Physical oceanography
Lecture 2

Wind-Driven Circulations in the Ocean and their Energy Transport

ICTP: The General Circulation of the Atmosphere and Oceans: A Modern Perspective

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Wind-driven circulation

- General circulation of the ocean: wind-driven gyres and other wind-driven circulations
- Description from observations
- Dynamics of wind-driven circulation
  - Ekman transport
  - (Eastern boundary currents and equatorial currents)
  - Sverdrup balance
  - Western boundary currents
  - (Antarctic Circumpolar Current)
- Observed wind curl and Sverdrup transport
- Heat transport
  - Total
  - Estimate of transport by wind-driven subtropical gyres

Wind-driven circulation

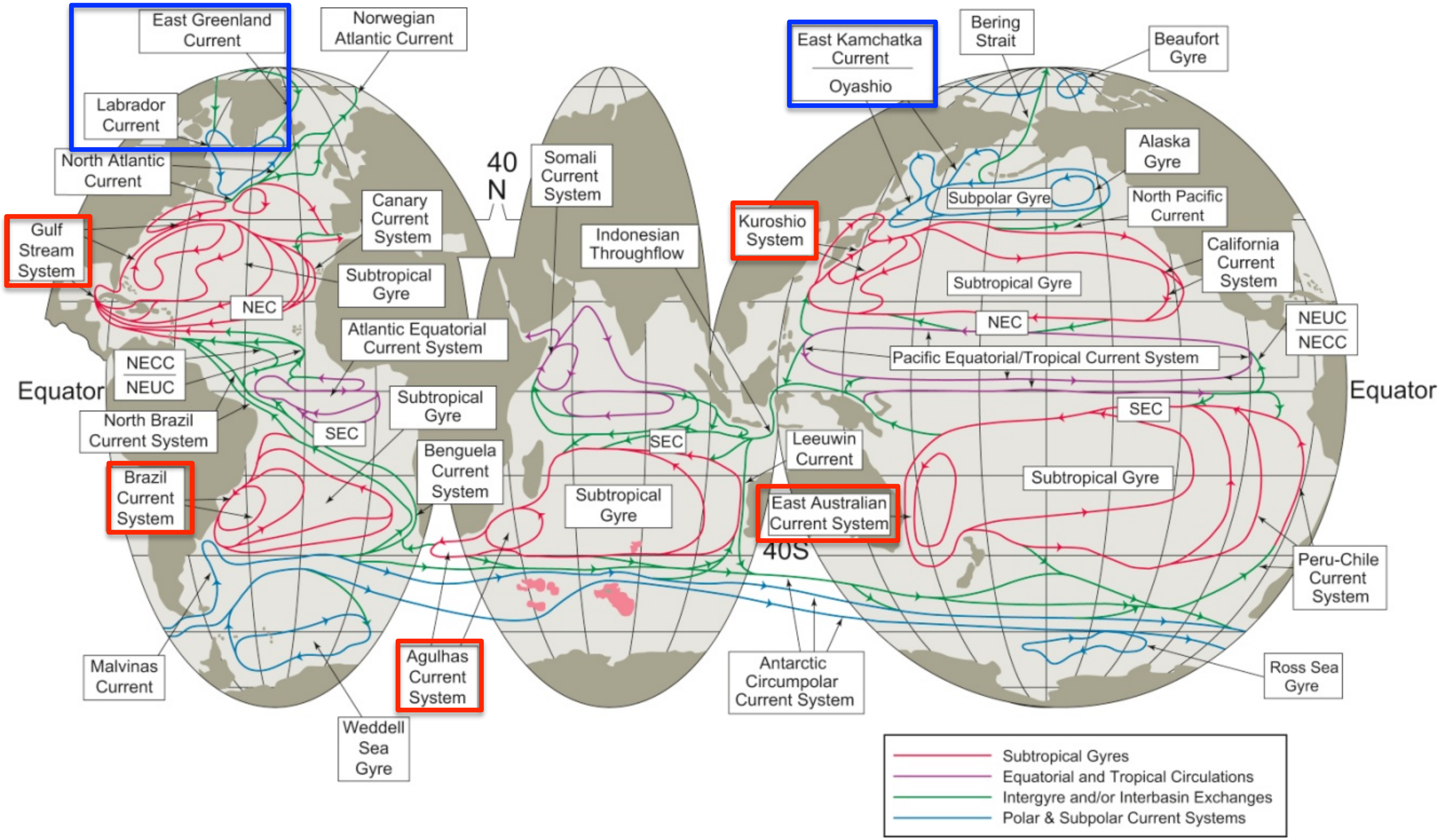
Ocean circulation is forced by

(1) Wind stress and
(2) Buoyancy changes (air-sea-land-ice fluxes, and diffusion)

Diffusion is a slow process associated with turbulence in the water column. Turbulence results from (1) wind inputs into internal waves, (2) buoyancy inputs that cause very small overturns in the surface mixed layer, (3) internal tide breaking against topography, and (4) cascade of energy into smaller scales from unstable currents.

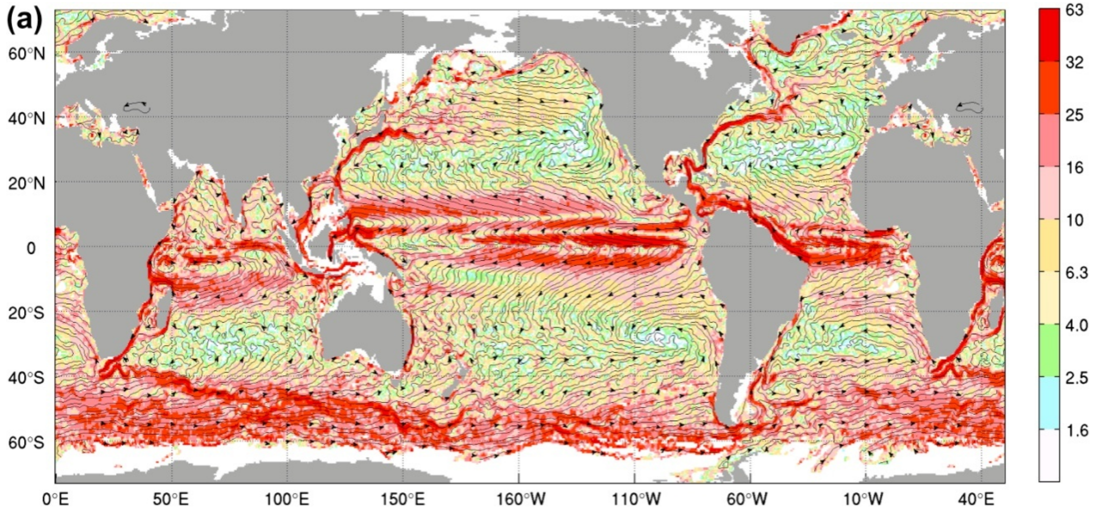
In this lecture, we consider the wind-driven upper ocean circulations, and the heat transports associated with changes in temperature (due to air-sea fluxes) along the pathways of this wind-driven circulation.

- Surface circulation: note the asymmetries (strong western boundary currents, weaker gyres)

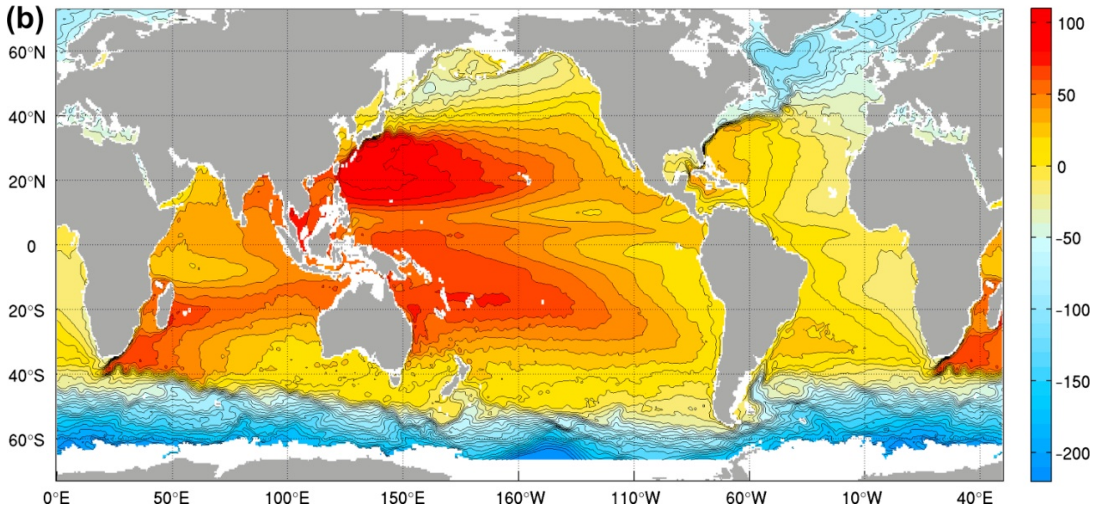


DPO FIGURE 14.1

Wind-driven circulation: surface circulation



Surface velocity streamlines (complete velocity including geostrophic and Ekman, based on surface drifters). Color is speed in cm/sec.

