Meridional Overturning Circulation

Physics and Dynamics of the Ocean
2022-2023

1) MOC dynamics in a nutshell
2) Ocean Heat Transport

Abyssal circulation dynamics

Thermohaline = temperature and salinity processes

Thermohaline processes that most strongly impact deep waters:

1. deep convection: 1000 to 1500 dbar (or more) overturn due to buoyancy loss (mostly cooling that causes densification)
2. brine rejection: salt rejected from sea ice during formation, most effective when mixed into a shallow layer, say, on a continental shelf. B.R. in some special sites makes the densest ocean waters.
3. diffusion: mixing of heat and salt. Diapycnal diffusion is essential for deep waters to warm and upwell diapycnally (balances the other two densification processes)

Abyssal circulation dynamics

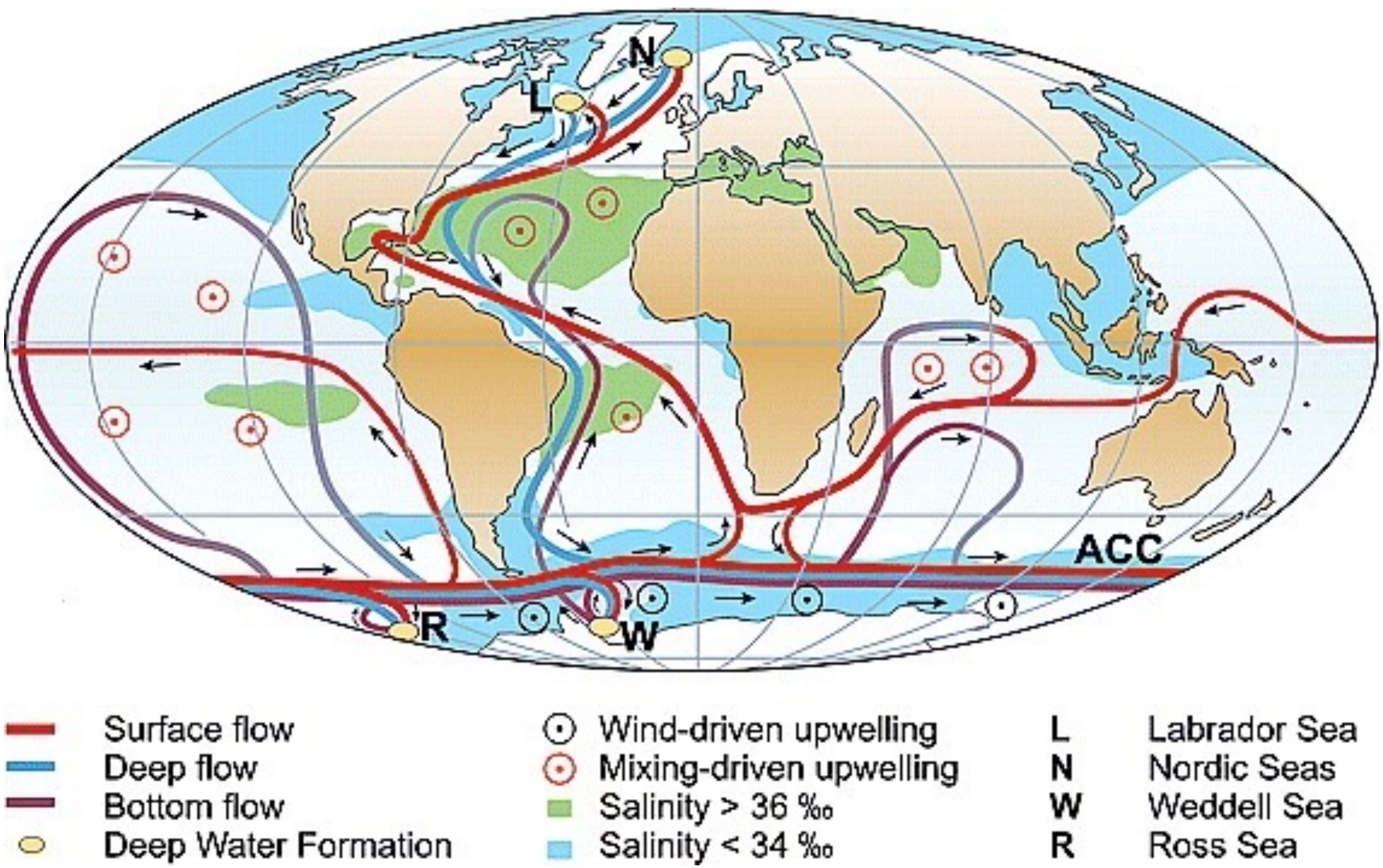
Controversy on names:

"Thermohaline circulation": widely used to describe this very large-scale overturn. Involves sources of dense water and Deep Western Boundary Currents and return warm flow to feed the isolated dense sources. Caveat: thermohaline forcing can also be important on more local scales and in the upper ocean

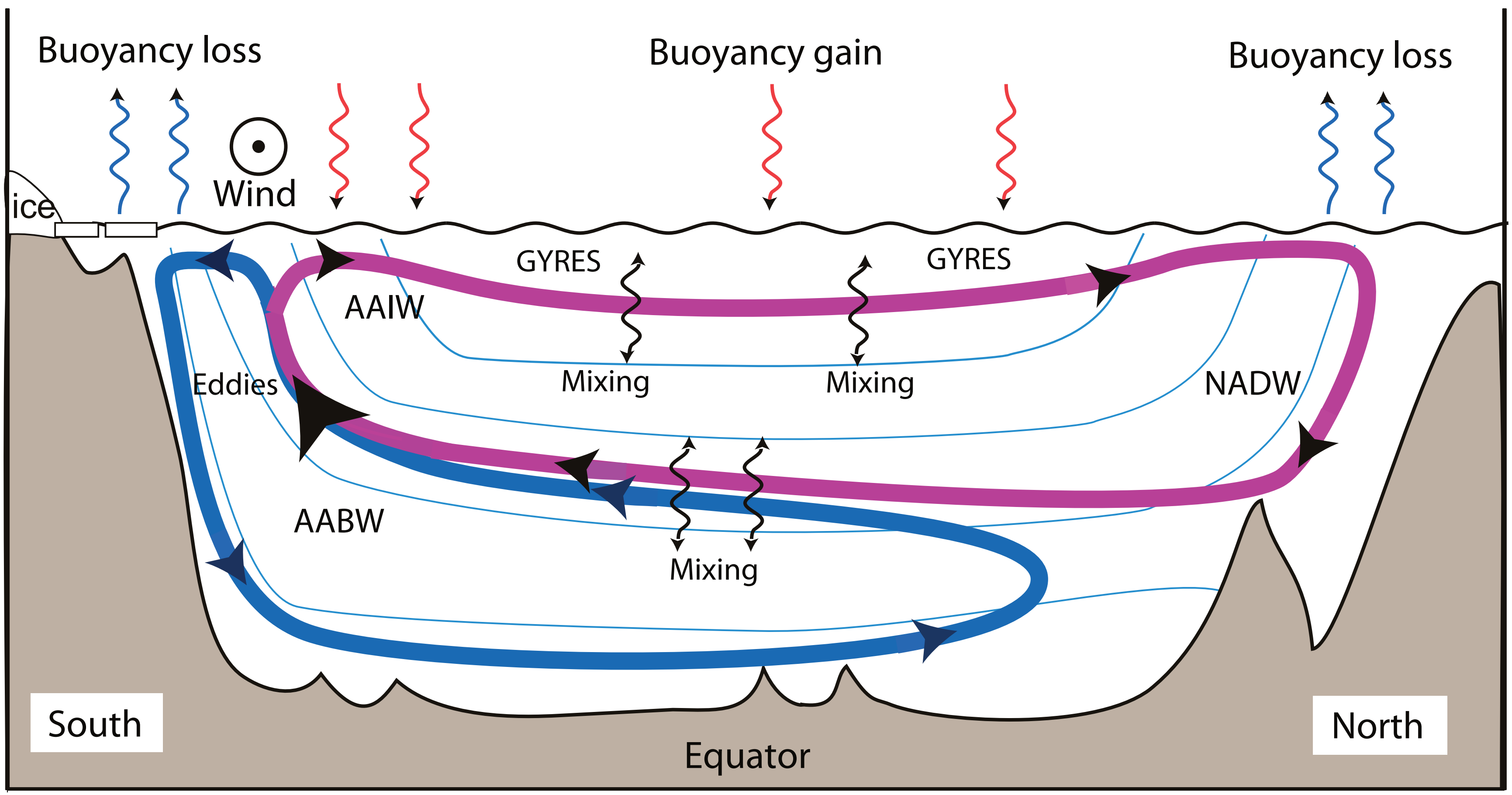
In physical oceanography, we also refer to "abyssal circulation" when discussing the theory of deep circulation (*See Stommel-Aaron's Model*)

"Meridional overturning circulation": essentially the same as THC, but acknowledging that diffusion is a very important factor in controlling the flow, that diffusion itself does not result from thermohaline forcing (but from turbulence due to the **wind** and **tides**), and that wind also upwells deep waters

Meridional Overturning Circulation

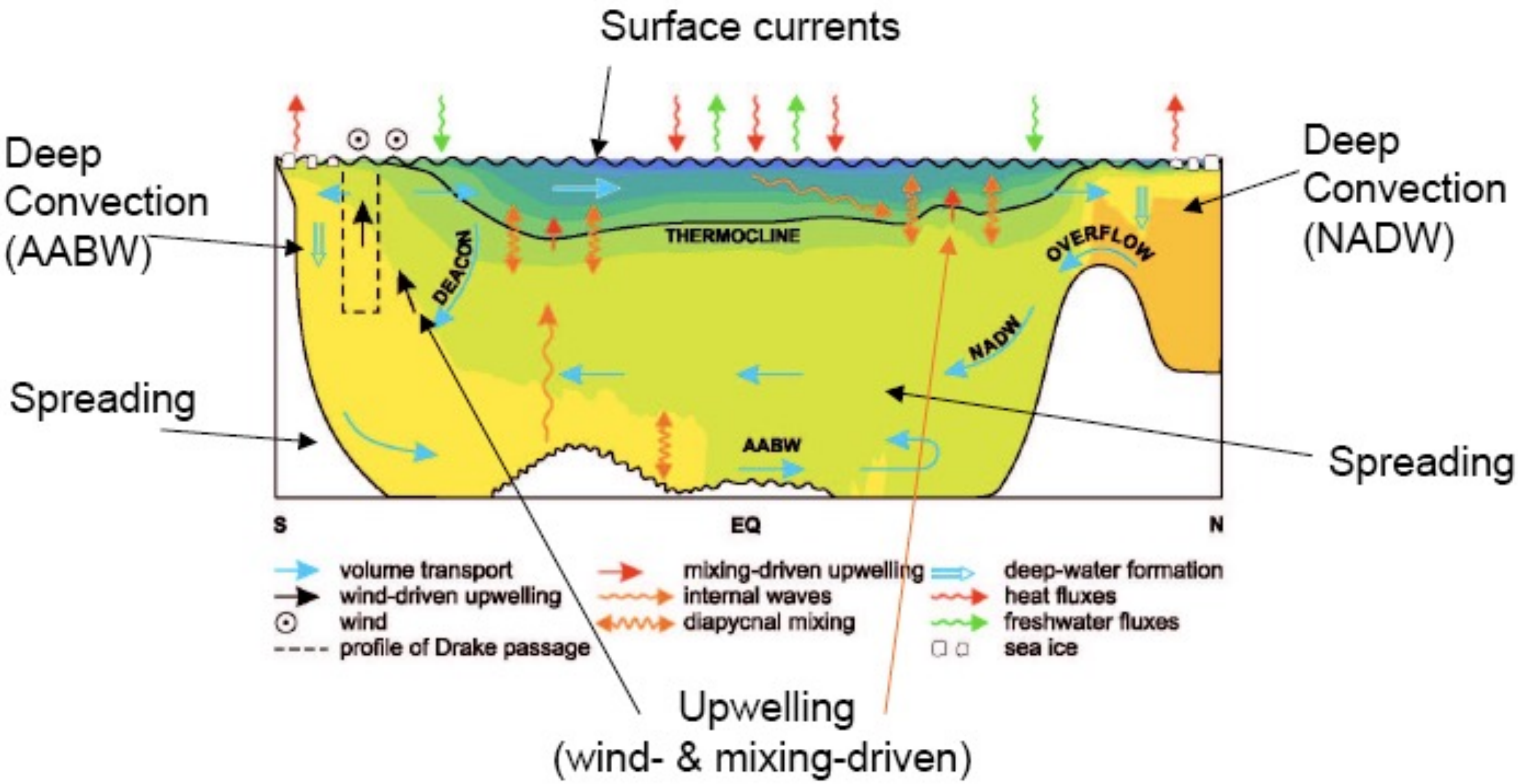


Buoyancy and Wind-driven MOC



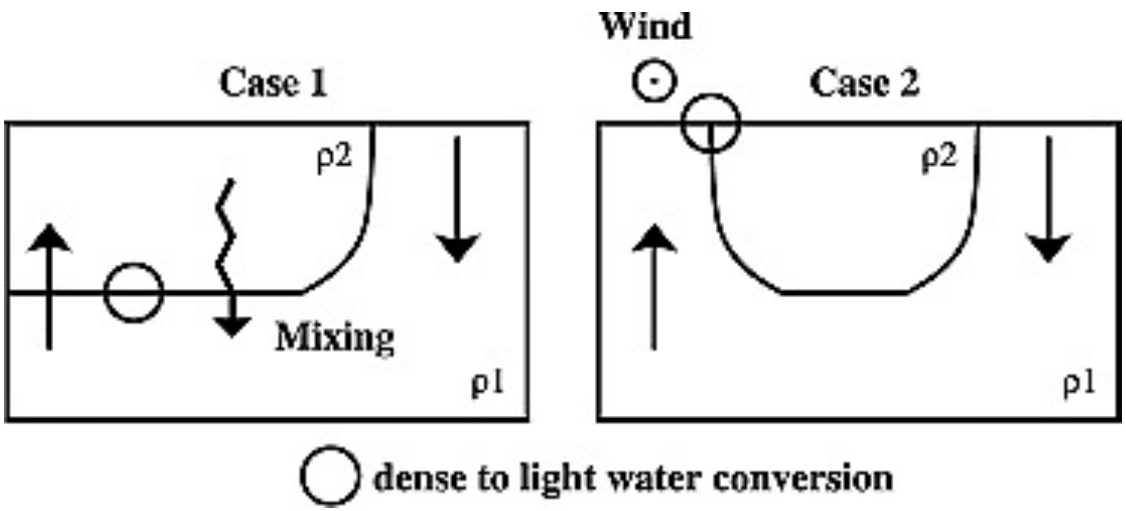
What is thermo-haline circulation (THC) ?

