The approximately layered structure of the top-to-bottom ocean

We can use four layers to describe the world's oceans.

1. **Upper ocean** (down through the permanent pycnocline)
2. **Intermediate layer**
3. **Deep layer**
4. **Bottom layer**

Upper ocean

<u>Characterization</u>: Surface mixed layer down through the main pycnocline.

<u>Location</u>: In the tropics and subtropics and into the subpolar regions (bounded by the Antarctic Circumpolar Current to the south, and the northern marginal seas to the north)

<u>Formation mechanisms</u>: late winter mixed layer properties are “subducted” into the ocean interior

Mixed layer properties are set by air-sea fluxes, and depth by wind stirring or buoyancy-driven convection

Intermediate layer

<u>Characterization</u>: large-scale salinity maximum and minimum layers.

<u>Location</u>: just below the pycnocline in most of the ocean (especially tropics and subtropics), roughly 1000 to 2000 m depth.

Originate from very specific sources ("injection sites") in the Labrador Sea, the Mediterranean Sea, the Red Sea, the Okhotsk Sea, and the Drake Passage region.

<u>Formation mechanisms</u>: Deep convection (reaching to about 1500 m); vigorous; otherwise nearly-isopycnal spreading

Deep layer

Characterization: This is a thick layer below the intermediate layer and above the bottom waters, characterized by extrema of salinity, oxygen, nutrients.

Location: Roughly from 2000 to 4000 m depth.

The "North Atlantic Deep Water (NADW)" originates through deep water formation processes north of the N. Atlantic (joined by Labrador Sea and Mediterranean Sea intermediate waters). It is relatively "new".

The "Pacific Deep Water (PDW)" originates through slow upwelling of bottom waters in the Pacific, and is the oldest water in the ocean. The "Indian Deep Water" is similar to the PDW.

The "Circumpolar Deep Water (CDW)" is a mixture of these new (NADW) and old (PDW and IDW) waters, plus new deep waters formed in the Antarctic (Weddell Sea etc.).

Deep layer (continued)

Formation mechanisms and history: varied including

- deep convection (Nordic Seas, Labrador Sea)
- brine rejection (Antarctic contribution to deep water)
- upwelling (ocean-wide)
- vigorous mixing at specific sites (strait overflows)
- spreading along isopycnals with minimal mixing

Bottom layer

Characterization: Densest, coldest layer

Location: ocean bottom, usually connotes very dense water from the Antarctic.

Various names:

"Antarctic Bottom Water (AABW)"

"Lower Circumpolar Deep Water" (LCDW)

Formation mechanism: *brine rejection* close to Antarctica

Water masses and water types

Water mass: "body of water with a common formation history"

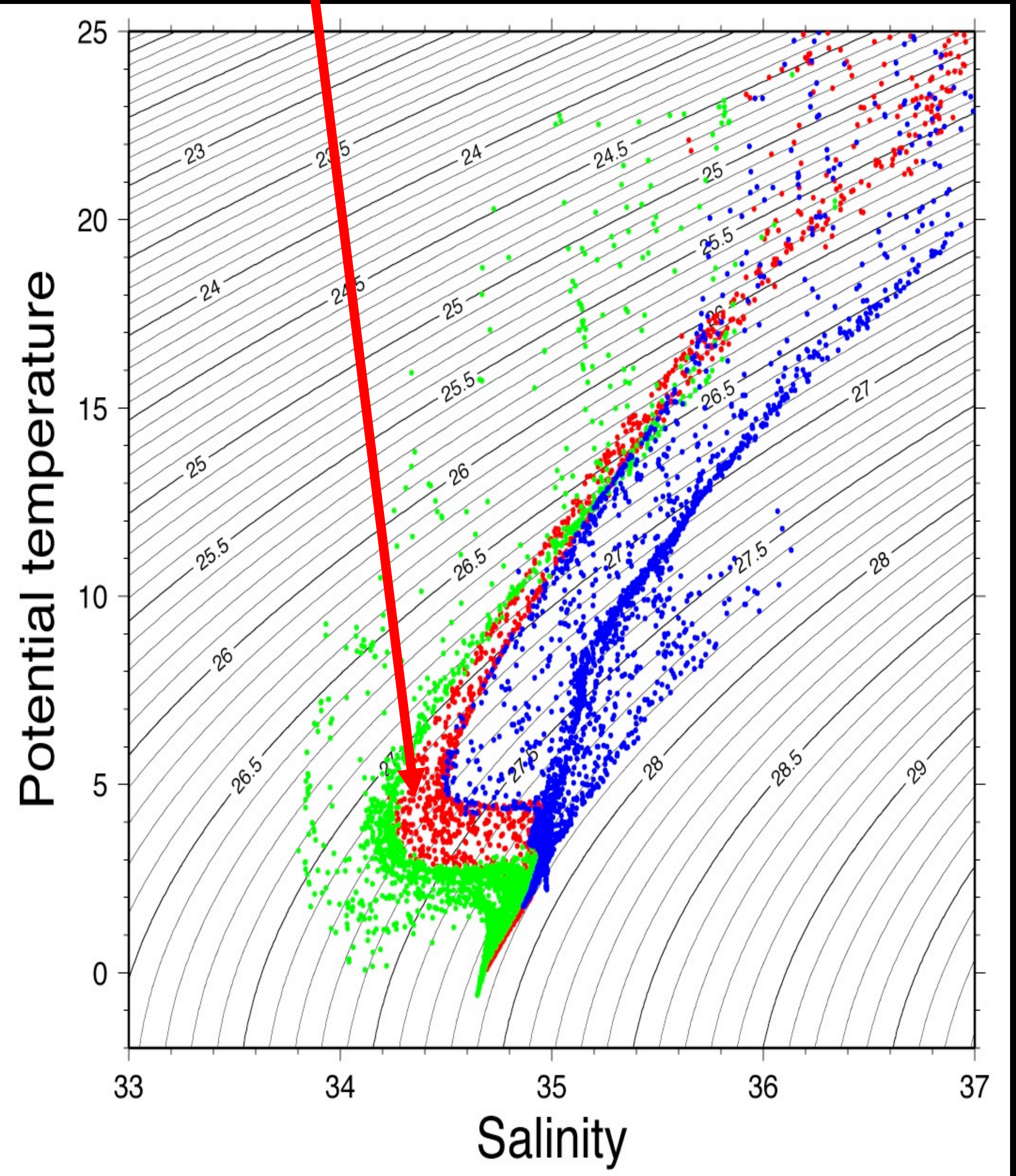
Water type: point on a temperature-salinity diagram

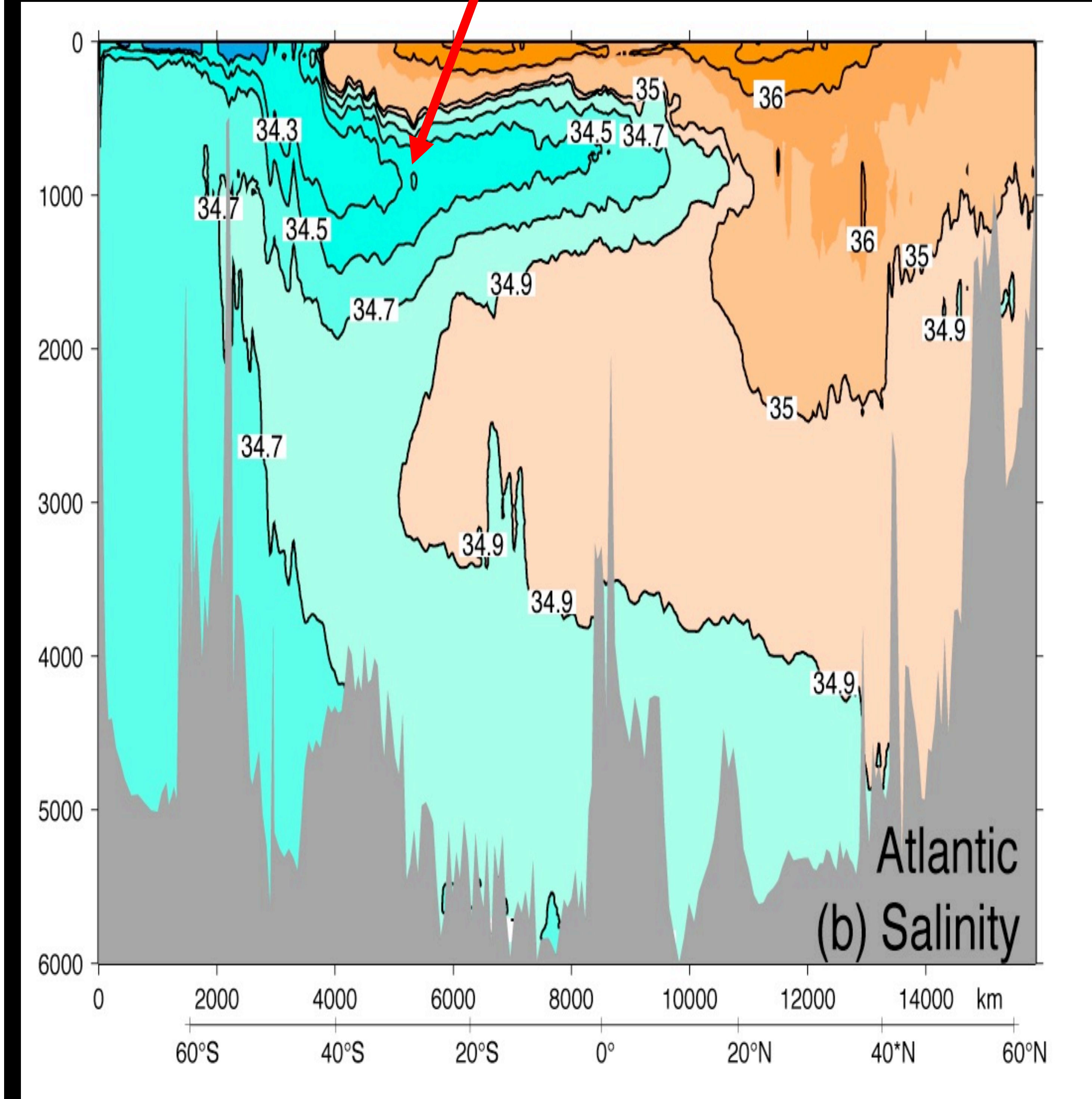
Source water type: water type at the source of a water mass

In practice, we just name the first, but are always aware that there are specific properties at the sources.