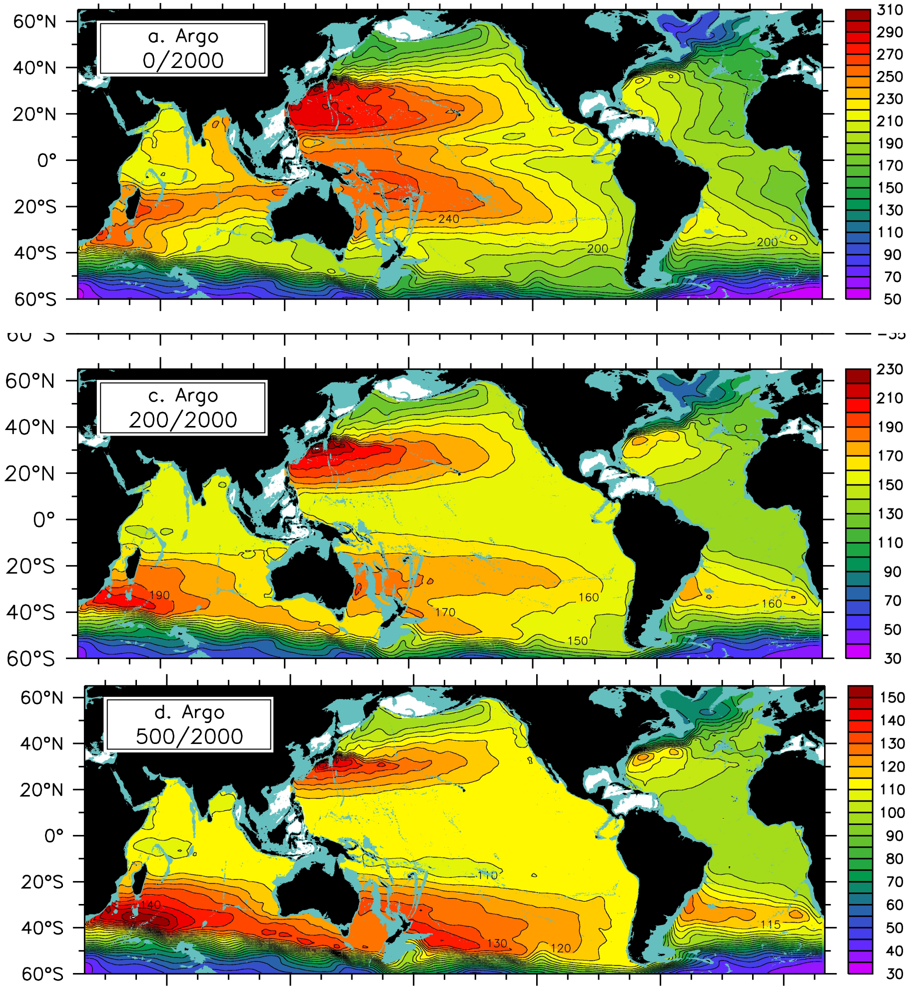


Surface height in cm, based on assumption of geostrophy, using surface drifter observations with Ekman velocity removed.

(i.e. streamfunction of the geostrophic flow)

Note western boundary intensification of the circulation **FIGURE 14.2**

- General circulation of the ocean: vertical structure of gyres



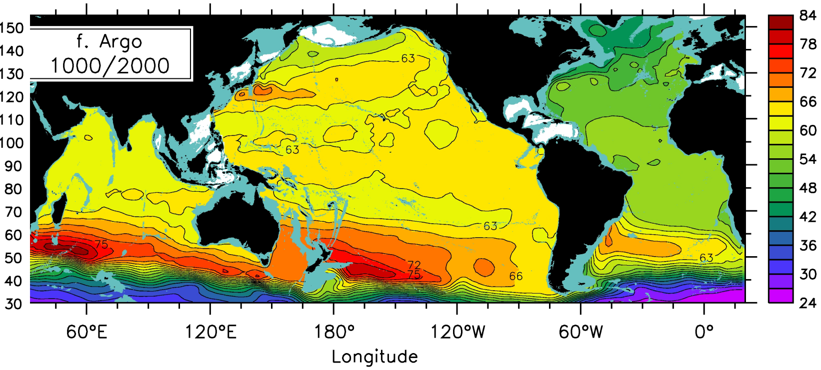
surface

With increasing depth, gyres weaken, shrink towards their western boundaries, and shrink towards the poles.
They remain western-intensified.

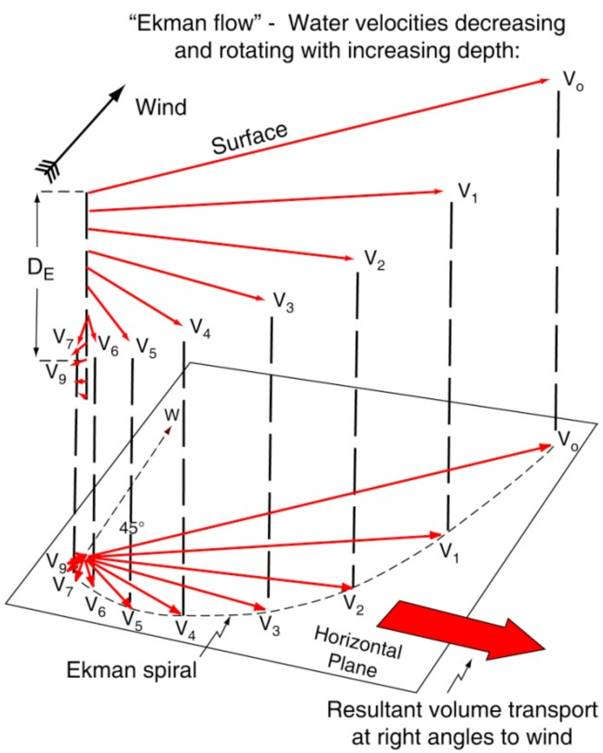
200 m

500 m

1000 m



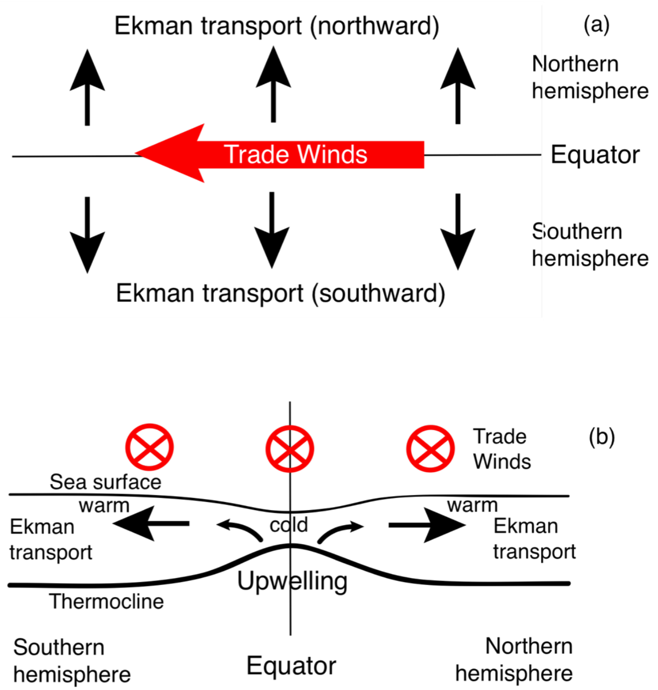
- Dynamics of wind-driven circulation
  - Ekman transport: already discussed
  - (Eastern boundary currents and equatorial currents)
  - Sverdrup balance
  - Western boundary currents
  - (Antarctic Circumpolar Current)



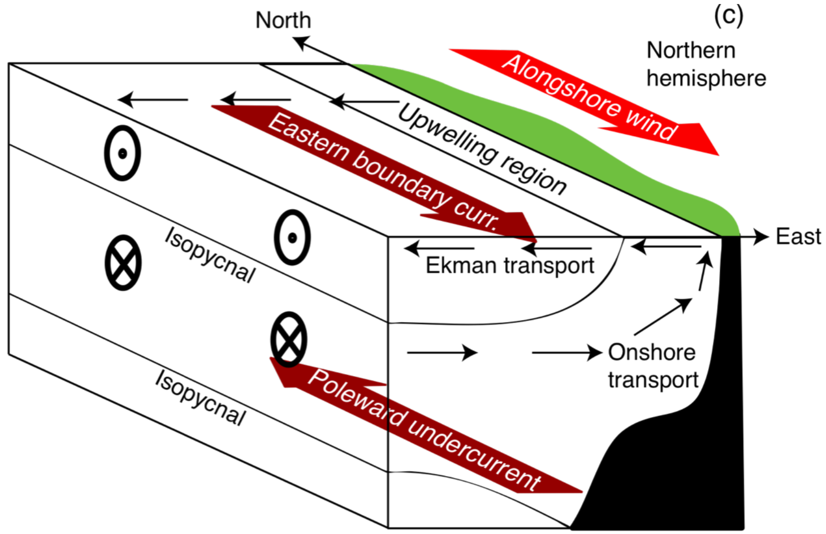
Ekman: recall that net Ekman transport is exactly at right angles to the wind stress

Wind-driven circulation: boundary and equatorial upwelling

Equatorial
(1) Frictional flow down-wind right on equator, creates upwelling in eastern equatorial region
(2) Poleward frictional Ekman transport away from equator creates upwelling along equator