THC is that part of the ocean circulation which is driven by fluxes of heat and freshwater across the sea surface and subsequent interior mixing of heat and salt.



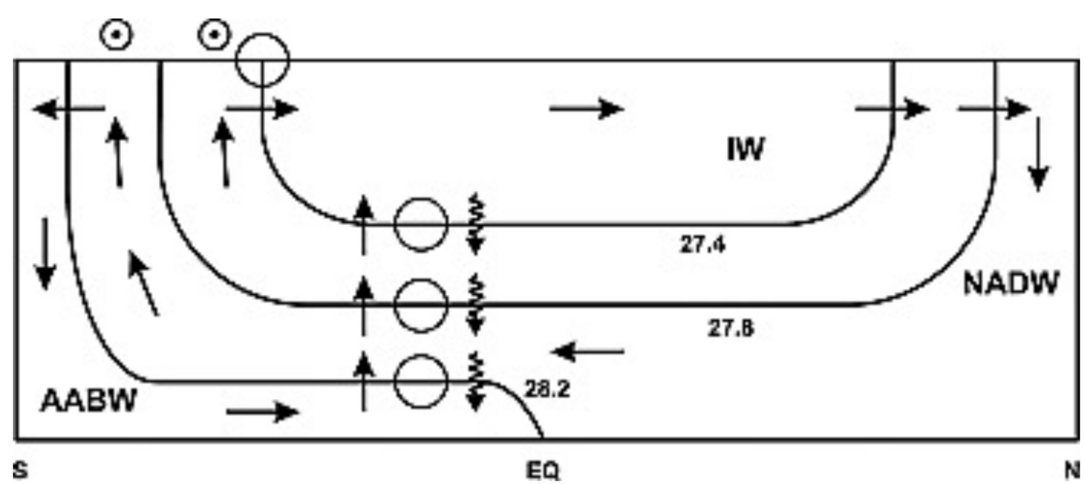
Its drivers are: (a) turbulent diapycnal mixing, (b) wind-driven upwelling in the Southern Ocean

Mixing & Winds



Sketch of the two extreme cases: “only diapycnal mixing” (case 1) and “only wind-driven upwelling” (case 2). The curved line indicates the thermocline that separates denser from lighter waters. The open circles indicate regions of dense-to-light conversion of water masses.

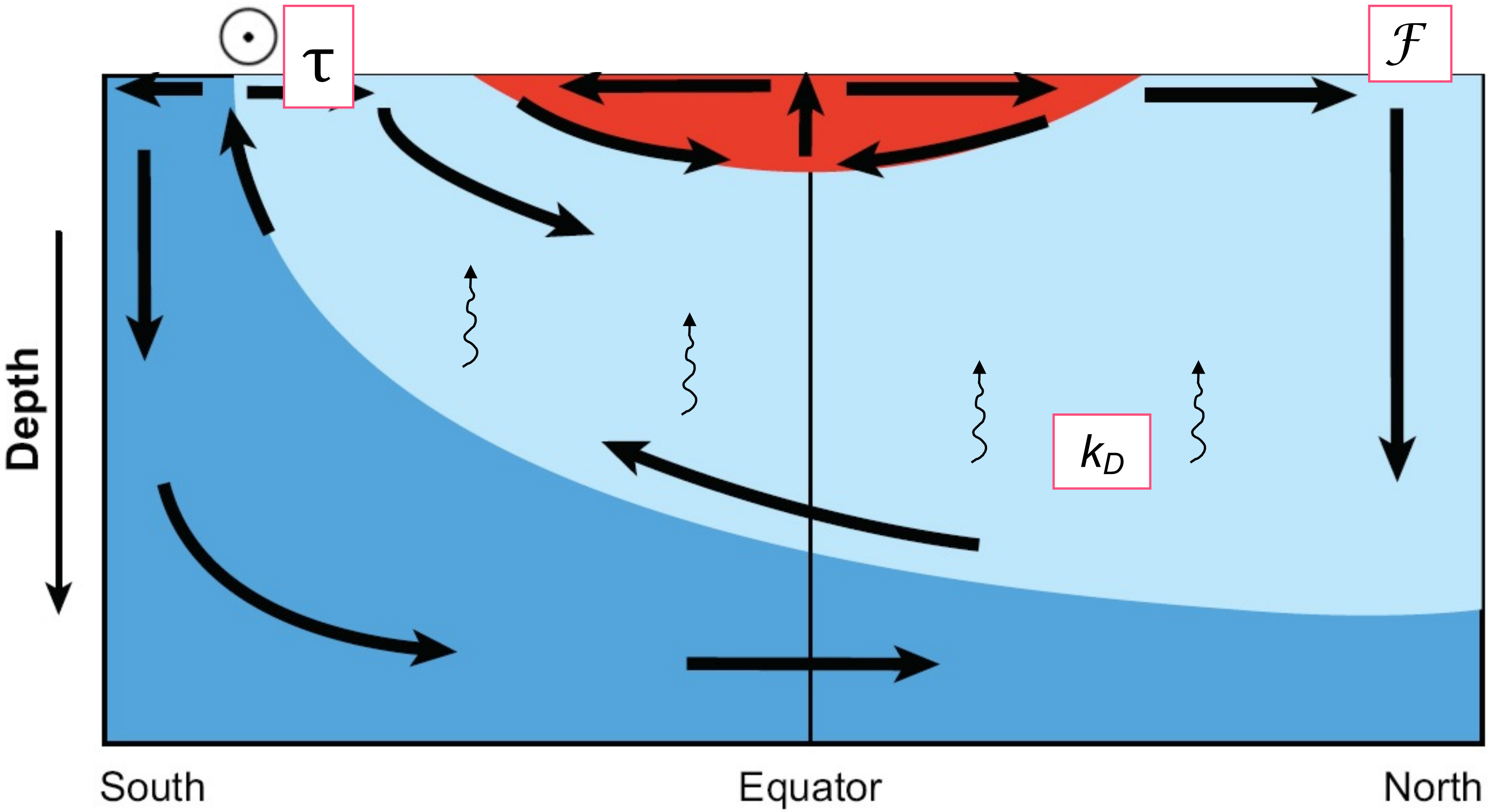
Schema of the AMOC. The two cells are driven by both diapycnal mixing and wind-driven upwelling.



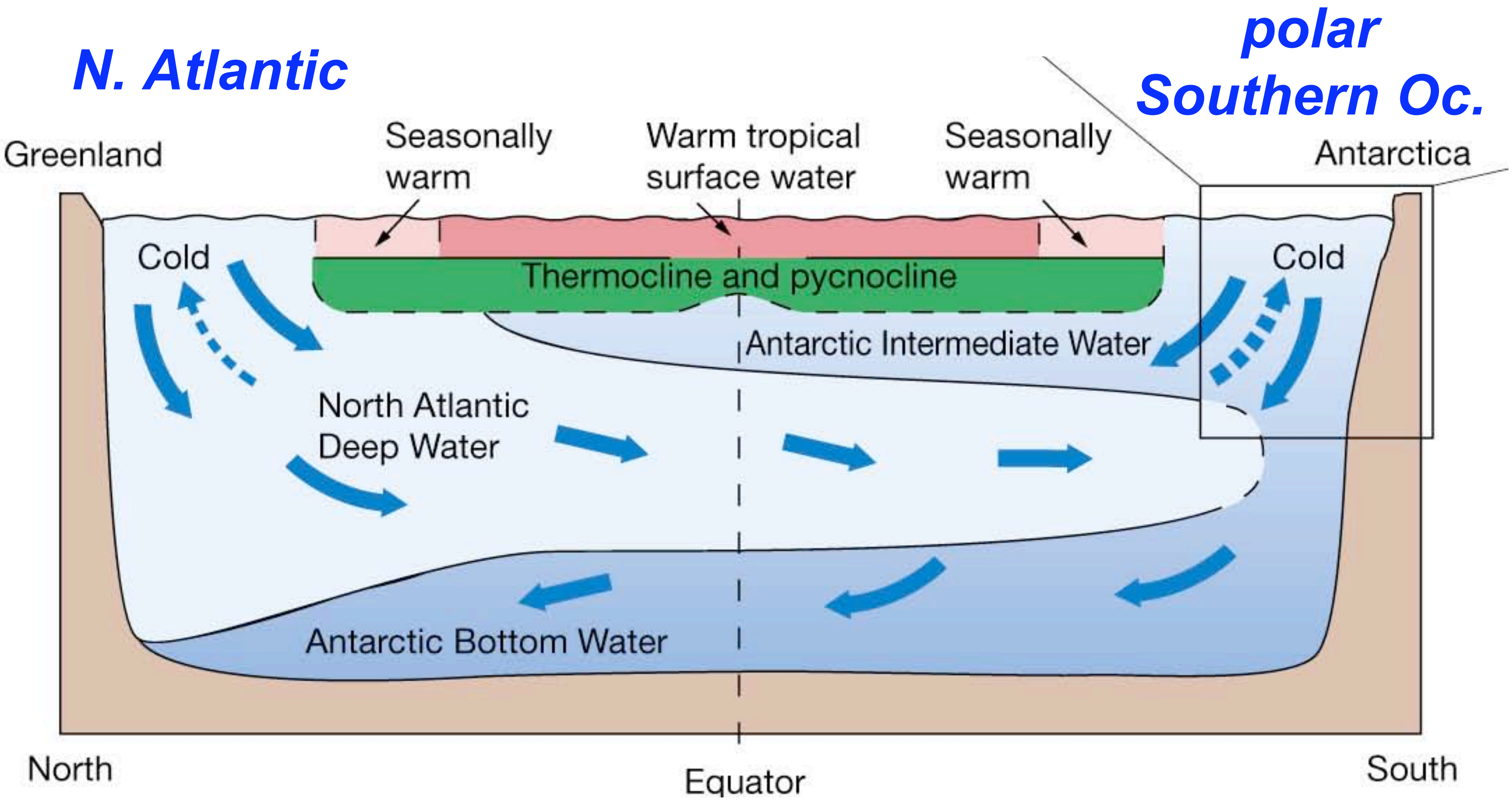
Important parameters: τ – *wind stress in the Southern ocean*

