, Mt = kg / m sec

Estimating Ekman Transport (mass and volume)

Mt * α * width of interest = Vt

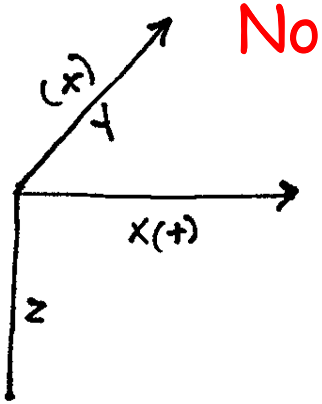
kg/m sec * m^3/kg * m = m^3/sec

Note:

Recall α (specific volume) = $1/\rho$

Ekman generated mass transport within the coordinate system (Northern Hemisphere)

Note: x & y subscripts



$MT_x = \frac{\tau_y}{f}$ zonal (Eastward) component

$MT_y = \frac{\tau_x}{f}$ meridonal (northward) component

This mass transport is in units of kg /m sec

Think of kg per linear meter 90° to wind per sec

Is all this theory correct?

- Older textbooks says that Ekman spirals have not been observed in nature (e.g., OC 1st Ed).

- No longer true:
  - ADCP measurements have demonstrated these spirals in the open ocean
  - Spirals are shallower than predicted, and the surface current appears to be less than 45^o

- Ekman's theory is an accurate approximation of the real ocean (given assumptions)

Wind-driven Vertical Flow

- Dominant process causing vertical flow in most of the world's ocean
- Density driven circulation (thermohaline flow) mostly at high latitudes (deep-water)
- Eckman flow causes surface convergence and divergence. The convergent / divergent flow can reach 1000 m (or even 2000 m) in the open ocean
- How does this happen, given the shallow depth (~ 20 – 30 m) of the Ekman layer?

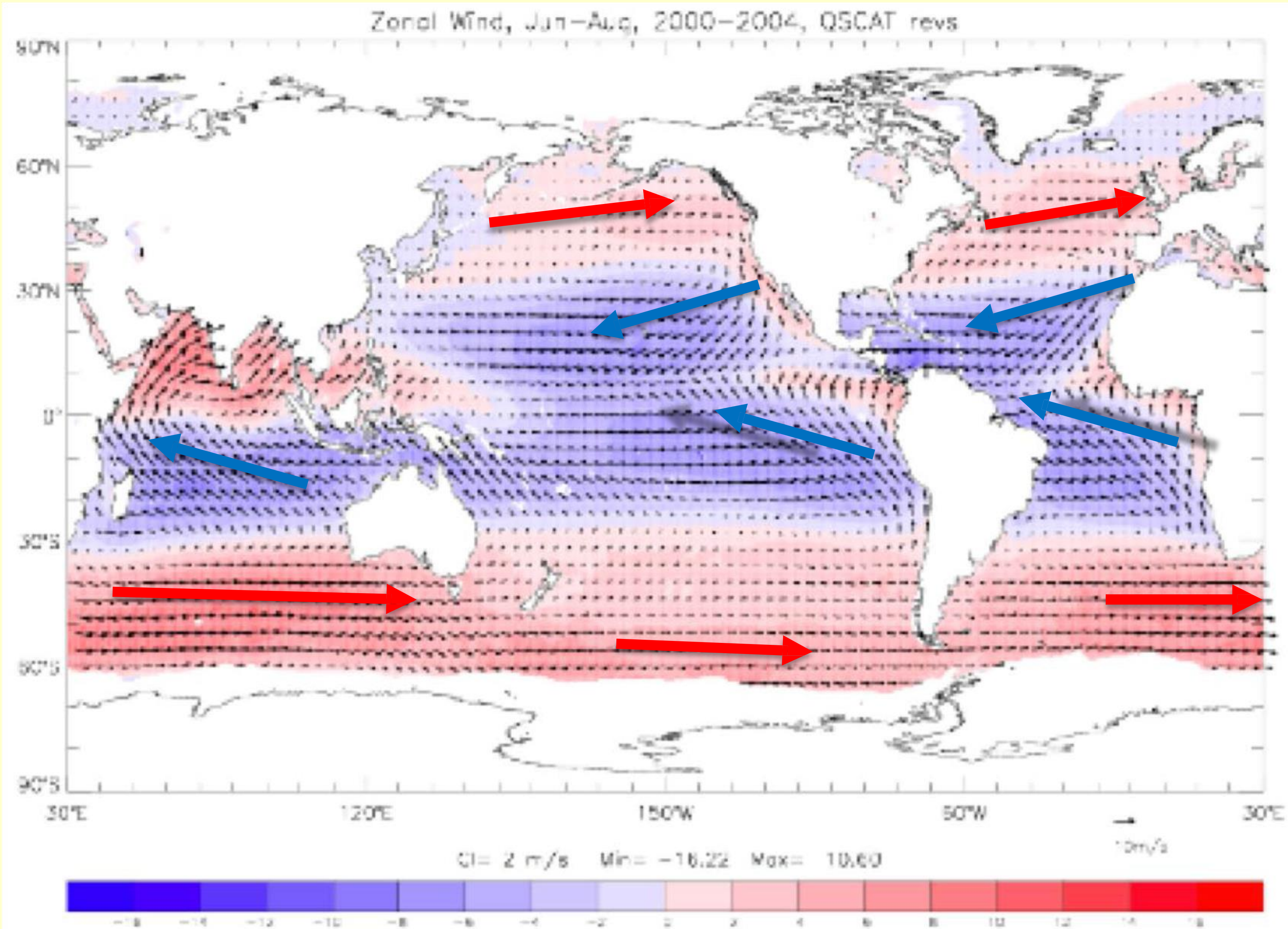
Convergence and divergence of Ekman flow

- This horizontal flow causes vertical flow (upwelling and downwelling), which generate pressure gradients to great depths (1000 m)

- This process effectively communicates the effect of wind driven circulation to water flow at intermediate depths in the sea

