Subtropical Cells: a Lagrangian view

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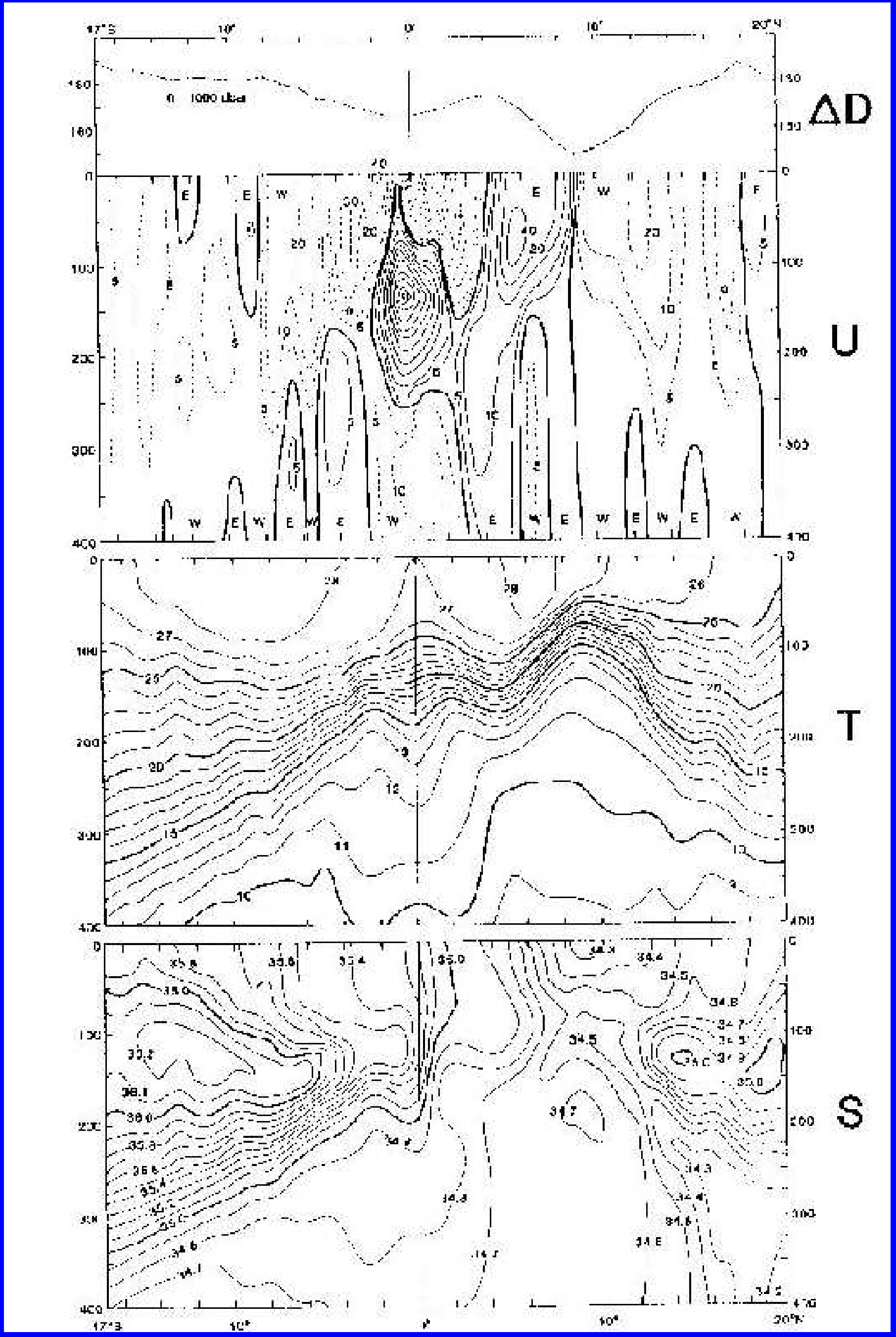


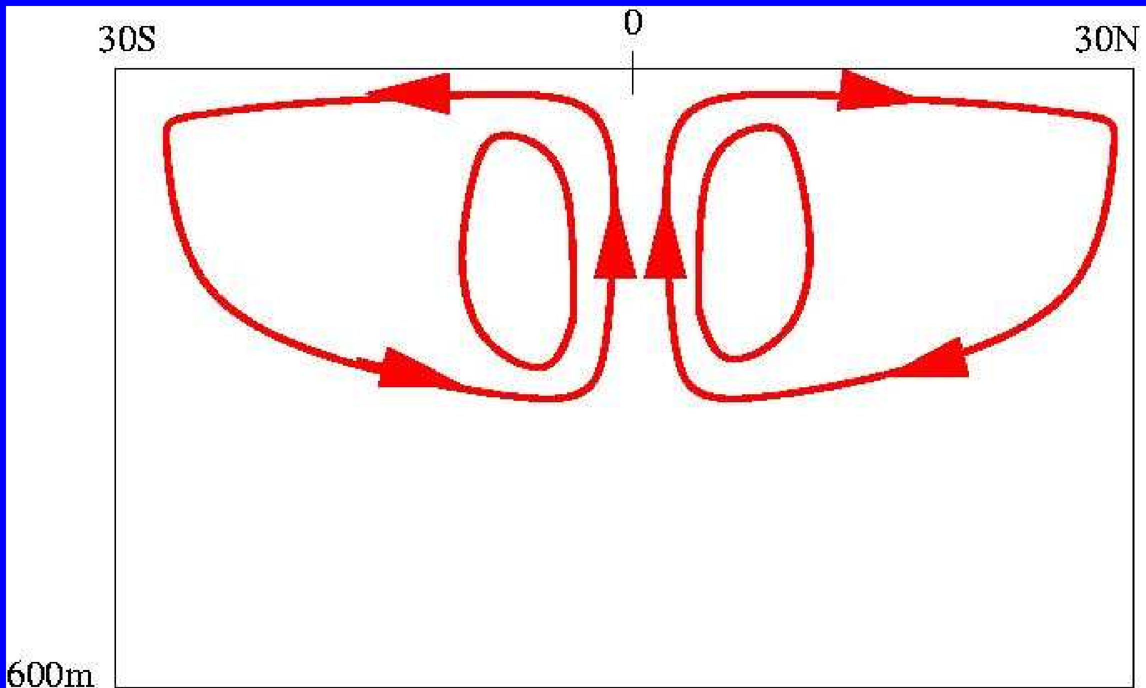
Pacific cross-sections

(Hawaii-Tahiti)

Wyrtki and Kilonsky 1984

Subtropical Cells in the Pacific

Ekman divergence (easterlies) at the equator drive upwelling. Ekman convergence off-equator drives downwelling and geostrophic convergence towards the equator.



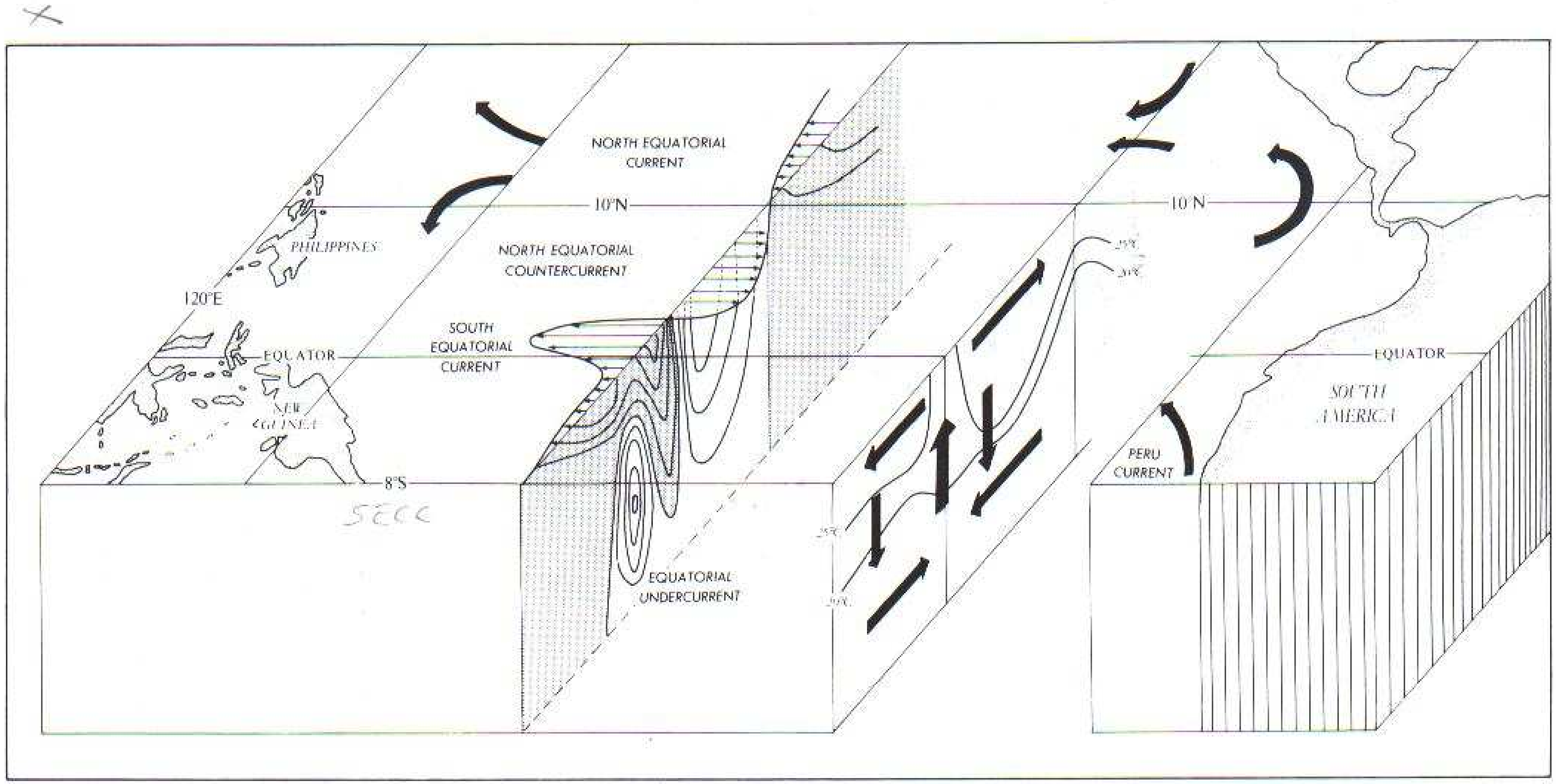


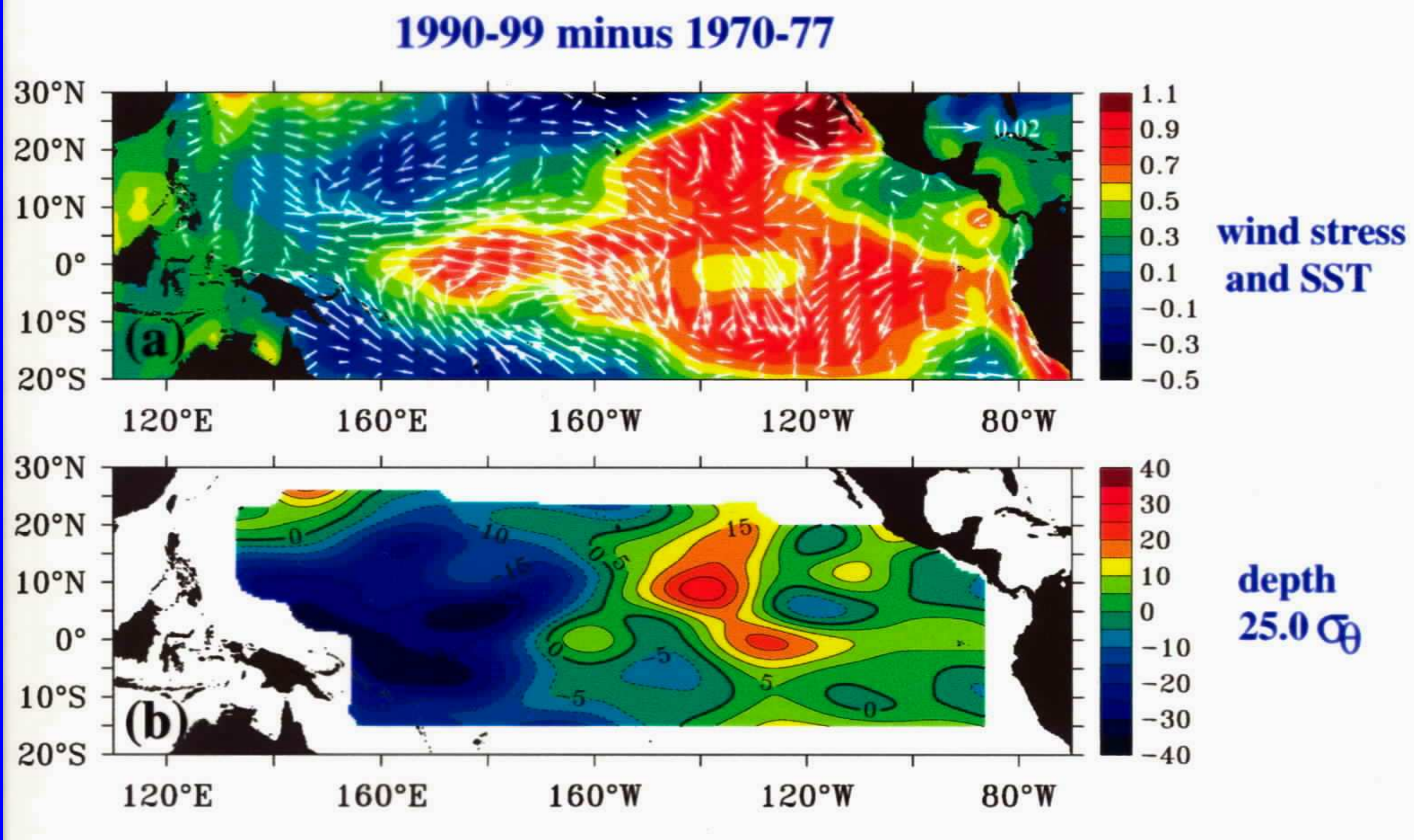
Figure 2.1. A schematic diagram of the horizontal and vertical circulation in the tropical Pacific Ocean.

