



Lecture 15

- *Ocean Structure and Water Masses*
- *Forcing at the ocean-atmosphere interface:*
 - *heat fluxes, E-P, wind stress*
- *Ocean general circulation*

Reading

Robert Stewart 2008 (see the class web-site):

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Why are we interested in the ocean in relationship to climate?

- Ocean SSTs are critical for the atmospheric circulation, clouds and precipitation
- Ocean transports heat poleward
- Ocean has a high heat capacity (provides thermal inertia to the system)
- Ocean provides longer timescales to the climate system (as compared to atmospheric timescales) via slow ocean adjustment to surface forcing -> possibility of coupled modes (e.g. El Niño)

Seasonal heat storage over 1m² area of ocean and land

$$C_p \approx 4.0 \times 10^3 \text{ J} \cdot \text{kg}^{-1} \cdot ^\circ\text{C}^{-1}$$

(specific heat for water and rock)

$$C_{p(\text{rock})} = 800 \text{ J} \cdot \text{kg}^{-1} \cdot ^\circ\text{C}^{-1}$$

$$\text{Density of water: } 1000 \text{ kg/m}^3$$

$$\text{Density of rock: } 3,000 \text{ kg/m}^3$$

Depth: Ocean upper (mixed) layer -100m

Depth: Rock – 1m

Area: 1m²

$$\begin{aligned}\Delta E_{\text{ocean}} &= C_{p(\text{water})} m_{\text{water}} \Delta t \\ &= (4000)(10^5)(10^\circ) \text{ Joules} \\ &= 4.0 \times 10^9 \text{ Joules}\end{aligned}$$

$$\Delta t = 10^\circ\text{C}$$

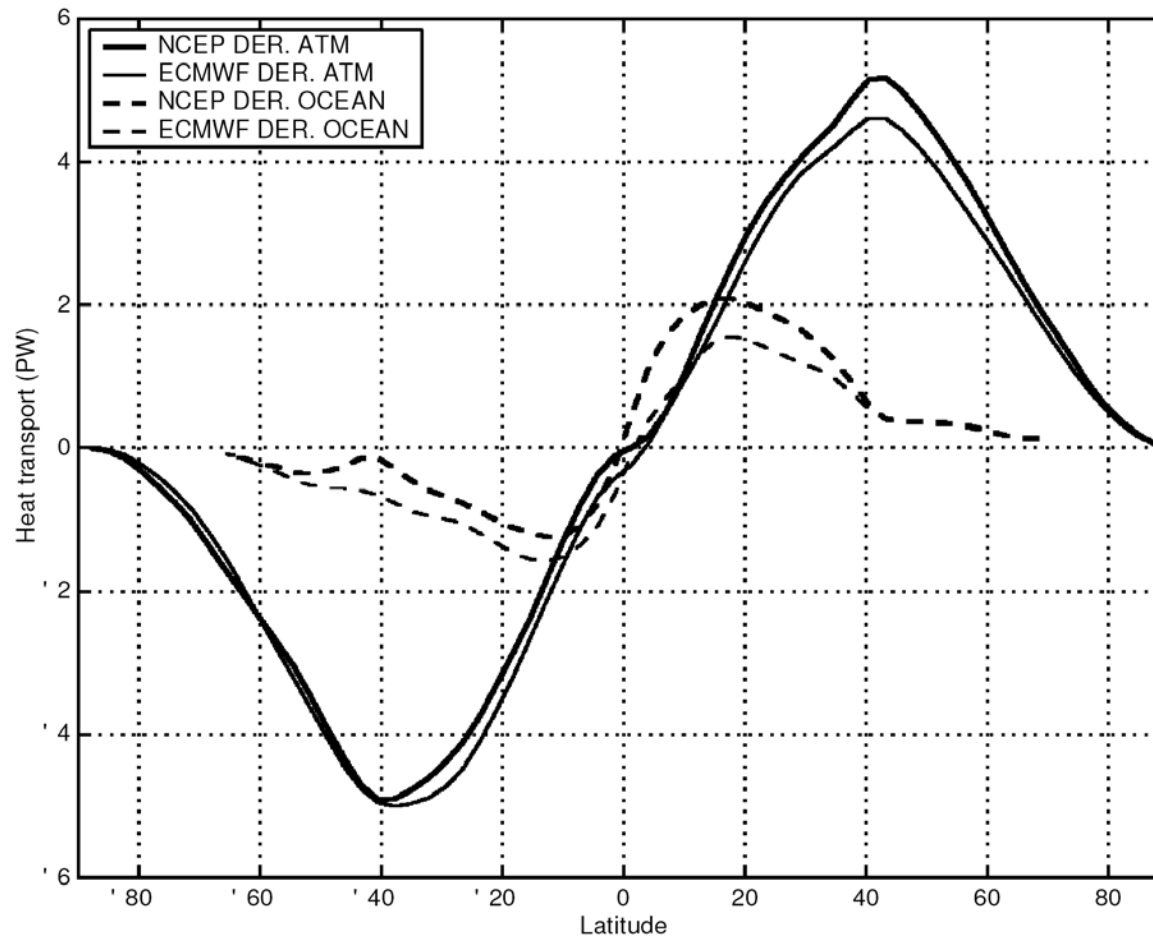
(seasonal variations in temperature)

$$\begin{aligned}\Delta E_{\text{land}} &= C_{p(\text{rock})} m_{\text{rock}} \Delta t \\ &= (800)(3000)(20^\circ) \text{ Joules} \\ &= 4.8 \times 10^7 \text{ Joules}\end{aligned}$$

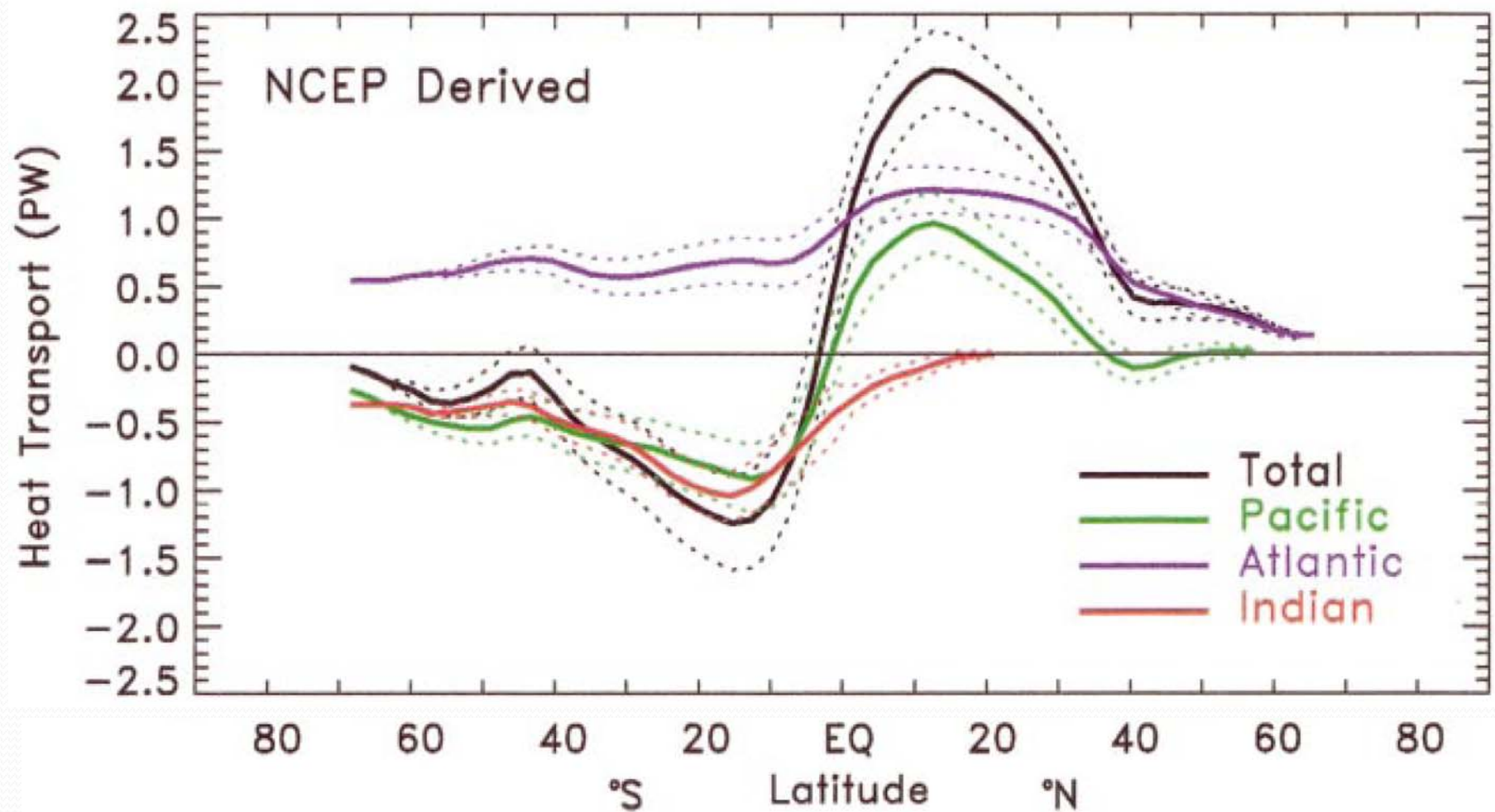
$$\Delta t = 20^\circ\text{C}$$

$$\frac{\Delta E_{\text{ocean}}}{\Delta E_{\text{land}}} = 100$$

Heat storage over land is two orders of magnitude smaller than that in the ocean!



Zonally averaged atmospheric (solid lines) and oceanic (dashed lines) northward heat transports as computed from NCEP (thick lines) and ECMWF (thin lines) reanalyses (Trenberth *et al.* 2001); in petawatts (10^{15}). Man's global energy consumption is about 0.016 pW

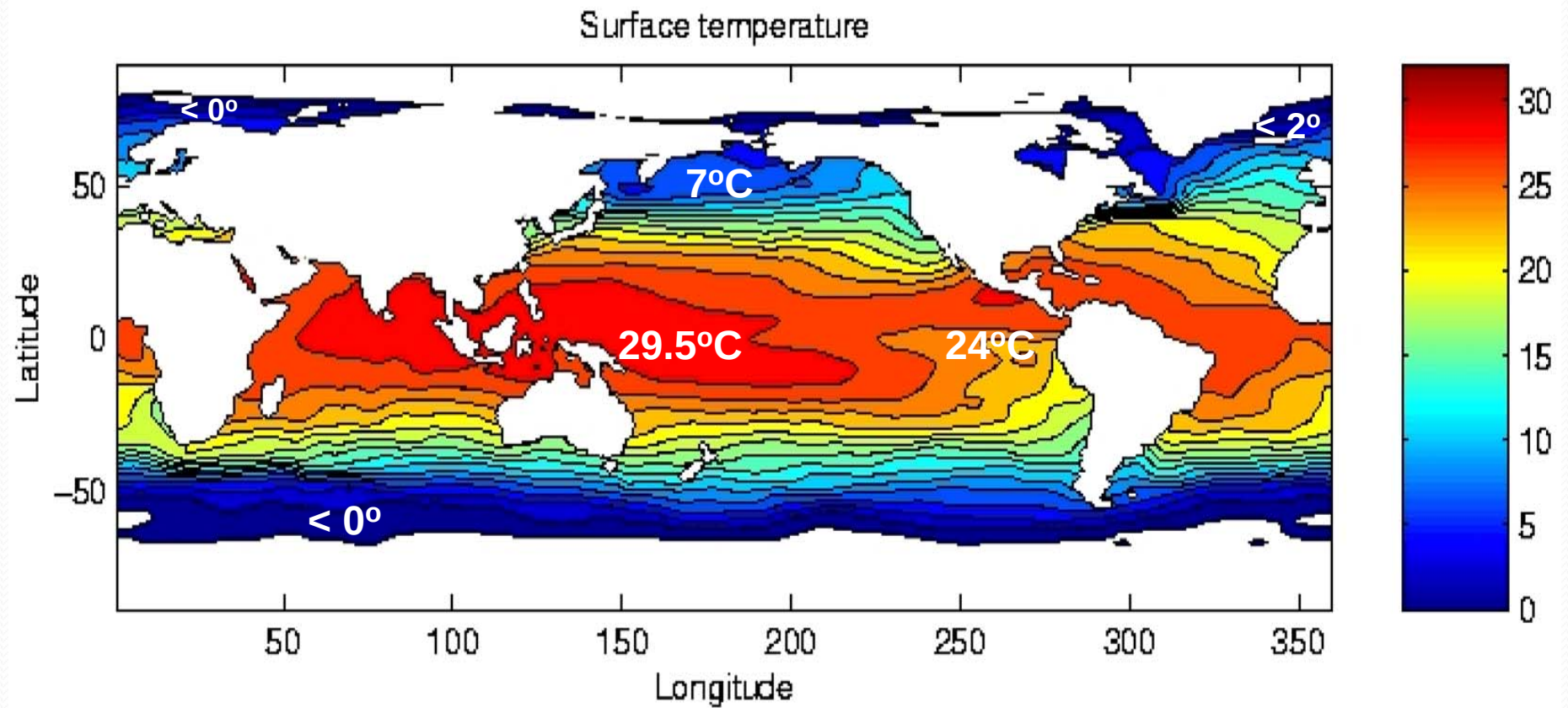


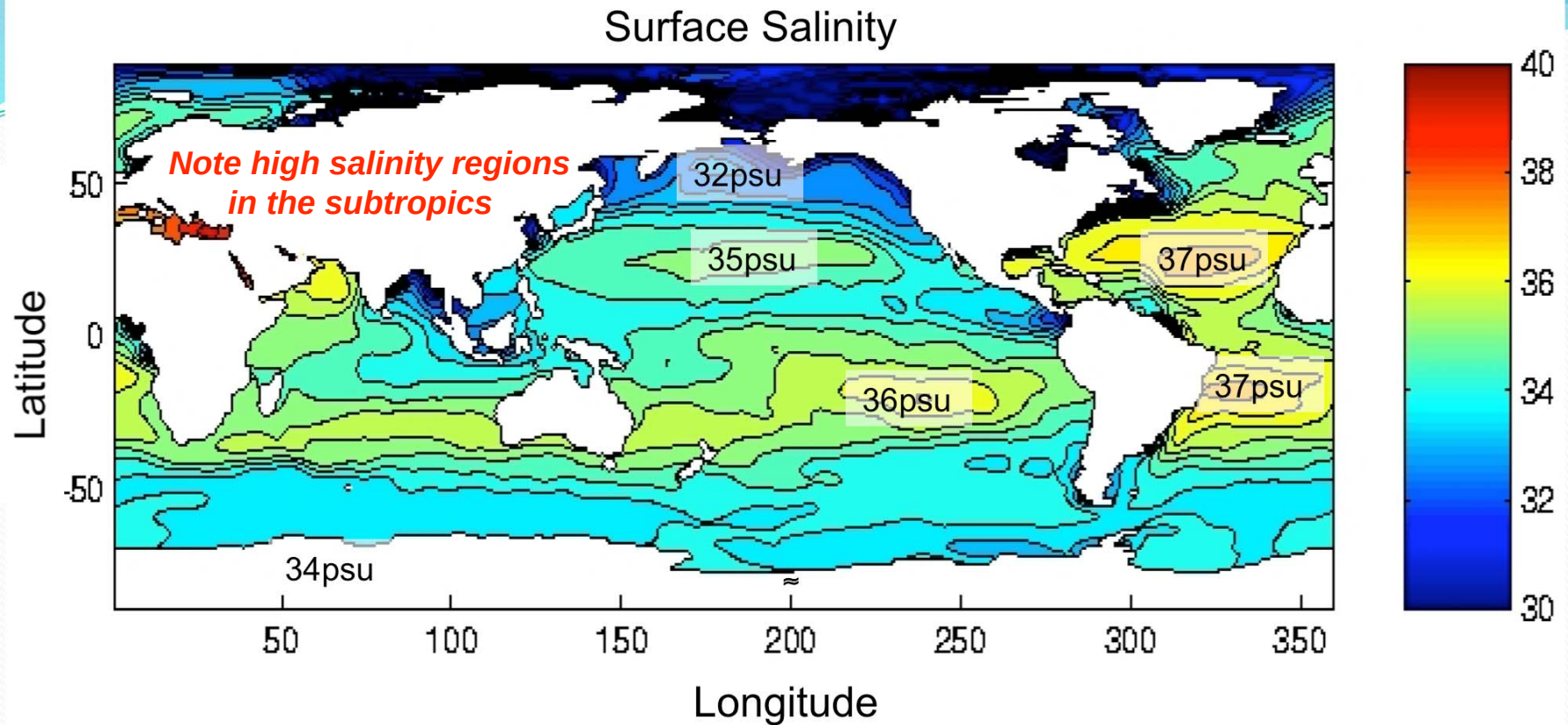


Ocean thermal structure

Ocean thermocline and mixed layer

Annual mean distribution of ocean surface temperature (SST)





