Some ways ocean circulation affects climate:

- **biological productivity ➔ gas exchange**
- **direct transport of gases (e.g., the carbon cycle)**
- **ice ➔ albedo**
- **heat exchange with atmosphere**

"heat content" or "internal energy" per volume can be approx:

$$E = c_p \rho \theta$$

ρ = density of seawater $\approx 1030\ \mathrm{kg/m^3}$
θ = potential temperature
c_p = specific heat $\approx 4000\ \mathrm{J\ kg^{-1}\ K^{-1}}$

“Heat Budget” of ocean tells us

- **how ocean stores and moves heat**
- **how ocean exchanges heat with atmosphere**

$$\int E_t dV + H = Q + D$$

Physical interpretation of terms:

$$H = \int_{\text{all}} c_p \rho \theta \vec{u} \cdot \vec{n} dA = \text{lateral advective heat transport}$$

$$Q = \int \int c_p \rho \kappa_V \theta_z |_{\text{BOT}}^{\text{TOP}} dx dy = \text{heat exchange with atmosphere}$$

$$D = \int_{\text{sides}} c_p \rho (\kappa_A \vec{\nabla}_H \theta) \cdot \vec{n} dA = \text{lateral eddy heat transport}$$

$$\int E_t dV + H = Q + D$$

Several possibilities: including

1. **Q = 0 (thermally passive ocean)**
2. **D – H small, Q = $\int E_t$ dV (ocean is thermal flywheel)**
3. **D – $\int E_t$ dV small, Q = H (ocean moves heat around)**

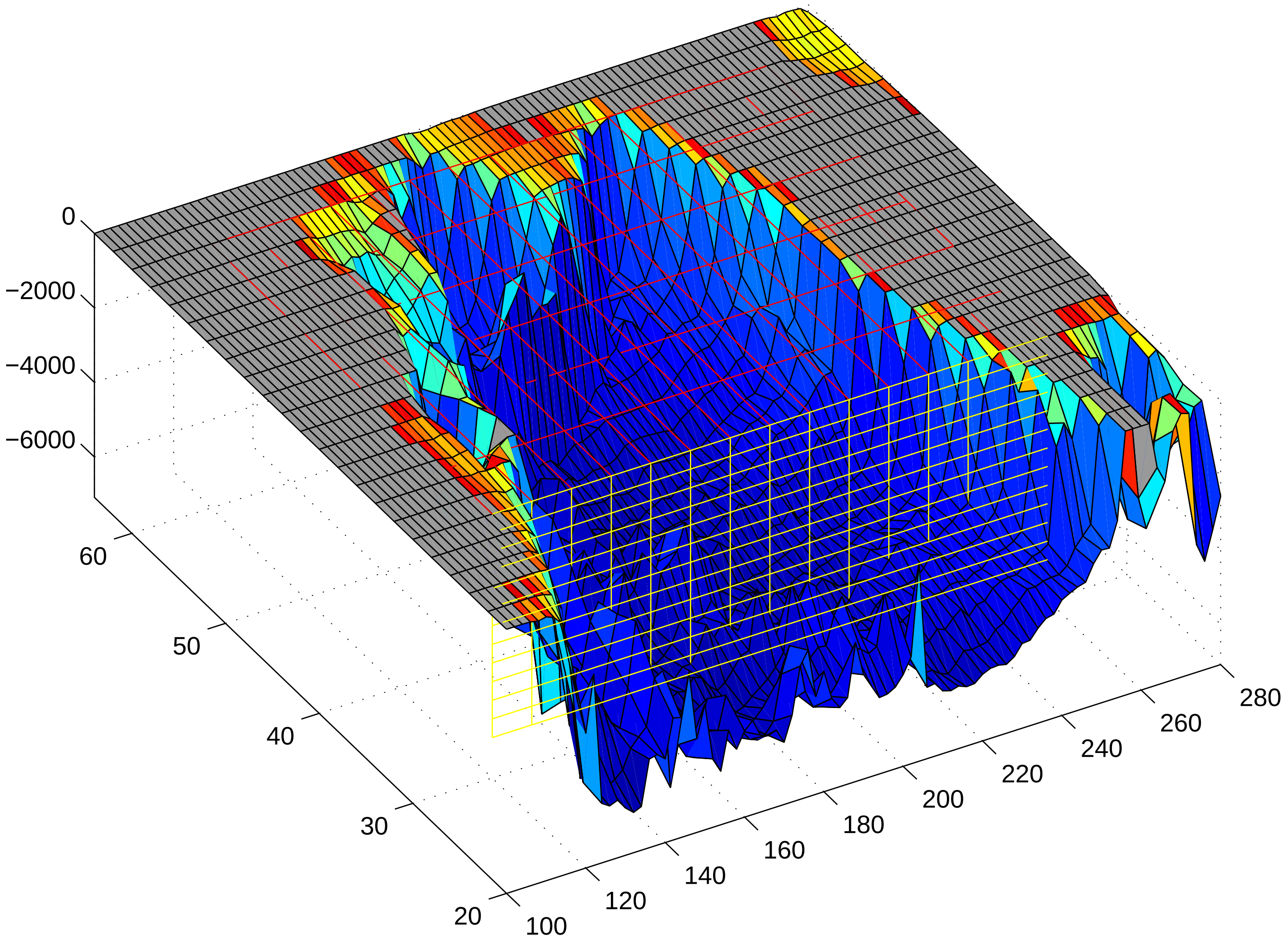
1 ➔ good approx global and annual average
2 ➔ good approx some places for timescales ≤ seasonal
3 ➔ good approx annual average

What determines Q(x,y)?
Need to consider both atmosphere dynamics and global oceanic velocity and temperature field.

$$H = \int_{\mathrm{all}} c_p \rho \theta \vec{u} \cdot \vec{n} dA$$

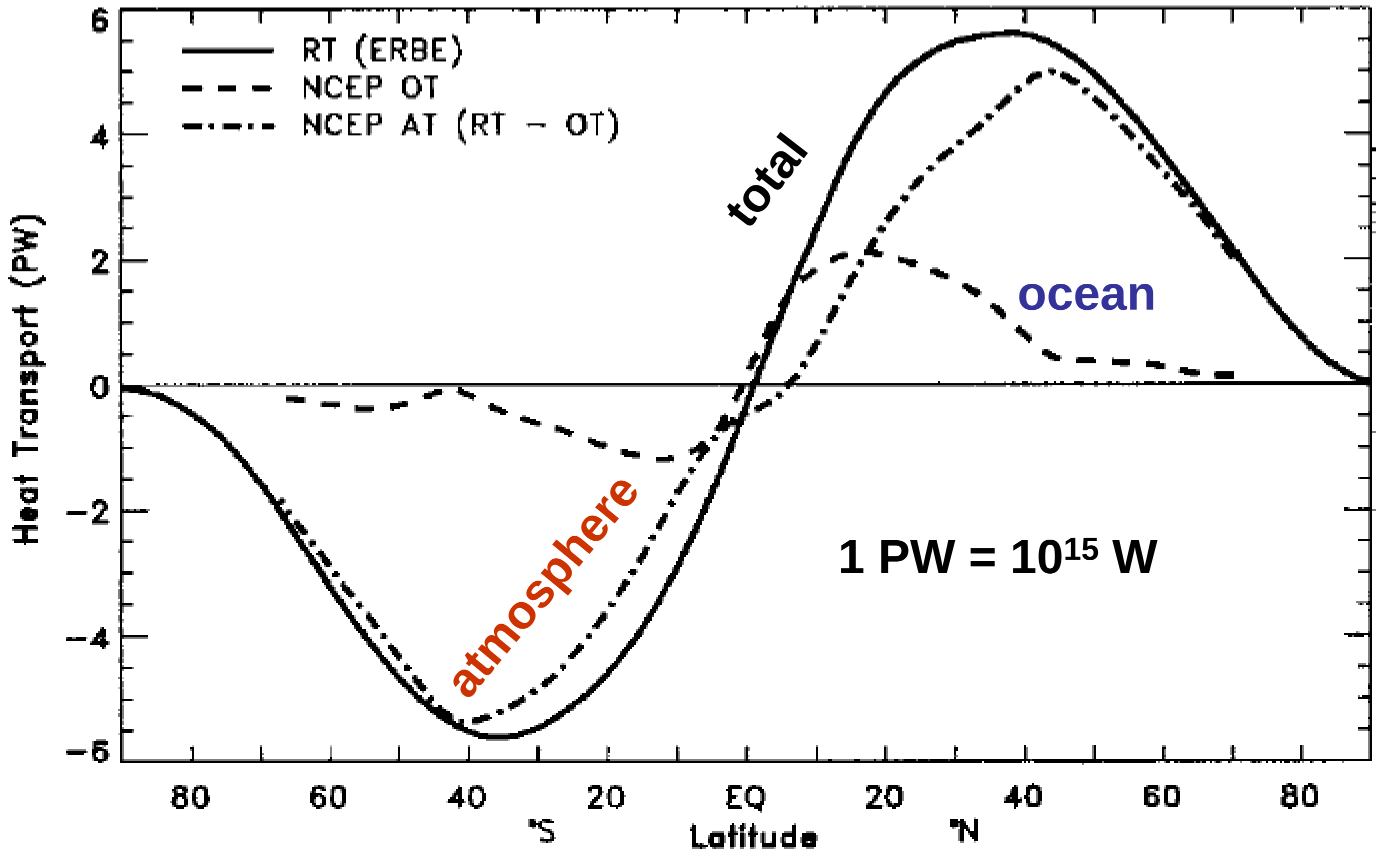
Similar expressions exist for transport of salt and other tracers.

When calculating *H*, we often choose domain so that most of the lateral boundaries are "walls", except for a 1 or 2 zonal sections (as shown). u●n = 0 on bottom, and if we can neglect u●n through the top, *H* is simply meridional heat transport.

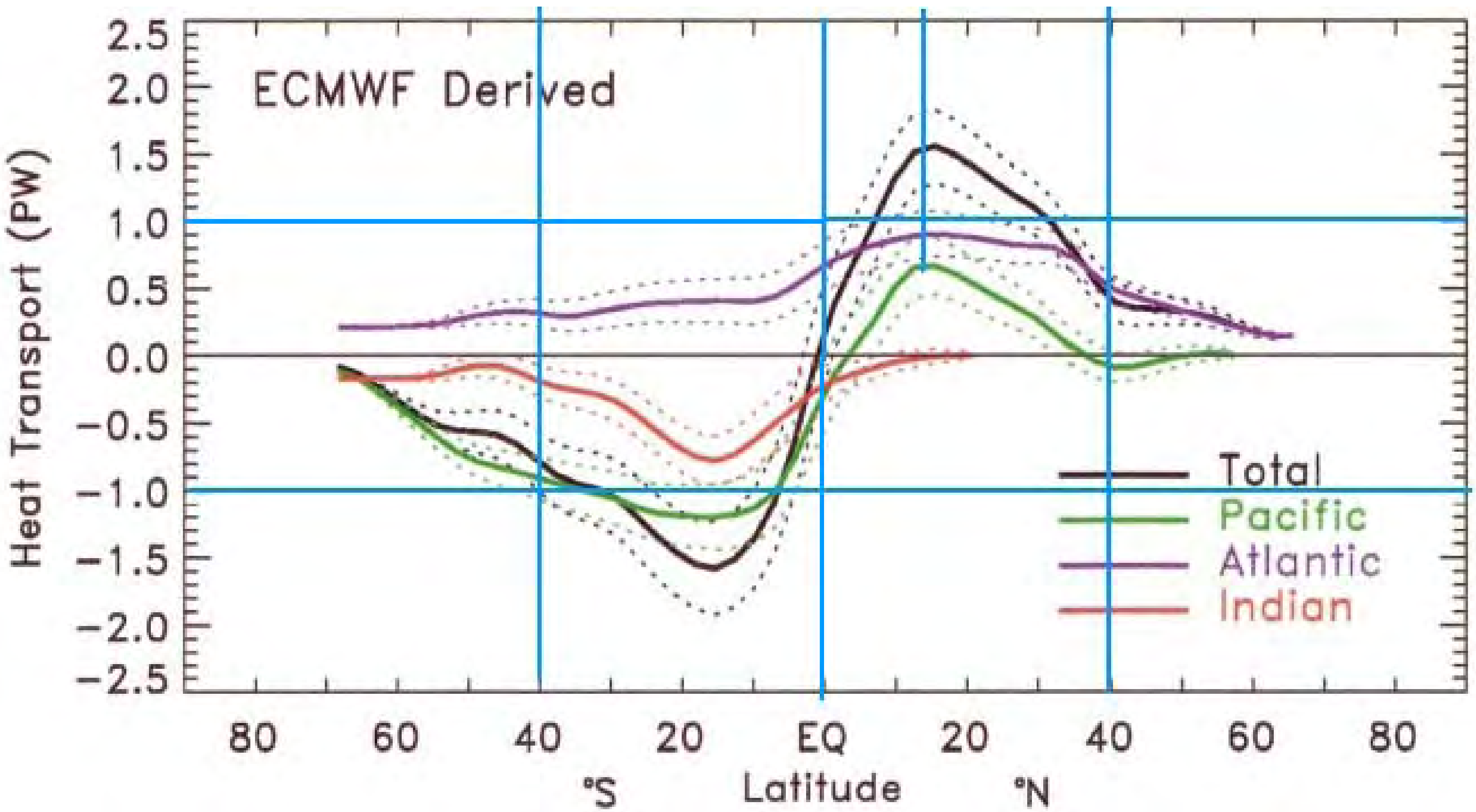


Ocean and Atmospheric Meridional Heat Transport

Ocean clearly important in tropics
Latest observations ➔ smaller ocean role at high latitudes
(still significant uncertainties)



Trenbirth and Caron, 2001: J Clim, 3433-3443



Trenberth & Caron (2001)

Rules for Density

1) Density hardly changes

   $\rho \approx 1000\ kg/m^3 = 1\ gm/cm^3$ everywhere in ocean

2) Density increases with S:

   At T=0 and p=0,

   $\rho(S=0) = 999.8$, $\rho(S=35)=1028.1$

3) Density increases with p:

   At S = 35 psu, T = 0 C, p = 4000 dbar, $\rho = 1046.4$

4) Density decreases with T

5) Rate of change w.r.t. T depends on T,p

   $|d\rho/dT|$ smaller if water is **colder** or **deeper**

6) In ocean, variations due to p are greatest, **but** variations due to T & S more important:

   u responds to **horizontal** ρ variations (indep of p)

Equation of State

Accurate formula for $\rho(T,S,p)$ can be found in Gill (1982)

Rough approximation:

$$\rho = 999.83 + C(p) + \beta(p)S - \alpha(T,p)T - \gamma(T,p)(35-S)T$$

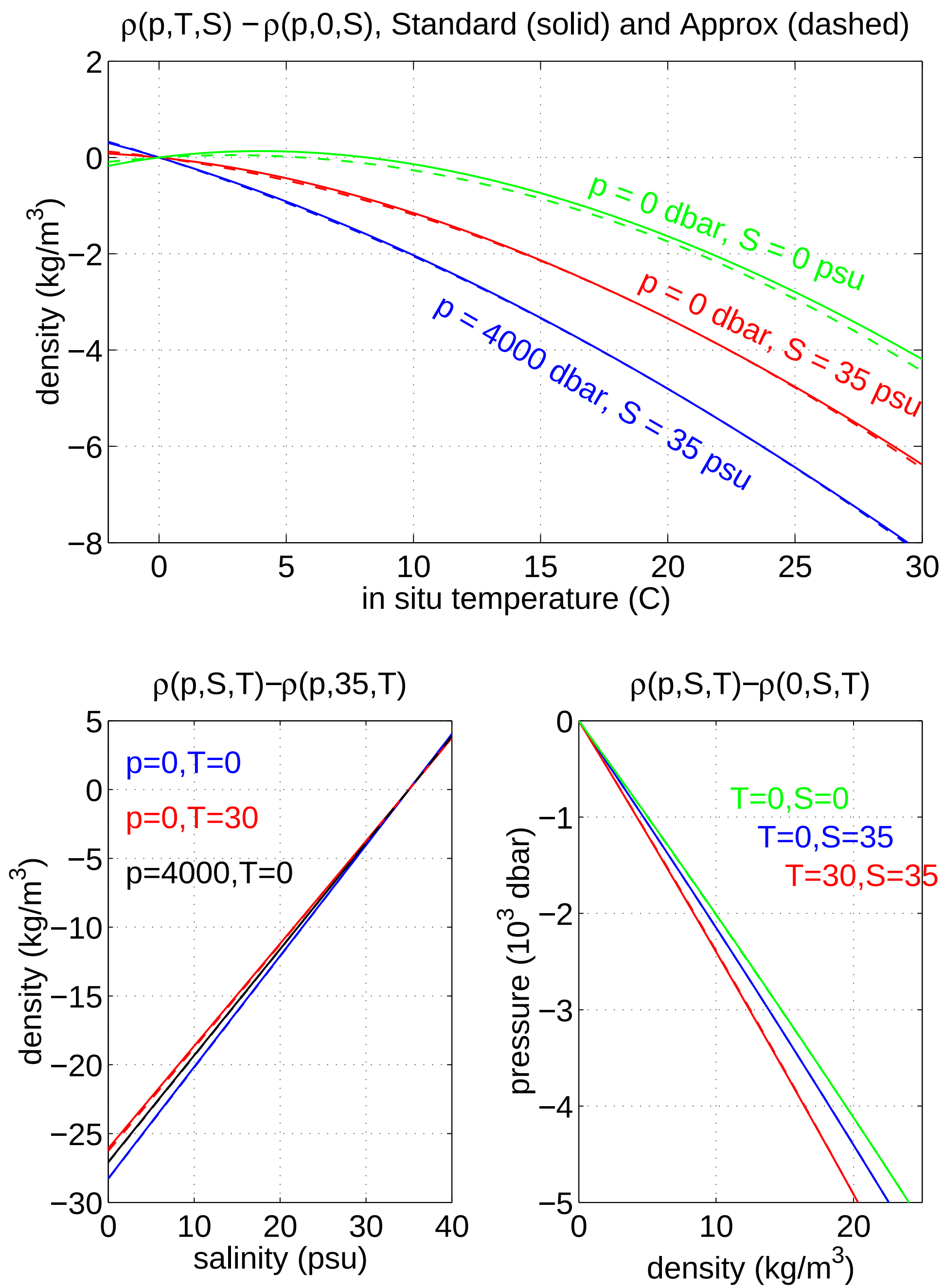
Where

$C \approx 5.05(p/1000\ \text{dbar})\ \text{kg/m}^3$

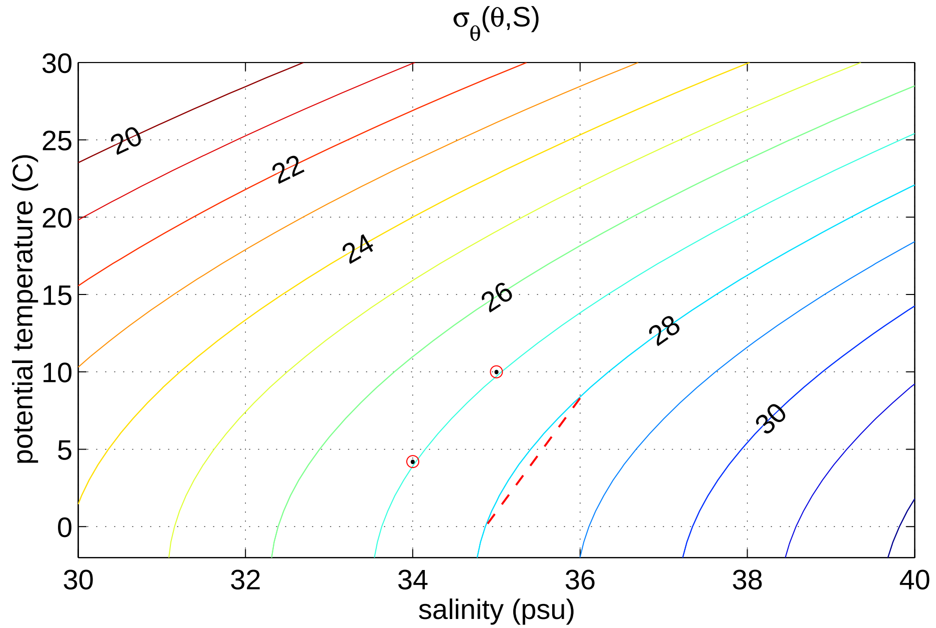
$\beta \approx .8\ \text{kg m}^{-3}\ \text{psu}^{-1}$