Philander, 1990

Why interest in Subtropical Cells?

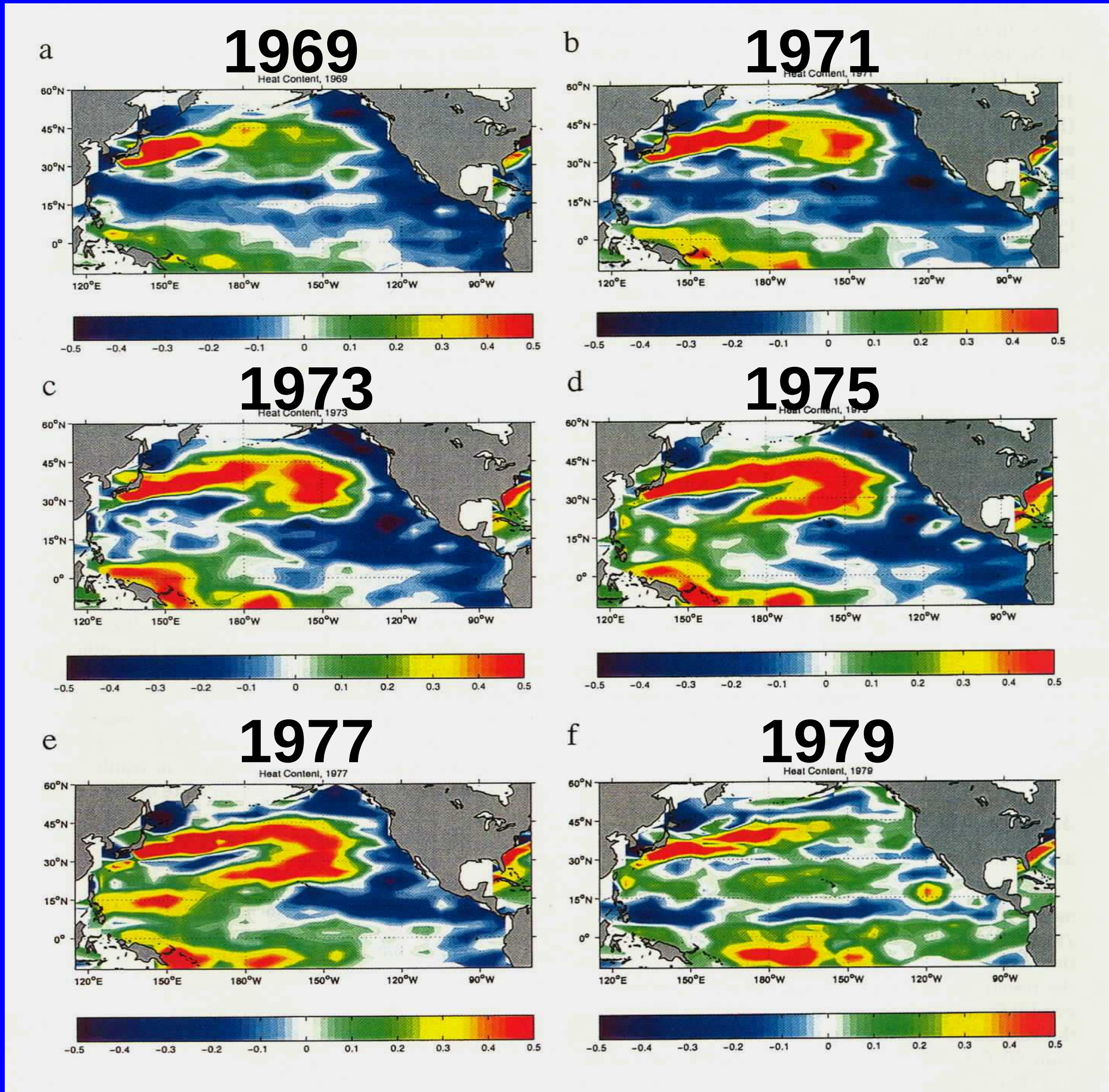
STCs ventilate the tropical thermocline, they set its properties on which interannual variability (e.g. ENSO) depends

STCs may play an active role in decadal variability in the tropical oceans.

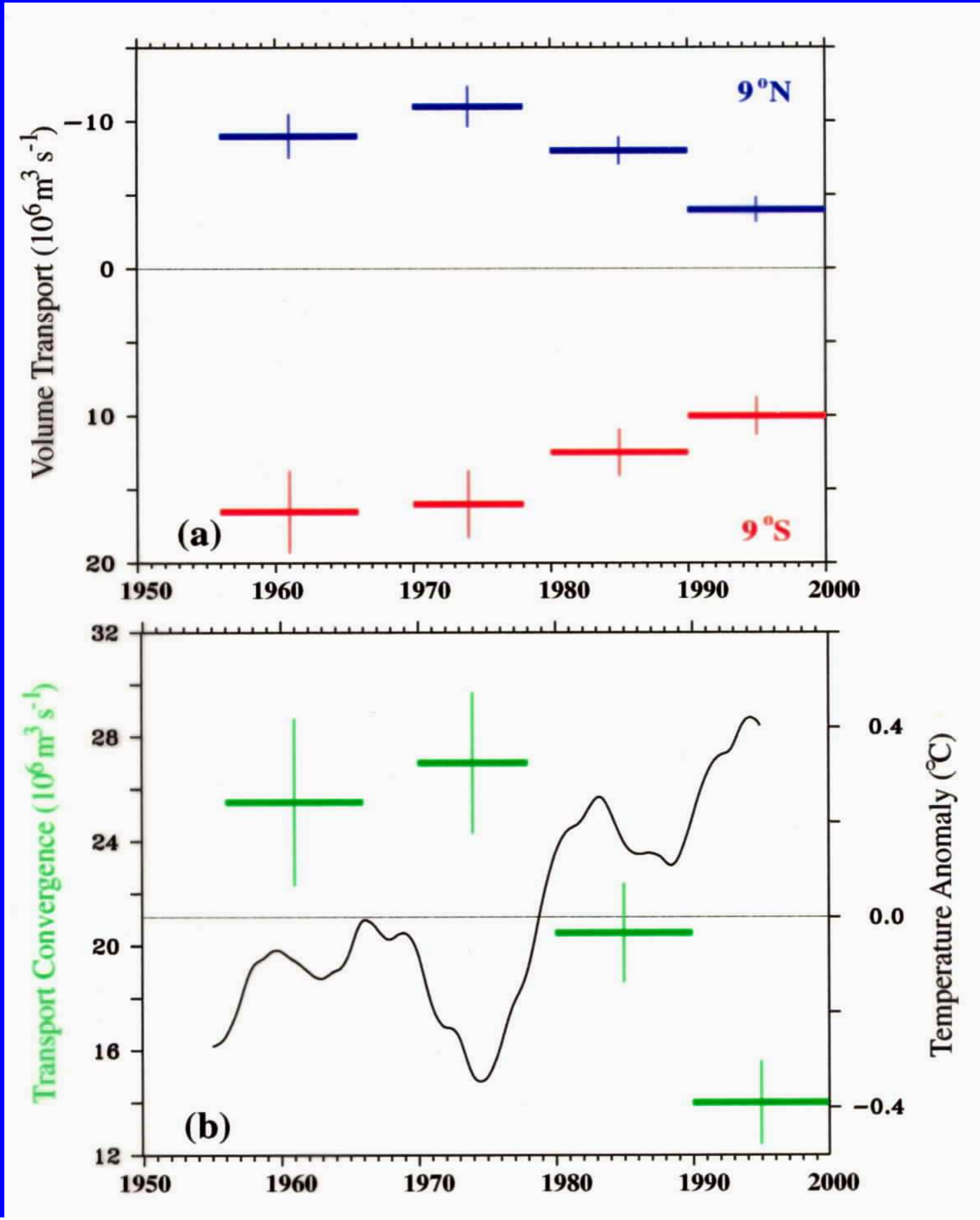


McPhaden and Zhang *Nature*, 2002

Upper 400 m heat content anomalies



Hazeleger et al *JGR* 2001



McPhaden and Zhang, *Nature*, 2002

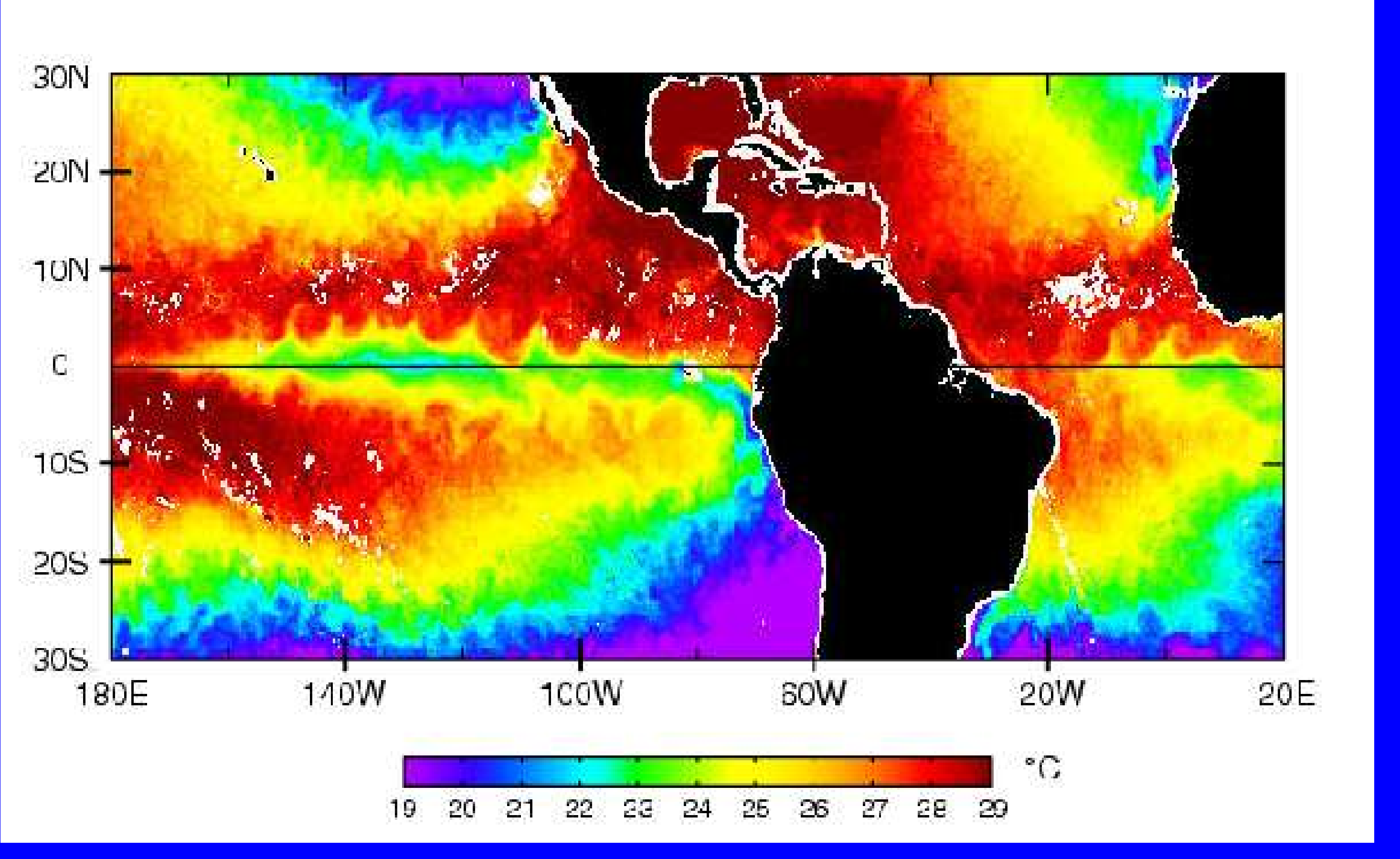
From where is the tropical thermocline ventilated?

Subduction patterns
Pathways (western boundary vs interior)
Water mass transformation

What is the fate of water masses in the Equatorial Undercurrent?

***Lagrangian trajectory analysis** (Döös 95, Blanke and Raynaud 97)*
***using transports from the eddy-permitting "OCCAM" model** (Webb ea 94).*
DX=0.25 deg, 36 layers, ECMWF 6-hourly winds, temperature and salinity restored.

Tropical Instability Waves in SST composite



The role of eddies

Separate between mean (overbar) and eddy (prime) components

Eddy: can be spatial or time average

$$X = X' + \overline{X}$$

Transformed Eulerian mean theory

Example: zonal mean buoyancy equation

$$\frac{\partial \bar{\rho}}{\partial t} - \bar{w}\frac{\rho_0 N^2}{g} = -(\overline{v'\rho'})_y + \bar{Q} \qquad \bar{w} = \frac{\partial \overline{v'\rho'}}{\partial y}\frac{g}{\rho_0 N^2} + w^*$$

$$\frac{\partial \bar{\rho}}{\partial t} - w^*\frac{\rho_0 N^2}{g} = \bar{Q}$$

Obtain v* using mass conservation.

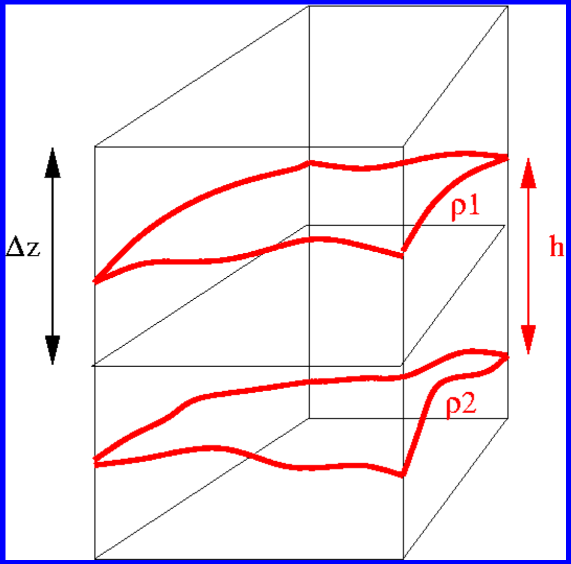
Similar for deviations of a time average.

v* and w* are the residual mean velocities. Note that w* relates directly to the diabatic heating Q in steady state. It is the residual mean velocity that advects active and passive tracers!!