The Red Sea – up to 39 psu (strong evaporation) ;

The Mediterranean Sea – up to 38psu (strong evaporation);

The Arctic Ocean, near surface – 30psu (sea ice melting + river run-off);

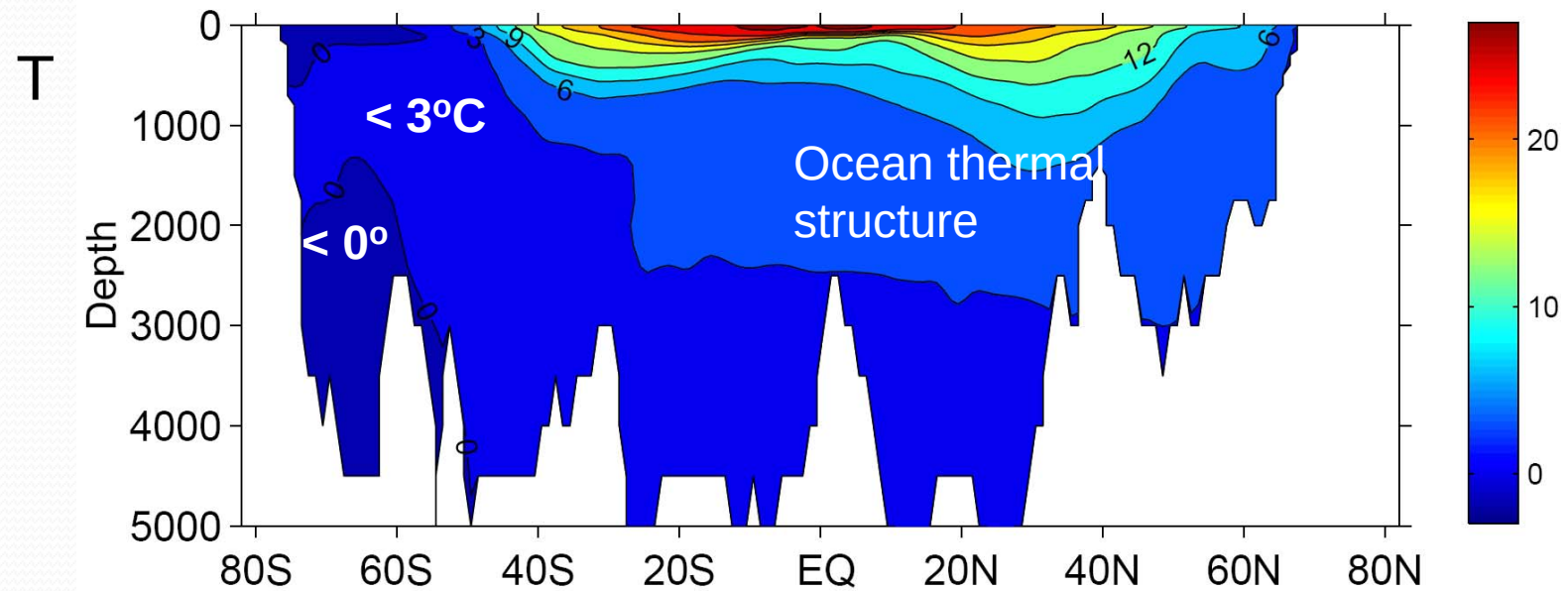
The Black Sea, the Baltic Sea – 17psu (river run-off)

Mean ocean salinity ~35 psu

psu - practical salinity unit

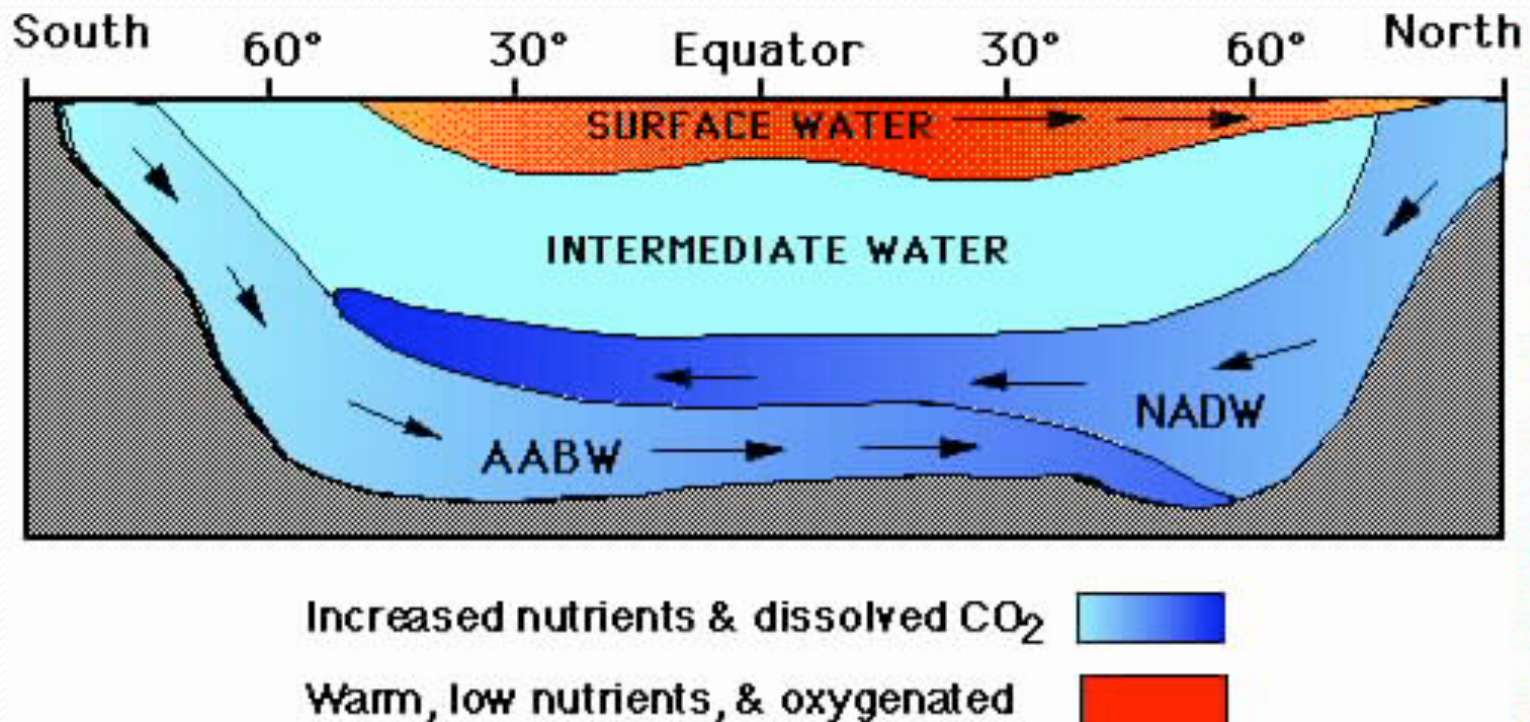
$psu \approx ppt = g/kg$

Atlantic Ocean



The average ocean temperature is 3.8°C

Ocean water masses and circulation routes

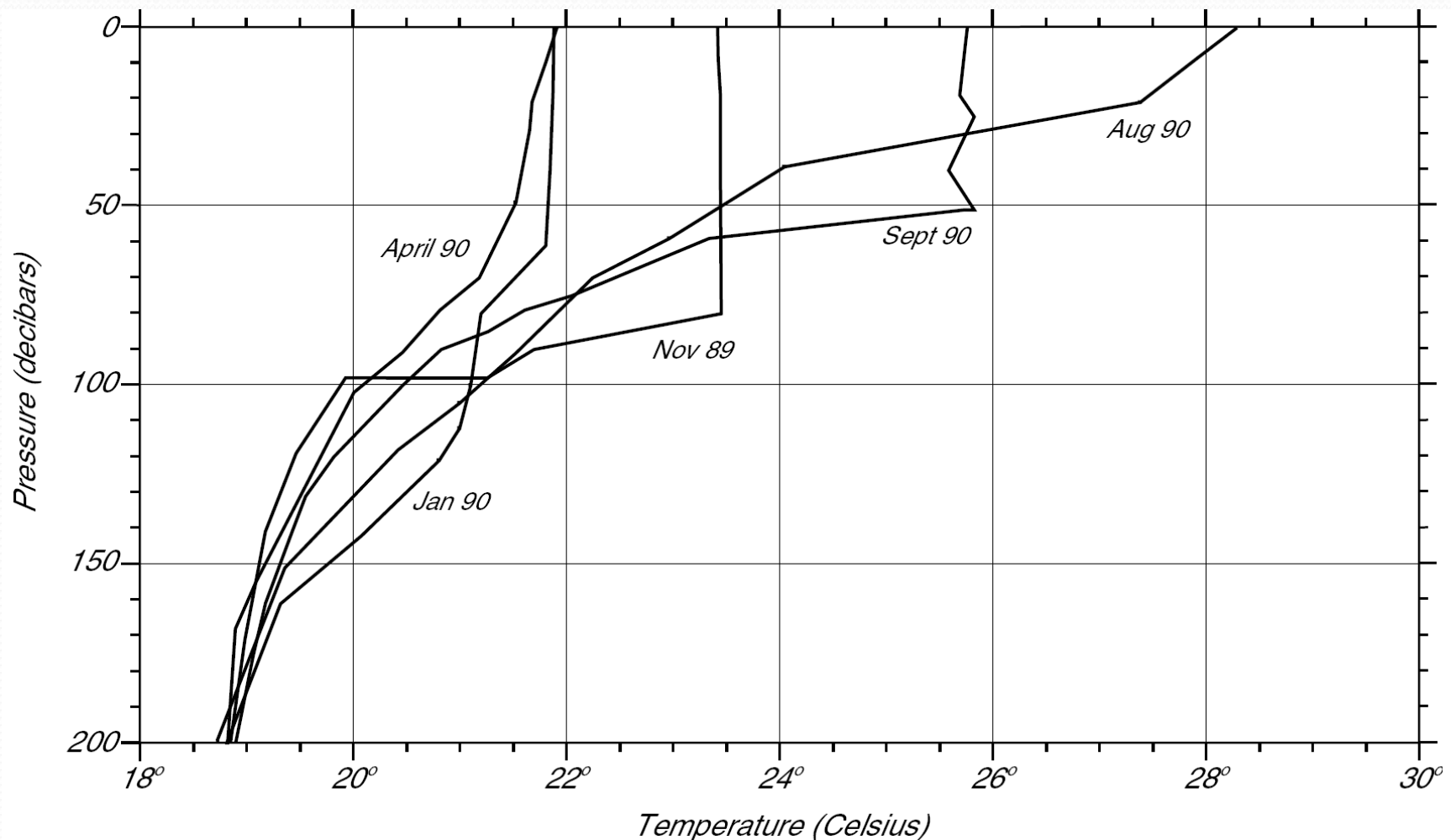


*Why is the ocean cold: most of the ocean water comes from high latitudes. Sometimes this process is called **ocean “ventilation”** (also the thermohaline circulation – the THC, the ocean meridional overturning, ocean abyssal circulation)*

NADW – the North Atlantic Deep Water

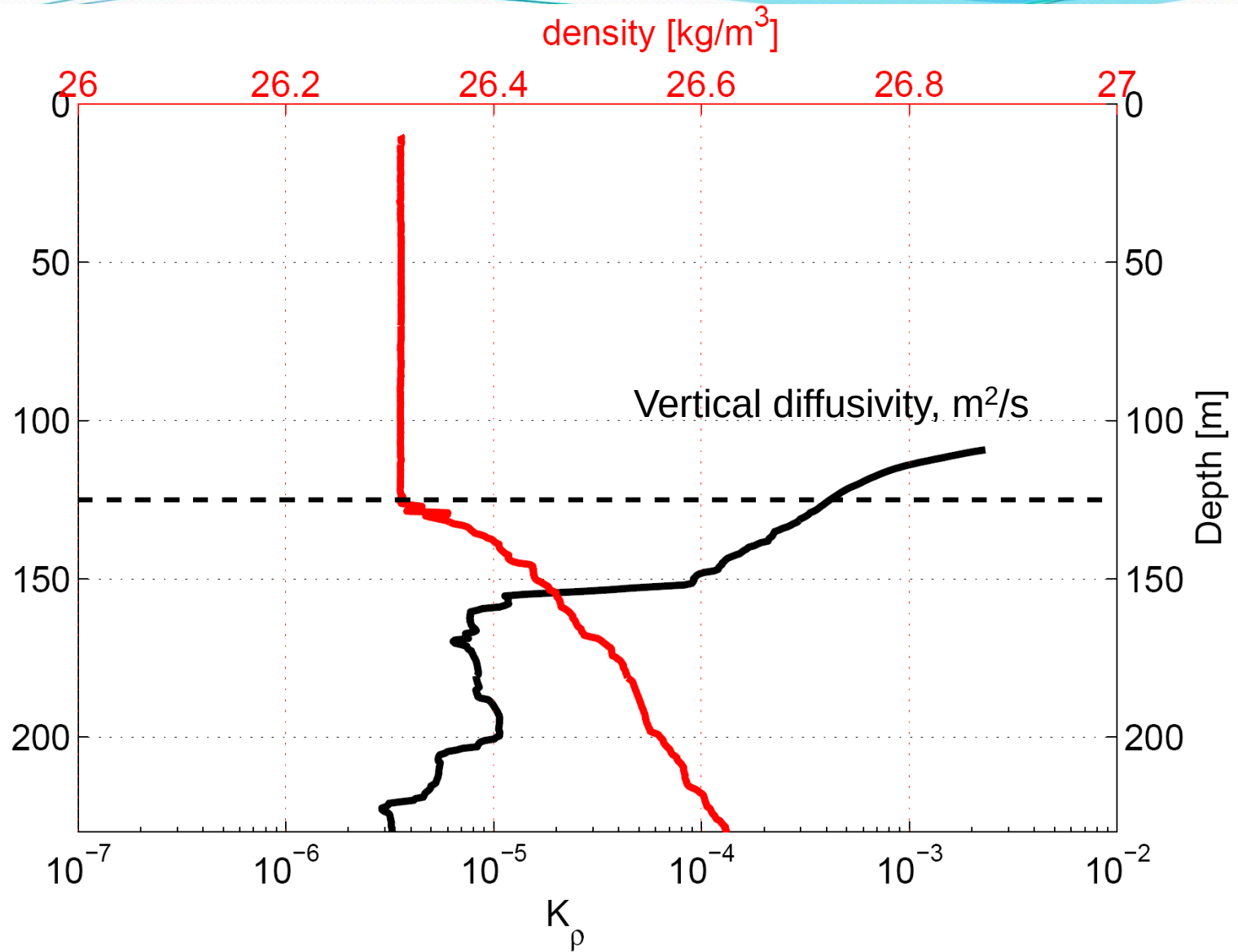
AABW – the Antarctic Bottom Water

Mixed layer (in terms of temperature) from November 1989 to September 1990 at the Bermuda Atlantic Station at 31.8°N 64.1°W.



