# Ekman transport, pumping & gyres

# Frictional effects: Ekman layer

- Near the Earth's surface the geostrophic balance breaks down because of friction, even in the limit of small Rossby number:

$$-fv \approx -\frac{1}{\rho}\frac{\partial P}{\partial x} + \upsilon \frac{\partial^2 u}{\partial z^2}$$

- The layer over which this occurs is called the Ekman layer, whose thickness $h_{Ek}$ is on the order of

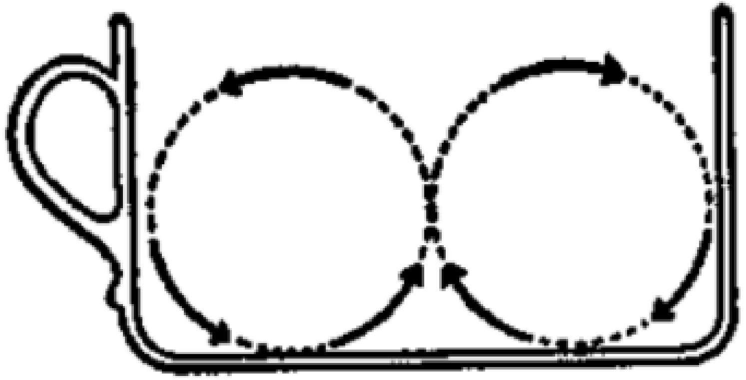
$$h_{Ek} \cong \sqrt{\frac{\upsilon}{f}}$$

This is about 50m for the ocean and a 500-1000m for the atmosphere

# Ekman layer in action: tea leaves in a cup

- Set in circular motion water in a cup with tea leaves. Let it spin down and watch the tea leaves accumulate in the center

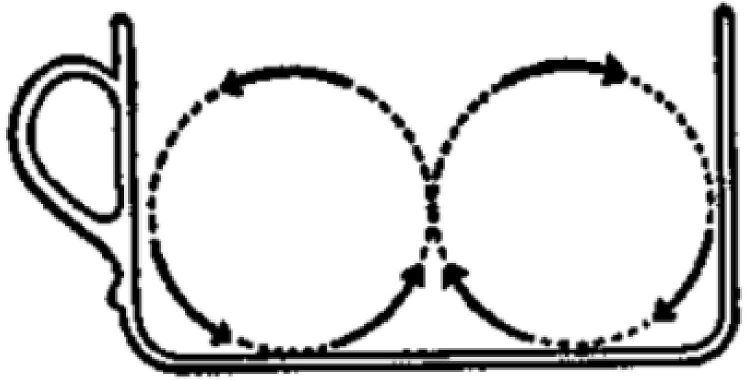
- "***Rest*** frame" interpretation: inward radial pressure gradient is approximately balanced by centripetal acceleration (V^2/r). Near the bottom the centripetal acceleration is weaker (while horizontal pressure gradient is unchanged) so there is an imbalance and inward flow



# Ekman layer in action: tea leaves in a cup

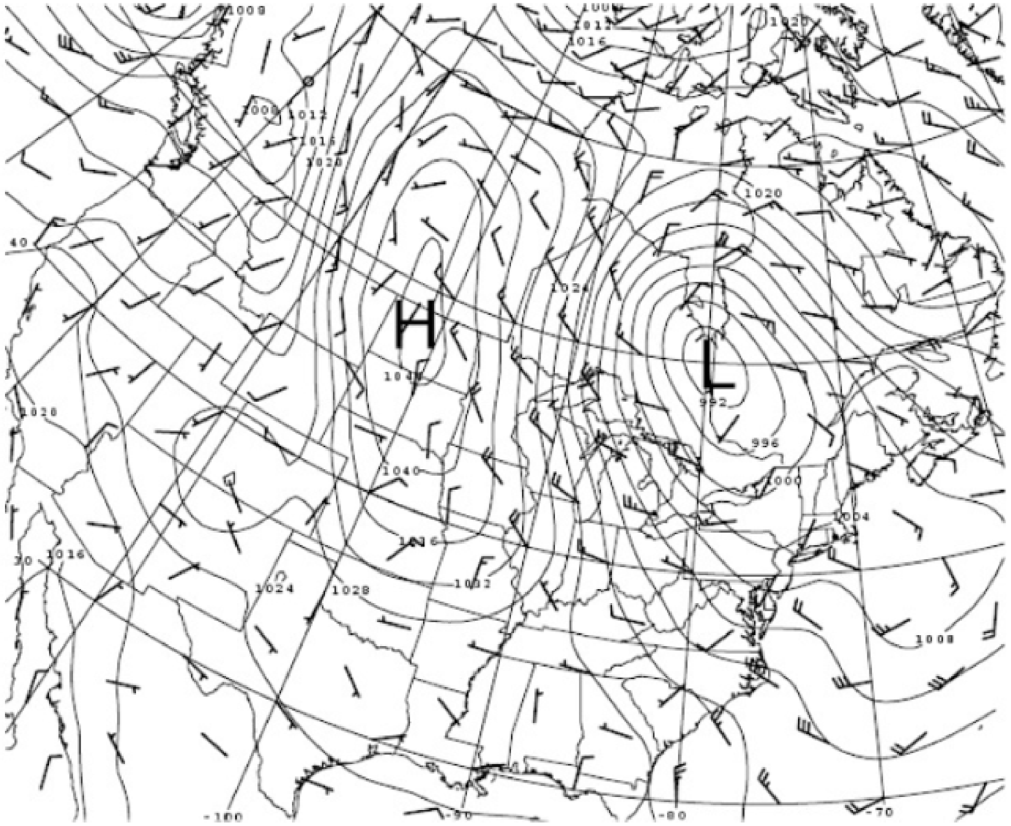
- Set in circular motion water in a cup with tea leaves. Let it spin down and watch the tea leaves accumulate in the center

- "***Rotating*** frame" (take it anti-clockwise, as seen from the lab) interpretation: the flow near the bottom is clockwise and a Coriolis force acts on it towards the center (this force is larger than the advection of angular momentum in the limit Ro<<1). So there is an imbalance and inward flow



# Ekman layer in the atmosphere (near the Earth's surface)

- Flow is inward in low pressure systems (cyclones) →upward motion
- Flow is outward in high pressure systems (anticyclones) → downward motion
- **NB** Useful result: the inward/outward mass flux integrated over the depth of the Ekman layer is at a right angle to the surface friction force (="Ekman transport")

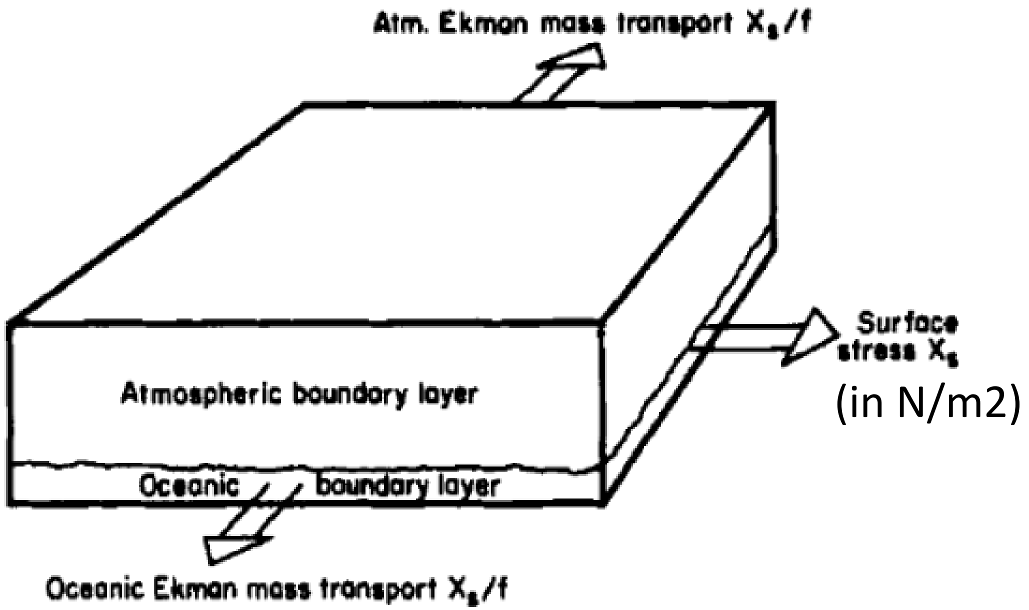



Surface weather chart on 10/02/2008 with surface flow (arrows with quiver every 5m/s) and surface pressure (ci=4hPa). From Tandon & Marshall (2008)