Residual mean velocity in a model

Level representation: $\overline{u\Delta z} = \overline{u}\,\Delta z$

Isopycnal representation: $\overline{u_\rho h_\rho} = \tilde{u}_\rho \overline{h}_\rho = (\overline{u}_\rho + u^*)\overline{h}_\rho$



Eddy-induced velocity, "bolus" or residual velocity: $u^* = \dfrac{\overline{u_\rho' h_\rho'}}{\overline{h}_\rho}$

Mean velocity in level representation obeys mass conservation unlike mean velocity in isopycnal coordinates:

$$\nabla_3 \cdot (\overline{u}) = 0 \qquad \nabla_{hor} \cdot (\overline{u}_\rho) \neq 0$$

Meridional Streamfunction
OCCAM model (Indo-Pacific)

Eulerian   Residual mean   Eddy-induced

z

σ

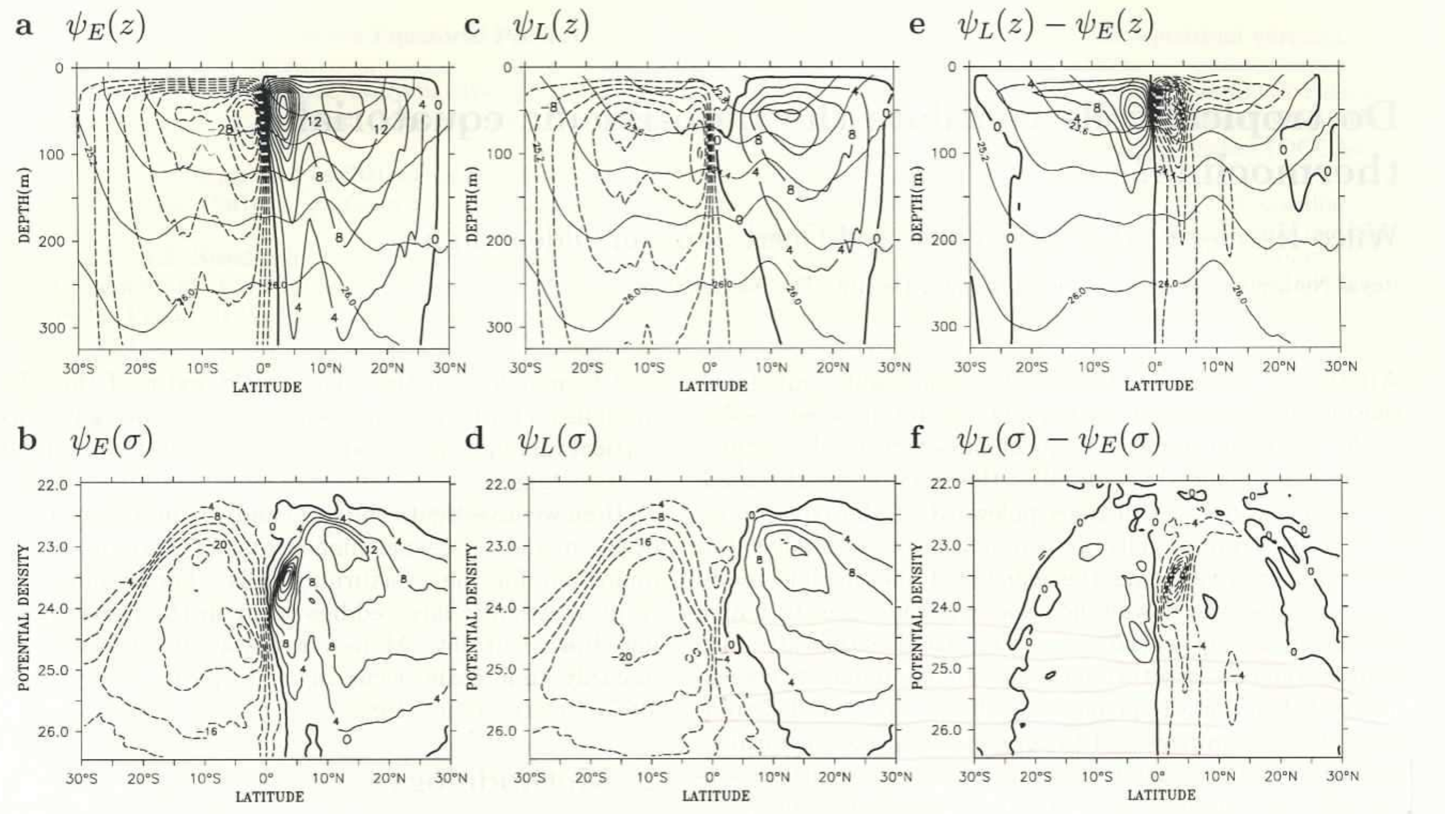
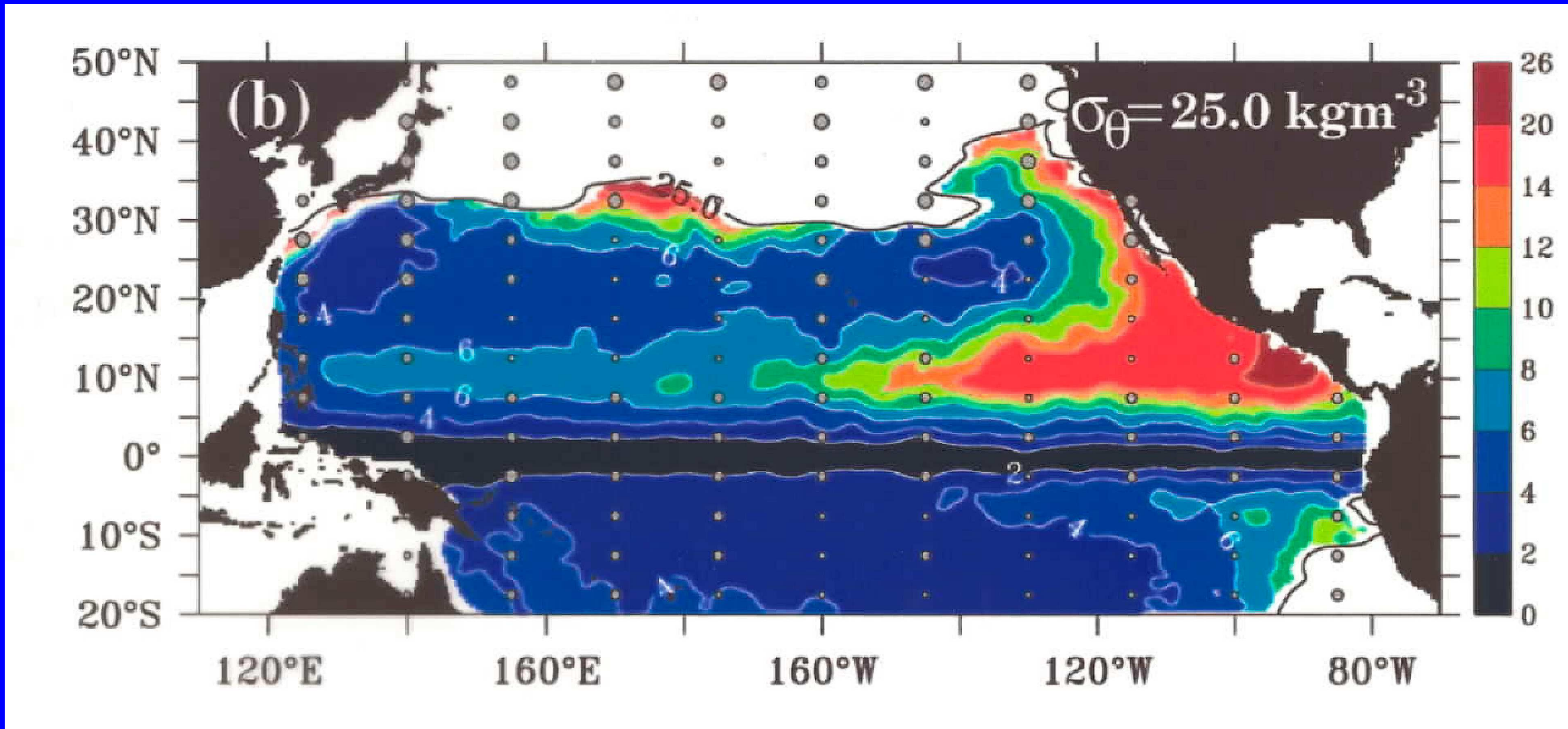


Figure 1. Eulerian and Lagrangian meridional stream function in the Indo-Pacific Ocean (in Sv=10^6 m^3s^{-1}). (a) $\psi_E(z)$, (b) $\psi_E(\sigma)$ (c) $\psi_L(z)$ (d) $\psi_L(\sigma)$ (e) $\psi_L(z)$-$\psi_E(z)$ (f) $\psi_L(\sigma)$-$\psi_E(\sigma)$. Zonally averaged potential density (kg m^{-3}) contours are overlayed in (a,c,e).

Hazeleger et al., *GRL*, 2001

Potential Vorticity



McPhaden and Zhang
Nature, 2002

EUC in OCCAM

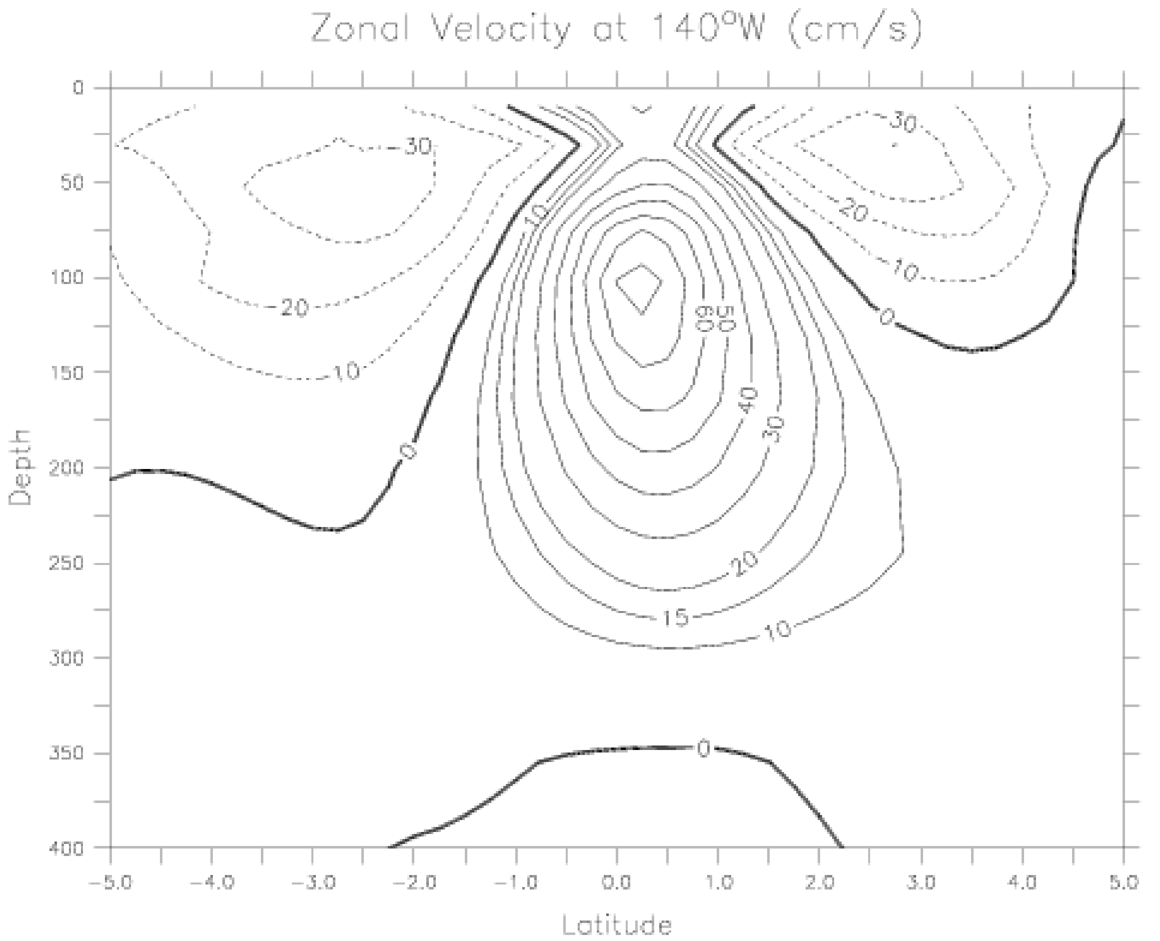
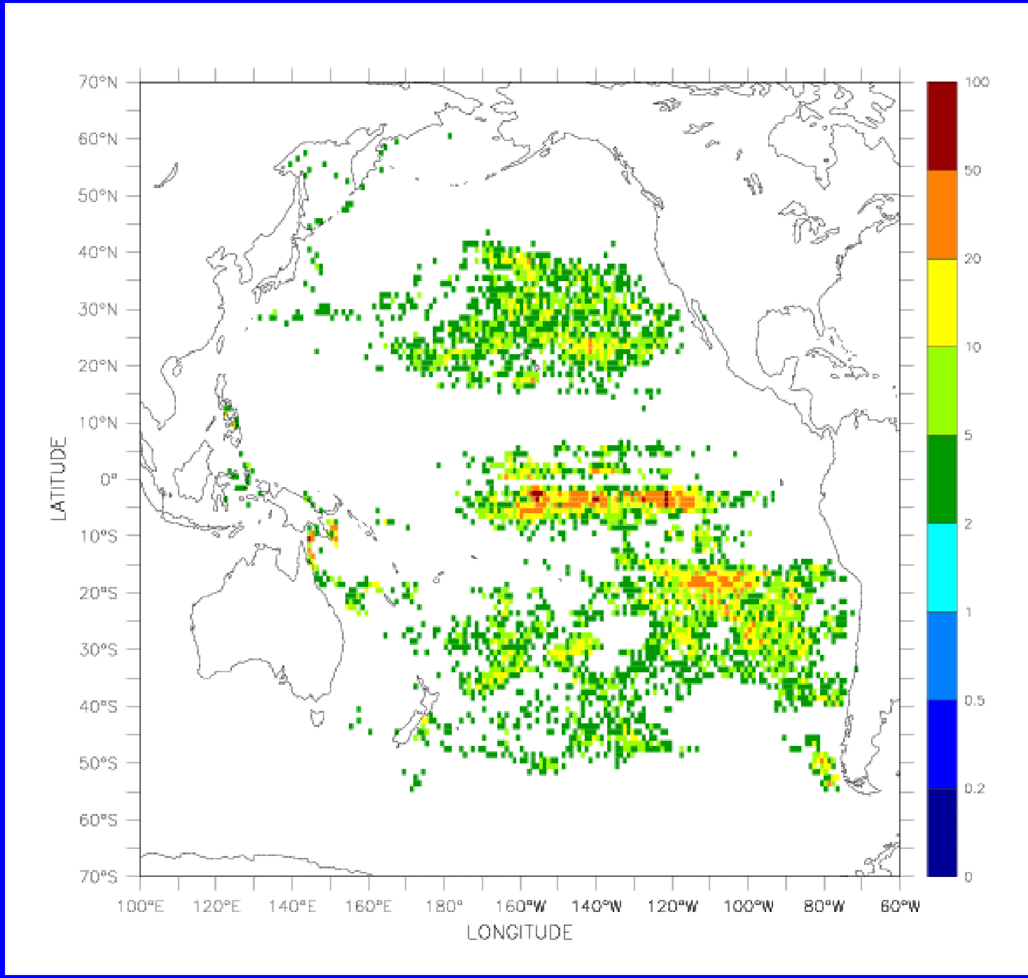