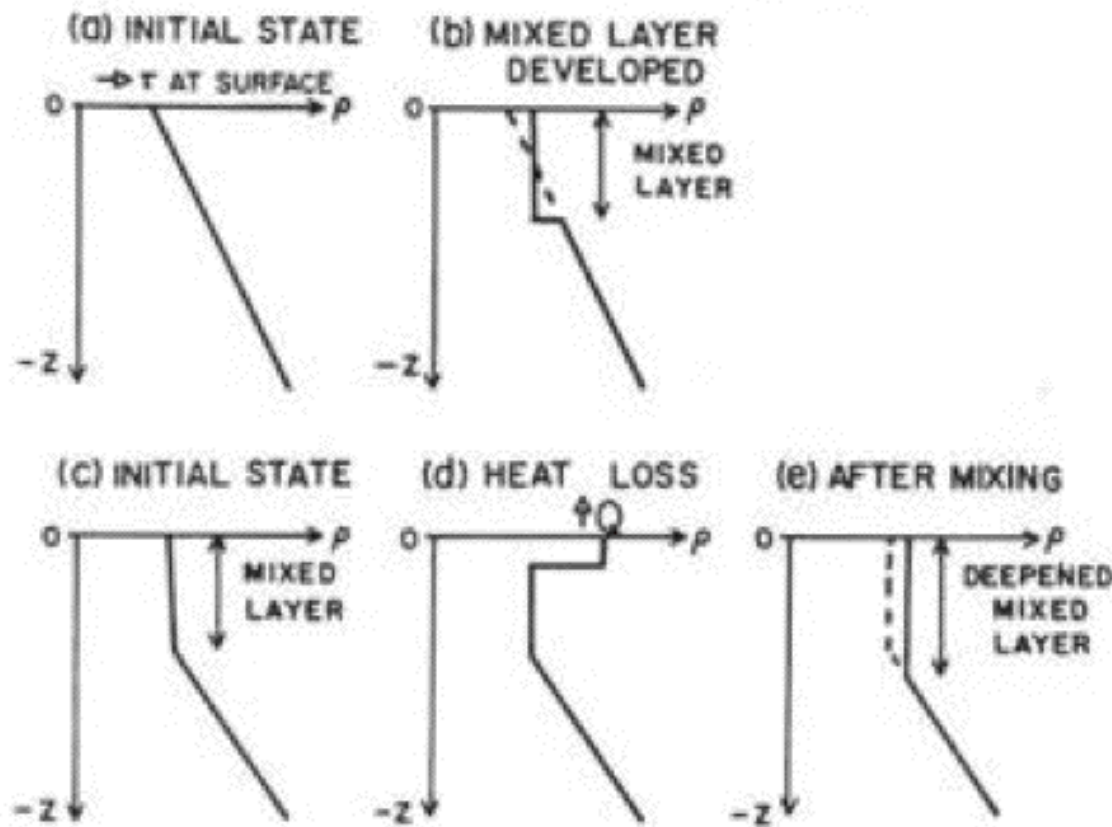
Ocean heat loss in the Fall/Winter leads to the formation of a uniform mixed layer

Ocean mixed layer defined in term of density



North Atlantic Tracer Release Experiment

Surface mixed layer: buoyancy and turbulent mixing effects

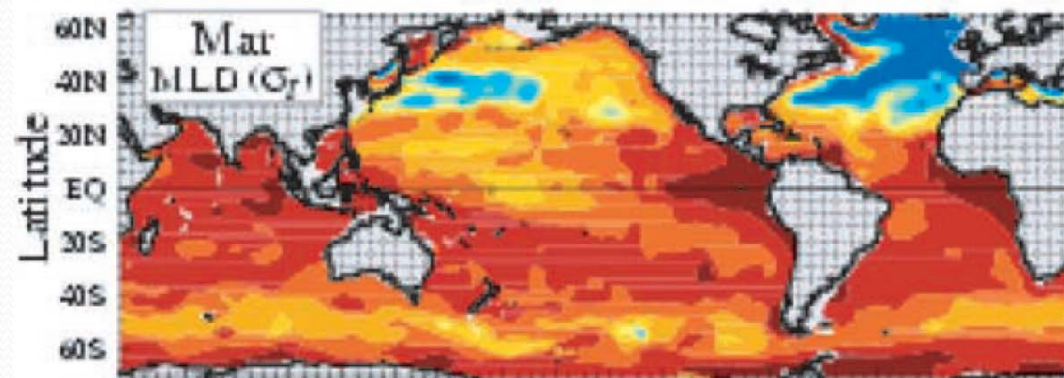


Mixing by
turbulence only

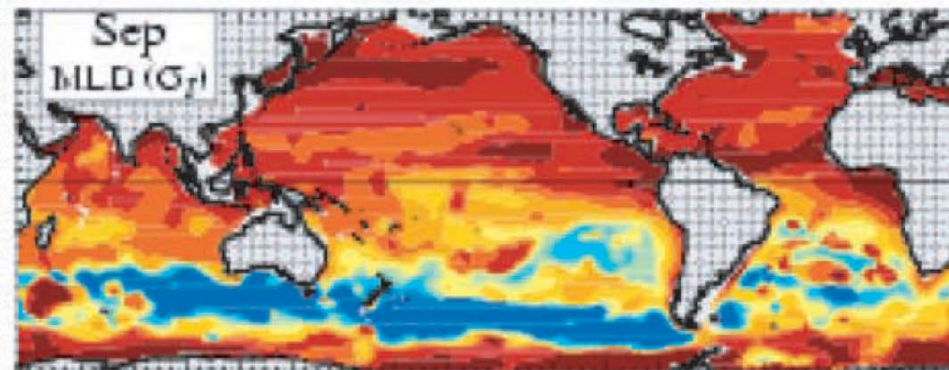
Mixing by heat
loss

Development of mixed layer depends on turbulence input (wind velocity), heat loss or gain (also salt), and pre-existing stratification

Observed mixed layer depth



$\Delta T = 0.8^\circ\text{C}$
Kara et al 2003



Others use
 $\Delta T = 0.5^\circ\text{C}$



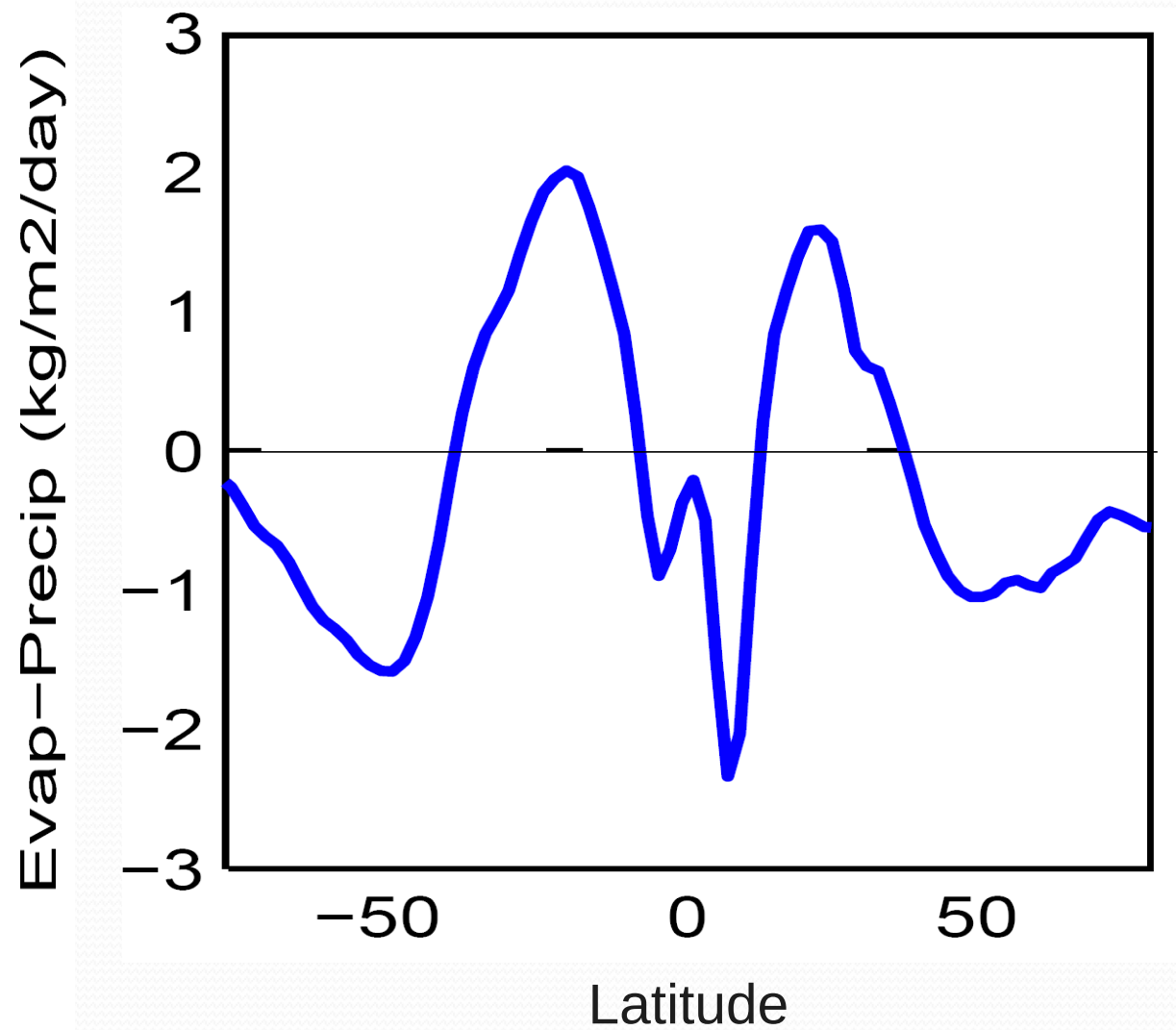
Important points:

- 1) *Variations in ocean density with depth in many parts of the ocean (tropics to mid-latitudes) are predominantly controlled by temperature (not salinity). In other words, ocean vertical **stratification** is typically controlled by temperature.*
- 2) *Usually there is a layer of relatively uniform temperature near the ocean surface – the so-called **mixed layer**. Depth – typical from 20m to 100m, but can go to ~1000m.*
- 3) *In the tropics, subtropics and mid-latitudes the warm surface waters and colder deep waters are separated by a layer with rapidly changing temperatures (large dT/dz) – **the thermocline**. There are two types of thermocline – seasonal and permanent.*
- 4) . **Abyssal water** – cold deep water with very weak stratification