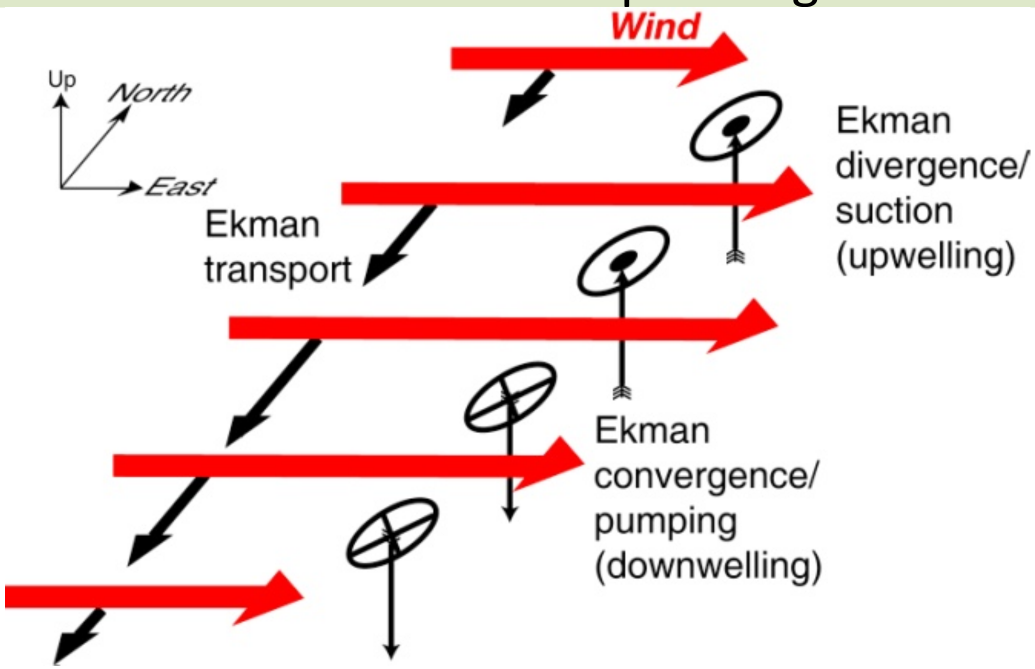


Land boundary
(northern hemisphere, like California coastline)
Alongshore wind forces Ekman transport offshore, creating coastal upwelling



DPO Fig. 7.13

Wind-driven circulation: Ekman upwelling and downwelling



Positive wind-stress curl

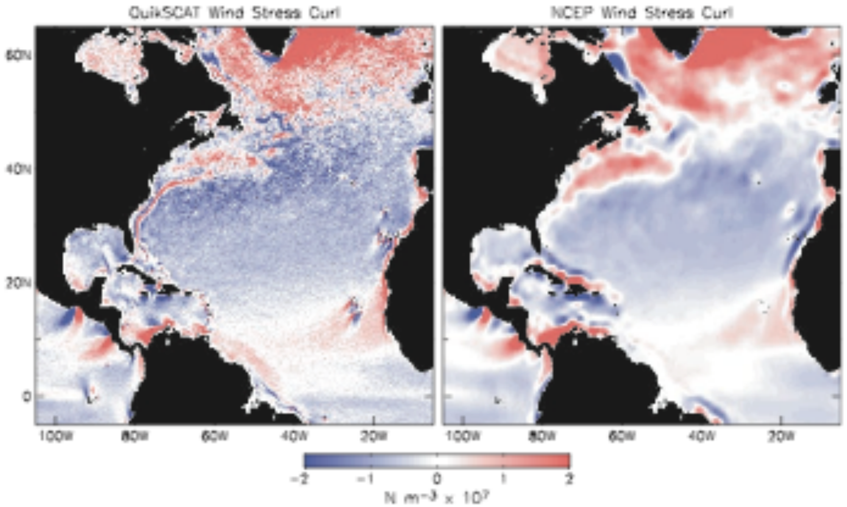
Negative wind-stress curl

Convergences create downwelling
Divergences create upwelling

This wind stress field has a non-zero curl $\nabla \times \boldsymbol{\tau}$

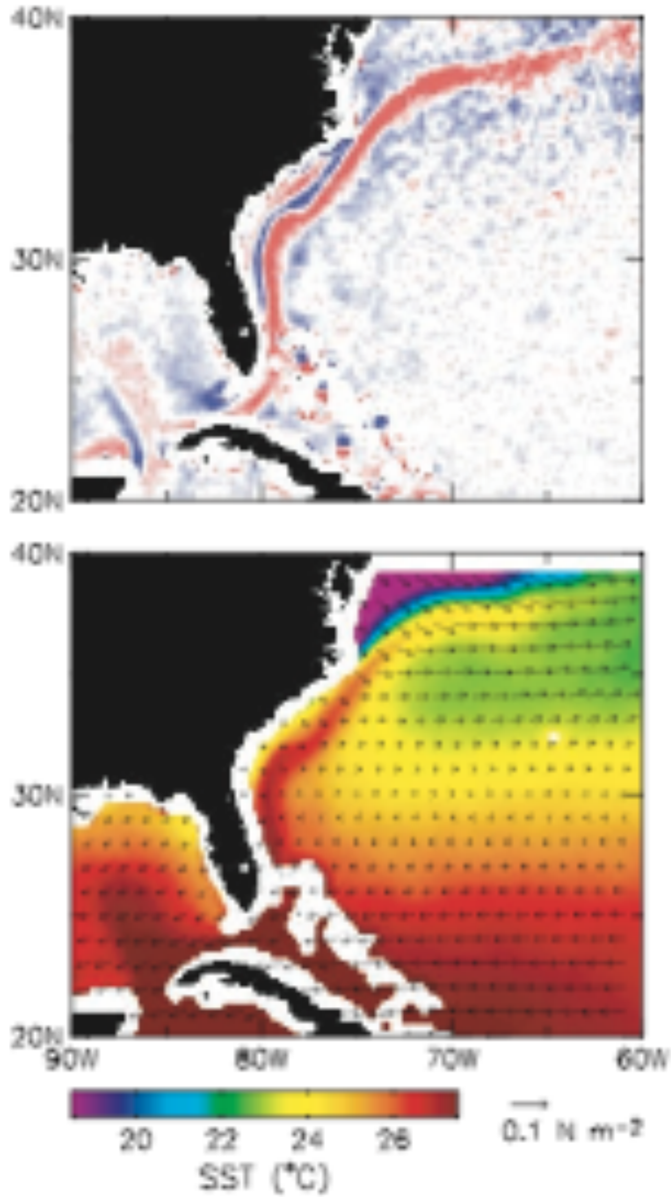
Where the curl is positive, there is upwelling (northern hemisphere).
Where curl is negative, there is downwelling out of the Ekman layer.

Wind-driven circulation: wind stress curl



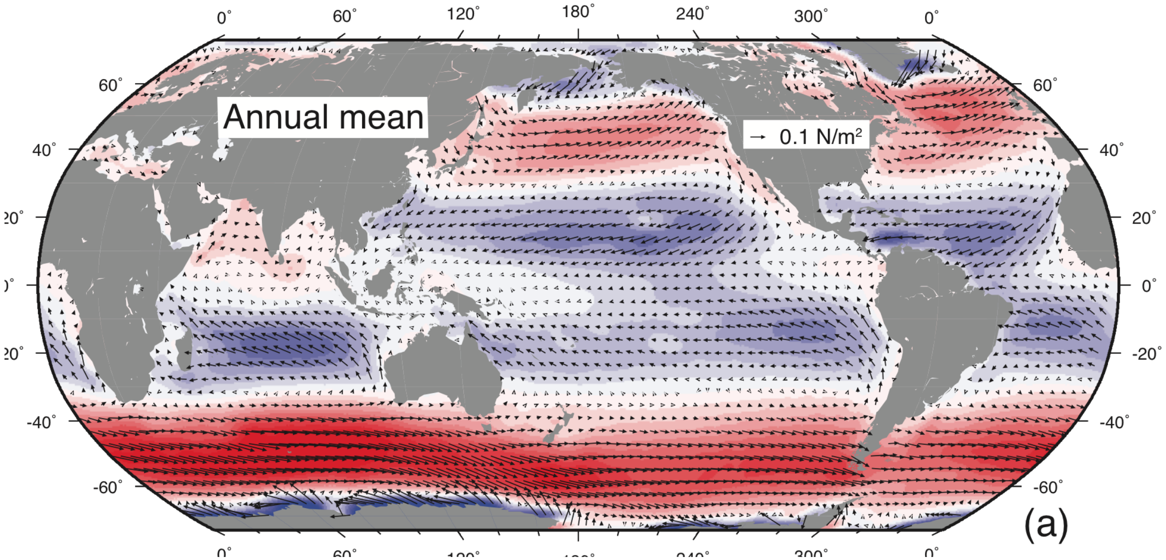
Wind stress curl from satellite QuikSCAT winds is MUCH better than from NCEP reanalysis

Wind stress curl following Gulf Stream and other major currents suggests the impact of strong SST fronts on the winds, as is now being corroborated in a number of studies

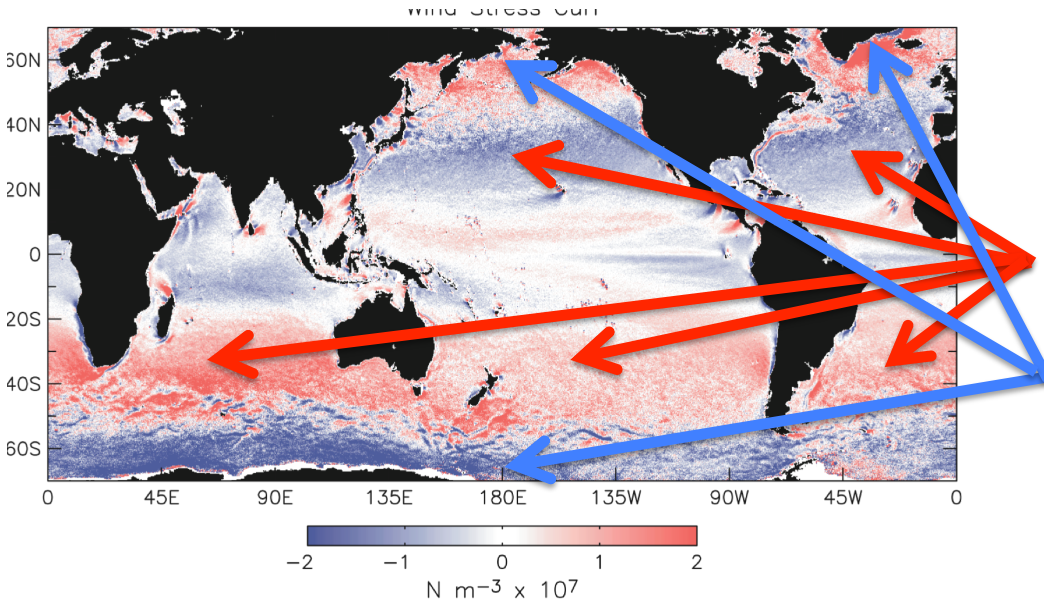


Chelton et al. (2004)