k_D – *diapycnal diffusivity*

$\mathcal{F}$ – *surface freshwater fluxes*

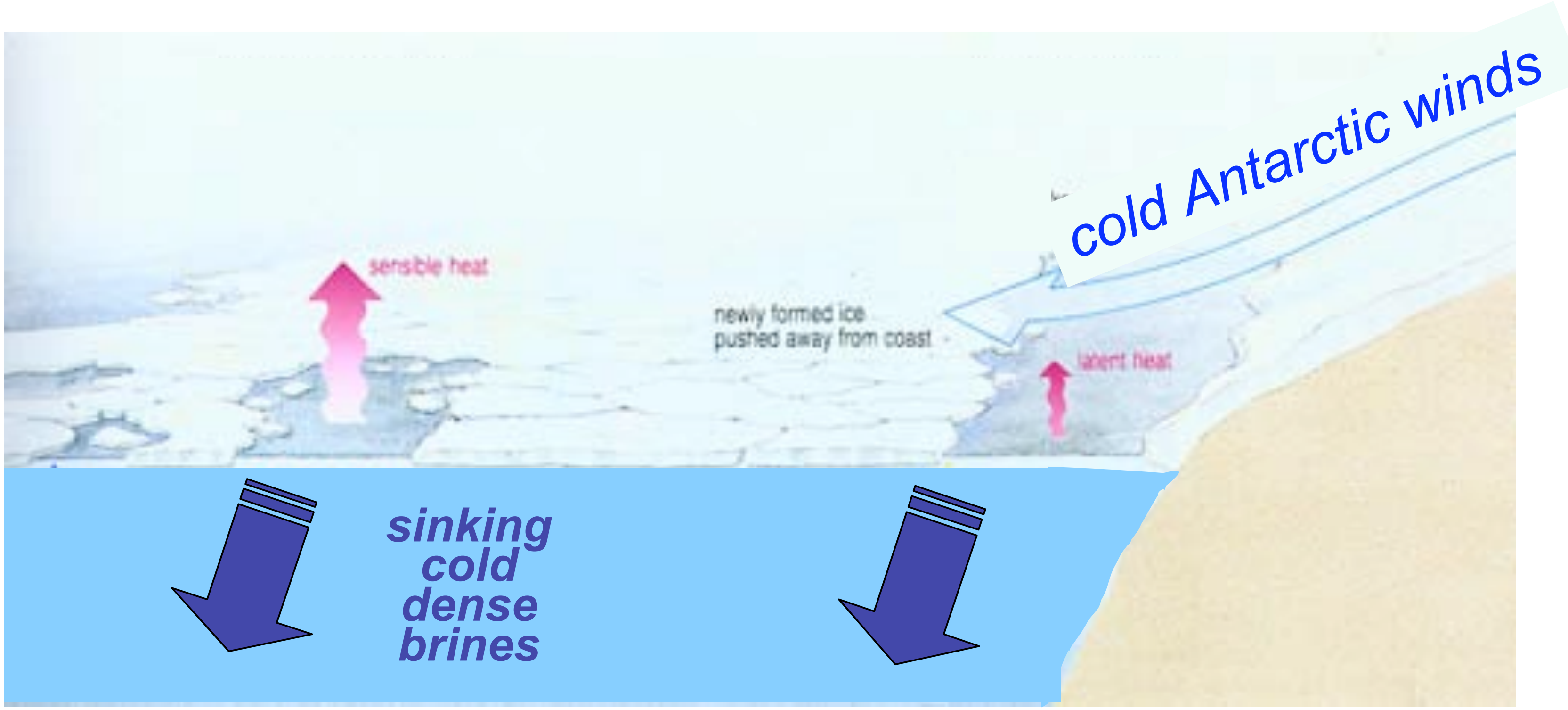


polar sources of deep water



waters cooled at high latitudes fill the ocean interior with cold, dense water

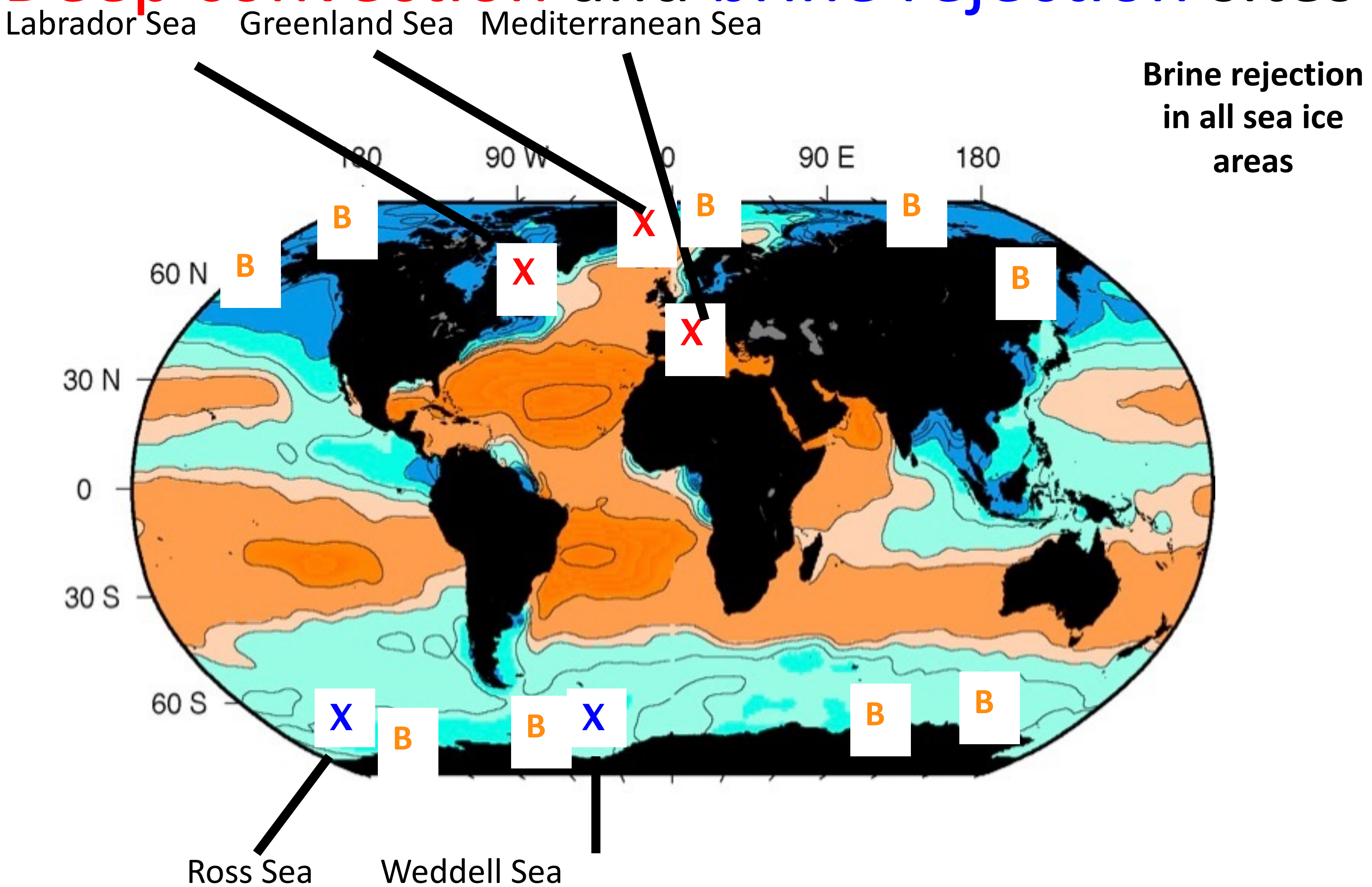
the Antarctic sea-ice factory



cold winds blow sea-ice out to sea as it formed, allowing continual formation of new sea ice… as sea ice is formed from sea water, salt is rejected, enriching salt content below

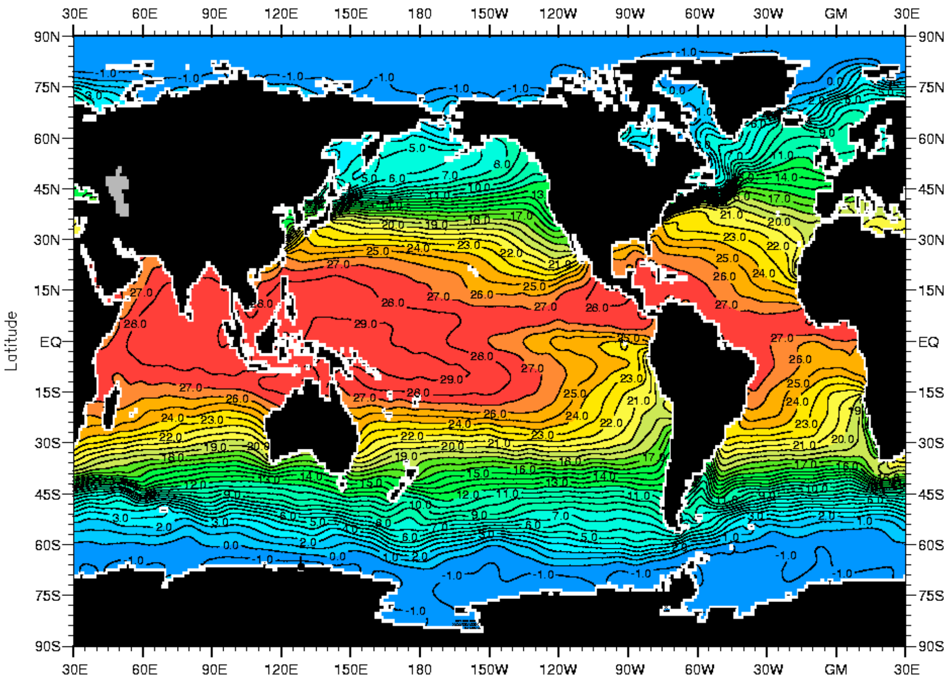
the extra salt promotes deep water formation (i.e. "Antarctic Bottom Water")

Deep convection and brine rejection sites

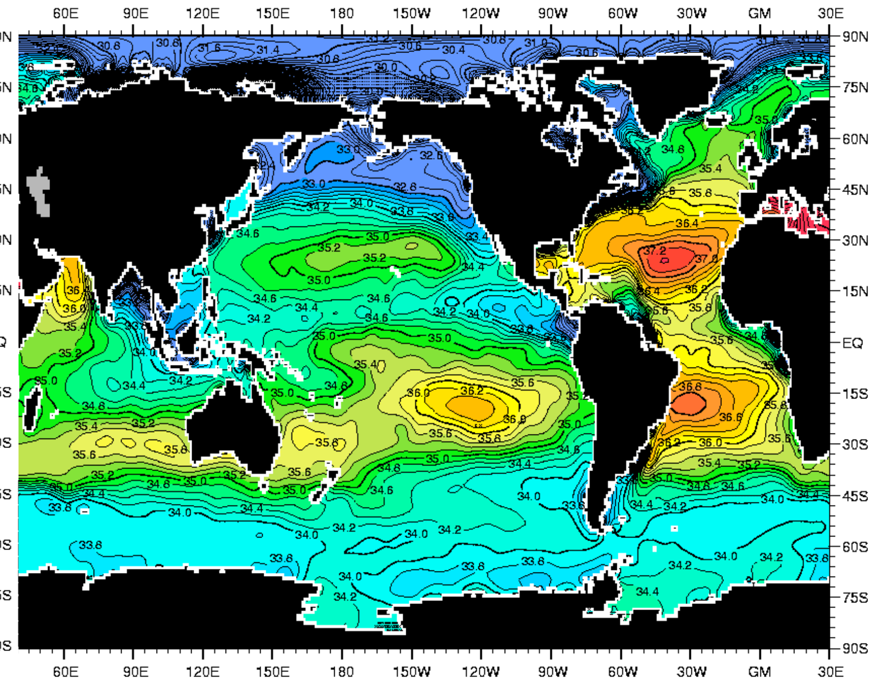


clicker question:

temperature



salinity

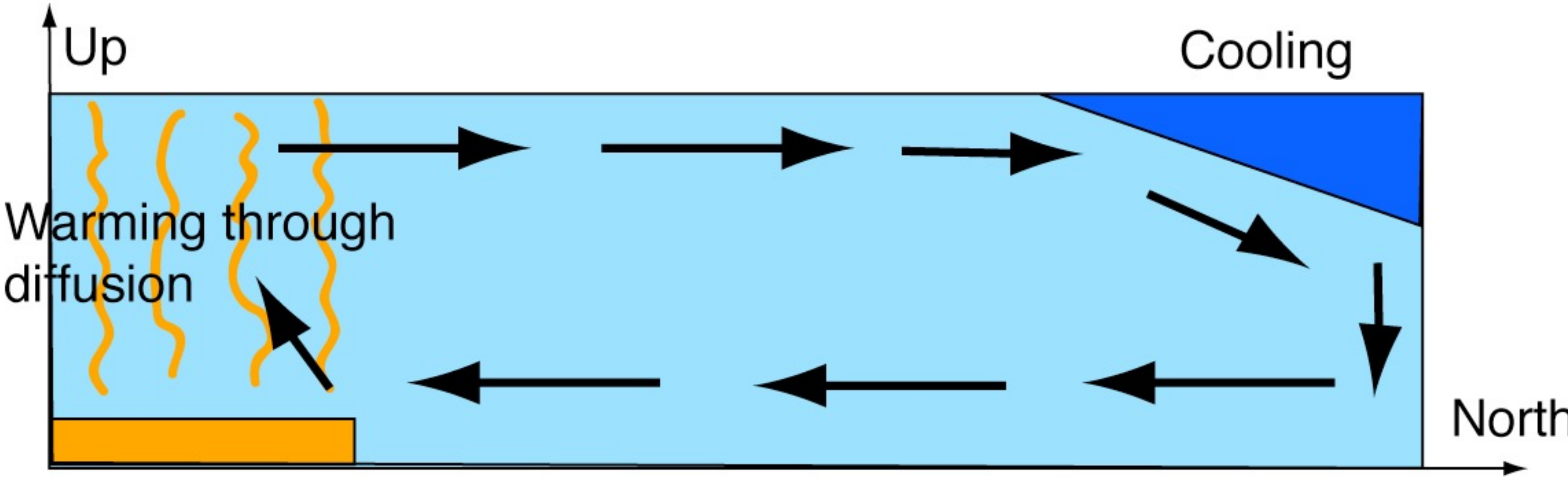


surface waters are cold throughout the high latitudes, so why might deep water formation occur in the N. Atlantic but not in the N. Pacific?

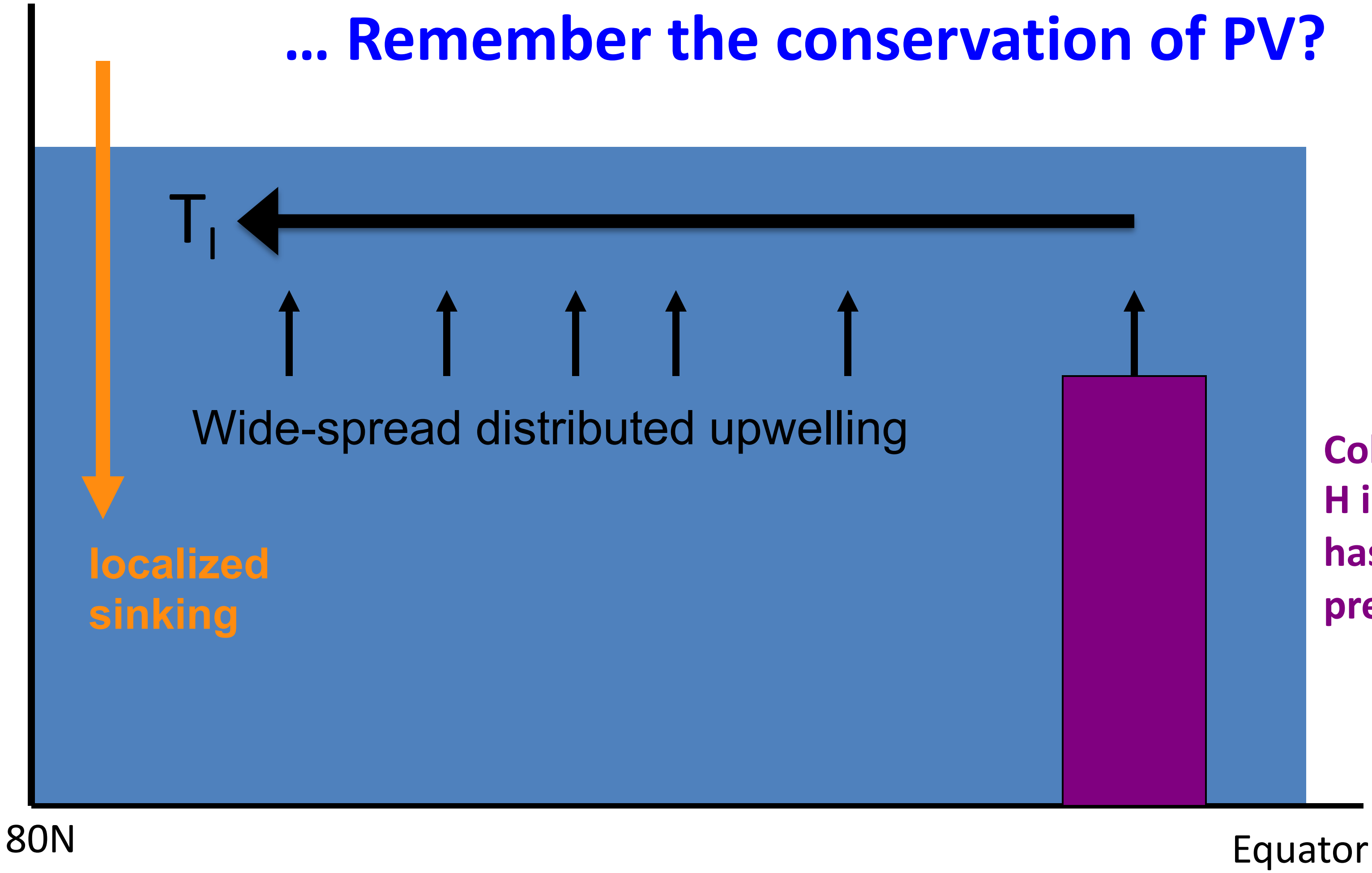
a) not *really* cold in N. Pac, b) not windy enough, c) Coriolis wrong direction, d) <u>not salty enough</u>, e) too sunny