$\alpha \approx .071[1+.351(p/1000\ \text{dbar}) + (.068\ \text{C}^{-1})T]\ \text{kg/m}^3$

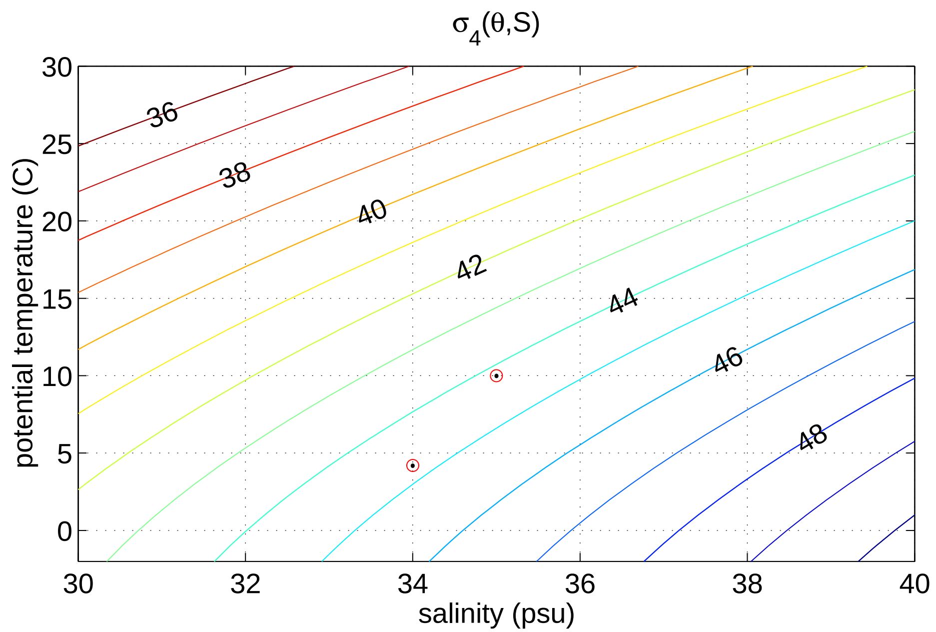
$\gamma \approx .003\ \text{kg m}^{-3}\ \text{psu}^{-1}\ \text{C}^{-1}$



ρ(p,T,S) − ρ(p,0,S), Standard (solid) and Approx (dashed)
density (kg/m3)
in situ temperature (C)
p = 0 dbar, S = 0 psu
p = 0 dbar, S = 35 psu
p = 4000 dbar, S = 35 psu
ρ(p,S,T)−ρ(p,35,T)
p=0,T=0
p=0,T=30
p=4000,T=0
salinity (psu)
ρ(p,S,T)−ρ(0,S,T)
pressure (103 dbar)
T=0,S=0
T=0,S=35
T=30,S=35



$\sigma_\theta(\theta,S)$
potential temperature (C)
salinity (psu)
20
22
24
26
28
30



$\sigma_4(\theta,S)$
potential temperature (C)
salinity (psu)
36
38
40
42
44
46
48

Potential Density and Some Nomenclature

If water has given θ, S, and p,
its **potential density** = $\rho(T=\theta,S,p=0)$.
This is a way to filter out uninteresting dependence on p.

Because density is always about 1000, useful to define
"sigma-t": $\sigma_t = \rho(T,S,0) - 1000$
"sigma-theta": $\sigma_\theta = \rho(\theta,S,0) - 1000$
Can define with reference to other depths, such as

$$\sigma_1 = \rho(\theta,S,1000\text{ dbar}) - 1000$$

Net Annual-Average Heat Flux into Ocean

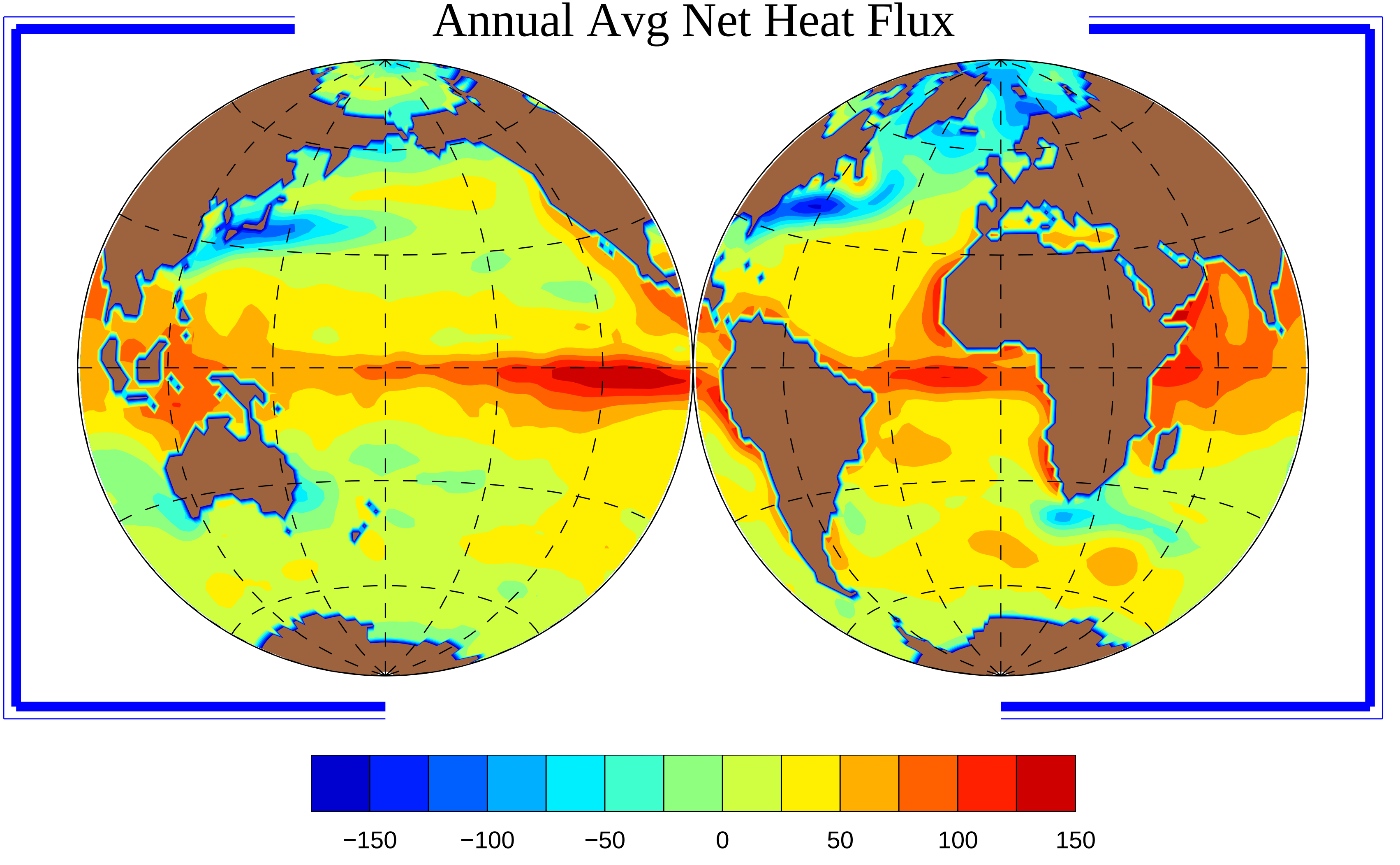
General pattern:

- absorbs heat near equator, loses heat at high latitudes
  - (as expected)
- Sea's heat transport comparable to atmosphere:
  - Significant role in moderating meridional T gradient
  - Indicates importance of ocean circulation.
- Typical values O(50 W/m^2)

Some interesting details:

- heat gain largely in east, heat loss in west
- Pacific heat gain especially big
- Atlantic heat loss especially big

Annual Avg Net Heat Flux



Evaporation/Precipitation Patterns

Evap. minus Precip (and runoff) drives S variations

No (significant) salt fluxes through surface,

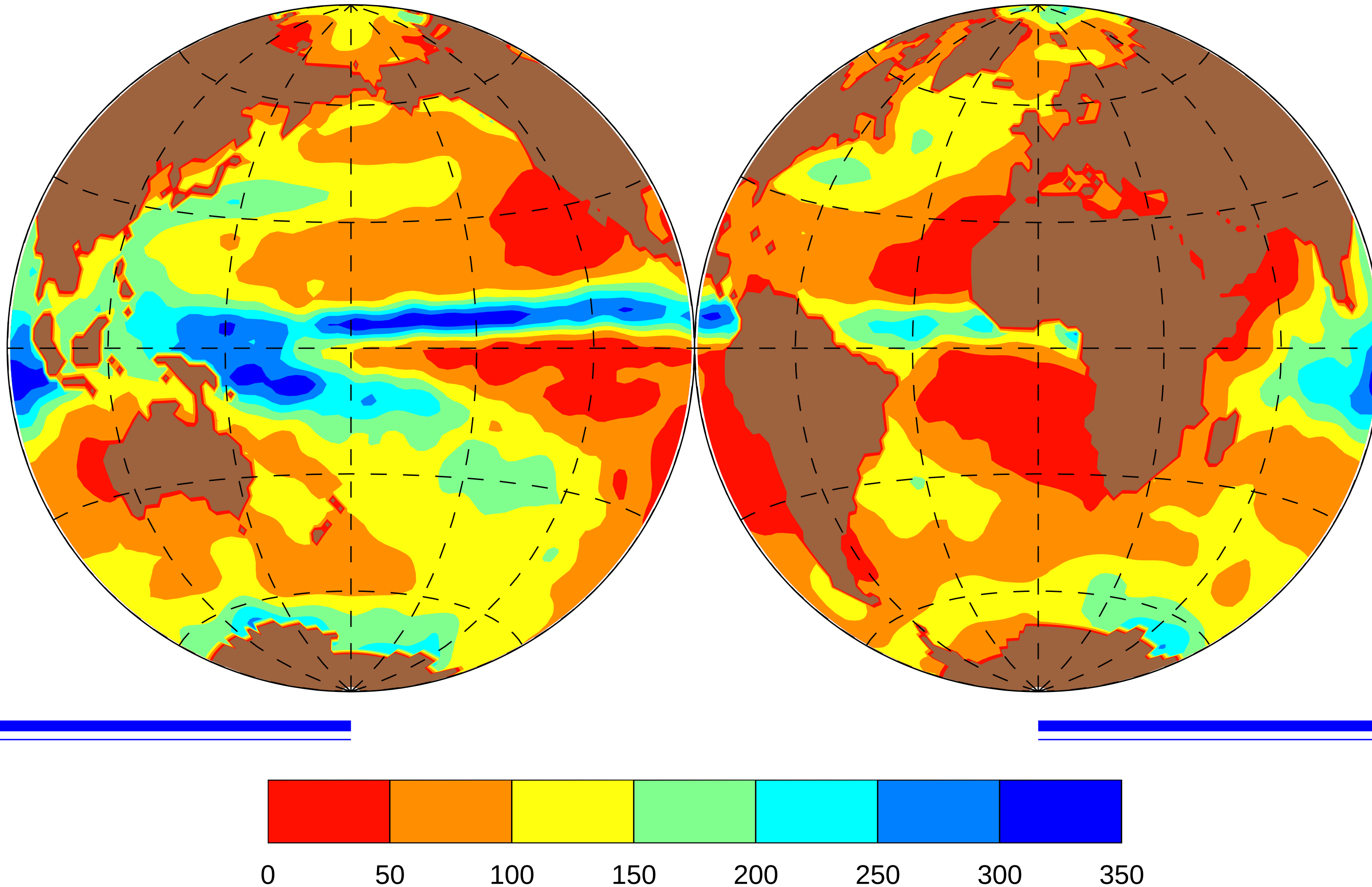
But freshwater fluxes can increase/decrease S dilution.

General pattern:

- Net precip in tropics and high latitudes
- Net evap in subtropics

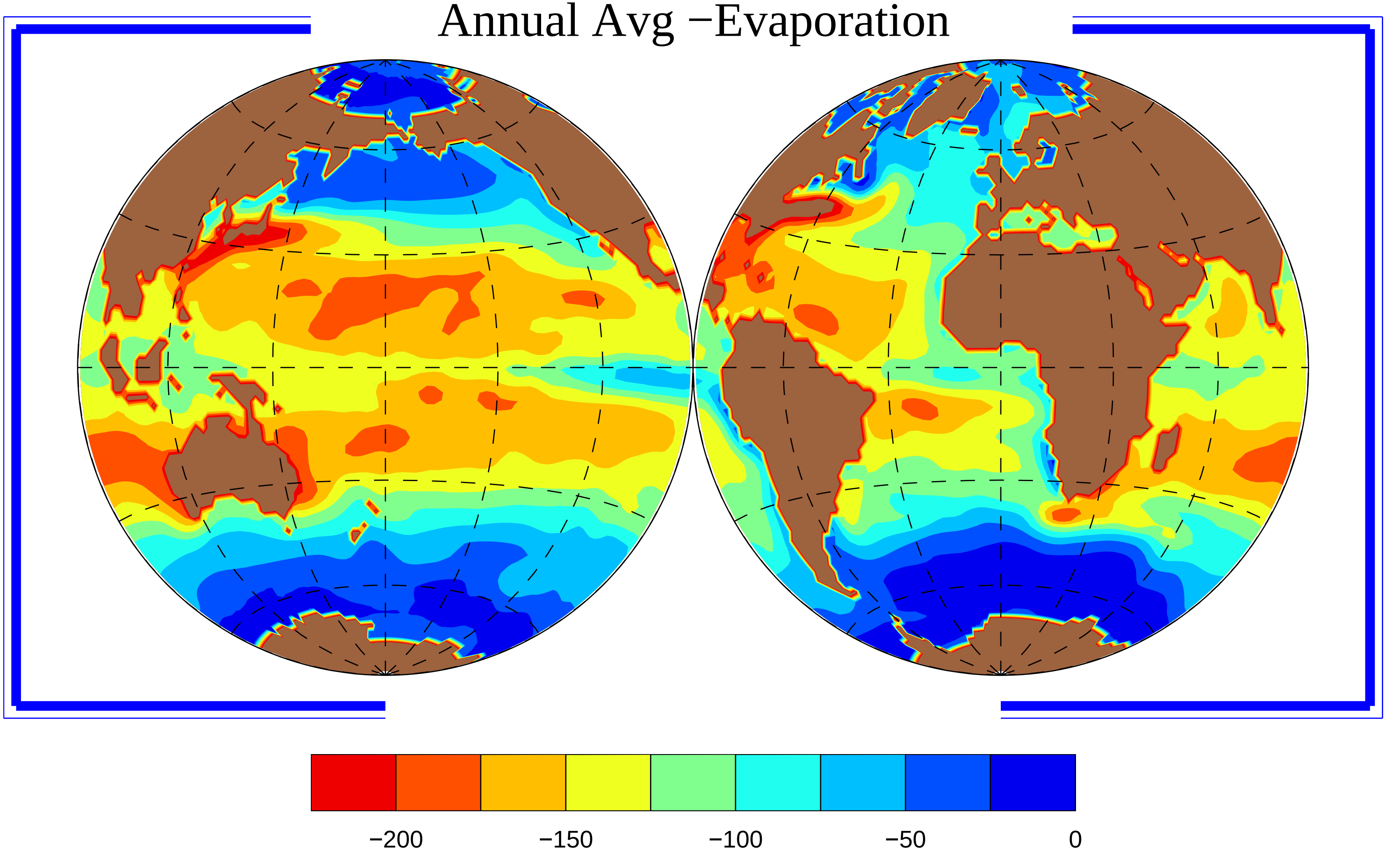
Typical values Order(1 m/yr)

