Ekman dynamics→ simplified model: a homogeneous ocean of const. density and pressure driven by a uniform wind stress. We seek for a steady solution in which frictional stress and Coriolis force are in balance.

$$f\upsilon = -\nu \frac{d^2 u}{dz^2}$$

$$fu = \nu \frac{d^2 \upsilon}{dz^2}$$

z is depth, f =2Ωsinϕ is Coriolis parameter (>0 in NH, <0 in SH), u and v are the zonal and merid. ocean currents, ν a 'viscosity' parameter. At each level, the Coriolis force is balanced by the momentum flux convergence=friction from within the mixed layer)

Boundary conditions: at surface, the vertical shear of the current is tied to the wind stress; at depth, currents approach zero at infinite depth. τ_x and τ_y are the wind stress in N/m^2, and the ρ_0 the seawater density. ν is the momentum diffusion coefficient

$$\left.\begin{aligned} \nu \frac{du}{dz} &= \frac{\tau_x}{\rho_o} \\ \nu \frac{d\upsilon}{dz} &= \frac{\tau_y}{\rho_o} \end{aligned}\right\} \text{ at } z = 0; \qquad u = \upsilon = 0 \text{ at } z \to -\infty$$

$\nu \sim 30 m^2/s$

The solution of the above eq.s with these boundary conditions give the ***Ekman spiral.*** They can be integrated over depth to give the **depth-integrated volume transport:**

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

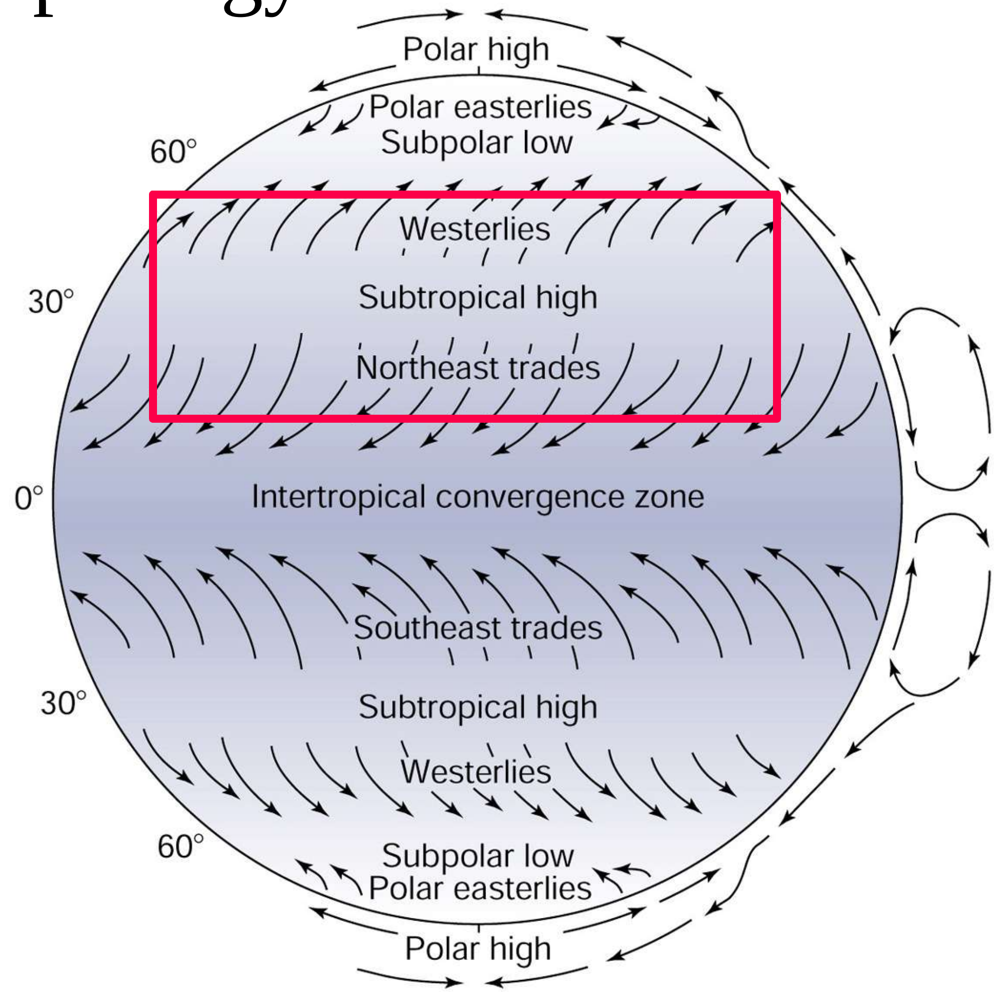
(volume per unit time across a unit meter of horizontal distance)

$\forall \propto 1/f$ → more efficient at the eq.