Abyssal circulation dynamics

Diffusion (diapycnal, i.e. across isopycnals) is required to return convected/cooled waters back upwards to surface

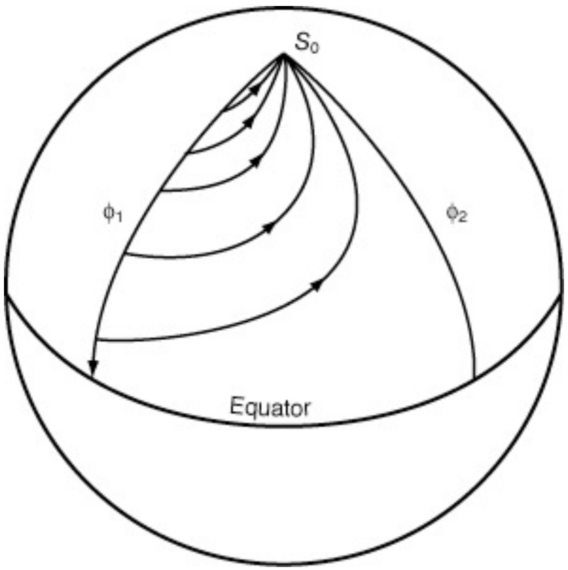


… Remember the conservation of PV?



Column stretching H increases, so f has to increase to preserve f/H

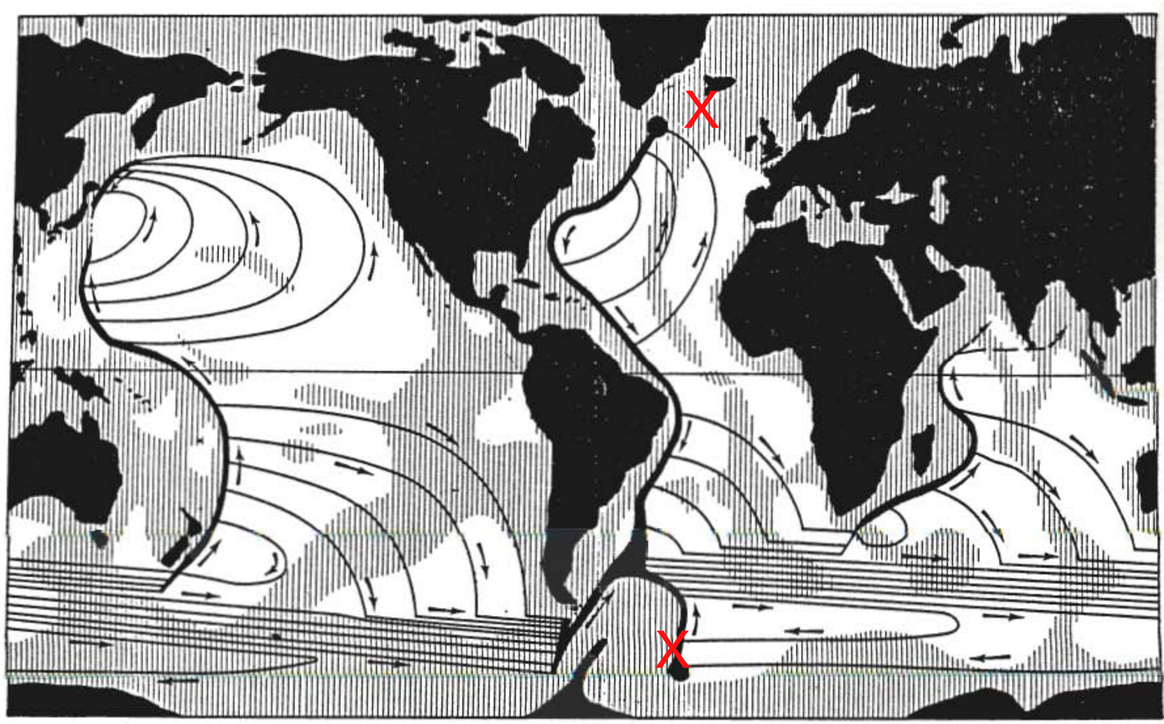
Abyssal circulation: Stommel-Arons model



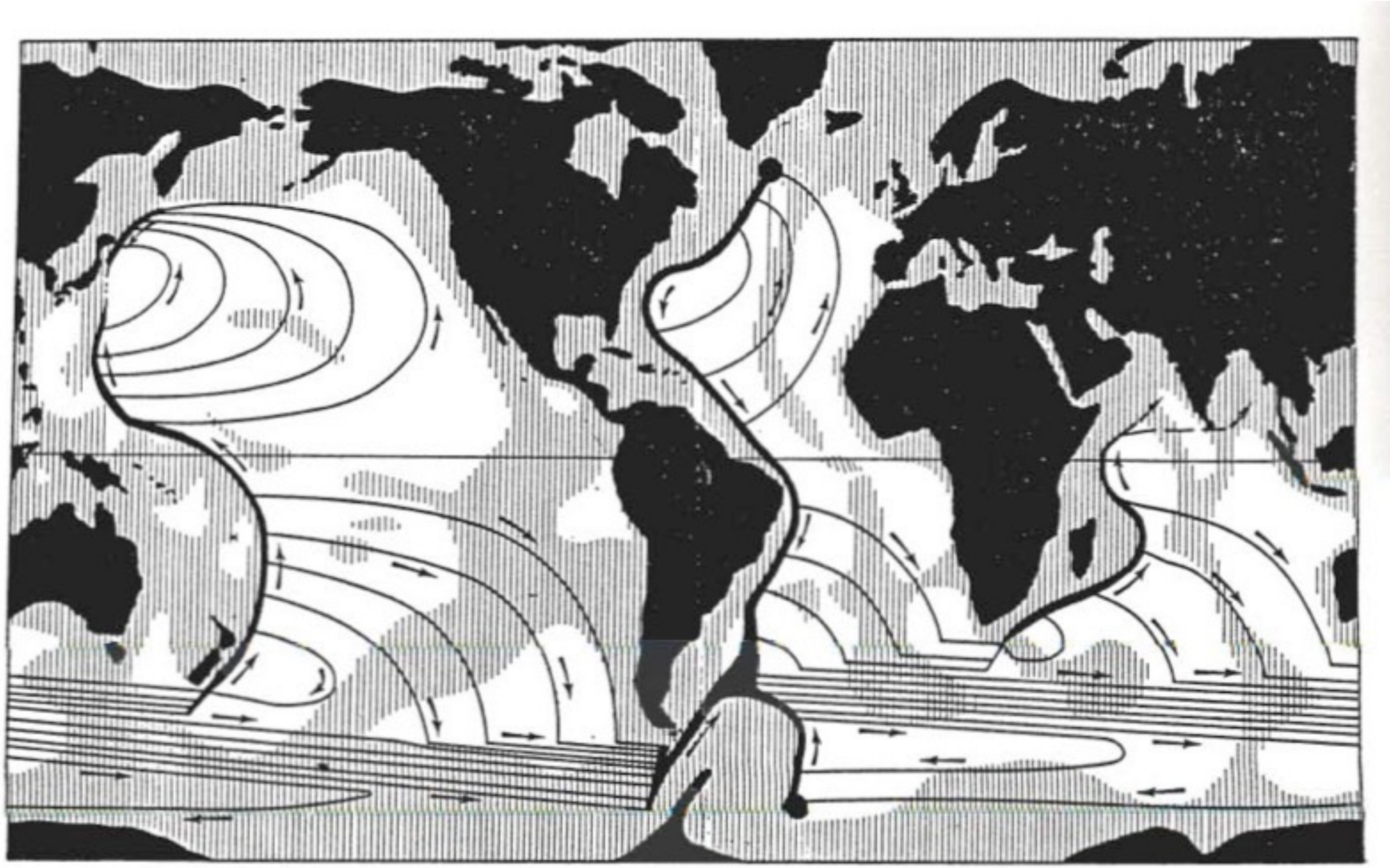
Local deep water sources

General upwelling

Yields poleward interior flow, connected with Deep Western Boundary Currents



Very idealized model of global DWBCs (Stommel, 1958)

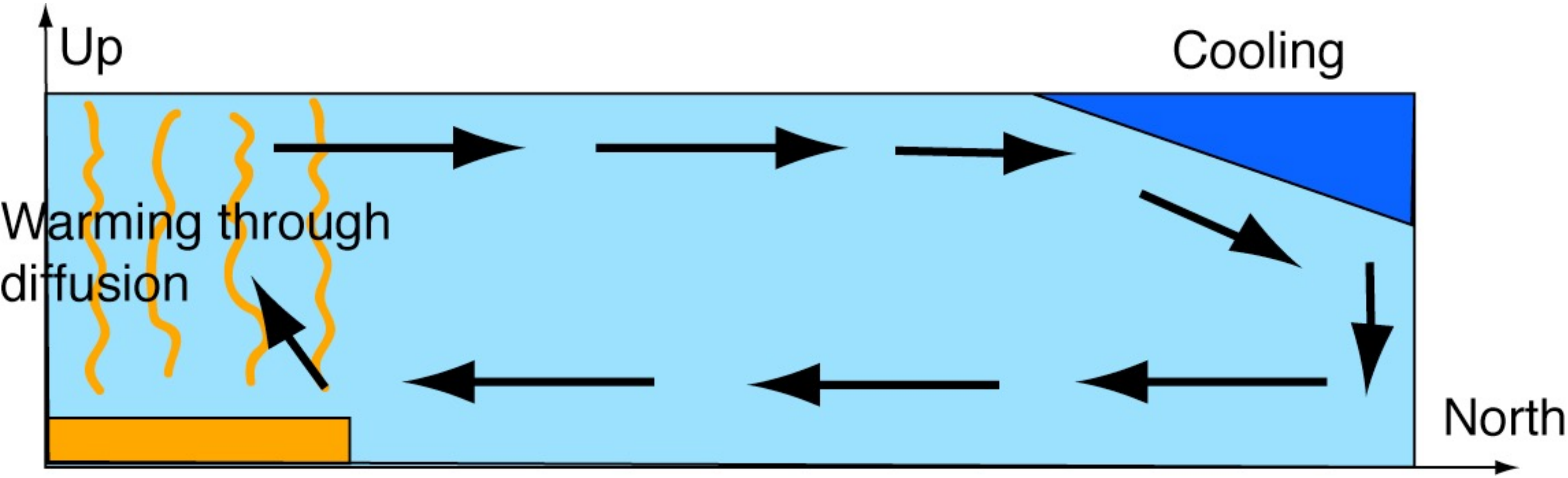


No topography

2 sources:NADW and AABW (very idealized versions!!!)

Poleward (weak) interior flow, strong DWBCs to connect flows

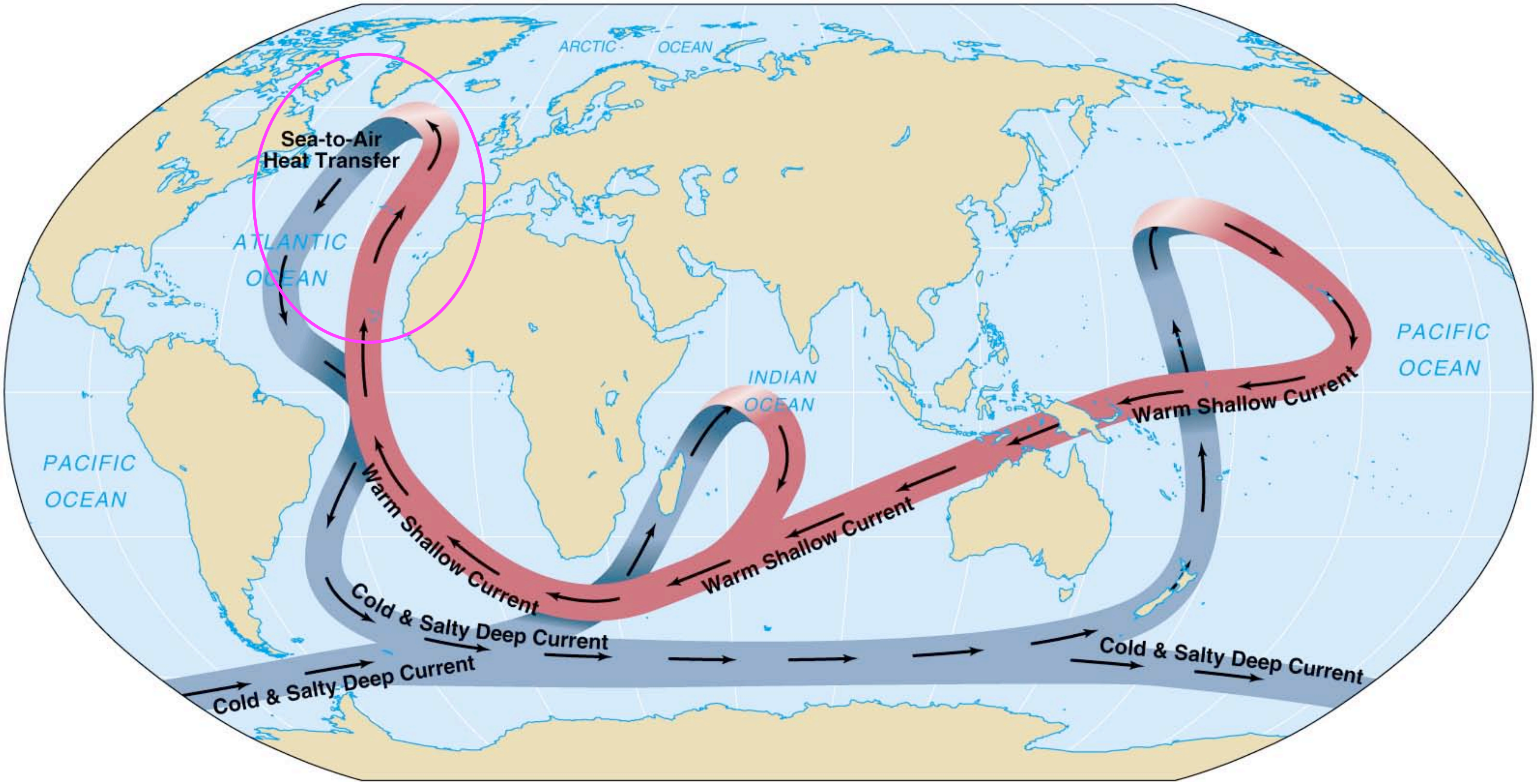
What about the upwelling part of the meridional overturning?