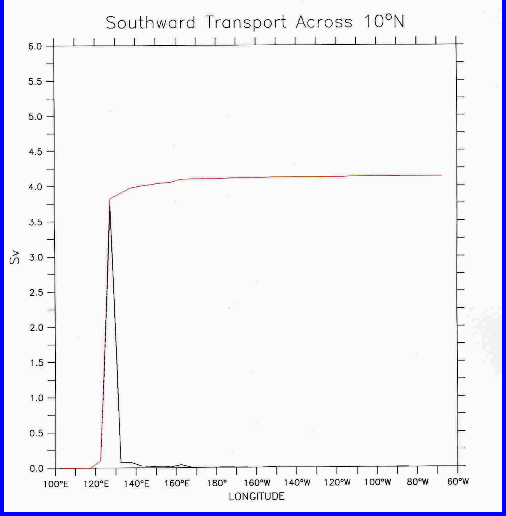
Figure 1. Equatorial Undercurrent speed (cm/s) at 140° W during the spring in OCCAM.

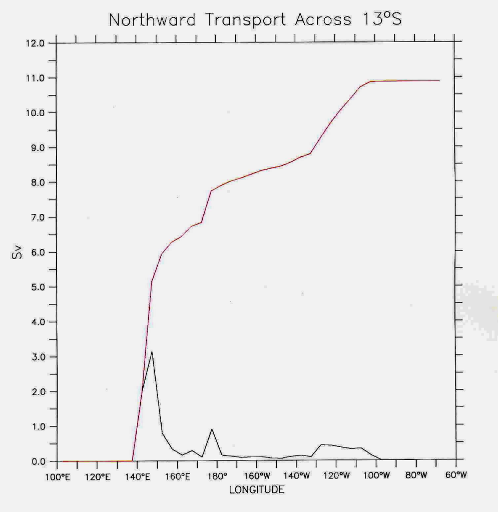
Goodman, Hazeleger, de Vries, and Cane, 2004 submitted

Sources of EUC in the Pacific

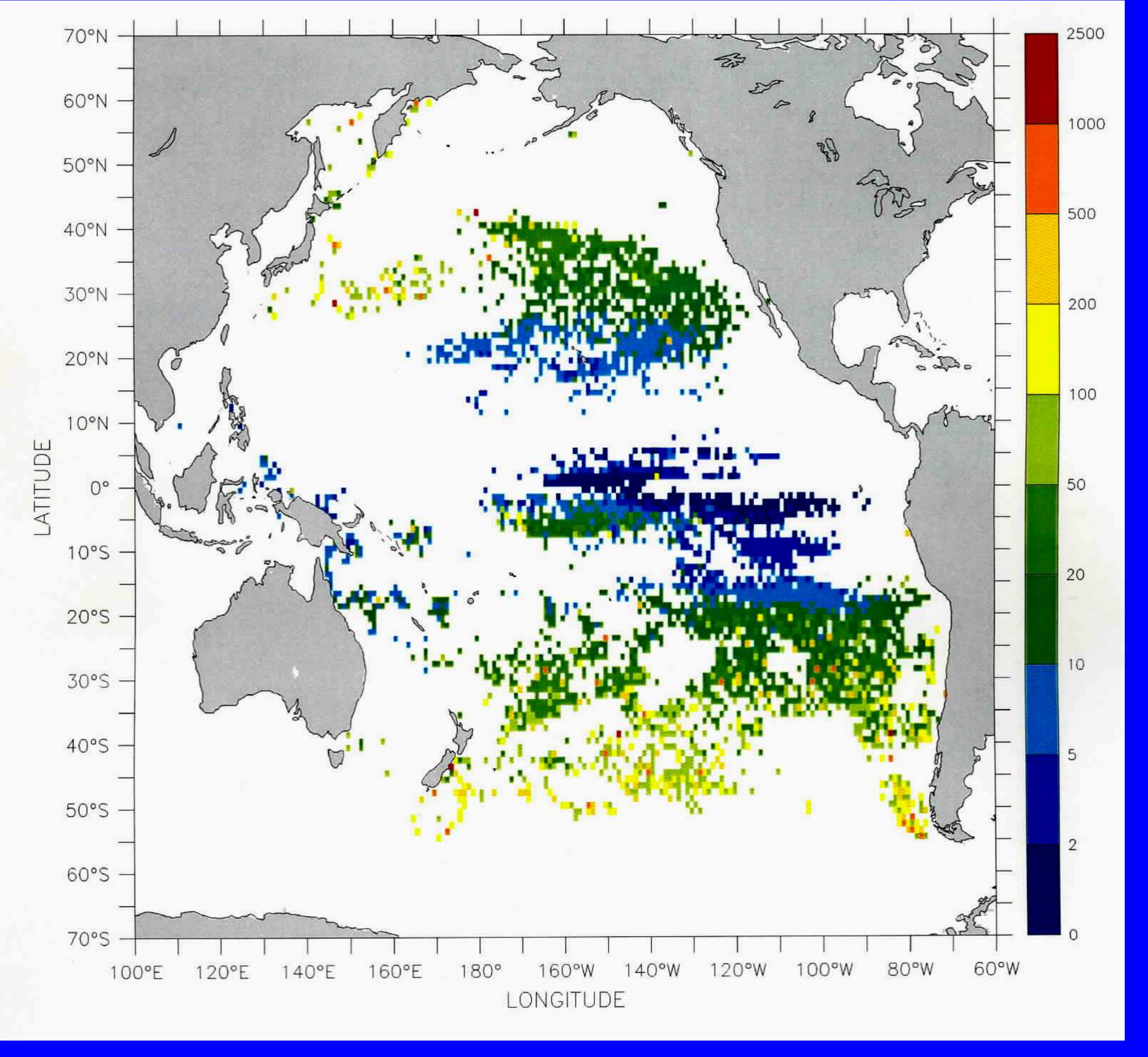
Volume Ventilated (10^3 m^3/s)







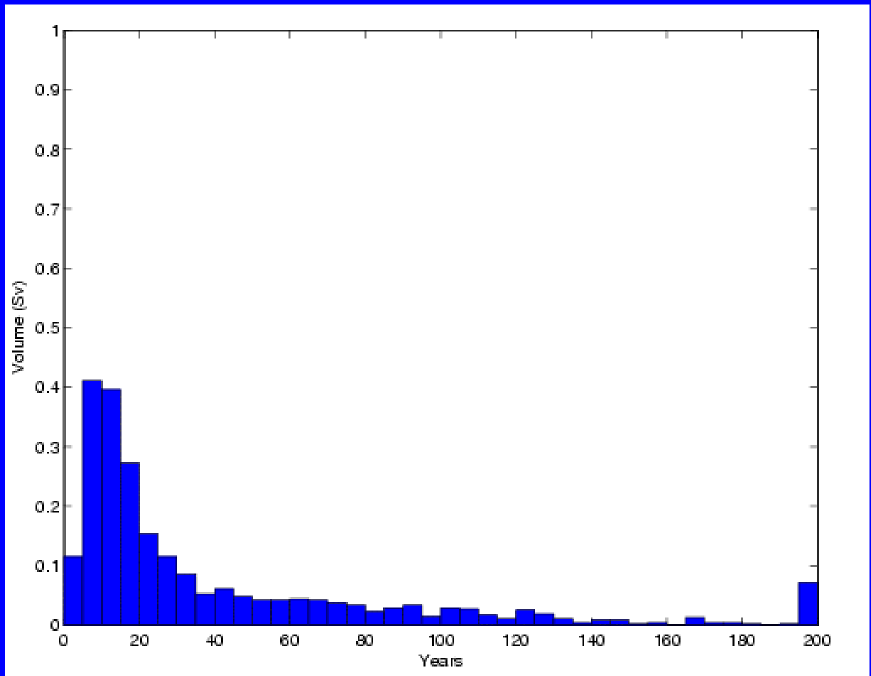
Average Time Between Subduction and the EUC (years)

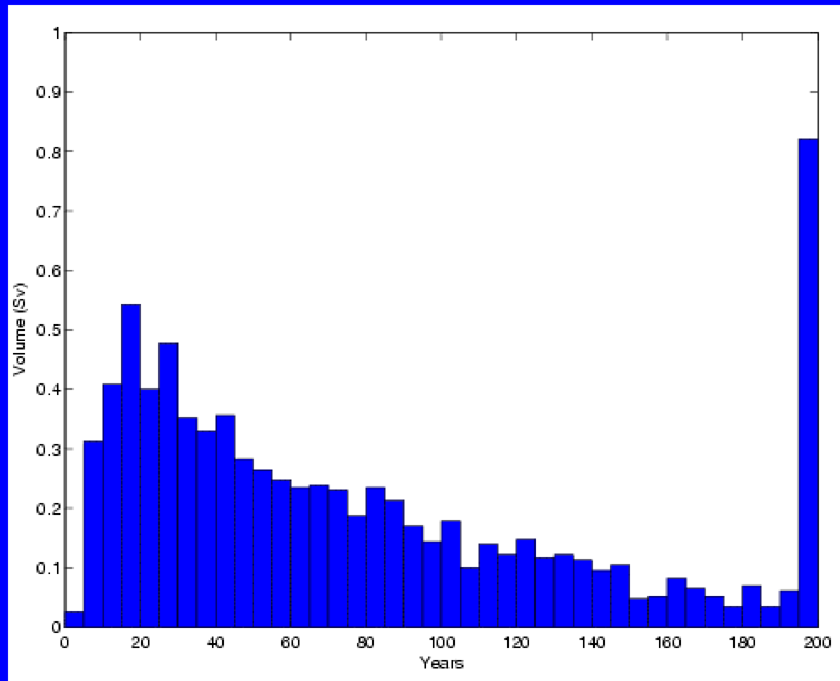


Time between subduction and the EUC (years)