Annual Avg Precipitation



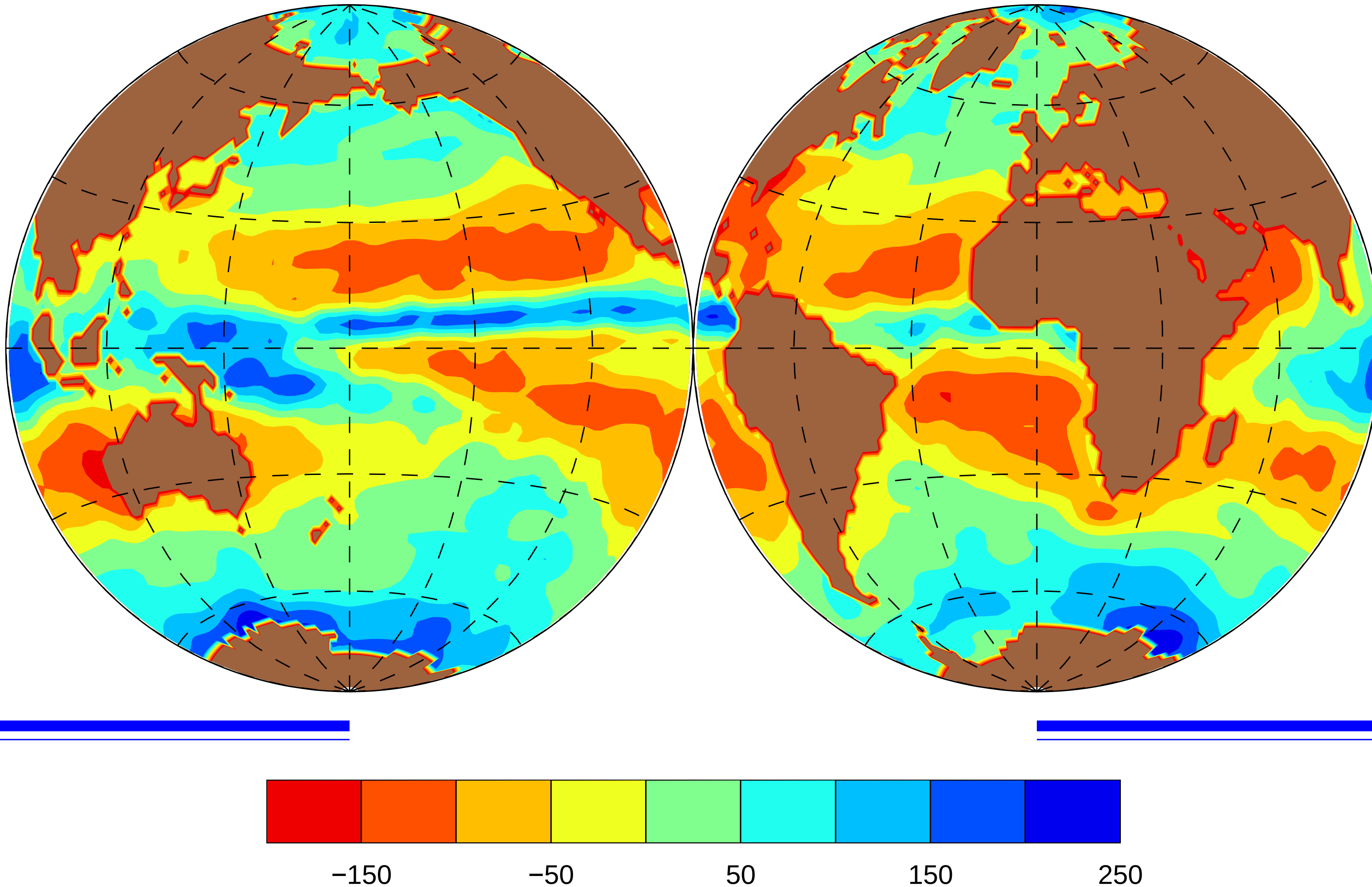
from COADS, cm/yr

Annual Avg −Evaporation



from COADS, cm/yr

Annual Avg P−E



from COADS, cm/yr

Surface Property Distributions

Temperature: general pattern as would be expected

warm in tropics, cold at high latitudes

up to about 6 C winter-summer difference

SST lags land temperature

Salinity: general pattern follows forcing

high values in subtropical evaporation regions

low values in tropics and high latitudes

some regional extreme values

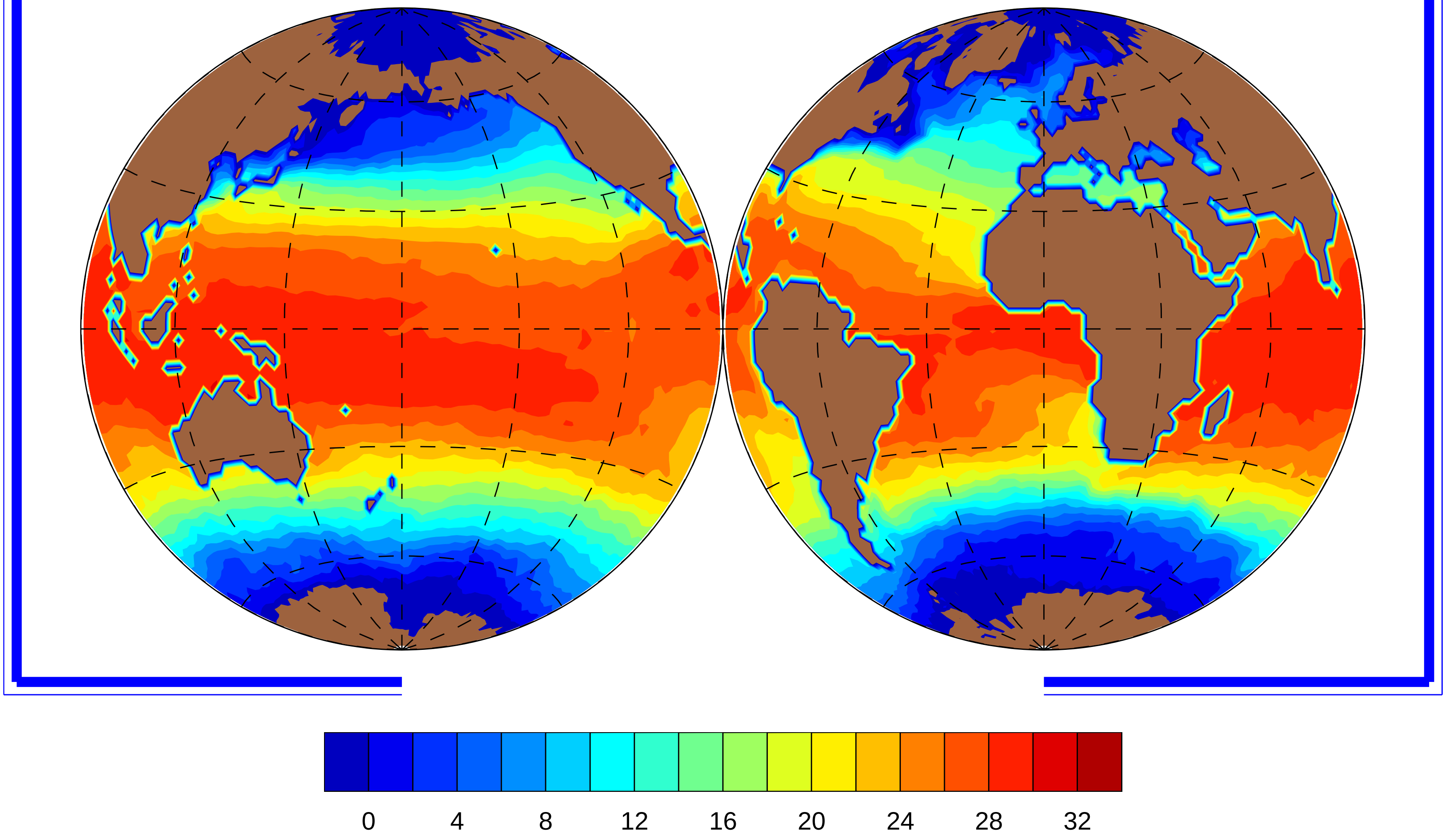
Density: dominated by T variations

2-D patterns: zonal and inter-basin differences

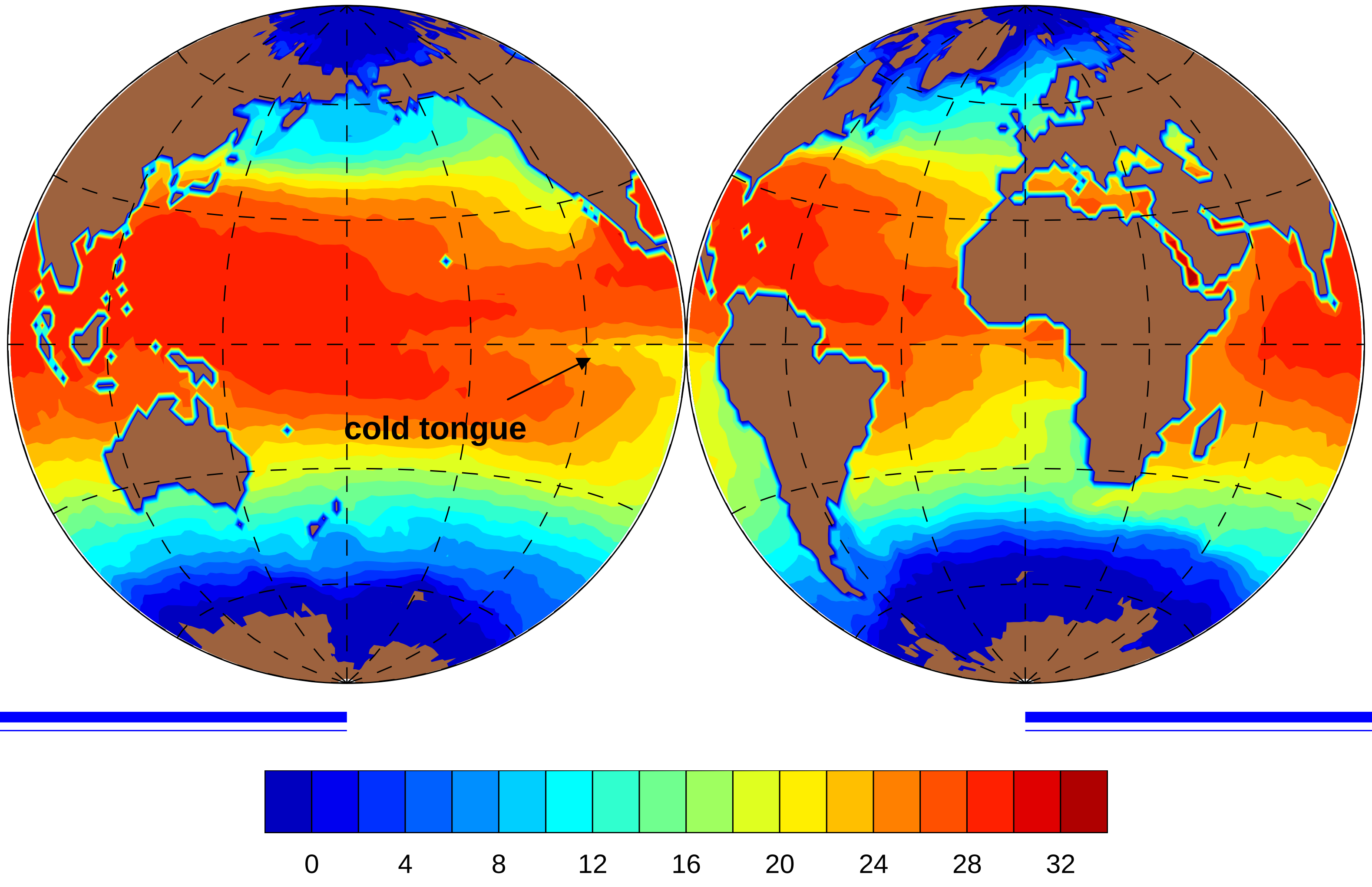
indications of effects of ocean currents?a

