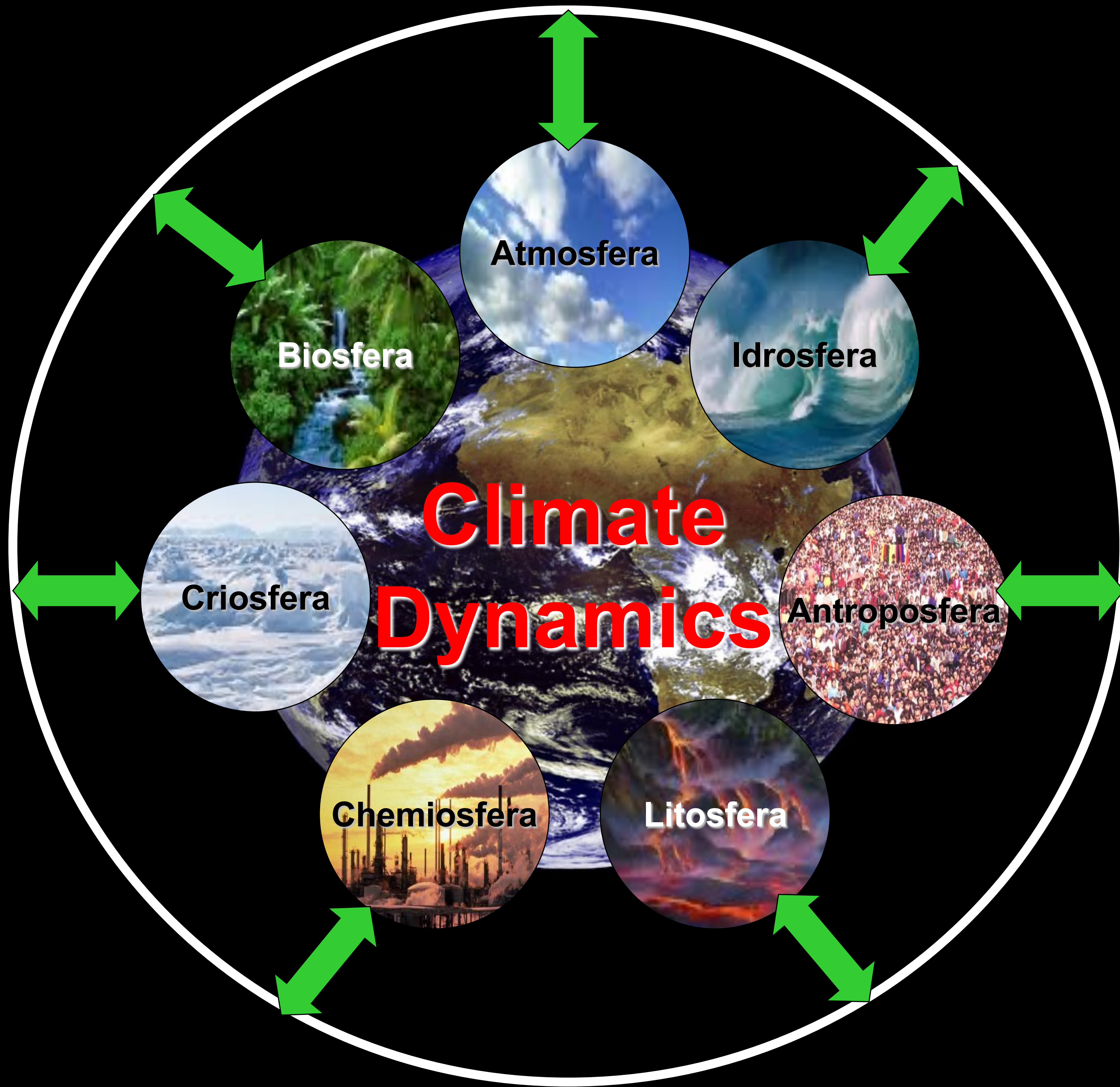
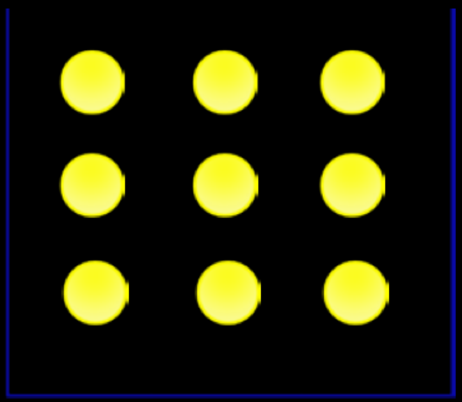