- Not valid at the eq. (f=0)

How to create a subtropical gyre circulation I

Recall that surface winds in the 15-45 degree range consists of easterly trades and midlatitude westerlies…..



The above relationships thus gives the total Ekman transport over the mixed layer given the wind stress, density of seawater ρ_0, and the Coriolis parameter f. Note that

- *Meridional* wind stress gives a *zonal* transport, and *zonal* wind stress a *meridional* transport (as we talked about before);
- the transport goes as the ***inverse*** of the Coriolis parameter f - the closer it is to the equator, the more 'effective' the Ekman transports.
- Relationship breaks down at the equator (since f=0 there).

Example: suppose the zonal wind stress in the subtropics at 30 degrees N is 0.15 N/m^2 to the west. What is the Ekman transport associated with this wind stress?

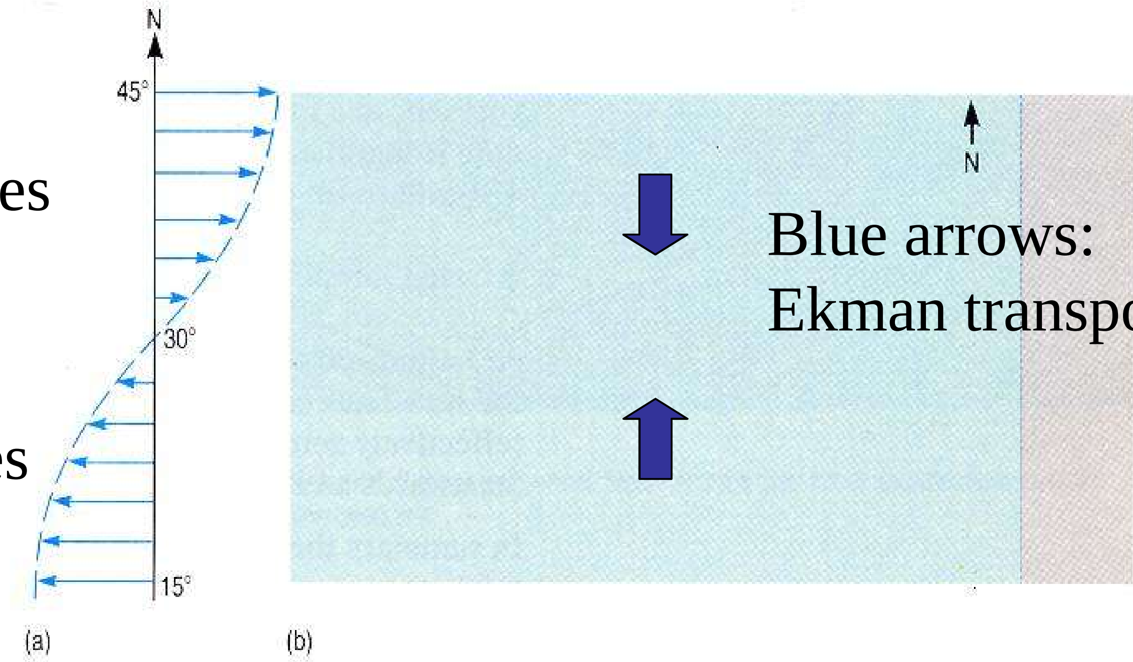
Ans: $\tau_y = 0\ N/m^2$ so no zonal volume transport. $\tau_x = -0.15\ N/m^2$ (note sign).