Western boundary pathways

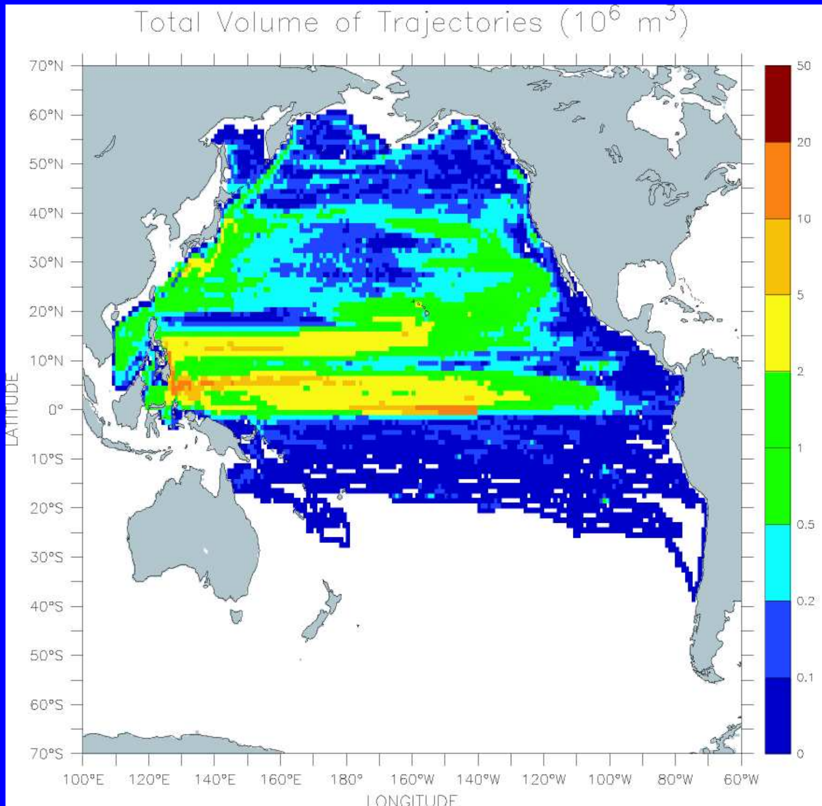
Interior pathways



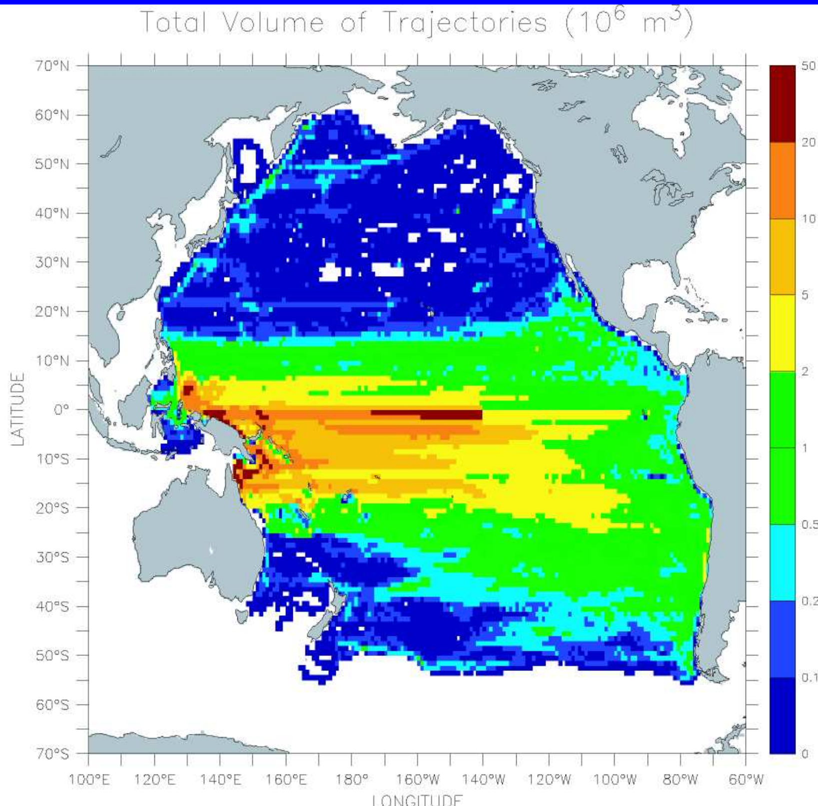


Footprints of trajectories: from subduction sites to EUC

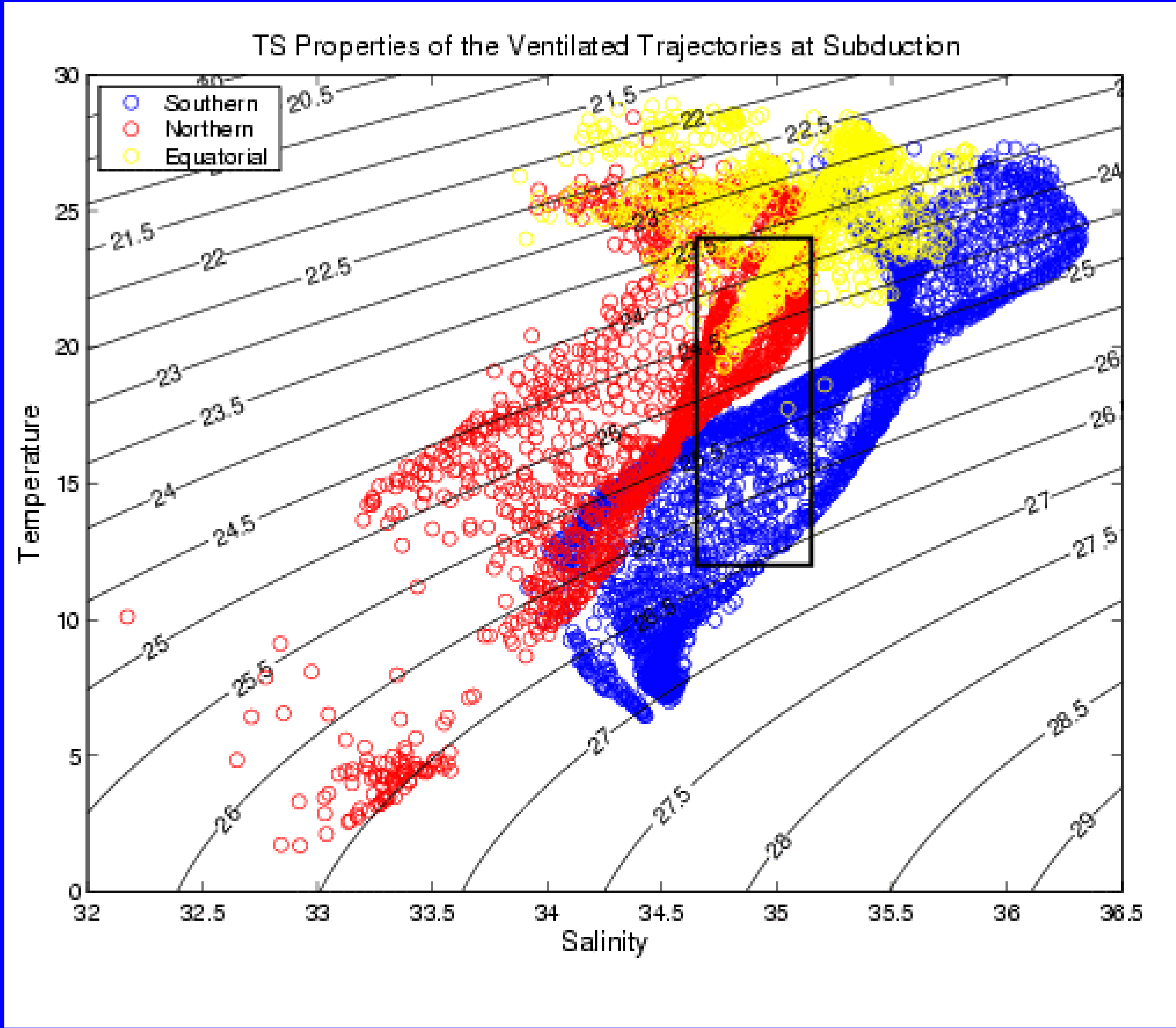
North Hem. origin



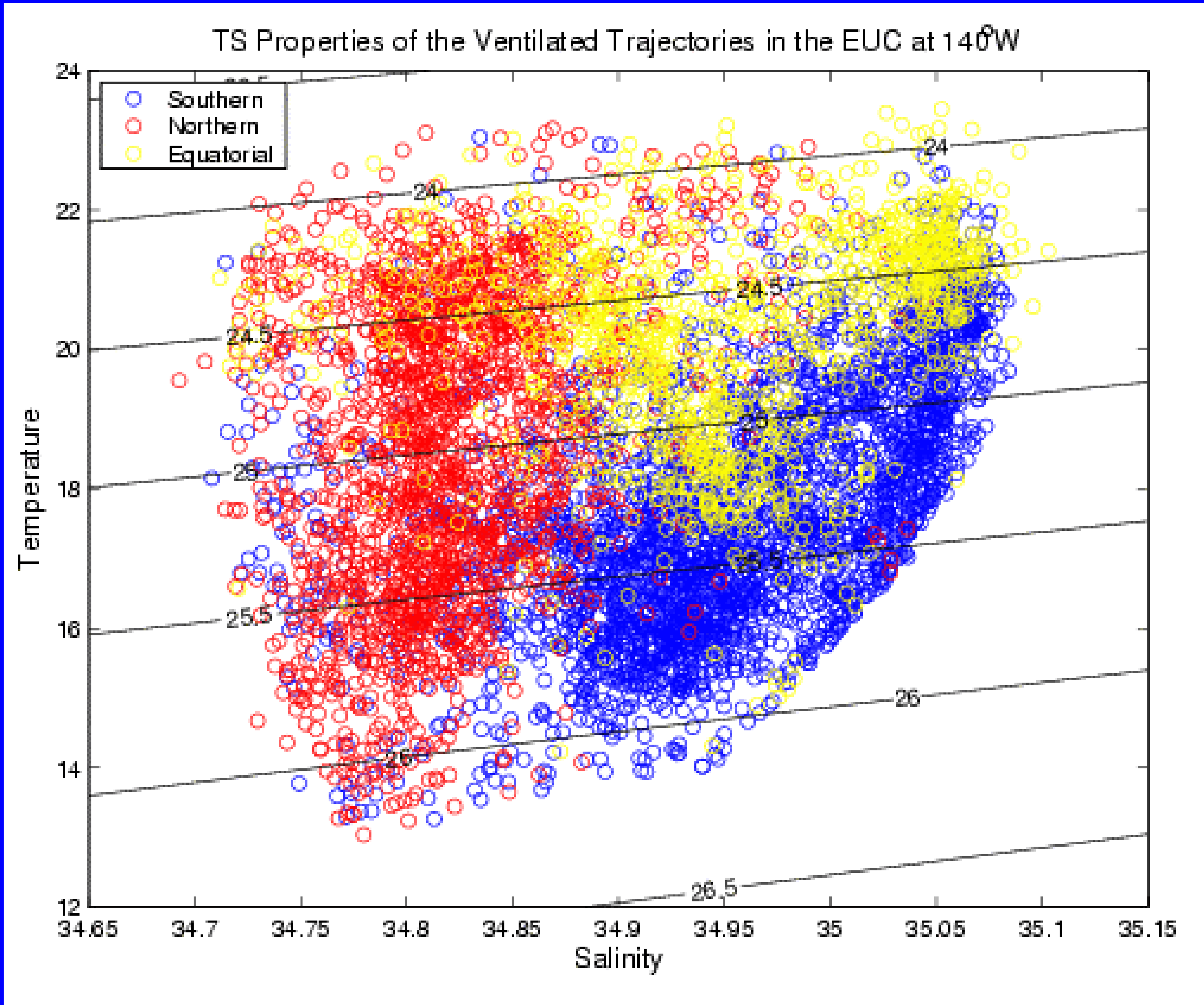
South. Hem. origin



Transformation



Transformation



Transformation

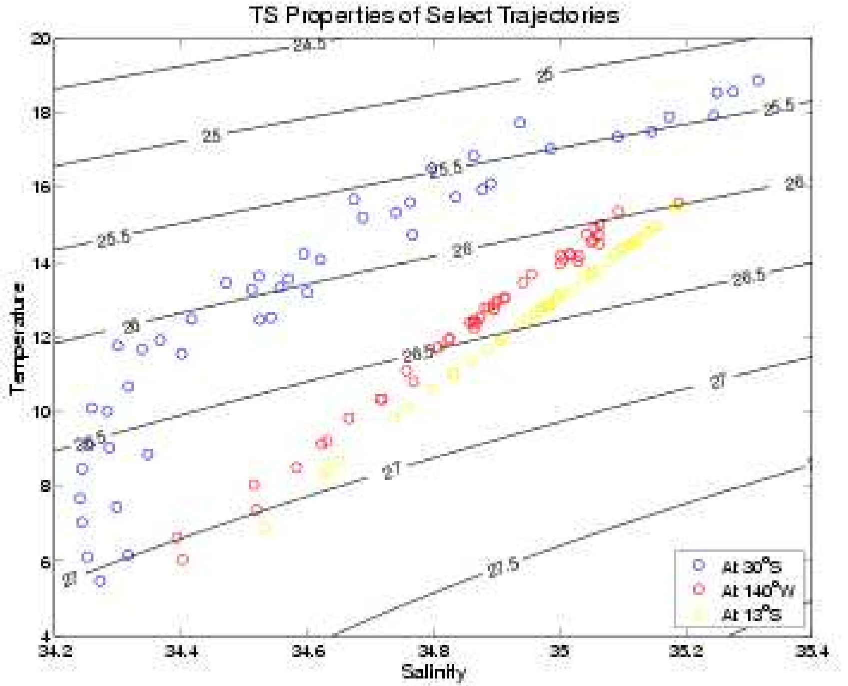


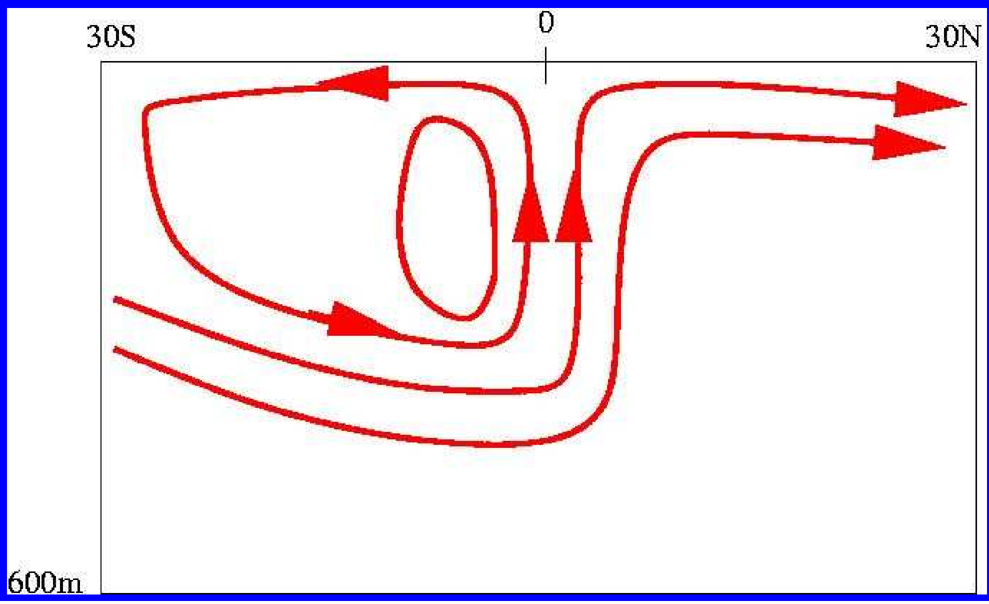
Figure 11. Temperature versus salinity properties of the selected trajectories (see text for selection criteria) at 30°S (blue), 140°W (red), and 13°S (yellow).

NB. Most transformation occurs before the parcels enter western boundary current region!