Diffusion (diapycnal, i.e. across isopycnals) is required to return convected/cooled waters back upwards to surface

It can be argued that the diapycnal diffusivity governs the overall strength of the overturn, rather than the convection rates (which are small). This is true in numerical models!

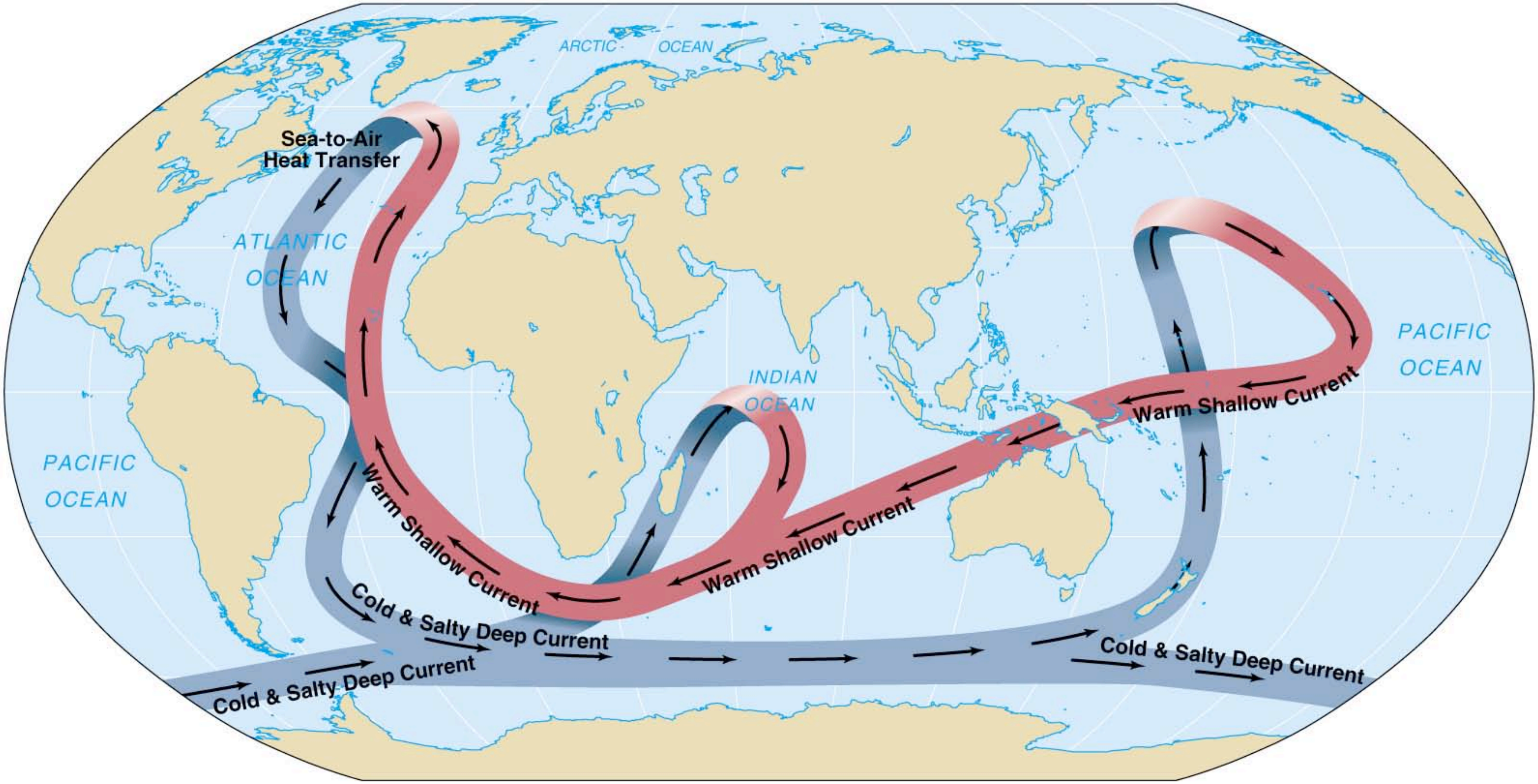
the ocean "conveyor belt"



deep circulation dominated by a continuous circuit associated with formation of deep water in the N. Atlantic (i.e. NADW)

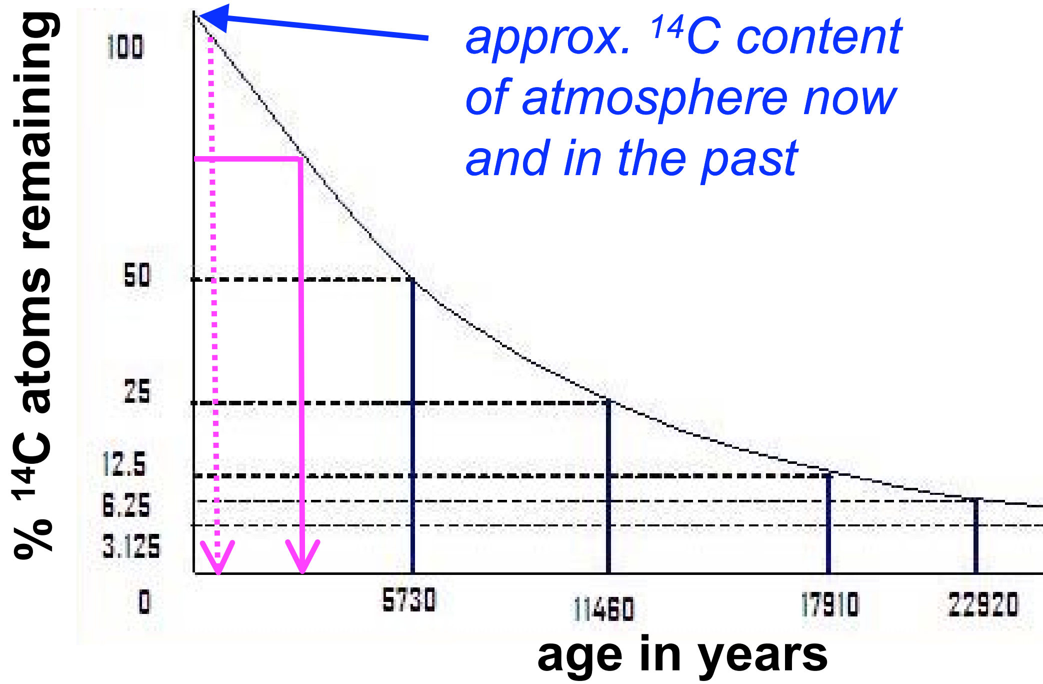
"what goes around comes around"

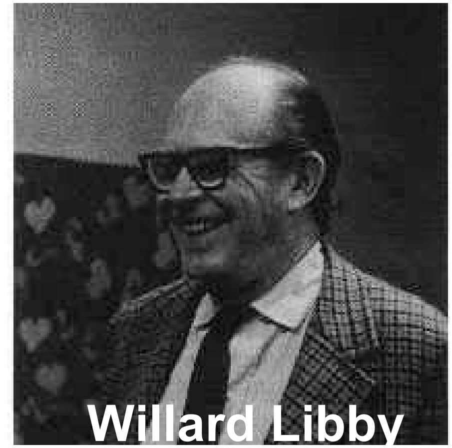
the ocean "conveyor belt"



long route implies long time to complete circuit
how long?

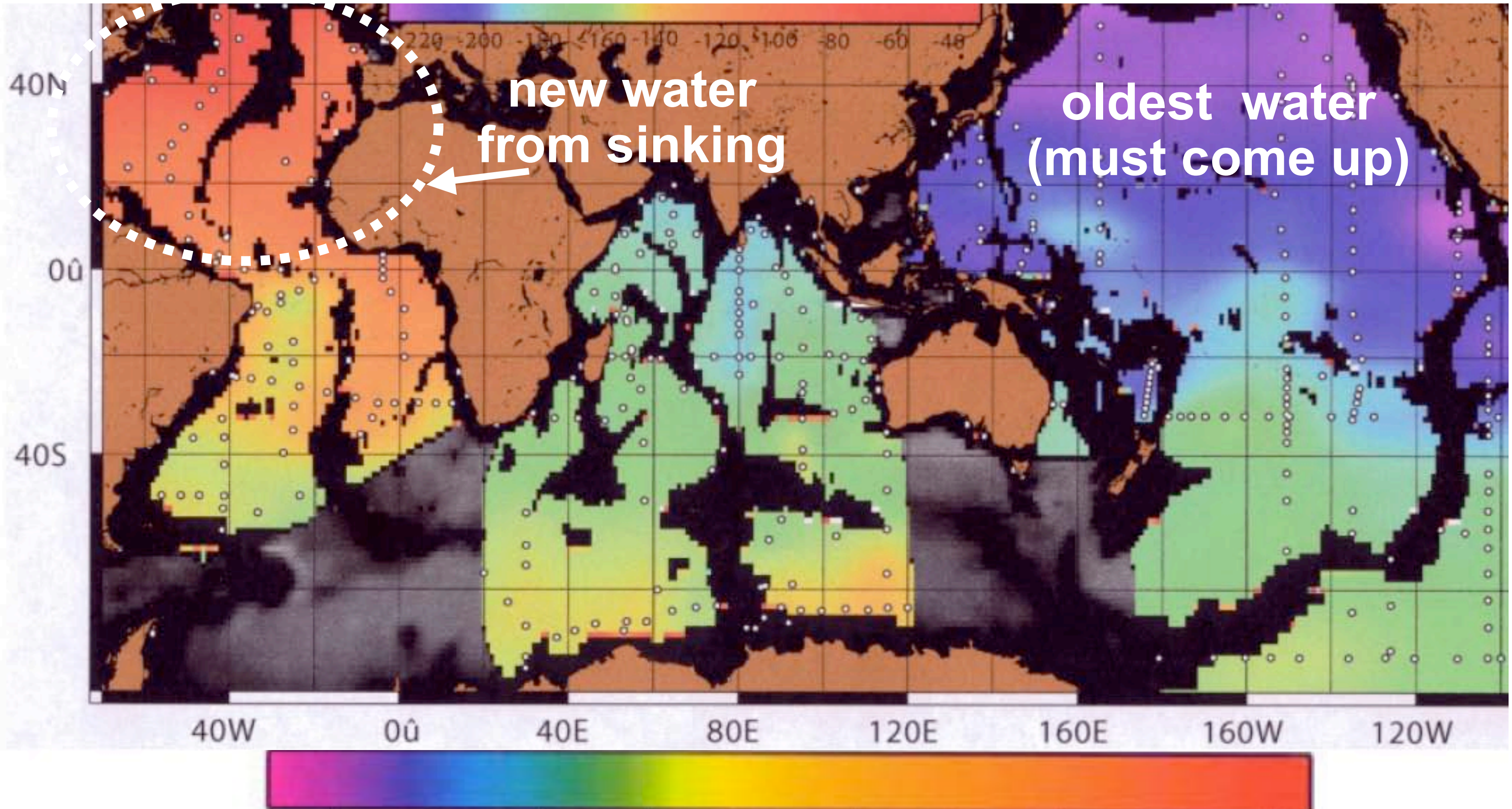
how old is the deep ocean?