T and S data from Levitus *et al.* (1994), *World Ocean Atlas*

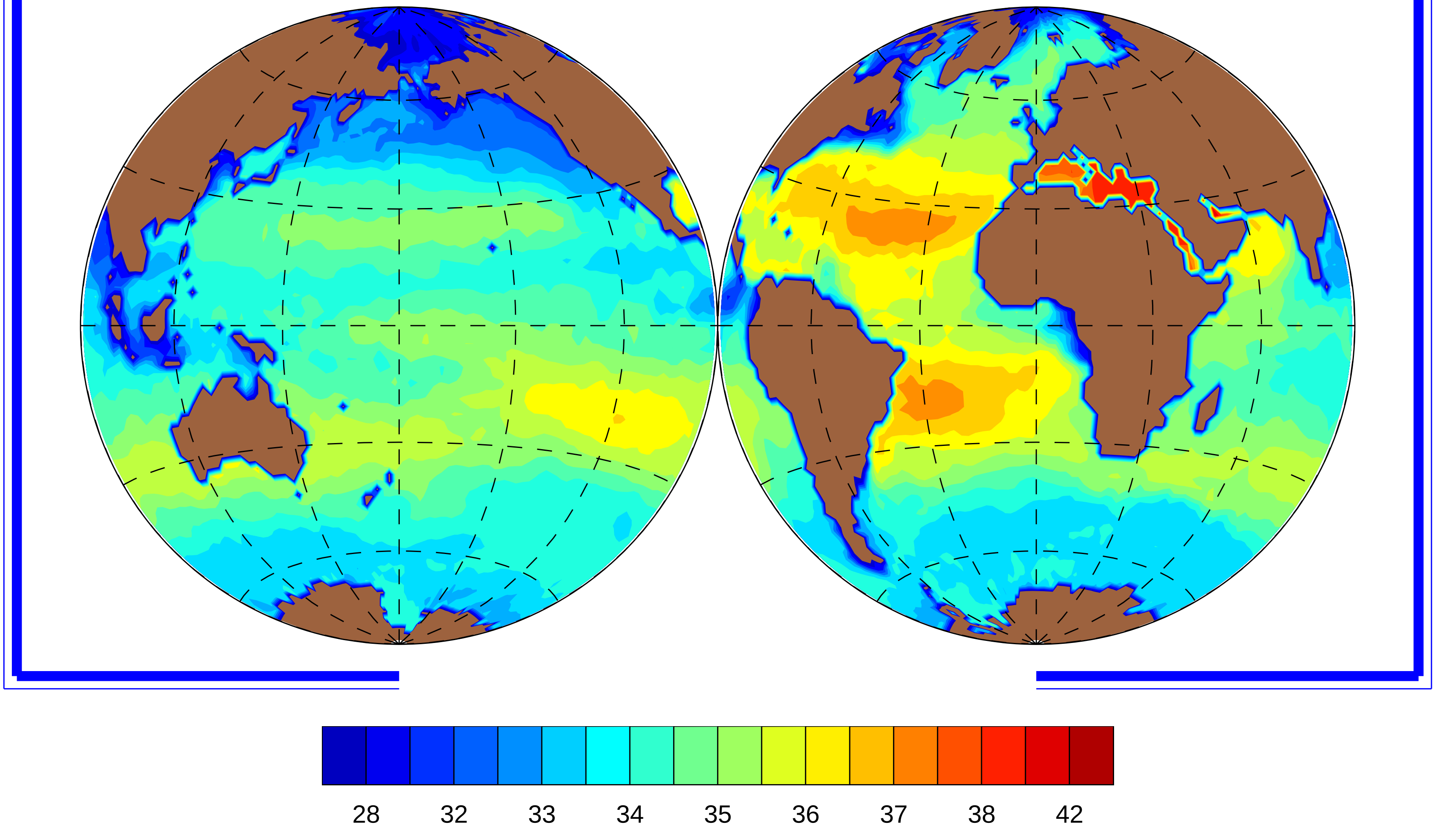
Mar SST



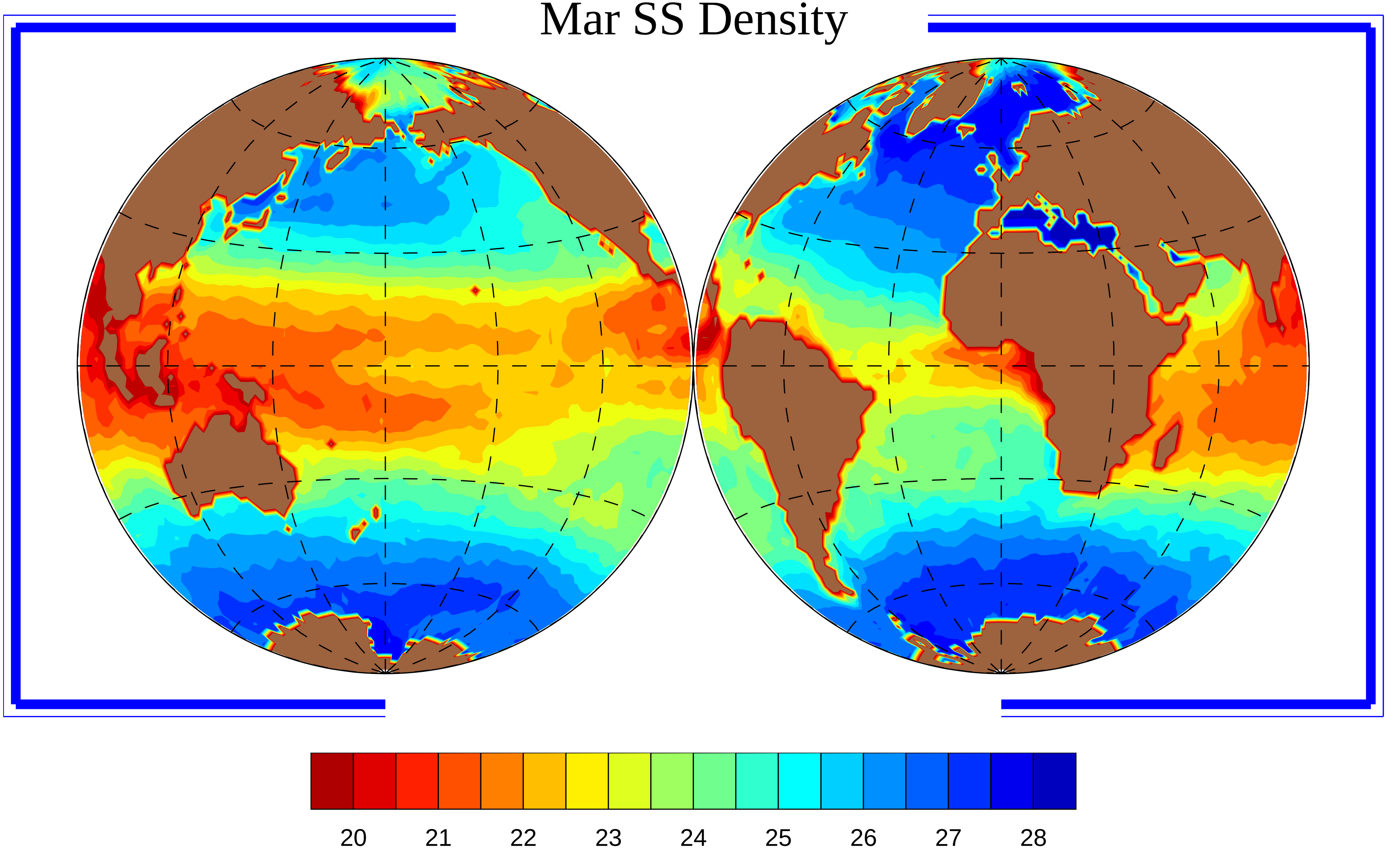
Sep SST



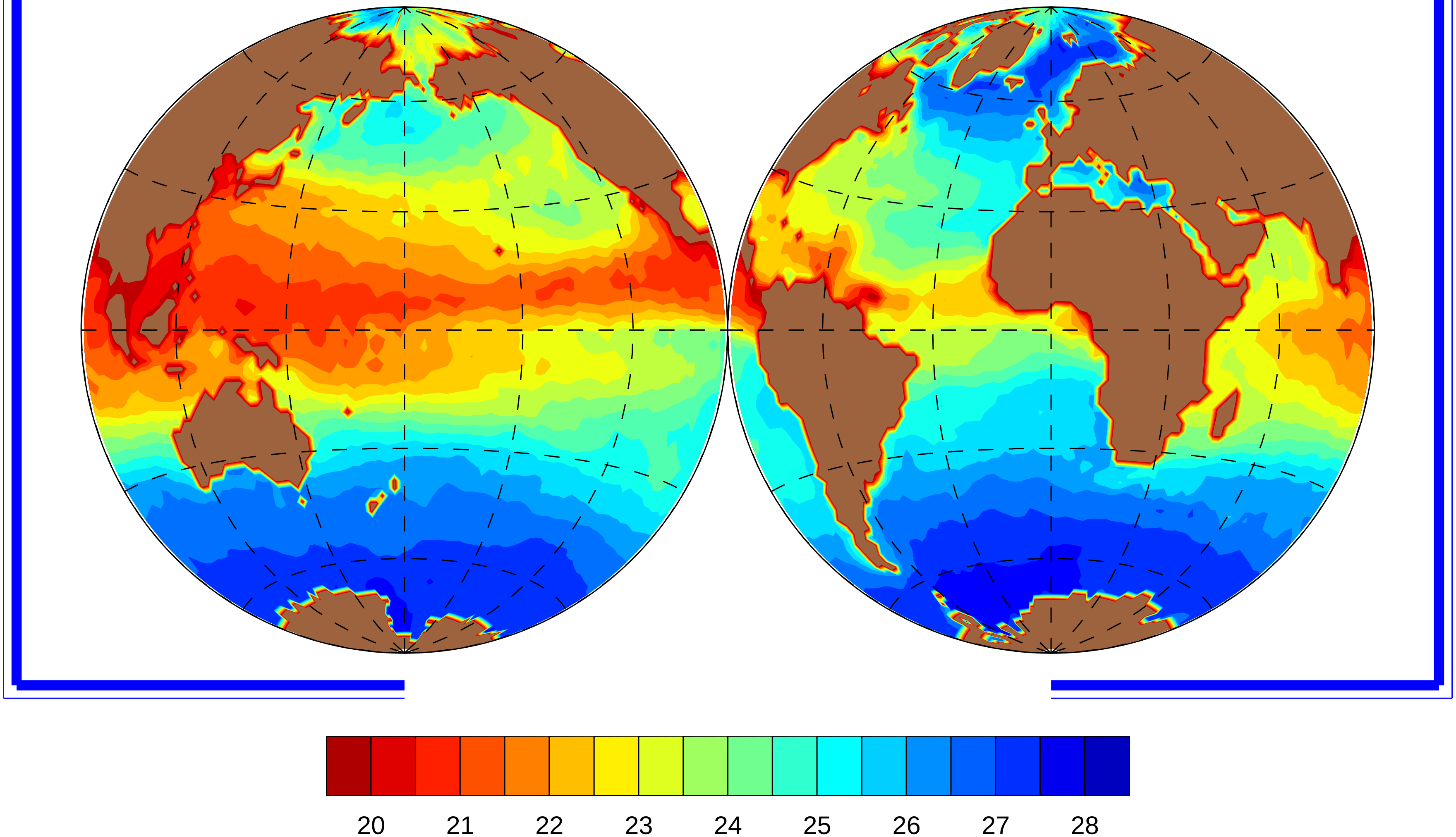
Mar SSS



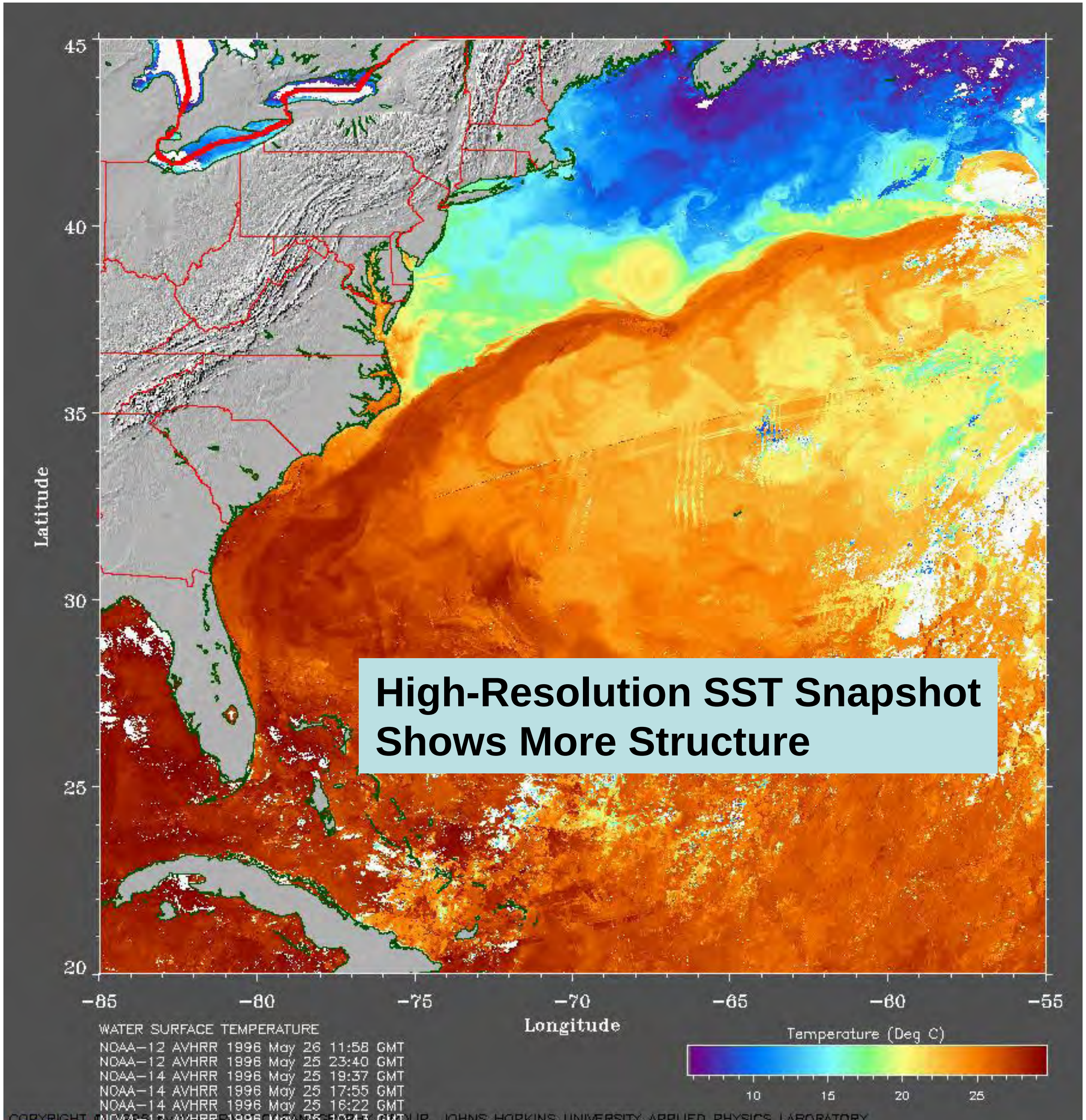
Mar SS Density

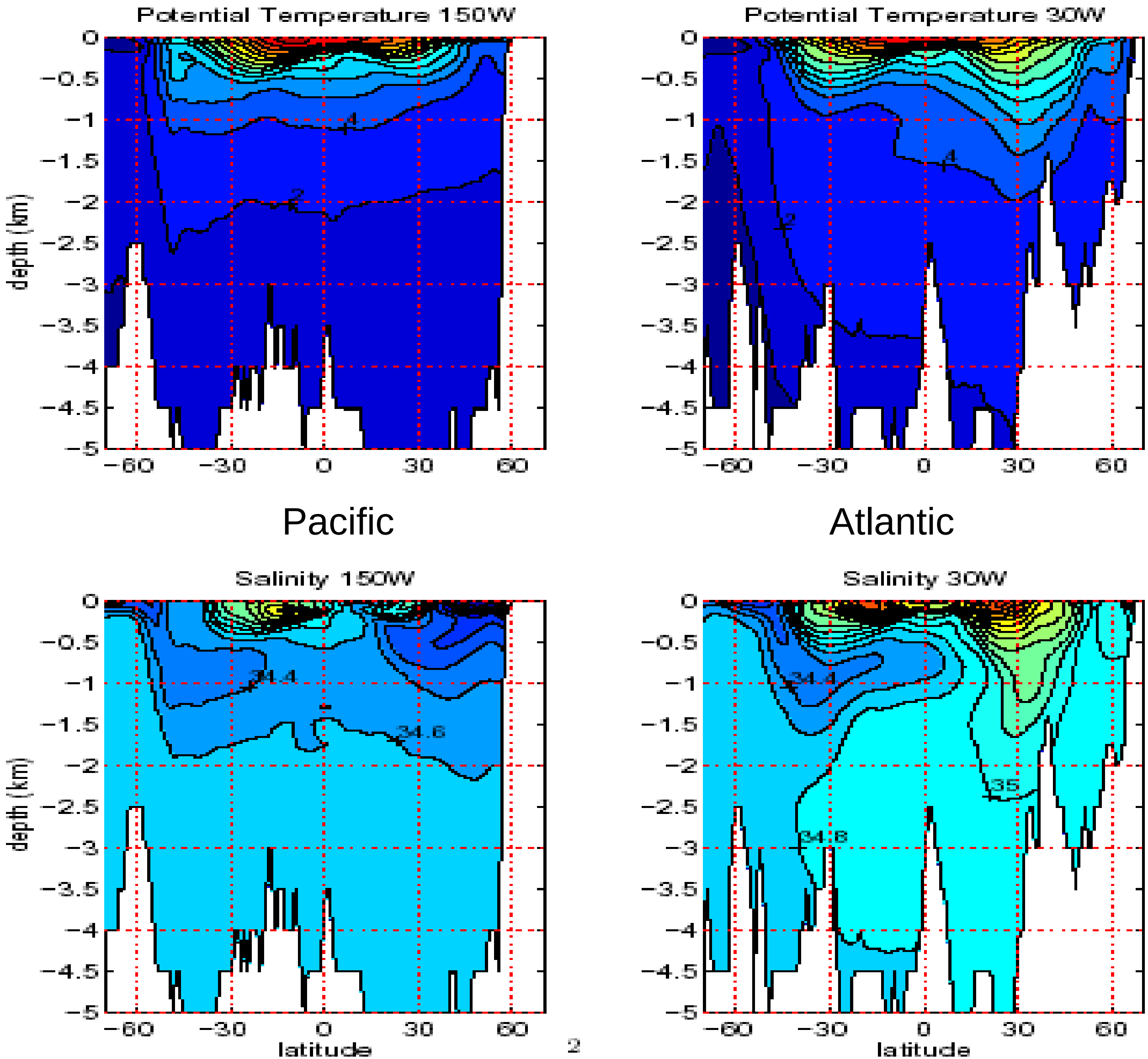


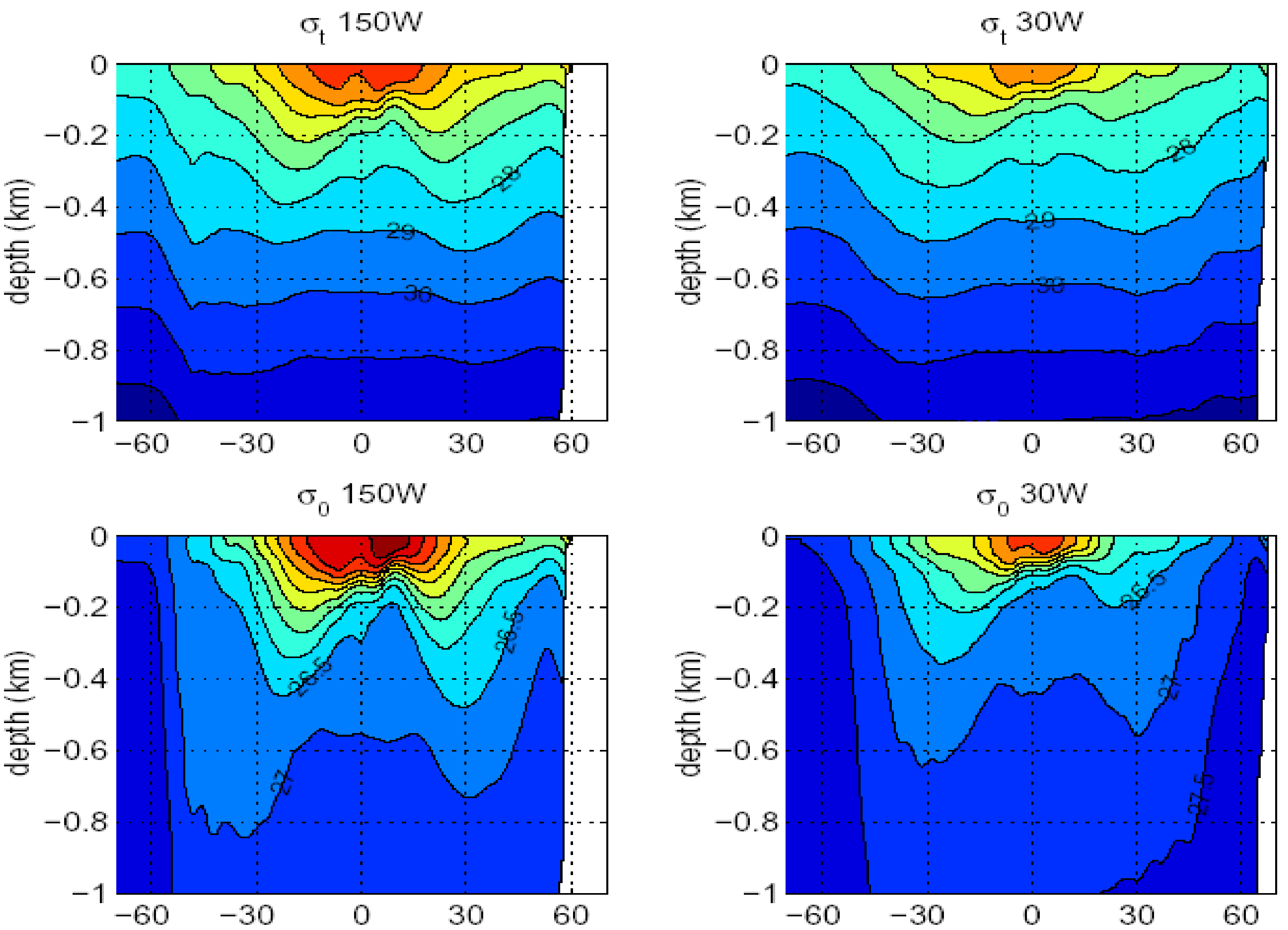
Sep SS Density



High-Resolution SST Snapshot Shows More Structure




Potential Temperature 150W
Potential Temperature 30W
Pacific
Atlantic
Salinity 150W
Salinity 30W
depth (km)
latitude
0
−0.5
−1
−1.5
−2
−2.5
−3
−3.5
−4
−4.5
−5
−60
−30
0
30
60
4
2
34.4
34.6
35



σ_t 150W
σ_t 30W
σ_0 150W
σ_0 30W
depth (km)
0
−0.2
−0.4
−0.6
−0.8
−1
−60
−30
0
30
60
28
29
30
26.5
27
27.5

Meridional-Depth Profiles

Warm tropical water is just a thin layer at top of ocean

- most of ocean is < 5 C
- warm layer has “double bowl” shape
- structure very similar in Atlantic and Pacific

Salinity has more complicated structure

- subsurface “tongues” of fresh water
  - create minima and maxima in S(z) in places
  - indications of deep flow?

T and S data from Levitus *et al.* (1994), *World Ocean Atlas* (meridional sections)
And *World Ocean Atlas (2001)* (global sea surface properties)

Surface Mixed Layer

Top of ocean relatively homogenous: “mixed layer”

Mixed layer grows thicker via:
• wind stirring
• convection due to cooling/salinification

Mixed layer grows thinner via:
• solar heating
• desalinification (precipitation)

Hence ML depth varies greatly in space/time
    10 – 1000 m depth
Shallower at low latitudes, daytime, summer
Deeper at high latitudes, night, winter

Strong Seasonal Variation of Mixed Layer Depth

- Shallowest at the end of the summer due to long exposure to solar heating and little wind stirring.

- Storminess and cooling during autumn and winter deepen the mixed layer.

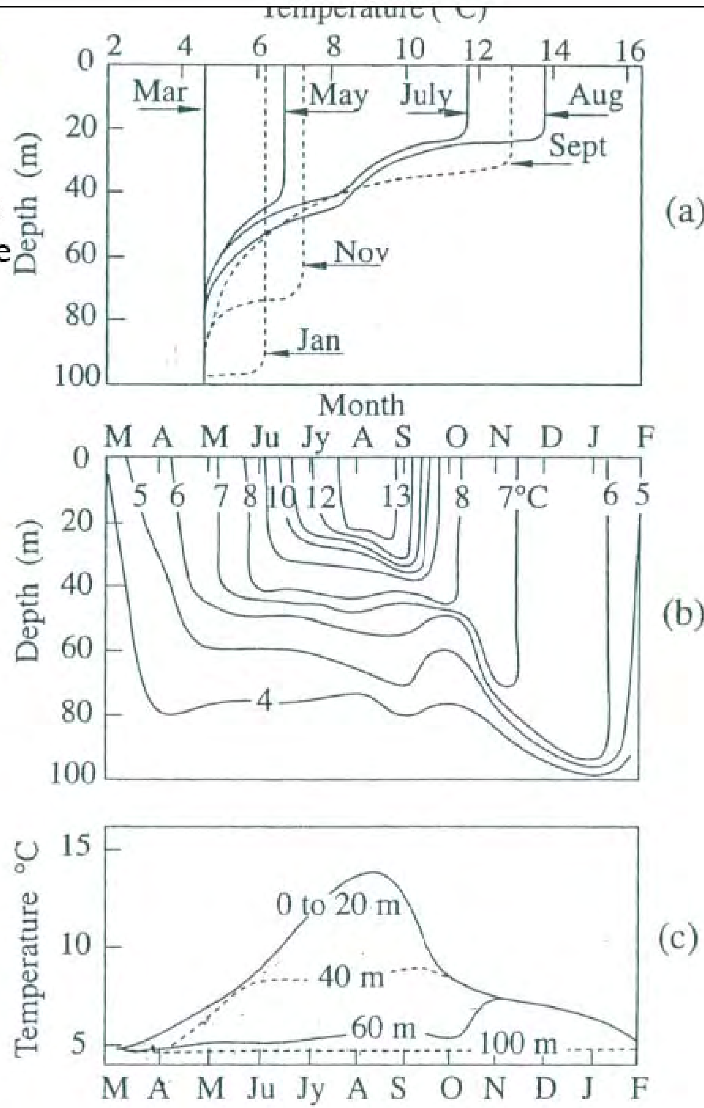


Fig. 7.6 Seasonal variation of temperature in the upper ocean at 50°N, 145°W in the eastern north Pacific. (a) Vertical profiles of temperature by months, (b) temperature contours, and (c) temperatures at various depths versus time of year. [From Pickard and Emery (1990). Reprinted with permission from Pergamon Press Ltd., Oxford, England.]

