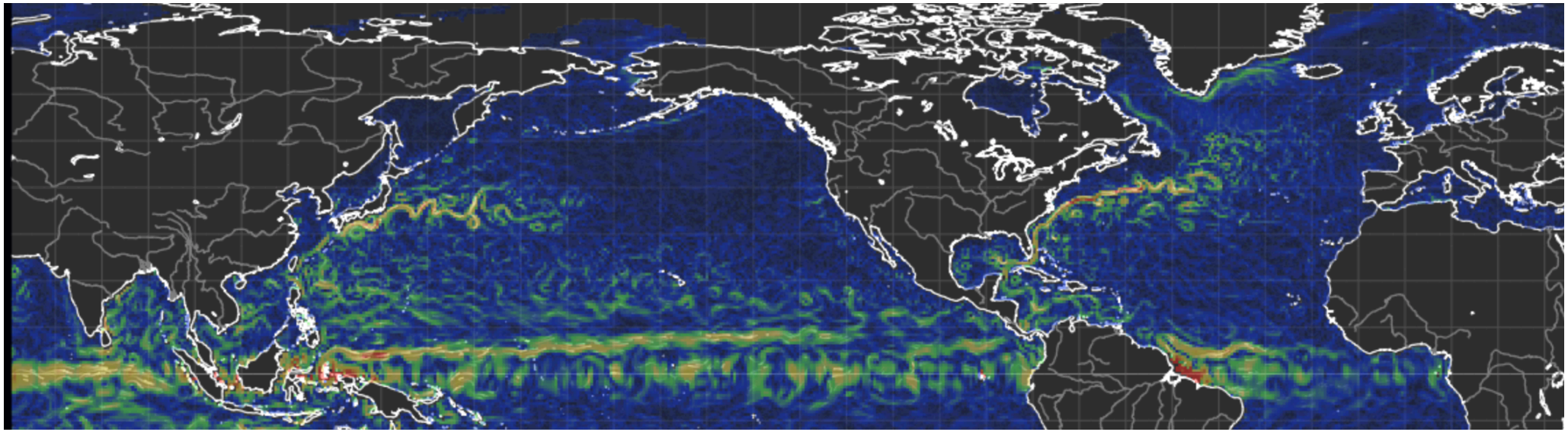


# SIO 210: Dynamics VII: Sverdrup balance and western boundary currents

- Sverdrup balance for the large-scale circulation
- Western boundary currents
- Pacific wind-driven circulation

READING:
DPO: Chapter S7.7.1 and S7.7.2; S7.8.1, S7.8.3
(or same sections in regular Chapter 7)

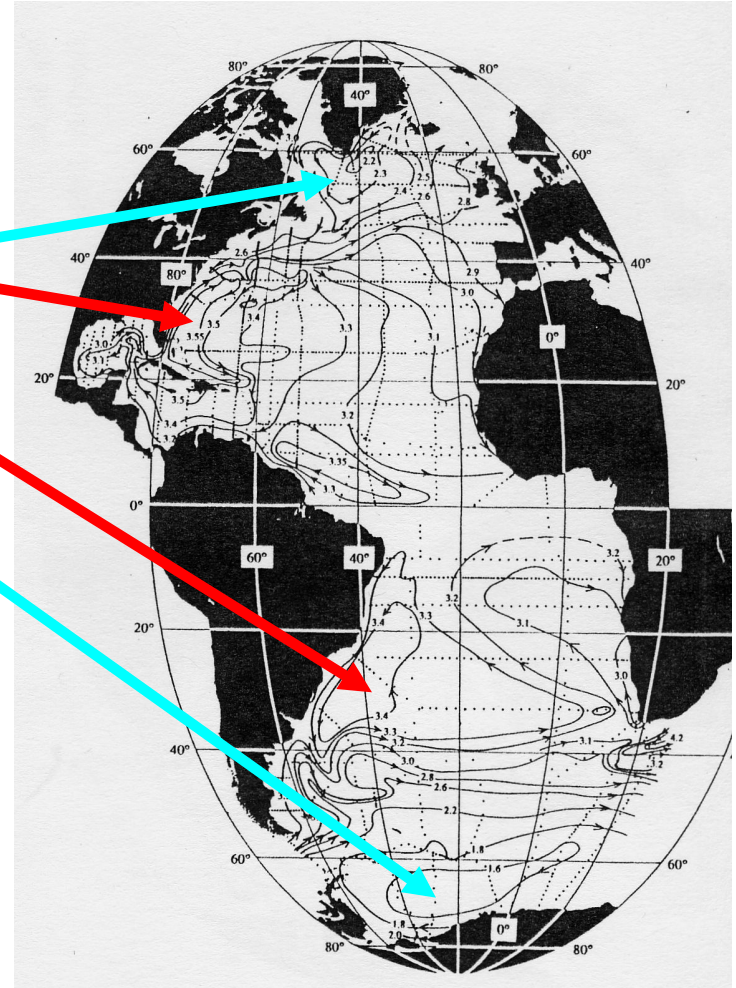
Atlantic surface circulation (adjusted steric height) (Reid, 1994)

Note:

Subtropical gyres (anticyclonic)

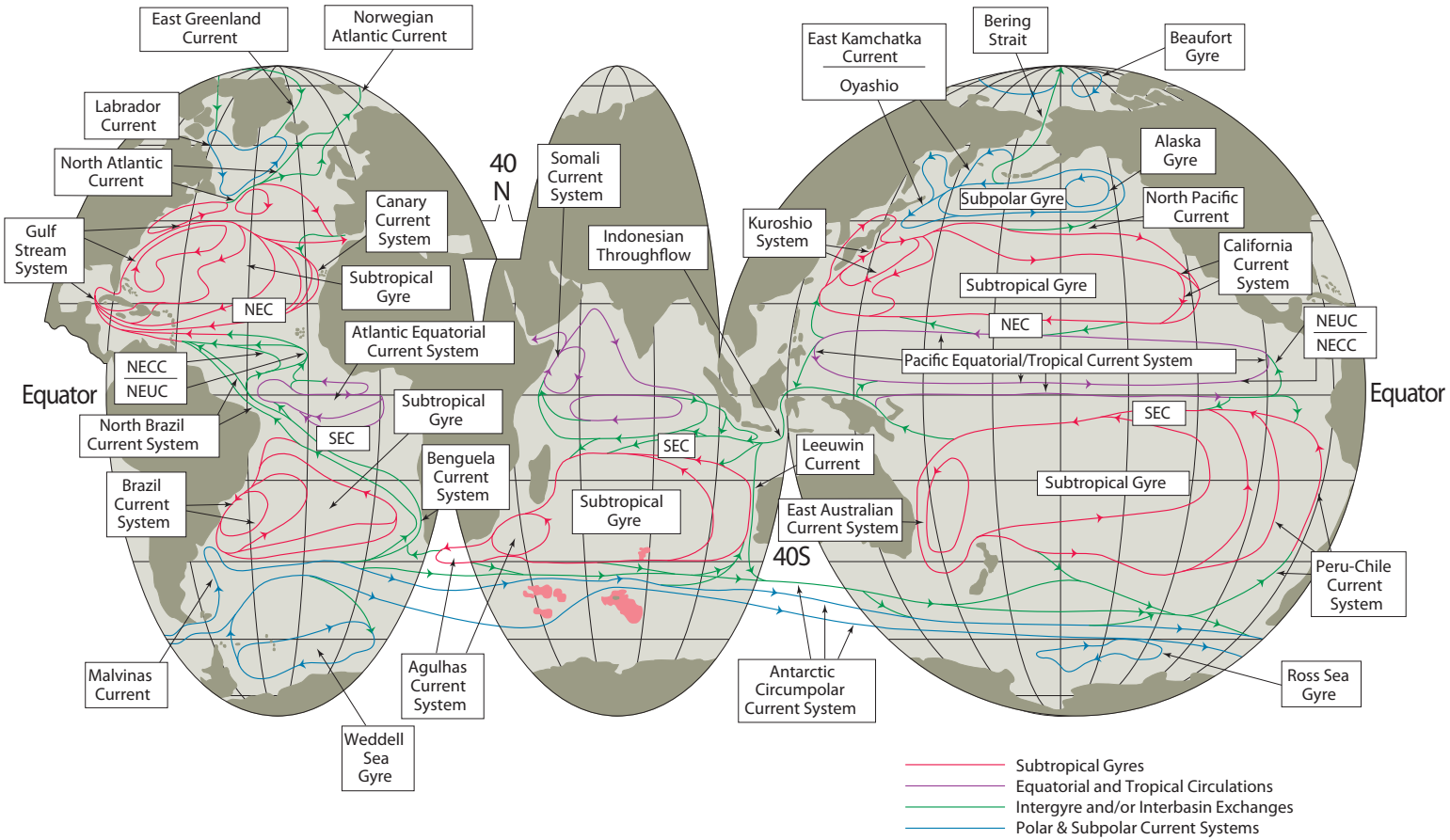
Subpolar gyres (cyclonic)

Note: westward intensification of the currents - strong currents are all on the western boundary, regardless of hemisphere




DPO Fig. 9.2a

# Schematic of surface circulation (modified from Schmitz, 1995)




Why are there gyres? Why are circulations intensified in the west?