# Coupling of oceanic & atmospheric Ekman layers

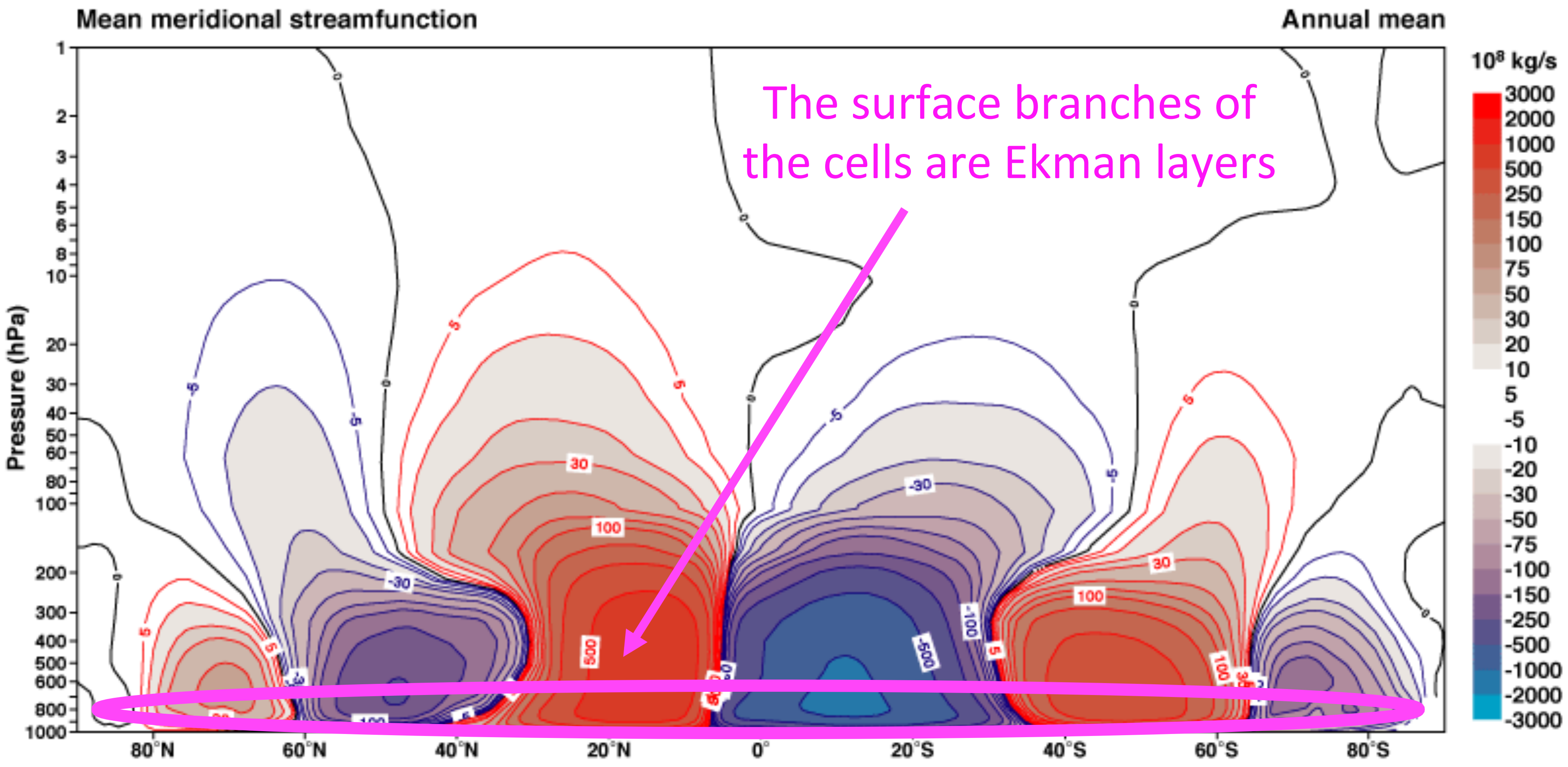
- Over the ocean the same frictional force is shared by the atmosphere and the ocean at the sea surface

- This drives the same amount of mass transport in the outward/inward circulation: the Ekman transport are equal in magnitude but opposite in direction



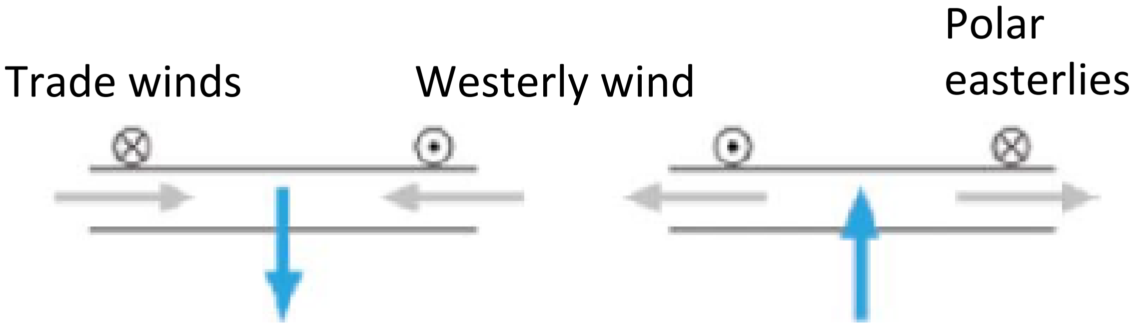

From Gill (1982, Chapter 9)

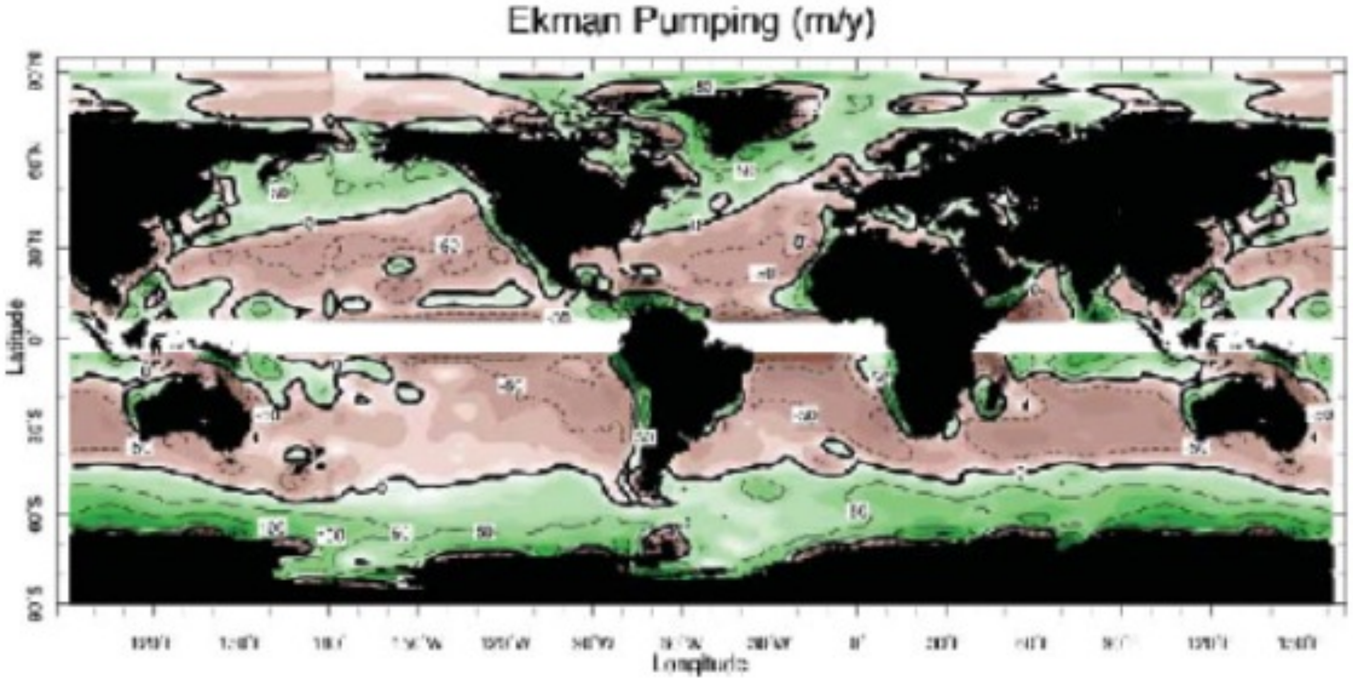
# Ekman layers and Hadley, Ferrell, polar cells