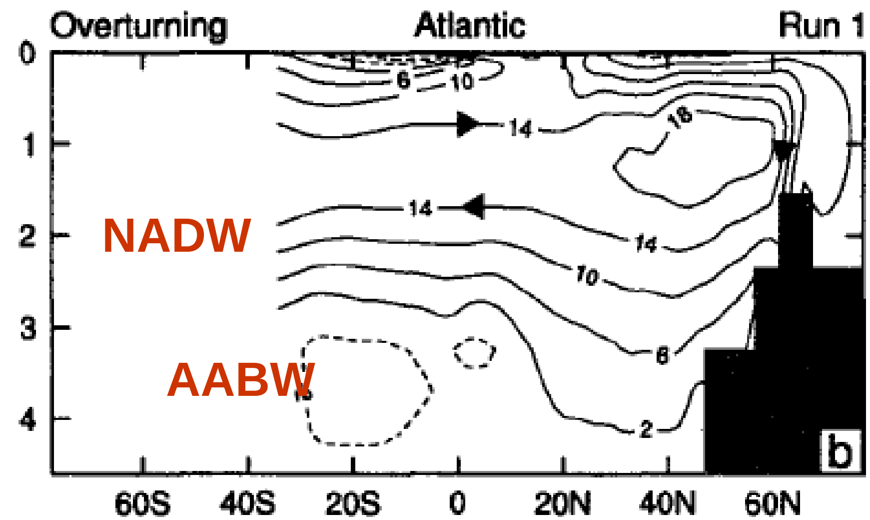
Oceanic Overturning Circulation(s)

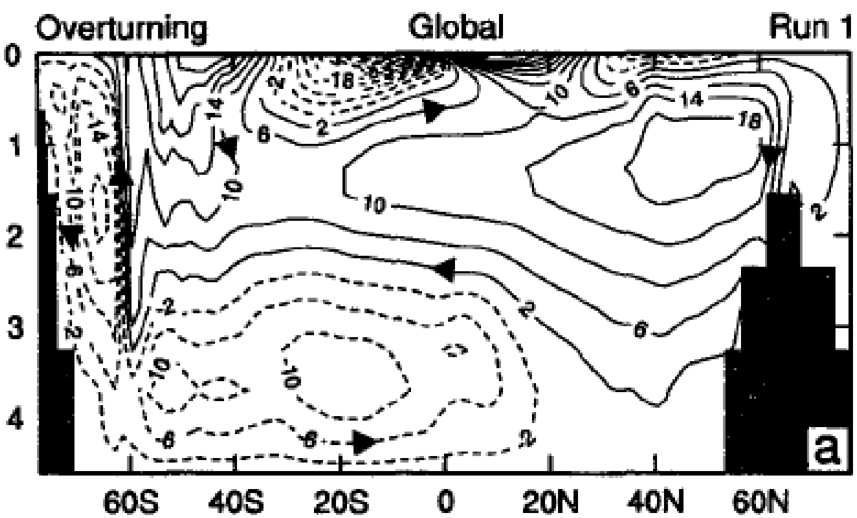
Sub-Tropical Cells

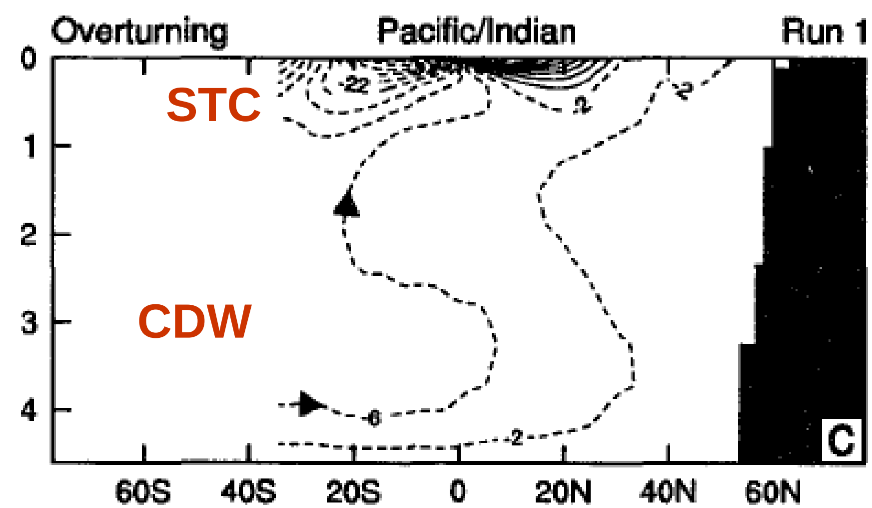
North Atlantic Deep Water

Antarctic Bottom Water

Circumpolar Deep Water







Near-global ocean model, Hirst *et al.* (1996, *JPO*)

How do we know the DMOC exists?

Tracers hint at deep flows in Atlantic:

Relatively salty North Atlantic Deep Water (NADW) moves southward at 2 – 4 km depth

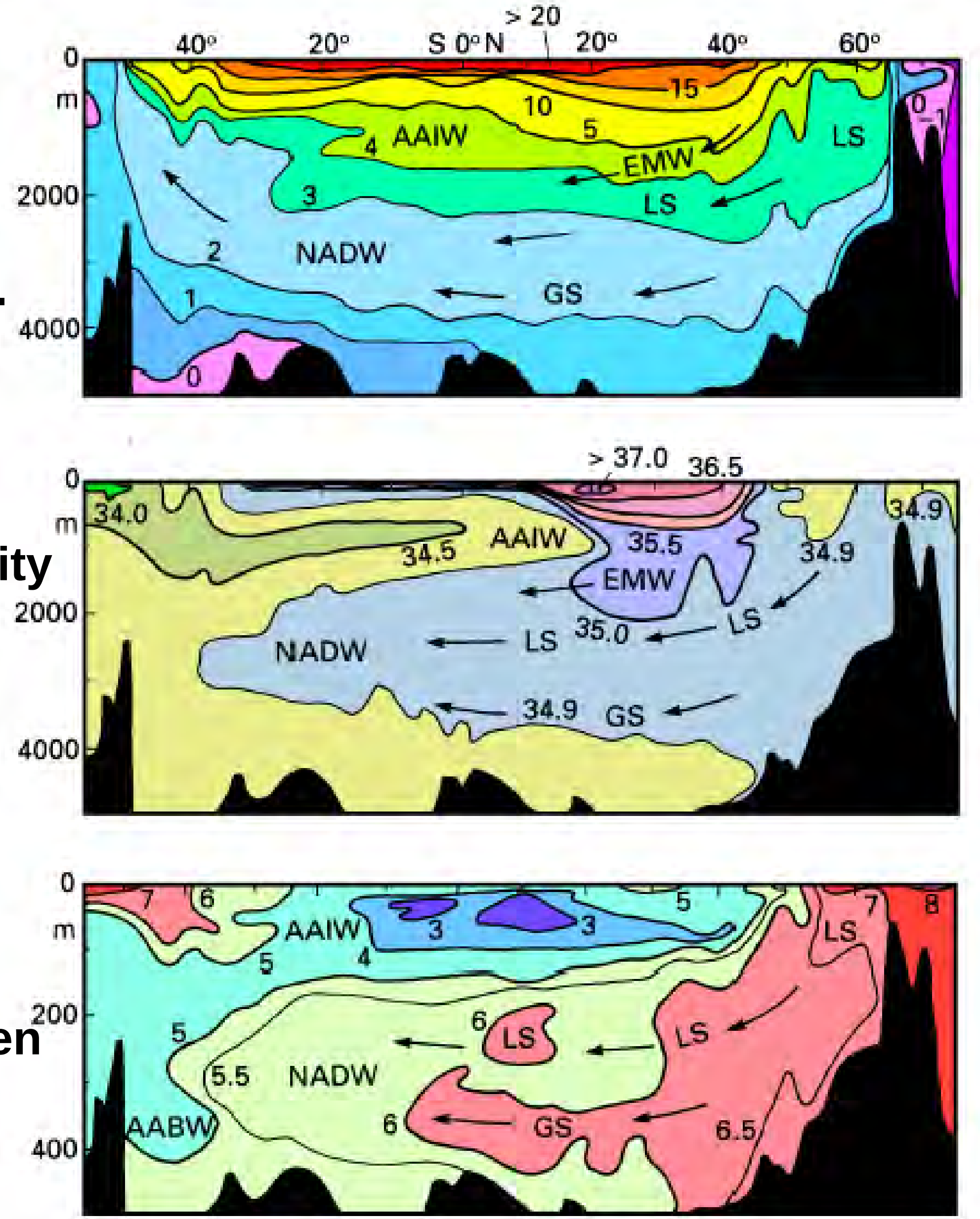
Relatively fresh Antarctic Bottom Water (AABW) moves northward near bottom

Relatively fresh Antarctic Intermediate Water (AAIW) moves northward at about 1 km depth.

Pot. Temp.

Salinity

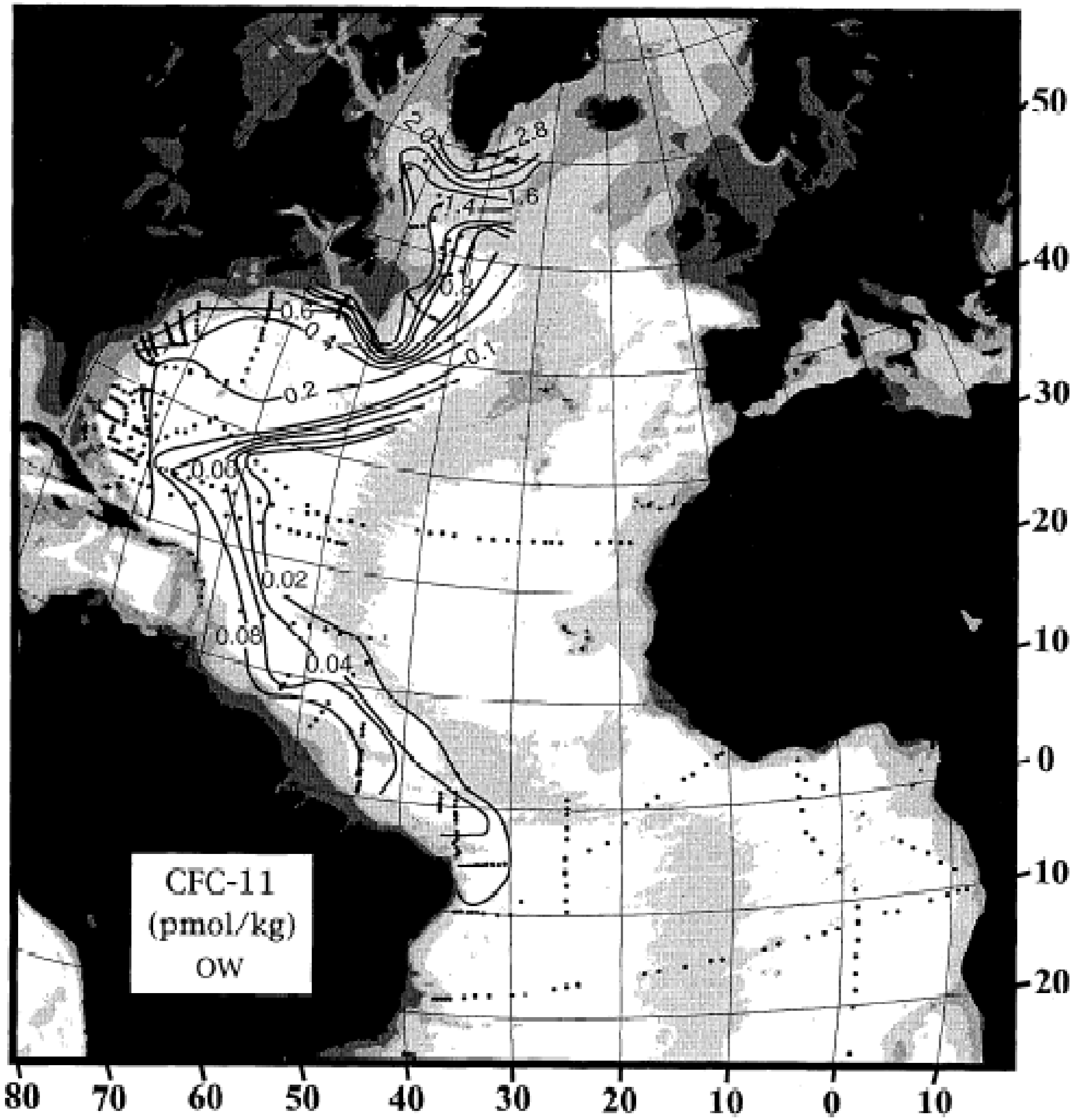
Oxygen



Tomczak and Godfrey, *Regional Oceanography*, ch 15, after Bainbridge (1980)

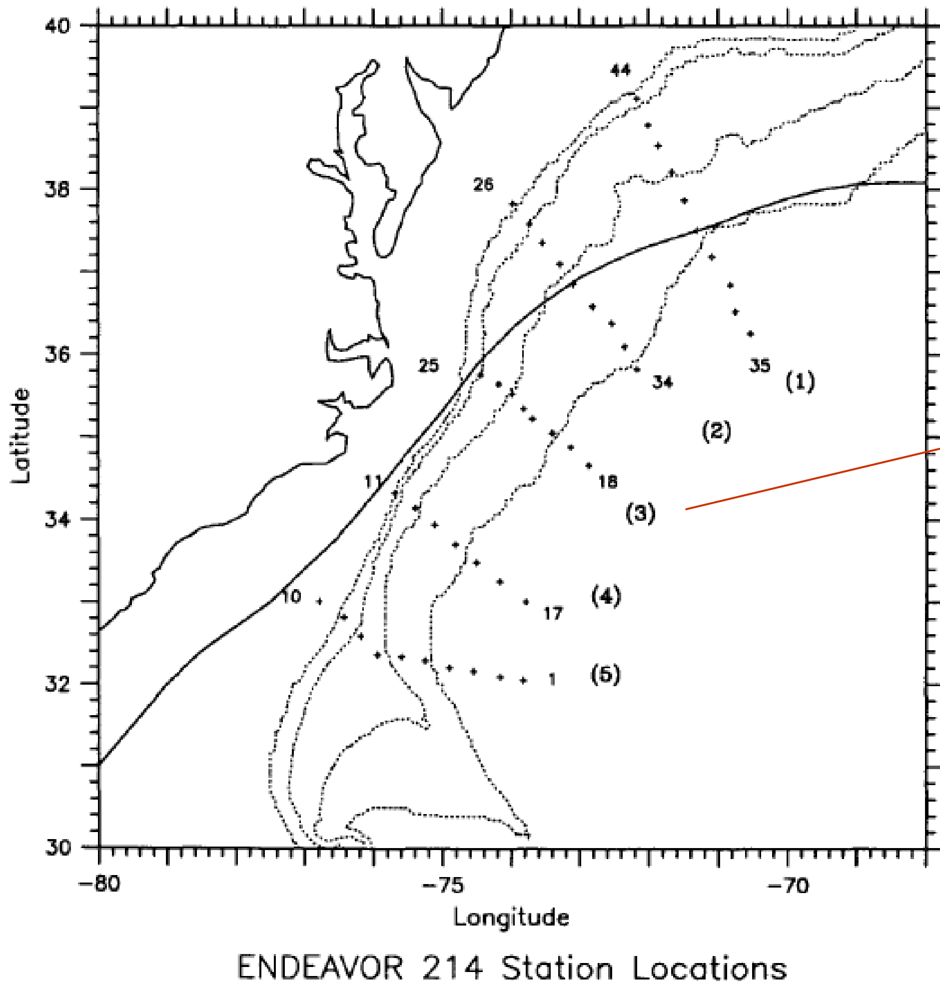
More tracer Evidence

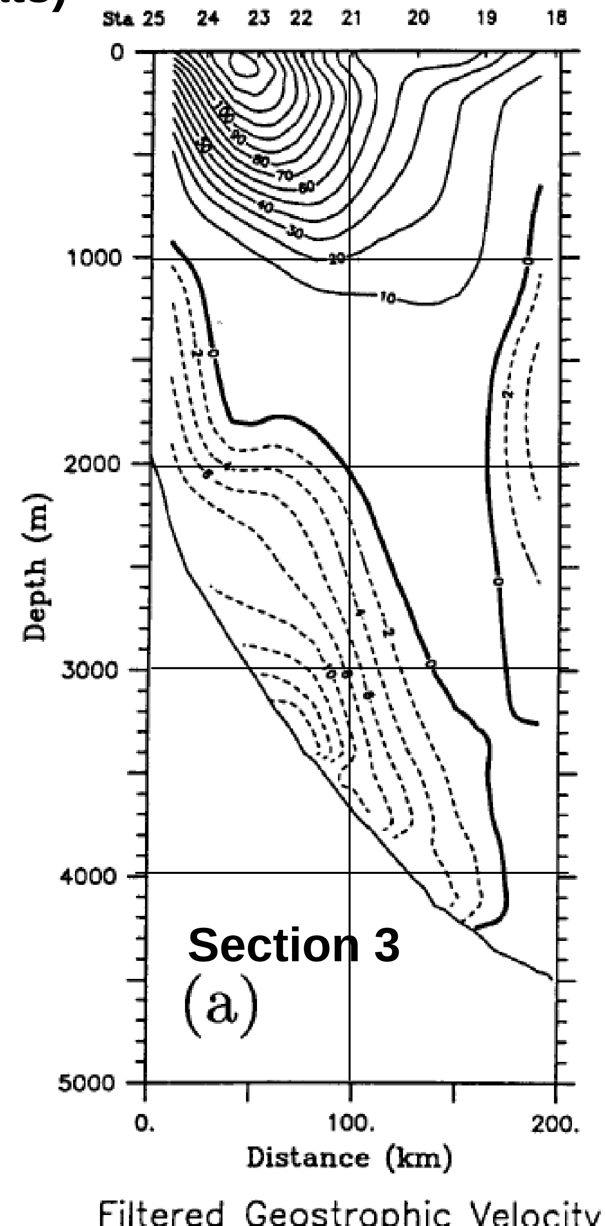
(freons from Atmosphere Since 1940s)