Wind-driven circulation: open ocean effects



Wind stress (note Trades and Westerlies)



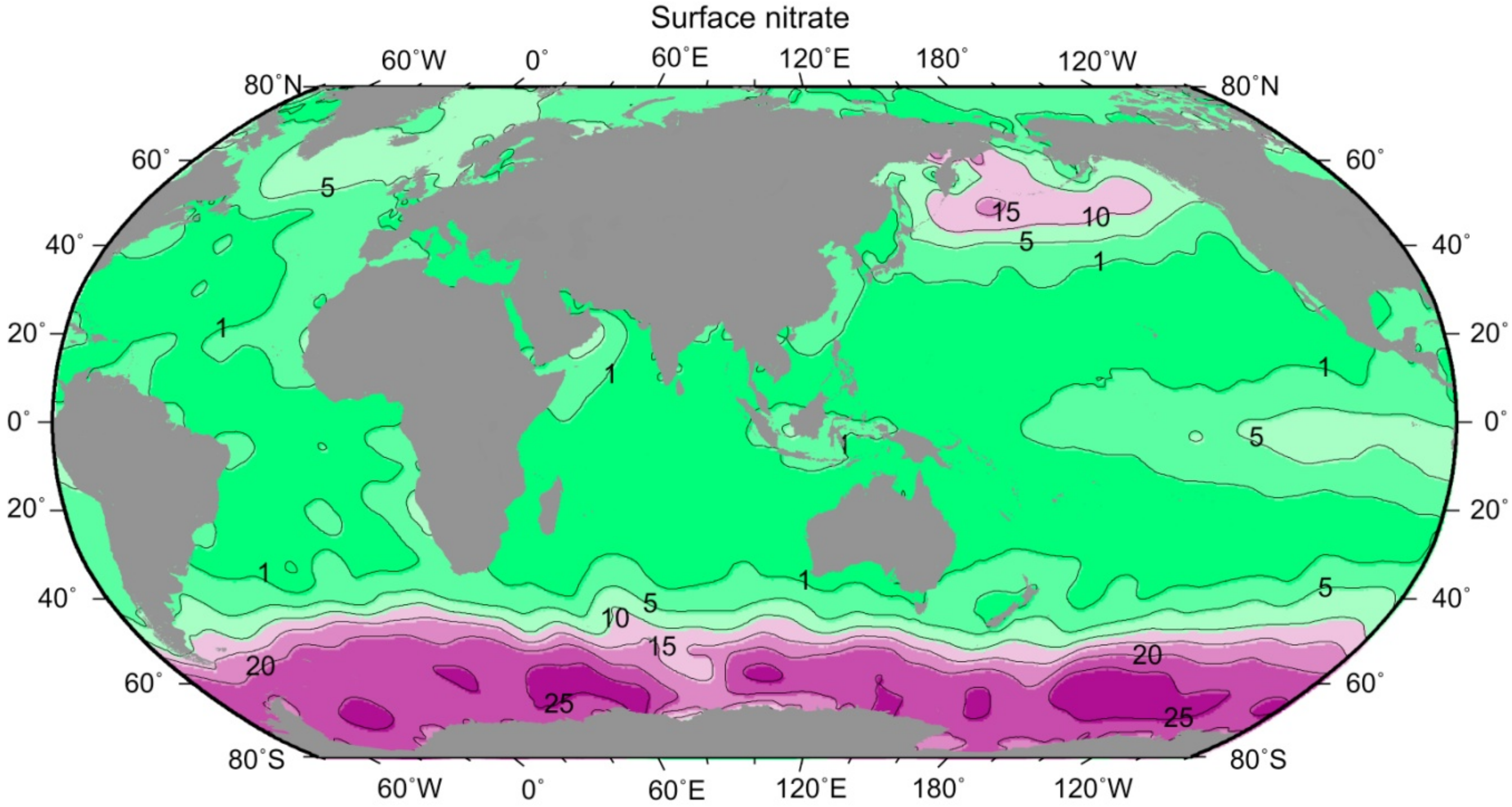
Wind stress curl (related to Ekman transport convergence and divergence) (Chelton et al., 2004)

Ekman downwelling

Ekman upwelling

DPO Fig. 5.16a,d

Wind-driven circulation: evidence of Ekman upwelling

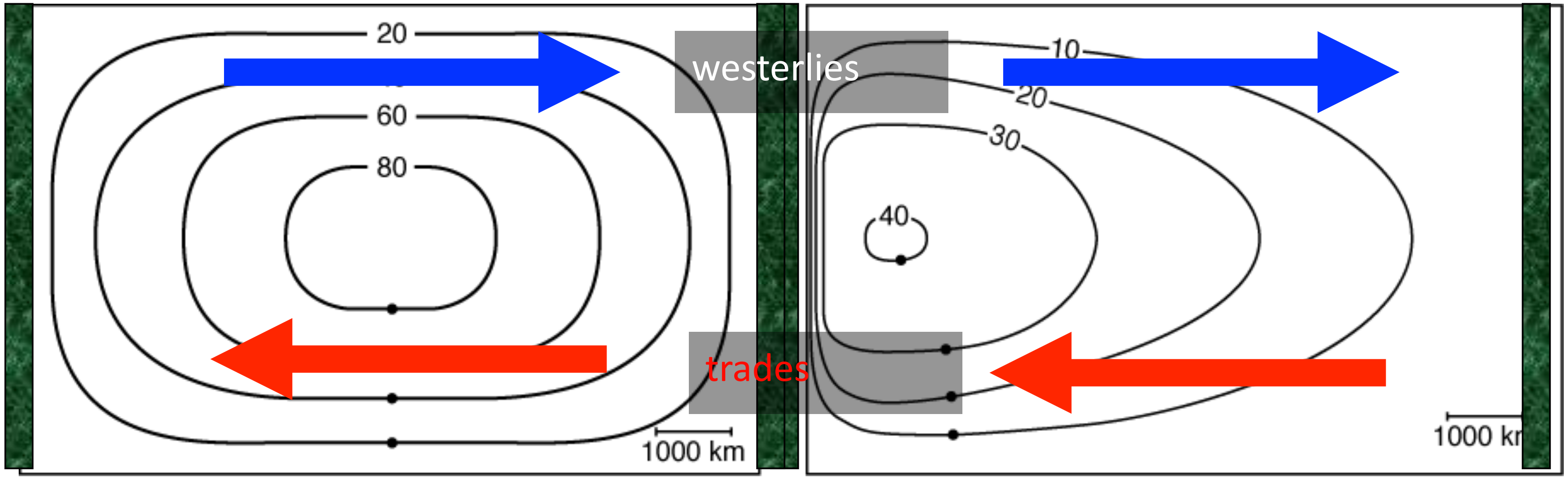


DPO Fig. 4.23

Presence of the nutrient nitrate at the sea surface is an indication of upwelling of nutrient-rich waters from below the euphotic zone (since nitrate is consumed by organisms within the sunlit surface layer, and regenerated below that layer by bacterial decomposition)

Wind-driven circulation: western intensification

How does the Ekman upwelling and downwelling drive the ocean gyres?
The answer is related to the observed asymmetry (western intensification) of the gyres.



what one might expect

what one observes

(Stommel figures for circulation assuming perfect westerlies and trades)

= LAND

DPO Fig. S7.31

Wind-driven circulation: potential vorticity

Conservation of potential vorticity (planetary and stretching)

From geostrophic balance, form the vorticity equation:

$-fv = -(1/\rho)\partial p/\partial x$

$fu = -(1/\rho)\partial p/\partial y$

$\Rightarrow f(\partial u/\partial x + \partial v/\partial y) + \beta v = 0$

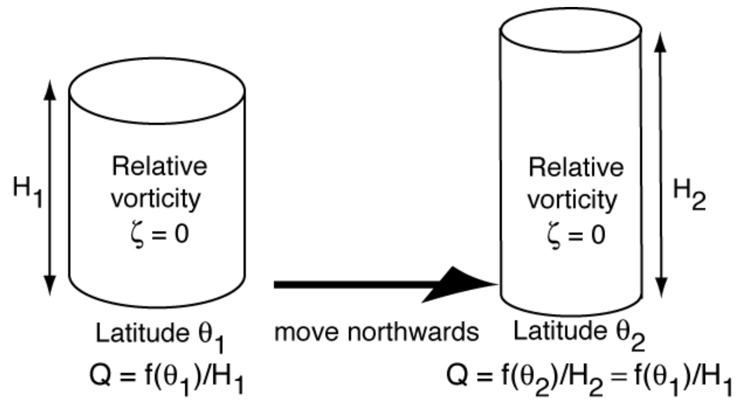
From continuity, $\partial u/\partial x + \partial v/\partial y = -\partial w/\partial z$

So $\beta v = f\partial w/\partial z$

(stretching of water column is balanced by meridional motion to a different f, hence different local planetary vorticity)