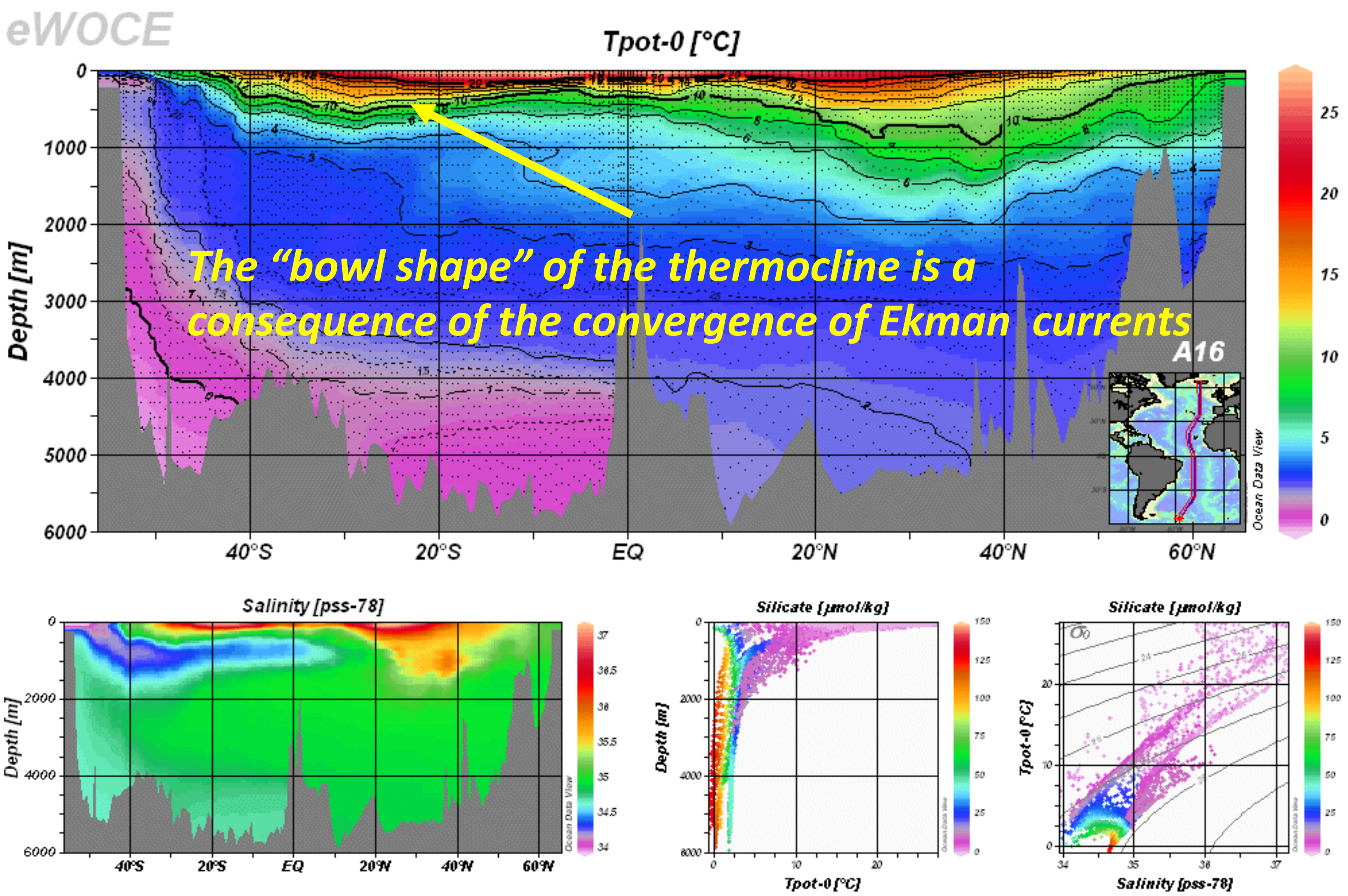


# Convergence/divergence of Ekman transport

- …leads to regions of downwelling and upwelling
- The associated vertical motion is on the order of ~30m/yr

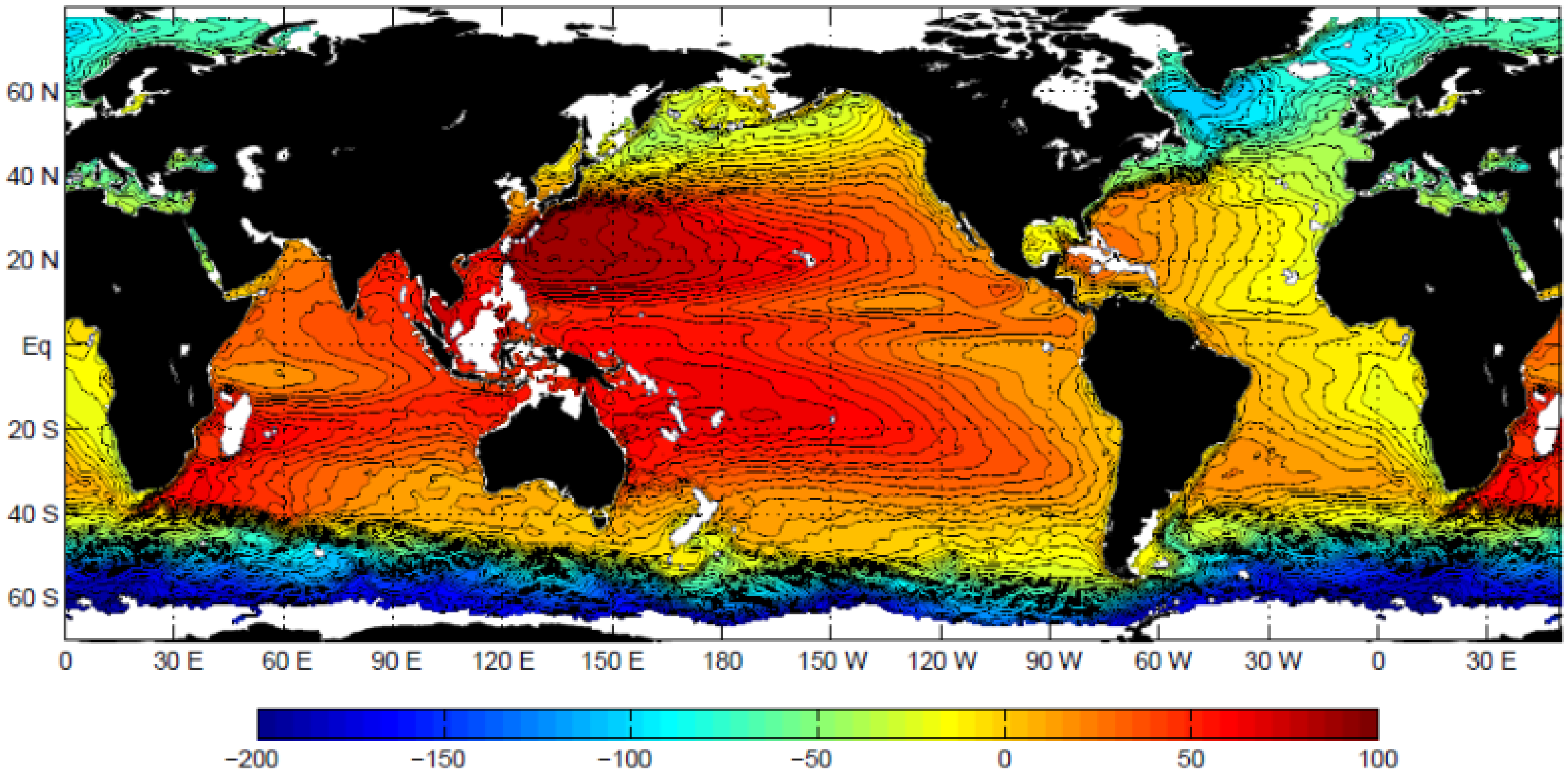


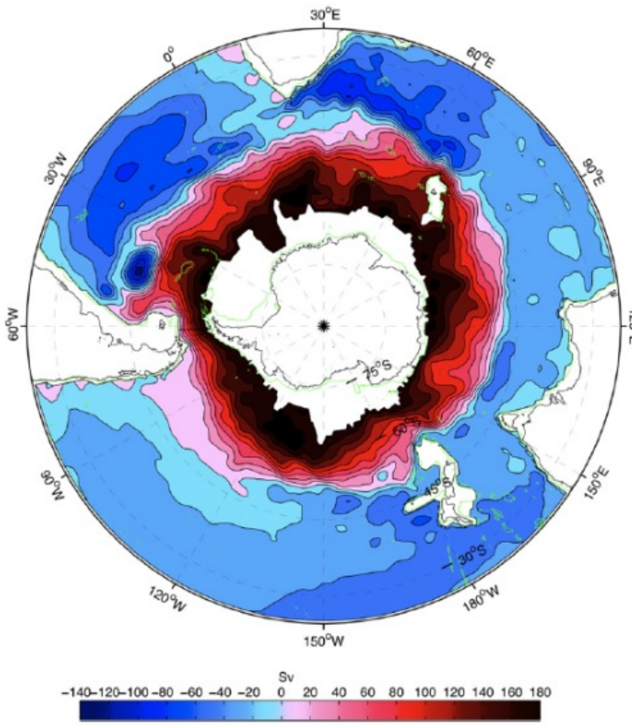

eWOCE
Tpot-0 [°C]
Depth [m]
0
1000
2000
3000
4000
5000
6000
40°S
20°S
EQ
20°N
40°N
60°N
25
20
15
10
5
0
A16
Ocean Data View
The “bowl shape” of the thermocline is a consequence of the convergence of Ekman currents
Salinity [pss-78]
Silicate [µmol/kg]
Tpot-0 [°C]
Salinity [pss-78]
Silicate [µmol/kg]
Tpot-0 [°C]