("western boundary currents")



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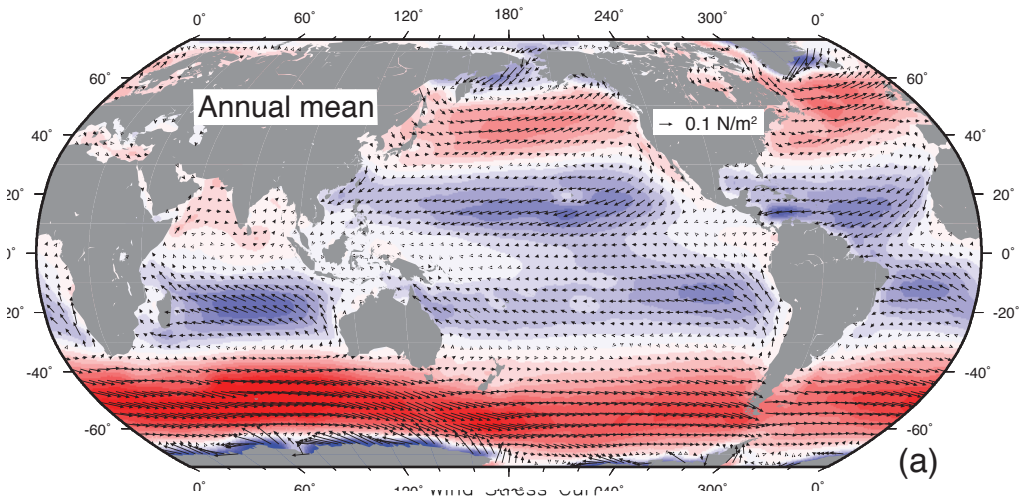
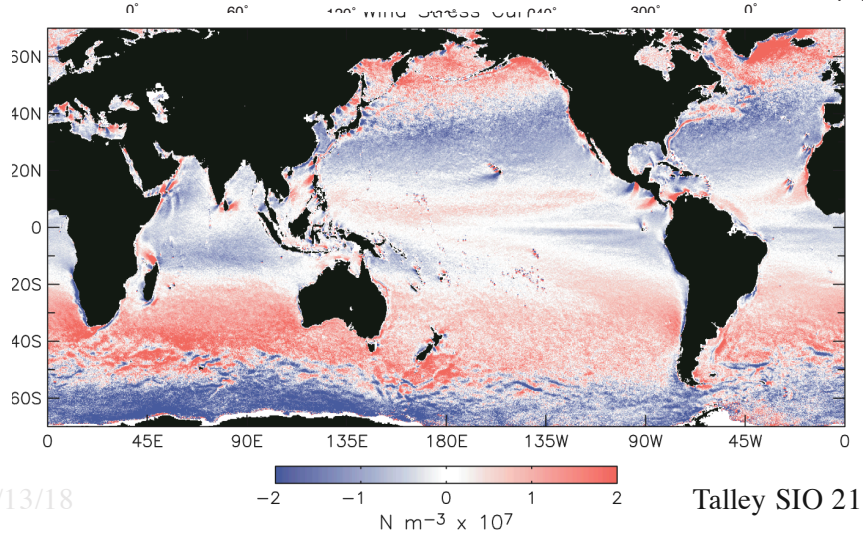
DPO Fig. 14.1

# Global surface wind stress and curl




Wind stress (note Trades and Westerlies)




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



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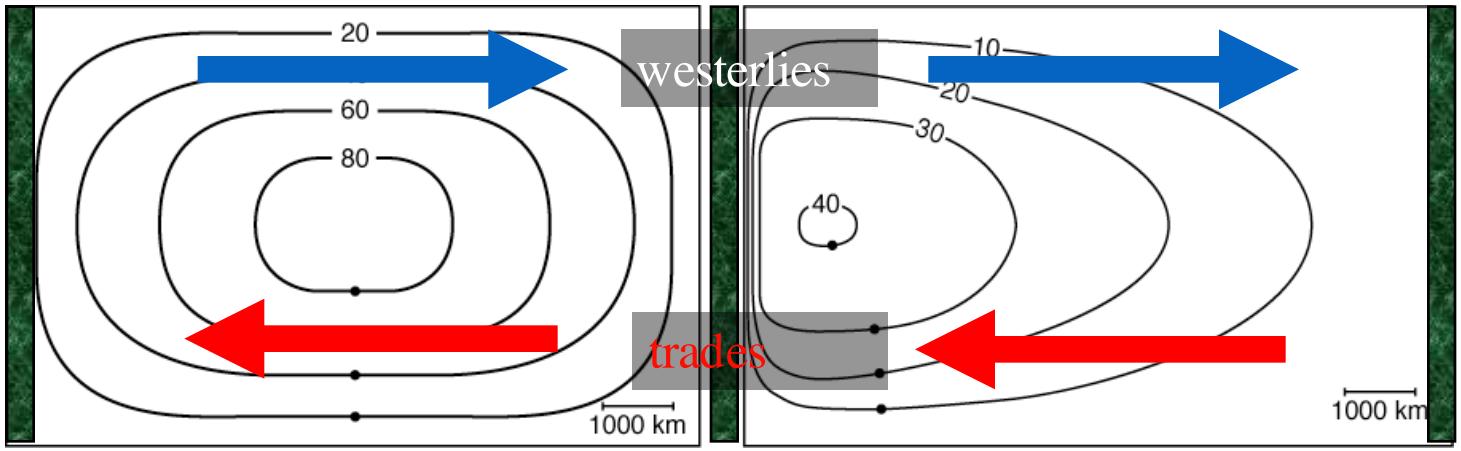
DPO Fig. 5.16a,d

# Observed asymmetry of wind-driven gyres




what one might expect

what one observes

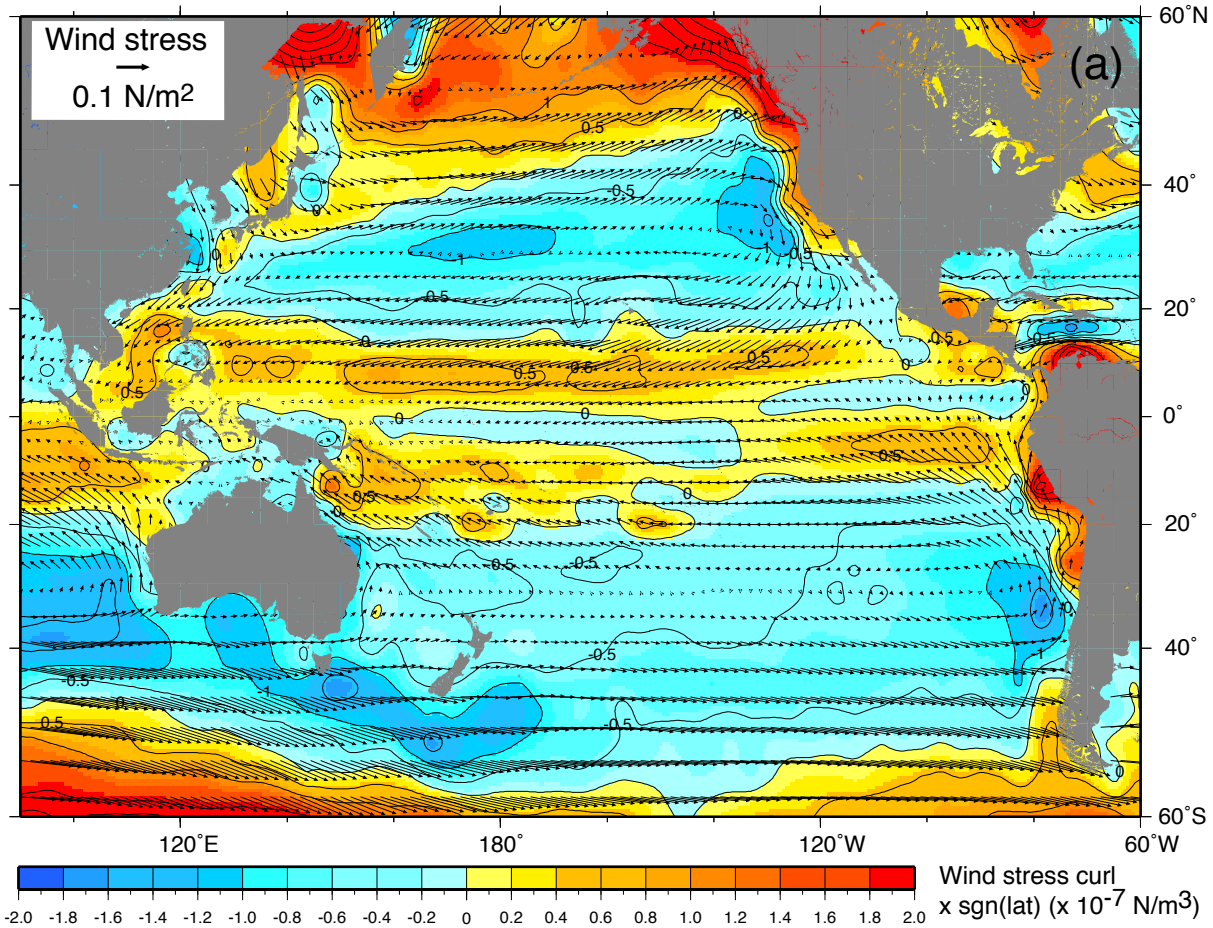
(especially if ignorant of Ekman layers)