Note that $f = 2\Omega \sin(pi/6) = \Omega$, and $\rho_0 \sim 1035\ kg/m^3$, so the meridional volume transport (applying the equation in the previous slide) is

$V_E = -(-0.15\ N/m^2)/(1035\ kg/m^3 \times 7.3 \times 10^{-5} s^{-1}) = 1.99\ m^2/s$ – **it is to the North**

Note that if you multiply V_E by the density of seawater, you get 2.05×10^3 kg/(m.s) which is the mass transport (i.e. 2.05×10^3 kg/s across a unit meter of zonal distance)

How to create a subtropical gyre circulation II



westerlies

NH

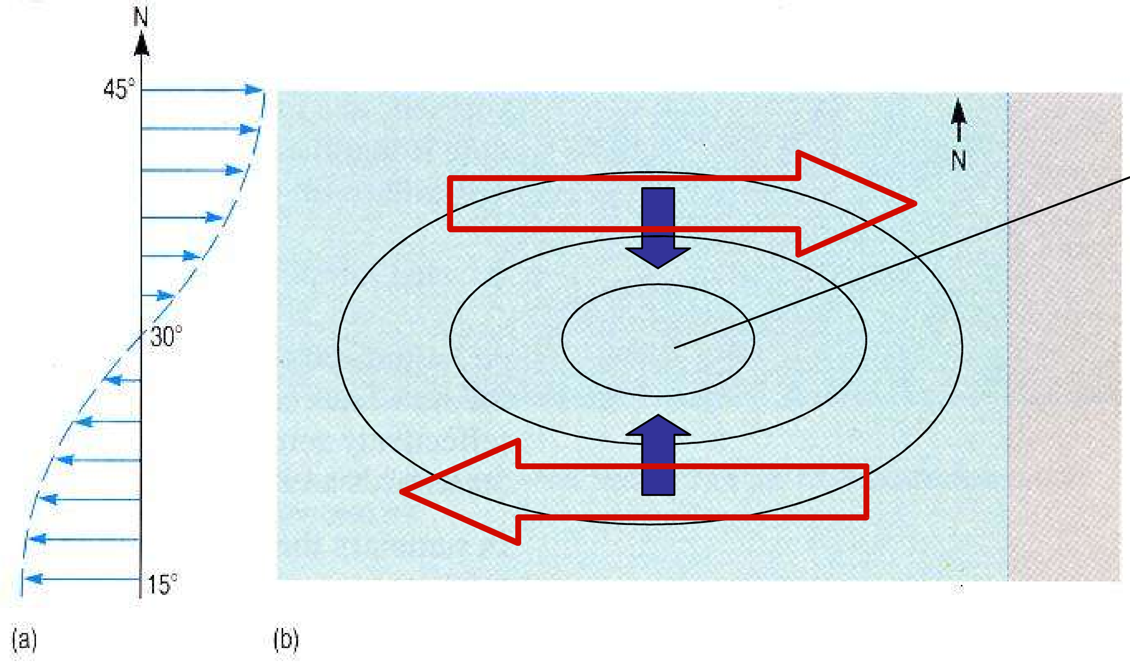
easterlies

Blue arrows:
Ekman transports

W E

Net convergence of surface flow

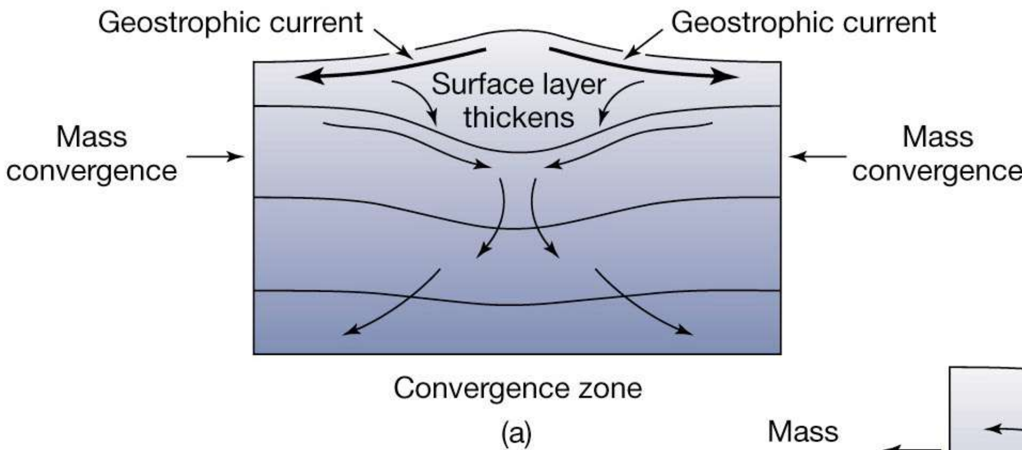
How to create a subtropical gyre circulation III