- half the ^{14}C decays away every 5730 years
- so measuring how much ^{14}C tells us how long since water absorbed new carbon (as CO_2) at the surface
- more ^{14}C means water was at the surface more recently
- less ^{14}C means water was at the surface less recently

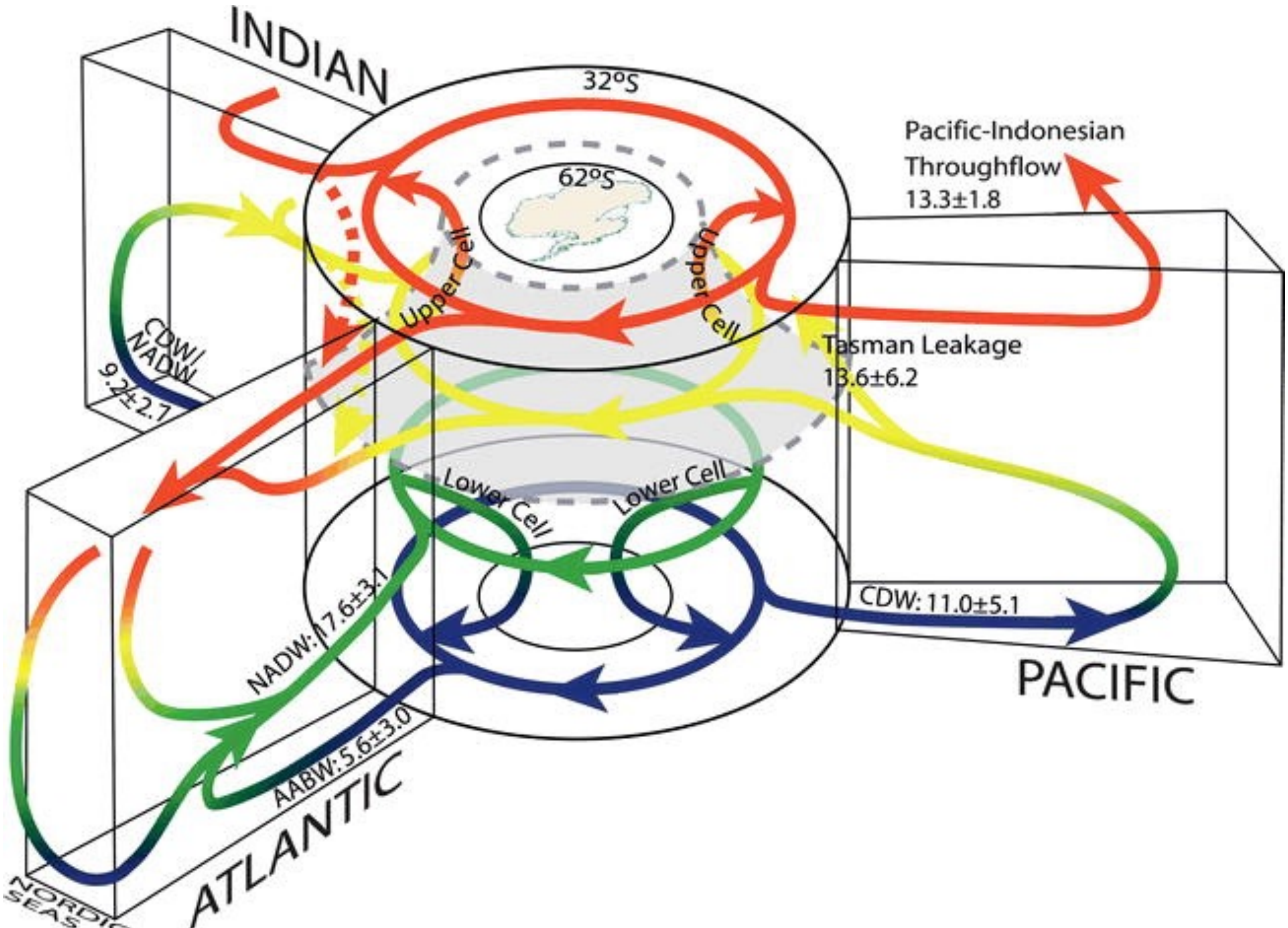
less ^{14}C means older water!



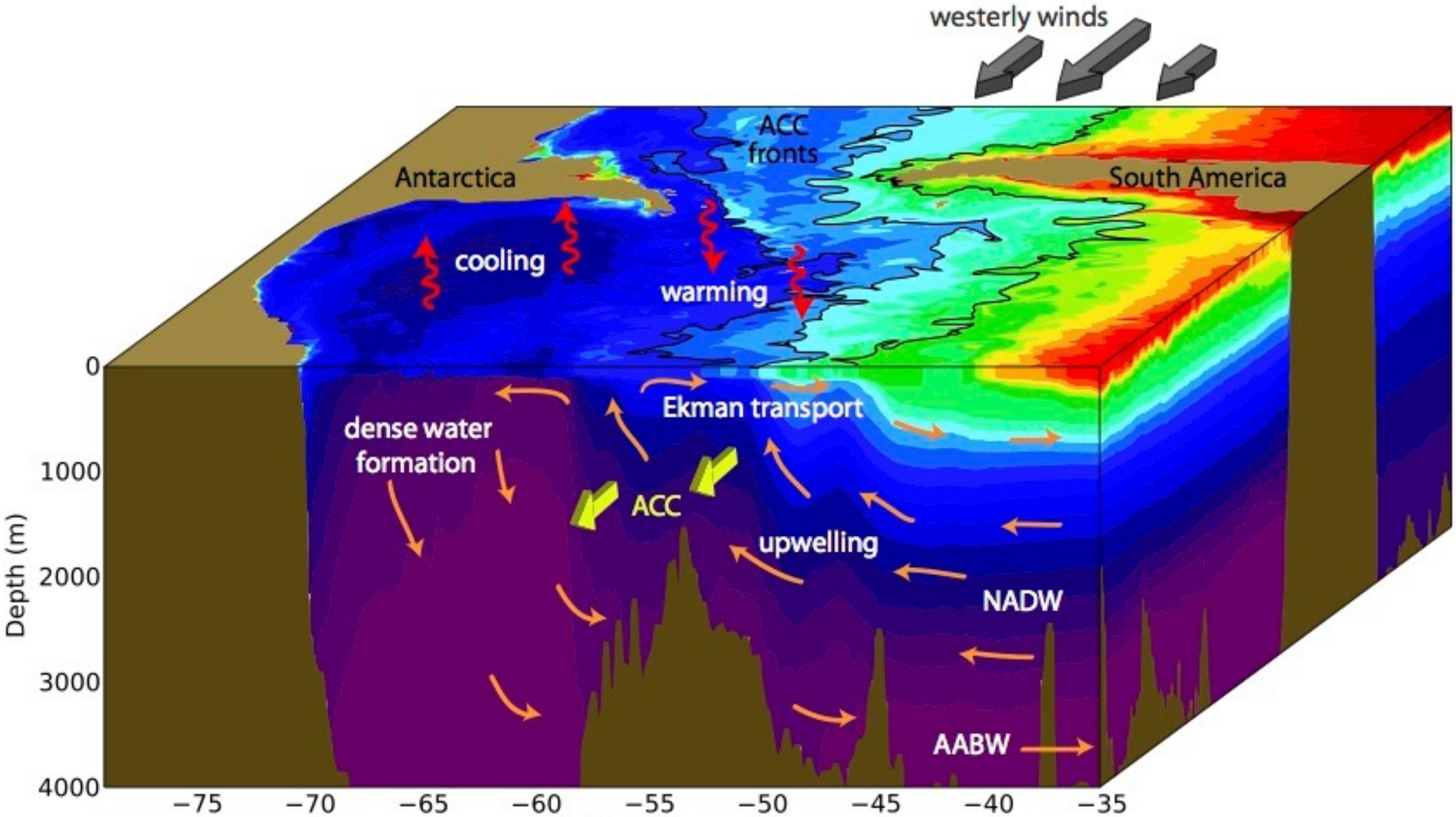
near bottom ^{14}C (% deviation from modern)

can estimate avg. timescale of deep circulation is 1000 years!

The Southern Ocean: a pivotal role

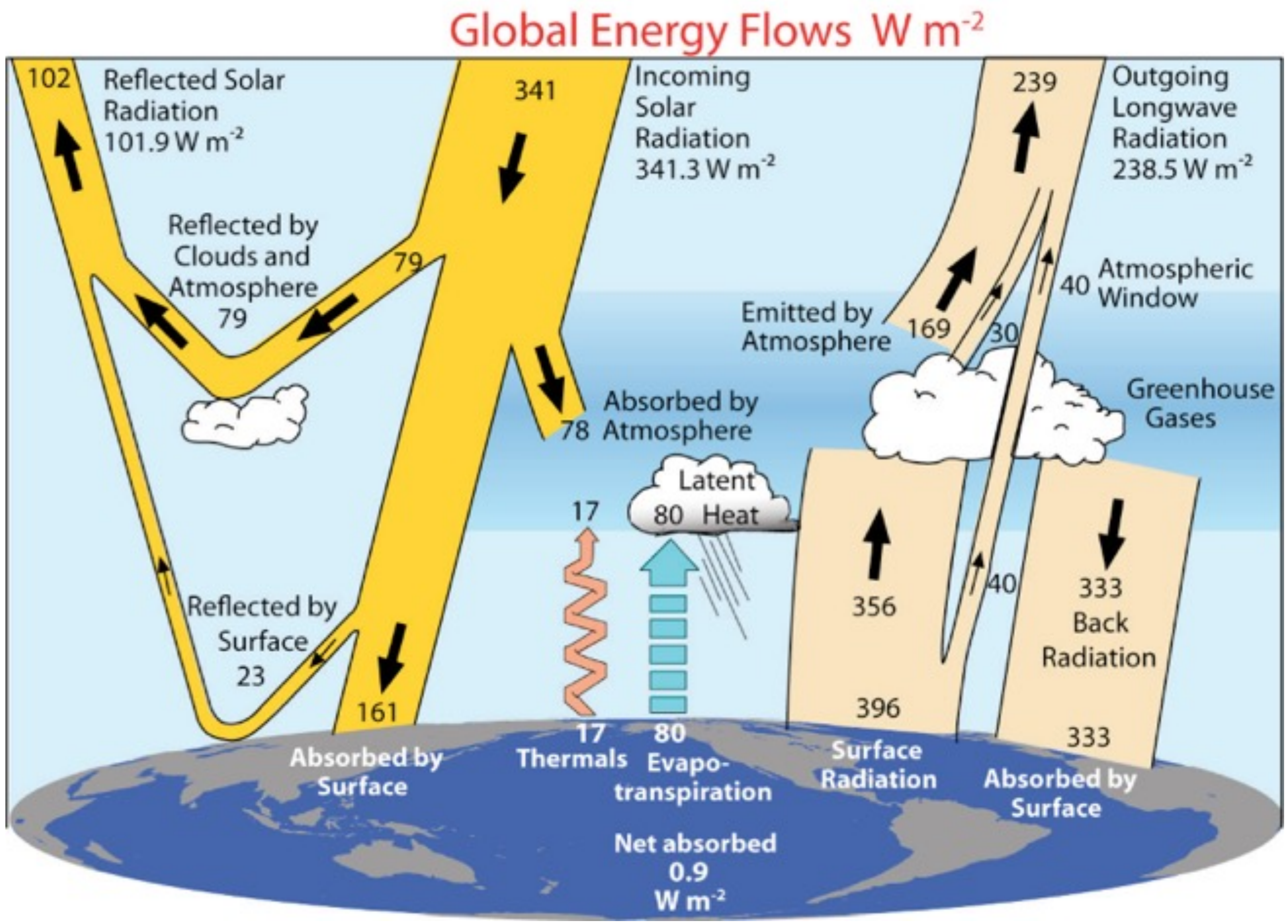


The Southern Ocean



Ocean Heat Transport

Earth's Heat Budget



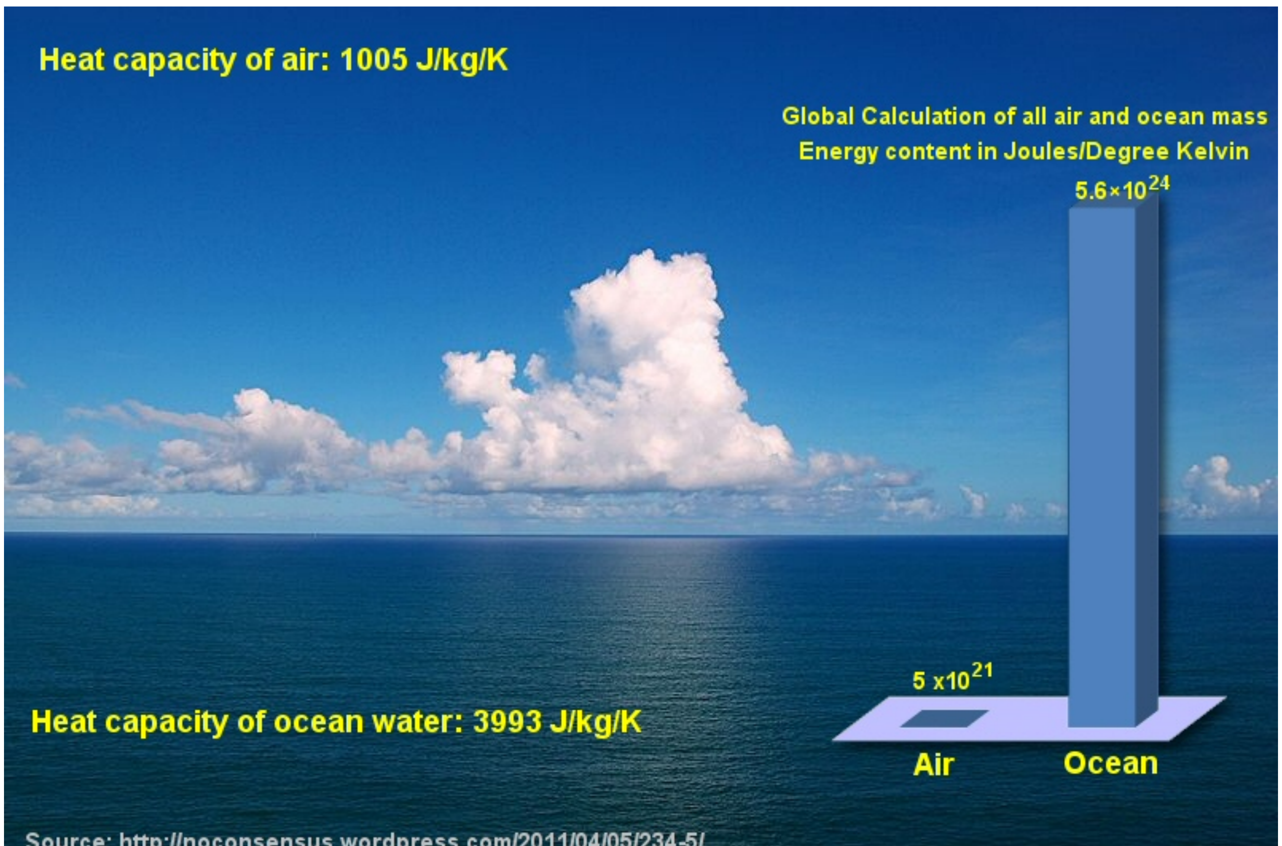
Notice that insolation balances infrared radiation at the top of the atmosphere

At the surface, latent heat flux and net infrared radiation tend to balance insolation, and sensible heat flux is small.