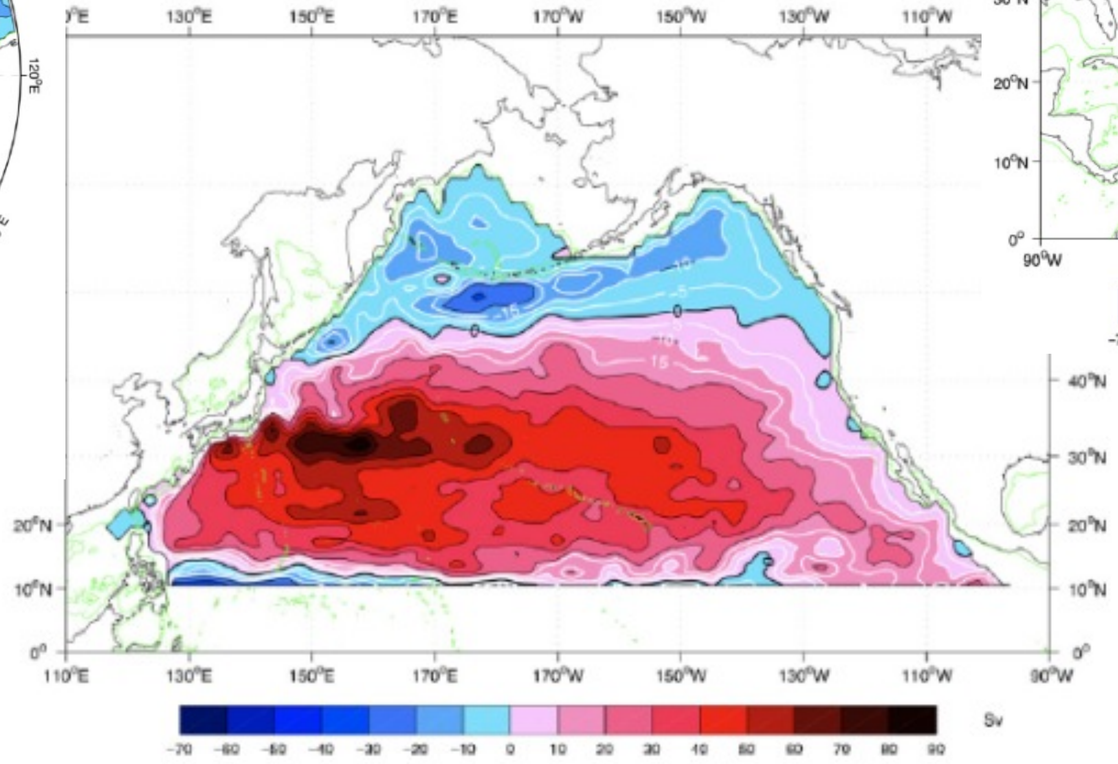
# Ocean gyres (as seen at the sea surface)

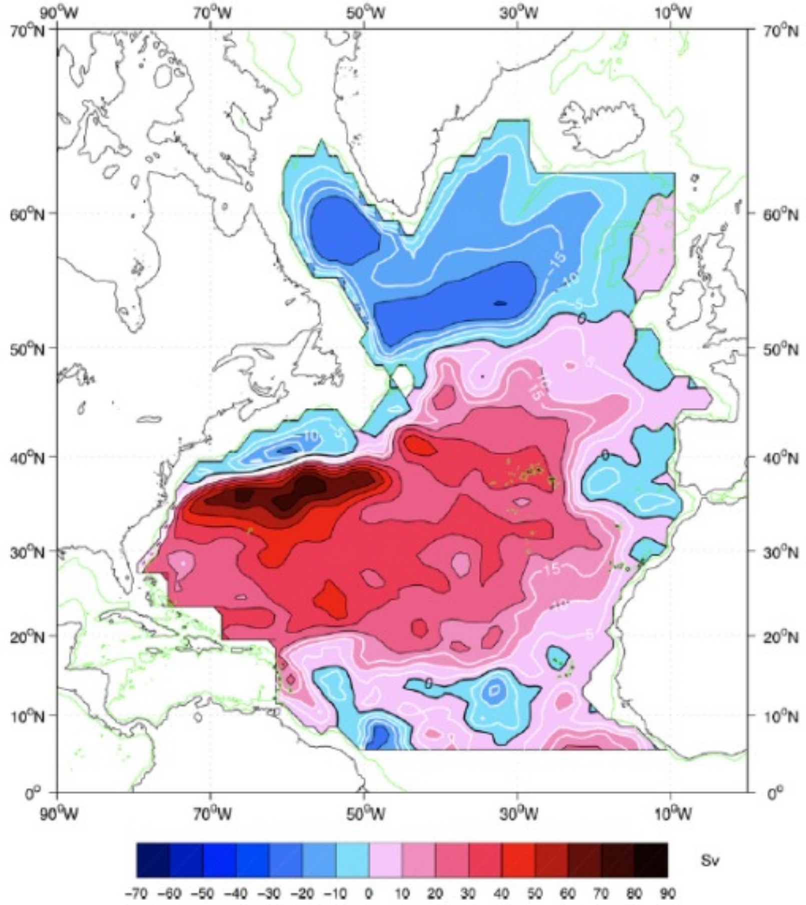
***Annual mean dynamic topography (1993-2002) from Maximenko et al. (2009)–CI = 10cm***