This is a form of the potential vorticity equation, noting that relative vorticity is negligible in the ocean interior

$$\frac{D}{Dt}\left(\frac{f+\varsigma}{H}\right) = 0$$



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

DPO Figs. S7.26

Wind-driven circulation: potential vorticity and Sverdrup balance

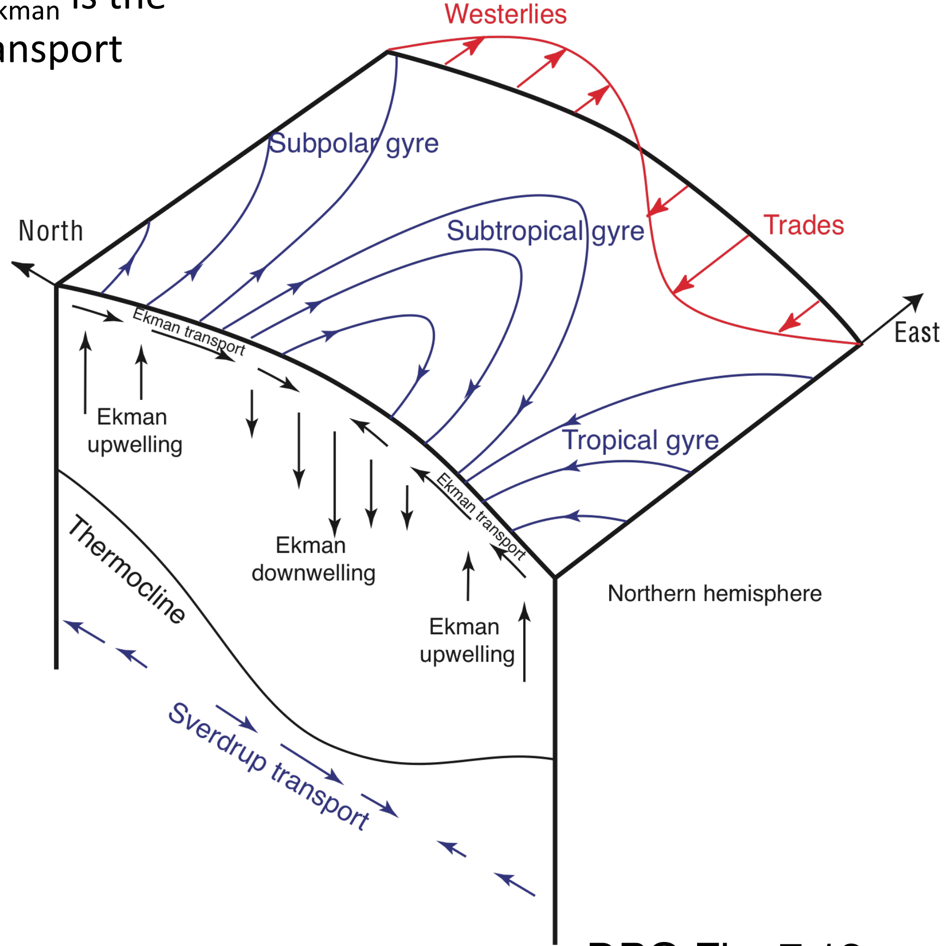
Integrating vertically, the meridional transport V is given by:

$\beta V = \beta \int v dz = f(w_{surface} - w_{deep}) \sim f\, w_{Ekman}$

which is is the “Sverdrup relation”, where w_{Ekman} is the upwelling and downwelling due to Ekman transport convergence, driven by the wind stress.

This yields the meridional direction of the transport in the ocean interior.

Between the maximum westerlies and maximum trades (in the subtropics), there is Ekman downwelling, and therefore equatorward flow.



DPO Fig. 7.13

Wind-driven circulation: western boundary currents

Western boundary currents: the return flow for the interior Sverdrup transport

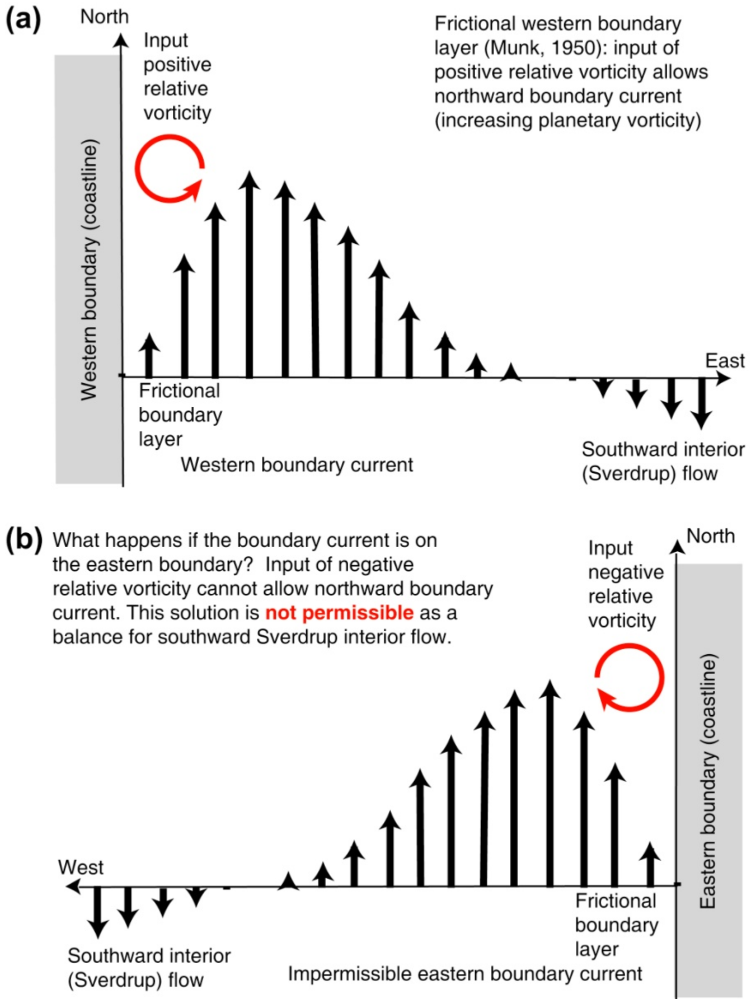


FIGURE S7.35

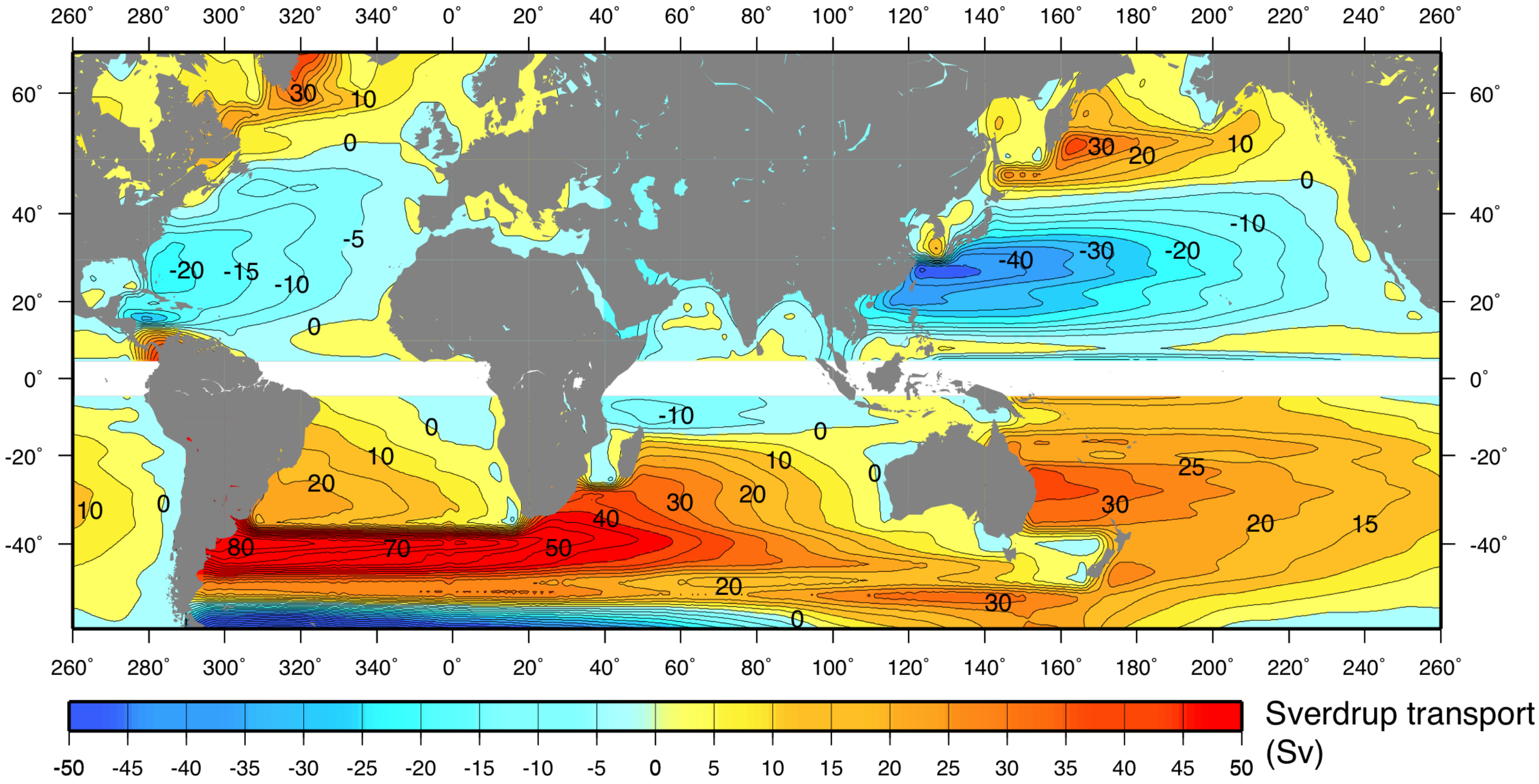
- The wind puts vorticity into the ocean (squashing/stretching)
- A viscous region is necessary to remove this vorticity – must be a narrow region next to a boundary

- Viscous boundary current puts in the opposite type of relative vorticity
- Can it be on ANY boundary?
- NO – has to be on a western boundary
- e.g. Ekman downwelling: wind puts in negative vorticity in gyre