Atmosfera
Biosfera
Idrosfera
Climate Dynamics
Criosfera
Antroposfera
Chemiosfera
Litosfera

Il Sole

- Fonte principale di energia per il Sistema climatico.
  Mette in moto l’Atmosfera e l’Oceano

- Il Sole imparte una media di 344 W/m^2 all’inizio dell’atmosfera

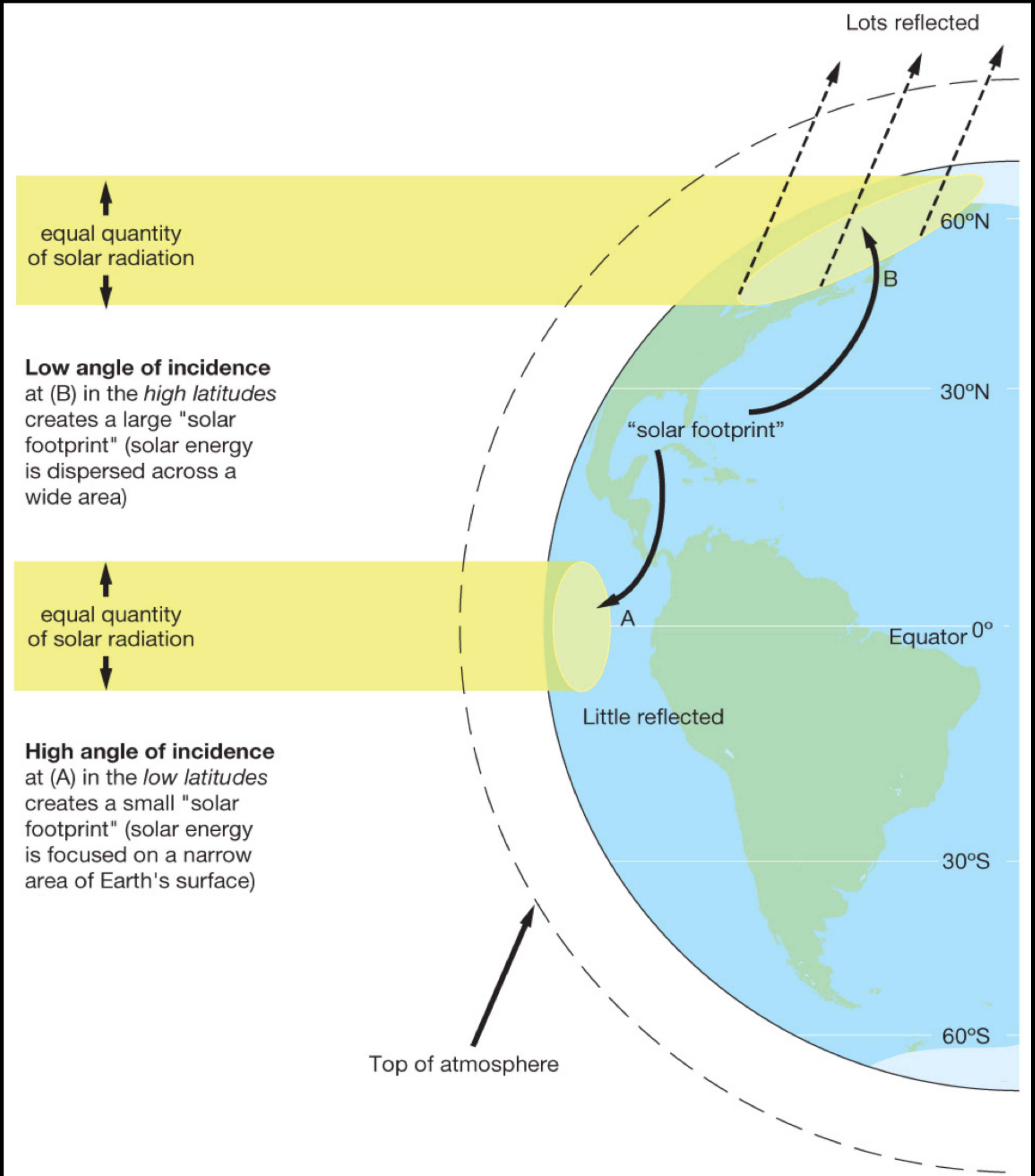
~9 lampadine da 40W per metro quadrato



- e l’energia è la capacità di fare lavoro
  - la misuriamo in Joules (J)
  - Il flusso di energia è 1 J/s = 1 Watt
  - e i W/m^2 sono l’energia (J) al secondo su un area di 1 m^2