Water mass

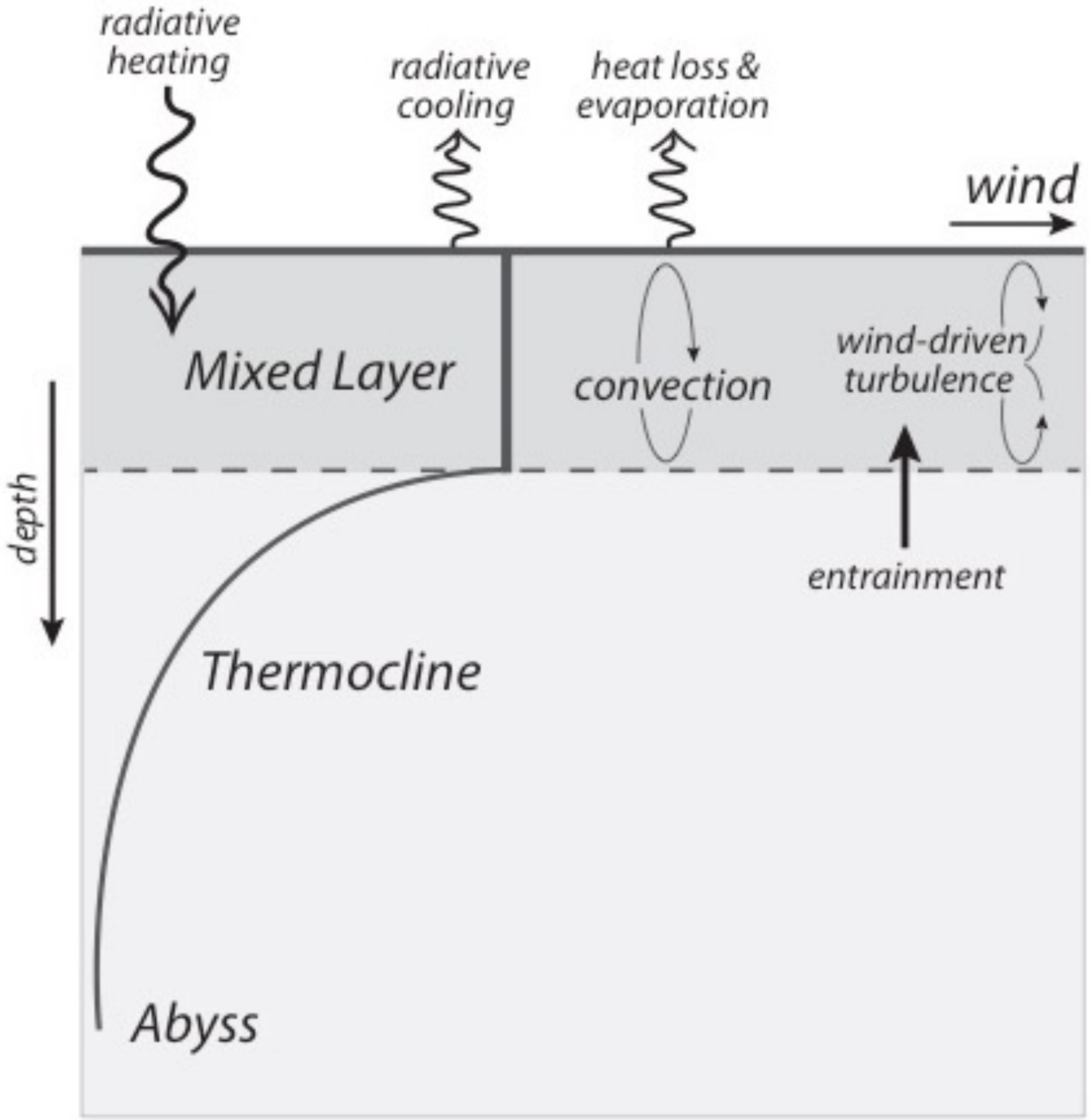
Example: Antarctic Intermediate Water - (a) low salinity layer, (b) originating in surface mixed layers near Antarctic Circumpolar Current