- e.g. WBC for downwelling gyre puts in the required positive vorticity

Wind-driven circulation

Sverdrup transport streamfunction calculated from observed wind-stress curl

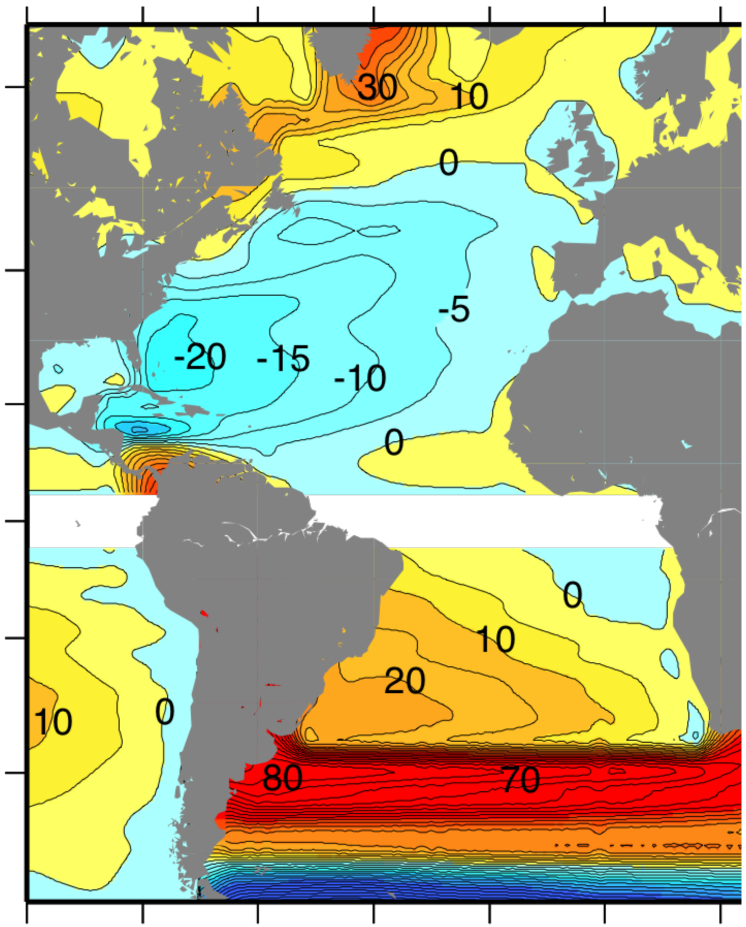


DPO Fig. 5.17

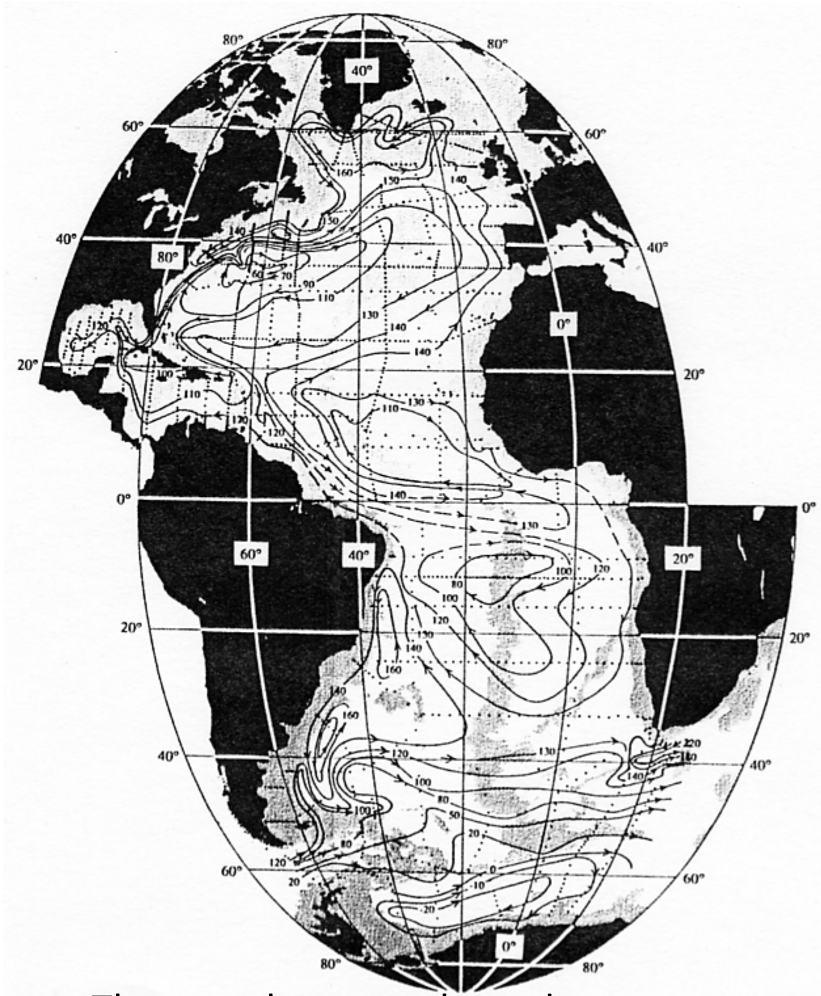
Integrate $\beta V = f\, w_{Ekman}$ zonally (in x) from the eastern boundary to obtain the geostrophic transport streamfunction Ψ, which is 0 on the eastern boundaries. Value at western boundary provides the total transport of the opposing western boundary current.

Wind-driven circulation: Sverdrup transport

Sverdrup transport streamfunction



Total geostrophic transport (Reid, 1994)



These pictures are similar in their gyre structures. The actual western boundary transports are larger than the Sverdrup transport, the western boundary currents pick up additional energy and also separate from the coast, flowing far out to sea before dissipating. The Antarctic Circumpolar Current structure is quite different from the Sverdrup prediction.

Wind-driven circulation: shallow overturning

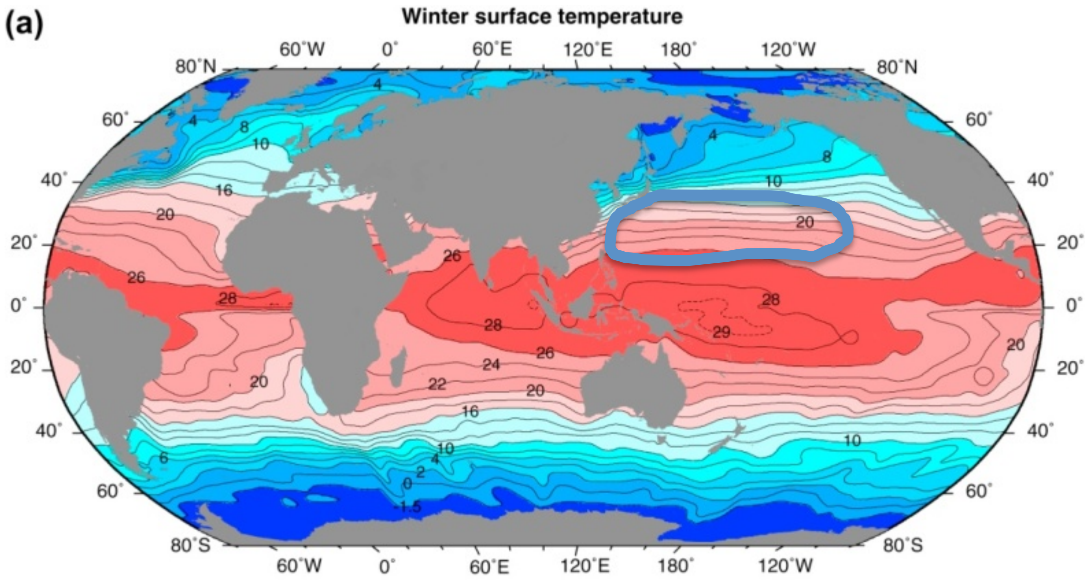
Wind-driven circulation in 3 dimensions: what happens given that the ocean surface is colder at higher latitudes and warmer at lower latitudes?

Cooler water in the northern part of the gyre circulates southward, encountering warmer surface water. It slides beneath the surface waters, following isopycnal (adiabatic) surfaces down into the ocean interior (just a few hundred meters down, not very far).

This process is called

"subduction"

The subducted cooler water is eventually heated (by diffusion or passage through the tropics) and returns to the surface as warmer water, flowing northward in, say, the Gulf Stream