- We will discuss this topic in more depth when we cover the geostrophic flow

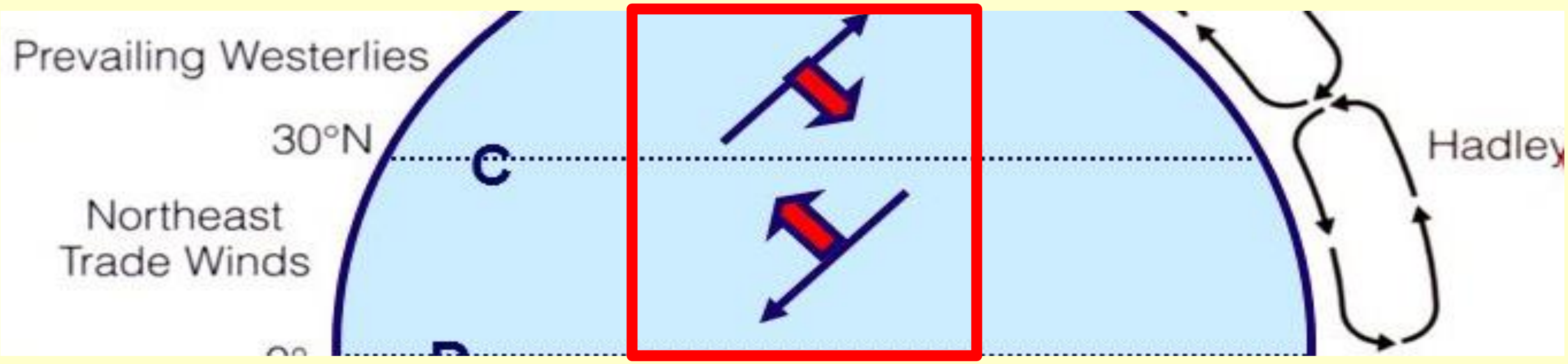
Observed Wind Stress



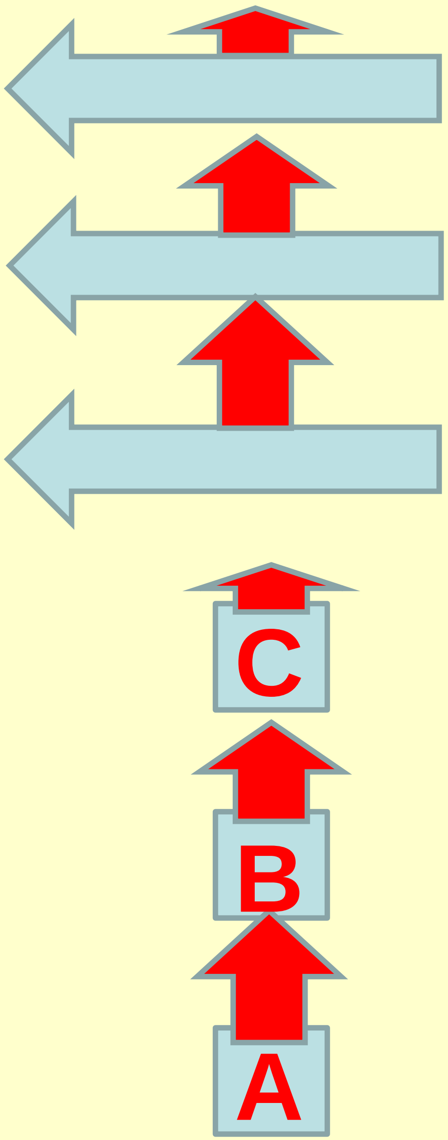
Blue = westward (easterly) Red = eastward (westerly)

Ekman Convergent Flow
(An Example)

Subtropical Convergence at 30 deg. N.
between the Westerlies and the Easterlies



Ekman Convergent Flow
(An Example)



$Mt_{(x)} = Tau_{(y)} / f$

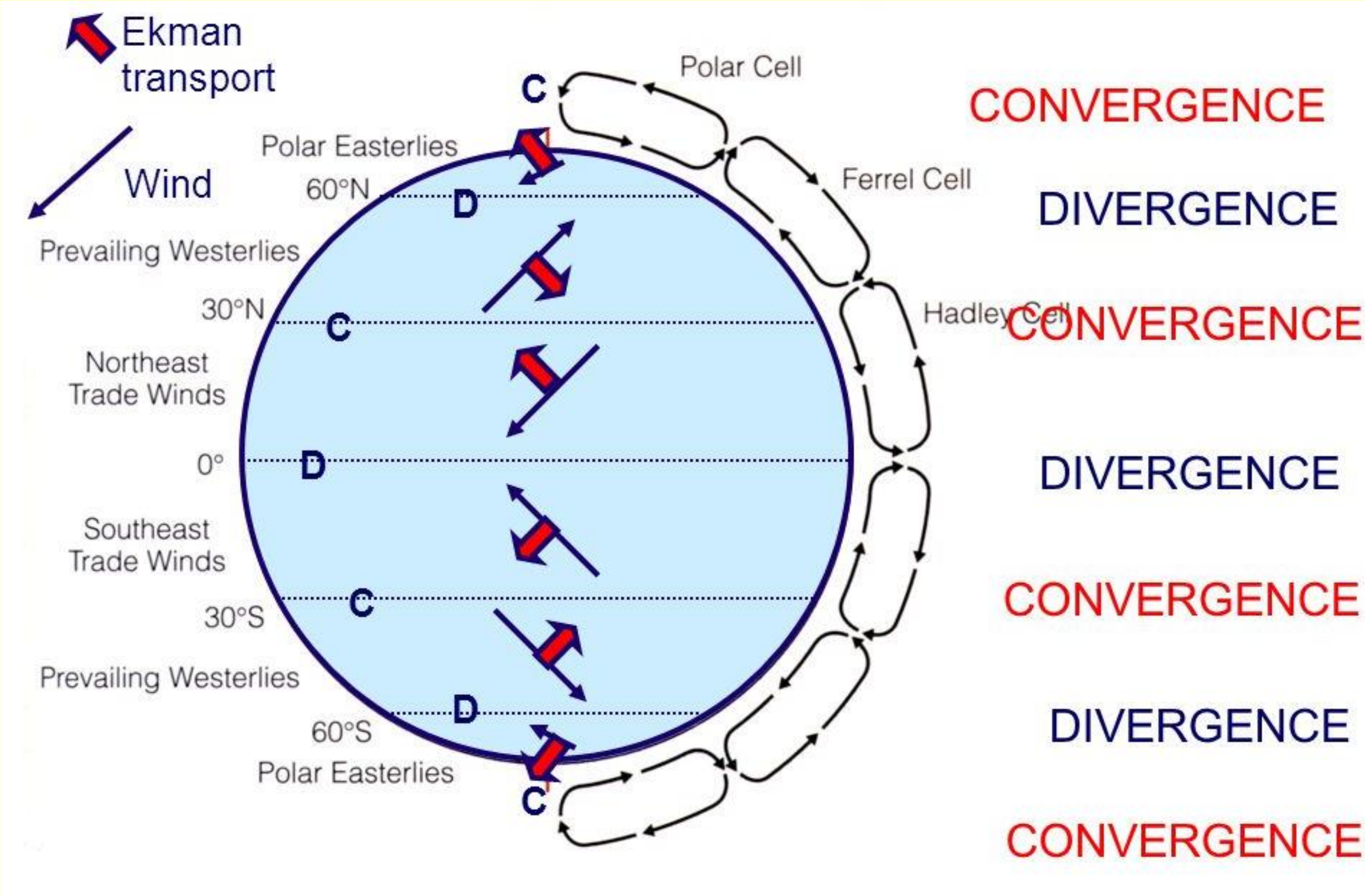
(where Tau is wind stress and f is coriolis parameter)