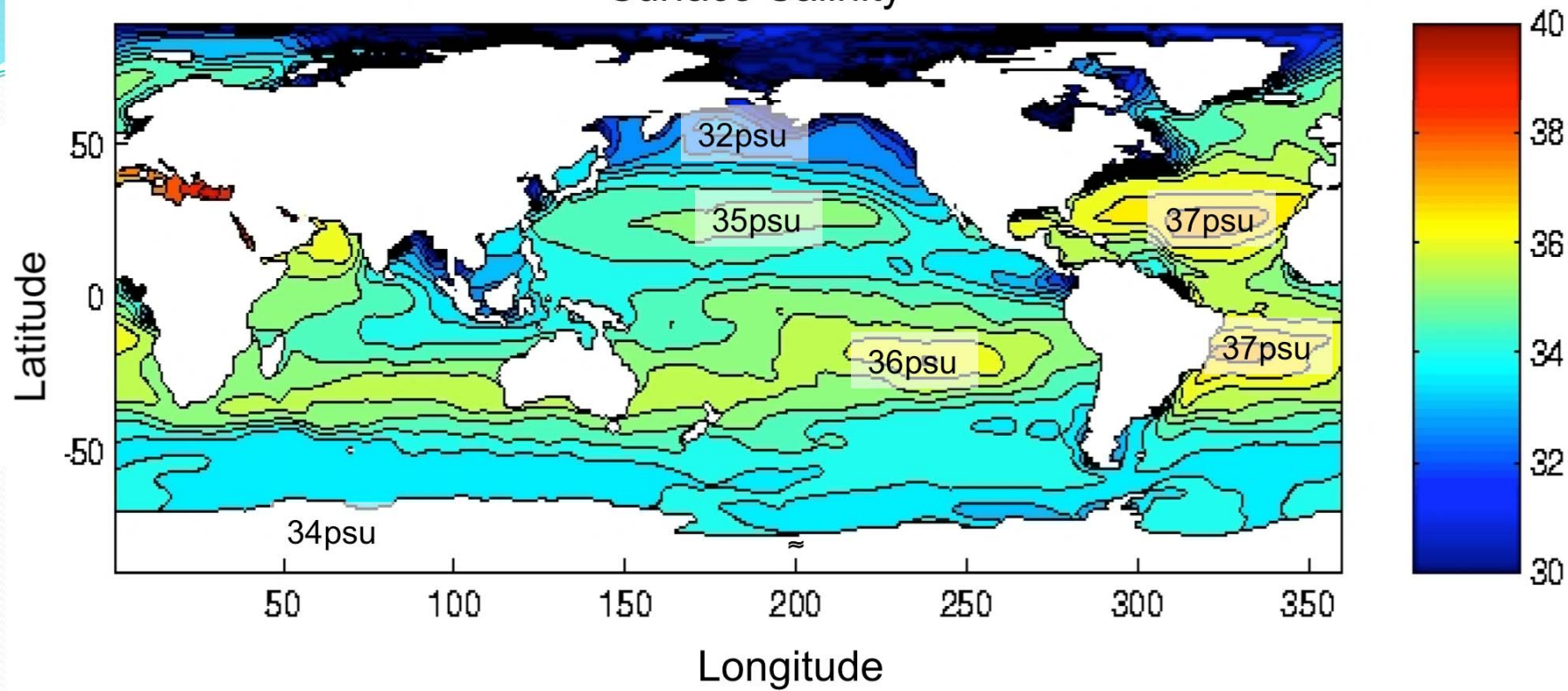


***Forcing at the ocean atmosphere interface:
heat fluxes, E-P, wind stress***

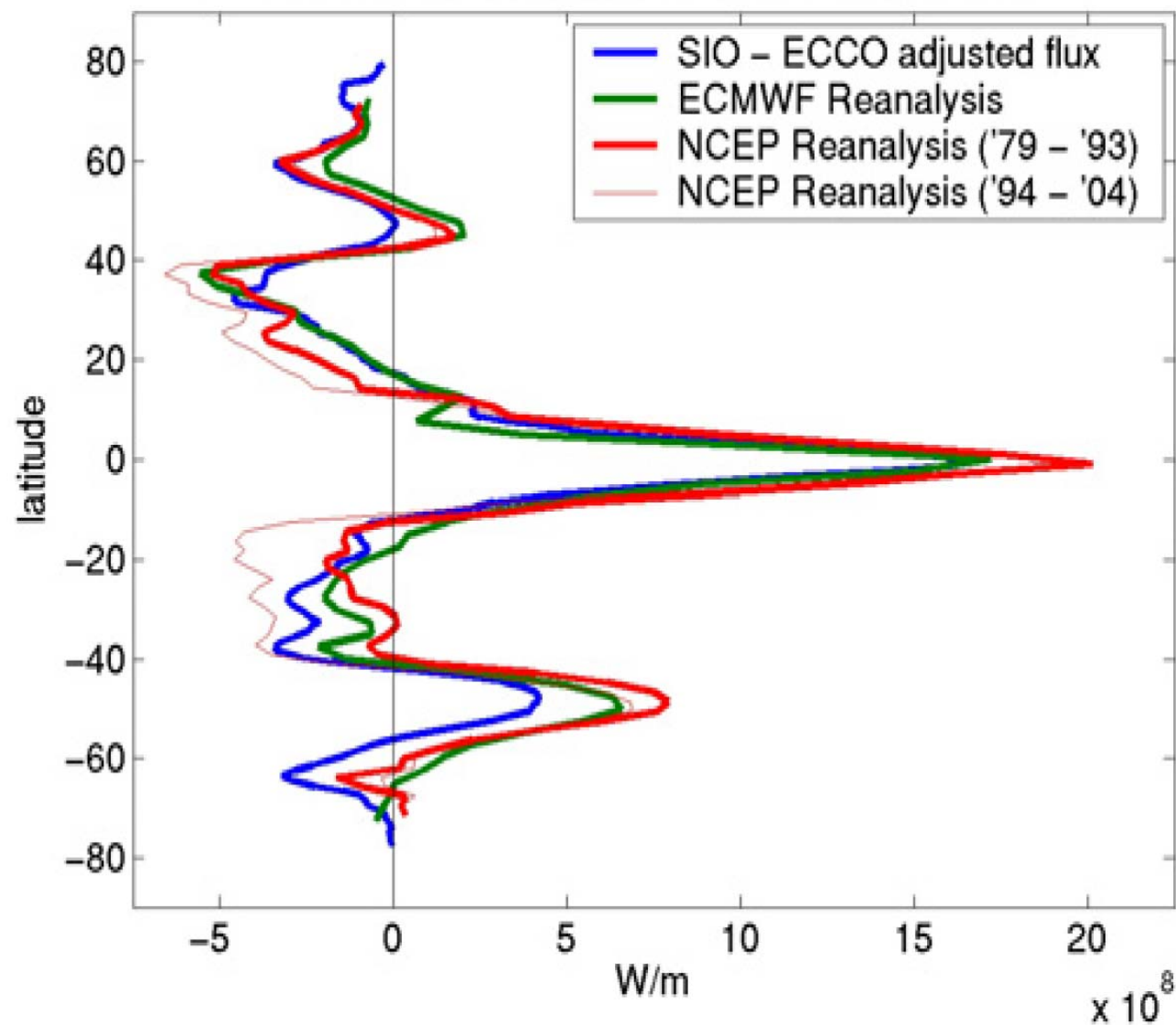
Zonally-averaged freshwater fluxes at the ocean surface (E-P)



Surface Salinity



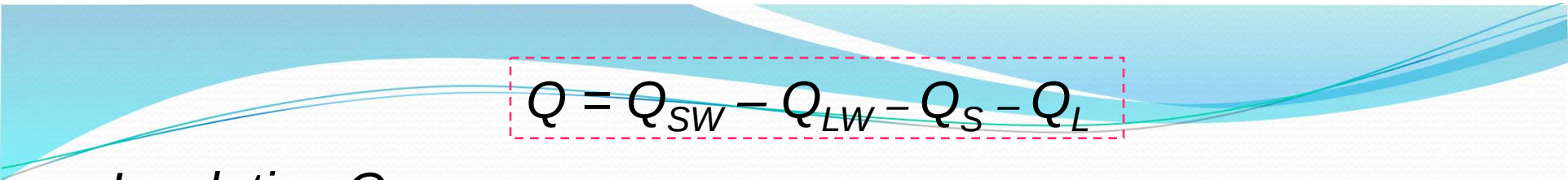
Zonally-integrated heat fluxes at the ocean surface





The net download heat flux into the ocean Q can be calculated as a sum of separate flux components:

$$Q = Q_{SW} - Q_{LW} - Q_S - Q_L$$


$$Q = Q_{SW} - Q_{LW} - Q_S - Q_L$$

Insolation Q_{SW}

-the flux of sunlight into the sea (short wave radiation)

Net Infrared Radiation Q_{LW}

- net flux of infrared radiation from the sea (i.e. long wave radiation emitted by the ocean surface minus long wave radiation emitted by the atmosphere in the direction of the ocean – the greenhouse effect is hidden here);

Sensible Heat Flux Q_S

- the flux of heat out of the sea due to conduction (i.e. heat transfer by turbulent convection between two surfaces with different temperatures);

Latent Heat Flux Q_L

-the flux of heat carried by evaporated water;

$$Q = Q_{SW} - Q_{LW} - Q_S - Q_L$$

Calculating surface fluxes: Bulk formulas for calculating the surface fluxes (including the wind stress)

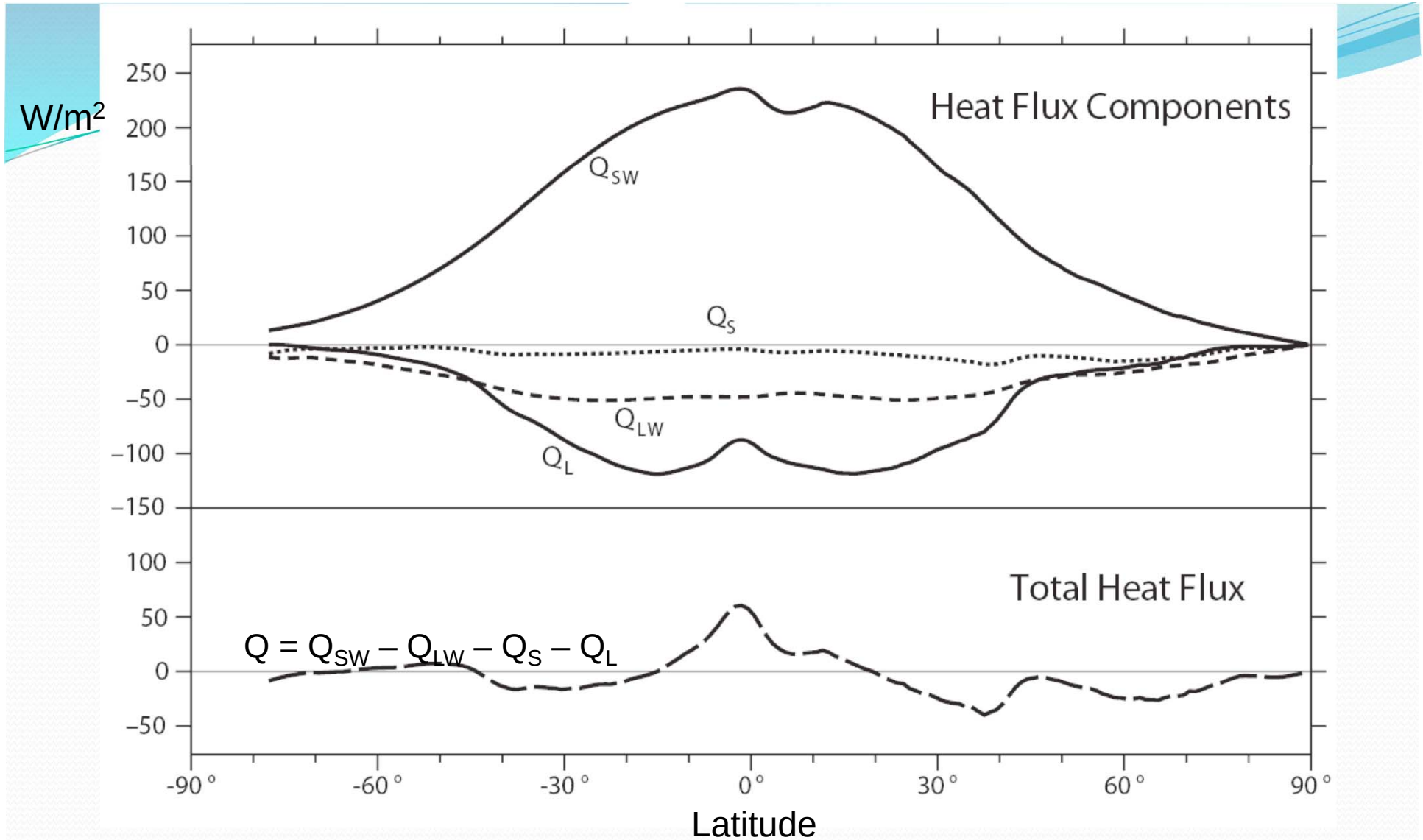
$$\tau = \rho_a C_D U_{10}^2$$

$$Q_S = \rho_a C_p C_S U_{10} (t_s - t_a)$$

$$Q_L = \rho_a L_E C_L U_{10} (q_s - q_a)$$

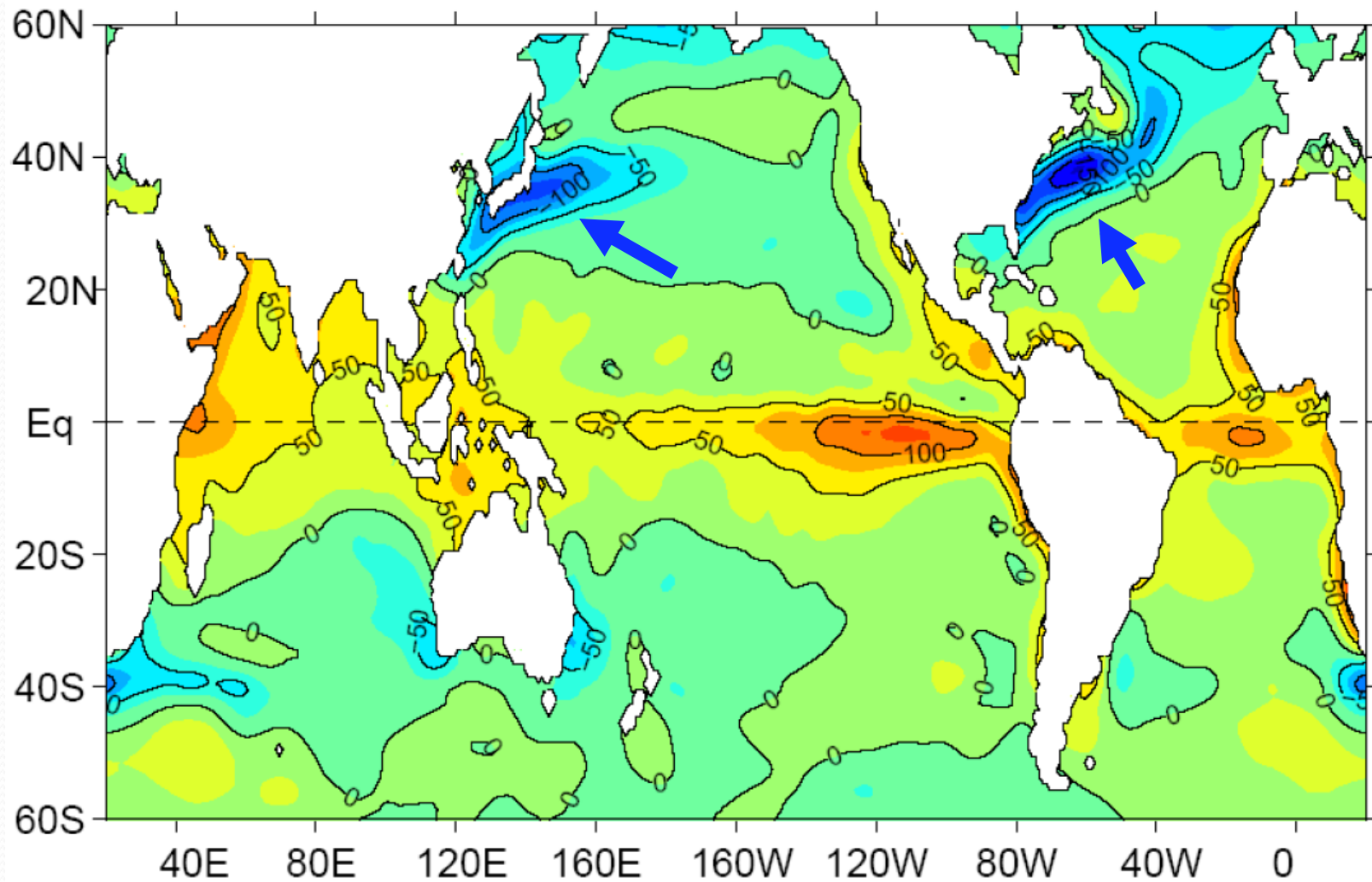
U_{10} – wind speed at 10 m above the sea level (mean values is 7.4m/s); ρ_a – density of air

C_p	Specific heat capacity of air	$1030 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$
C_D	Drag coefficient (see 4.3)	$(0.50 + 0.071 U_{10}) \times 10^{-3}$
C_L	Latent heat transfer coefficient	1.2×10^{-3}
C_S	Sensible heat transfer coefficient	1.0×10^{-3}
L_E	Latent heat of evaporation	$2.5 \times 10^6 \text{ J/kg}$
q	Specific humidity of air	kg (water vapor)/kg (air)
q_a	Specific humidity of air 10 m above the sea	kg (water vapor)/kg (air)
q_s	Specific humidity of air at the sea surface	kg (water vapor)/kg (air)
Q_S	Sensible heat flux	W/m^2
Q_L	Latent heat flux	W/m^2
τ	Wind stress	Pascals
t_a	Temperature of the air 10 m above the sea	K or °C
t_s	Sea-surface temperature	K or °C



Upper panel: Zonal averages of heat transfer to the ocean by insolation Q_{SW} , and loss by net infrared radiation Q_{LW} , sensible heat flux Q_S , and latent heat flux Q_L . **Lower panel:** Net download heat flux through the sea surface calculated from the data above (DaSilva et al 1995).