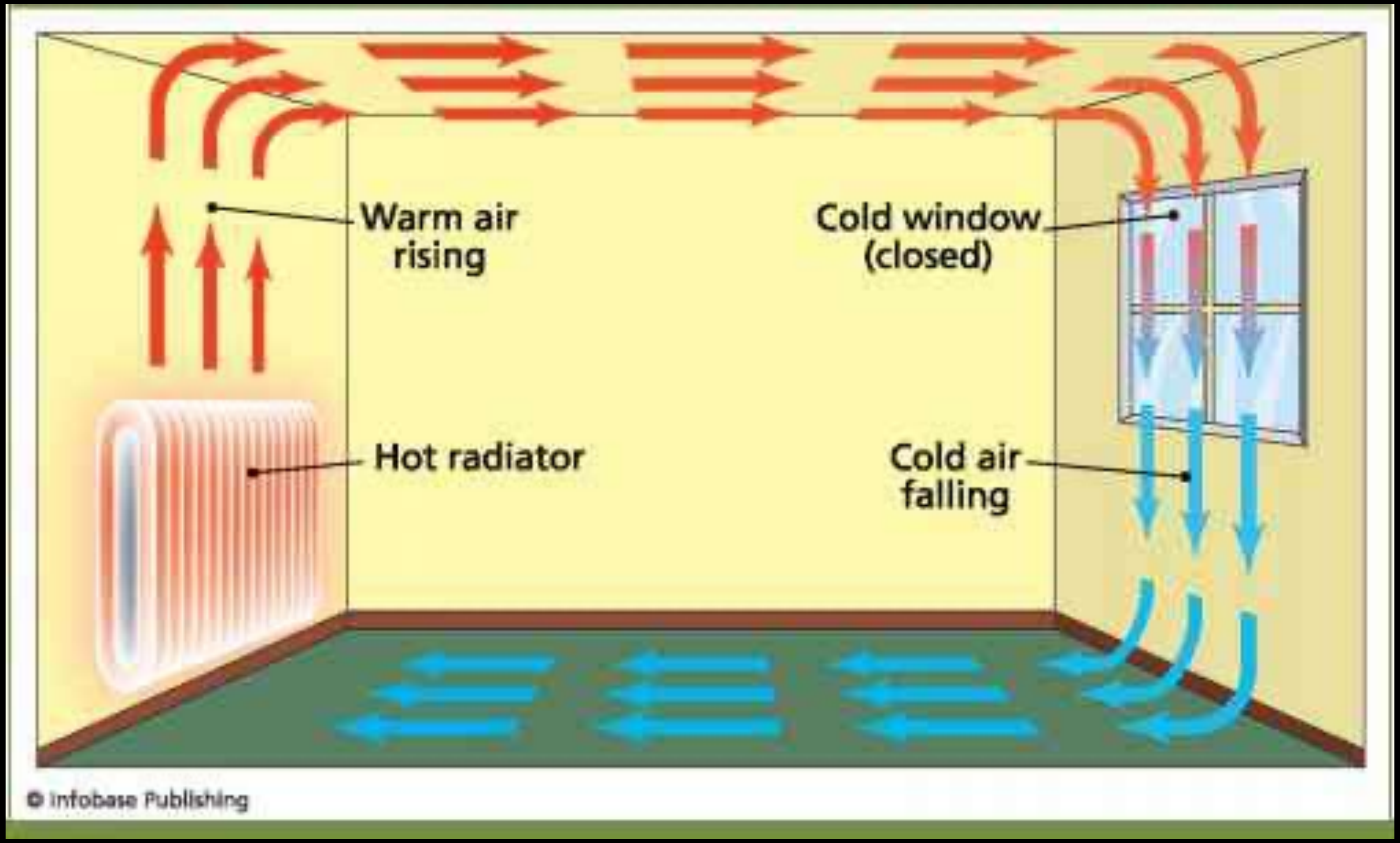
Riscaldamento solare non è uniforme

- Il riscaldamneto solare non è uniforme: l'equatore riceve più calore per unità di area delle alte latitudini
- L'Atmosfera (e l'Oceano) rispodono muovendo fluido caldo verso i poli e riportando fluido freddo verso l'equatore - riequilibrando l'input di calore