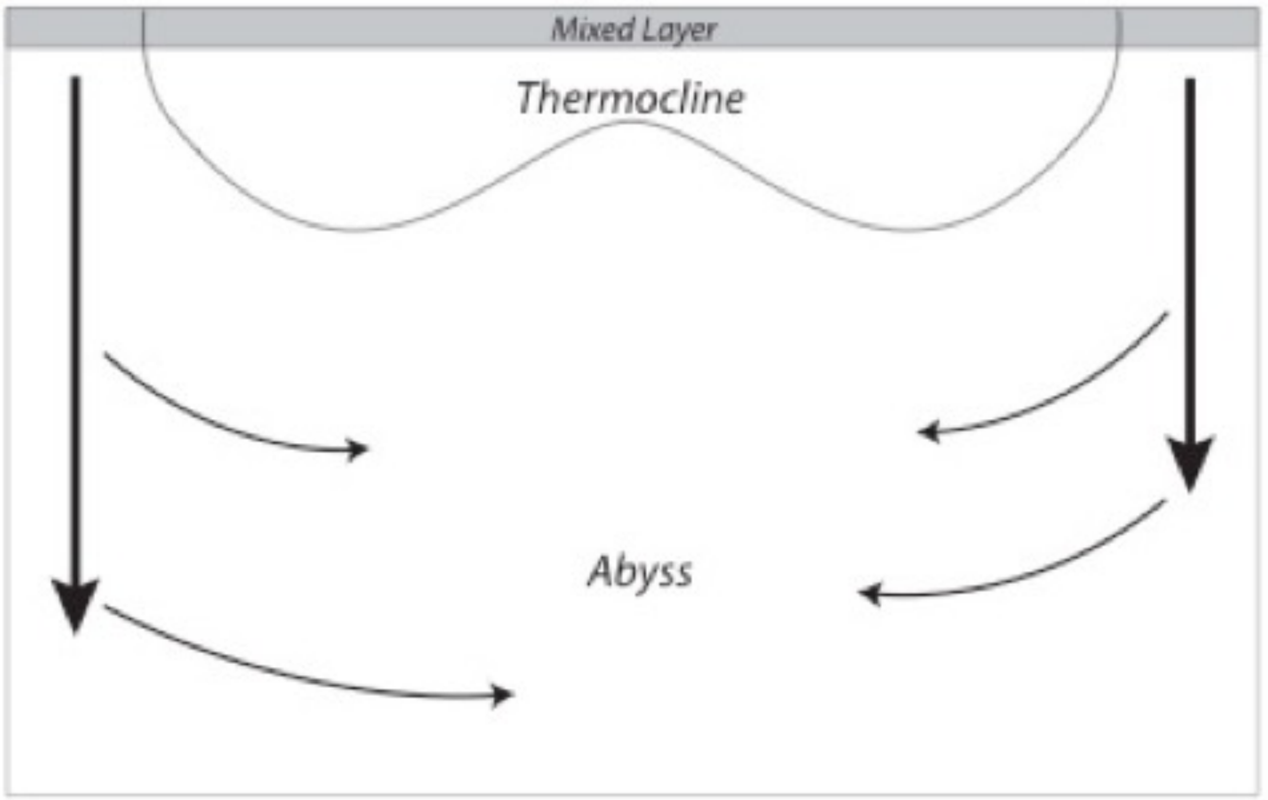




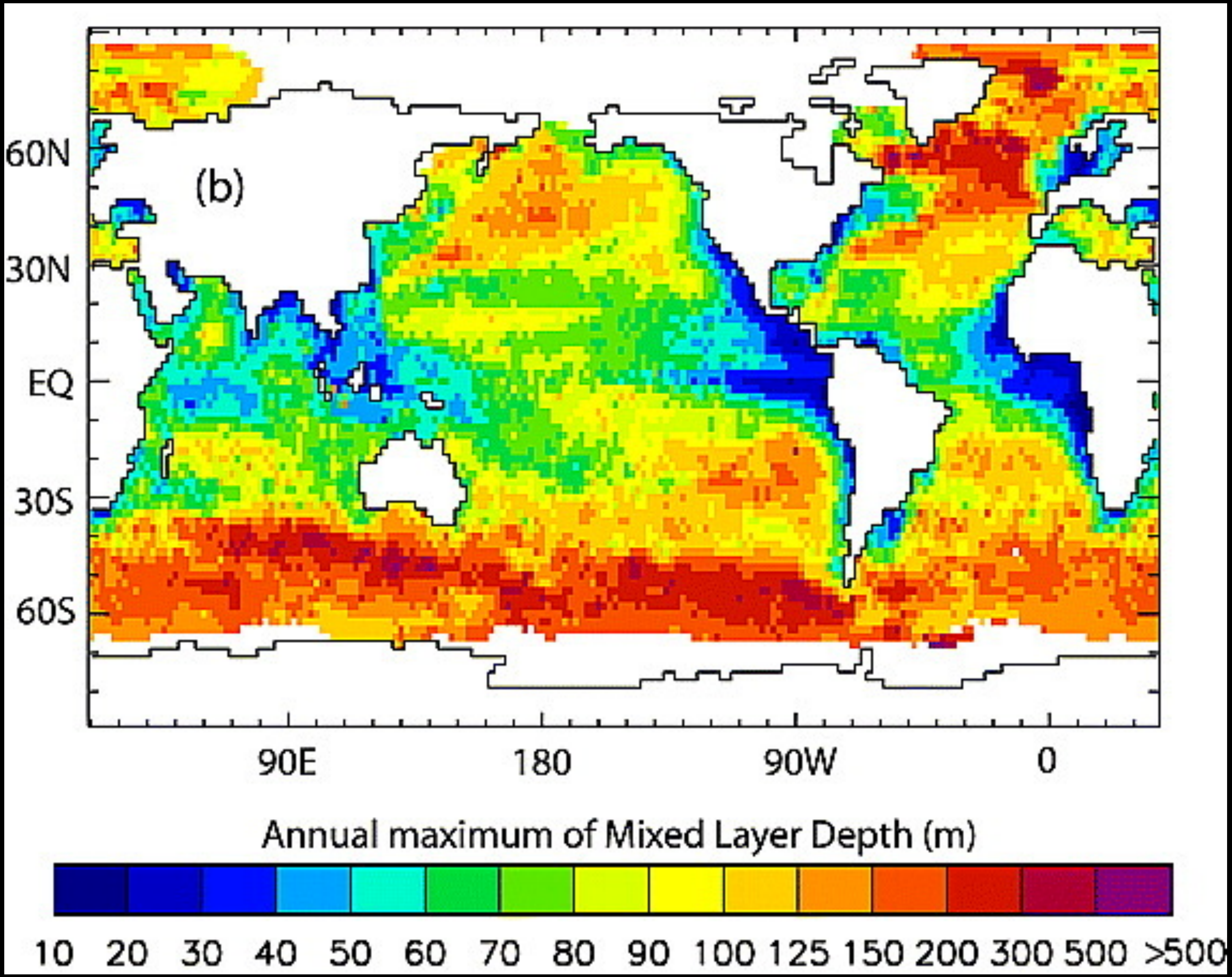
1. Mixed layers

- Surface layer of the ocean is almost always vertically mixed to some degree
- In summer, calm, warm conditions, the mixed layer might be very thin (several meters)
- At the end of winter, after the full season of cooling and storms, mixed layers reach their maximum thickness
- Mixed layers are created by
  - Wind stirring (max. depth of such a mixed layer is around 100 m)
  - Cooling and evaporation (increasing the density of the surface water), which creates vertical convection. Max. depth of these mixed layers can range up to about 1000 m, but is mainly 200-300 m.


radiative heating
radiative cooling
heat loss & evaporation
wind
Mixed Layer
convection
wind-driven turbulence
entrainment
depth
Thermocline
Abyss


Mixed Layer
Thermocline
Abyss

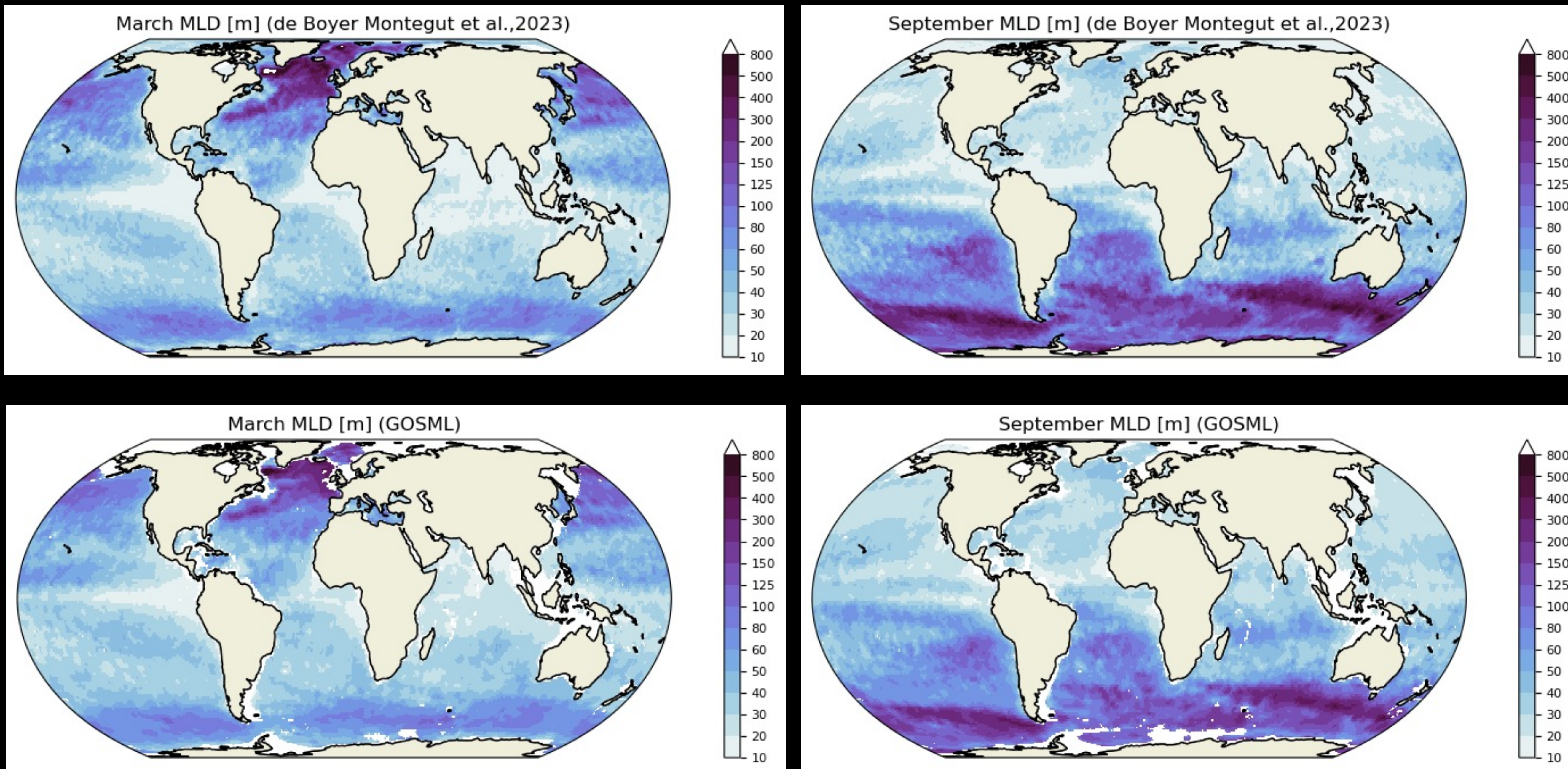
Maximum mixed layer depth (mainly late winter in each location)



Using delta T = 0.2° C

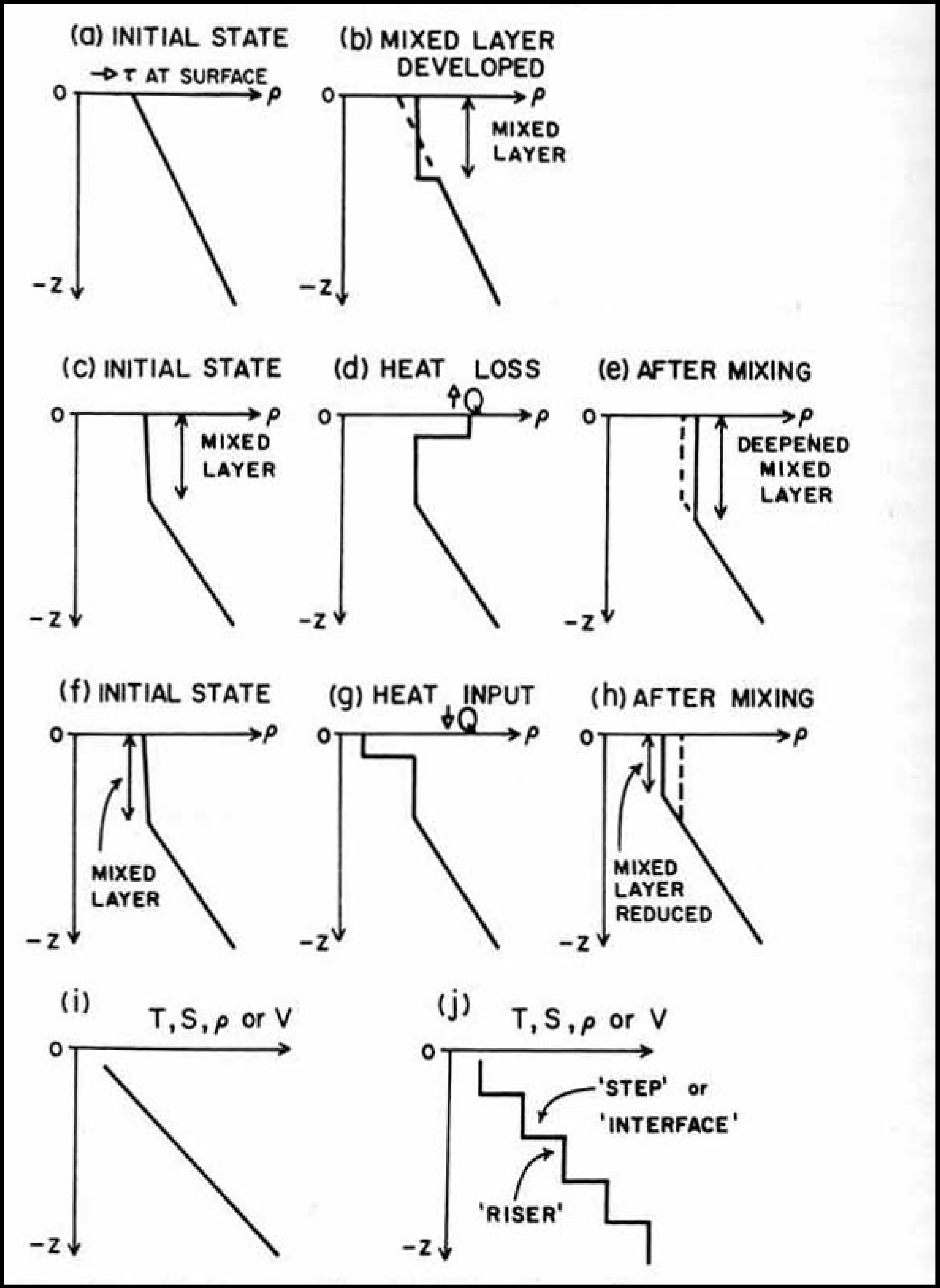
deBoyerMontegut et al. (JGR, 2004)