# Vertically averaged circulation (in Sv) from ocean floats & hydrography





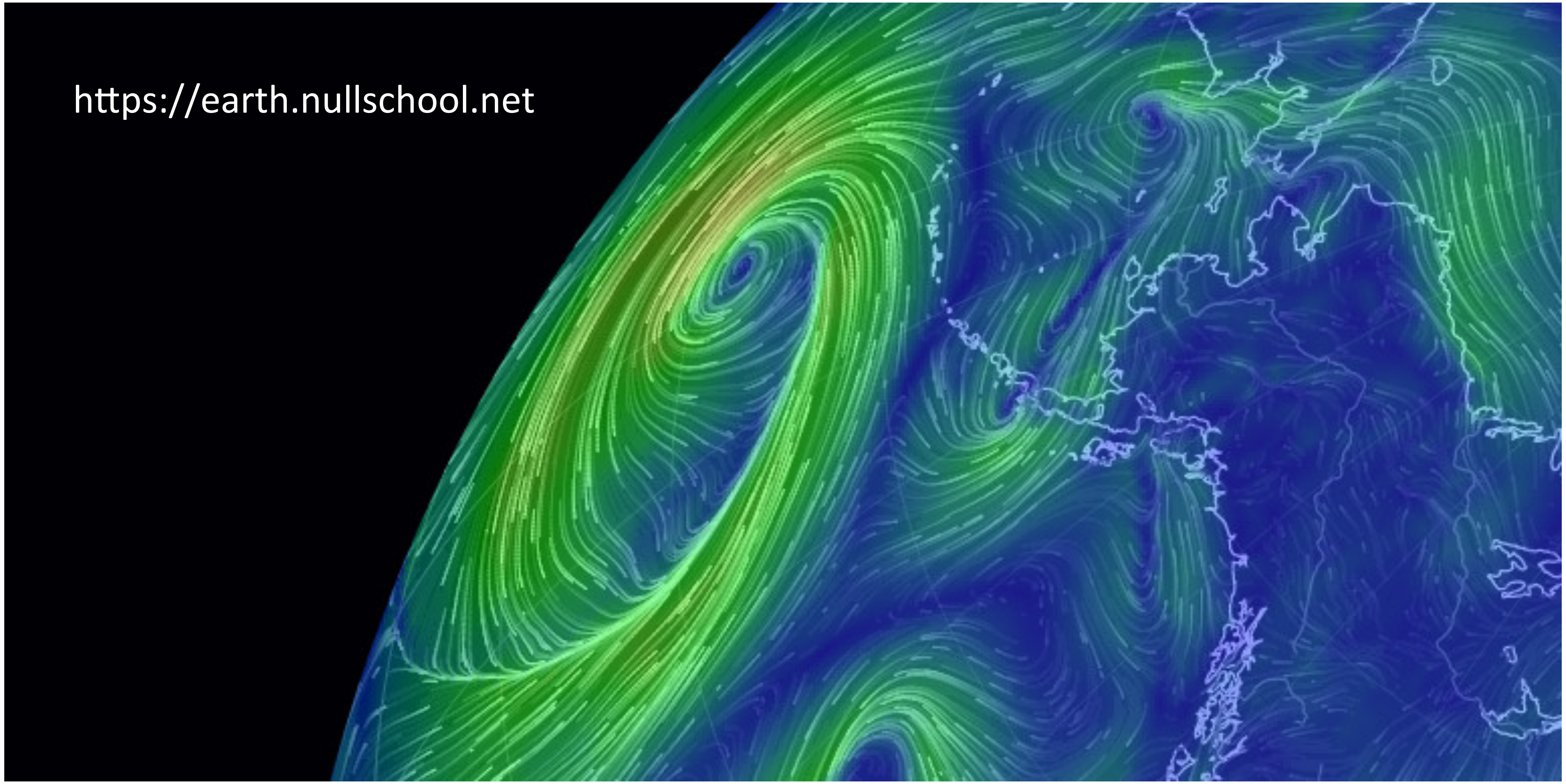


NB 1Sv = 10^9 kg/s

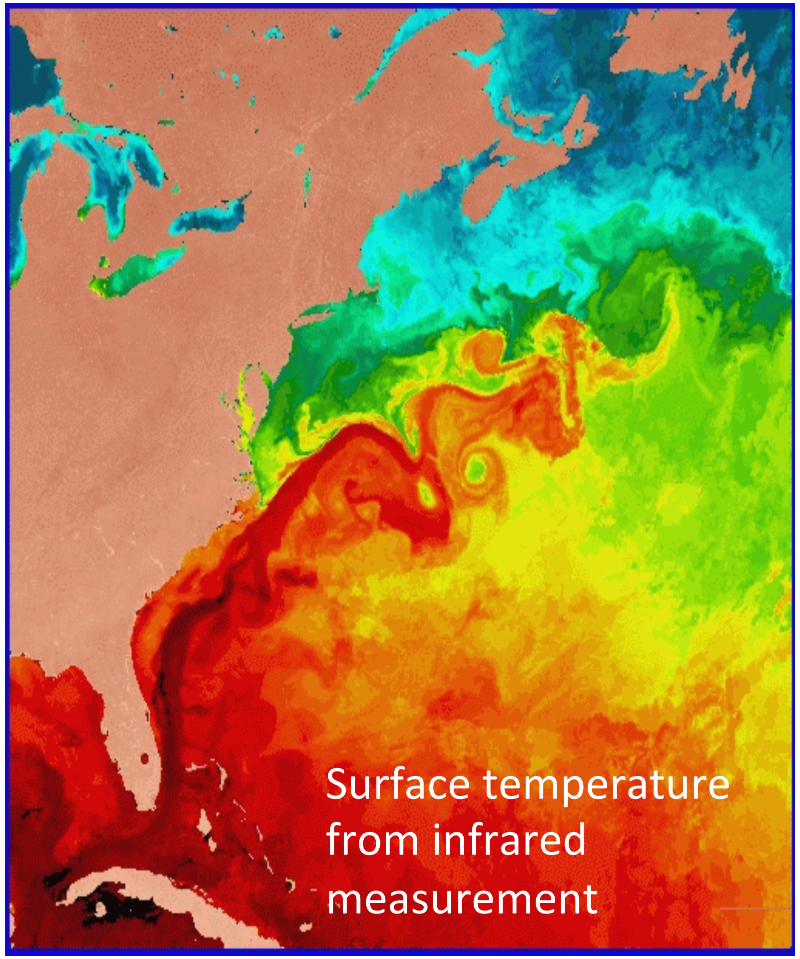
De Verdiere and Ollitraut (2016)