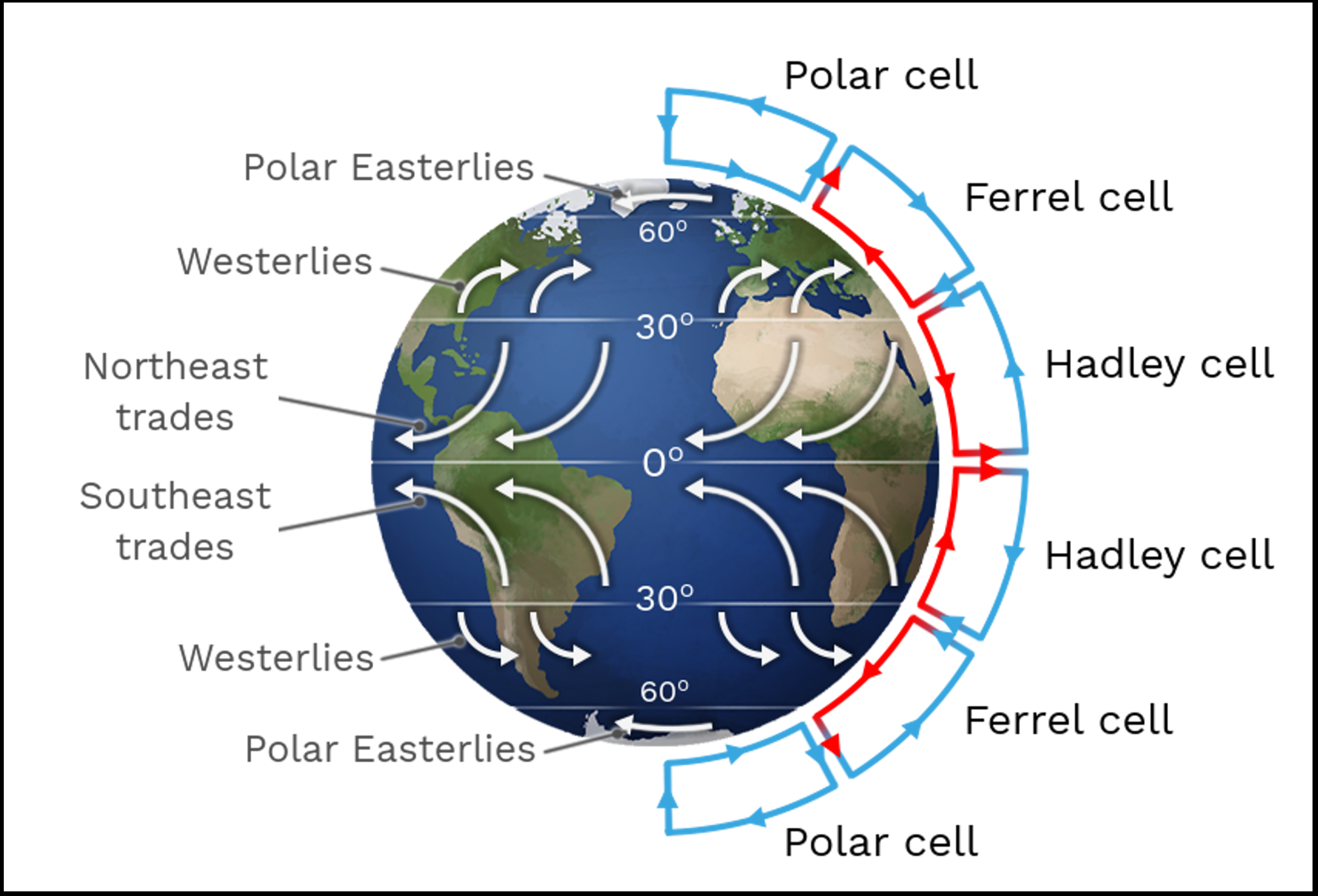
Riscaldamento solare non è uniforme

- Il riscaldamneto solare non è uniforme: l'equatore riceve più calore per unità di area delle alte latitudini
- L'Atmosfera (e l'Oceano) rispodono muovendo fluido caldo verso i poli e riportando fluido freddo verso l'equatore - riequilibrando l'input di calore