Maximum mixed layer depth (mainly late winter in each location)



deBoyerMontegut et al. (JGR, 2004) & GOSML

Mixed layer development



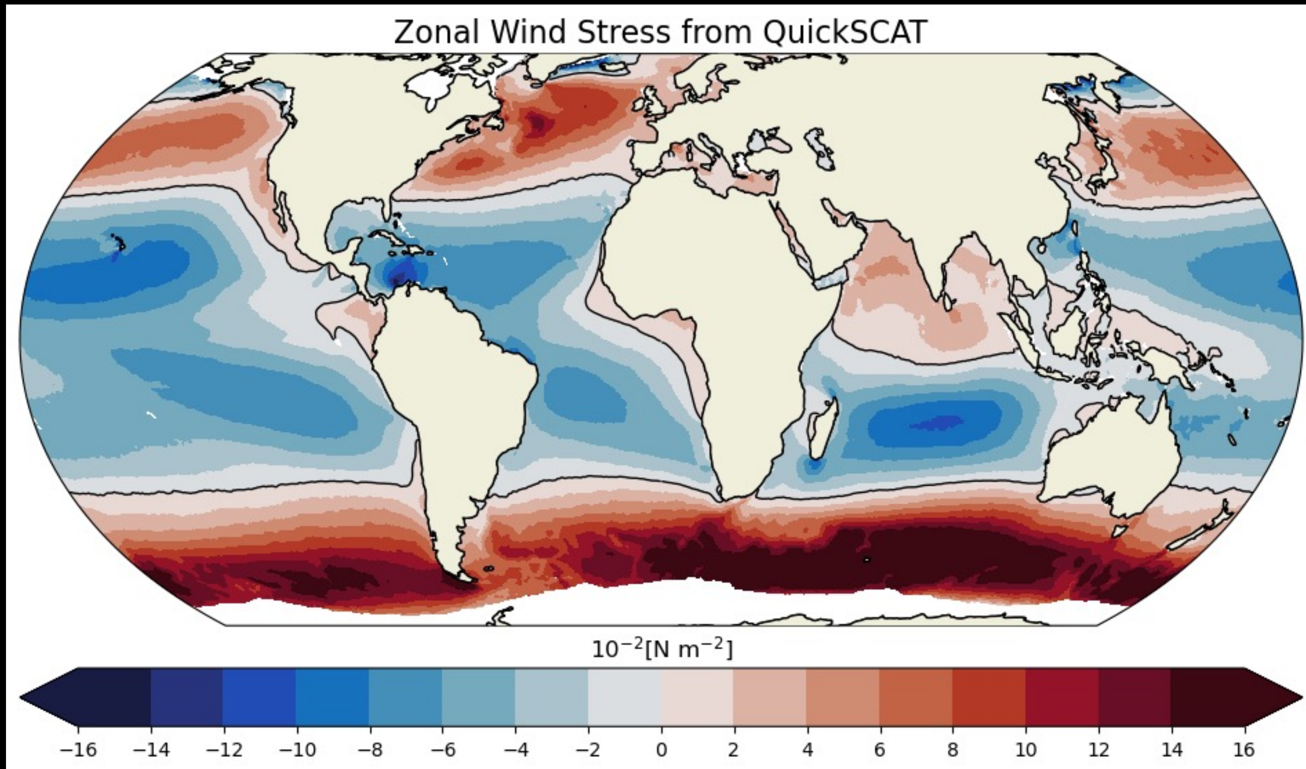
Winter development of mixed layer:

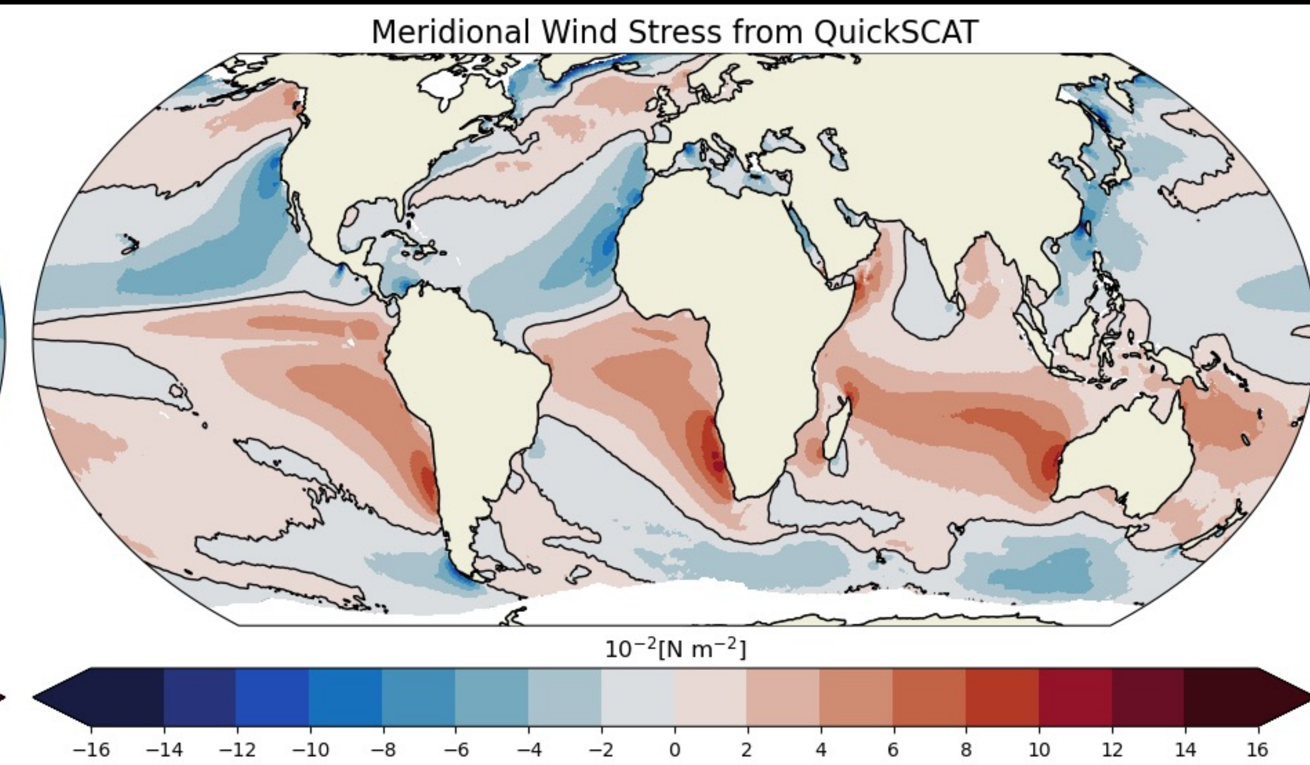
Wind stirring and cooling erode stratification, gradually deepening the mixed layer to maximum depth at the end of winter (Feb. to April depending on location)

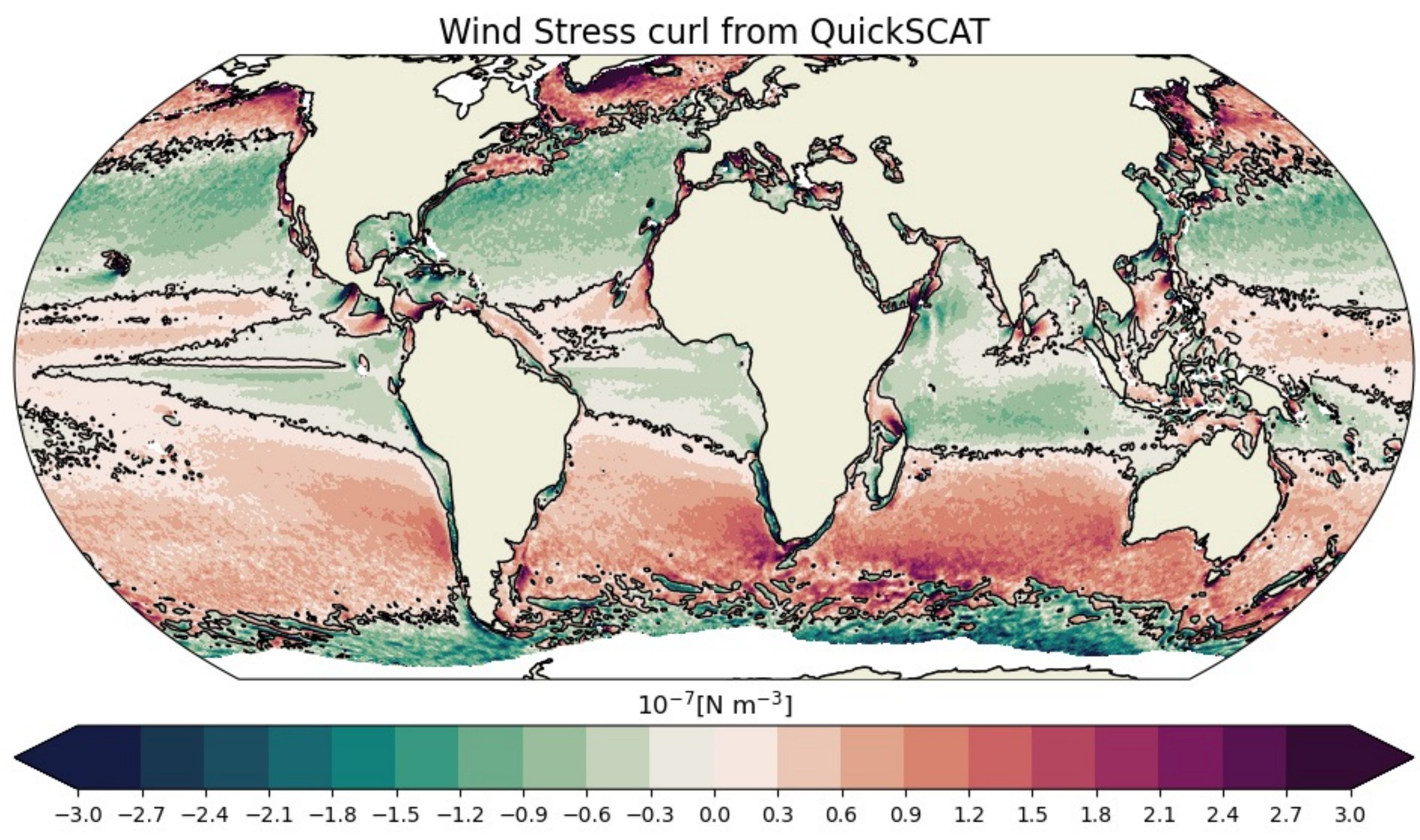
Summer restratification:

Warming at the top adds stratified layer at surface, usually leaves remnant of winter mixed layer below.