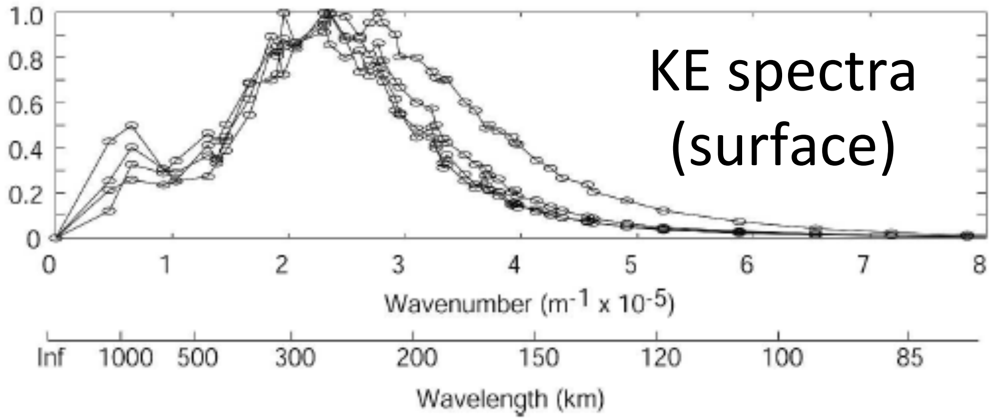
# Ocean eddies

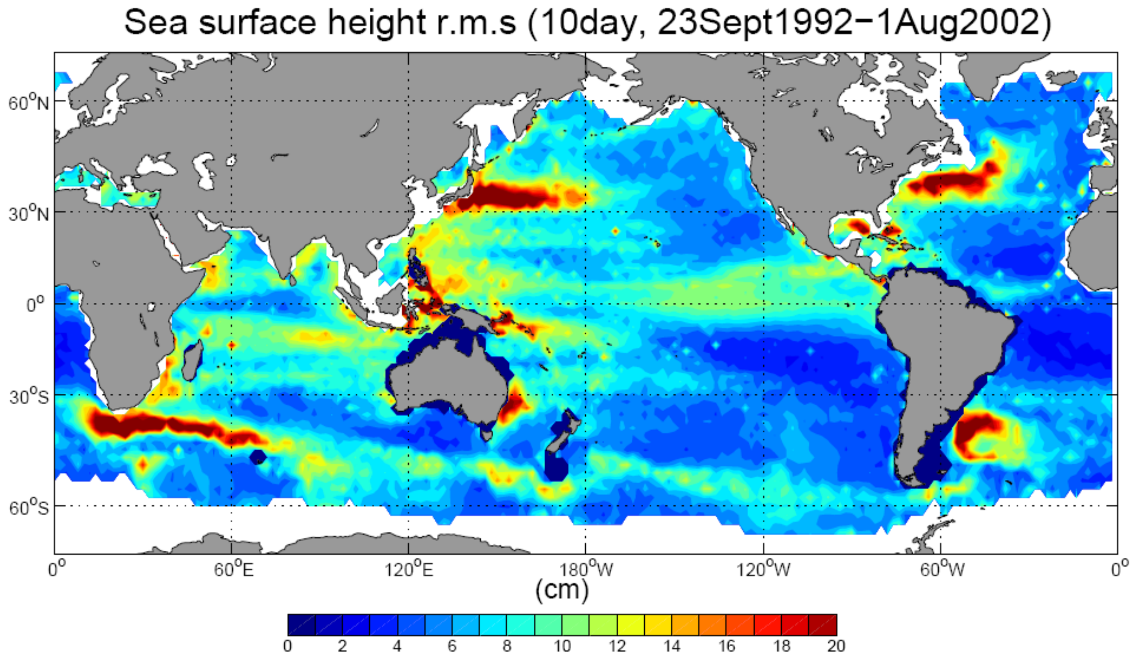
# Oceans and atmosphere in real time…



# In-situ observations are dominated by a "meso-scale"

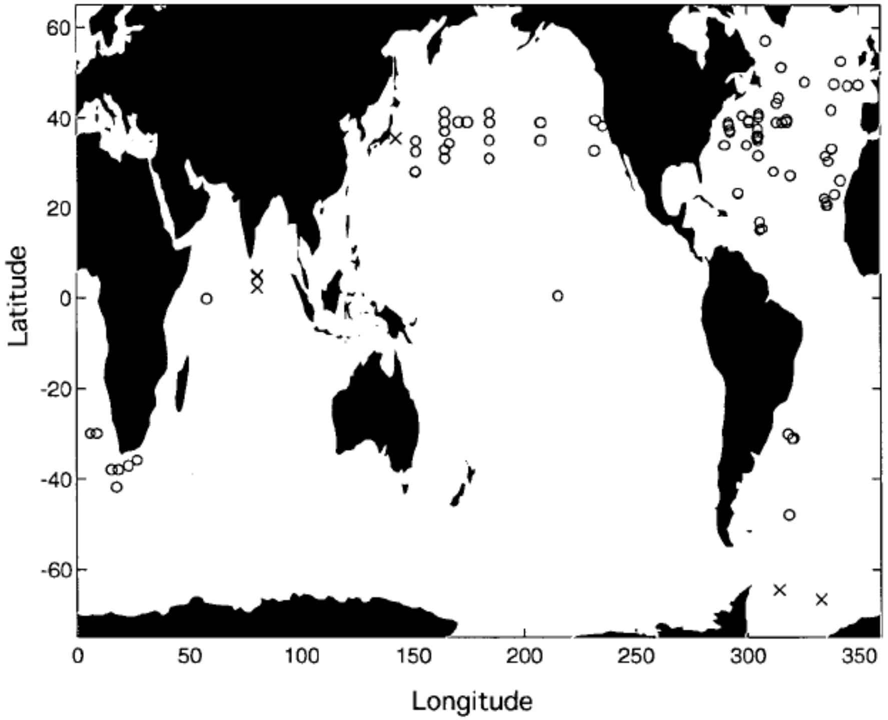


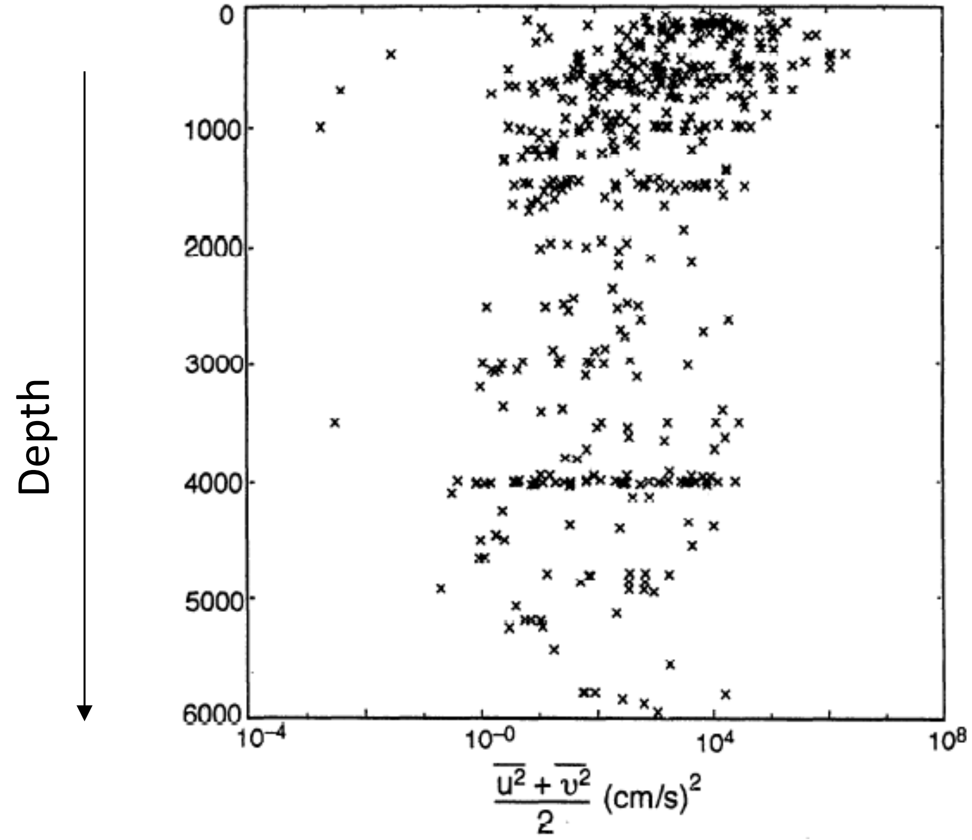



# In – situ velocity measurements

Location of “long” (~2yr) current meters



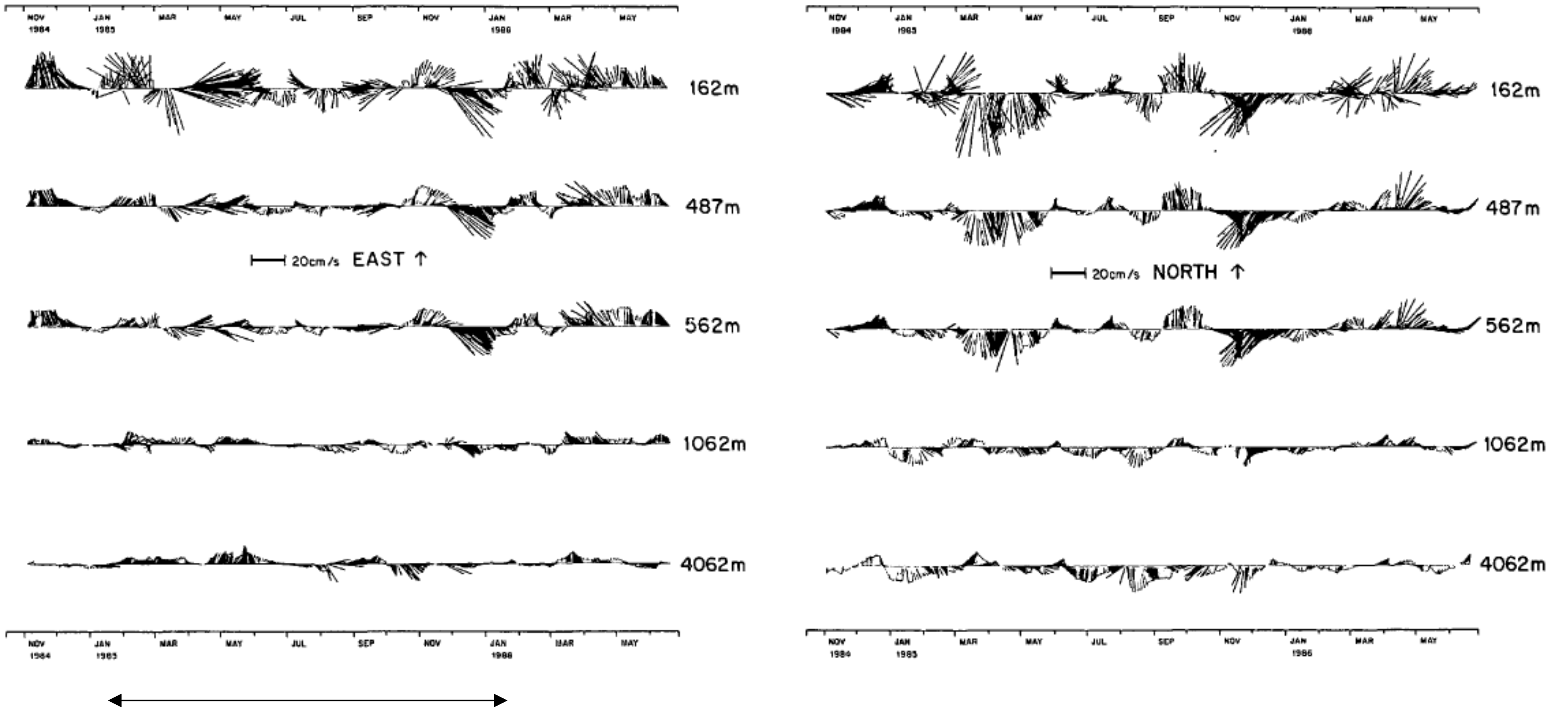

Amplitude of time variability




*From Wunsch (1997, 1999)*

NB: Energy at period < 1 day was removed

# Moorings in the North Atlantic interior (28N, 70W)



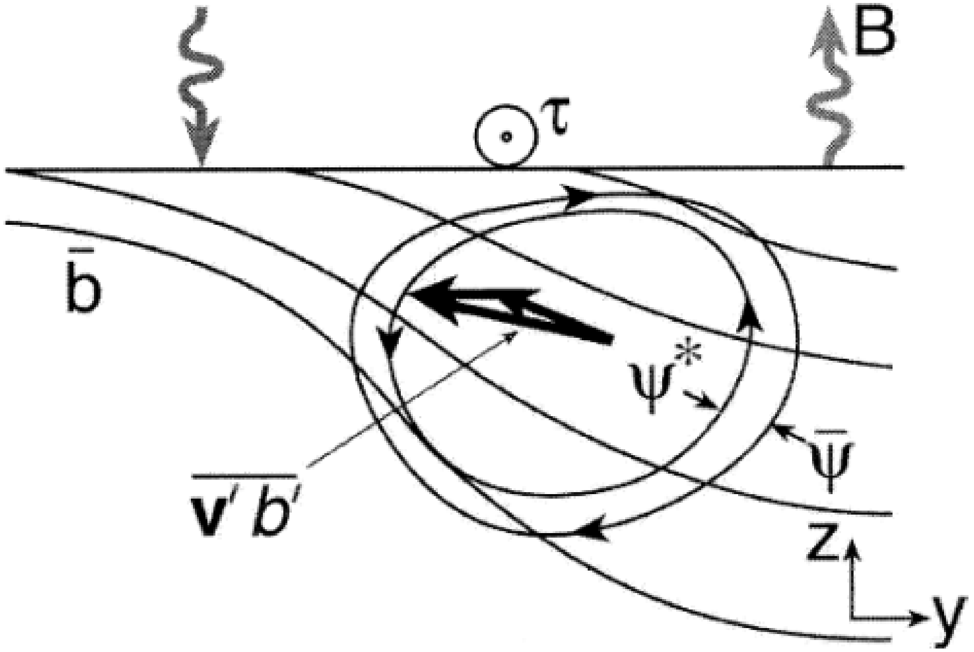

1 yr

NB: Same velocity vectors but rotated

Schmitz (1989)