Imagine Tau constant across latitude

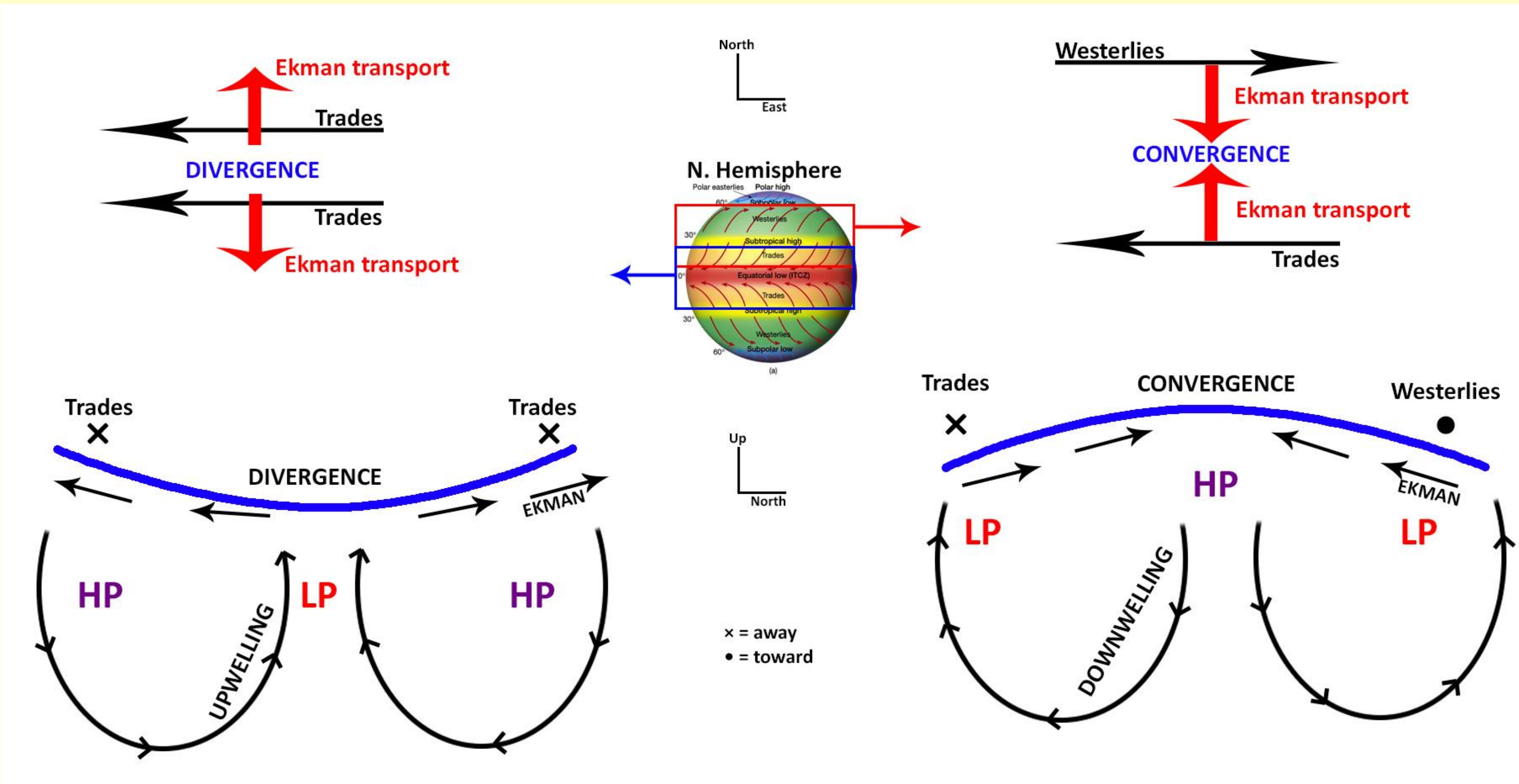
Because Coriolis increases with latitude, mass transport declines with latitude

This process causes surface convergence

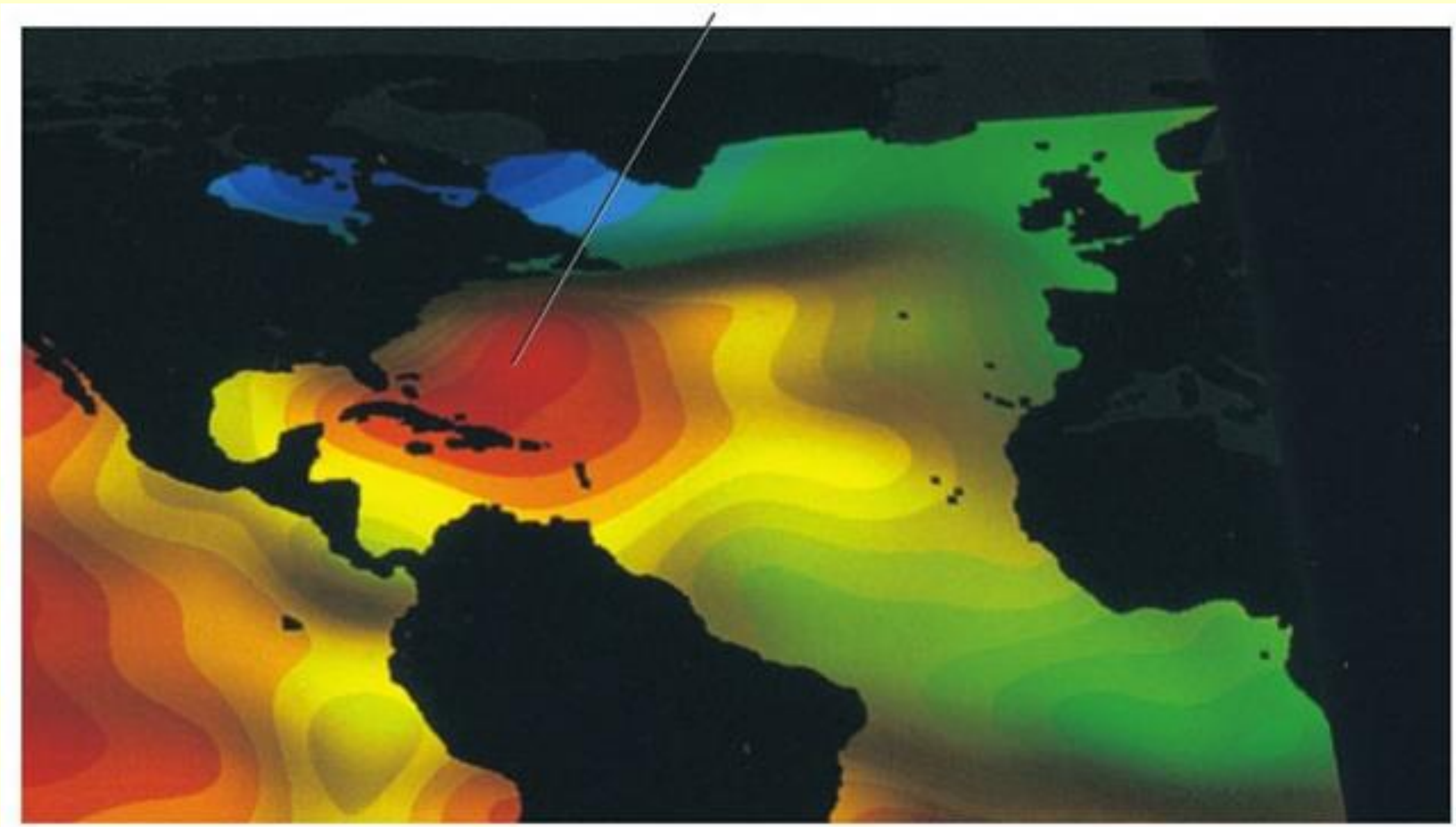
How does this work over the gyres as a whole?