(Stommel figures for circulation assuming perfect westerlies and trades)

= LAND

DPO Fig. S7.31

# Ekman pumping for the Pacific

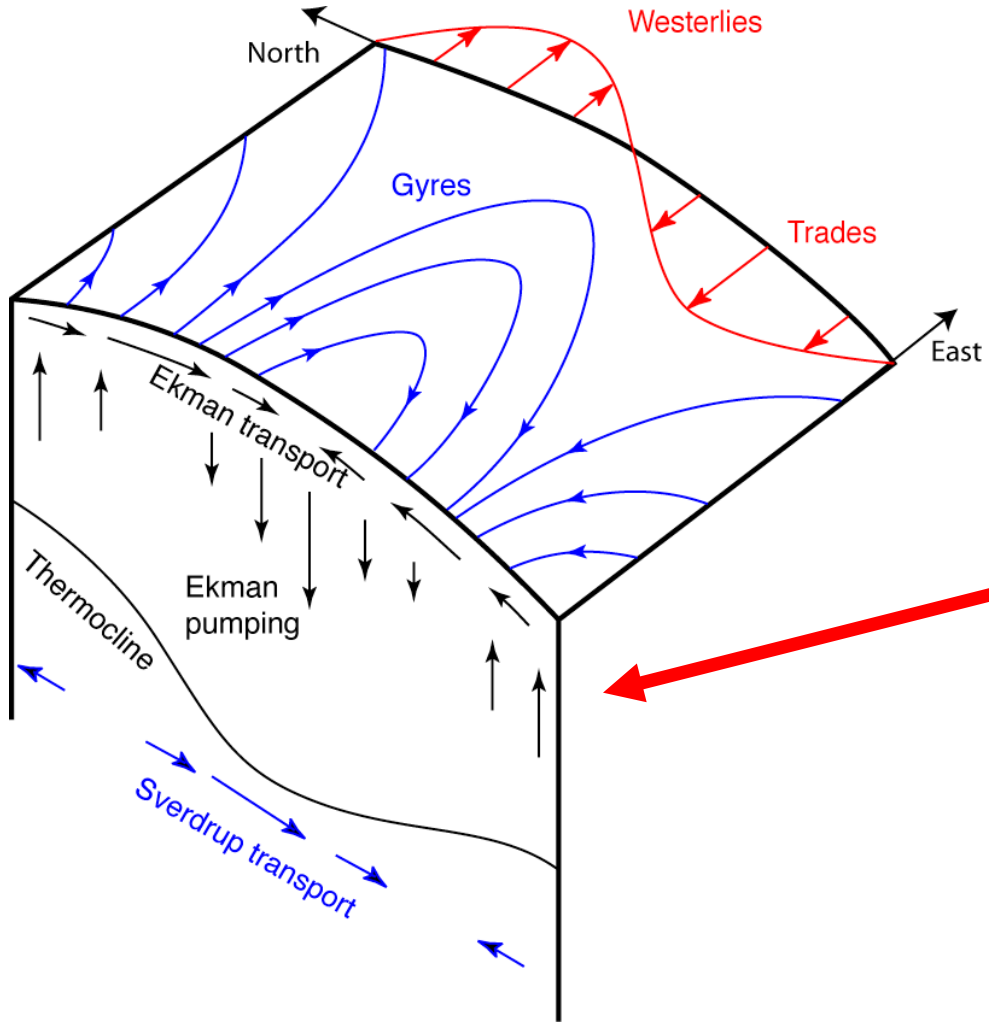



Blue regions: Ekman pumping (wind curl is negative in northern hemisphere and positive in southern hemisphere, leading to Ekman convergence)

Yellow-red regions: Ekman suction (vice versa)

DPO Fig. S5.10

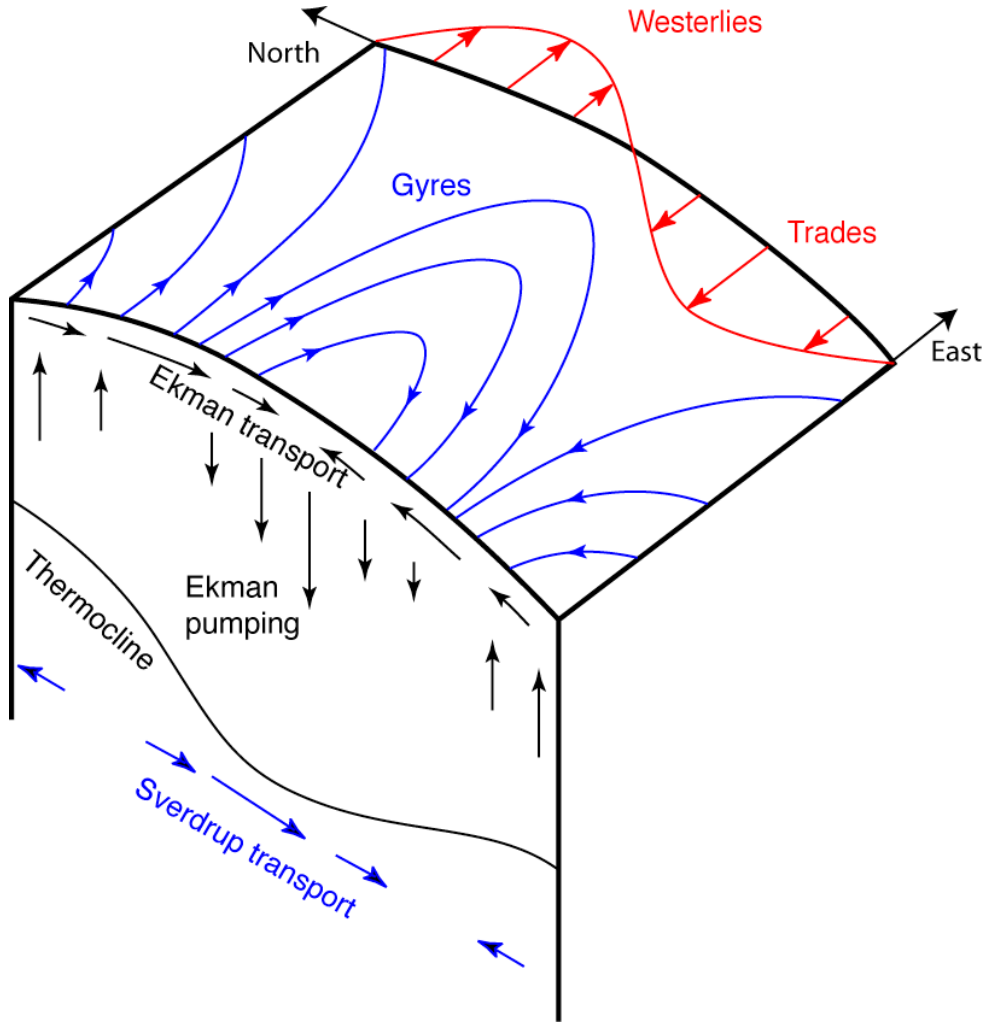
# Sverdrup balance




What is the interior ocean response to Ekman downwelling (pumping)?