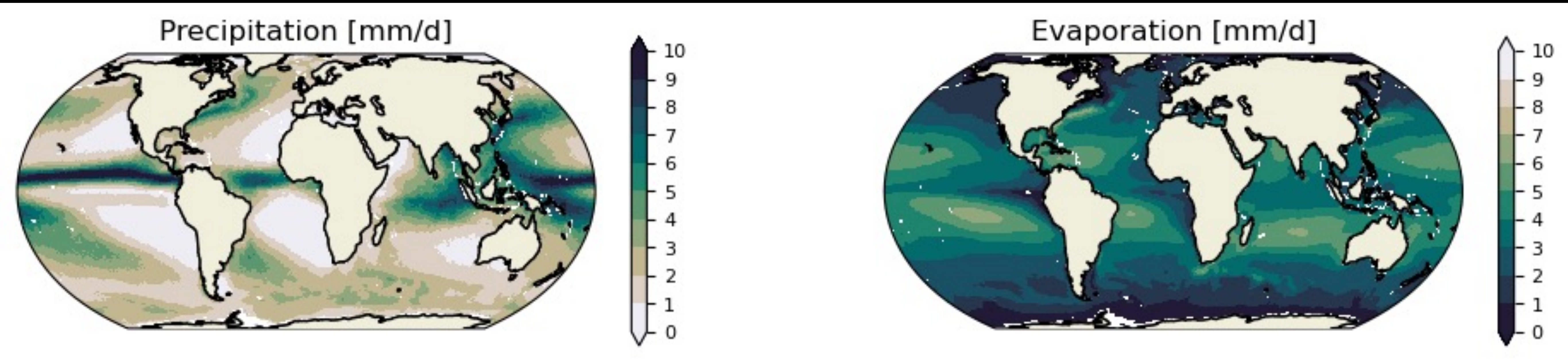
Momentum flux

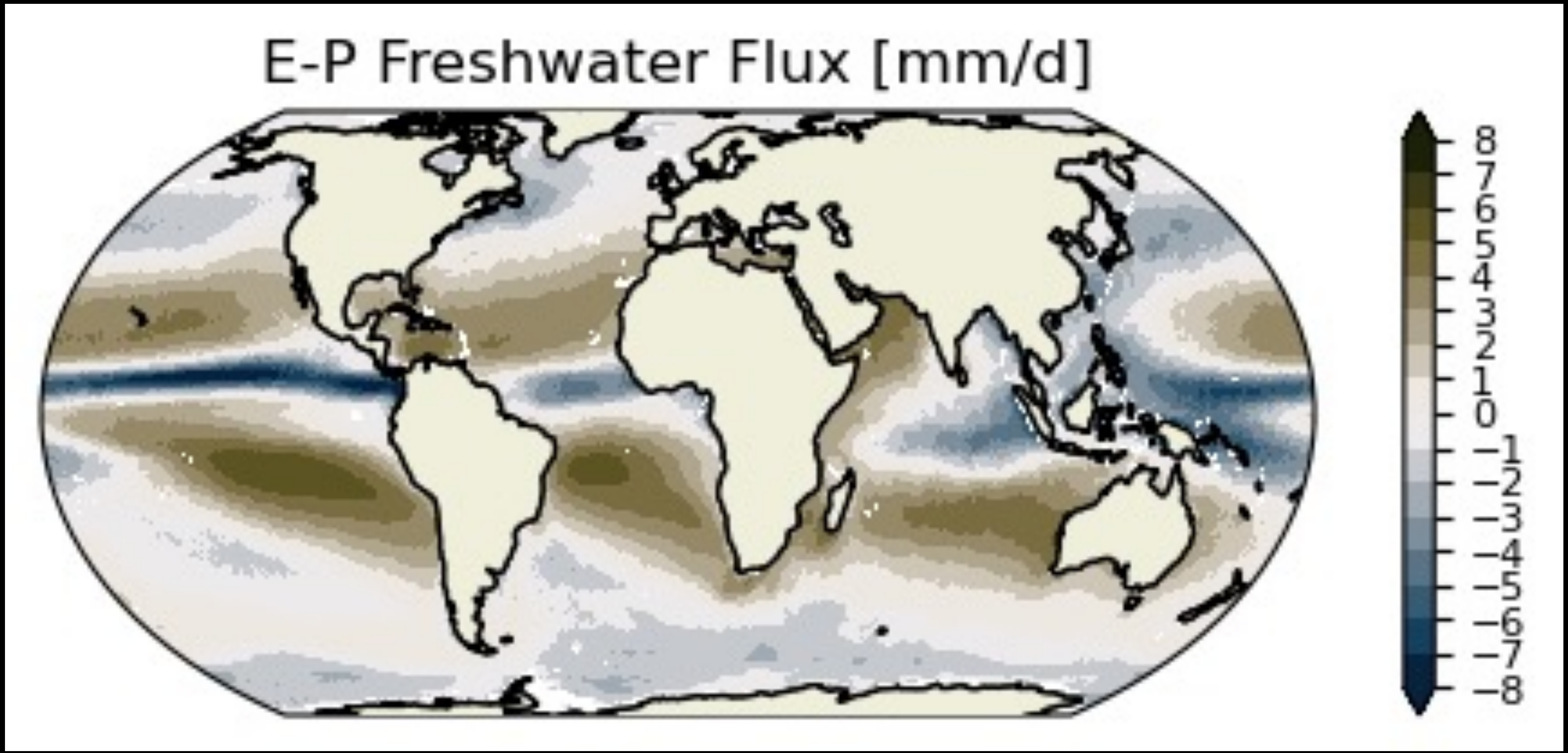




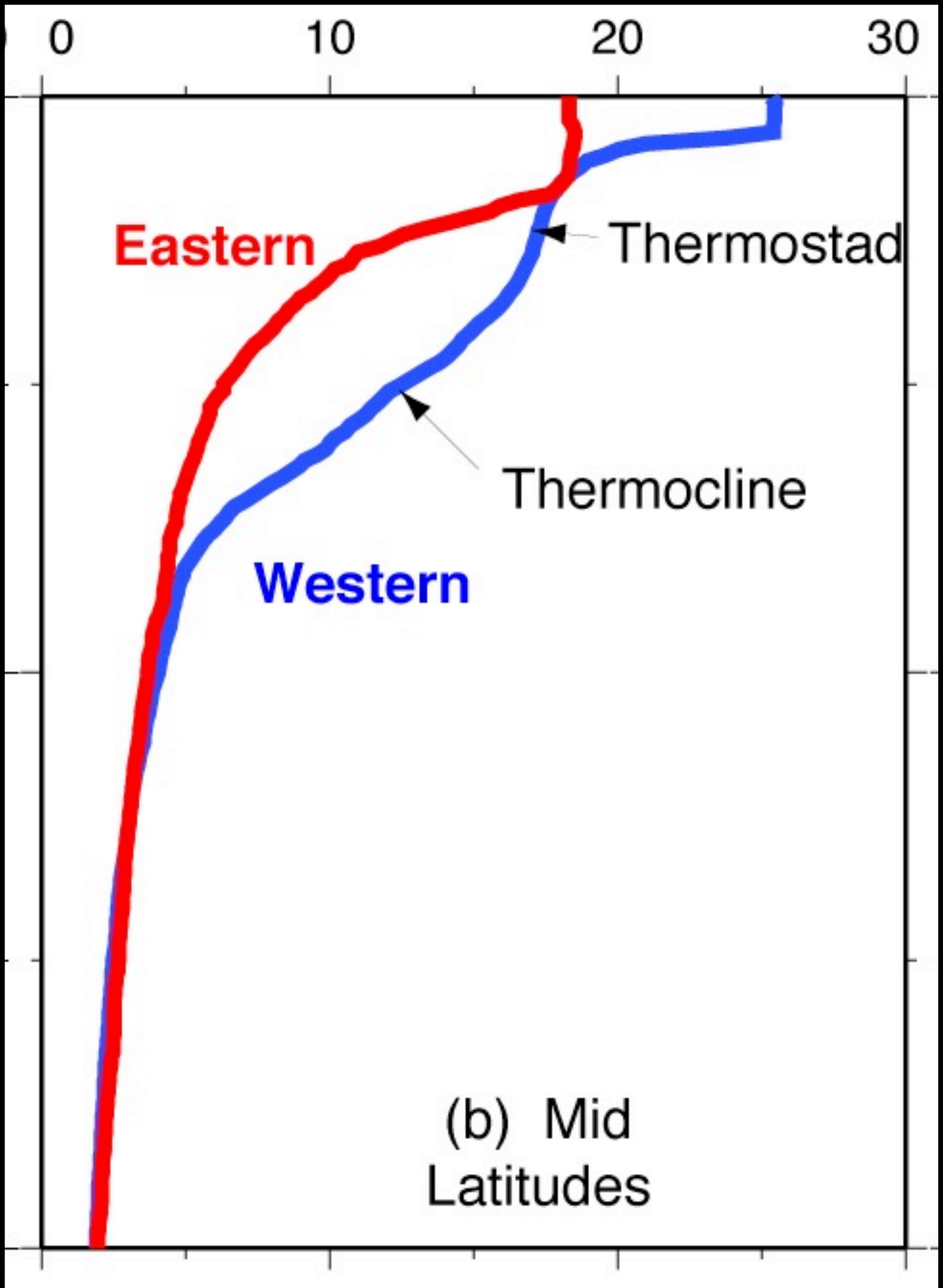


Air-sea freshwater flux and surface salinity





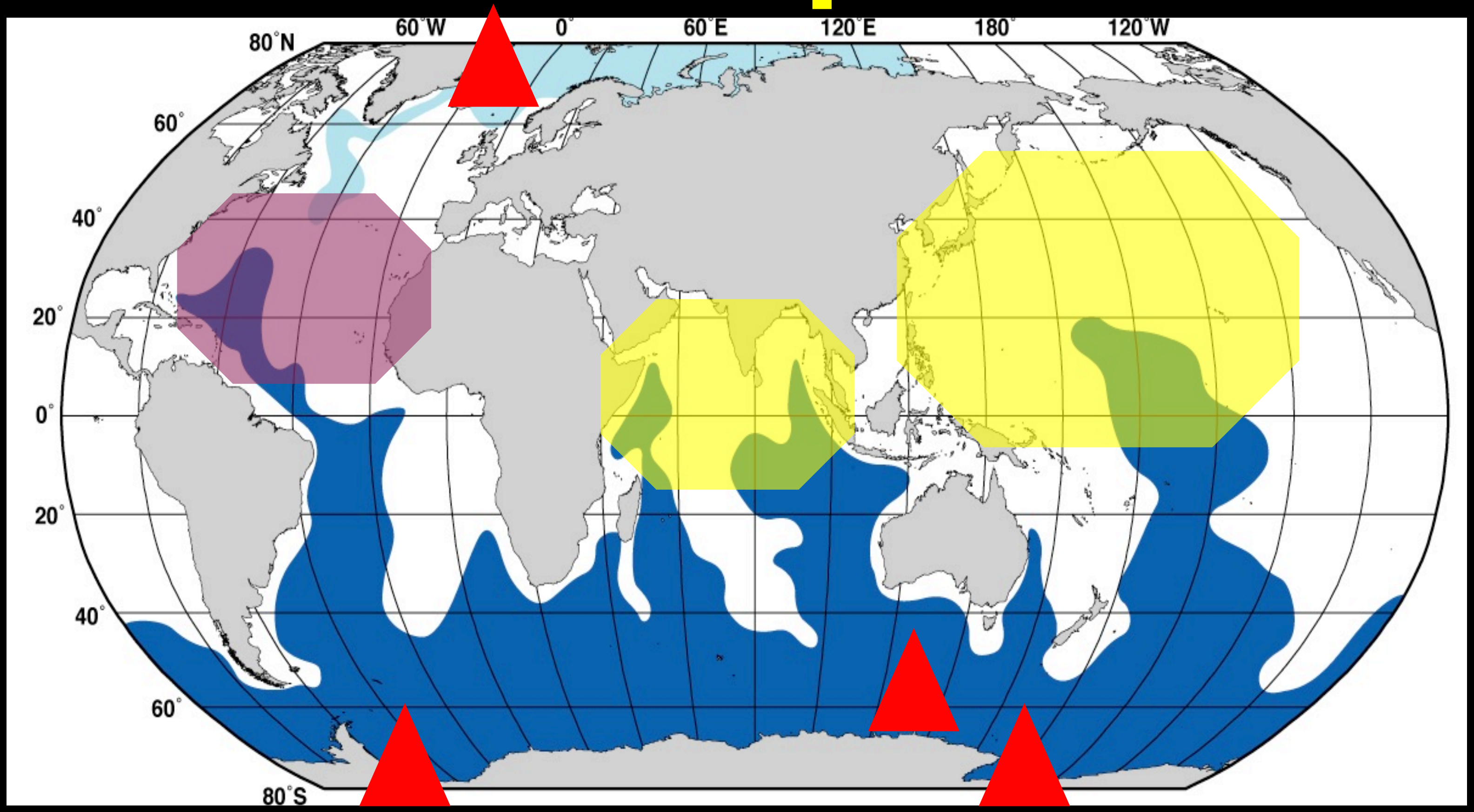
2. Thermocline (pycnocline)



Two physical processes:

1. **Vertical balance: mixing between warm, light surface waters and cold, dense deep waters**
2. **Circulation of denser surface waters down into interior and thus beneath the lower density surface layers**

3. Deep and bottom water



Deep and bottom water production sites

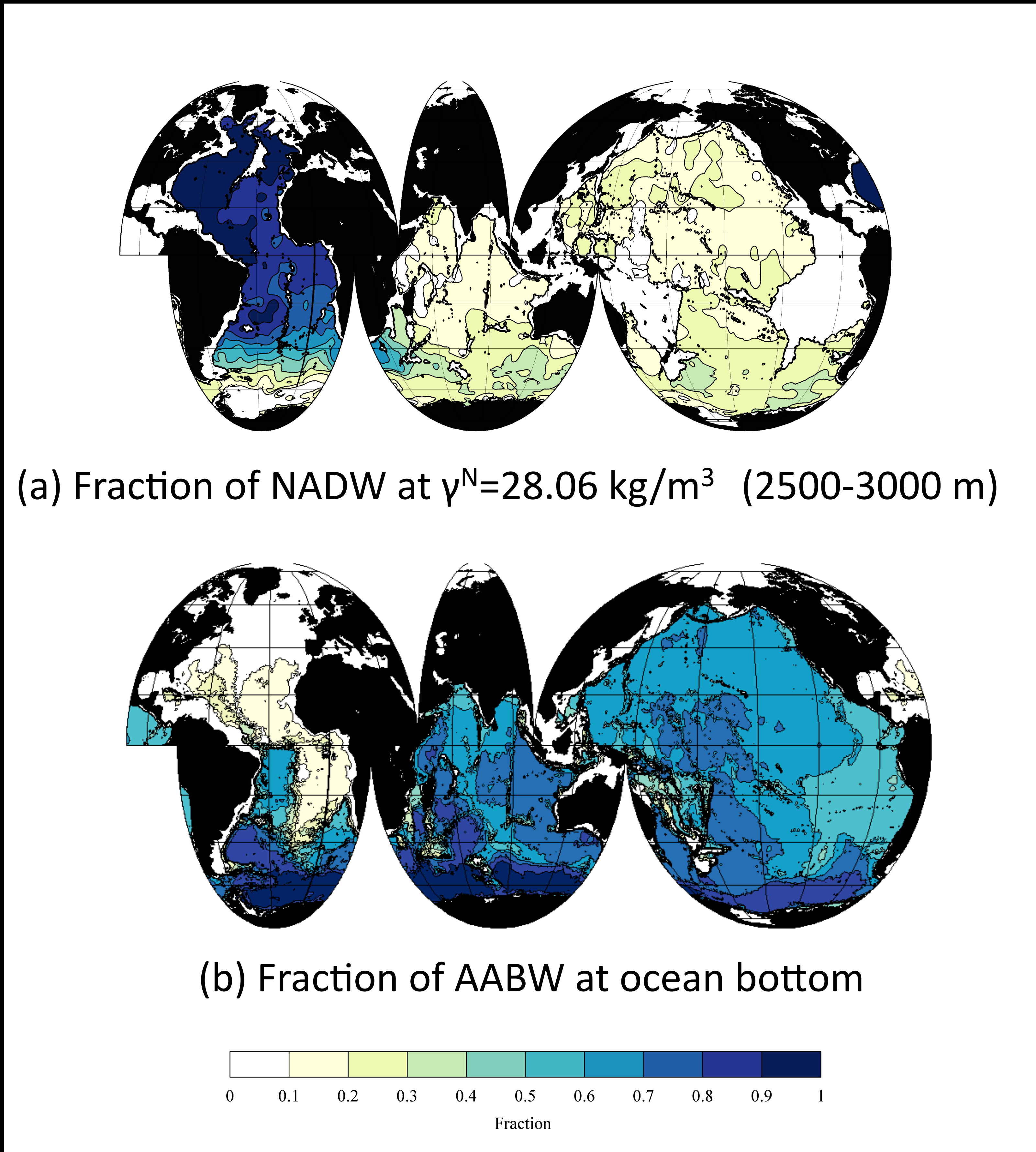