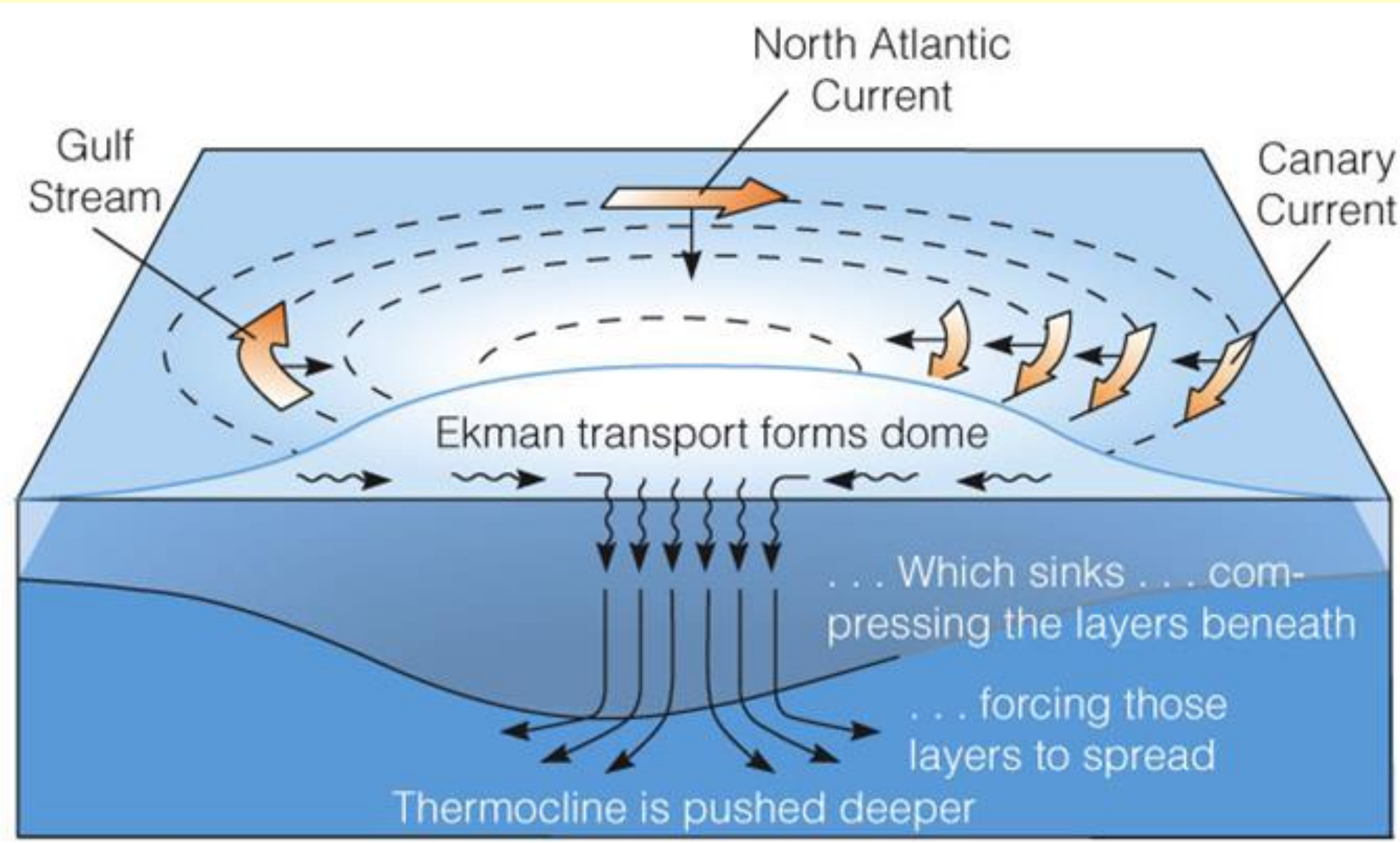
Ekman Convergent Flow (Two Examples)



Subtropical Gyre Surface Slope

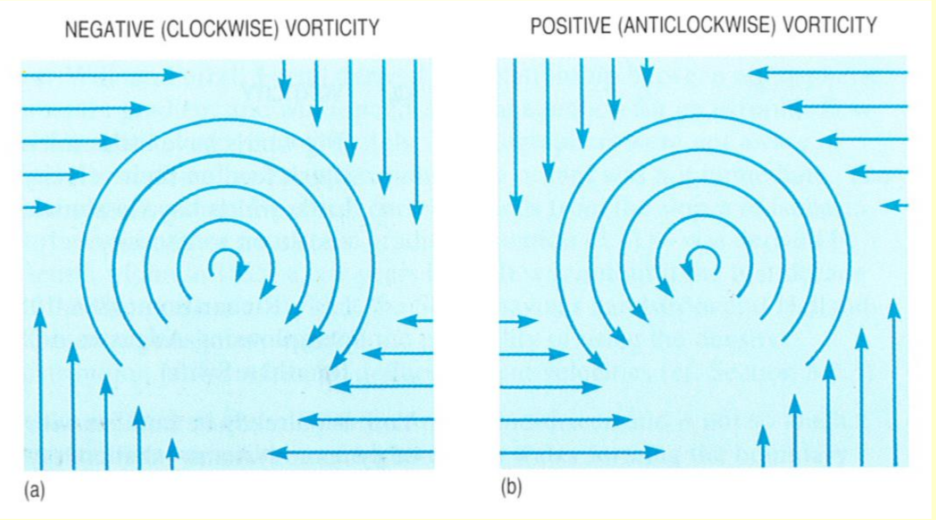


Surface Convergence in Anticyclonic Gyre



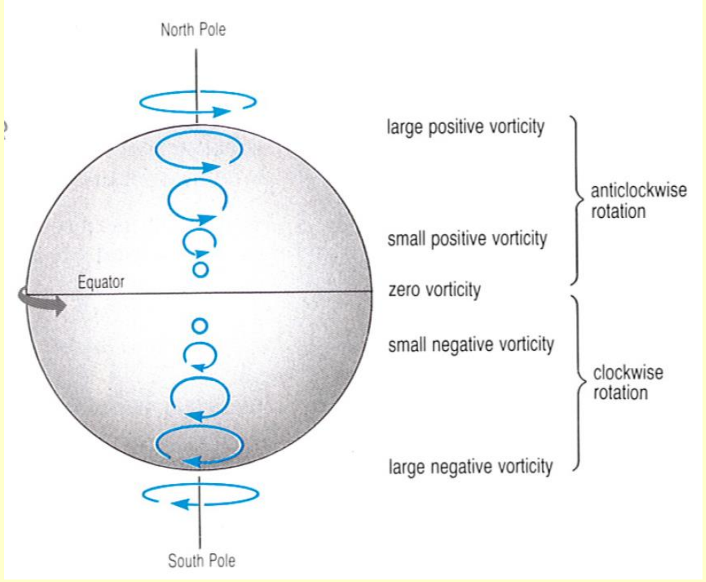
Vorticity

Consider conservation of angular momentum, as tendency to conserve vorticity (or one's tendency to rotate).