DPO Fig. 7.13

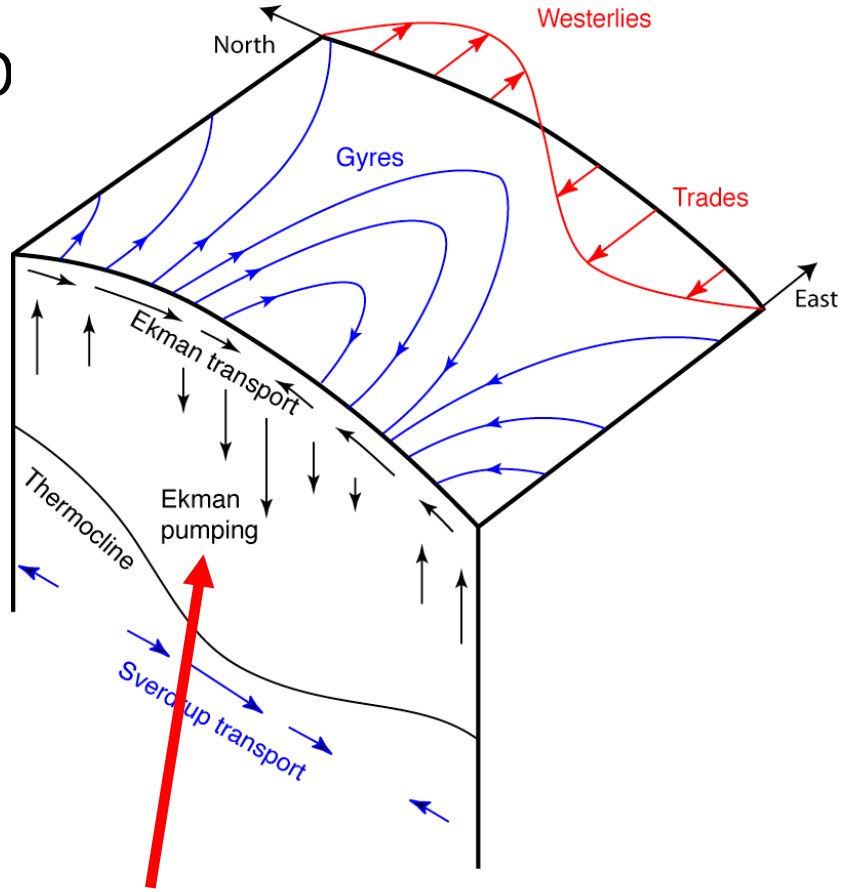
# Sverdrup balance




What is the interior ocean response to Ekman downwelling (pumping)?

DPO Fig. 7.13

# Sverdrup




- Ekman pumping provides the squashing or stretching.
- The water columns must respond. They do this by changing latitude.
- (They do not spin up in place for the large-scale circulation.)

Squashing -> equatorward movement  Stretching -> poleward

TRUE in both Northern and Southern Hemisphere

DPO Fig. 7.13

# Potential vorticity (review from previous lecture)

CONSERVED, like angular momentum, but applied to a fluid instead of a solid

Potential vorticity Q = (planetary vorticity + relative)/(column height)

Potential vorticity $Q = (f + \zeta)/H$ has three parts:

1. Vorticity ("relative vorticity" $\zeta$) due to fluid circulation

2. Vorticity ("planetary vorticity" f) due to earth rotation, depends on local latitude when considering local vertical column

3. Stretching 1/H due to fluid column stretching or shrinking

The two vorticities (#1 and #2) add together to make the total vorticity $= f + \zeta$.

The stretching (height of water column) is in the denominator since making a column taller makes it spin faster and vice versa.

# How does Ekman transport drive underlying circulation?

## Potential vorticity and Sverdrup transport

$$Q = (f + \zeta)/H$$

If there is Ekman convergence (pumping downward), then H decreases. This must result in a decrease of the numerator, $(f + \zeta)$. Since we know from observations (and "scaling") that relative vorticity does not spin up in the large-scale circulation, f must change, which means that the latitude must change

$$Q \sim f/H$$

If there is a decrease in H, then there is a decrease in latitude - water moves towards the equator.

Sverdrup transport = meridional flow due to Ekman pumping/suction

# Sverdrup balance and relation to winds

(1) The vorticity equation for really large-scale flows is:

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

v is the meridional (south-north) flow
w is the vertical velocity.

(2) We vertically integrate this (from bottom of ocean to top) to get the meridional transport V.
We assume that the vertical velocity w at the ocean bottom is 0, and the vertical velocity w at the top is due to Ekman pumping/suction $w_{Ek}$

$$\beta V = f(w_{Ek} - 0)$$

(3) The Ekman pumping is due to variation (curl) in the wind stress

$$w_{Ek} = \left(\frac{\partial(\tau^{(y)}/\rho f)}{\partial x} - \frac{\partial(\tau^{(x)}/\rho f)}{\partial y}\right) = \text{"}curl\text{"}(\tau/\rho f)$$

SO therefore

$$\boxed{\beta V = f\,\text{"}curl\text{"}(\tau/\rho f)}$$

"Sverdrup balance"

# Sverdrup transport derivation (FYI for dynamicists)

Geostrophic balance and continuity:

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

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

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

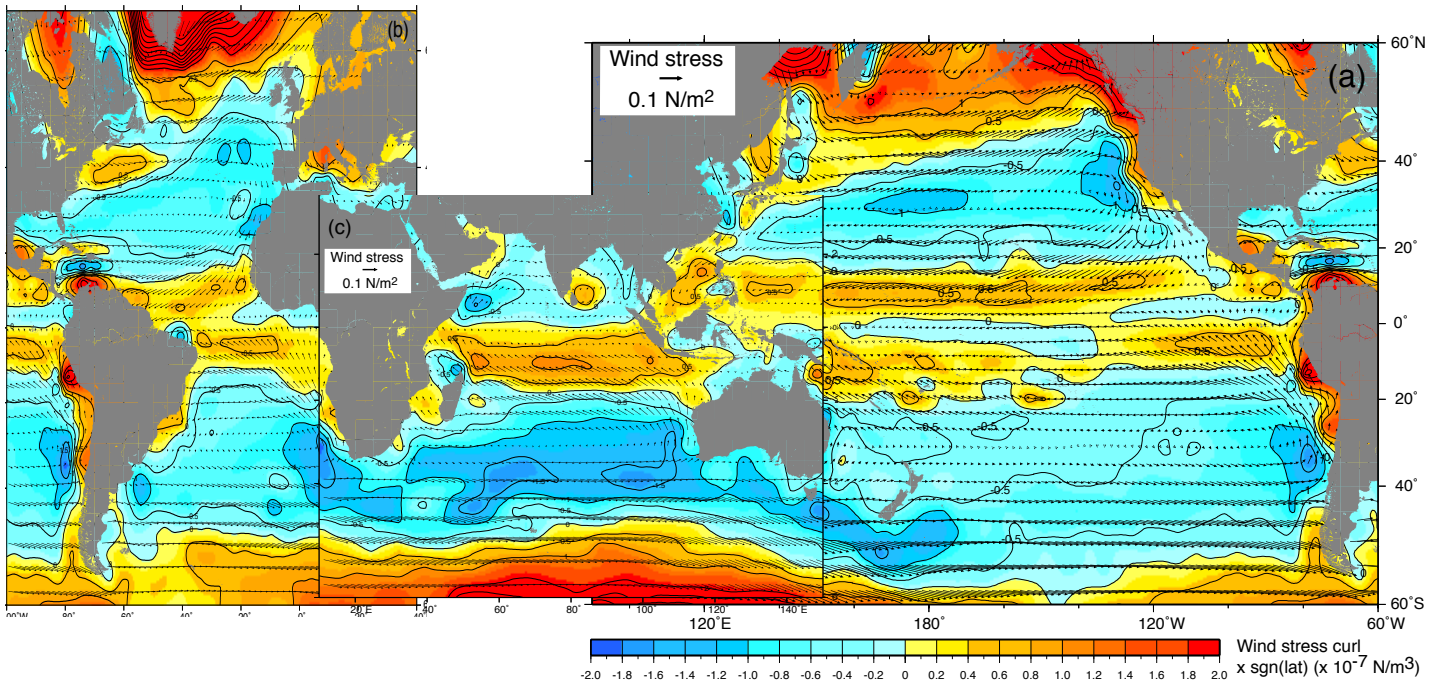
Combine the first two equations, allowing for variation in the Coriolis parameter with latitude

$$f\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + \frac{df}{dy}v = 0$$

Define β = df/dy ("beta parameter"), rewrite; Vertically integrate

$$\beta v = f\frac{\partial w}{\partial z} \Rightarrow \beta V = f(w_{Ek} - 0) = f\left(\frac{\partial(\tau^{(y)}/\rho f)}{\partial x} - \frac{\partial(\tau^{(x)}/\rho f)}{\partial y}\right)$$