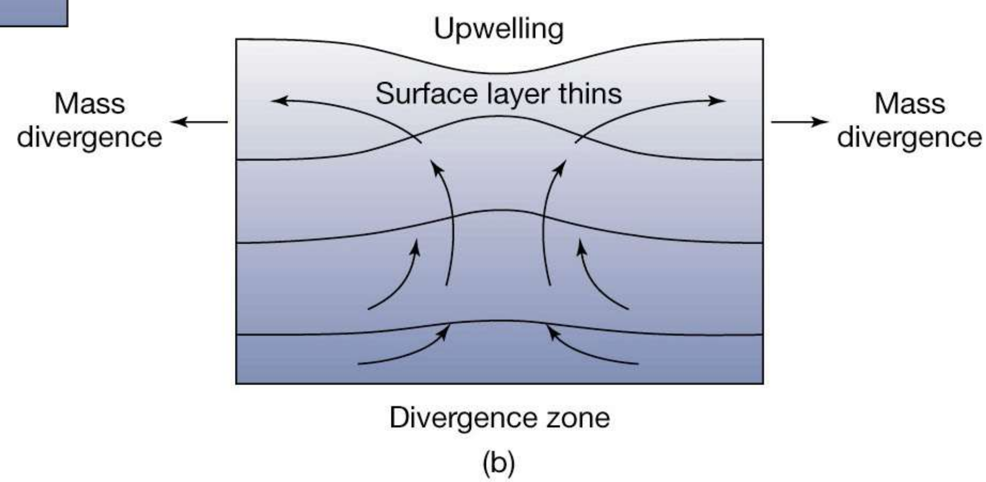
Ocean surface 'domes' up, and a geostrophic ocean current is produced that balances the resulting pressure gradient.

Blue: Ekman flow
Red: Geostrophic flow

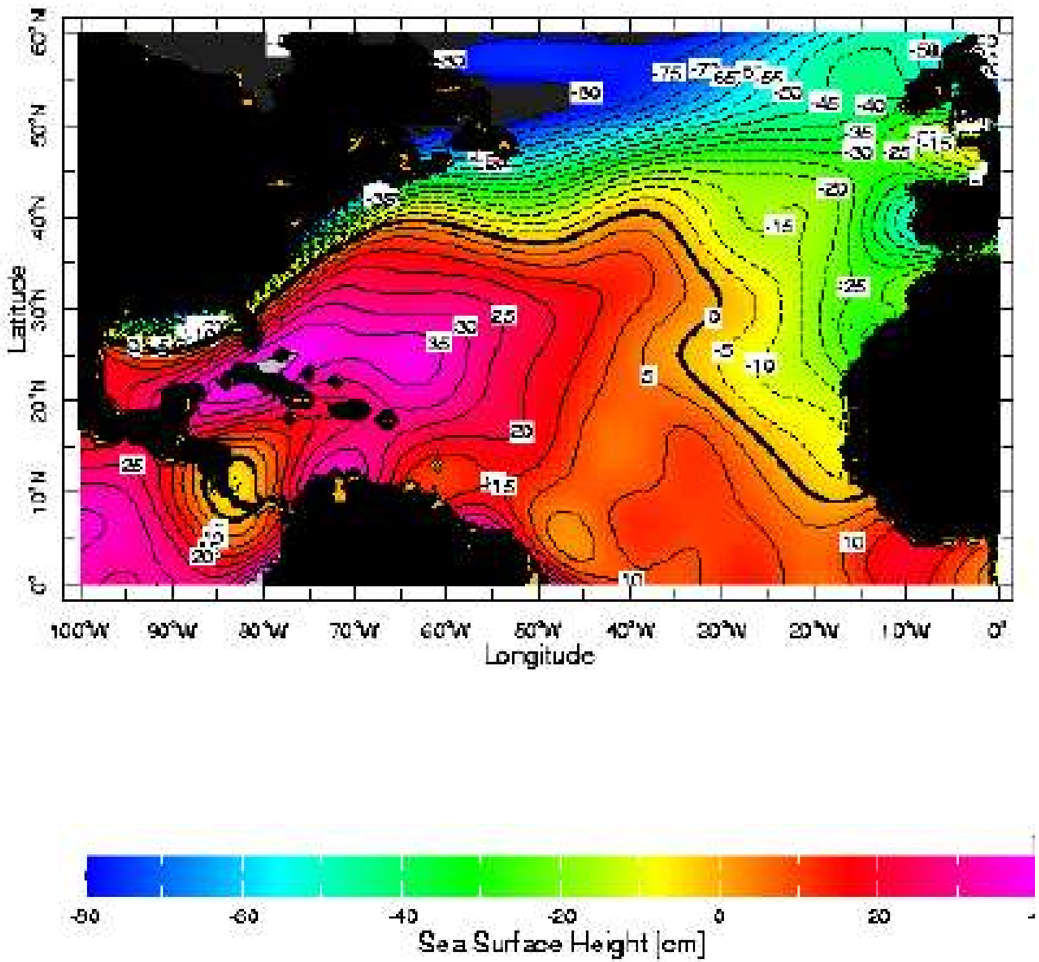
The convergence of waters by the Ekman transports cause **downwelling**