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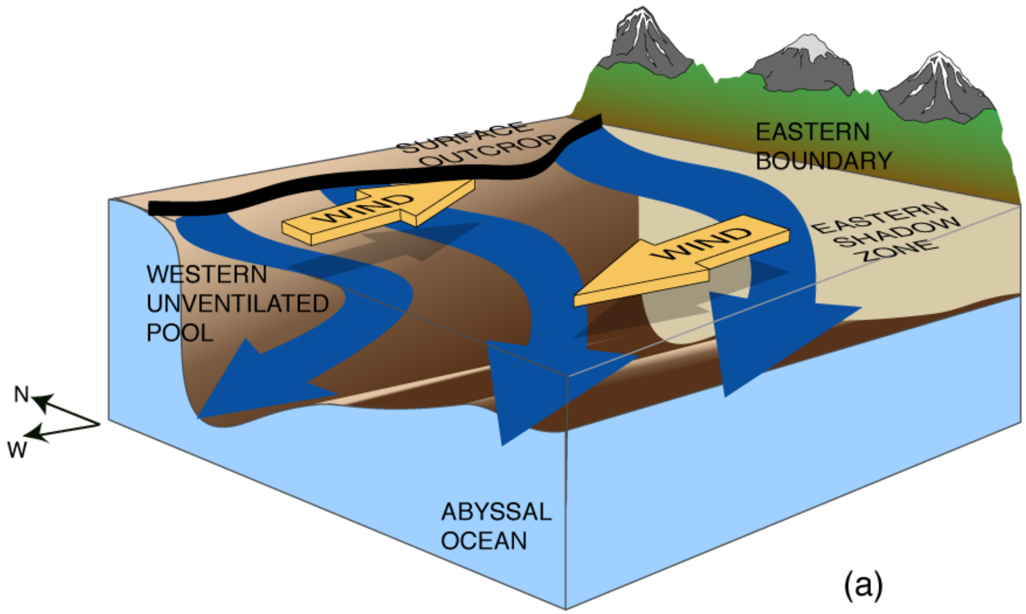
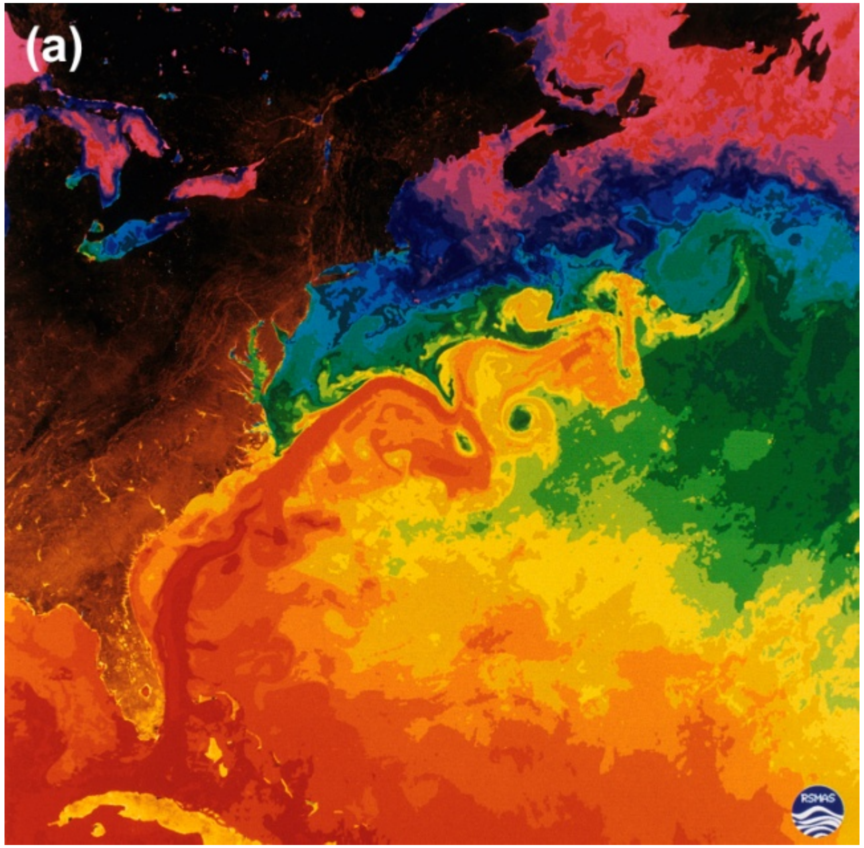


DPO Fig. 7.15

Wind-driven circulation: heat transports



Heat transport in a subtropical gyre:
The warm Gulf Stream flows northward. Its waters cool, move eastward and join the southward flow of the subtropical gyre.

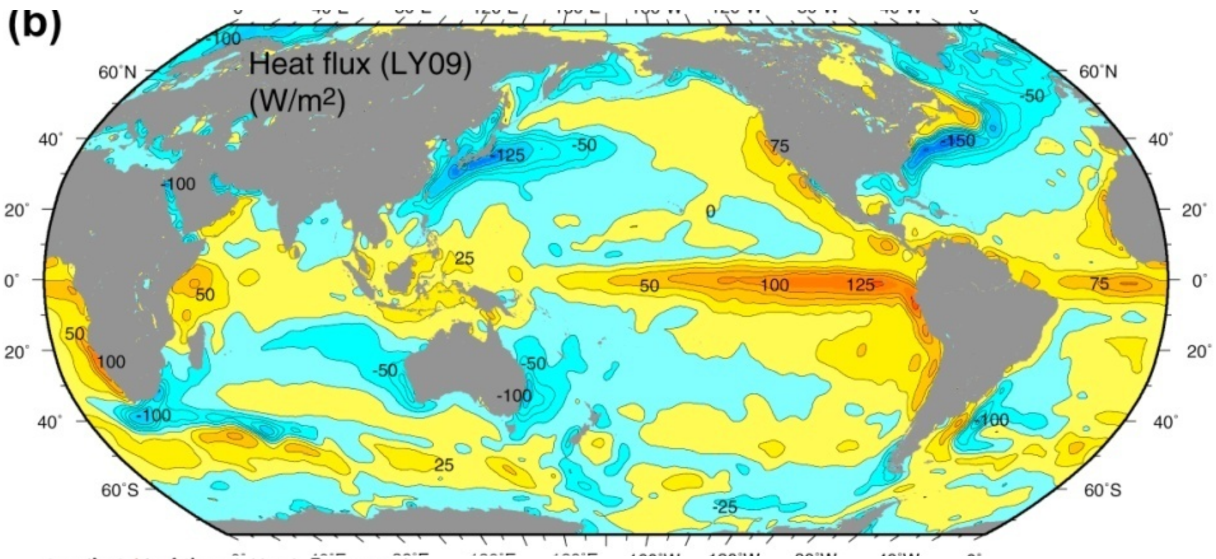
The northward flow of warm water and southward return flow of cooler water means that there is a
northward heat transport

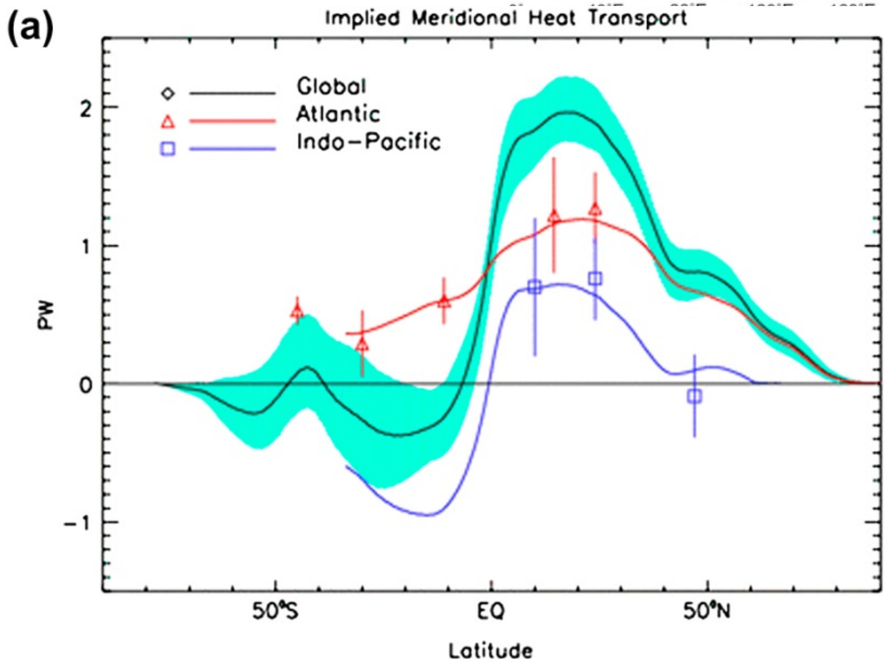
Heat transport =
Volume transport x (T_{diff})x (ρc_p)

(really the integral, but MUST have complete balanced northward and southward volume transport.)

In the subpolar gyre, there is a southward flow of cold water in the western boundary current and northward flow of warmer water in the gyre. This also results in a northward heat transport.

Wind-driven circulation: heat transport



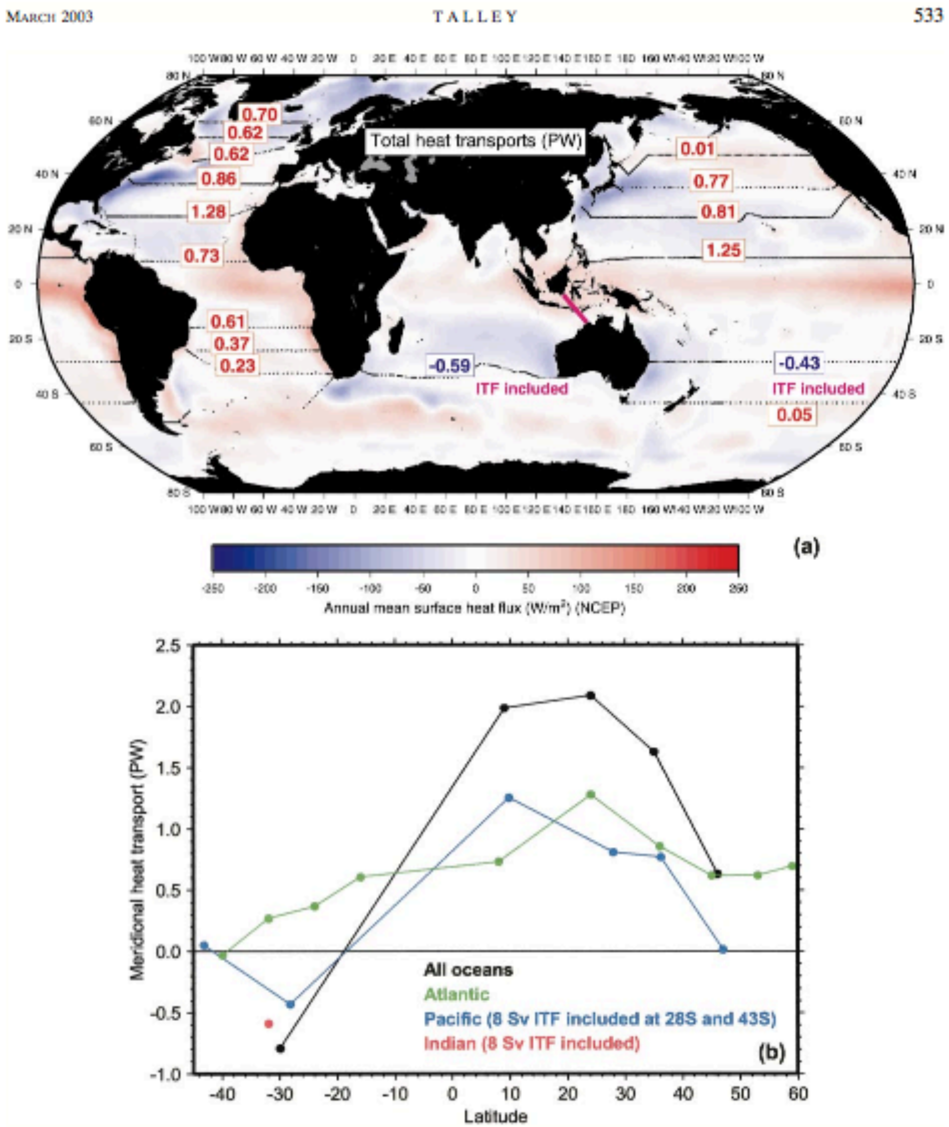


Meridional heat transport (in PetaWatts, where 1 PW = 10^{15} W).