# Ekman upwelling/downwelling map




Blue regions: Ekman pumping -> equatorward Sverdrup transport

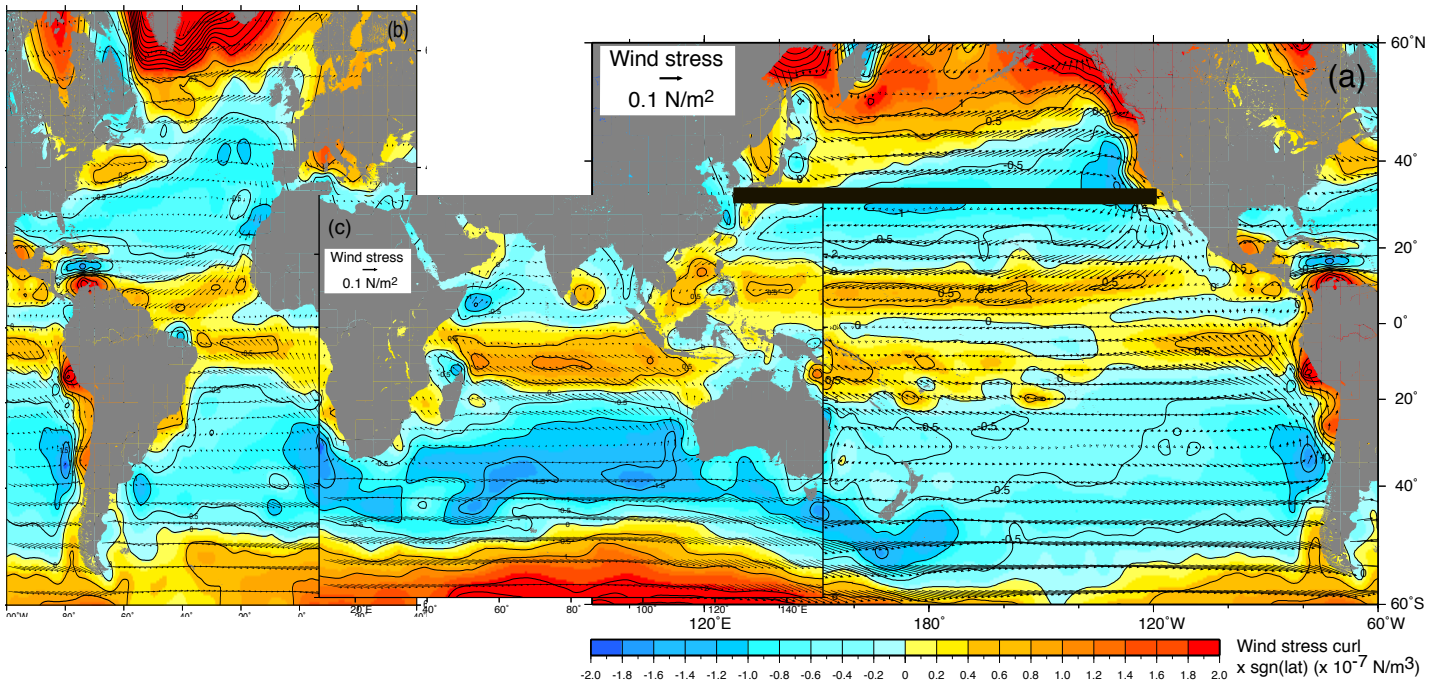
Yellow-red regions: Ekman suction -> poleward Sverdrup transport



Talley SIO 210 (2018)

DPO Fig. S5.10

# Calculate Sverdrup transport from Ekman pumping




To calculate total meridional (north-south) Sverdrup transport north-south across a latitude, integrate the Sverdrup velocities along that latitude (black line) from east to west

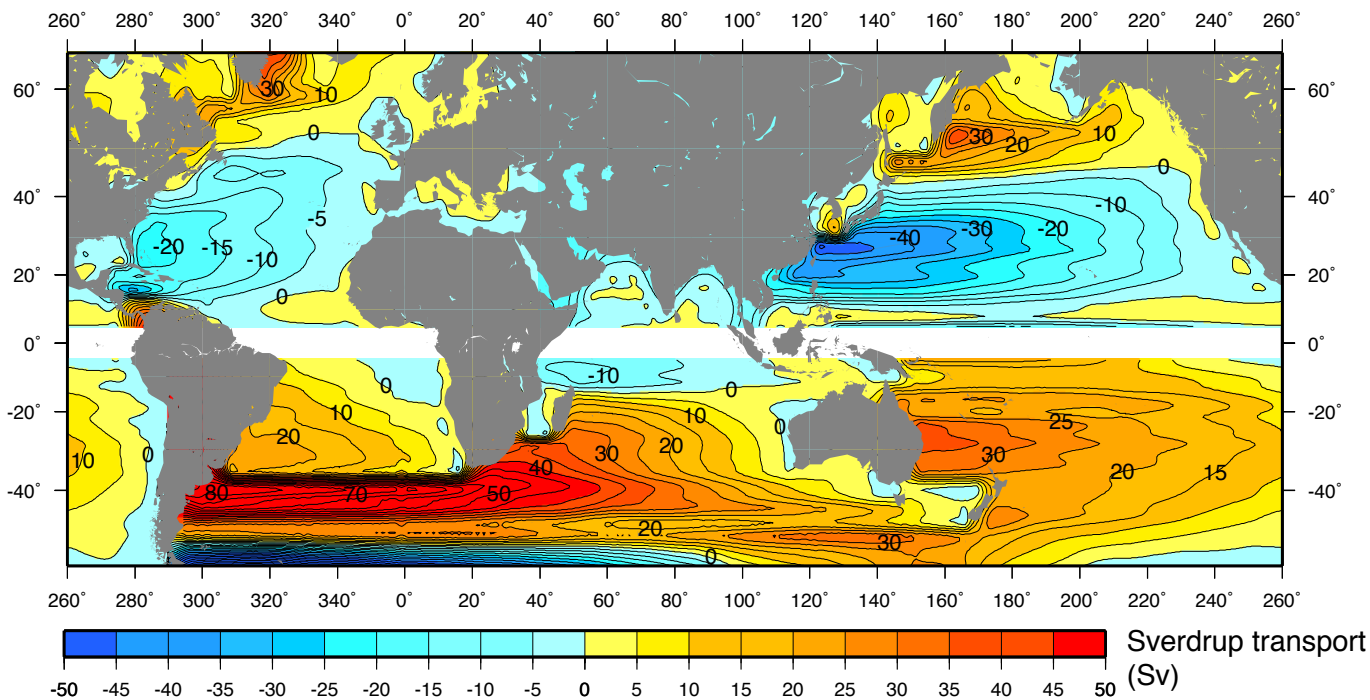


Talley SIO 210 (2018)