Subtropical Cells in the Atlantic

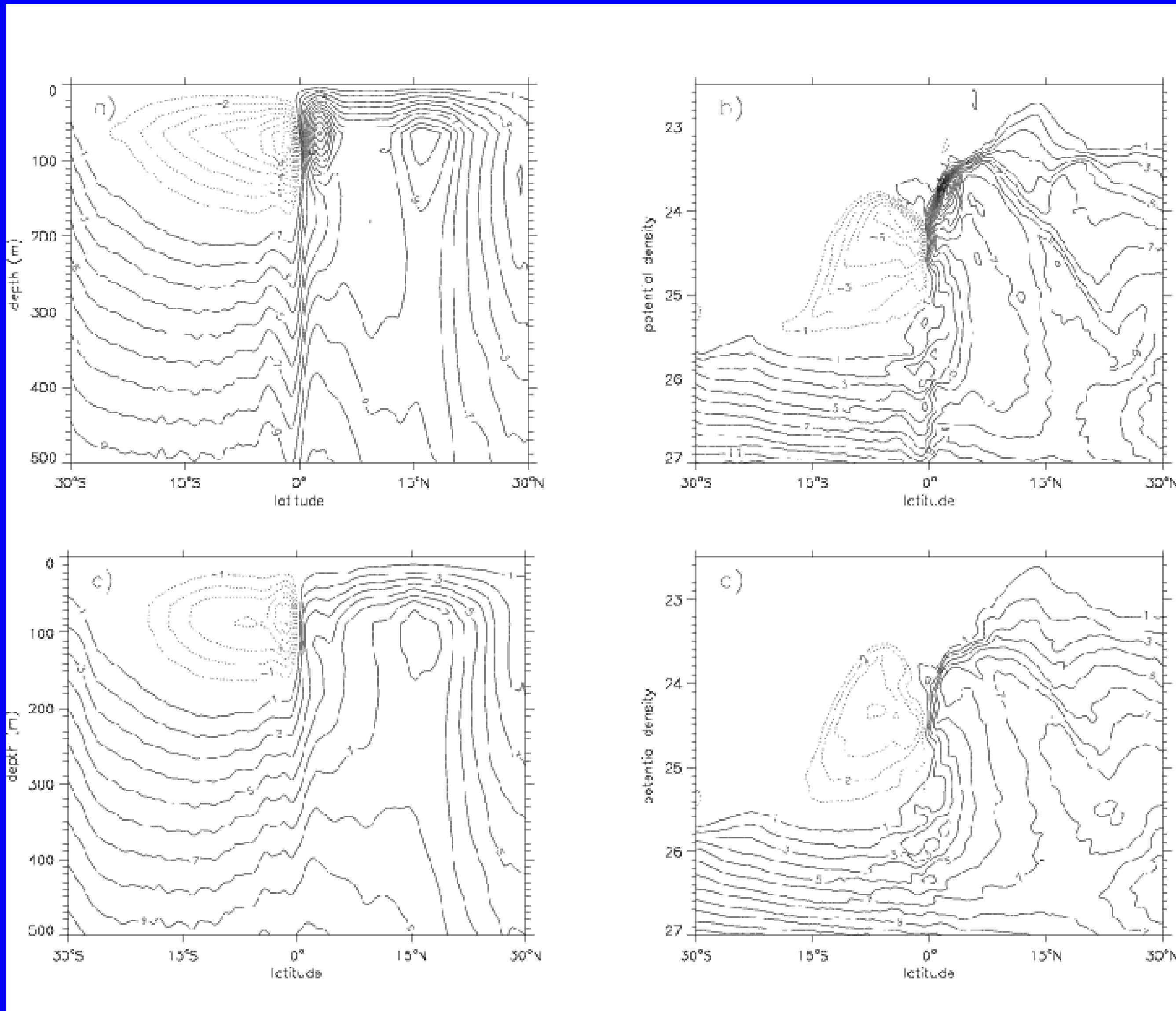
Ekman divergence (easterlies) at the equator drive upwelling. Ekman convergence off-equator drives downwelling and geostrophic convergence towards the equator.

Also, cross-equatorial transport due to basin-wide meridional overturning associated with North Atlantic Deep Water formation.



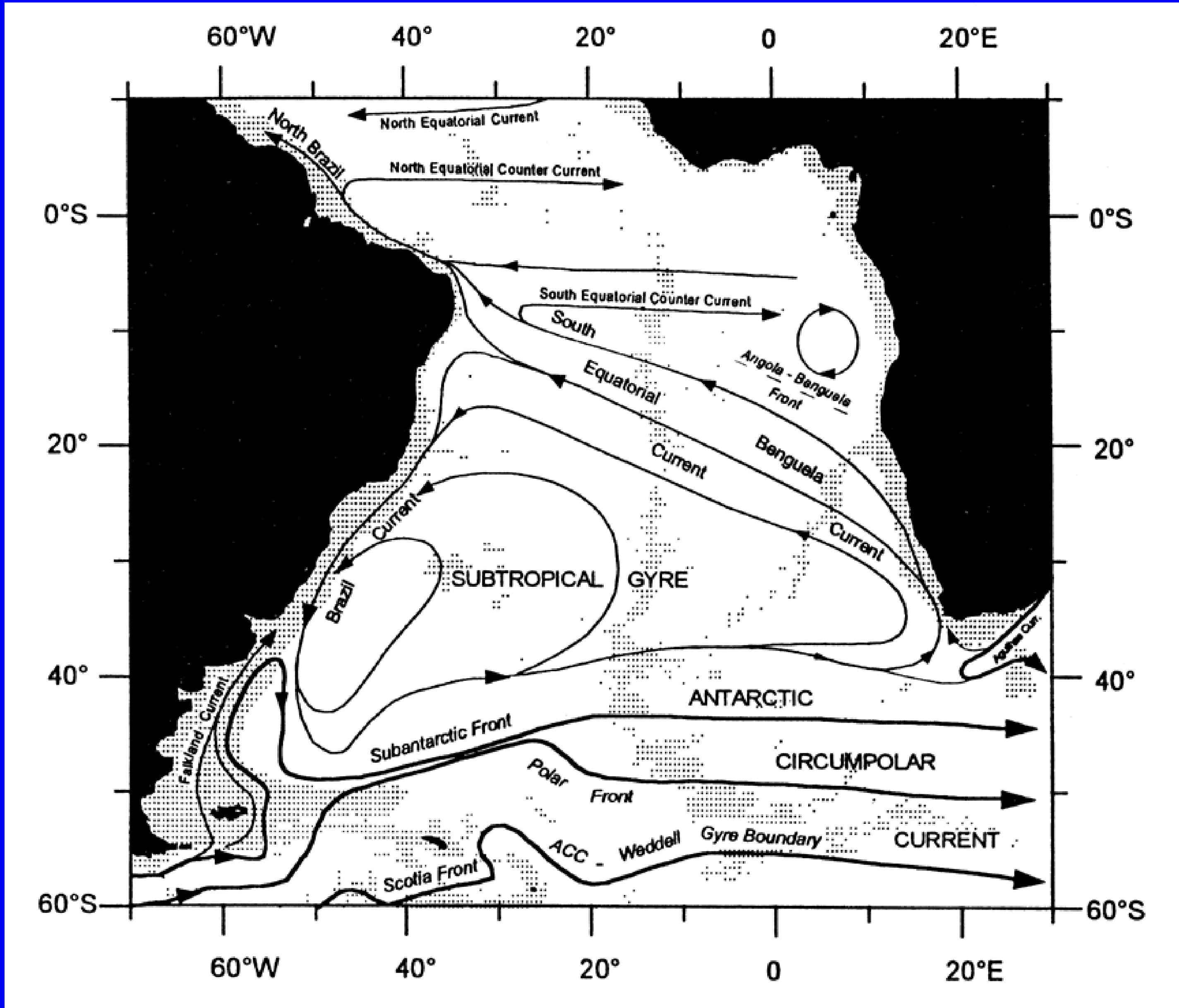
Meridional Streamfunction in the Atlantic (OCCAM, in Sv)

(Hazeleger, de Vries, and Friocourt, 2003, JPO)