The opposite - caused by divergence of surface waters – is called **upwelling**.



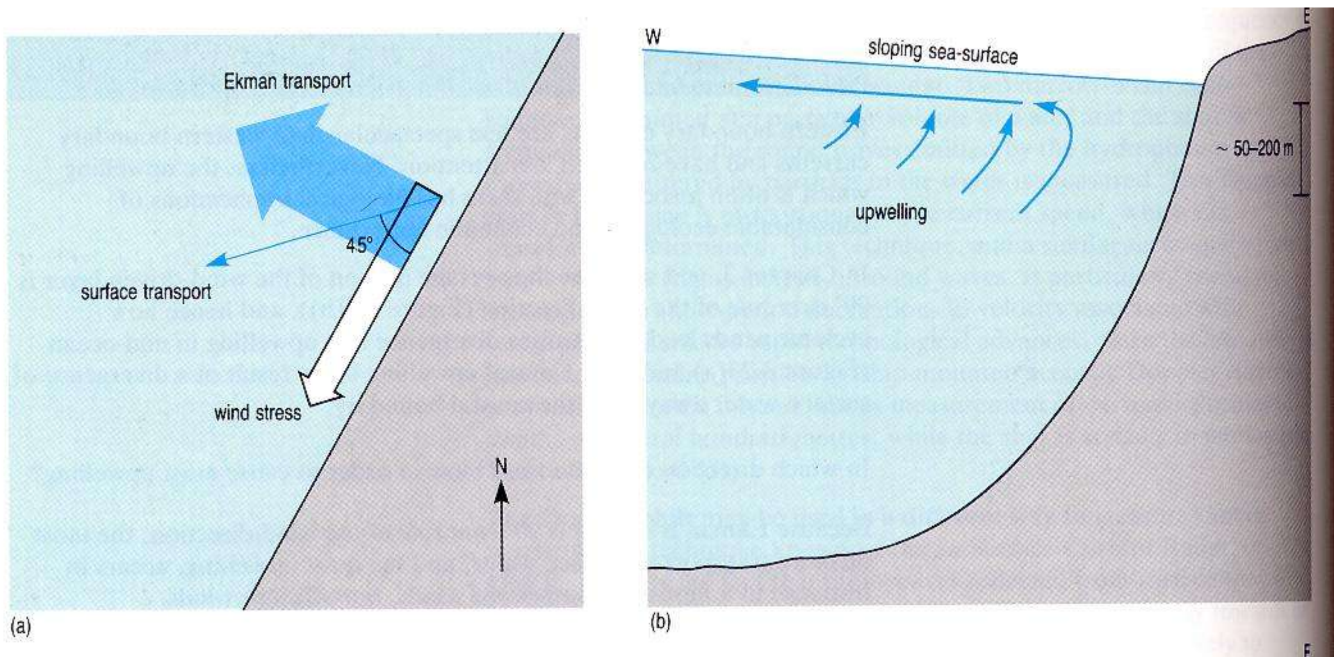
Annual mean north Atlantic sea surface height