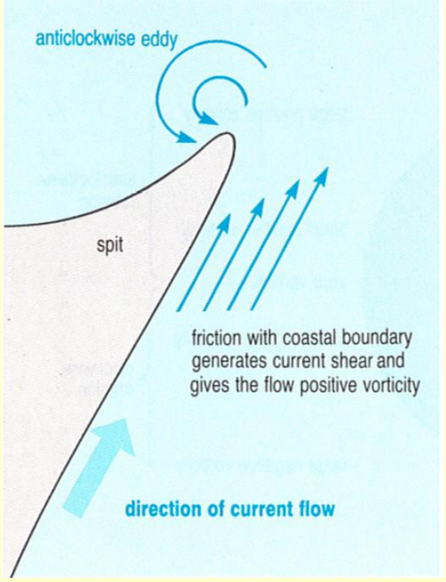


For example:

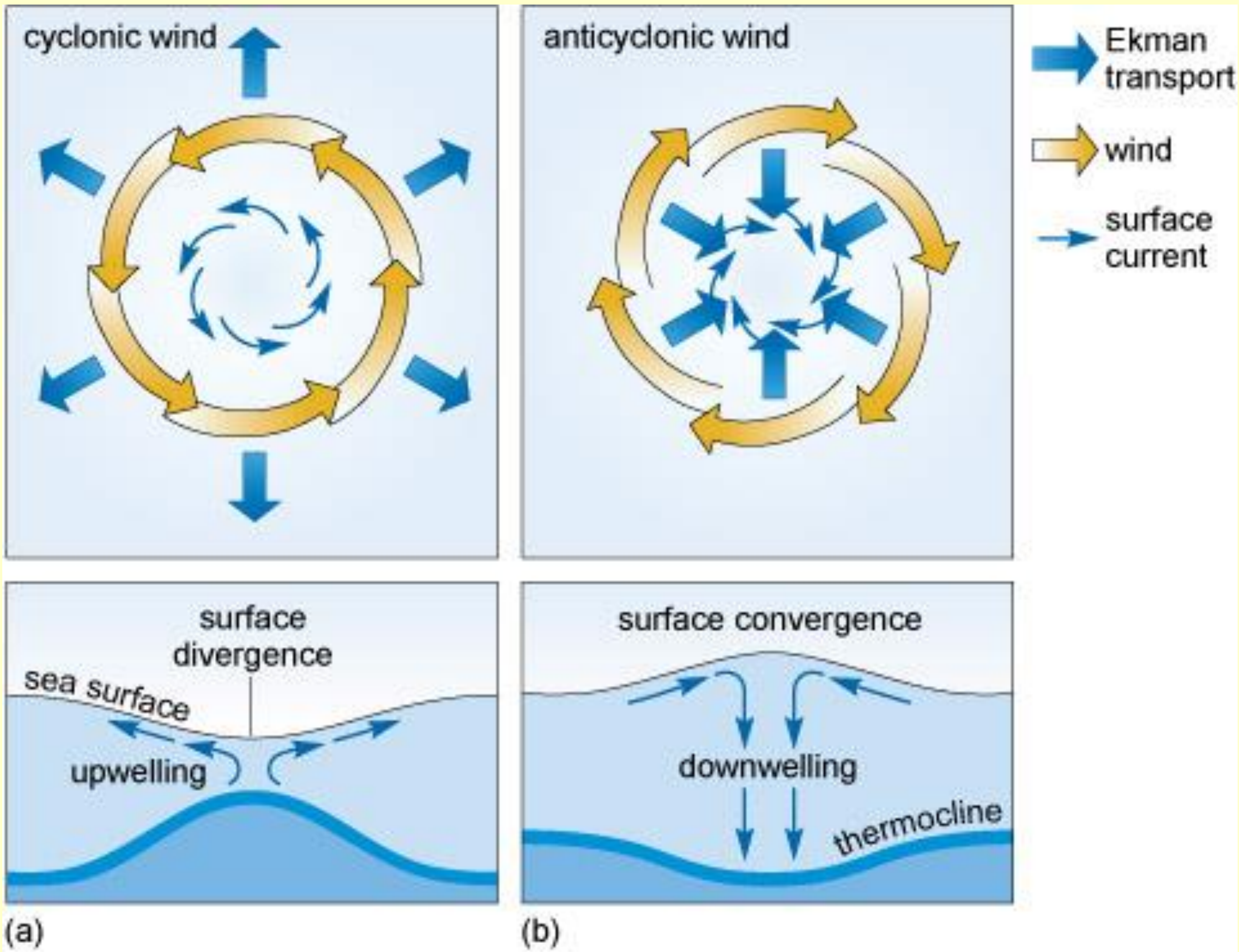
Vorticity from Earth's rotation



Unequal friction



Convergence and divergence in cyclonic and anticyclonic gyres



Wind Stress Curl

- Sum of Ekman driven flows (in X and Y) in the surface ocean (Ekman layer)

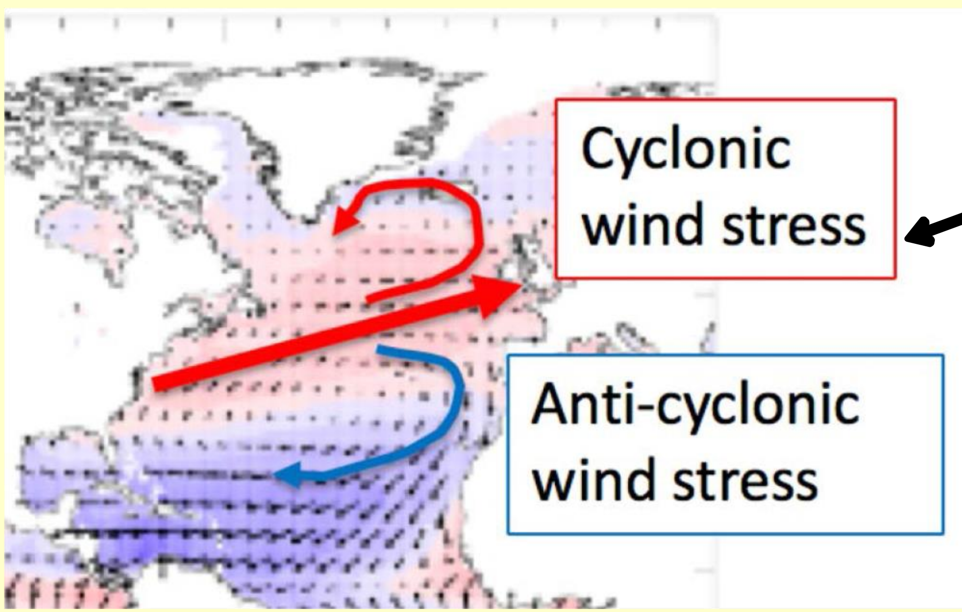
- We already visualized this process by comparing meridional Ekman transport from zonal winds
  - Convergence between trades and westerlies