- Nordic Seas Overflow Water (contributor to North Atlantic Deep Water): high oxygen; deep convection in the Greenland Sea, overflow

- North Atlantic Deep Water: high salinity, high oxygen;

- Antarctic Bottom Water: very cold, high oxygen; brine rejection along coast of Antarctica

- Indian and Pacific Deep Waters: low oxygen, high nutrients; slow upwelling and slow deep mixing of inflowing NADW and AABW

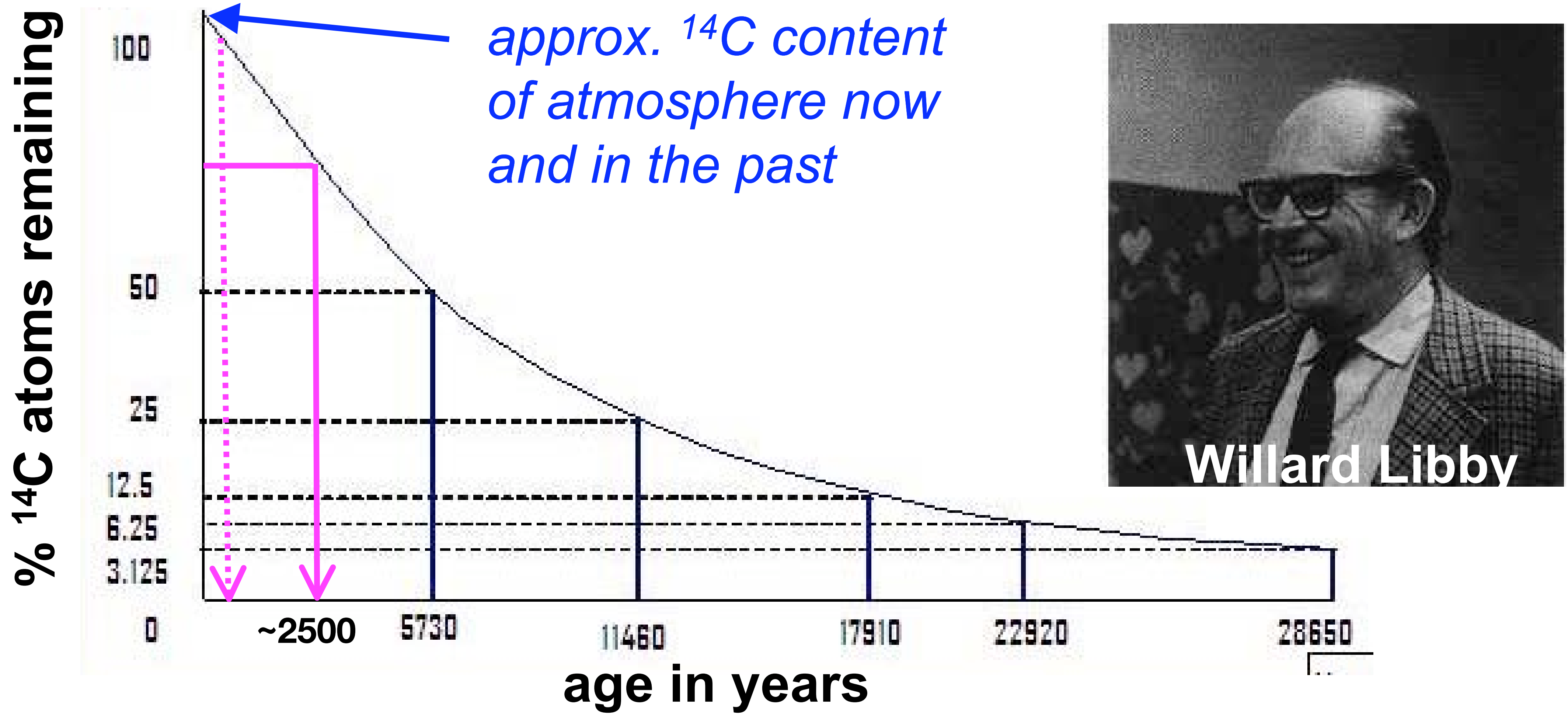
NADW and AABW in the abyssal ocean



NADW and AABW both occupy the deep and bottom layers, although AABW clearly dominates at the bottom.