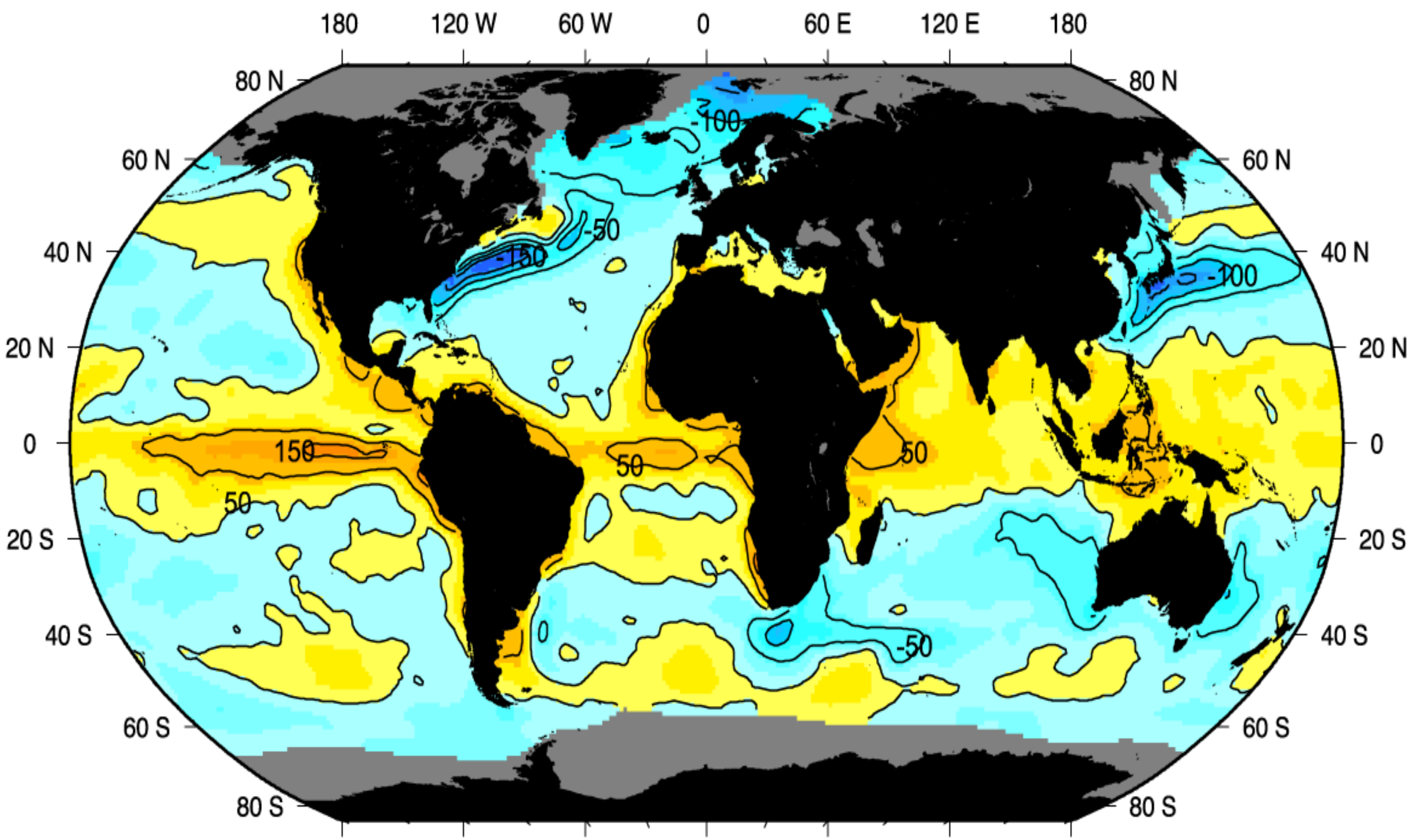
Note that only 20% of insolation reaching Earth is absorbed directly by the atmosphere while 49% is absorbed by the ocean and land

A few numbers

- The heat capacity of the ocean is about 1000 times larger than the heat capacity of the atmosphere
- The top 3.5 meters of the ocean hold as much energy as all of the air on the planet
- The ocean is by far the largest reservoir of heat in the climate system



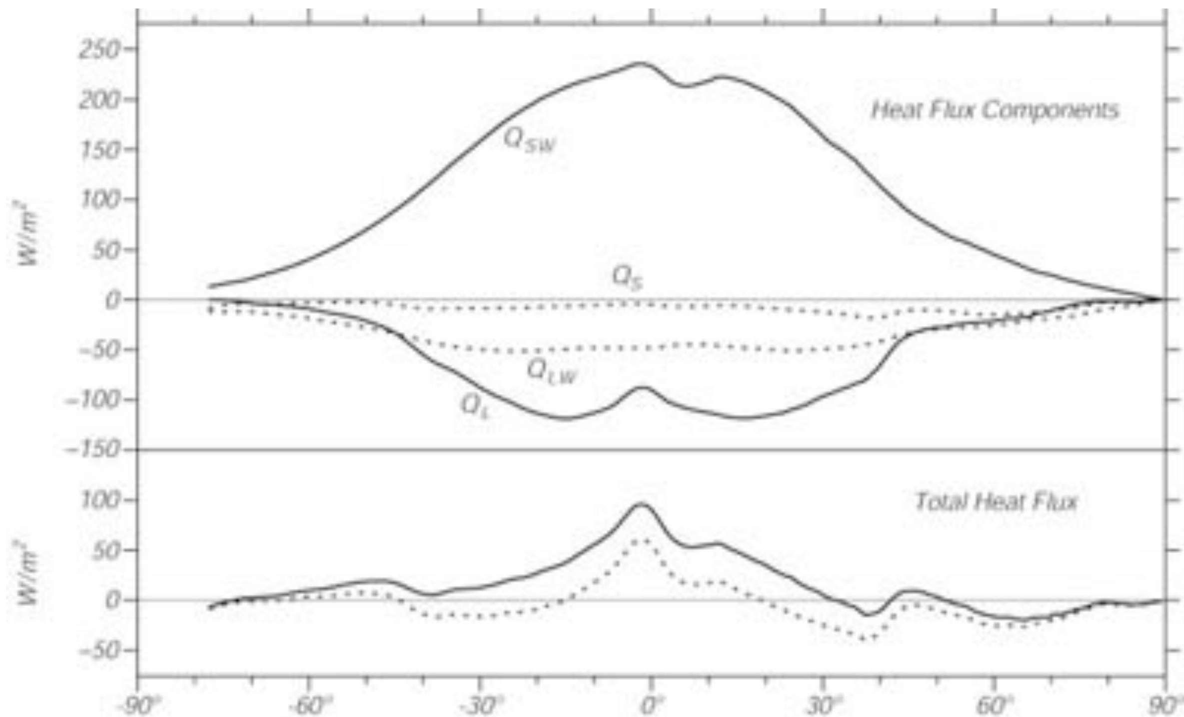
Surface heat flux (W / m²) into ocean



Yellow: heating

Blue: cooling

Zonal averages of heat transfer to the ocean by insolation Q_{SW}, and loss by long wave radiation Q_{LW}, sensible heat flux Q_S, and latent heat flux Q_L

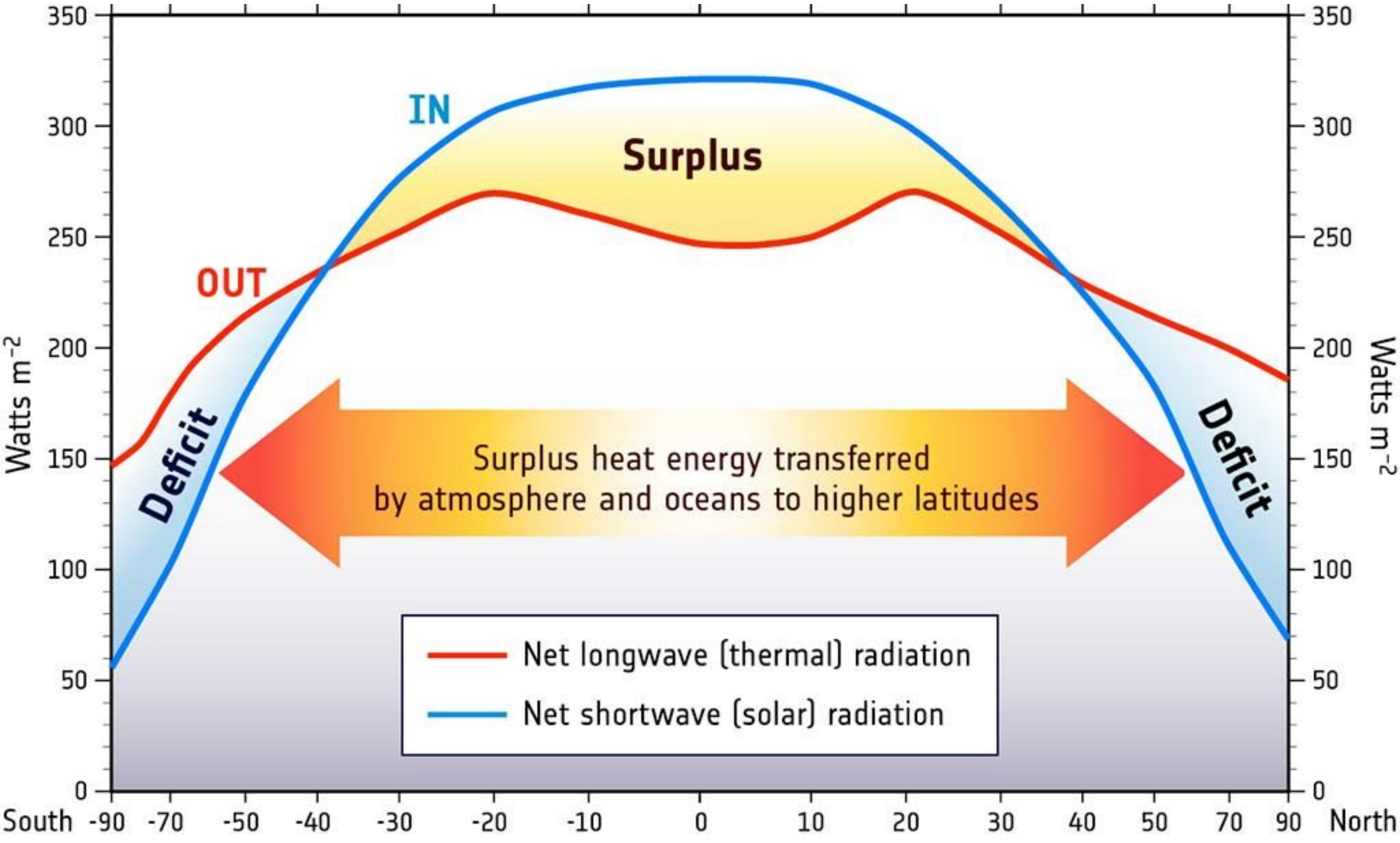


The zonal average of the oceanic heat-budget terms shows that insolation is greatest in the tropics, that evaporation balances insolation, and that sensible heat flux is small