- Changing zonal / meridional wind stress cause vertical motion due to convergence / divergence

- A more complete description given by wind stress curl (or the spin of the wind stress)

Wind Stress Curl

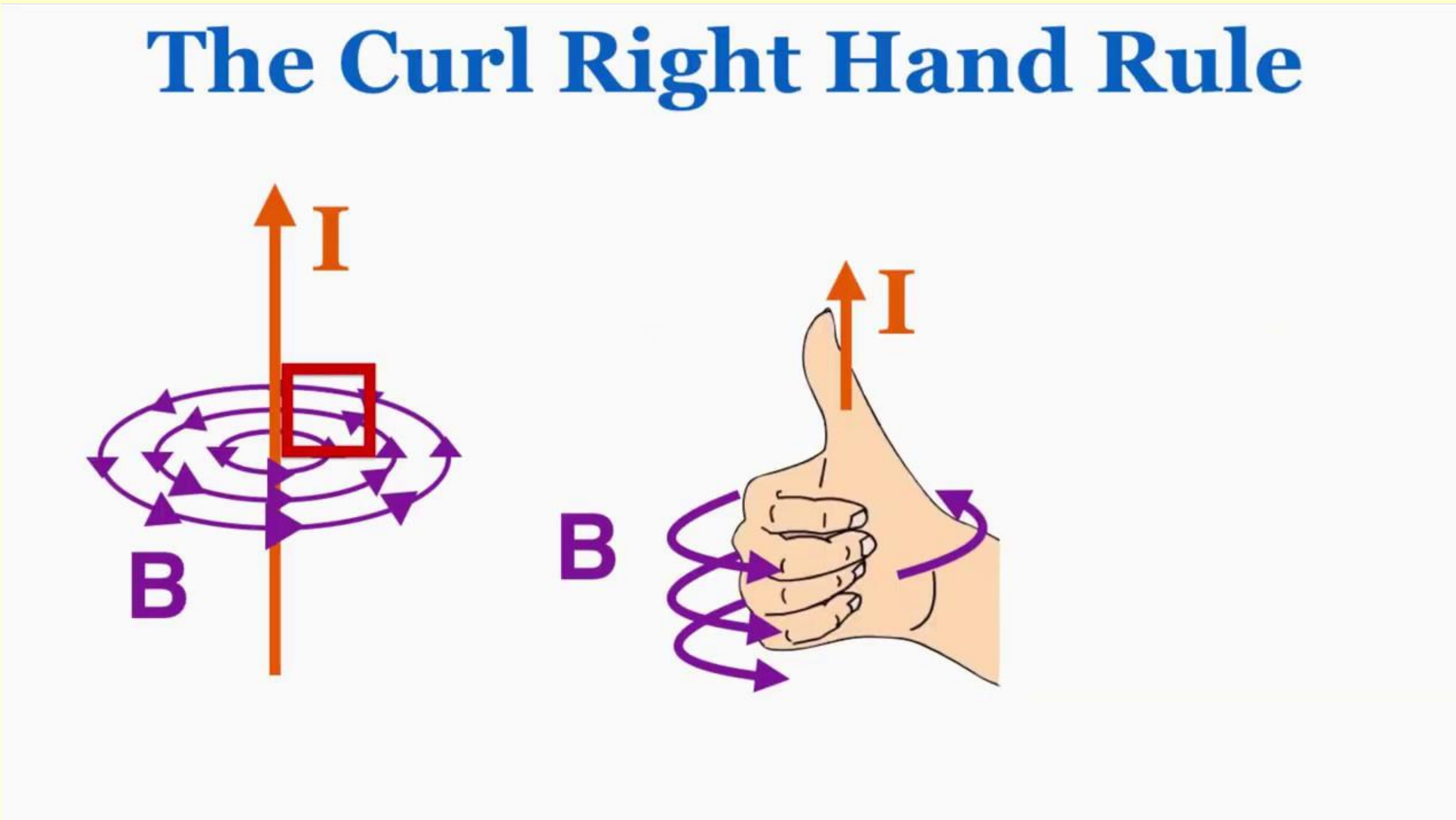
- Measures the spin of the wind stress
  - Use your right hand
  - Counter clockwise = thumb up = positive curl
  - Clockwise = thumb down = negative curl
  - Vertical velocity depends on the wind stress curl



Positive wind stress curl (Ekman upwelling)

Negative wind stress curl (Ekman pumping)

Right Hand Rule



7.5.4. Ekman Transport Convergence and Wind Stress Curl

When the wind stress varies with position so that Ekman transport varies with position, there can be a convergence or divergence of water within the Ekman layer. Convergence results in downwelling of water out of the Ekman layer. Divergence results in upwelling into the Ekman layer. This is the mechanism that connects the frictional forcing by wind of the surface layer to the interior, geostrophic ocean circulation (Section 7.8).

The vertical velocity w_E at the base of the Ekman layer is obtained from the divergence of the Ekman transport, by vertically integrating the continuity equation Eq. (7.11e) over the depth of the Ekman layer:

$$(\partial U_E/\partial x + \partial V_E/\partial y) = \nabla \cdot \mathbf{U}_E$$
$$= -(w_{surface} - w_E) = w_E$$

Horizontal Eckman Transport

A) Assume vertical transport at Surface = 0 (Wsurface)

Convergence (Negative)

Speed at base of Ekman Layer (WE)

B) Assume vertical transport at Surface = 0 (Wsurface)

Divergence (Positive)

Speed at base of Ekman Layer (WE)

Wind Stress Curl Equation

Mass transport in x and in y

$$\mathrm{curl}\left(\frac{\tau}{f}\right) = \frac{\partial\left(\frac{\tau_y}{f}\right)}{\partial x} - \frac{\partial\left(\frac{\tau_x}{f}\right)}{\partial y} = \rho w$$

Note: subscripts for the rate of change in wind stress in y in the x direction or change in wind stress in x in the y direction!

Wind Curl Equation

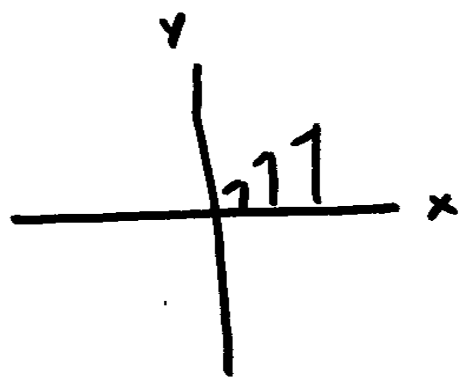
$$\text{curl}\left(\frac{\tau}{f}\right) = \frac{\partial\left(\frac{\tau_y}{f}\right)}{\partial x} - \frac{\partial\left(\frac{\tau_x}{f}\right)}{\partial y} = \rho w$$

so vertical flow can be calculated with wind stress gradients in x + y

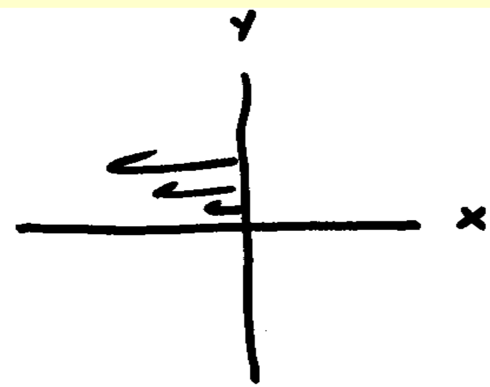
$$-\text{curl}\left(\frac{\tau}{f}\right) = \text{downwelling}$$