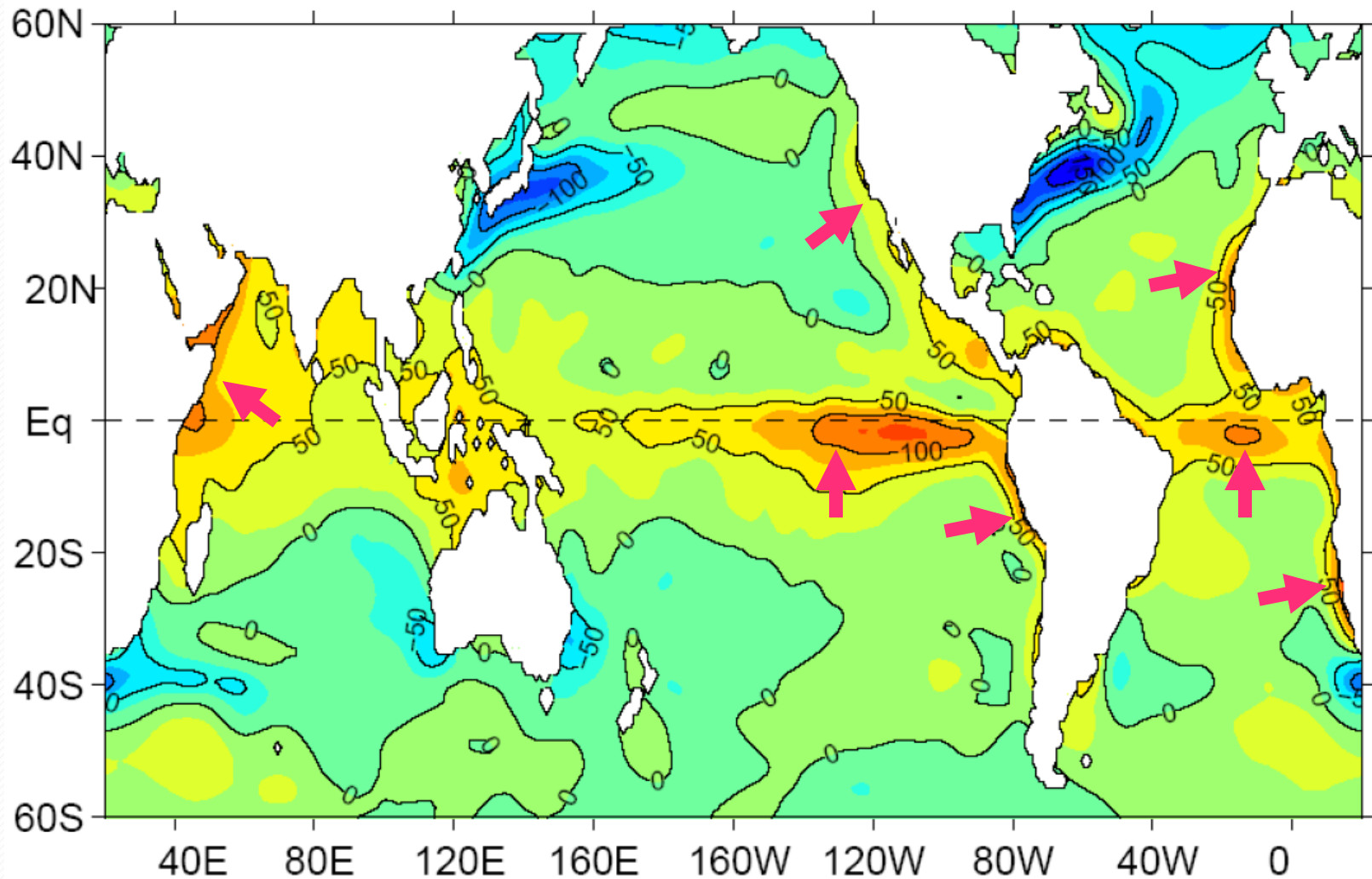
Net downward heat flux into the ocean, W/m^2



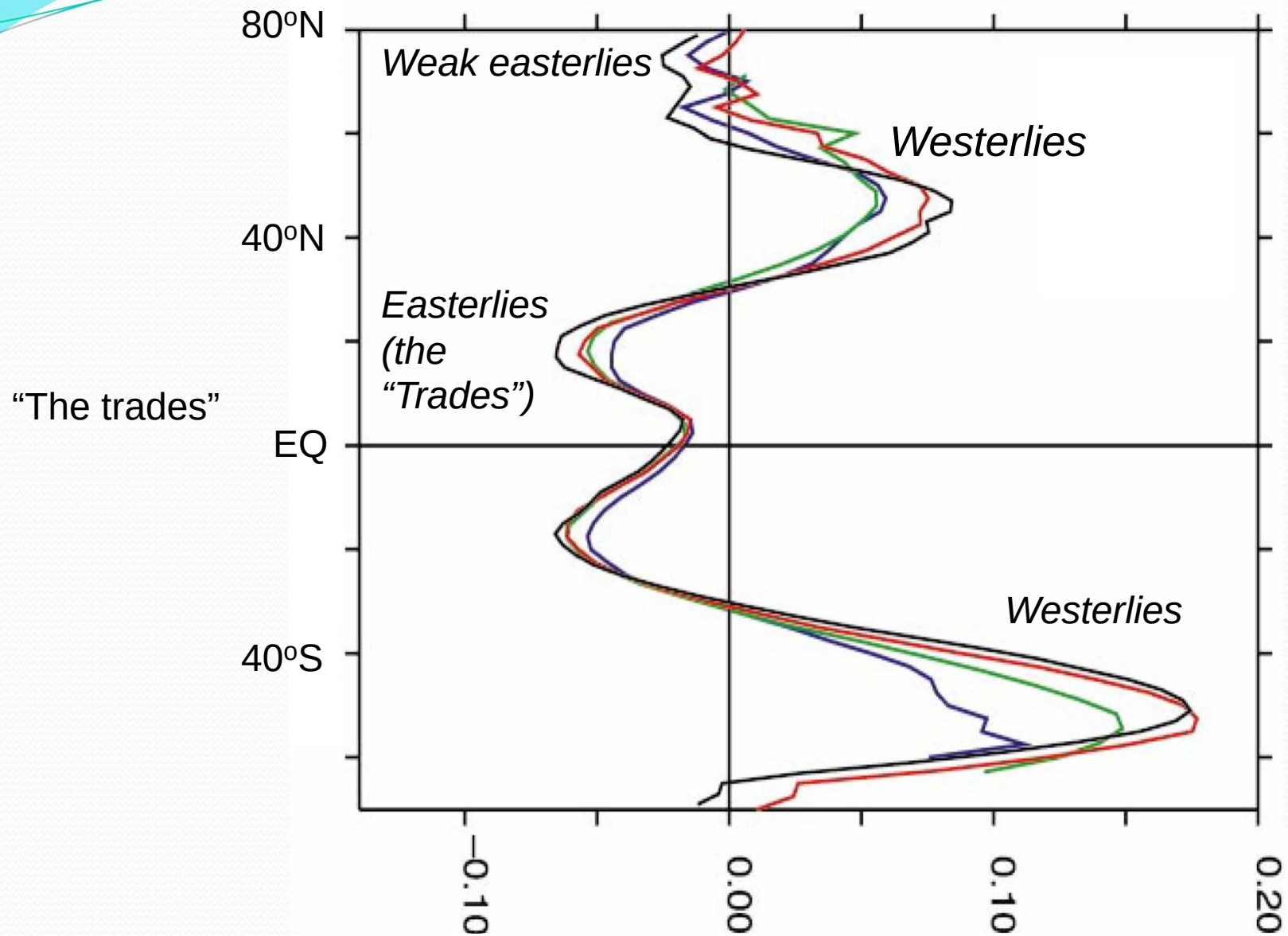
Comment 1 (importance of evaporative cooling or latent heat flux Q_L):

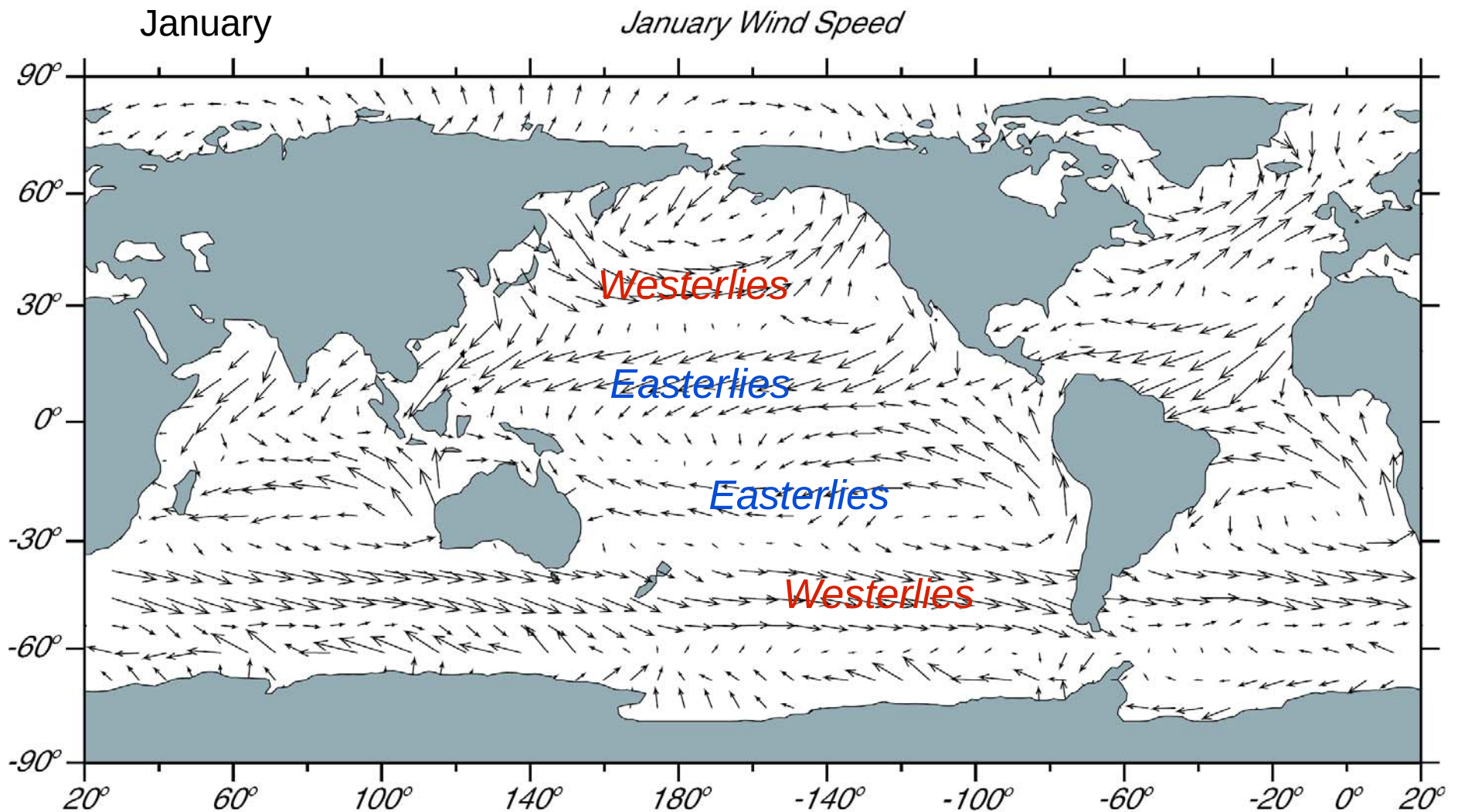
The regions of heat gain are mostly the regions of upwelling – equatorial or coastal; short wave radiation is important!

Net downward heat flux into the ocean, W/m^2



Mean zonal-averaged wind stress (Pa) over the ocean





Mean, sea-surface winds for January (Trenberth et al 1990). The winds near 140°W in the equatorial Pacific are about 8 m/s.

Note (1): The combination Easterlies/ Westerlies drive subtropical gyres
(2): the strong Westerlies in the Southern Hemisphere drive the ACC

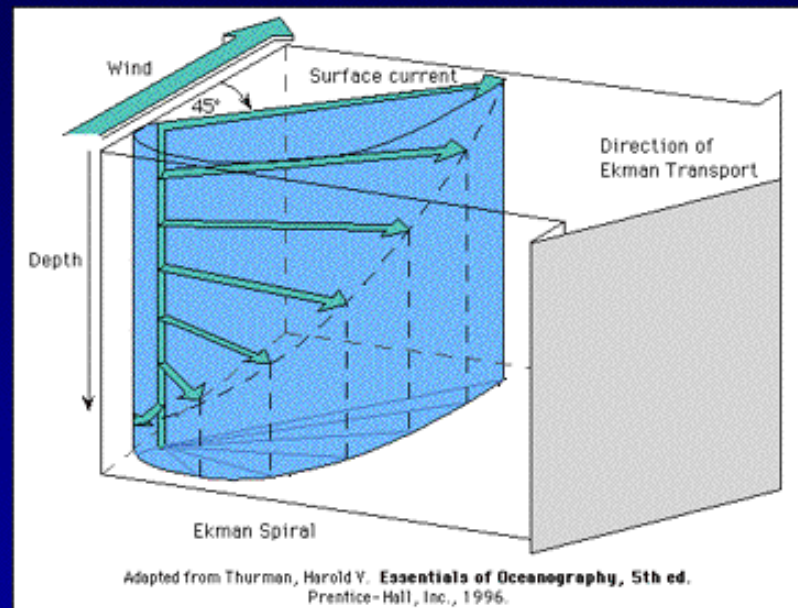
***Ocean upwelling and downwelling
(vertical mass transport)***