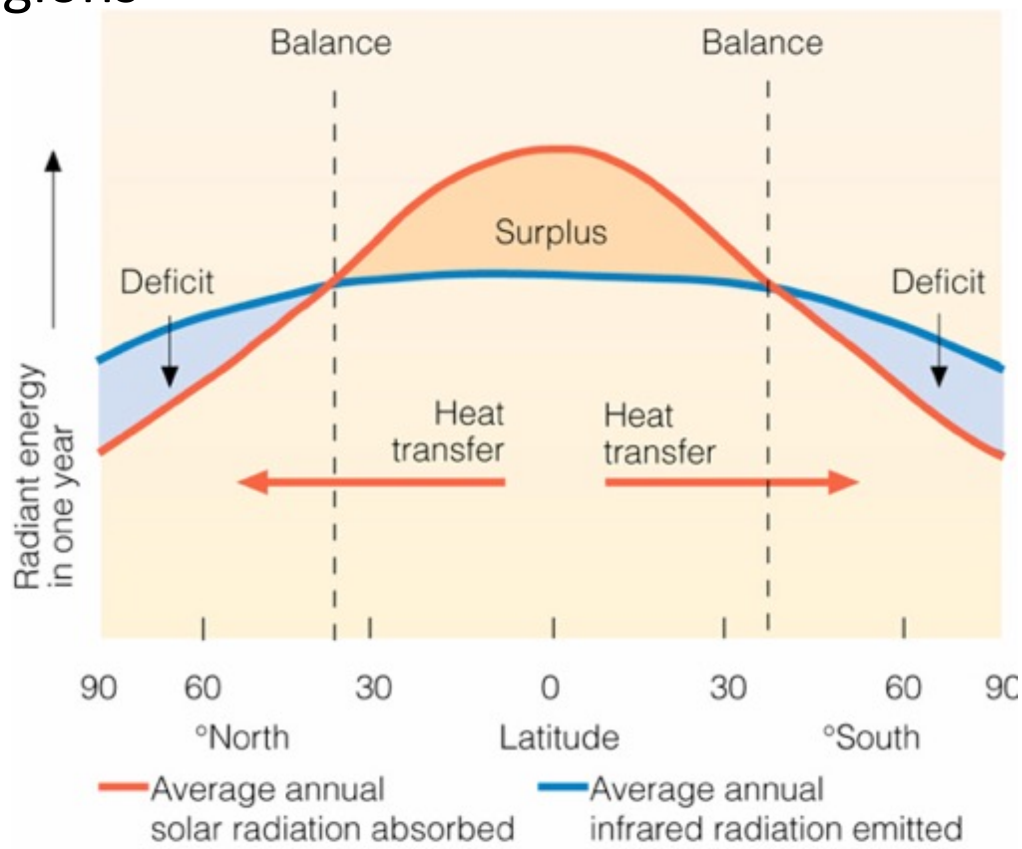
The earth's Radiation Balance

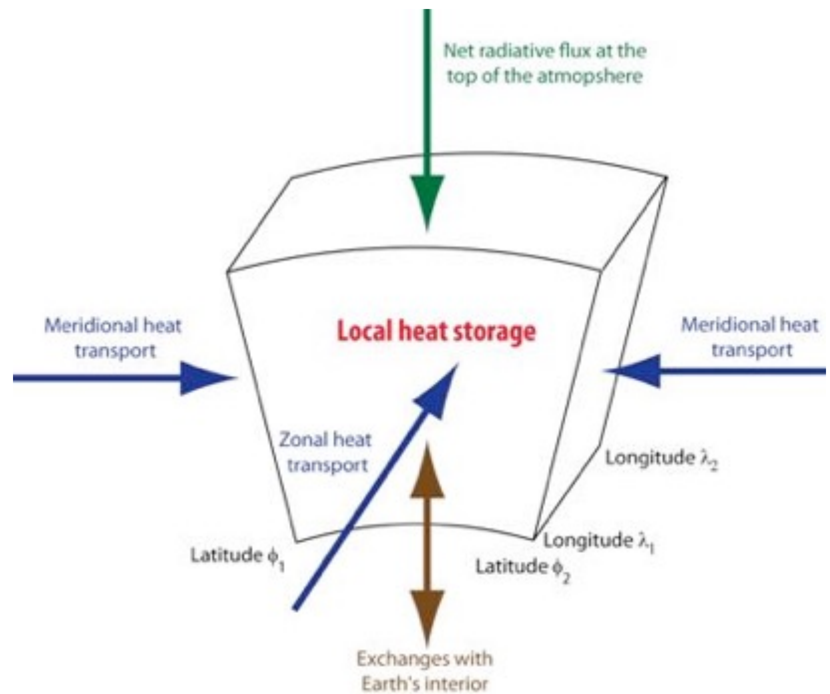
- A balance between incoming solar radiation and outgoing long-wave radiation
- The incoming radiation is “sunlight”, shortwave radiation, some of which is reflected back to space.
- The percentage of energy reflected is called the albedo, and the albedo is higher over lighter areas like snow and lower over darker areas like the ocean.
- Most of the incoming radiation occurs in the tropical and equatorial regions, so there is more incoming radiation than outgoing radiation for latitudes less that 35 degree.
- There is more outgoing radiation than incoming radiation in subpolar and polar regions.
- To maintain the heat budget at each latitude, **the ocean + atmosphere must transport heat poleward away from tropical regions toward polar regions**; and the maximum ocean +atmosphere heat transport occurs at a latitude of about 35 degree.

Heat Transport



Locally, heat storage by the climate system cannot compensate for the net radiative flux imbalance at the top of the atmosphere and, annually, the balance is nearly entirely achieved by heat transport from regions with a positive net radiative flux to regions with a negative net radiative flux. When the balance is averaged over latitudinal circles (zonal mean), this corresponds to a meridional heat transport from equatorial to polar regions





Ocean Heat Transport

- Most of the incoming radiation occurs in the tropical and equatorial regions, so there is more incoming radiation than outgoing radiation for latitudes less that 35 degree. There is more outgoing radiation than incoming radiation in subpolar and polar regions.
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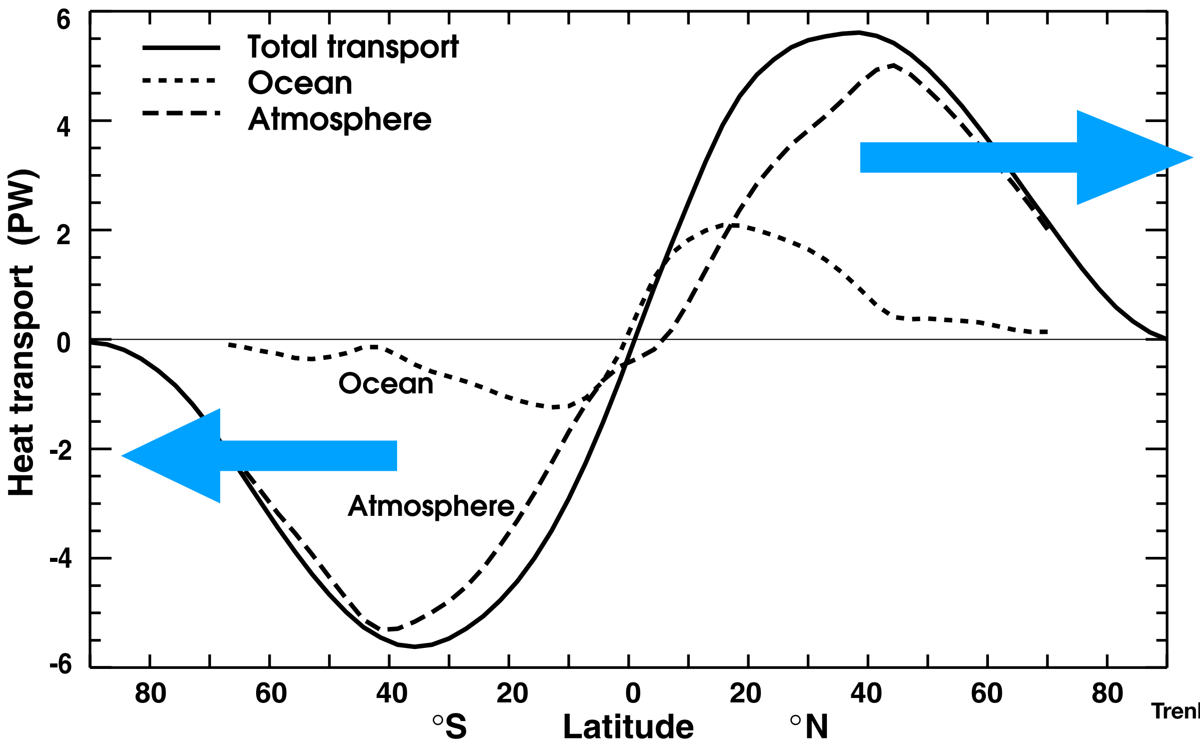
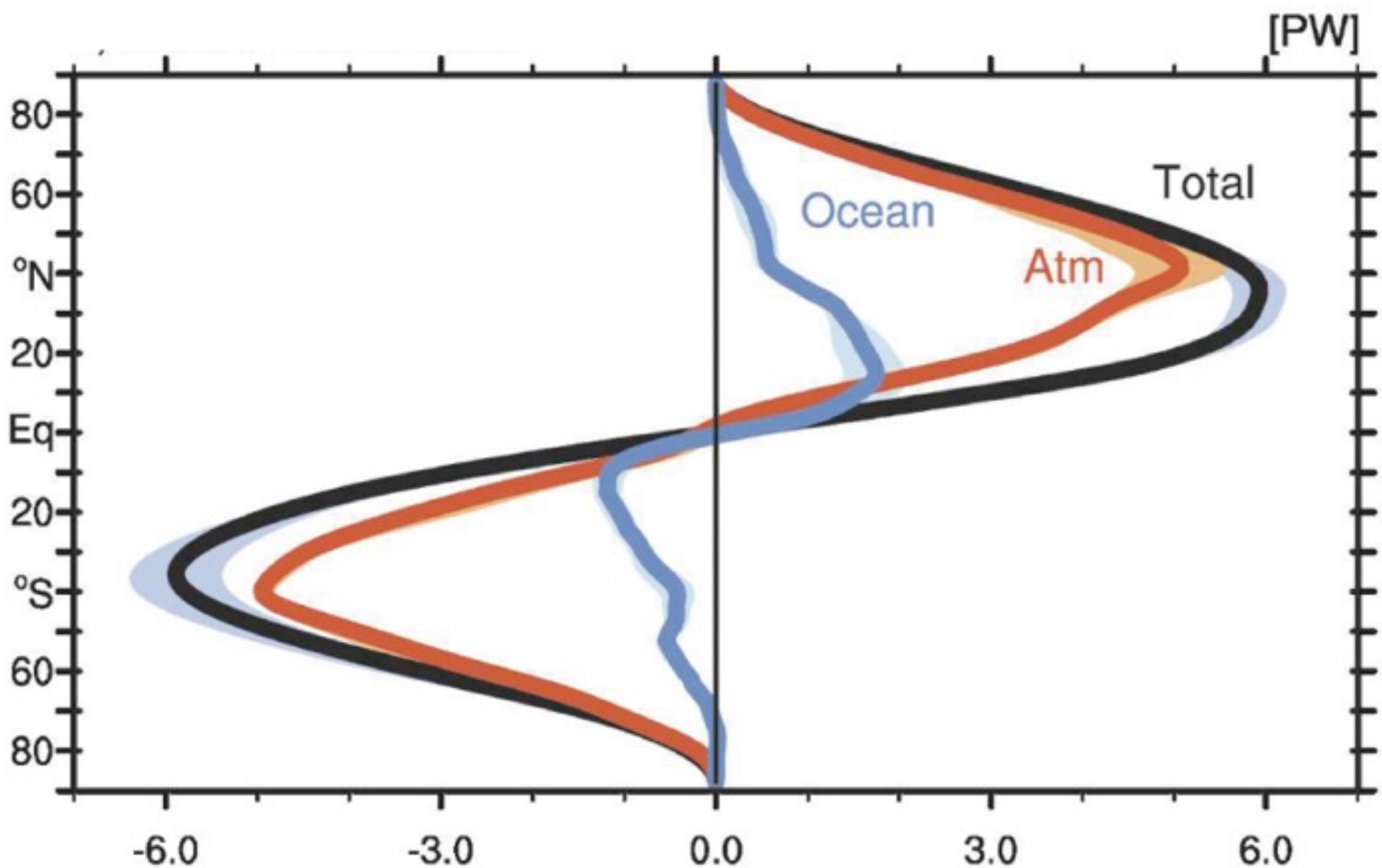
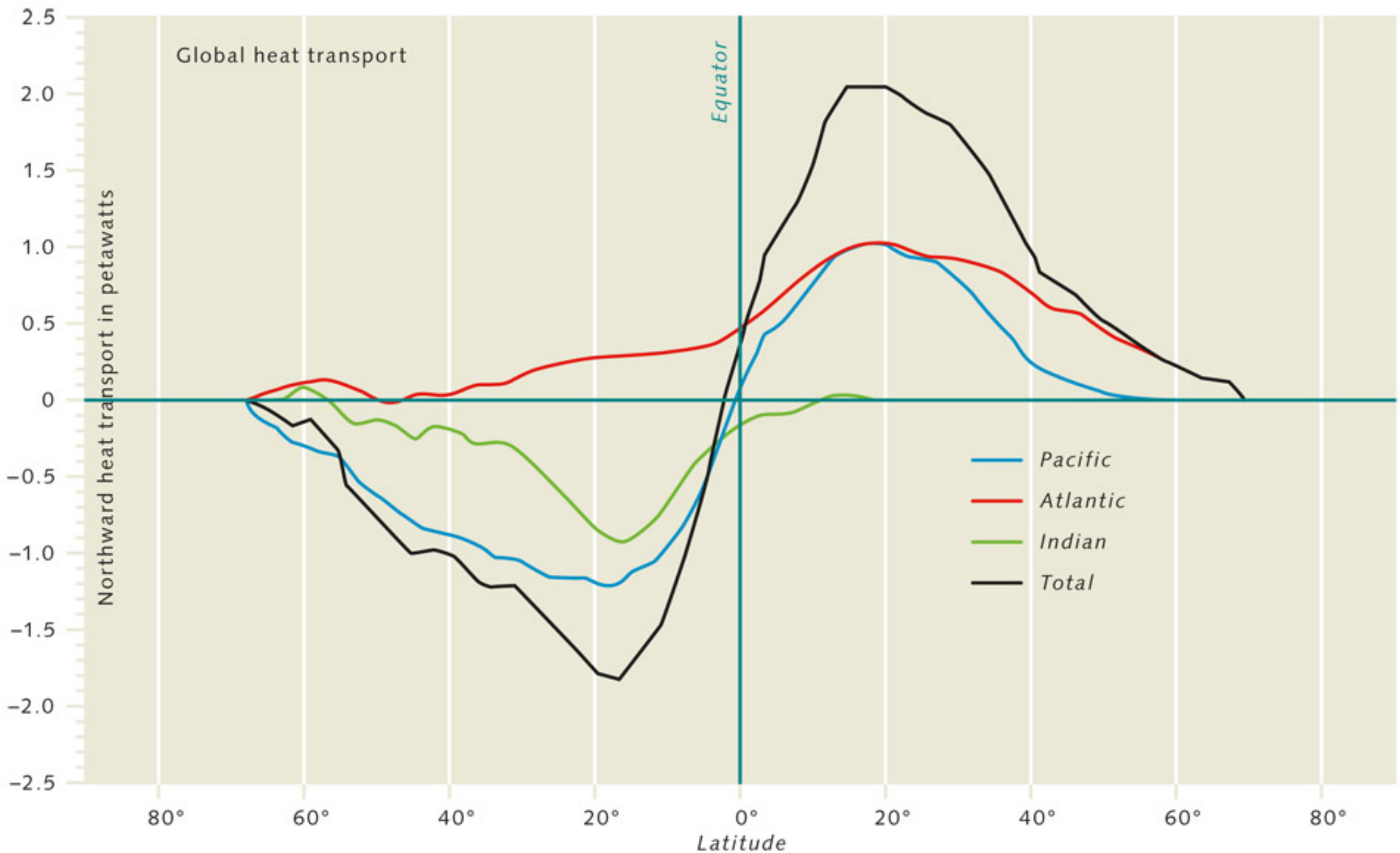


Trenberth and Stepaniak (2004)

The heat transport obtained is nearly zero at the equator, rising to more than 5PW at latitudes of about 35°, before declining again towards zero at the poles. It can be divided into an oceanic and an atmospheric contribution, the horizontal transport on continental surface being negligible. This shows that, except in tropical areas, the atmospheric transport is larger thanthe oceanic transport.



Ocean Heat Transport



Trenberth and Solomon (1994)