Convergent and divergent flow

$$\mathrm{curl}\left(\frac{\tau}{f}\right) = \frac{\partial\left(\frac{\tau_y}{f}\right)}{\partial x} - \frac{\partial\left(\frac{\tau_x}{f}\right)}{\partial y}$$



+ Y wind stress produces + x transport + slope → upwelling



− x wind stress produces + Y transport − Slope → upwelling

Units of Wind Stress Curl

$$\tau_{(wind)} = \text{pressure} = \frac{N}{m^2} = \frac{kg}{m\,sec^2}$$

$$\frac{\tau_{(w)}}{f} = \frac{\frac{kg}{m\,sec^2}}{\frac{1}{sec}} = \frac{kg}{m\,sec}$$

$$\frac{\partial\left(\frac{\tau_w}{f}\right)}{\partial x} = \frac{\frac{kg}{m\,sec}}{m} = \frac{kg}{m^2\,sec} \quad \text{units of curl}$$

$$\text{Curl}\left(\frac{\tau}{f}\right) = \rho \cdot w$$

So w (speed in z) $= \text{Curl}\left(\frac{\tau}{f}\right) \cdot \boxed{\alpha}$ or $\frac{kg}{m^2\,sec} \cdot \frac{m^3}{kg} = \frac{m}{sec}$

NOTE:

α = specific density

$\alpha = 1 / \rho$

(1/density)

Annual Mean Ekman Pumping

(calculated)

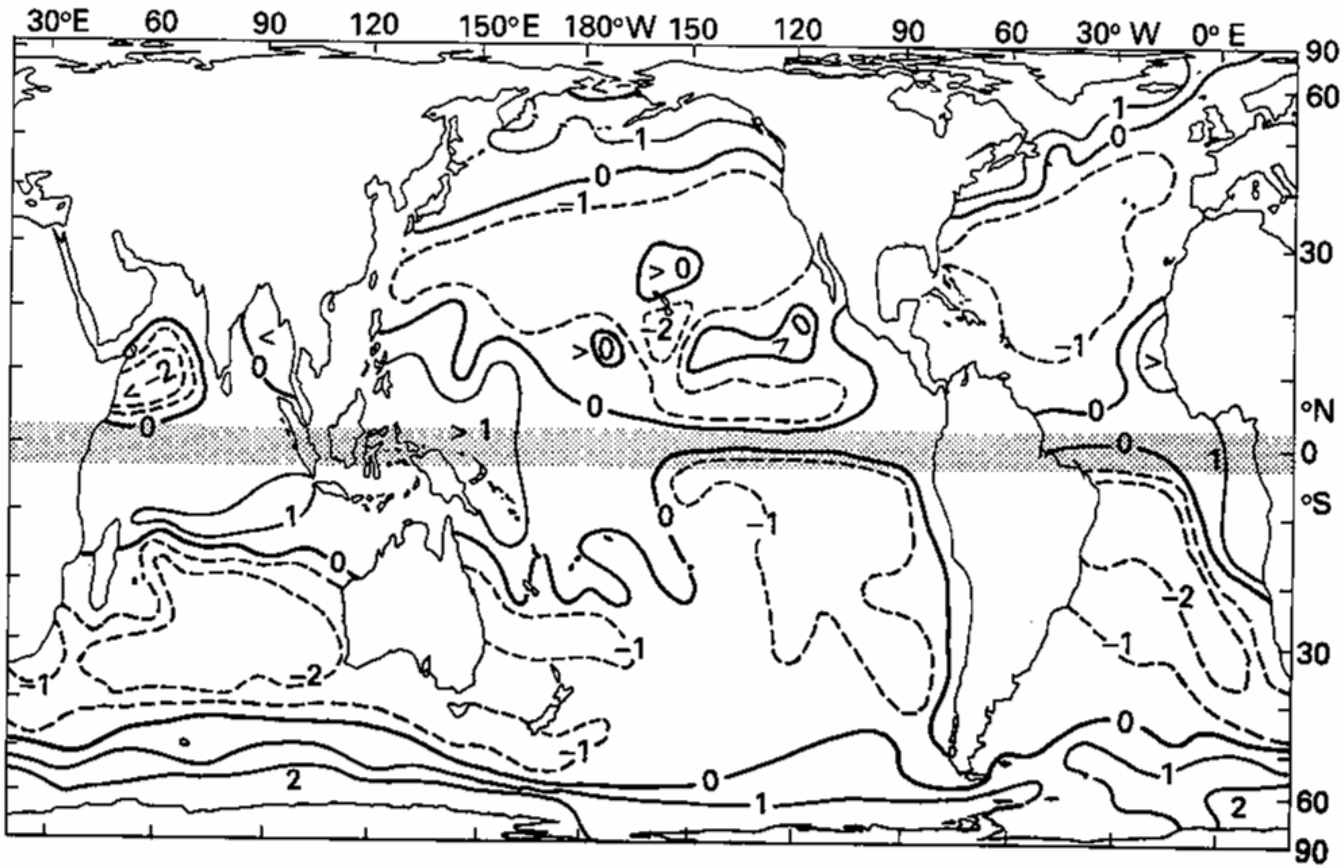


FIG. 4.3. Annual mean distribution of curl(τ/f), or Ekman pumping, calculated from the distribution of Fig. 1.4 (10^{-5} kg m^{-2} s^{-1}). Positive numbers indicate upwelling. In the equatorial region (2°N - 2°S, shaded) curl(t/f) is not defined; the distribution