DPO Fig. S5.10

# Sverdrup transport

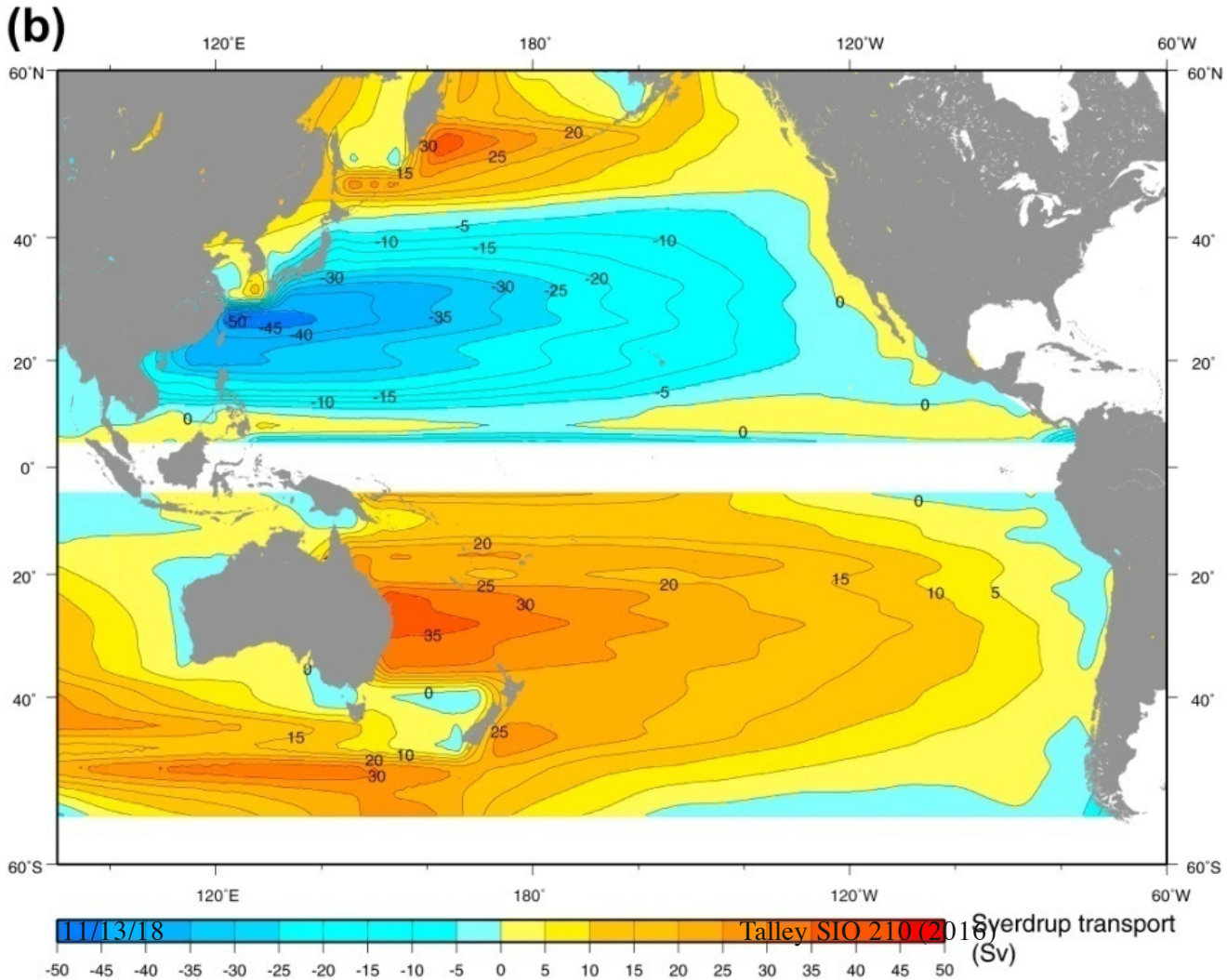
DPO Fig. 5.17




This map is based on the annual mean wind stress curl, integrated westward from the eastern boundary along a constant latitude in each basin. The transport at the western boundary (in units of Sverdrups!) is transport of the wind-driven Sverdrup gyre, and equals the predicted transport of the return flow in the western boundary current

# Sverdrup transport in Pacific

- Blue: southward
- Yellow-red: northward




Subpolar gyre

Subtropical gyre

Subtropical gyre

DPO Fig. S10.2

# Sverdrup transport interior in an Ekman downwelling regime

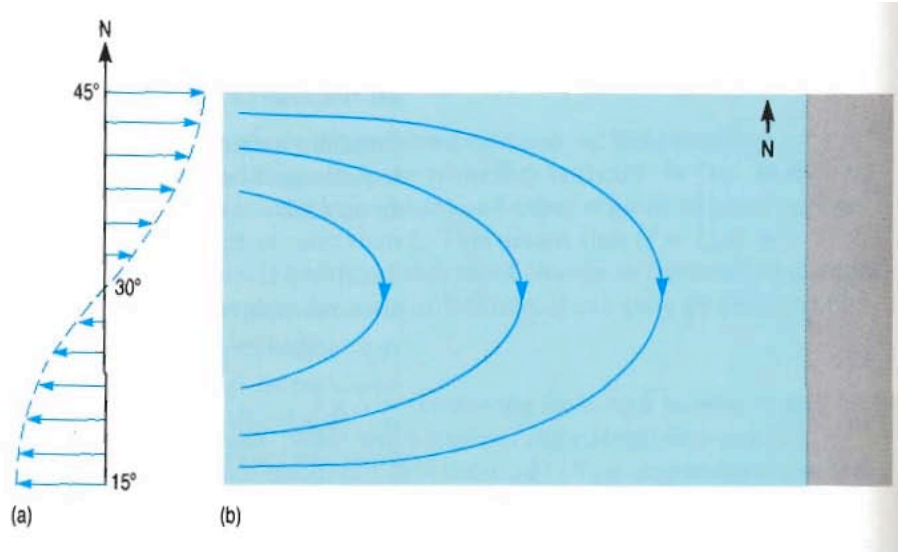


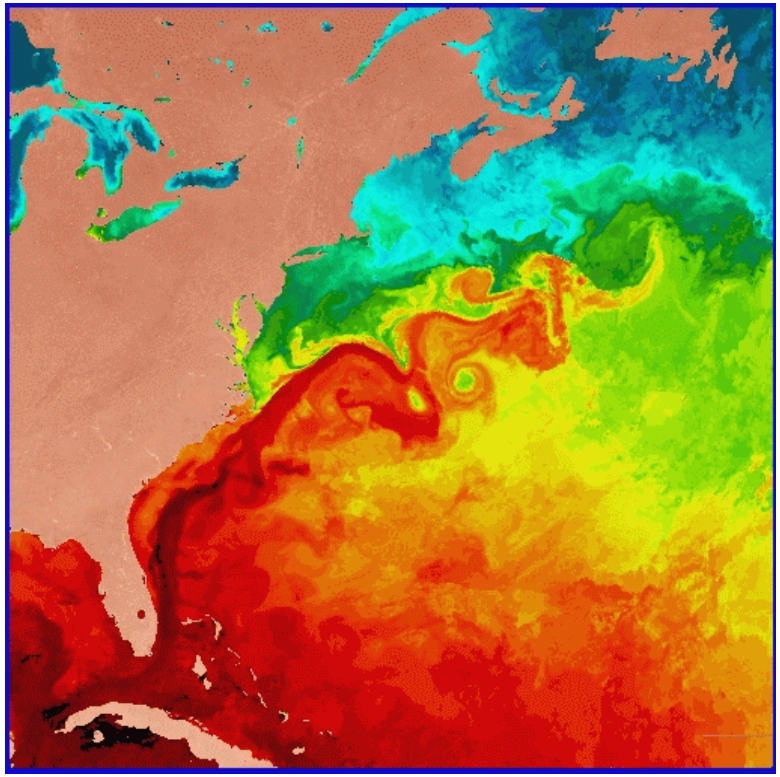

Figure 4.10 (a) As for Figure 4.9. (b) The 'depth-integrated' flow pattern that results from combining Ekman transports at right angles to the wind with geostrophic current flow in response to horizontal pressure gradient forces, according to Sverdrup.

Next: why does the southward flow connect to the western boundary and not to the eastern boundary???

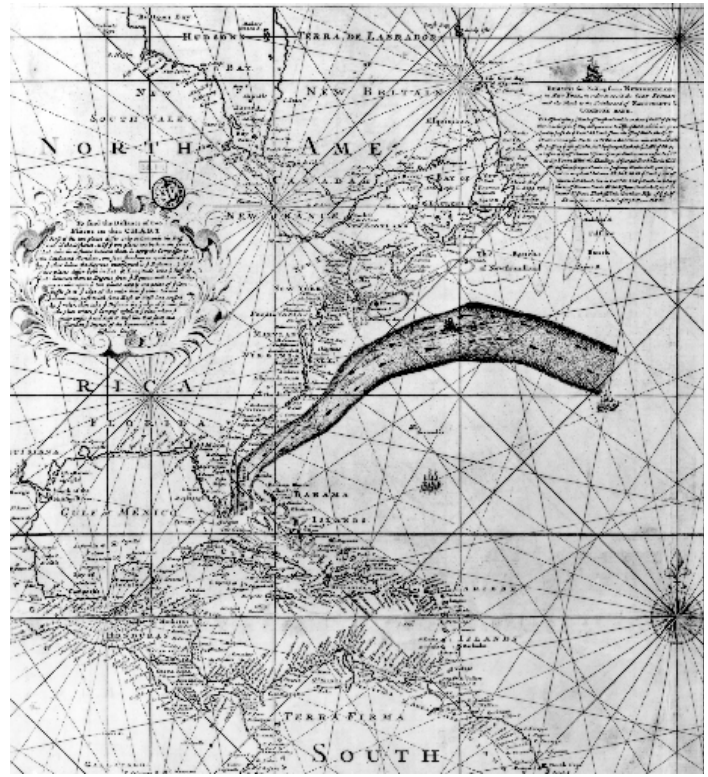
From Ocean Circulation text (Open University Press)

# Western boundary currents: Gulf Stream as an example

from sea surface temperature (satellite) and Benjamin Franklin's map



SST satellite image, from U. Miami RSMAS




Richardson, Science (1980)

DPO Fig. 1.1

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

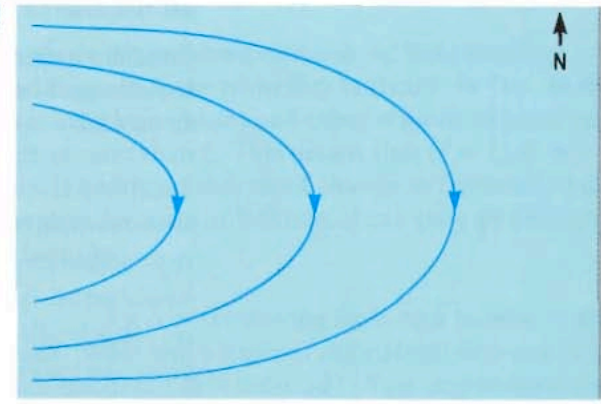
- The wind puts vorticity into the ocean (squashing/stretching), creating Sverdrup transport towards the equator/pole. (PV balance is Coriolis and stretching.)

- If winds create Sverdrup transport, where/how does the water return back to where it started?