Smethie *et al.* (2000, *JGR*)

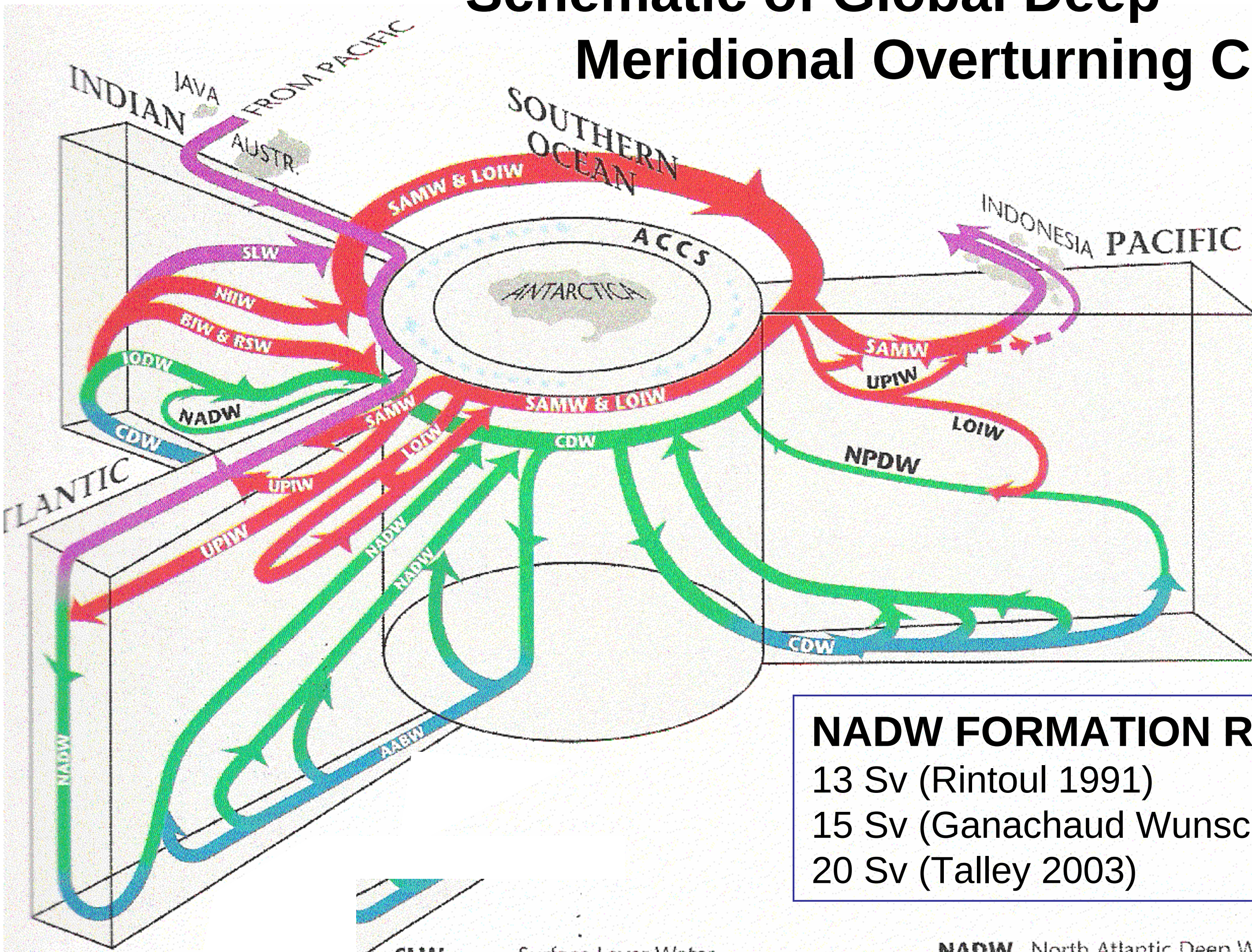
Geostrophic velocity shows DWBC in N Atl (from density measurements + "Pogo" floats)





Pickart and Smethie (1993, *JPO*)

Schematic of Global Deep Meridional Overturning Circulations



NADW FORMATION RATE
13 Sv (Rintoul 1991)
15 Sv (Ganachaud Wunsch 2000)
20 Sv (Talley 2003)

SLW	Surface Layer Water
SAMW	Subantarctic Mode Water
RSW	Red Sea Water
AABW	Antarctic Bottom Water
NPDW	North Pacific Deep Water
ACCS	Antarctic Circumpolar Current System
CDW	Circumpolar Deep Water
NADW	North Atlantic Deep Water
UPIW	Upper Intermediate Water, $26.8 \leq \sigma_\theta \leq 27.2$
LOIW	Lower Intermediate Water, $27.2 \leq \sigma_\theta \leq 27.5$
IODW	Indian Ocean Deep Water
BIW	Banda Intermediate Water
NIIW	Northwest Indian Intermediate Water

Schmitz (1996), cited in *Ocean Circulation and Climate*

Large E-W gradient in SST and sub-surface thermal structure in the tropical Pacific: Thermocline much shallower, SST lower in the East. This structure is in balance with the westward wind stress applied by easterly winds

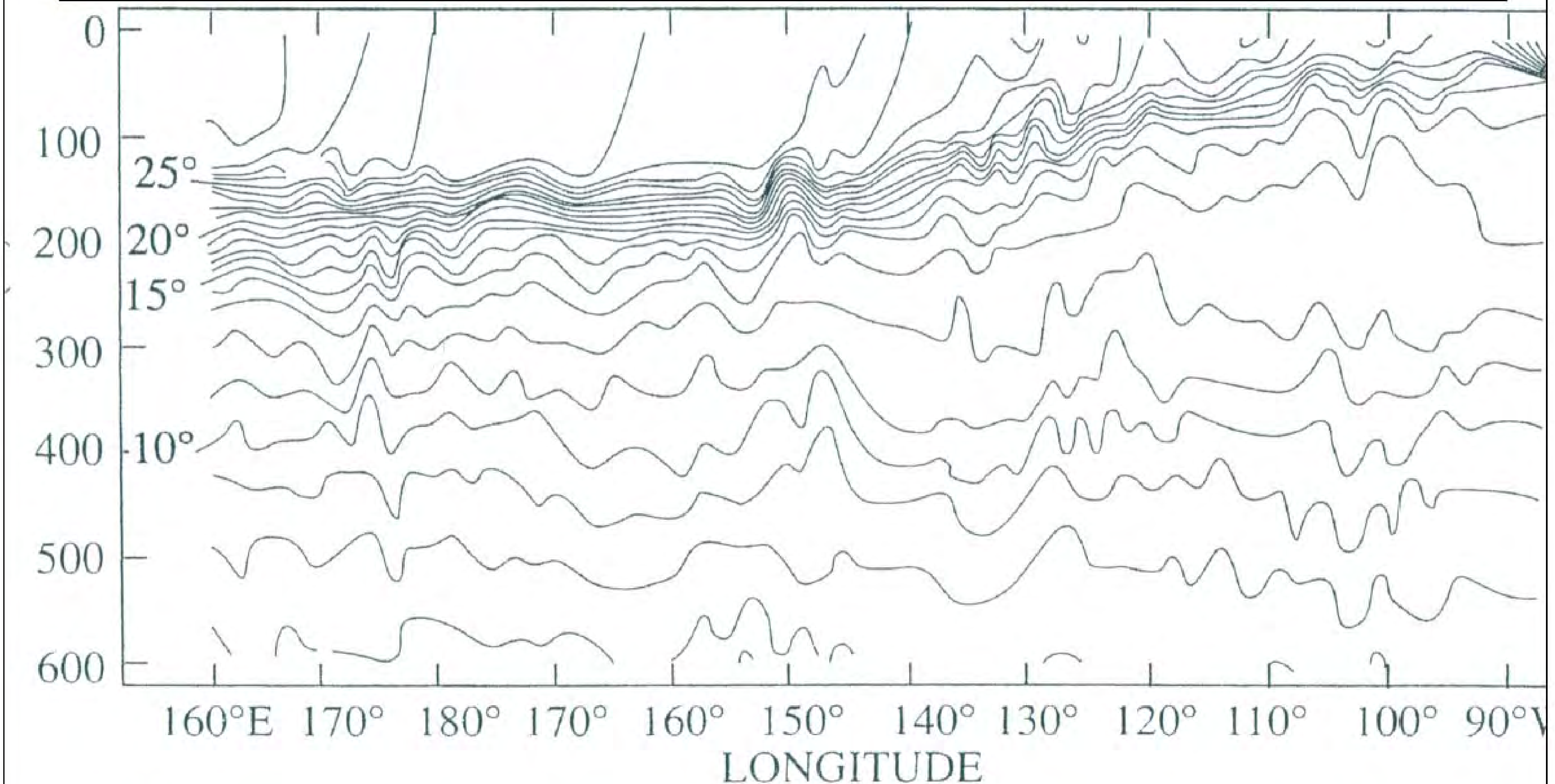
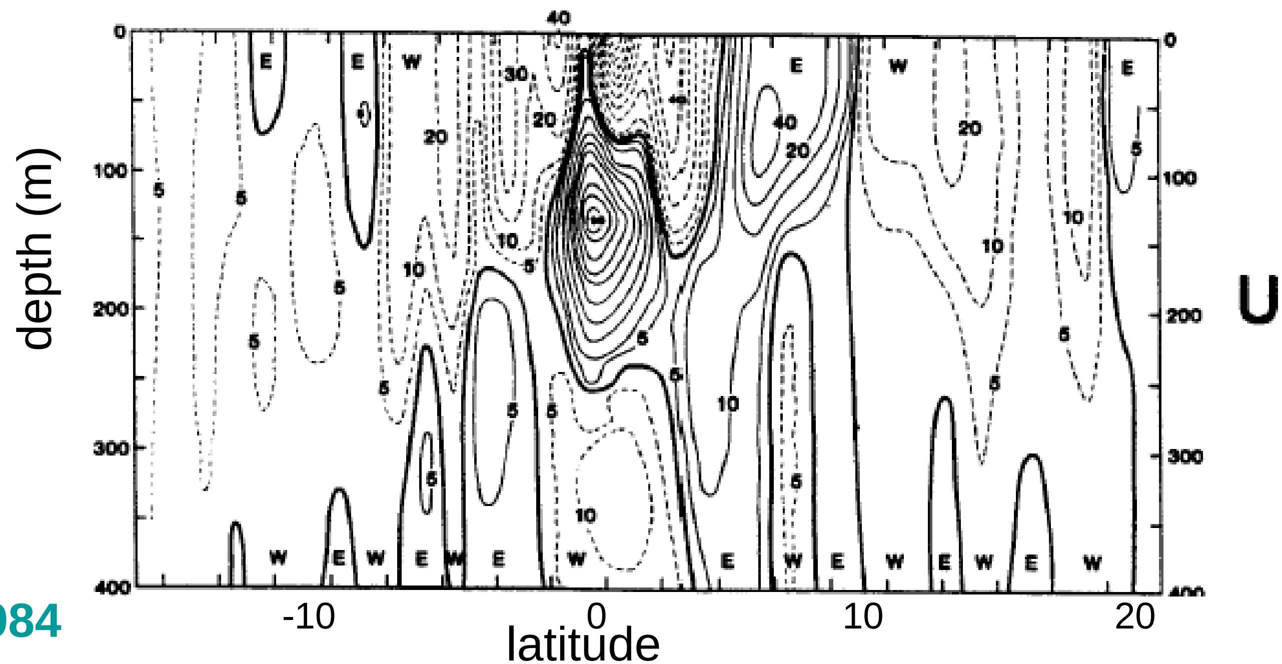


Fig. 7.12 Thermal structure of the equatorial Pacific Ocean showing the slope of the therm
). [From Colin *et al*. (1971).]

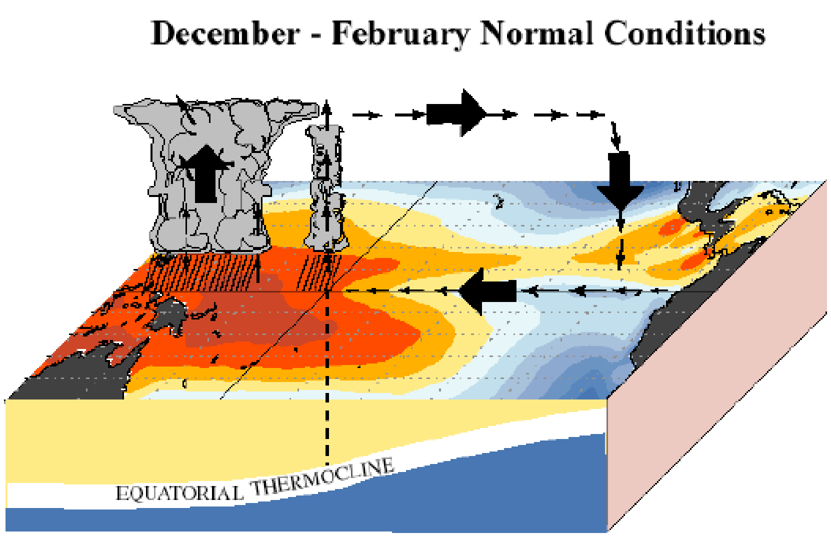
Equator has important vertical structure:

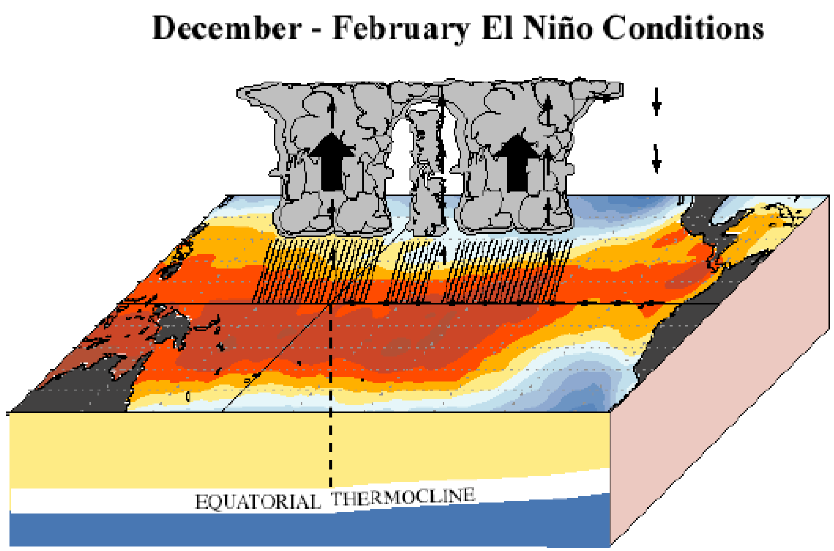
Surface flow: westward
Subsurface Flow: eastward
"Equatorial Undercurrent"
Flow upward along thermocline (see previous slide)
Important part of Subtropical Cell
colder subtropical water ➔ flows to equator ➔ flows E'ward and upwells ➔ returns poleward as Ekman transport



Wyrtki and Kilonsky, 1984

http://www.cpc.noaa.gov/products/analysis_monitoring/ensocycle/meanrain.shtml
http://www.cpc.noaa.gov/products/analysis_monitoring/ensocycle/enso_schem.shtml