1.wind-driven

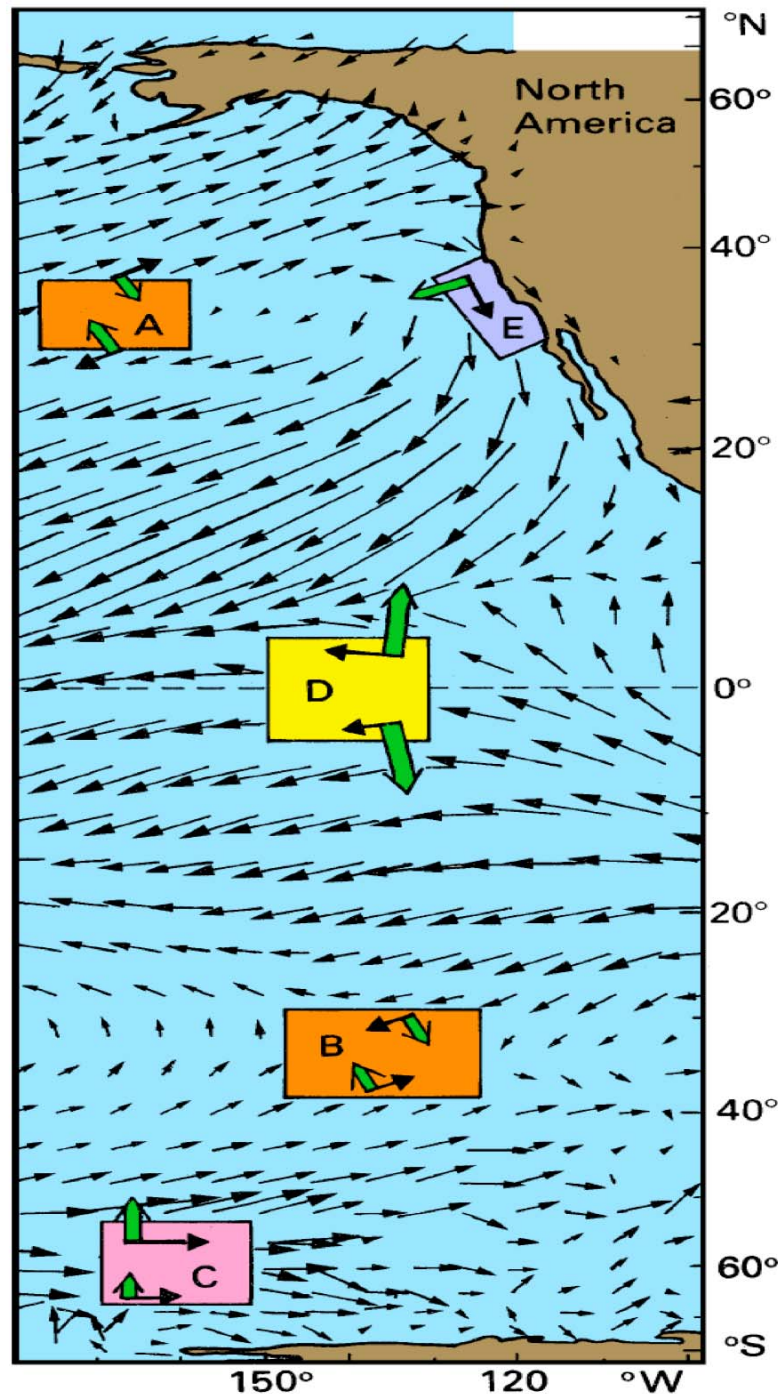
2.driven by mixing and convection

Ekman layer "transport", depth, velocity

- "Transport": 90° to wind, to right in NH and left in SH, $U_{Ek} = \tau / \rho f$ (units are m^2/s , not m^3/s so technically this is not a transport; need to sum horizontally along a section to get a transport).



- Typical size: for wind stress 0.1 N/m^2 , $U_{Ek} = 1 \text{ m}^2/s$. Integrate over width of ocean, say 5000 km , get total transport of $5 \times 10^6 \text{ m}^3/\text{sec} = 5 \text{ Sv}$.

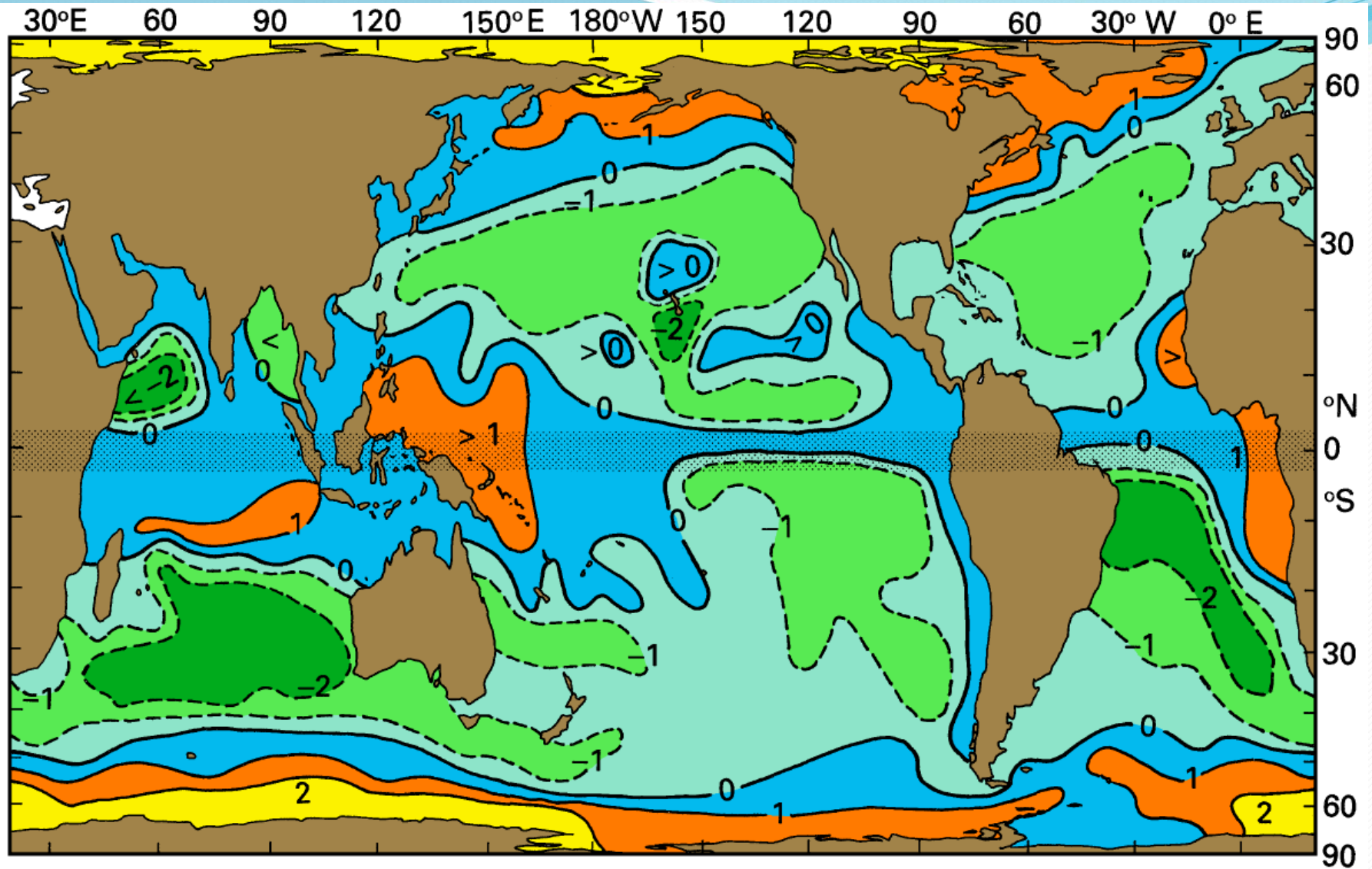


Examples of Ekman transport and Ekman pumping in the eastern Pacific Ocean. Full arrows indicate the wind, open arrows the Ekman transport resulting from the corresponding wind stress.

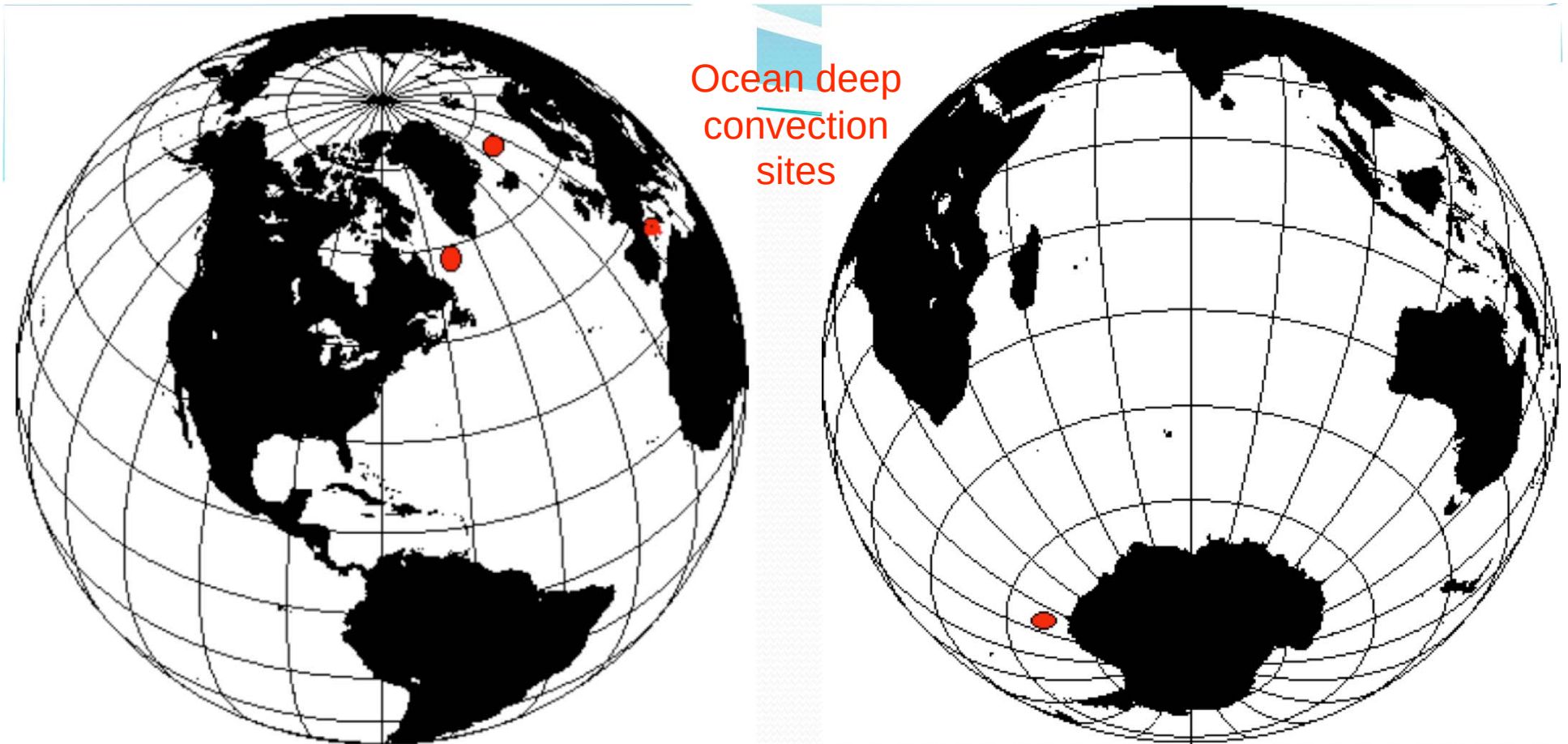
Note the change of direction of the Ekman transport relative to the wind across the equator and the decrease of the Ekman transport, for equivalent wind stresses, with distance from the equator.

Boxes A and B : Ekman transport convergence, Ekman pumping, downwelling;

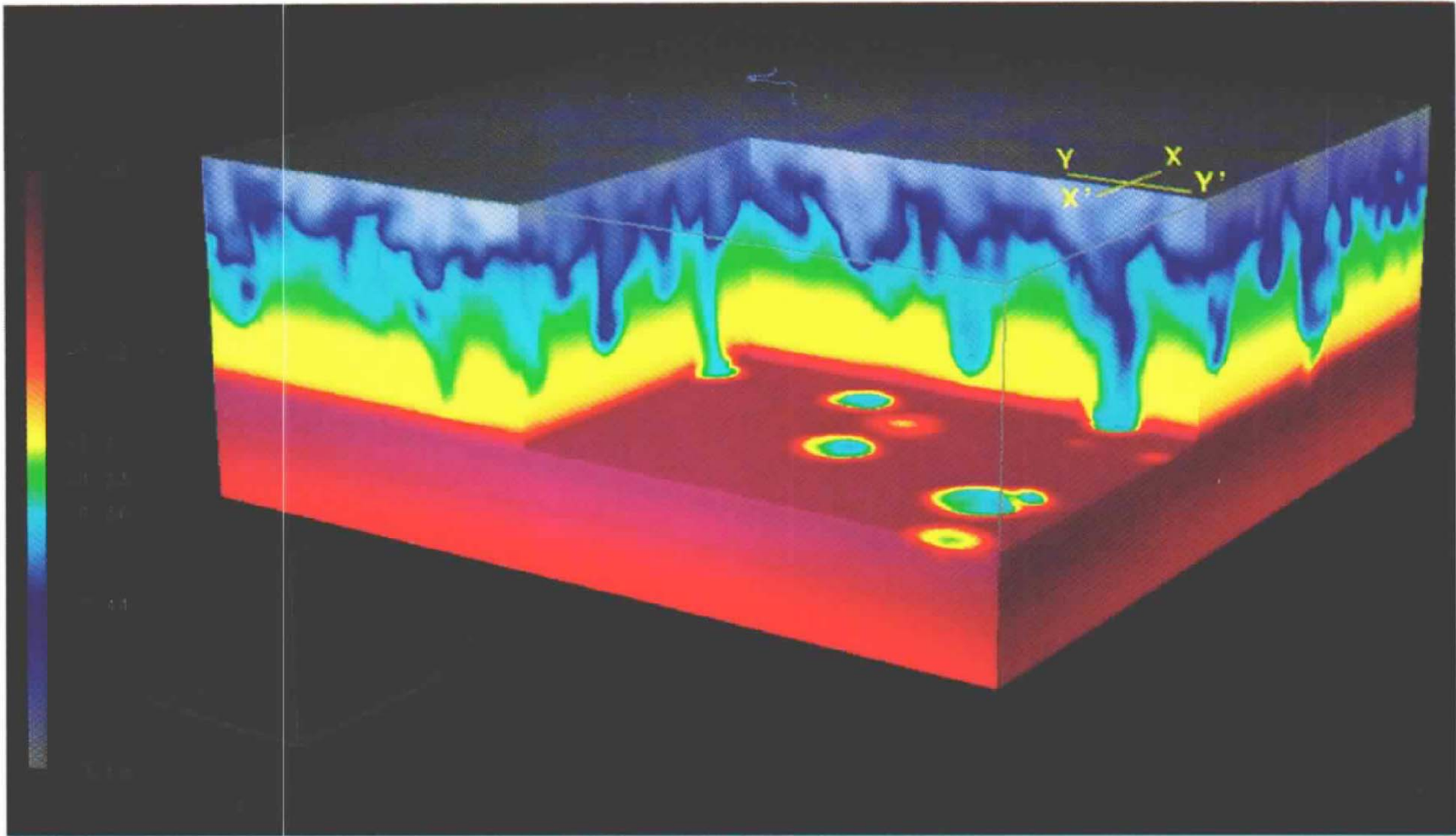
Boxes E,D,C: Ekman transport divergence, Ekman suction, upwelling