+

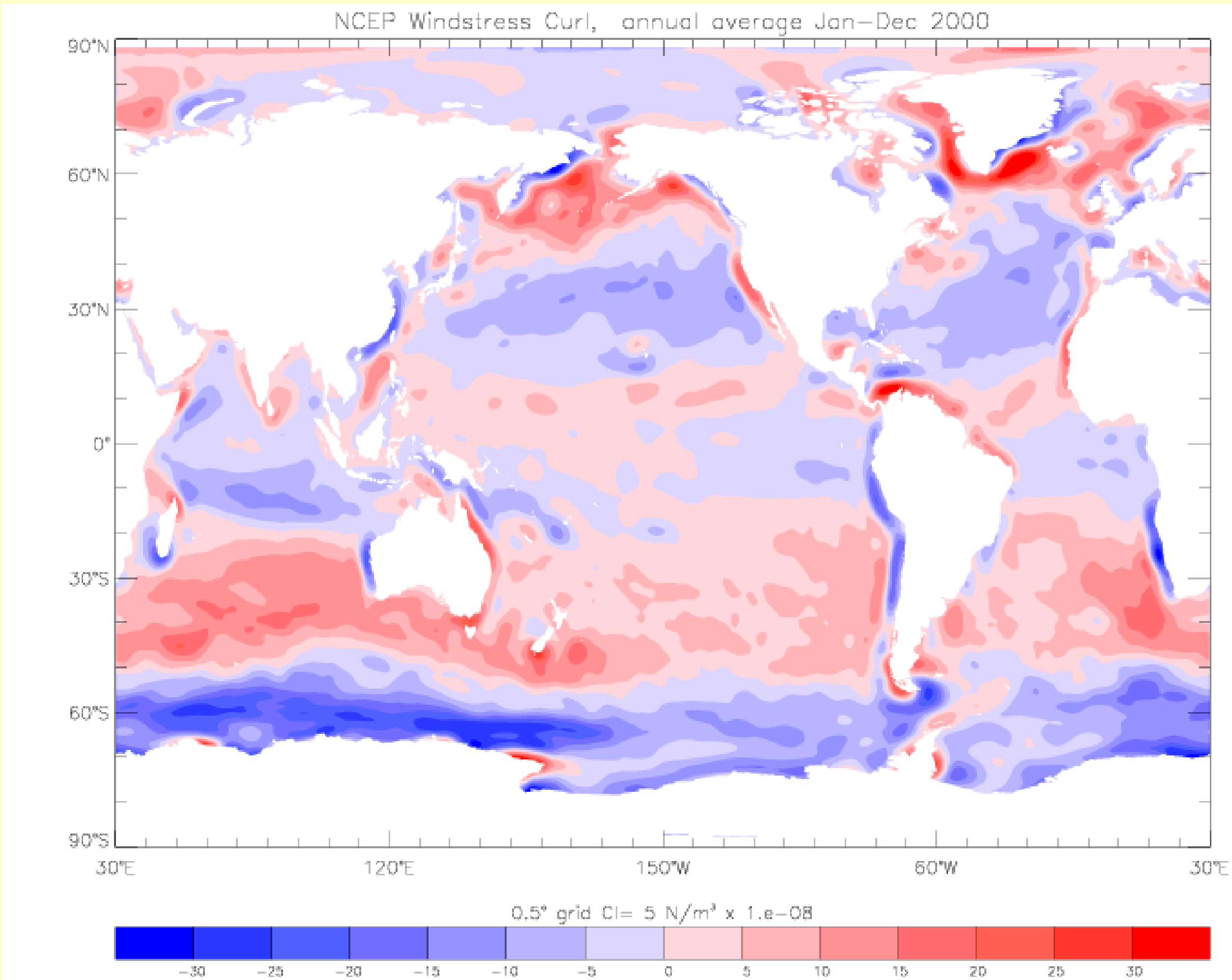
UP

-

Down

Units: kg / m^2 s

Annual Wind Stress Curl
(observed)



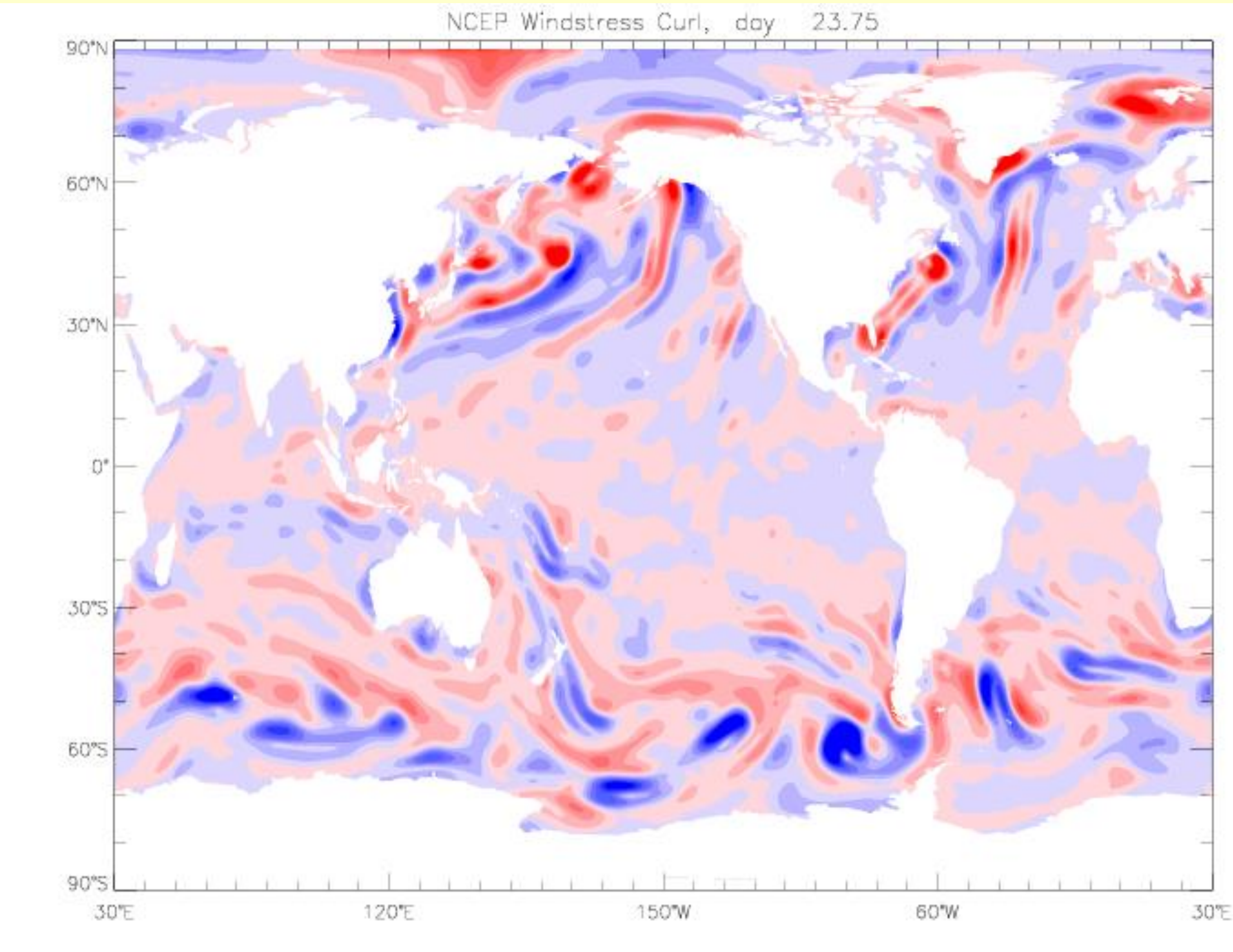
Units:
N / m^2

+
UP

-
Down

Estimated from satellite scatterometer measurements

Daily Wind Stress Curl
(observed)



Units:
N / m^2

+
UP

-
Down

Implications

- Are these theoretical foundations correct?
  - Coriolis Force
  - Ekman Transport

- Implications:

  Horizontal water motion leads to vertical water motion
  - Convergence / Divergence of Ekman flow
  - Wind Stress Curl