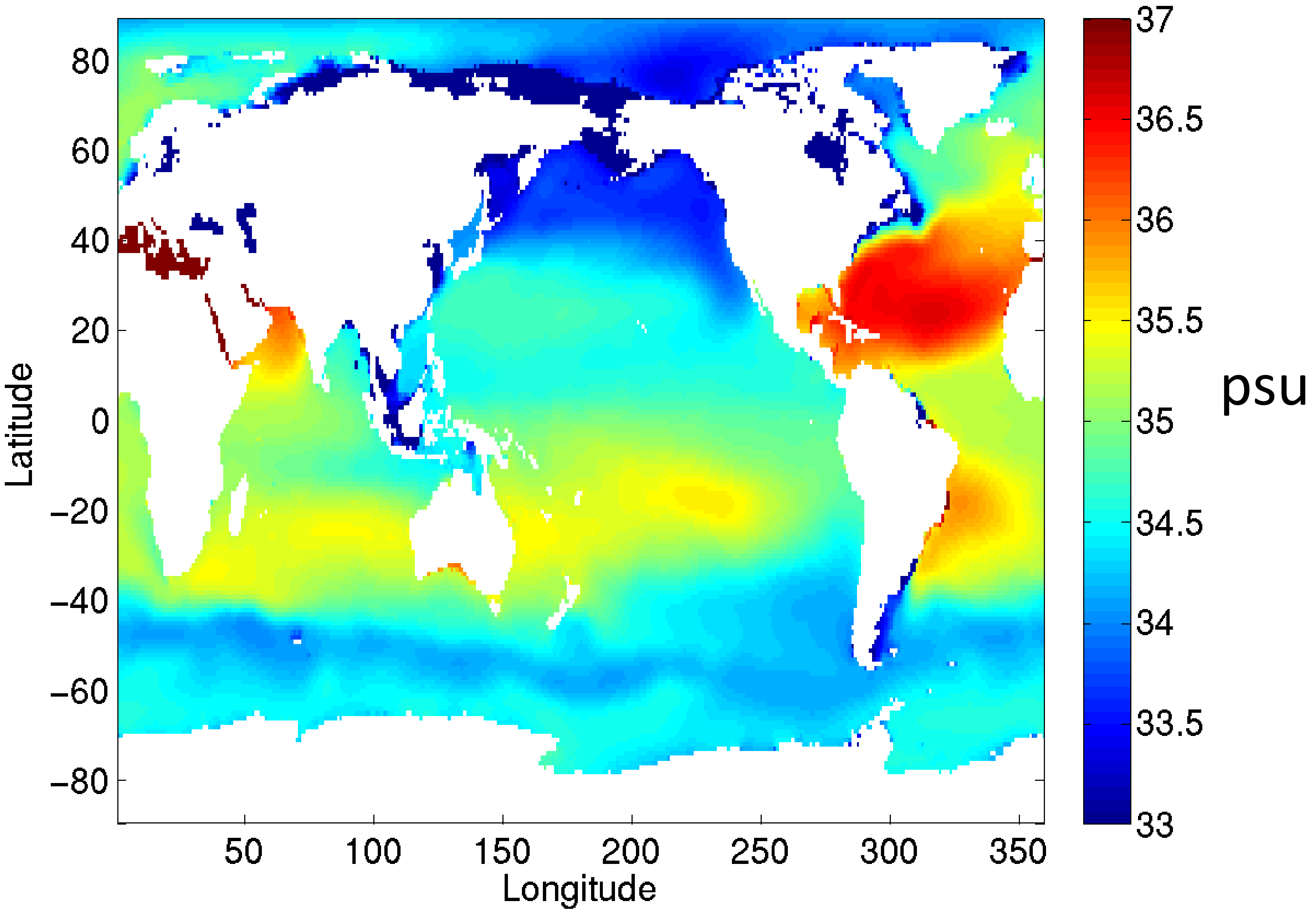
# Role of "ocean eddies"

- Upward transport of heat (warm fluid goes up, cold fluid goes down)
- This maintains sharp temperature variations in the vertical direction (warm at upper levels, cold at deeper levels)
- Stir tracers (physical, chemical, biological) throughout the ocean
- Key role in ocean heat uptake

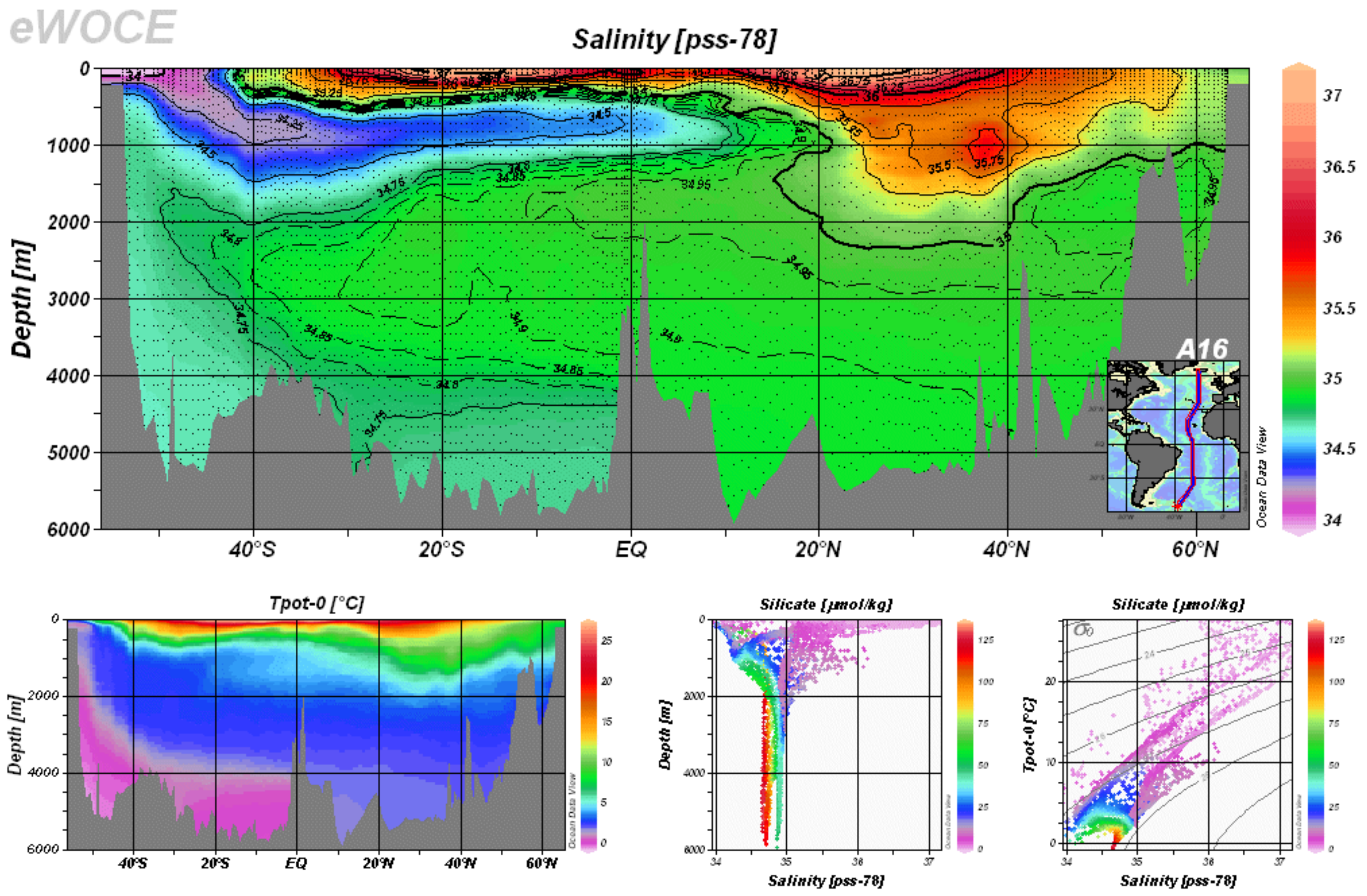


# “Thermohaline circulation”

# World Ocean Atlas Salinity (0-500m)



# The


eWOCE
Salinity [pss-78]
Depth [m]
0
1000
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40°S
20°S
EQ
20°N
40°N
60°N
A16
Ocean Data View
37
36.5
36
35.5
35
34.5
34
Tpot-0 [°C]
Depth [m]
Silicate [µmol/kg]
Salinity [pss-78]
Tpot-0 [°C]
Silicate [µmol/kg]
Salinity [pss-78]