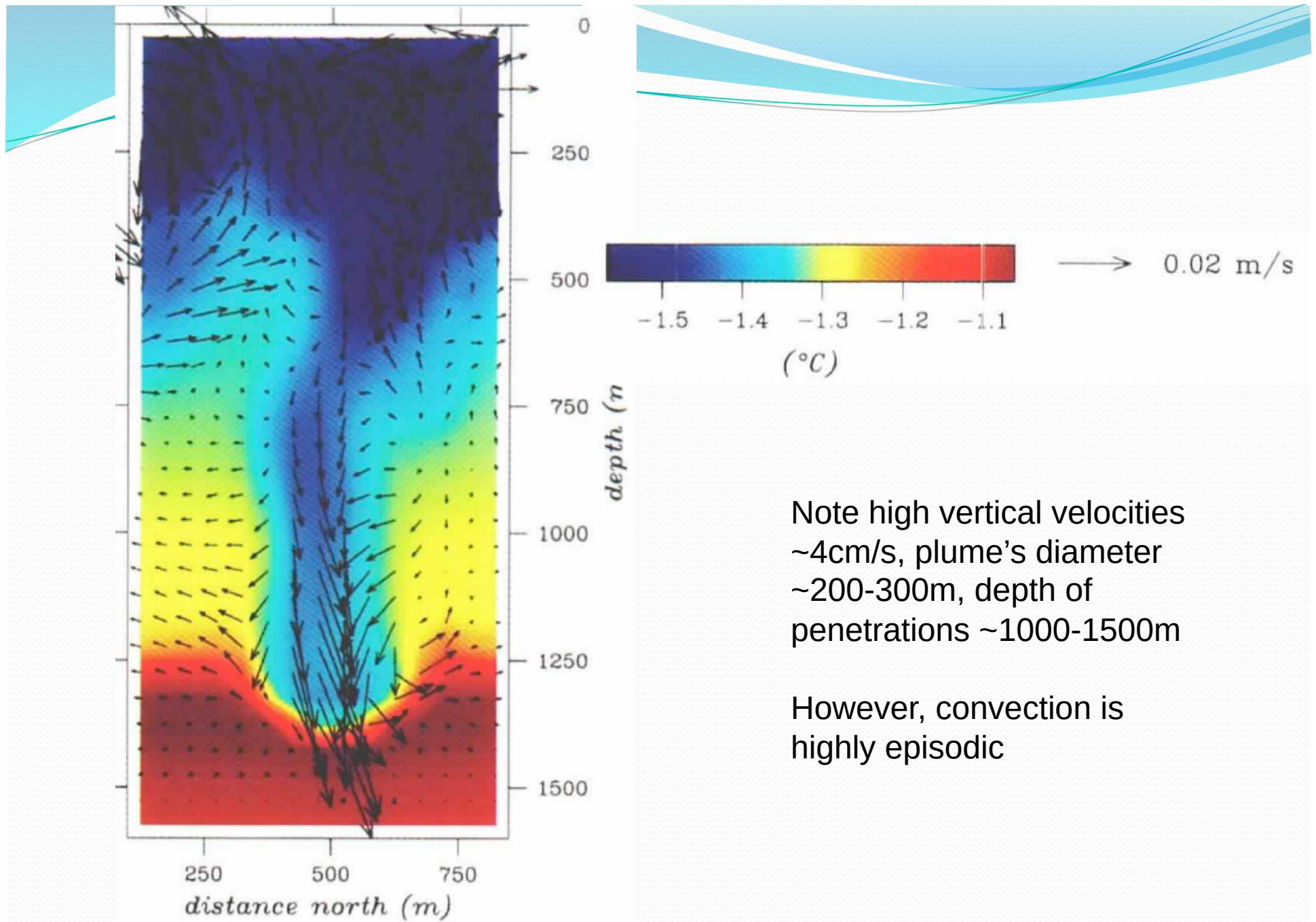
Annual mean distribution wind-driven upwelling/downwelling (10^{-6} m/s). Positive numbers indicate upwelling.



*Locations of **offshore** deep-water formation sites: in the southern hemisphere in **the Weddell and Ross Seas** off the Antarctic coast (where Antarctic Bottom Water is formed) and in the northern hemisphere in **the Labrador and Greenland Seas** (where North Atlantic Deep Water is formed). The North-Western Mediterranean site, while the least important, remains the best observed.*



Convective plumes: the plume's horizontal scale in the ocean $< 1\text{km}$





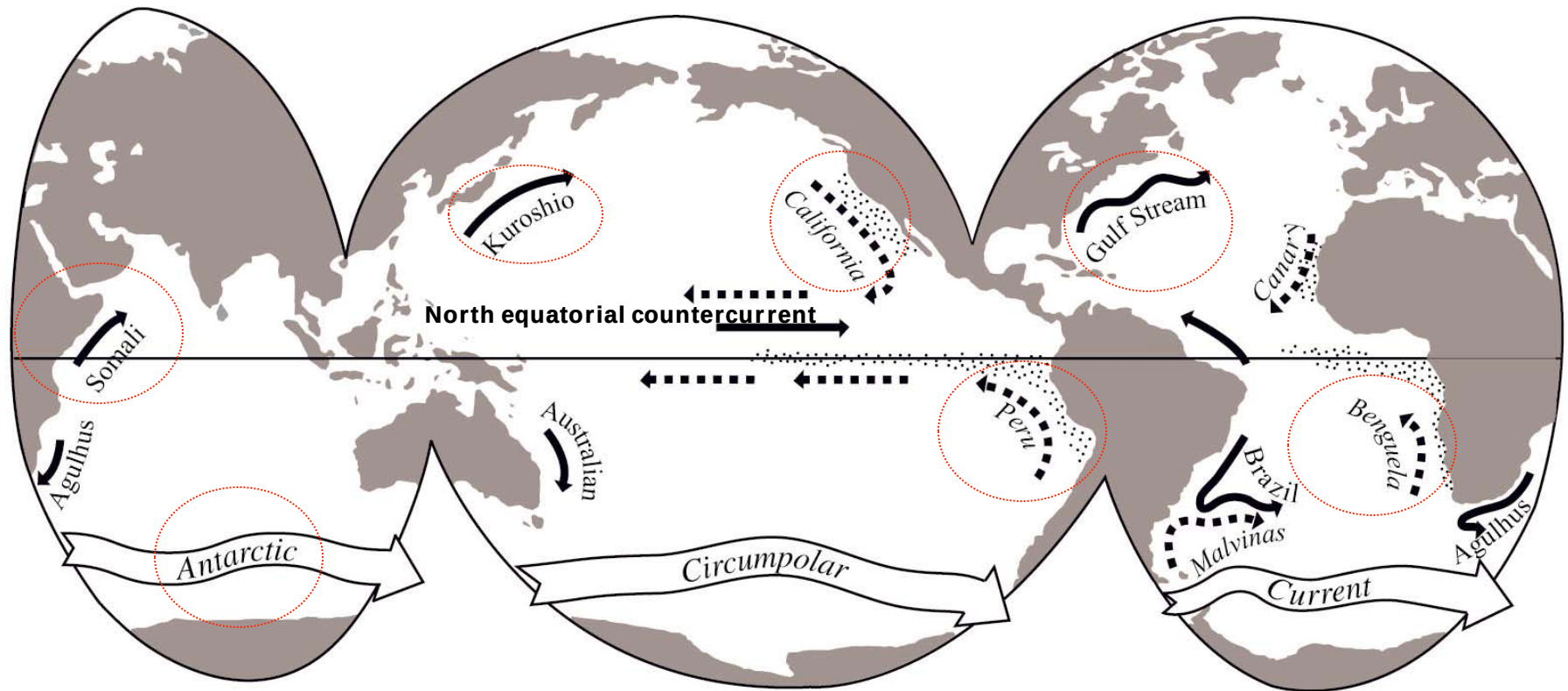
Ocean general circulation:

1. Wind-driven circulation

(relatively shallow, relatively fast)

2. The thermohaline circulation (includes abyssal circulation) – circulation that depends on large-scale meridional gradients of temperature and salt