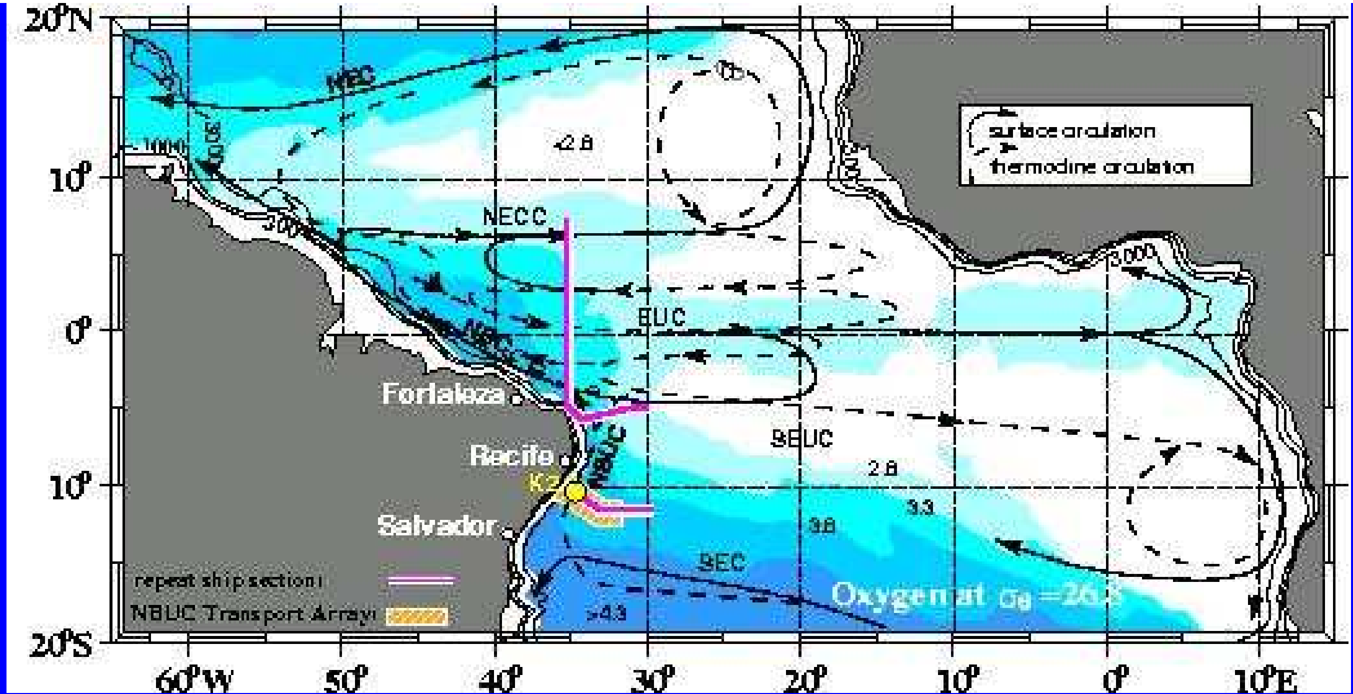


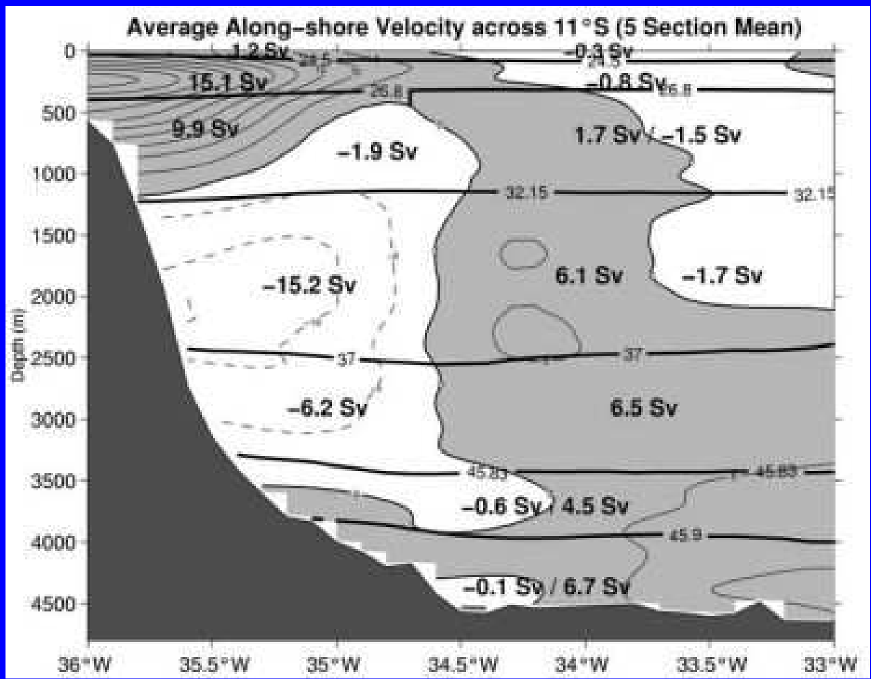
Eulerian

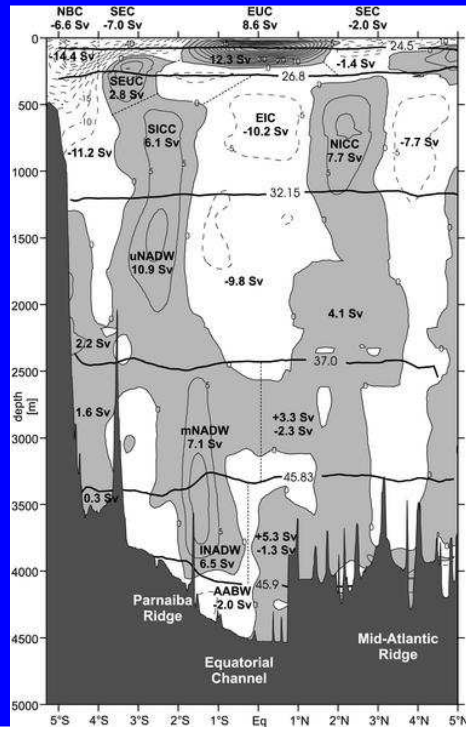
Residual mean



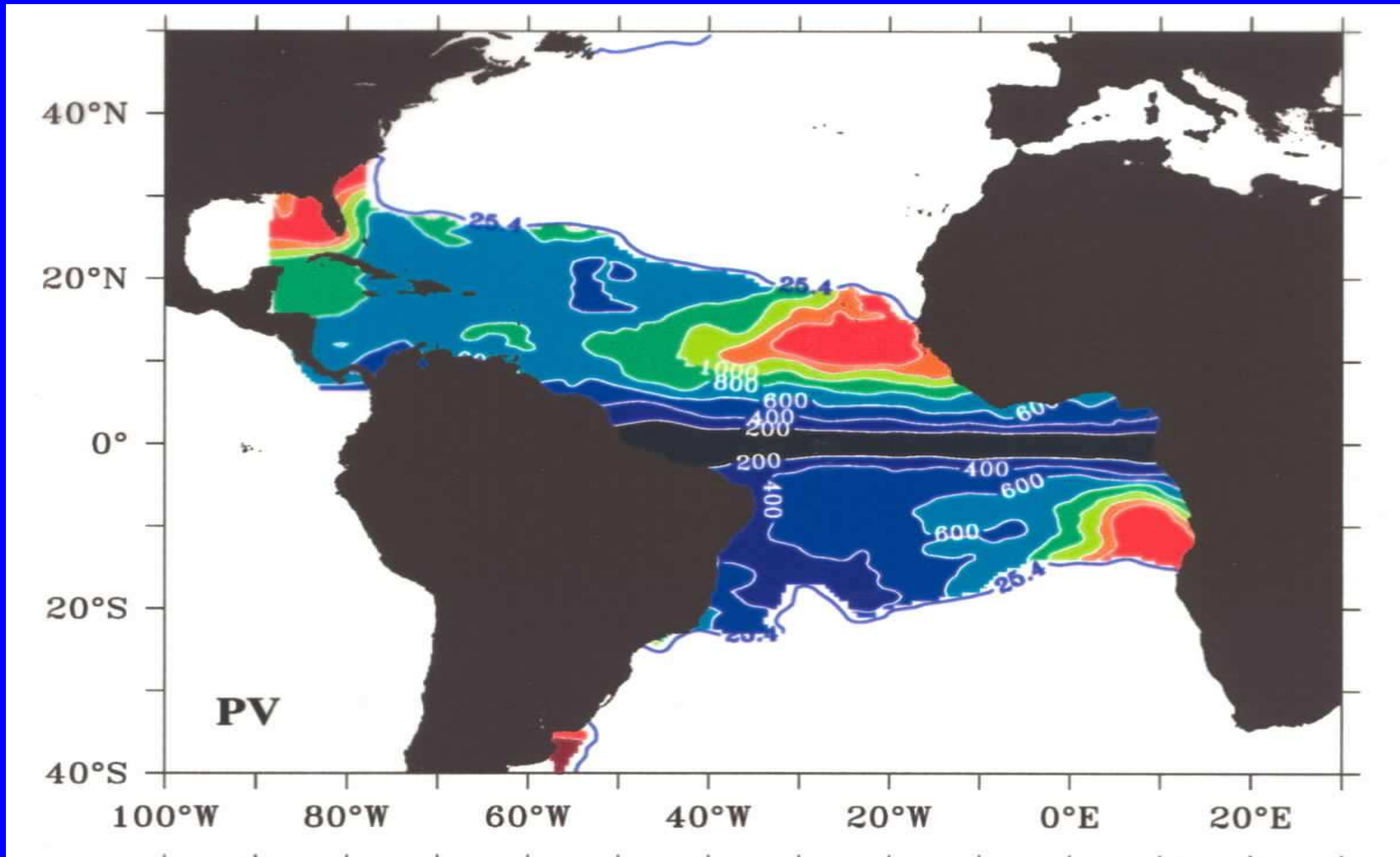
Peterson and Stramma 1995


20°N
10°
0°
10°
20°S
60°W
50°
40°
30°
20°
10°
0°
10°E
NEC
NECC
EUC
NBC
NBUC
SEUC
SEC
Fortaleza
Recife
Salvador
K2
surface circulation
thermocline circulation
repeat ship section
NBUC Transport Array
Oxygen at σθ=26.8
2.8
3.3
3.8
>4.3
3000
300
1000


Average Along-shore Velocity across 11°S (5 Section Mean)
1.2 Sv
-0.3 Sv
15.1 Sv
-0.8 Sv
9.9 Sv
-1.9 Sv
1.7 Sv / -1.5 Sv
-15.2 Sv
6.1 Sv
-1.7 Sv
-6.2 Sv
6.5 Sv
-0.6 Sv / 4.5 Sv
-0.1 Sv / 6.7 Sv
24.5
26.8
32.15
37
45.83
45.9
Depth (m)
36°W
35.5°W
35°W
34.5°W
34°W
33.5°W
33°W

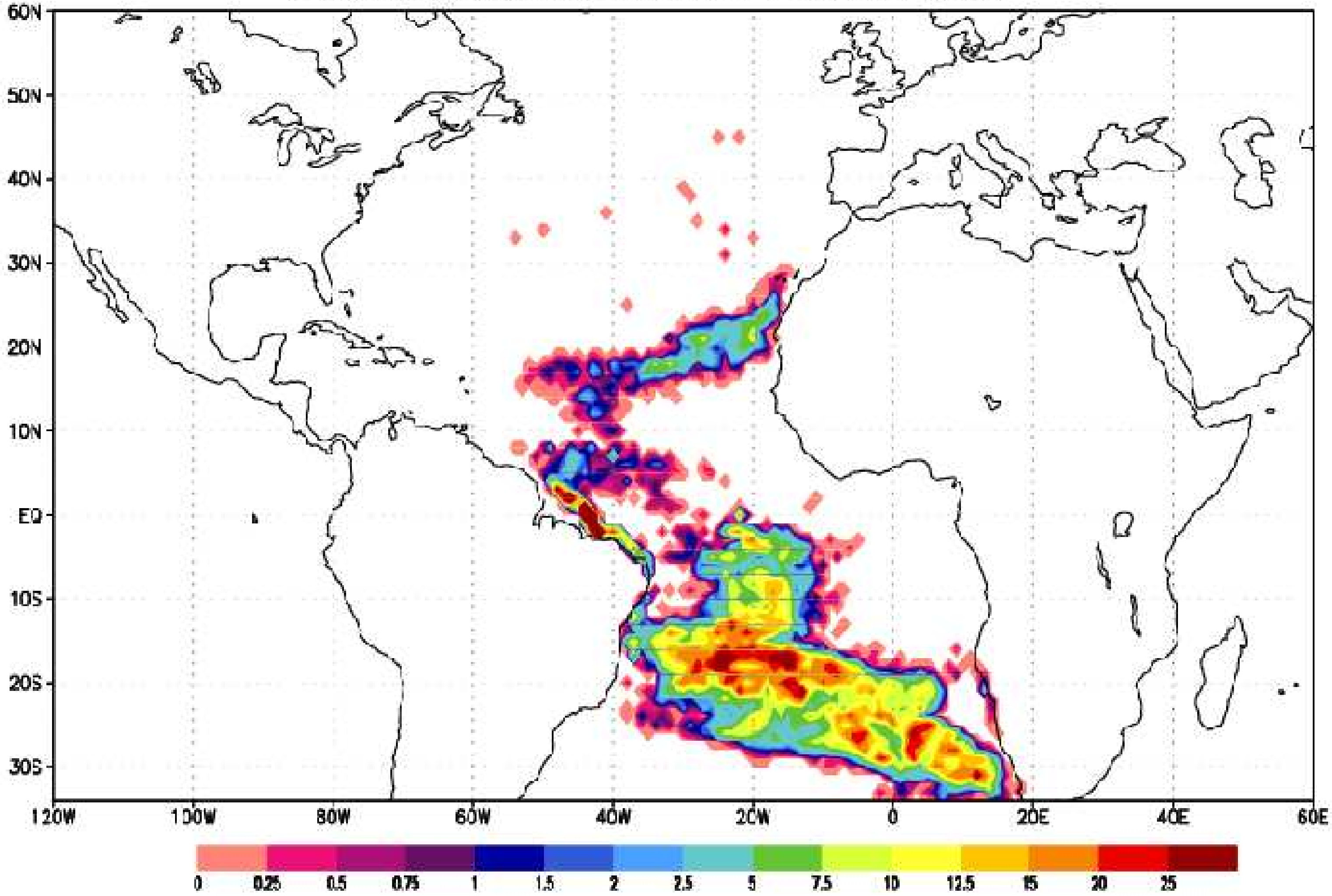

NBC -6.6 Sv
SEC -7.0 Sv
EUC 8.6 Sv
SEC -2.0 Sv
-14.4 Sv
12.3 Sv
-1.4 Sv
SEUC 2.8 Sv
SICC 6.1 Sv
EIC -10.2 Sv
NICC 7.7 Sv
-7.7 Sv
-11.2 Sv
uNADW 10.9 Sv
-9.8 Sv
4.1 Sv
2.2 Sv
1.6 Sv
mNADW 7.1 Sv
+3.3 Sv -2.3 Sv
0.3 Sv
lNADW 6.5 Sv
+5.3 Sv -1.3 Sv
AABW -2.0 Sv
Parnaiba Ridge
Equatorial Channel
Mid-Atlantic Ridge
depth [m]
24.5
26.8
32.15
37.0
45.83
45.9
5°S
4°S
3°S
2°S
1°S
Eq
1°N
2°N
3°N
4°N
5°N

Potential vorticity

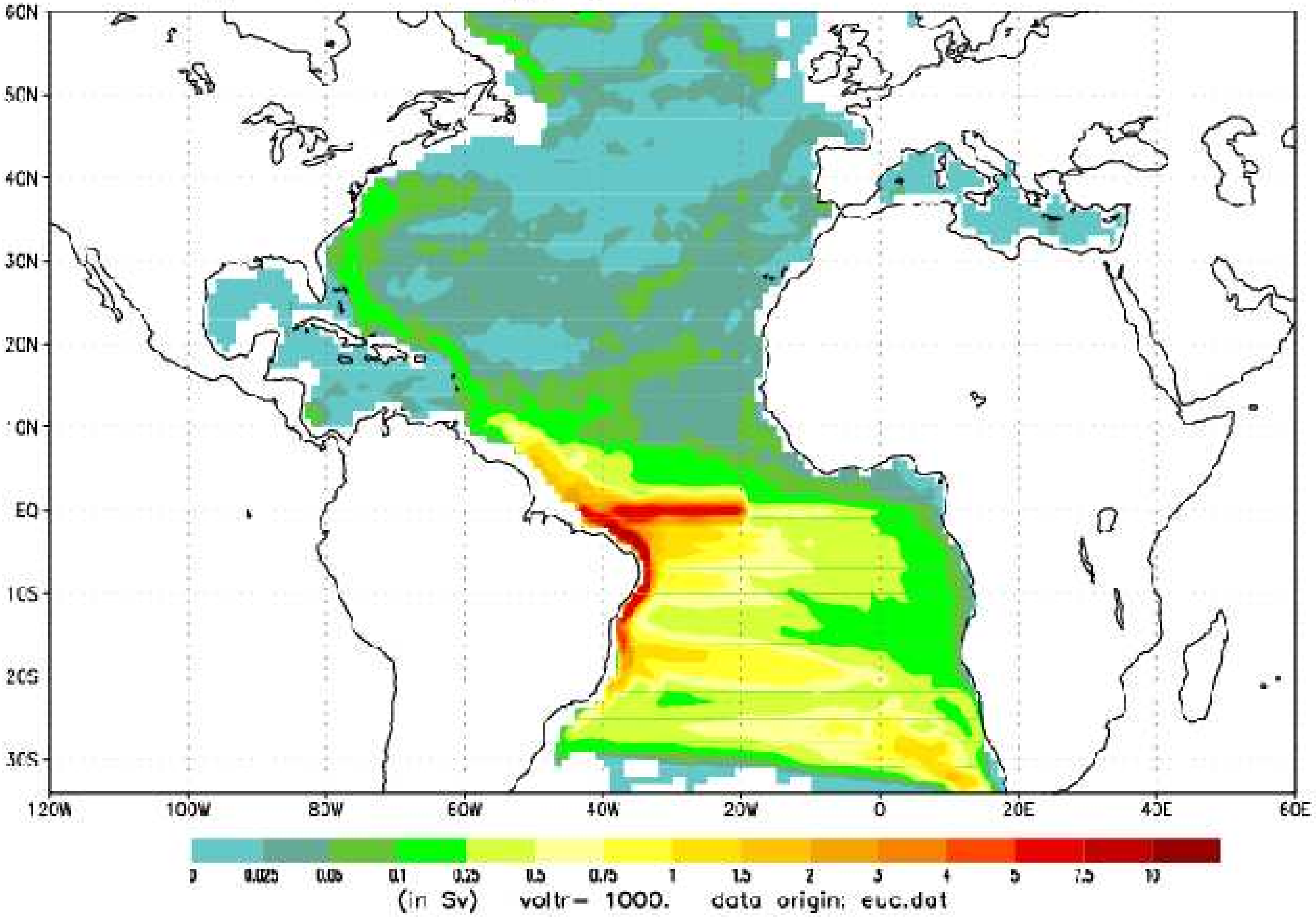


Zhang and McPhaden 2003

Sites where water subducts from the mixed layer into the interior before reaching the Equatorial Undercurrent