Calculated by Large and Yeager (2009) from their air-sea heat flux analysis (map above).

Red is Atlantic (note that it is northward at all latitude).
Blue is the sum of Indian-Pacific.

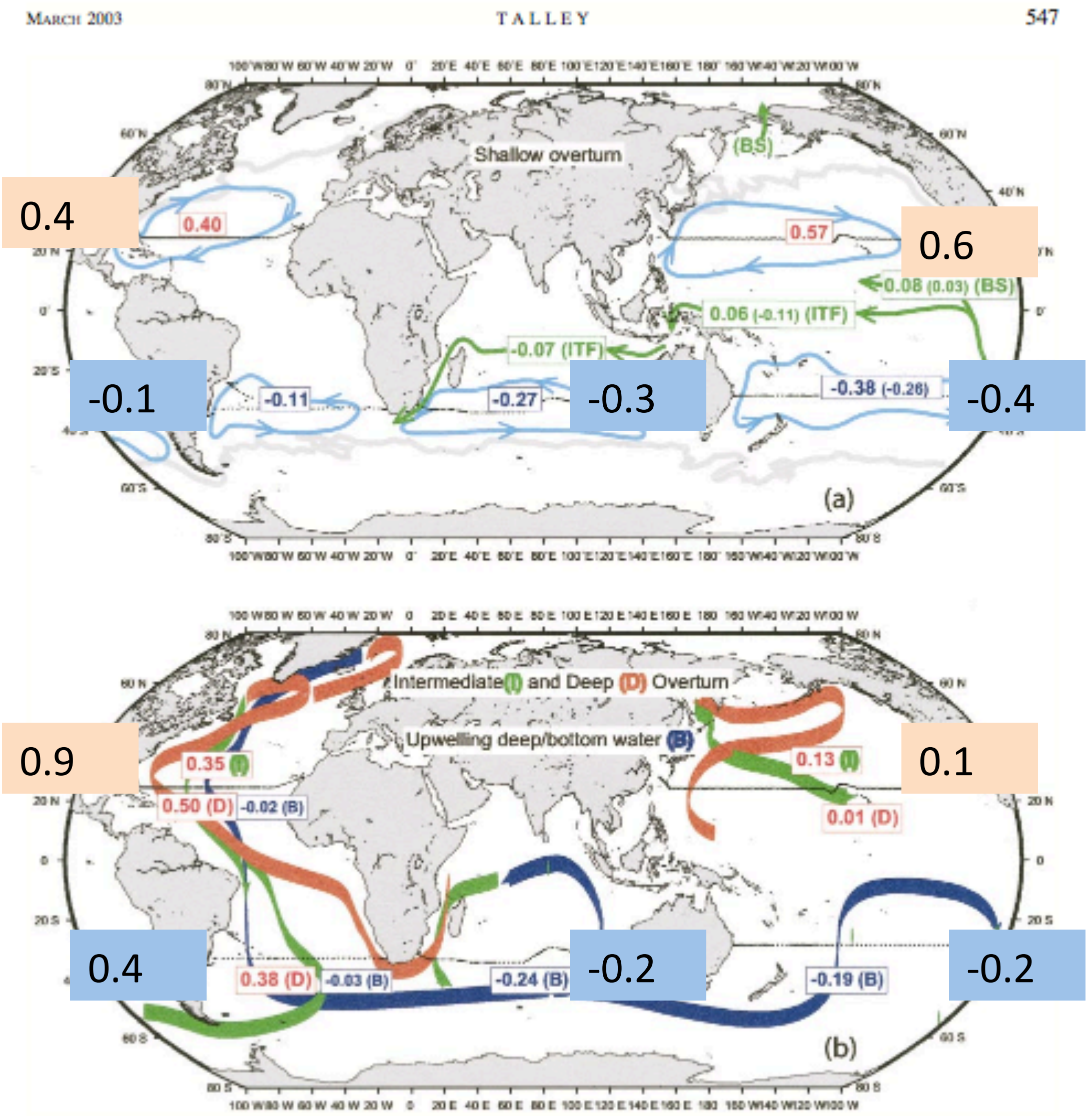
Wind-driven circulation: heat transport



Meridional heat transport calculated from ocean analysis of velocity and temperature at all depths and stations along the zonal sections shown.

(Talley, 2003)

Wind-driven circulation: heat transport

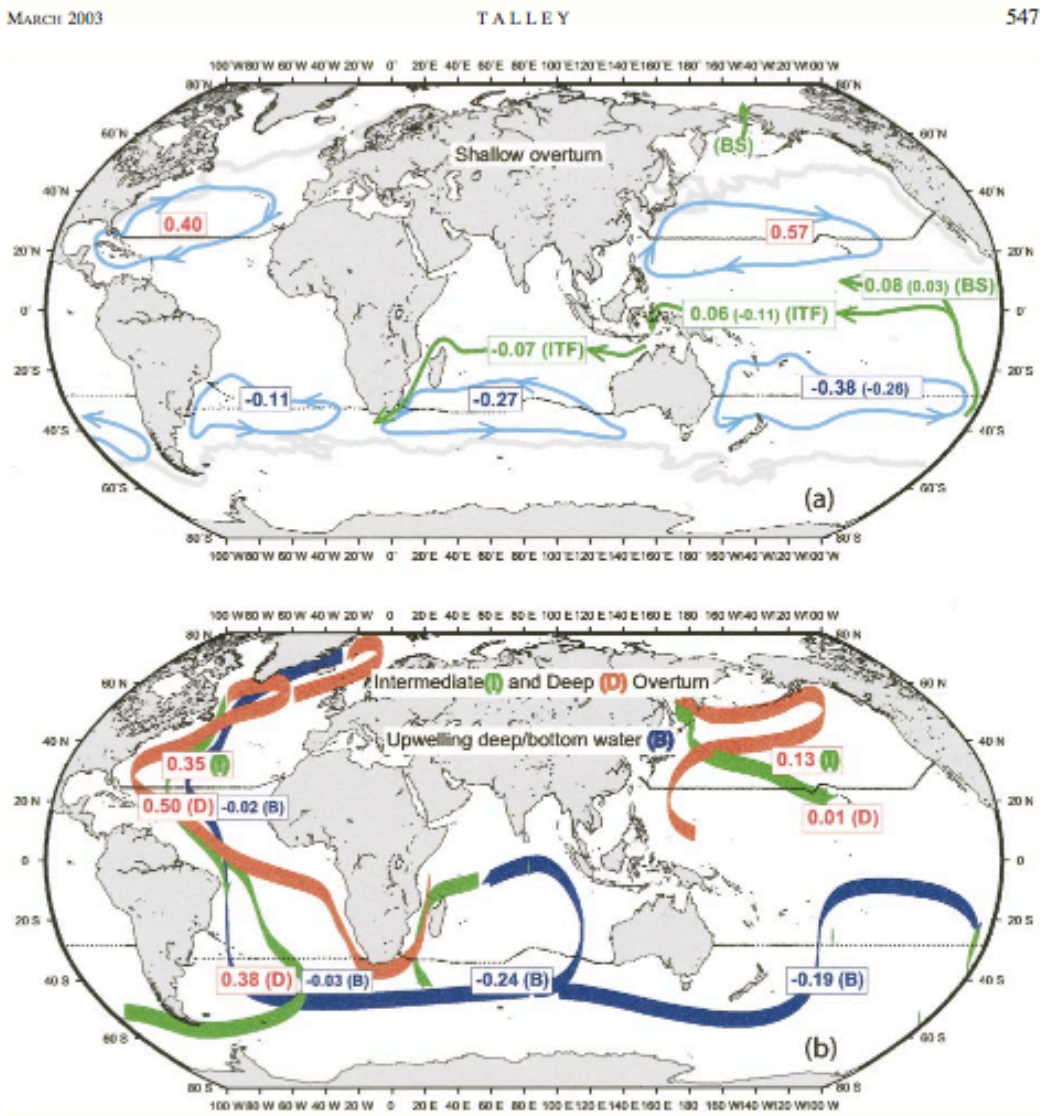


For the net heat transports, how much is carried by the wind-driven gyres and how much by the deeper meridional overturning? (to be discussed in next lecture).

The answer at mid-latitudes, i.e. for the subtropical gyres, is that the gyres carry a substantial fraction of the heat: about half.

(Talley, 2003)

Wind-driven circulation: heat transport



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