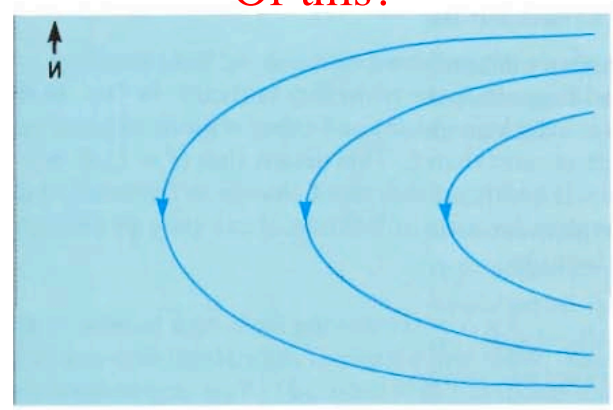
- It must return in a narrow boundary current where the relative vorticity can be strong (lots of horizontal shear). (PV balance is Coriolis and relative vorticity.)

- Is the boundary current on the western side or the eastern side?

Does the ocean look like this?



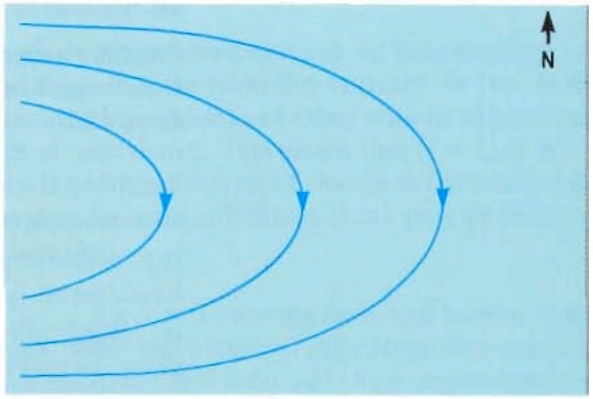

Or this?



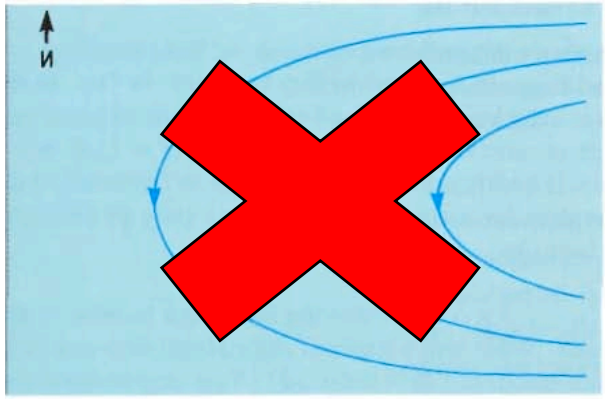
# Western boundary currents: the return flow for the interior Sverdrup transport

- 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 must put in positive vorticity

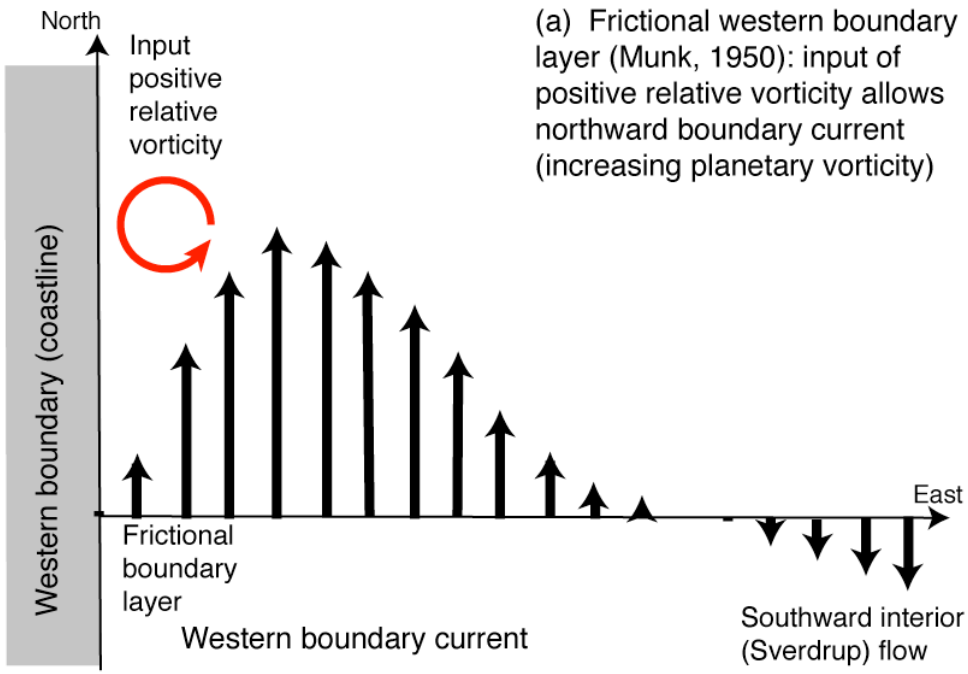
Does the ocean look like this?