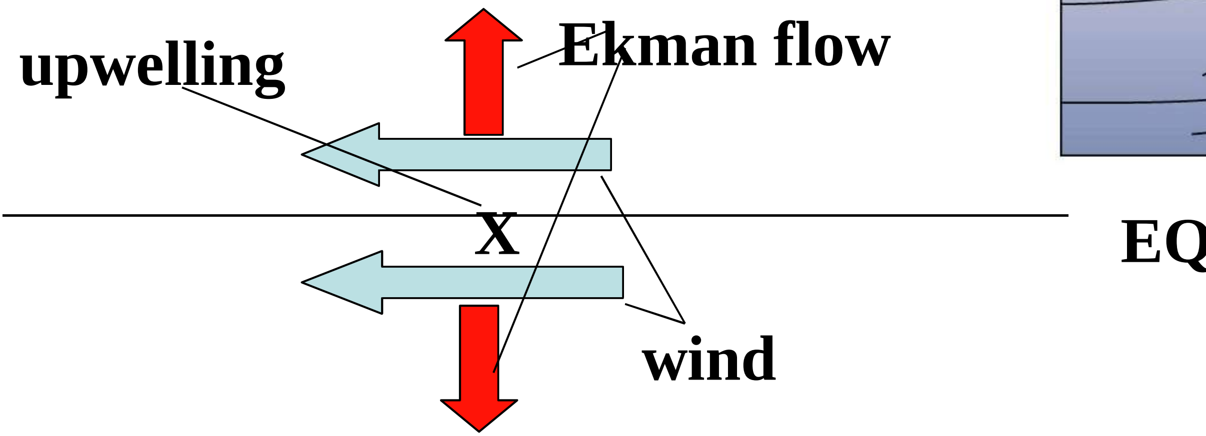
Note the sharper gradients on the western side of the basin, as opposed to the eastern side, which indicates the stronger Gulf Stream relative to the weaker eastern boundary currents.

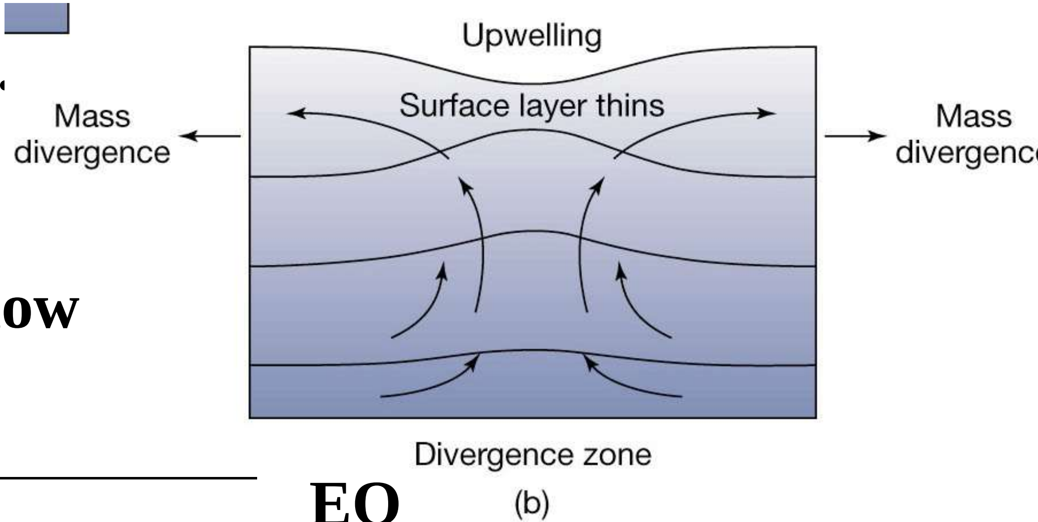
Why is the western boundary current more intense than the eastern return flow? It ultimately comes about due to the variation of the Coriolis parameter with latitude.