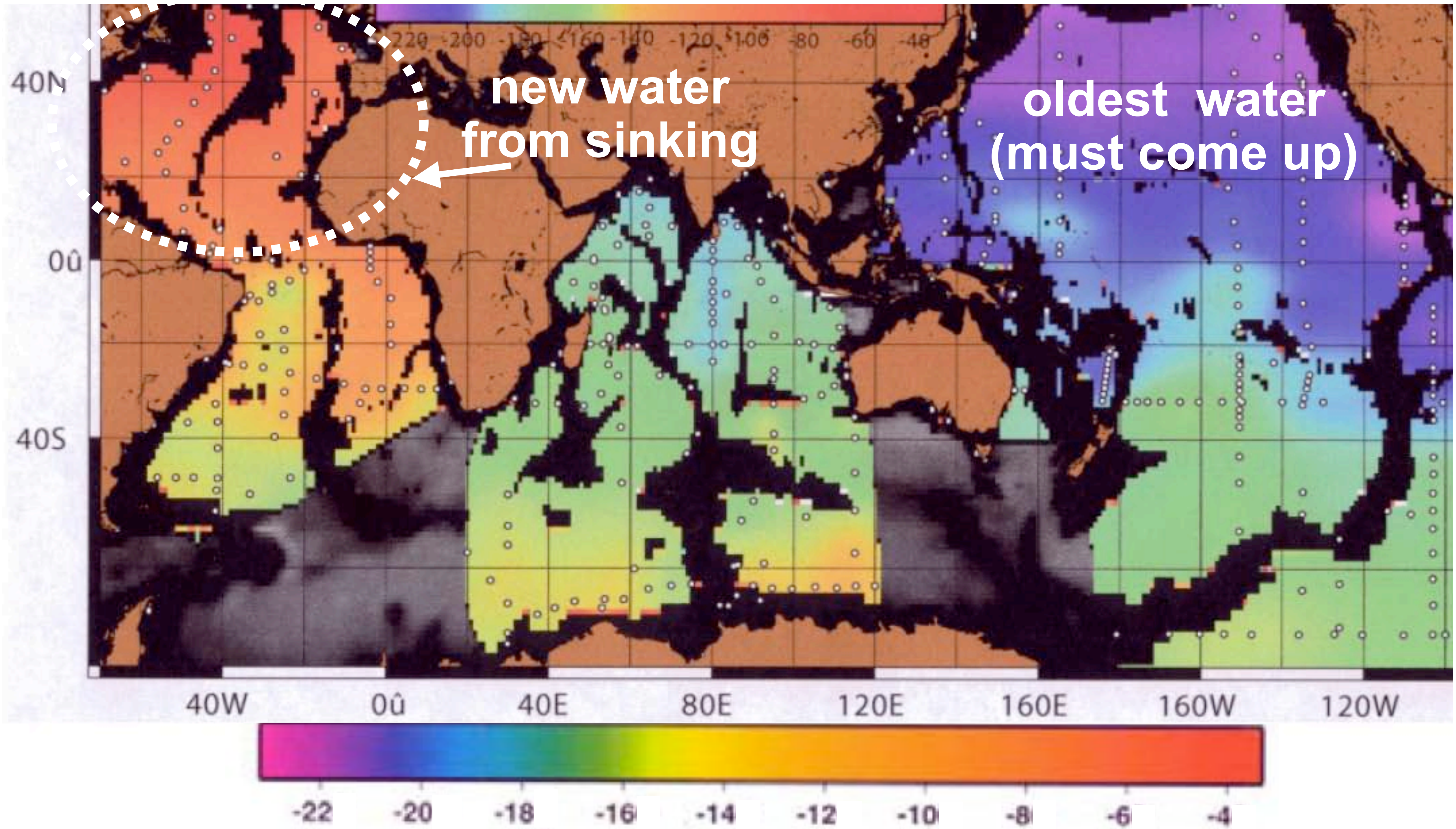
Maps of the fraction of water at mid-depth and at the bottom that are NADW or AABW. (Only two water masses were included in the analysis: these are the surface source waters.)

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!

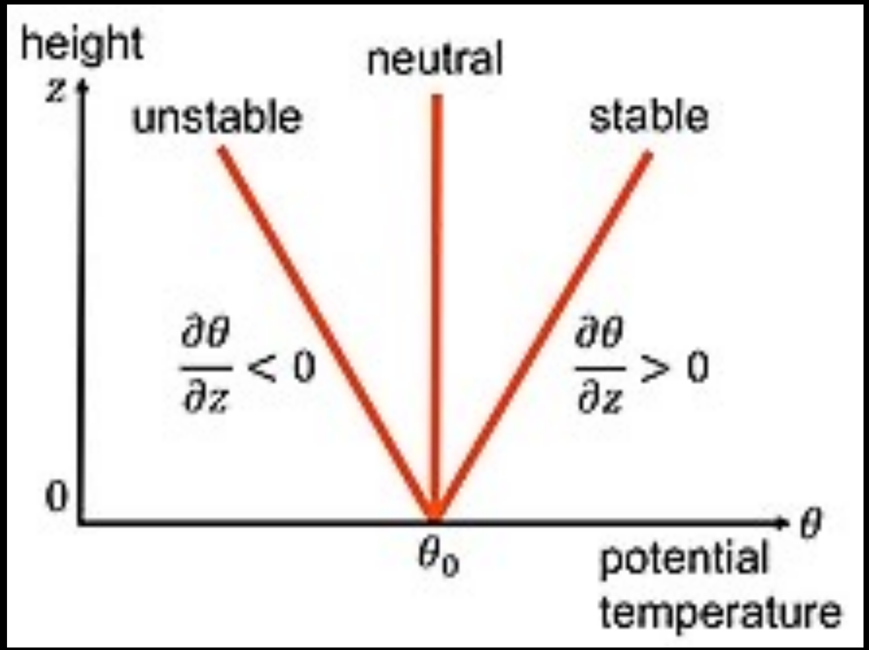


near bottom ^{14}C (% deviation from modern)

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

Static instability and Buoyancy Frequency

- Static stability of the ocean (atmosphere)
- Static stability of the environment can be measured through the vertical changes in temperature (or density)
- A parcel of fluid that is displaced vertically adiabatically tends to oscillate within a stable environment
- The frequency of those oscillations is called **Brunt-Vaisala frequency** or **buoyancy frequency N**.



$$N^2 = g\rho^{-1}\frac{\partial\rho}{\partial z} = g(\alpha\frac{\partial\theta}{\partial z} - \beta\frac{\partial S}{\partial z})$$

$$N^2 = \partial_z b; \ \ (b = -g\frac{\rho}{\rho_0})$$

4.8 Static instability, the parcel method and Buoyancy frequency

Consider a stratified ocean and a parcel of fluid initially at rest, and therefore in hydrostatic balance. We will focus on vertical displacements and the restoring force is gravity. Consider a small adiabatic displacement of the parcel upward by δz, without altering the background pressure field. If the parcel is now lighter then the local environment, it will feel an upward pressure gradient force larger than the downward gravitational force, it will accelerate upwards and will become buoyant. In this case the fluid is statically unstable. If, instead, the parcel finds itself heavier than its sorroundings, the downward gravitational force will be greater than the upward pressure force, the fluid will sink back to its original position and will oscillate. This condition is statically stable.

Consider an incompressible fluid in which the density of the displaced parcel is conserved, $D\rho/Dt = 0$. If the environmental profile is $\tilde{\rho}(z)$ and the density of the parcel is ρ, a parcel displaced to a level $z + \delta z$ will show a change in density with respect to the local environment equal to

$$\delta\rho = \rho(z+\delta z) - \tilde{\rho}(z+\delta z) = \tilde{\rho}(z) - \tilde{\rho}(z+\delta z) = -\frac{\partial\tilde{\rho}}{\partial z}\delta z, \tag{4.56}$$

where the derivative on the right-hand side is the environmental gradient of density.

If $\frac{\partial\tilde{\rho}}{\partial z} < 0$, the parcel will be heavier than its sorroundings and will sink back in a stable condition.

If $\frac{\partial\tilde{\rho}}{\partial z} > 0$, the parcel will be buoyant in a statically unstable fluid.

That is, the stability of a parcel of fluid is determined by the gradient of the environmental density.