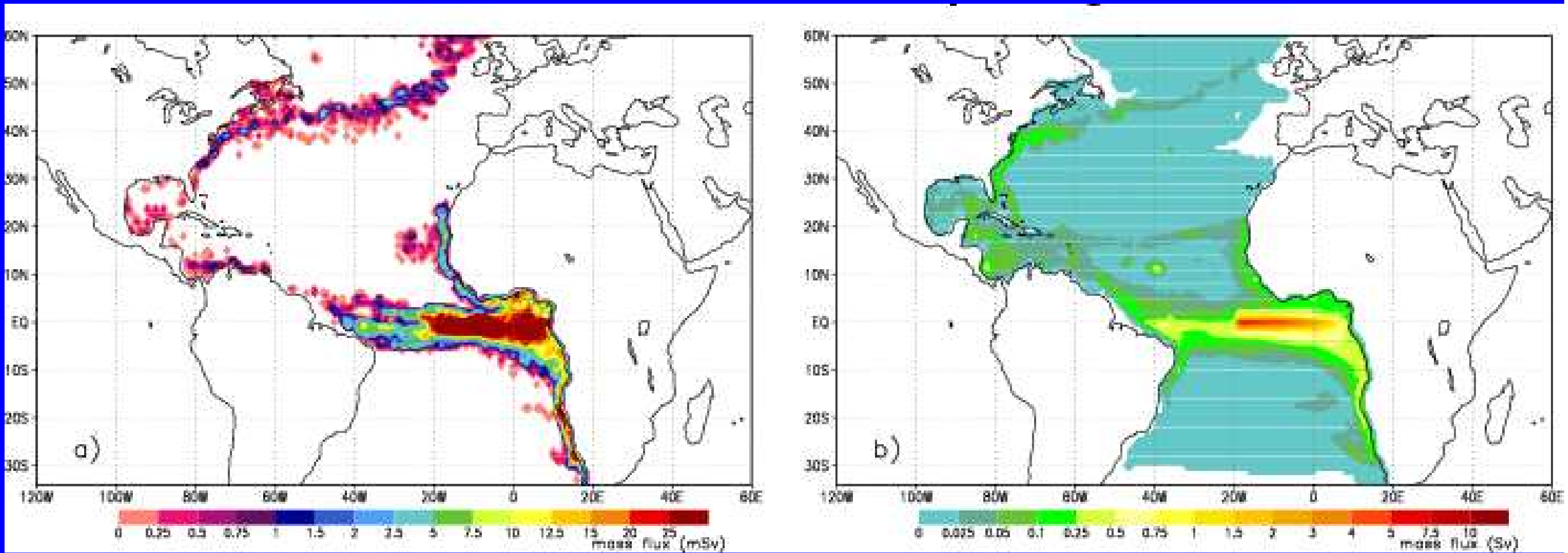
Footprints of transport from subduction sites to EUC



Fate of EUC

Sites where EUC water upwells

Footprints from EUC to base of ML

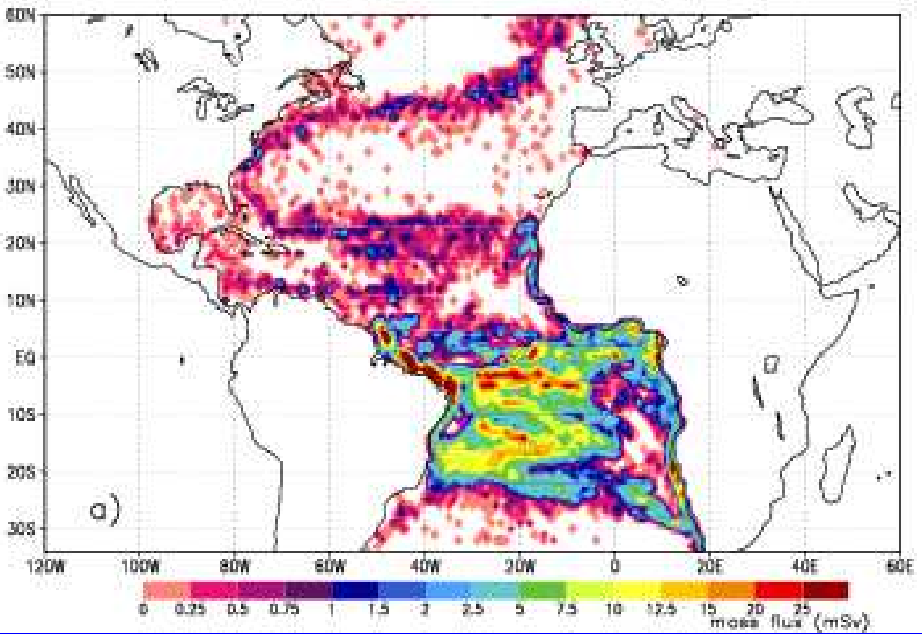


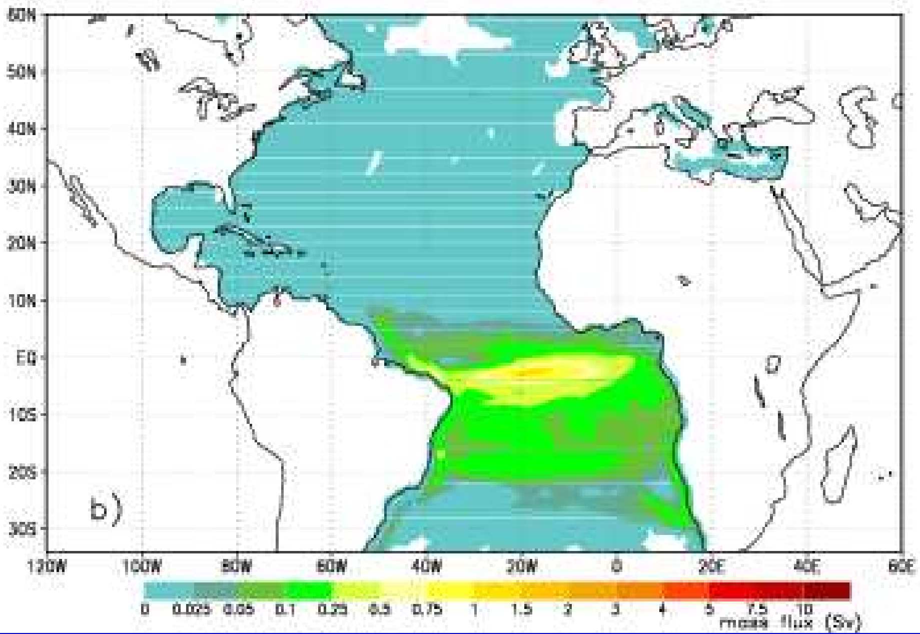
Hazeleger and de Vries, 2003

Fate of EUC

Sites where EUC water subducts for the first time after upwelling

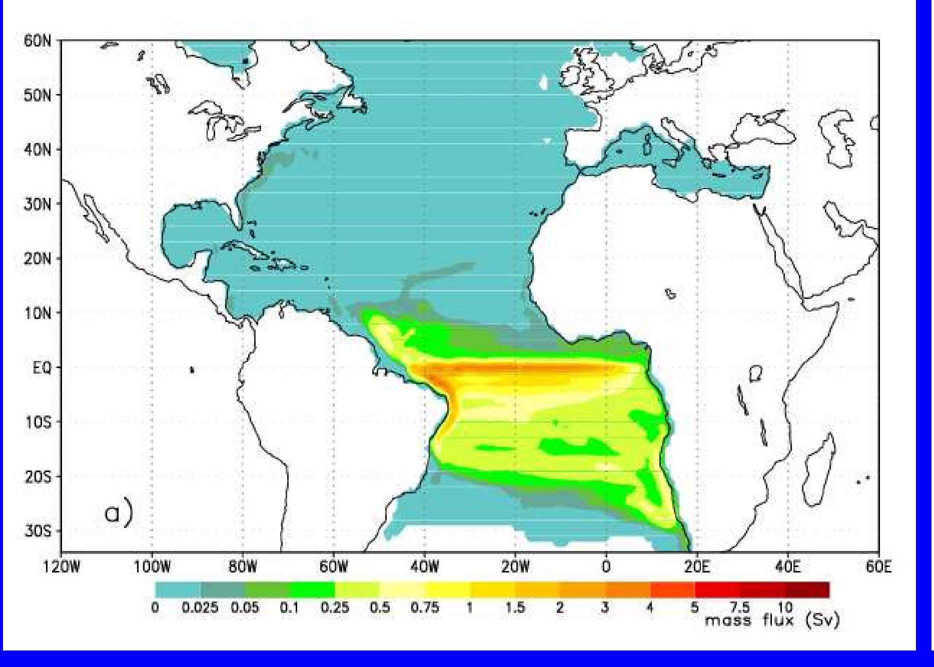
Footprints between upwelling and first time subduction



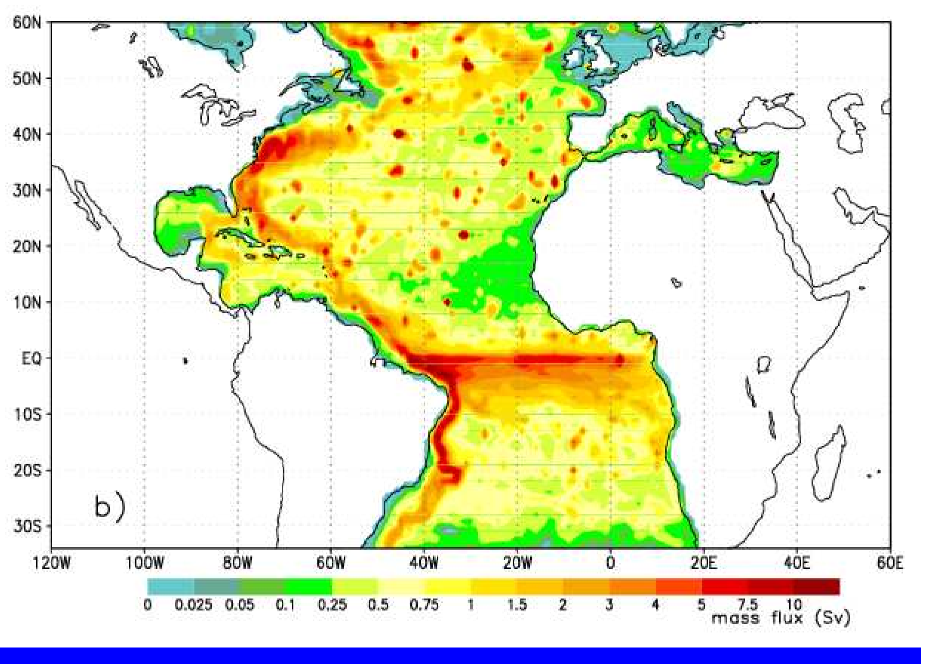


Fate of EUC

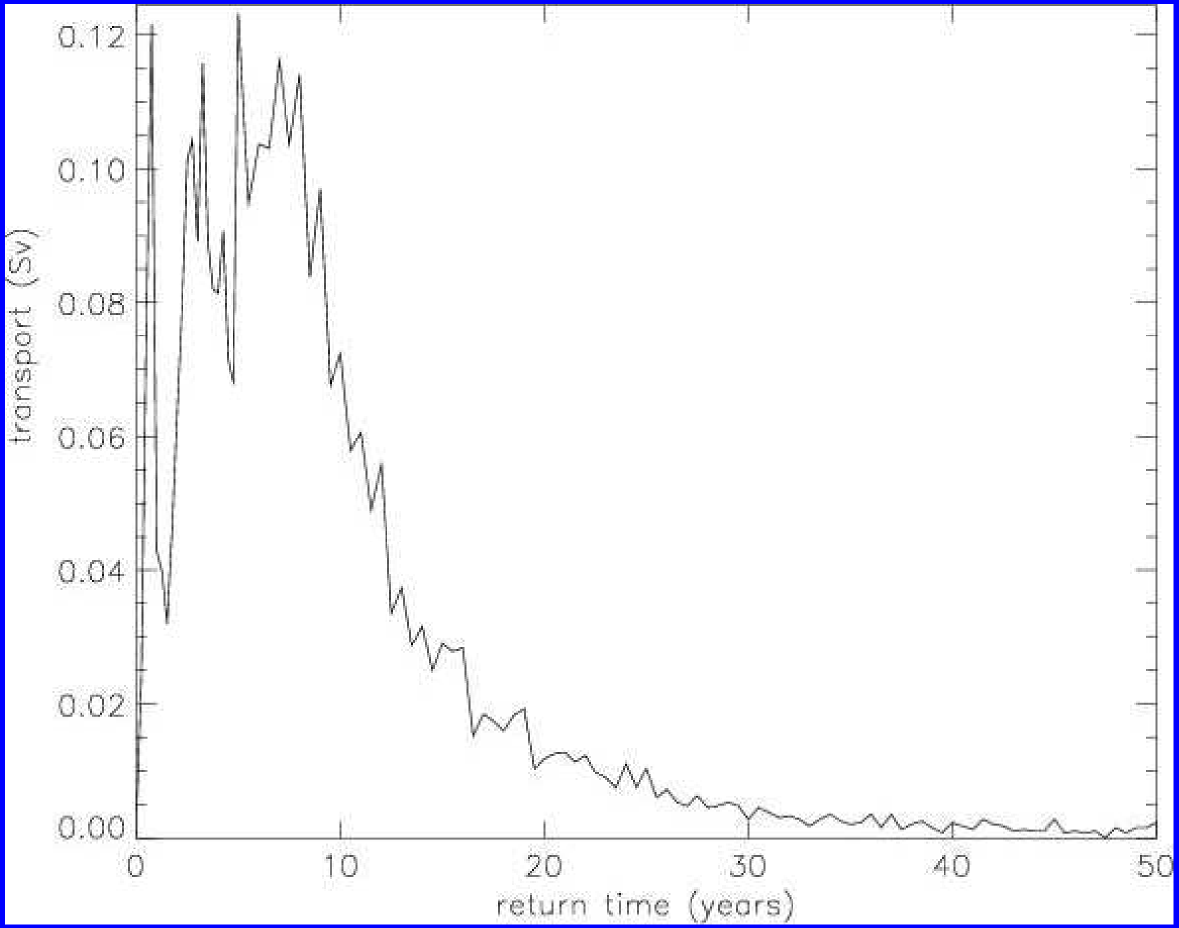
Footprints of EUC water taking part in the Subtropical Cells



Footprints of EUC water taking part in basin-wide Meridional Overturning



Return time in STC:
Time between upwelling of EUC water in mixed layer, subsequent downwelling and arrival into EUC again



Summary and conclusions

Equatorial thermocline is ventilated primarily through a western boundary pathway.

Atlantic: primarily from the South Atlantic due to the prescence of the basin-wide MOC.

Pacific: 2/3rd from the South Pacific, 1/3rd from the North Pacific.

Water masses transform their density already in the Subtropical Gyres.

High-frequency eddies compensate mean transport in Tropical Cells, and affect ventilation in the tropics.