Coastal upwelling: suppose this is the northern hemisphere, and the wind is parallel to the coastline as shown below. The Ekman flow as a result will be to the right of the wind - in other words, away from the coastline. But, in order to obey mass continuity, this has to be compensated for by bringing in water from below the mixed layer - i.e. upwelling. Since the upwelled water is cold, the upwelling regions have cold sea surface temperature.



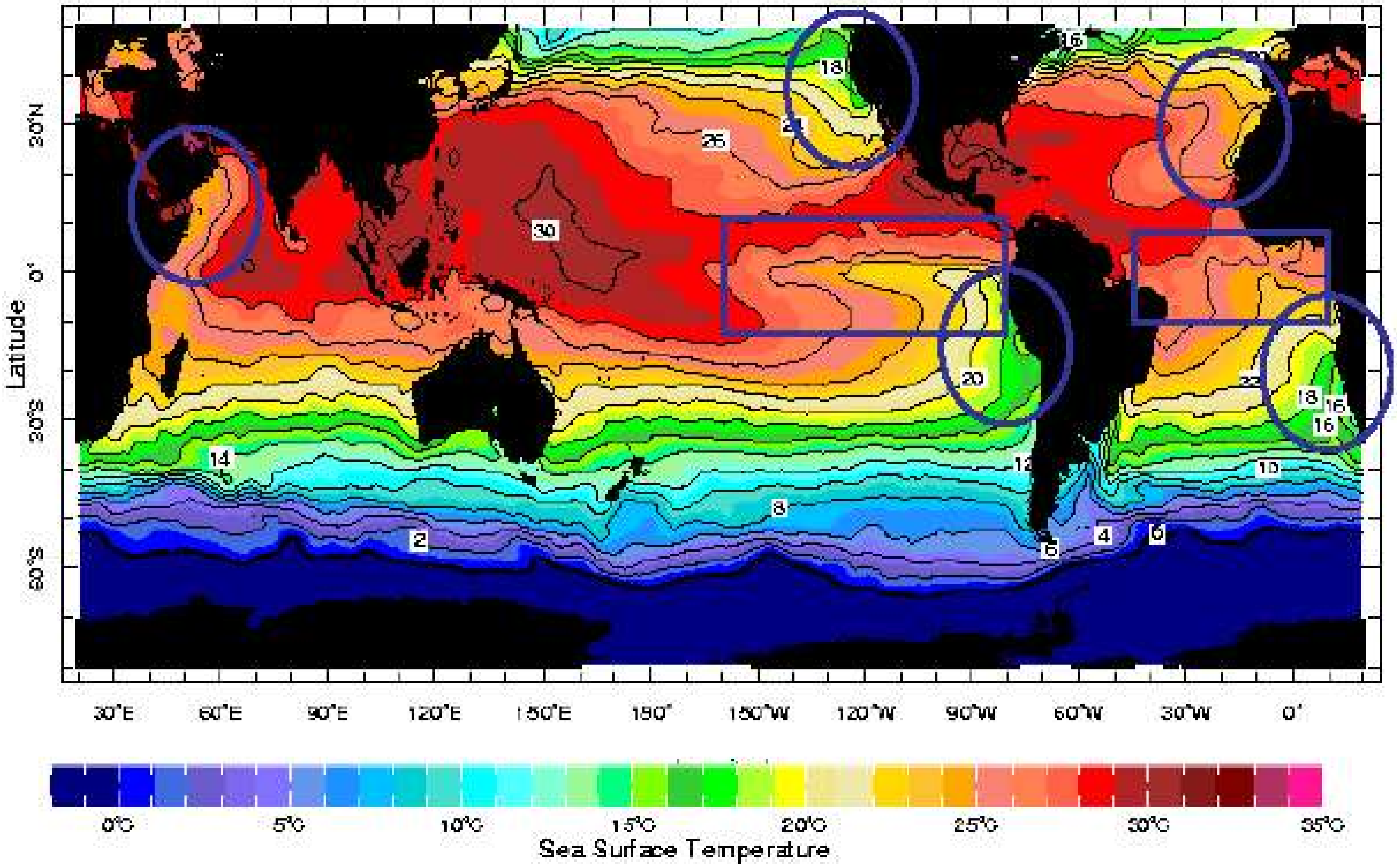
Equatorial upwellling.