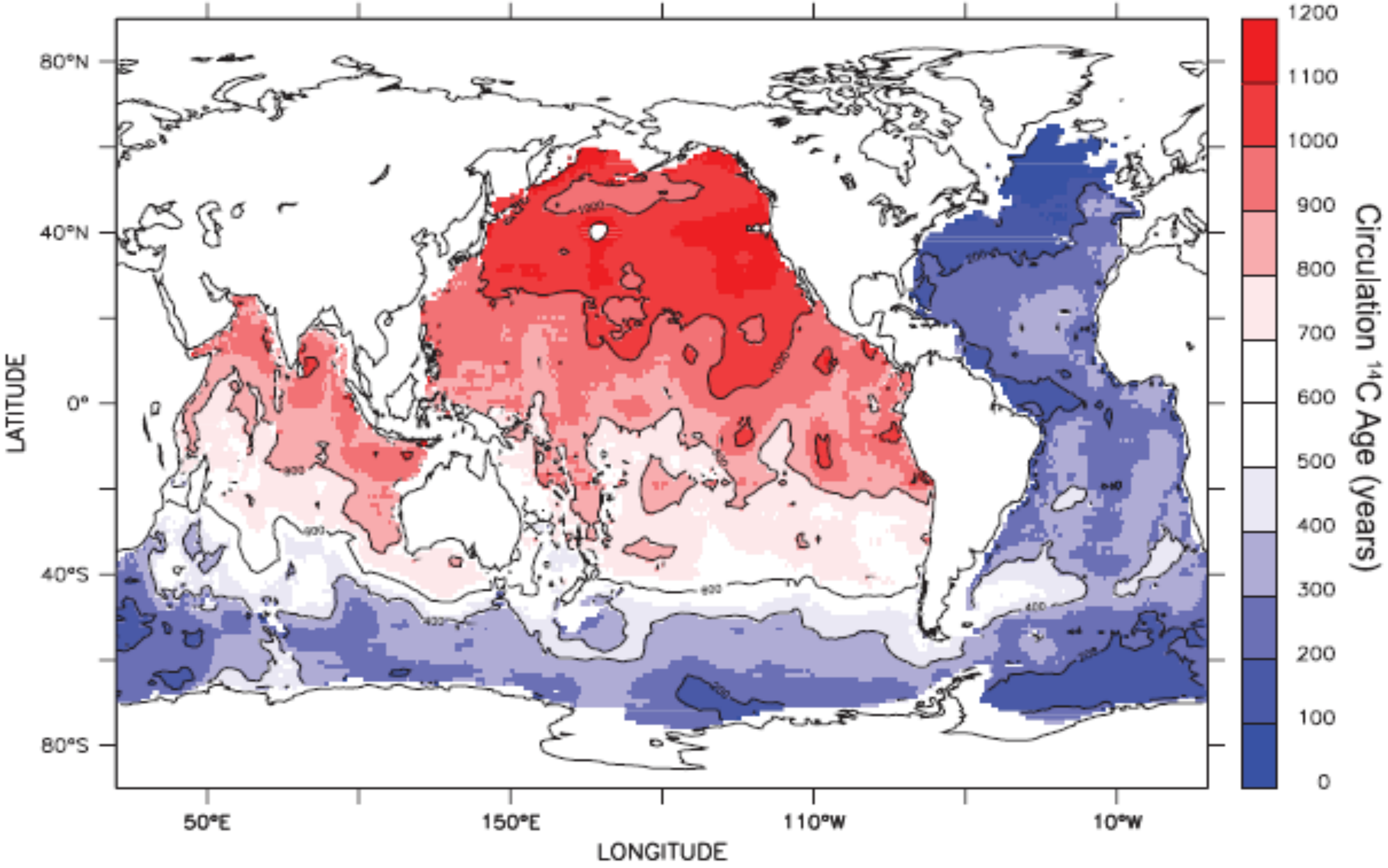
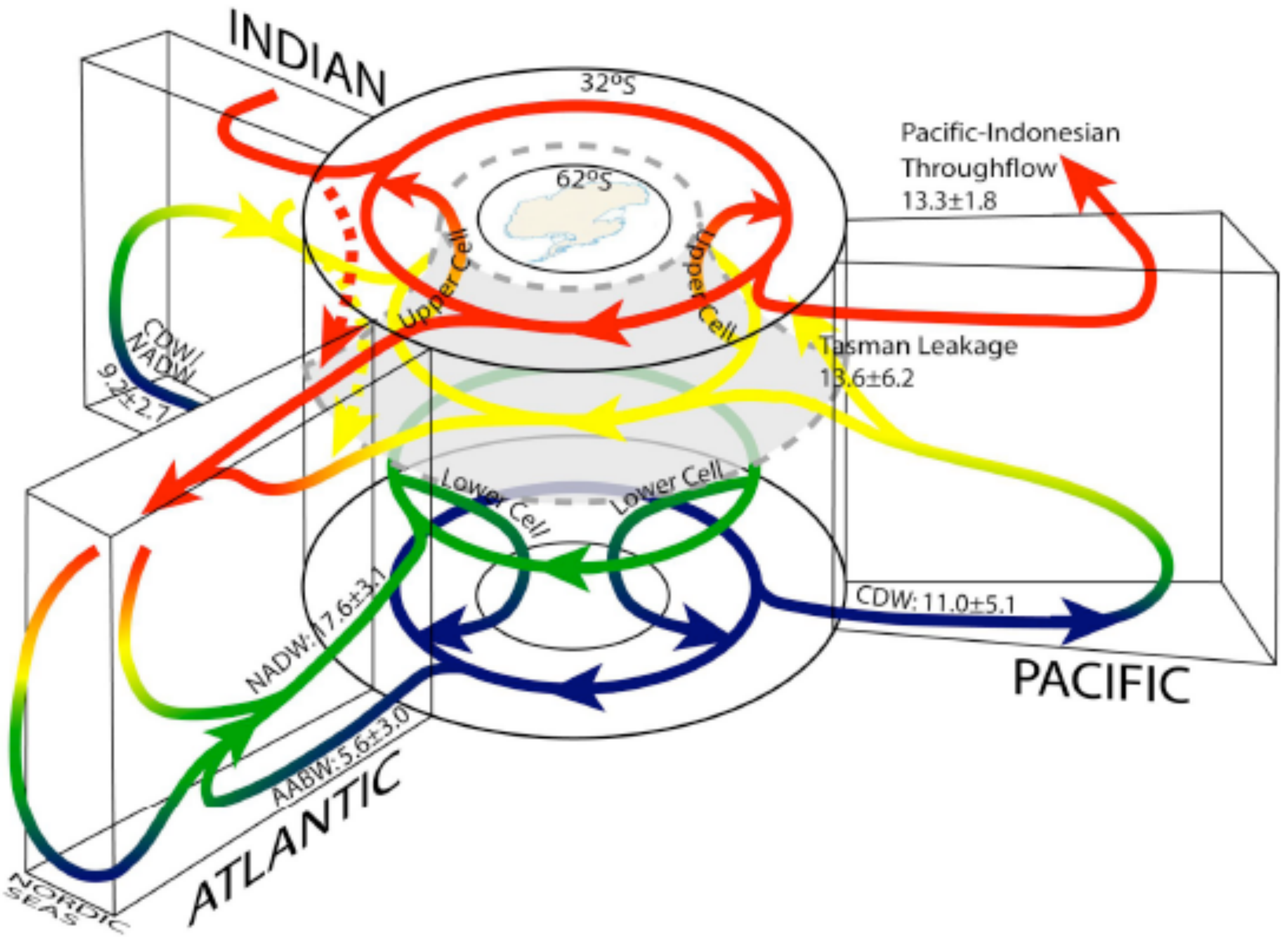



**Figure 4.** A map of circulation $^{14}C$ age below 1500 m. This is equivalent to conventional $^{14}C$ age (Figure 1) but accounts for surface ocean $^{14}C$ reservoir age and the different sources of deep water. Unit is years.

Matsumoto, JGR 2007




Speer and Lumpkin (2006)