Ocean wind-driven circulation



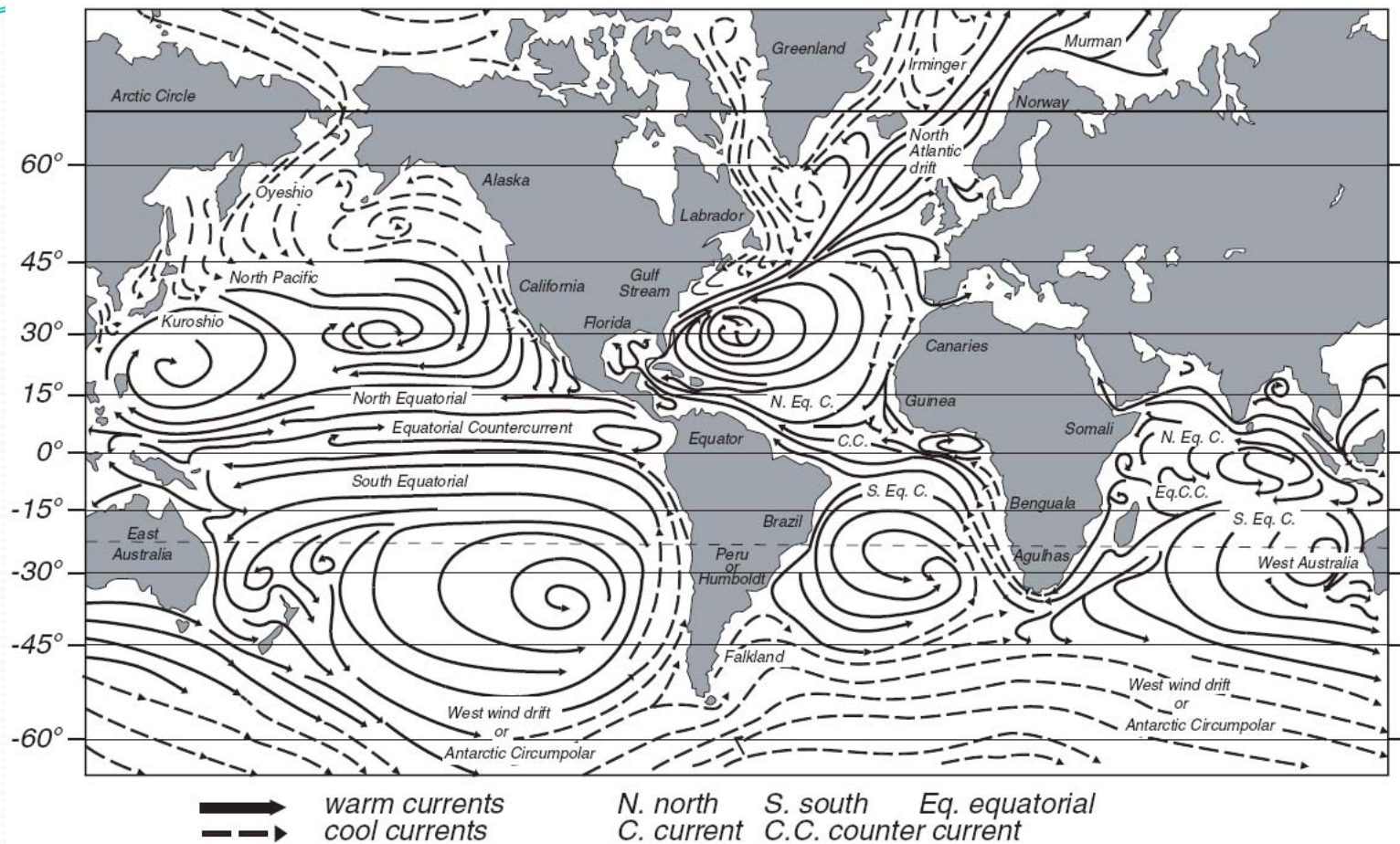
Regions of Upwelling



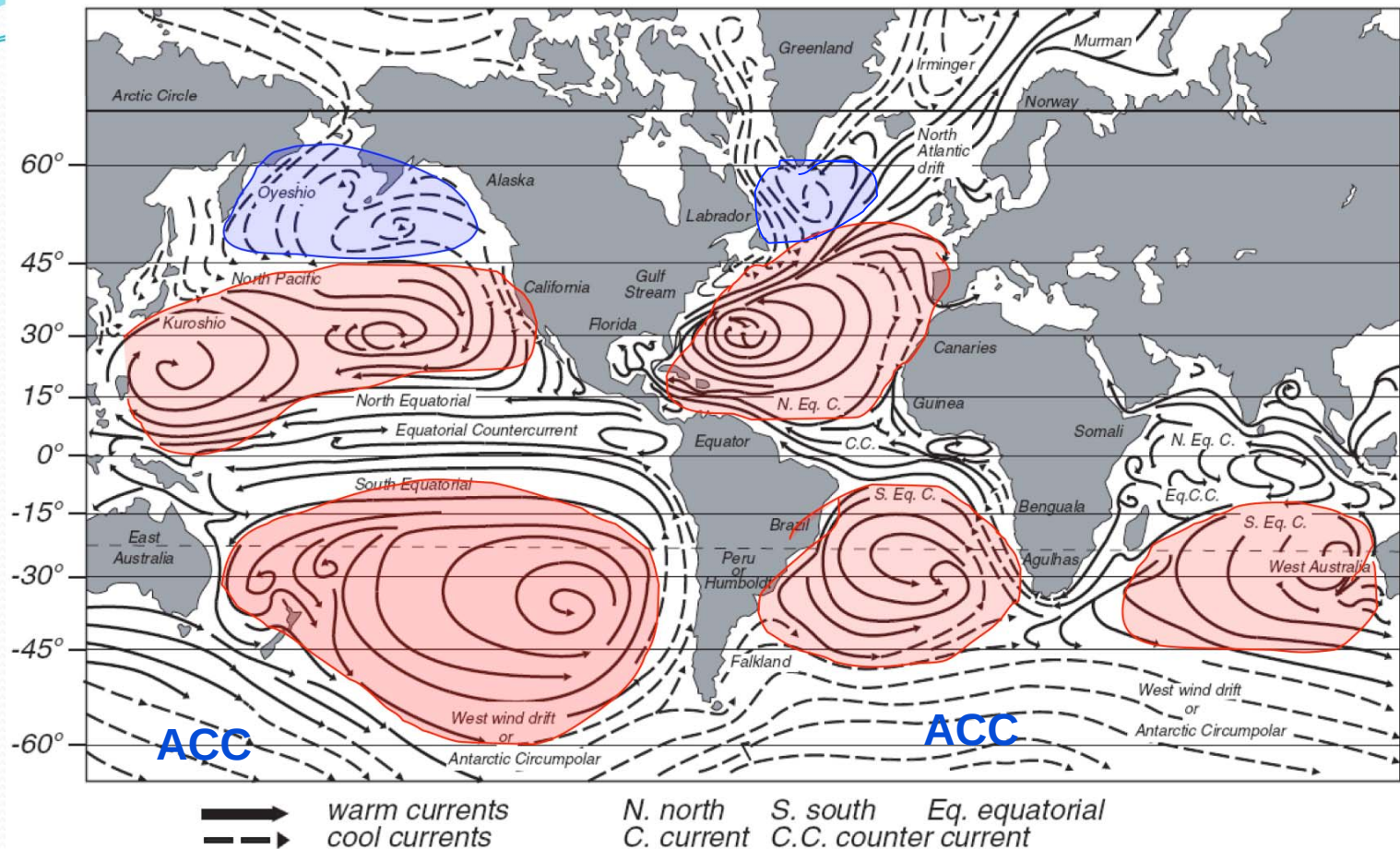
Warm Currents



Cold Currents



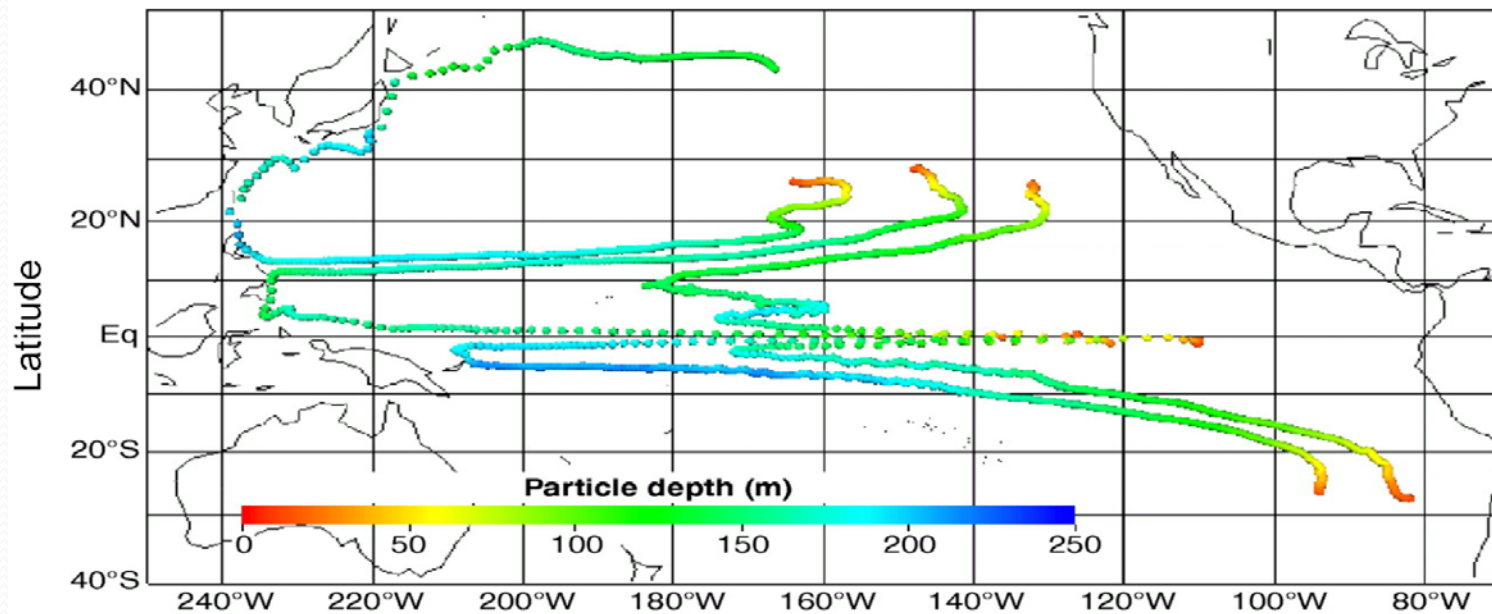
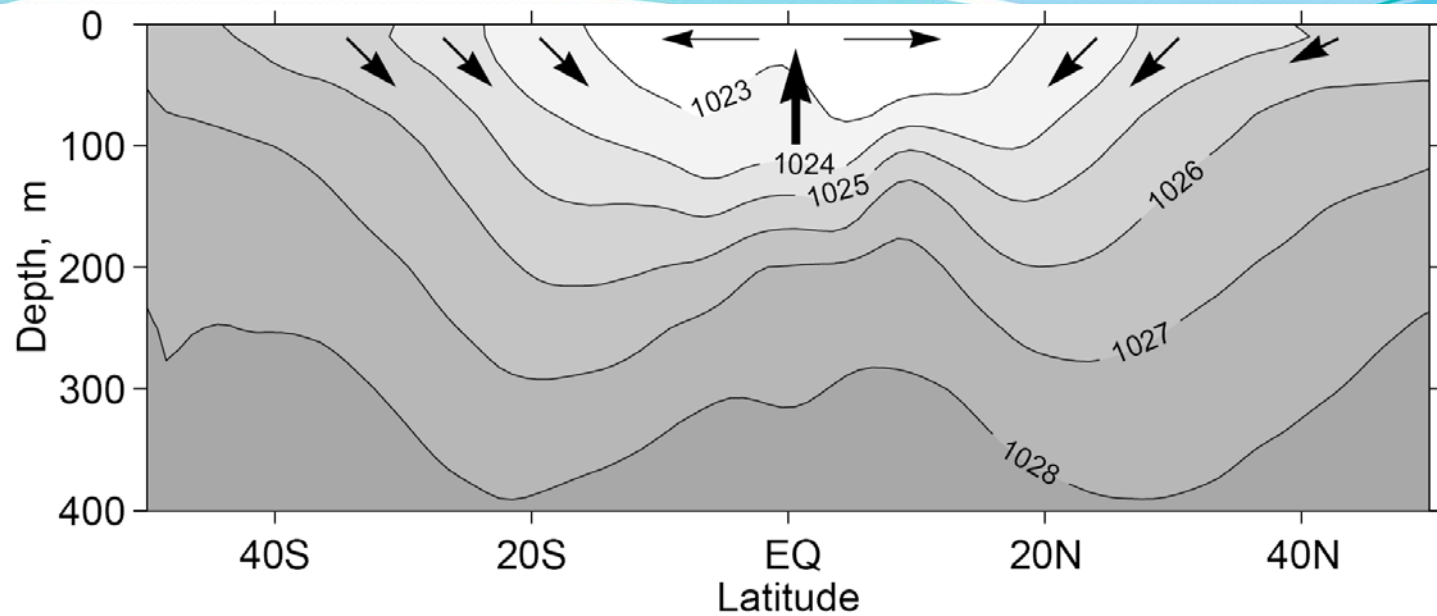
The time-averaged, surface circulation (mostly-wind-driven) of the ocean during northern hemisphere winter deduced from a century of oceanographic expeditions. After Tolmazin (1985).

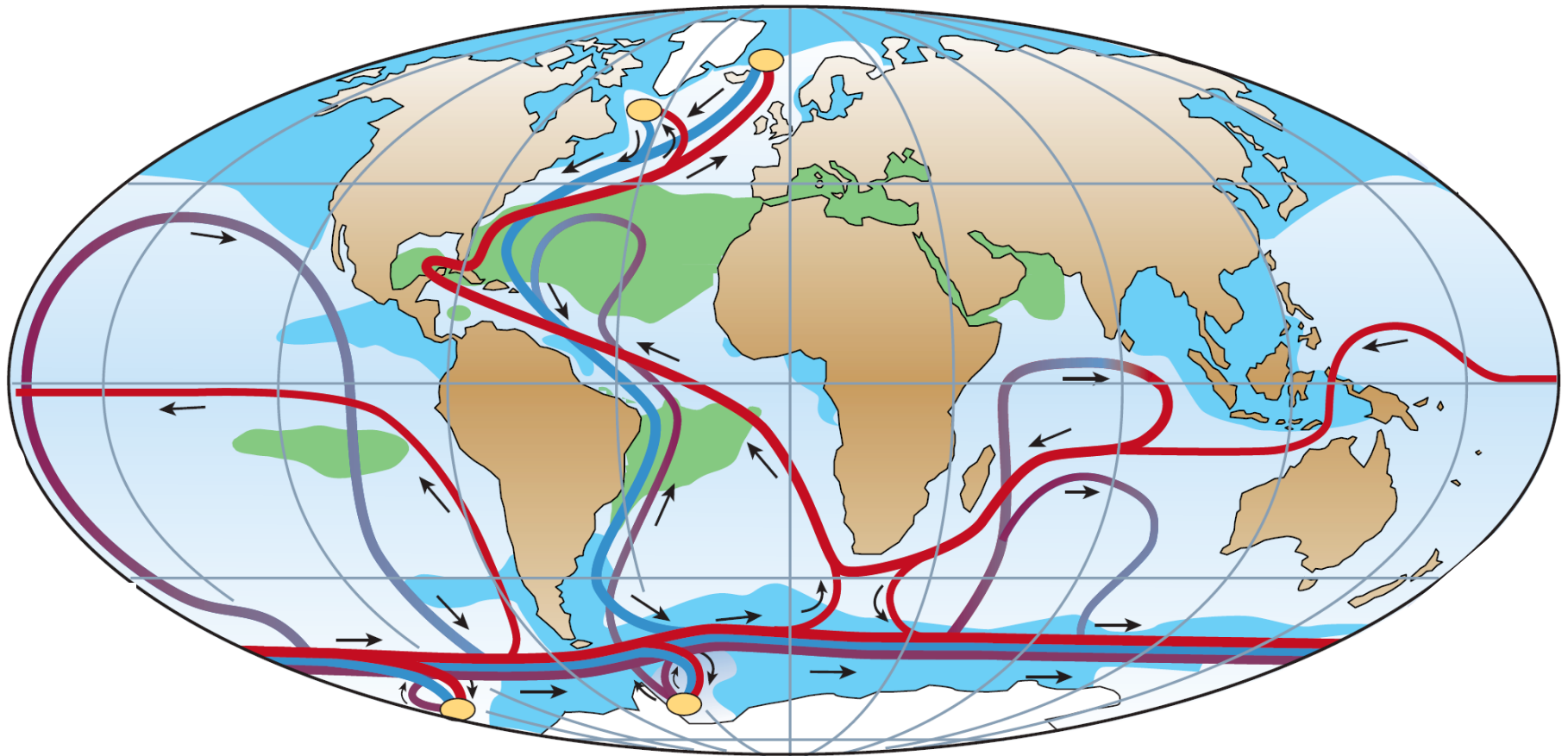


Main components of the ocean wind-driven circulation:

- 1) Subtropical gyres
- 2) Subpolar gyres
- 3) Equatorial circulation
- 4) The Antarctic Circumpolar current (ACC)

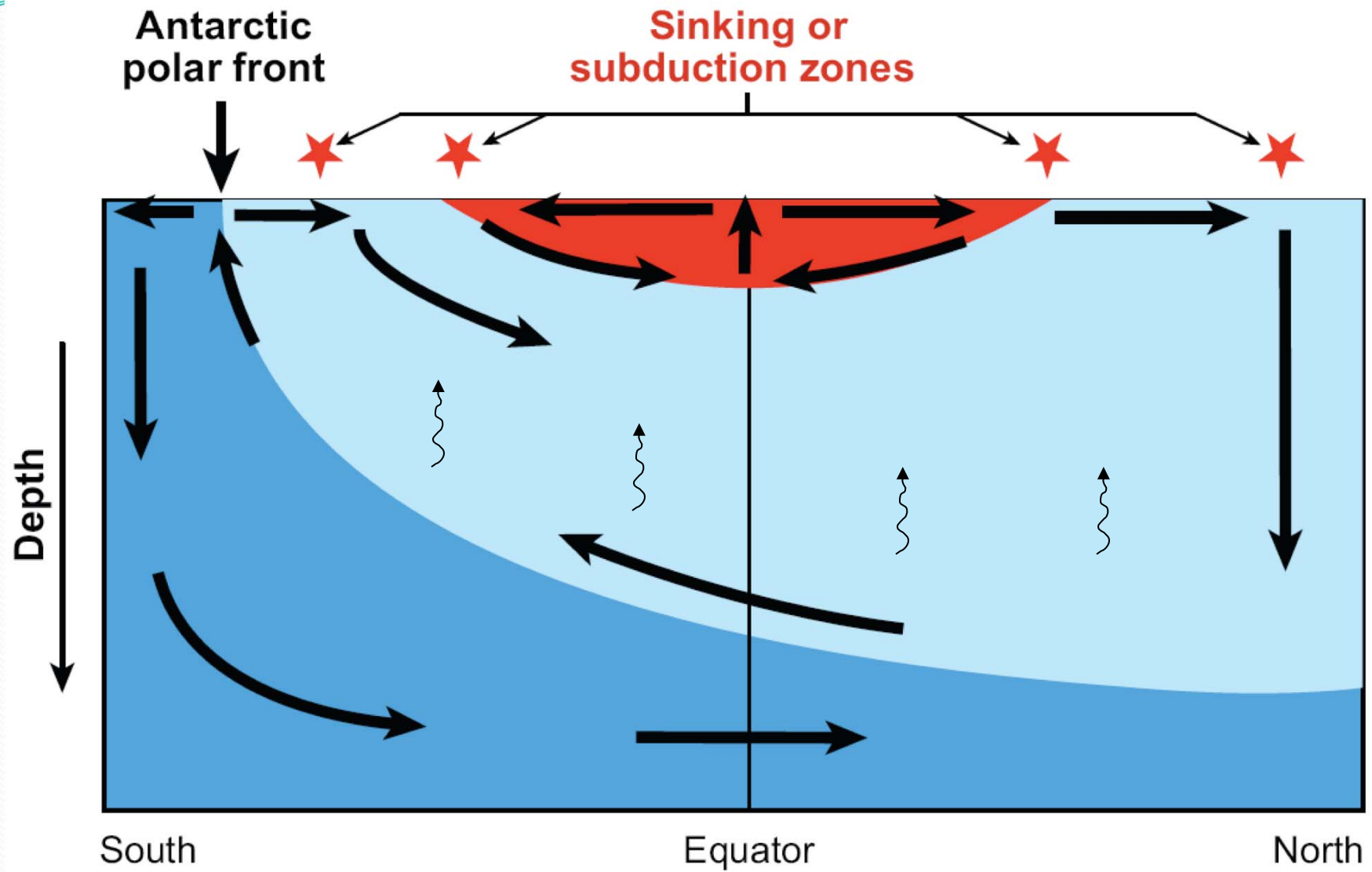
Water-parcel (Lagrangian) representation of the wind-driven circulation





A simplified cartoon of the global **thermohaline circulation** (the so-called 'conveyor belt', originally by Broecker, After Rahmstorf).

Ocean meridional overturning



Barreiro, Fedorov and co-authors 2007

Scales: ocean general circulation

Horizontal spatial scale: 100 to 10000 of kilometers

Vertical spatial scale: 1 to 5 km

Aspect ratio: $H/L = O(0.01)$ to $O(0.001) \ll 1$

Time scales: many years (from annual to, to decadal, to 100s of years). Seasonal, interannual to decadal/century fluctuation in flows which may or may not retain the same patterns.

Average current speeds:

1-5 cm/sec (horizontal) in the interior of the ocean,

50-150 cm/sec (horizontal) in the fastest currents such as the Gulf Stream and the Antarctic Circumpolar Current.

The vertical velocity for the general circulation is on the order of 10^{-4} cm/sec and is almost always inferred, not measured.