Equatorial upwellling. Recall that the winds on the equator are easterly - from the east. Now, consider what the Ekman flow would do north and south of the equator. Because of the reversal in the Coriolis parameter, it turns out that the Ekman flow is polewards in both hemispheres - in other words, the ocean circulation is diverging at the equator. In order to compensate for this divergence, water has to be brought up from below the mixed layer - hence equatorial upwelling. This mechanism is responsible for the ***cold tongues*** over the eastern equatorial Pacific and Atlantic.

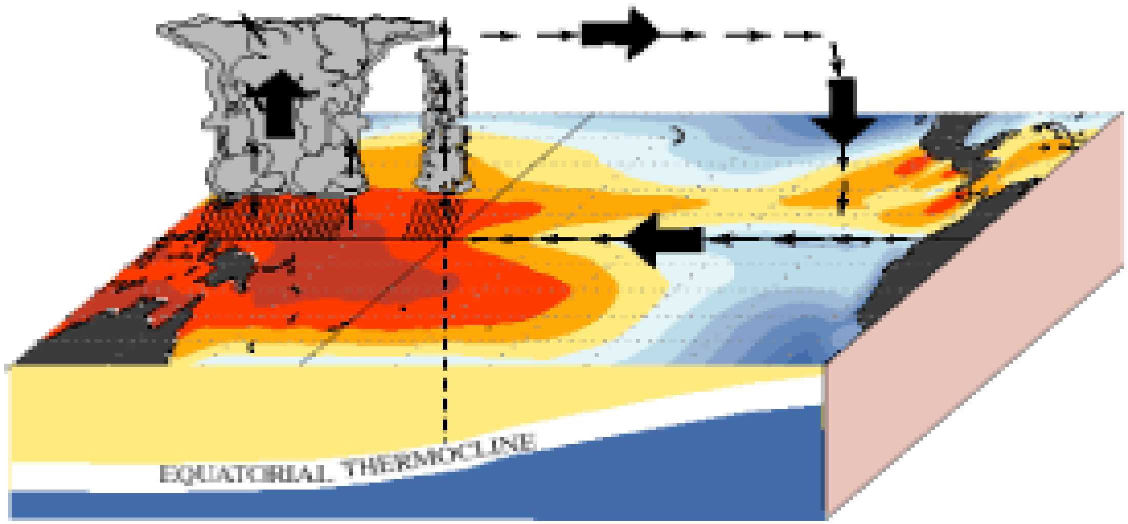
SST, 20 Aug 2003



Prominent equatorial (square) and coastal (oval) upwelling regions

Note: ‘SST’ is a common acronym for ‘sea surface temperature’

How to set up the Walker circulation



Why is sea surface temperature in the eastern equatorial Pacific cold, and the western equatorial Pacific warm (and convects there), despite the fact that both gets the same amount of incoming insolation?

The ocean and atmospheric conditions associated with the Walker circulation is an example of *ocean-atmosphere interaction* - the mutual actions of the two produce the climate.

Sequence of events that give rise to the tropical Pacific climate:

2. Suppose there is an initial zonal gradient in equatorial SST - slightly warmer to the west, cooler to the east.
2. Atmospheric convection prefers the warmer SST in the west, creating a low surface pressure there. The colder SST to the east produces a slightly higher surface pressure.
3. The east-west pressure gradient drives an easterly surface atmospheric flow (westward) in the tropics near the equator.
6. The easterlies stress does two things - i) it ‘piles up’ surface waters towards the west, deepening the thermocline to the west and shallowing it to the east; and ii) it drives ocean Ekman transports that result in equatorial upwelling.
9. The resulting ocean motions result in cold waters being upwelled in the east (note that there is also upwelling in the west, but since the thermocline is deeper there, the waters upwelled are warmer). This results in an ***increased*** east-west contrast in equatorial SST, from what we started off with.
6. The east-west SST contrast drives the atmospheric Walker circulation.

Note that this is a positive feedback, aka the ***Bjerknes feedback* -** zonal SST Contrast produces stronger equatorial easterlies, which would then increase the west-east tilt in the thermocline and hence the zonal contrast in SST, which feeds back on the winds…..