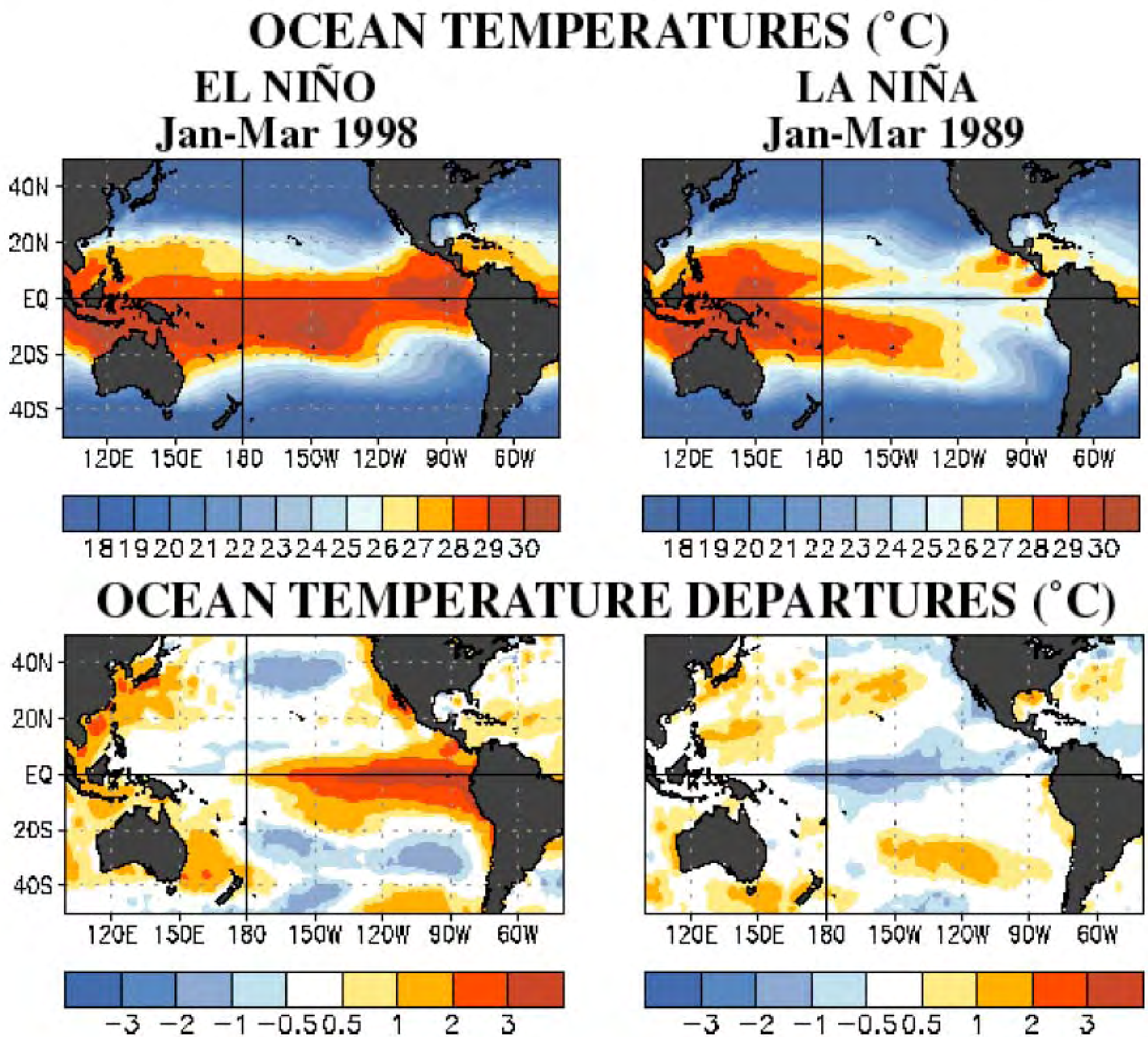


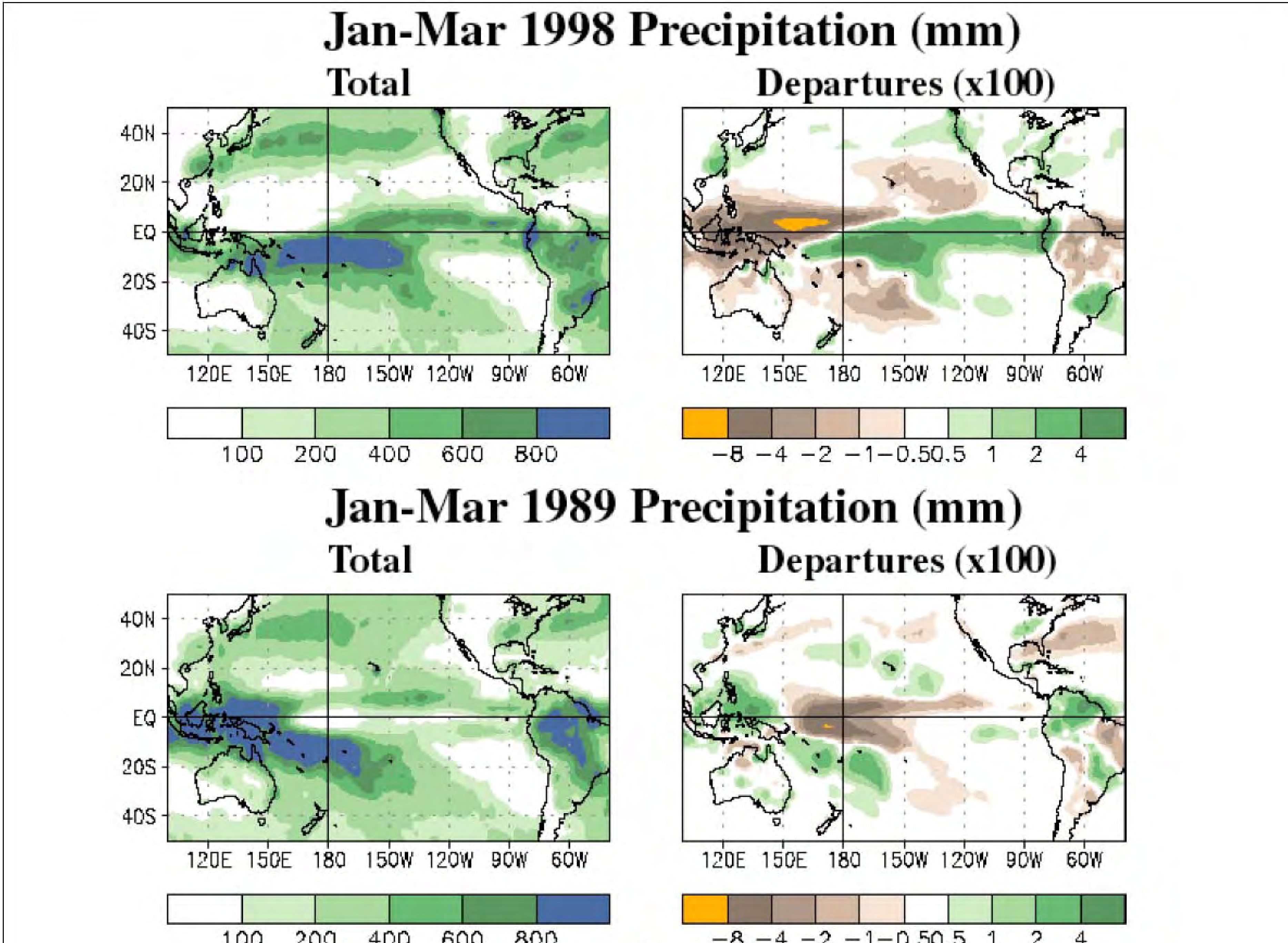


Relaxation of the Easterlies

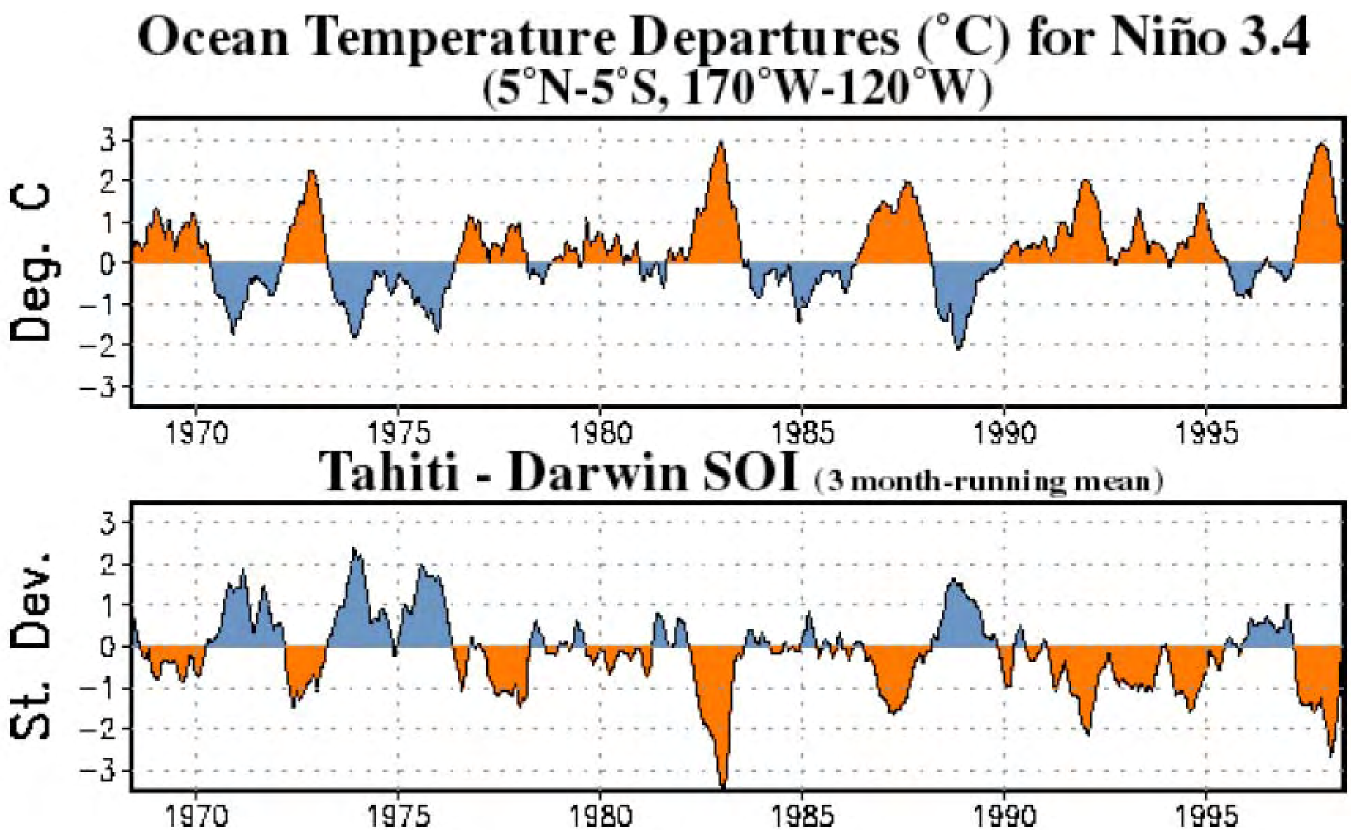
El Nino makes Cold Tongue go away

http://www.cpc.noaa.gov/products/analysis_monitoring/ensocycle/ensocycle.shtml

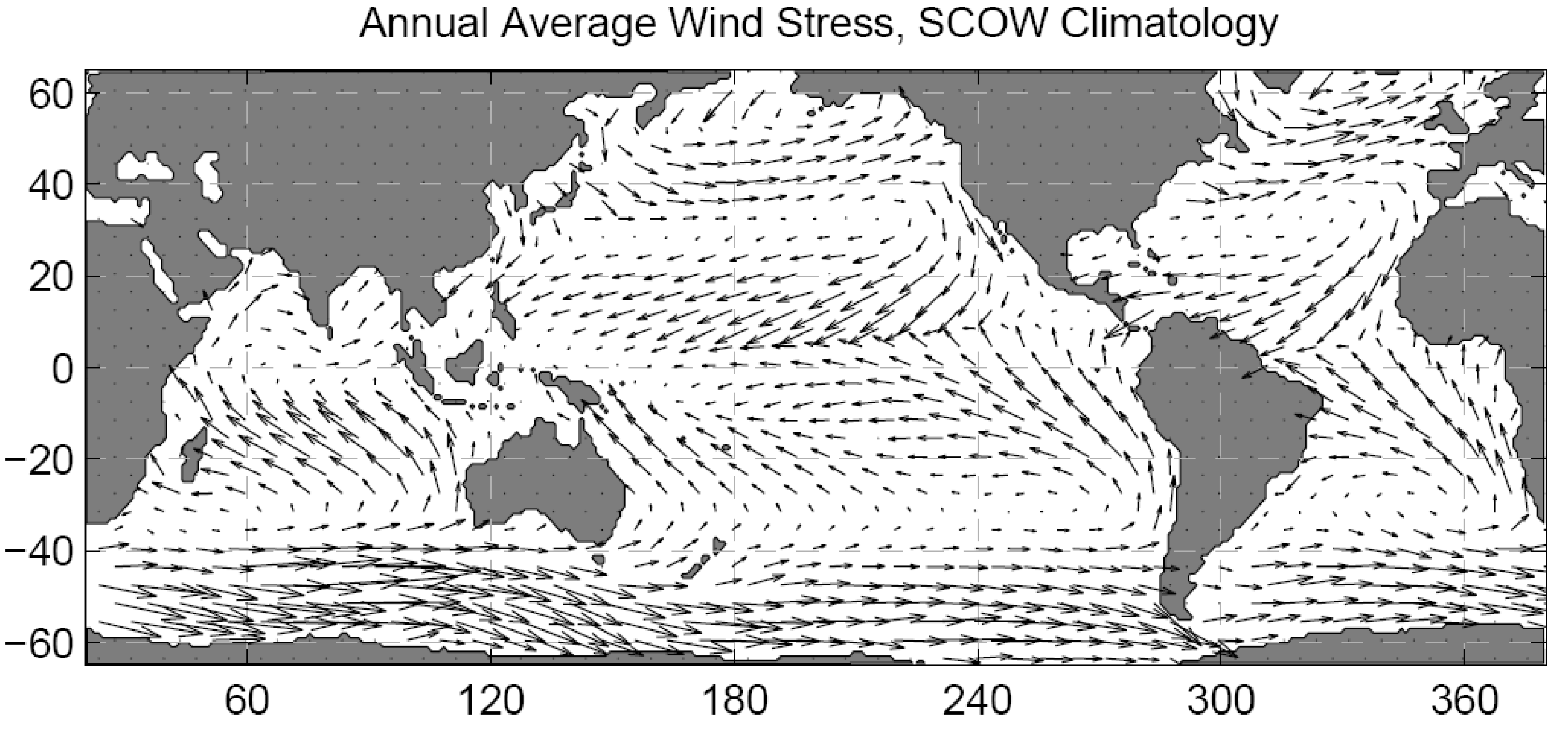



Jan-Mar 1998 Precipitation (mm)
Total
Departures (x100)
40N
20N
EQ
20S
40S
120E 150E 180 150W 120W 90W 60W
100 200 400 600 800
−8 −4 −2 −1 −0.5 0.5 1 2 4
Jan-Mar 1989 Precipitation (mm)
Total
Departures (x100)
40N
20N
EQ
20S
40S
120E 150E 180 150W 120W 90W 60W
100 200 400 600 800
−8 −4 −2 −1 −0.5 0.5 1 2 4

http://www.cpc.noaa.gov/products/analysis_monitoring/ensocycle/soi.shtml



Wind-Driven Gyres

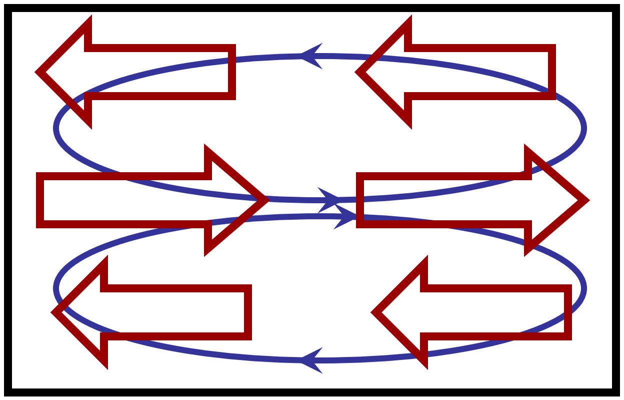


Consider water in basin forced by wind stress at surface:

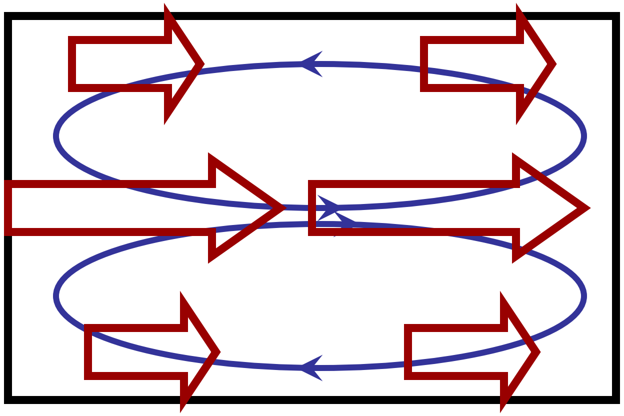
top view

Closed basin: water must form GYRES.

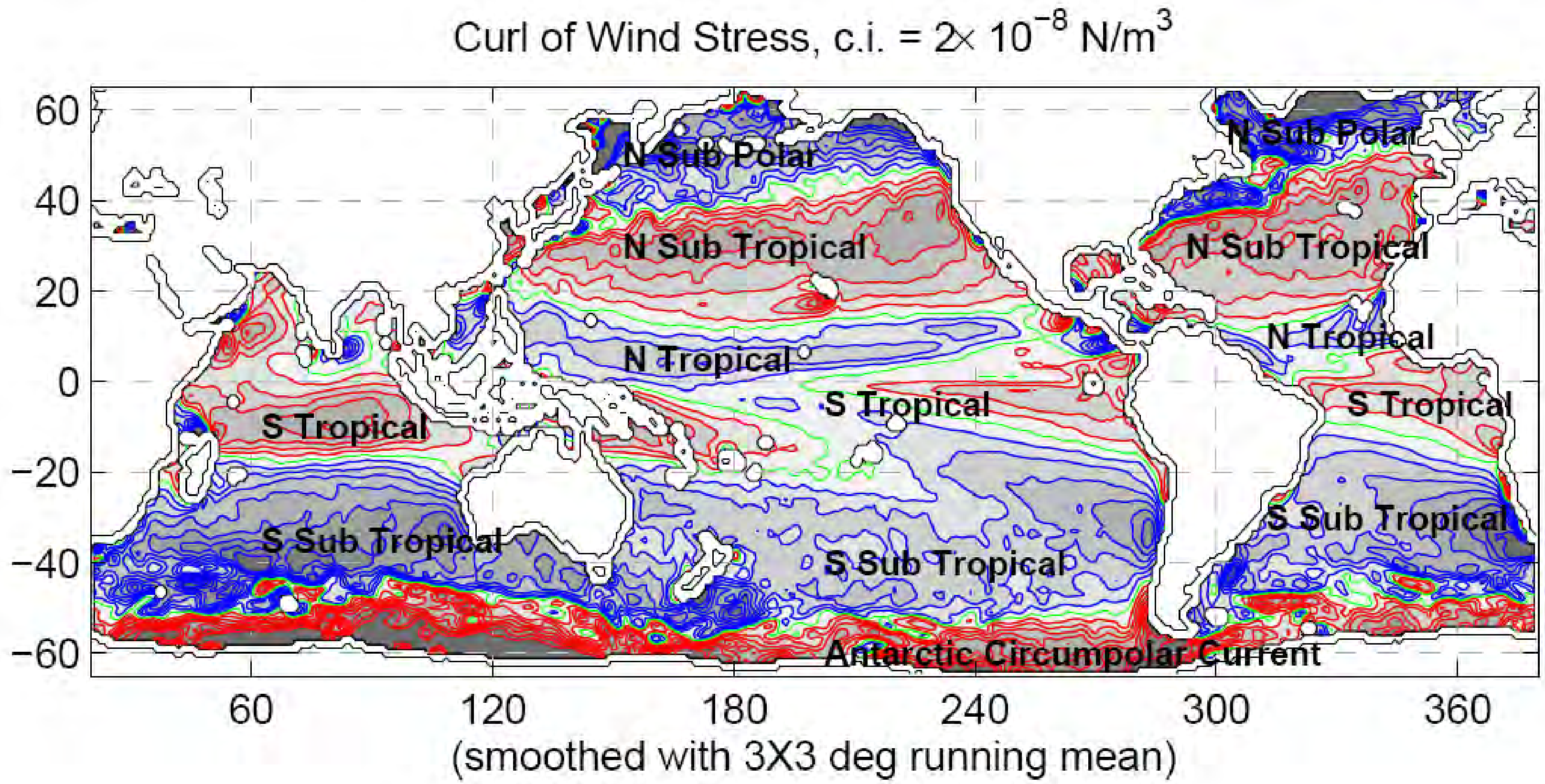
Direction based on wind shear



Can get water flowing in *opposite direction* to wind



Ocean Gyres (clockwise and counter-clockwise) follow the Wind Curl



Surface circulation and depth-averaged circulation shows gyres which are generally aligned with the regions of positive and negative wind curl (see observations on following slides).