The upward force, per unit volume, on the displaced parcel is

$$F = -g\delta\rho = g\frac{\partial\tilde{\rho}}{\partial z}\delta z \tag{4.57}$$

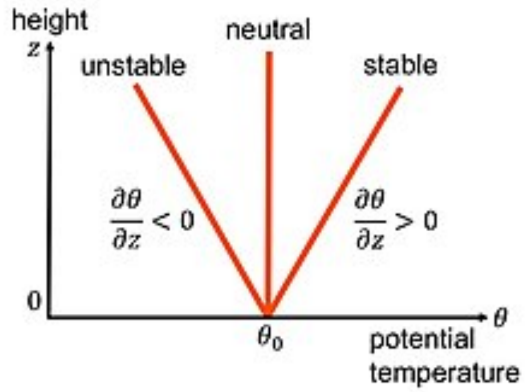


Figure 4.5: Possible temperature vertical profiles, in the atmosphere or ocean, giving rise to unstable, neutral or stable conditions.

and the equation of motion of the fluid parcel is thus

$$\rho(z)\frac{\partial^2 \delta z}{\partial t^2} = g\frac{\partial \tilde{\rho}}{\partial z}\delta z, \tag{4.58}$$

or

$$\frac{\partial^2 \delta z}{\partial t^2} = \frac{g}{\tilde{\rho}}\frac{\partial \tilde{\rho}}{\partial z}\delta z. \tag{4.59}$$

Static stability measures how quickly a water parcel is restored to its position in the water column if displaced vertically. If unstable, the water column has the potential to overturn.

In stable water column conditions ($\frac{\partial \tilde{\rho}}{\partial z} < 0$), the parcel experiences a restoring force and will oscillate at a given frequency:

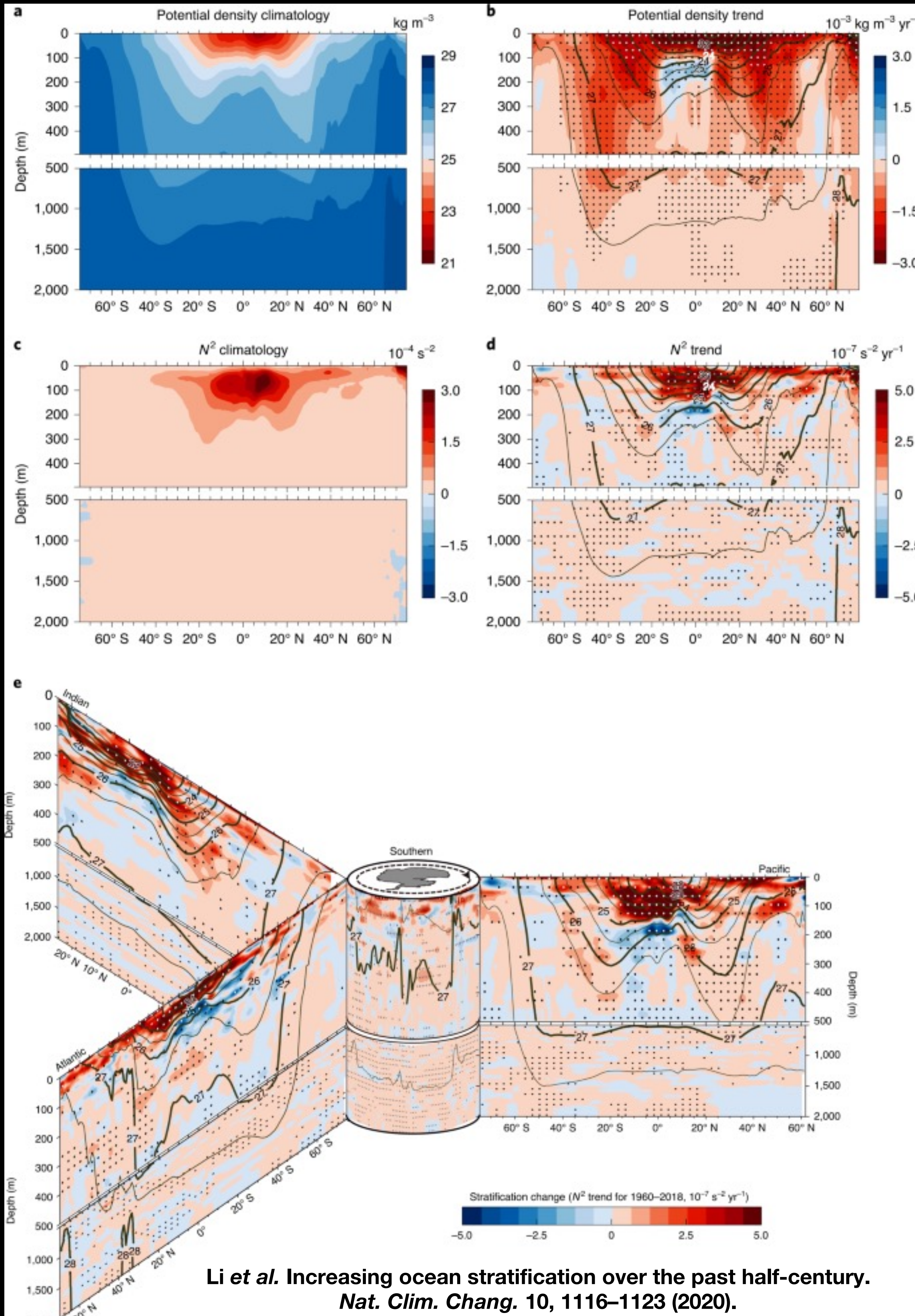
$$\frac{\partial^2 \delta z}{\partial t^2} = -N^2 \delta z, \tag{4.60}$$

where

$$N^2 = -\frac{g}{\tilde{\rho}}\frac{\partial \tilde{\rho}}{\partial z}, \tag{4.61}$$

and N is the Brunt-Vaisala frequency. In liquids, it is a good approximation to replace $\tilde{\rho}$ by ρ_0.

If $N^2 < 0$, the density profile is unstable, the parcel continues to ascend and convection occurs. This is the condition for convective instability. Convection causes fluid parcels to mix and reduces an unstable profile to neutral stability.



Li *et al.* Increasing ocean stratification over the past half-century. *Nat. Clim. Chang.* 10, 1116–1123 (2020).

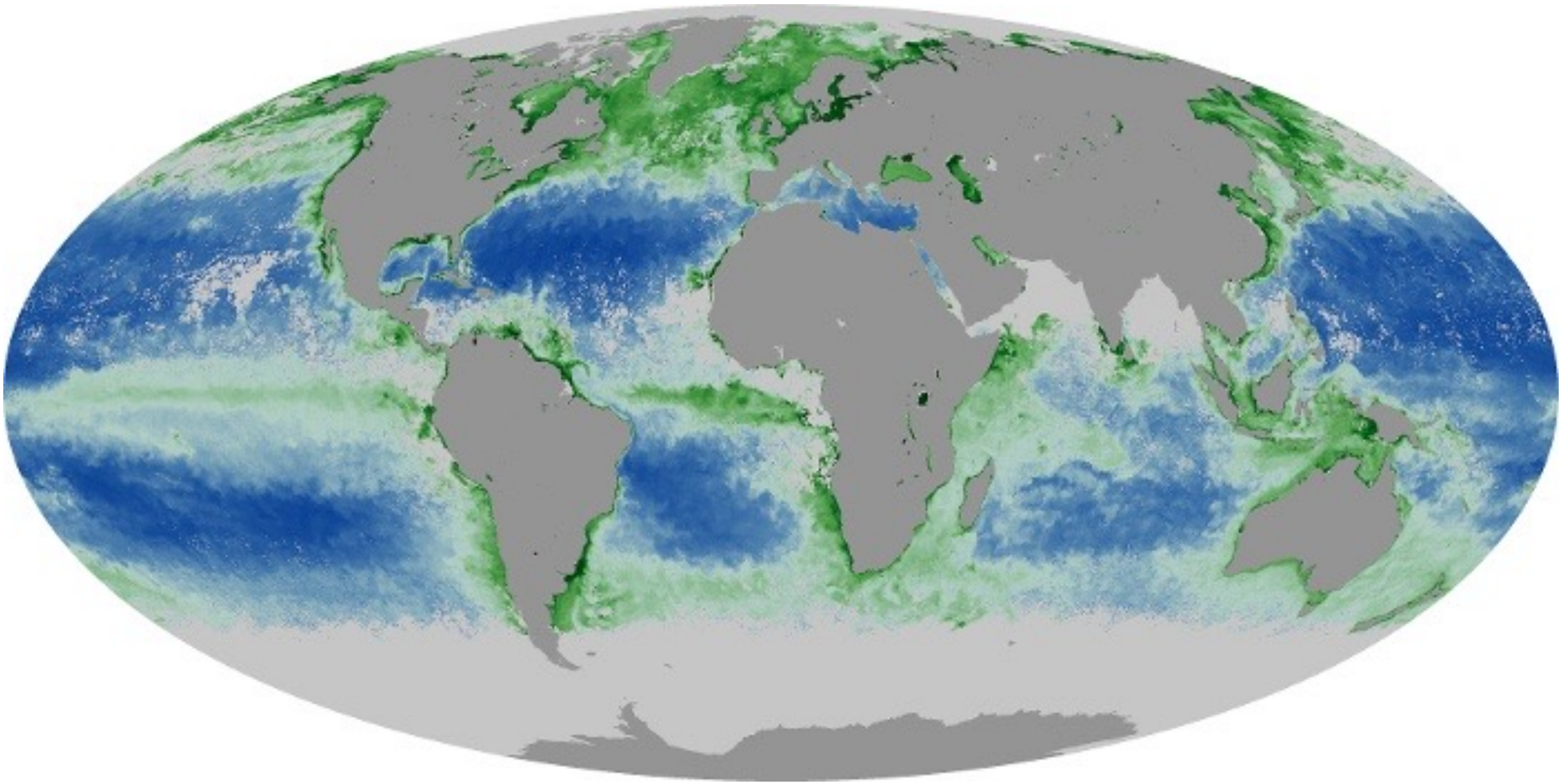
Seawater generally forms stratified layers with lighter waters near the surface and denser waters at greater depth. This stable configuration acts as a <u>barrier to water mixing</u> that impacts the efficiency of vertical exchanges of energy, carbon, oxygen and other constituents.

Stratification globally has increased by a substantial 5.3% between 1960–2018

Increasing stratification has important climate implications. The expected <u>decrease in ocean ventilation</u> could affect ocean heat and carbon uptake, water mass formation/destruction.

Also implications for density-driven ocean circulation changes and, in particular, the Atlantic Meridional Overturning Circulation, which already shows some evidence of slowdown

Can you see Dynamics? you will ...



(Chl-a concentration at the surface as seen from satellite in July 2007)