~~Or this?~~



# Western boundary currents: why is the return flow for the Sverdrup transport on the western boundary?

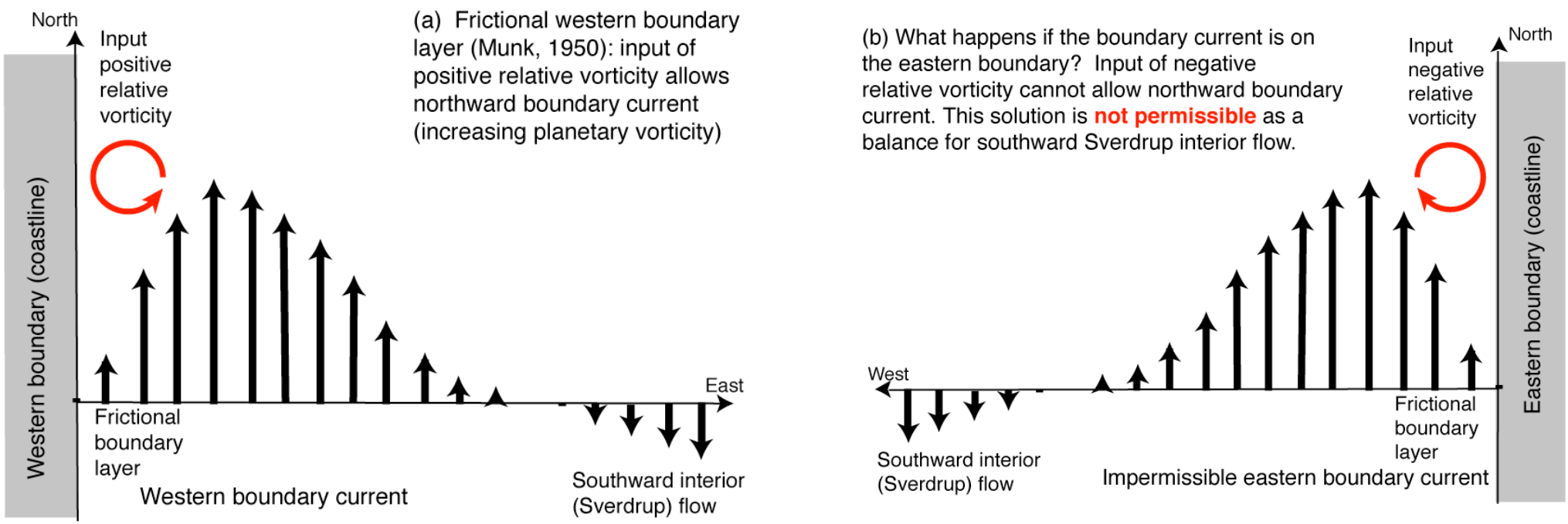







DPO Fig. 7.14

# Western boundary currents: why is the return flow for the Sverdrup transport on the western boundary?



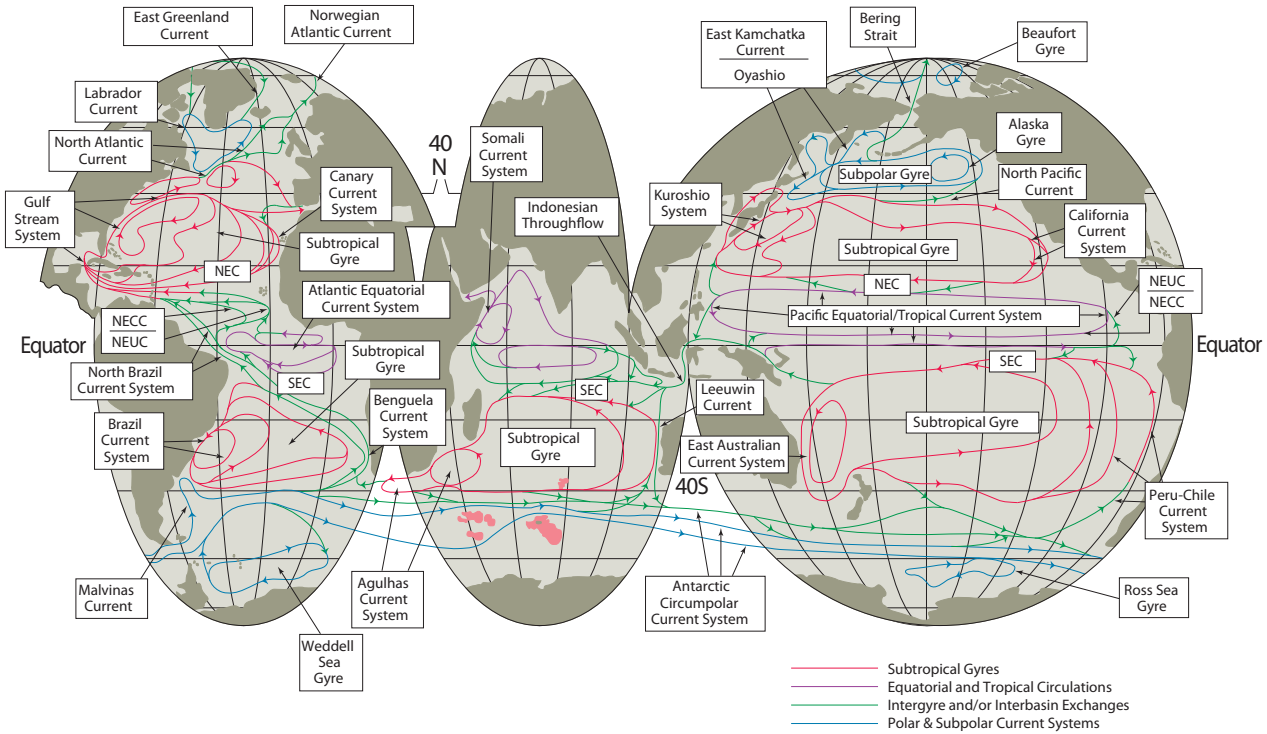





DPO Fig. 7.14

# Global gyres and western boundary currents

Each ocean has gyres with western boundary currents. In fact, a WBC is likely to be found on any western (or even slightly western) boundary

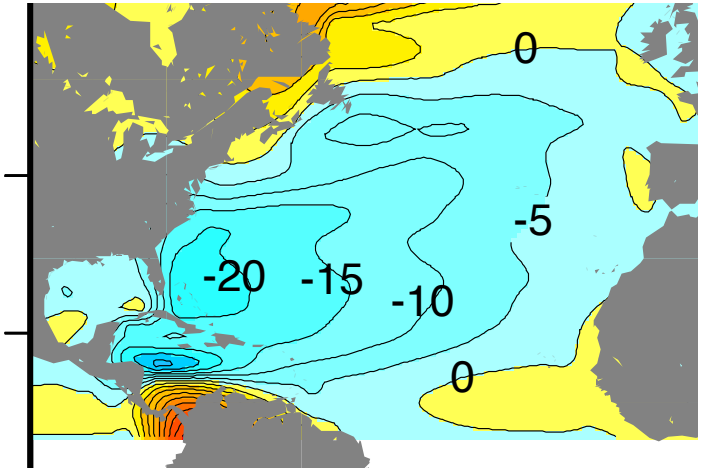


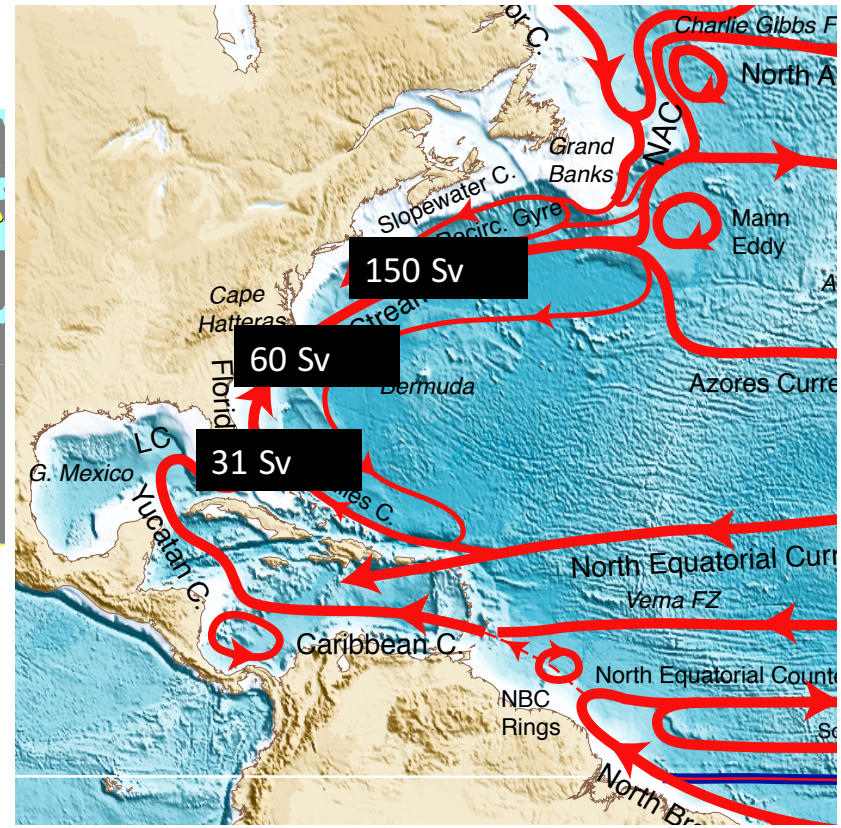



Talley SIO 210 (2018)

DPO Fig. 14.1

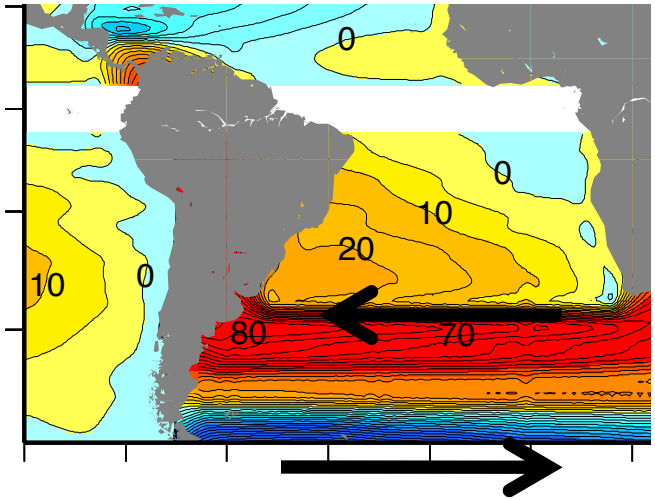
# Deficiencies in the theory: Sverdrup transport and actual total transport

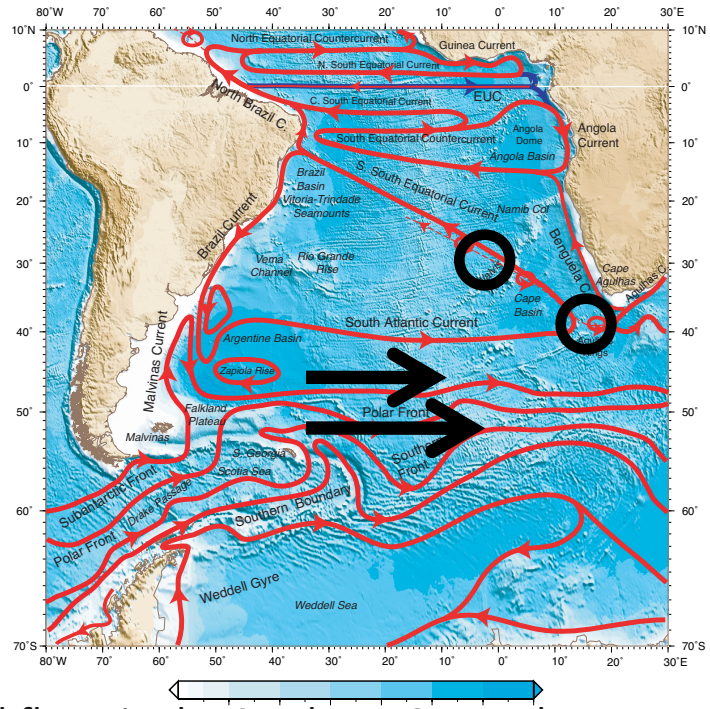



Sverdrup transport generally underestimates subtropical gyre WBC transports, especially after their "separation points", where their dynamics becomes "inertial", not governed by Sverdrup dynamics

# Deficiencies in the theory: Sverdrup transport and actual total transport




Sverdrup balance also suggests strong zonal flows in the Southern Ocean that are not observed (Agulhas from Indian Ocean does not jet westward to South America, but breaks up into eddies that move westward into Atlantic)