Observed Pacific Surface Geostrophic Flow

Note
Strong
Western
Boundary
Currents

N. Eq.
Counter Cur.

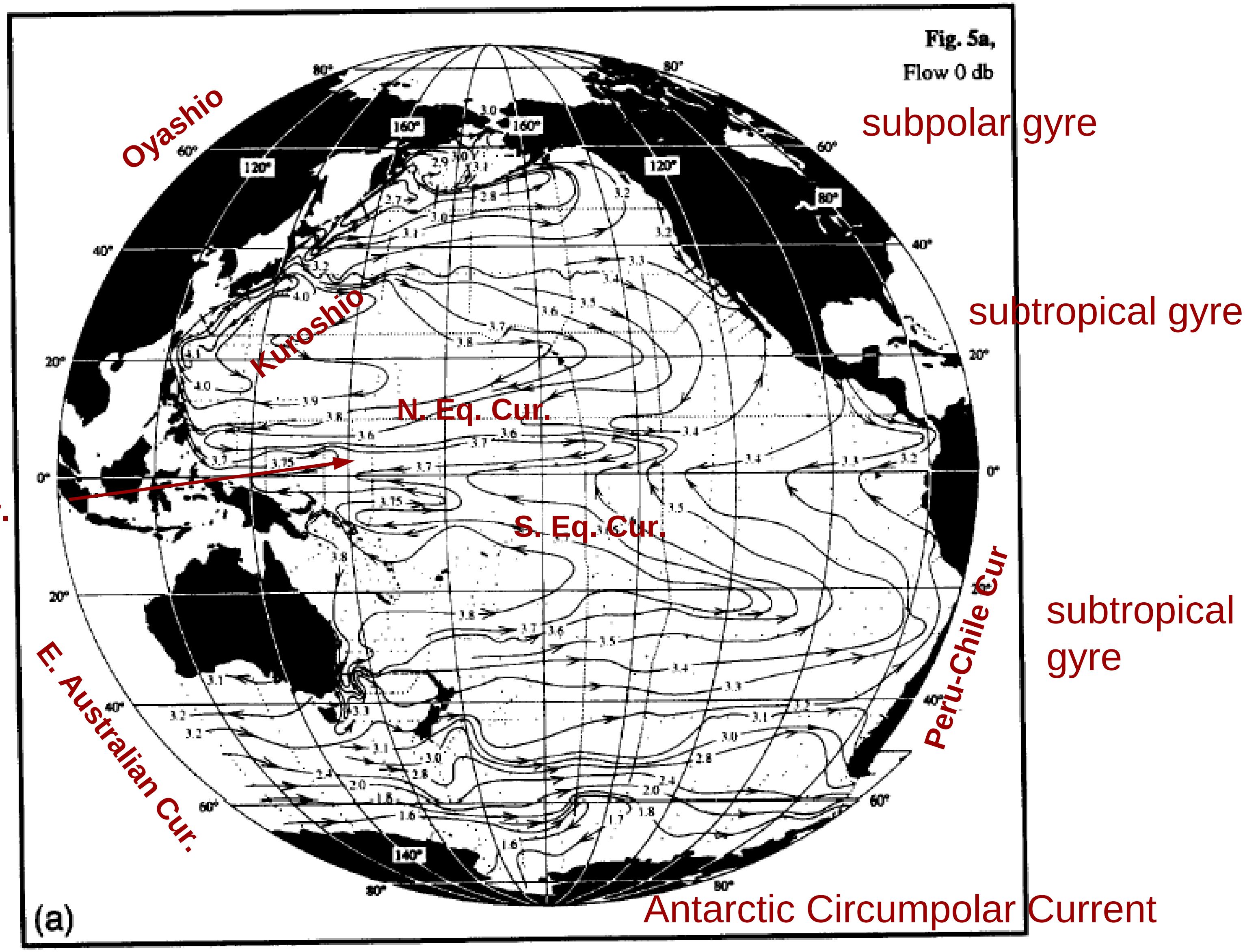
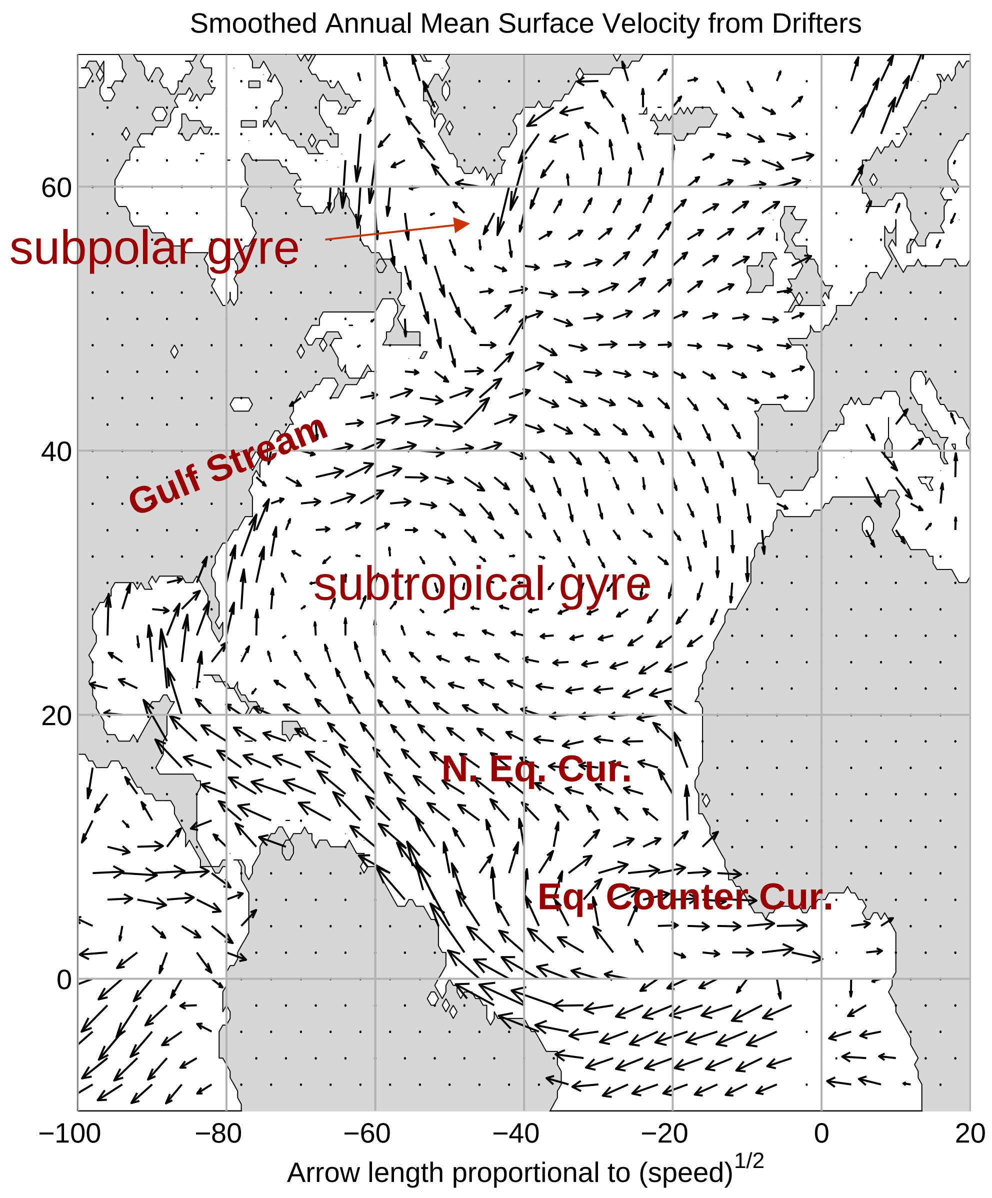
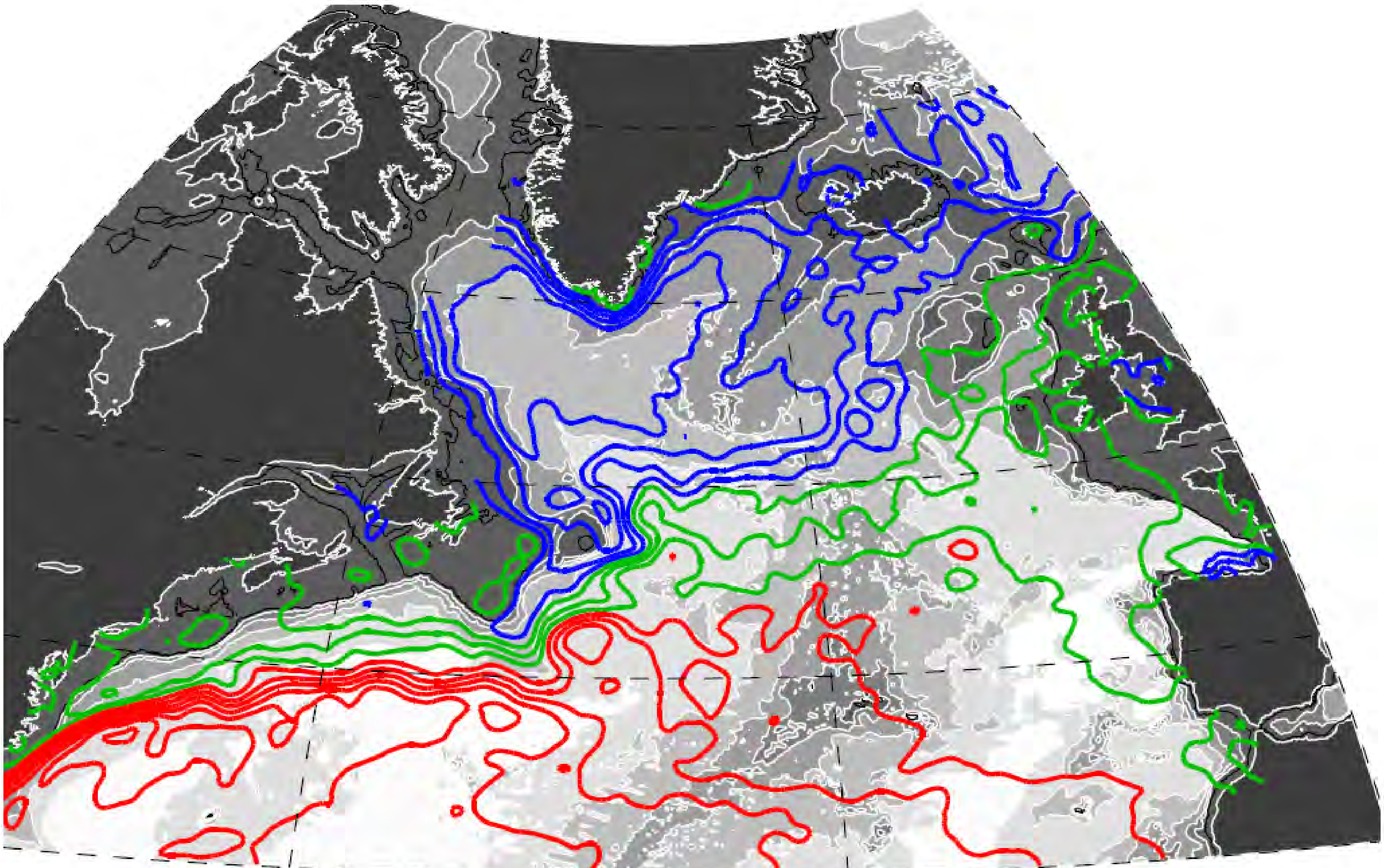


Fig. 5. (a) Adjusted steric height at 0 db (10 m^2s^{-2} or 10 Jkg^{-1}).

Reid (1997, Prog Oceanogr)



based on Hansen and Poulain (1996)



Observed Surface South Atlantic Geostrophic Flow

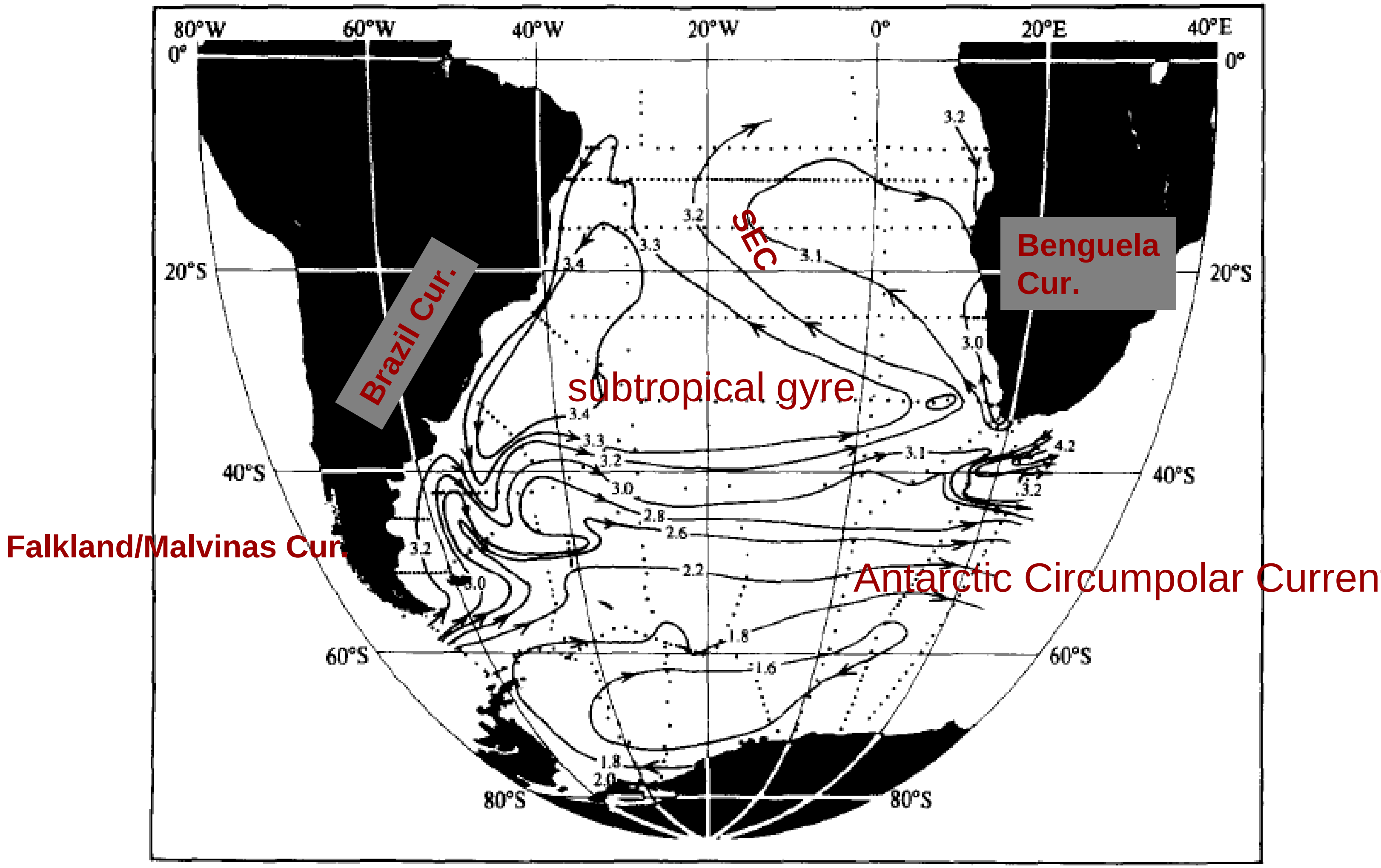
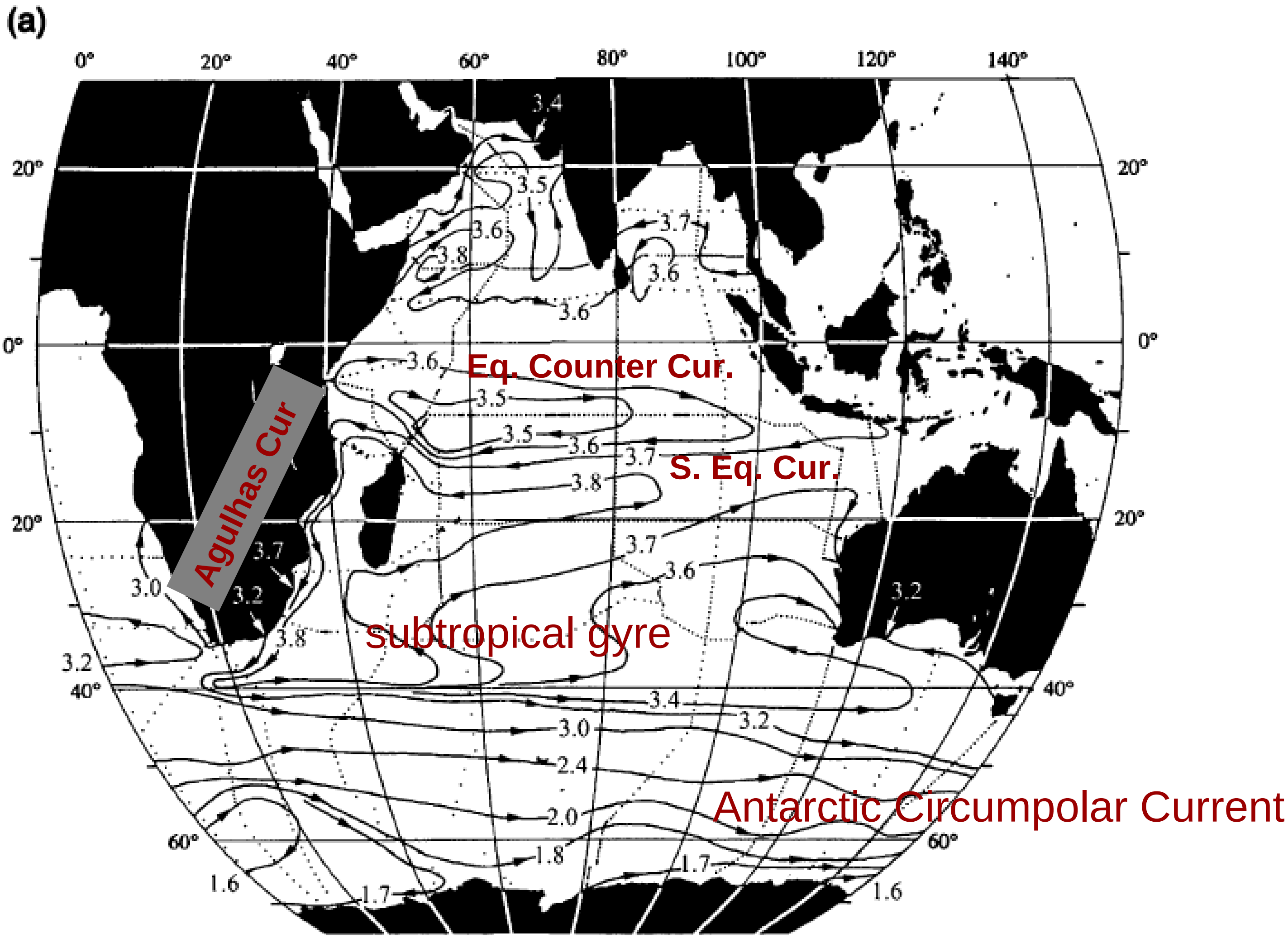


Fig. 7. Adjusted steric height ϕ_A at 0 db ($10\ m^2\ s^{-2}$ or $10\ J\ kg^{-1}$).

Reid (1989, Prog Oceanogr)

Observed Surface Indian Ocean Geostrophic Flow



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How much heat transport is associated with Subtropical Cells?