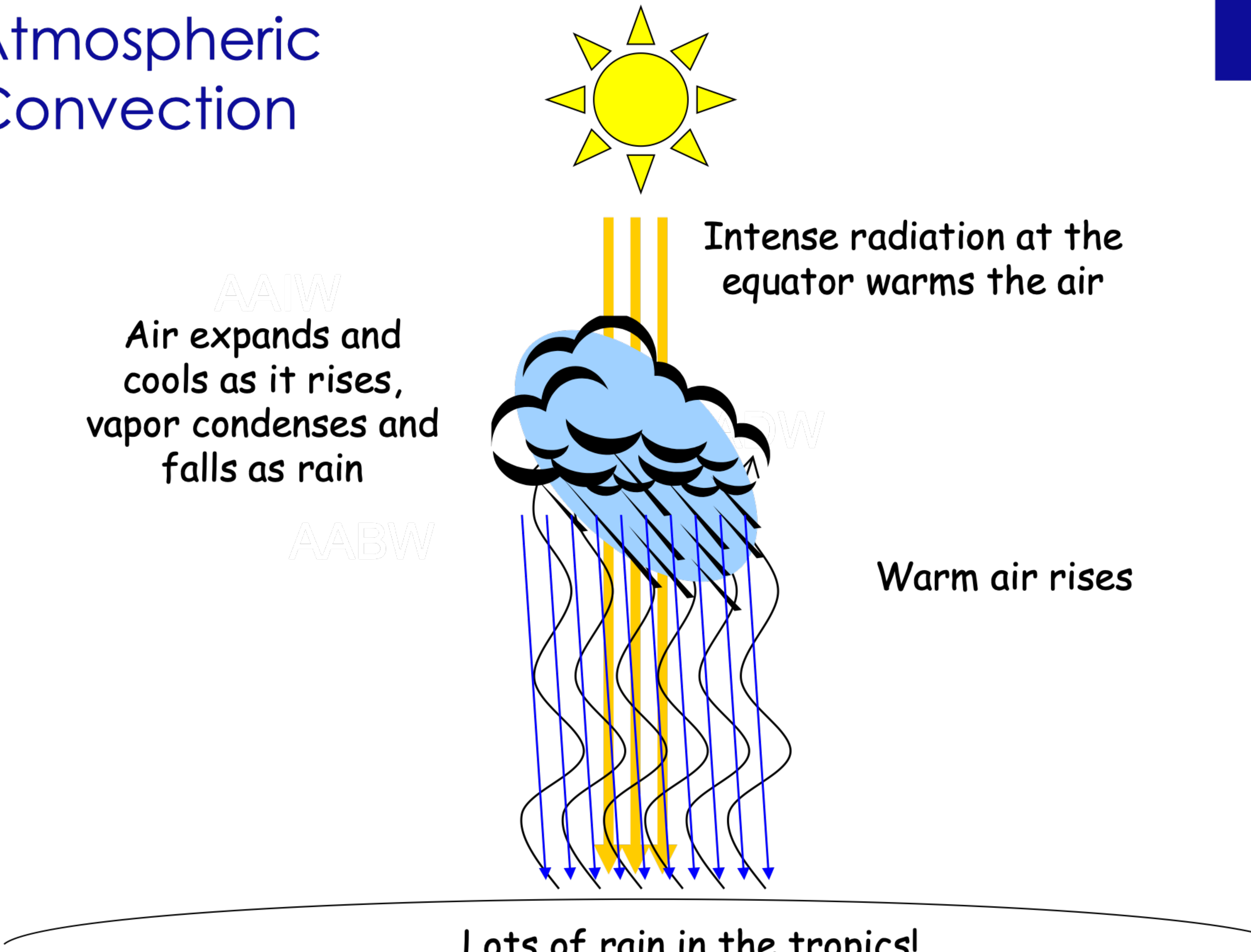


Riscaldamento solare non è uniforme

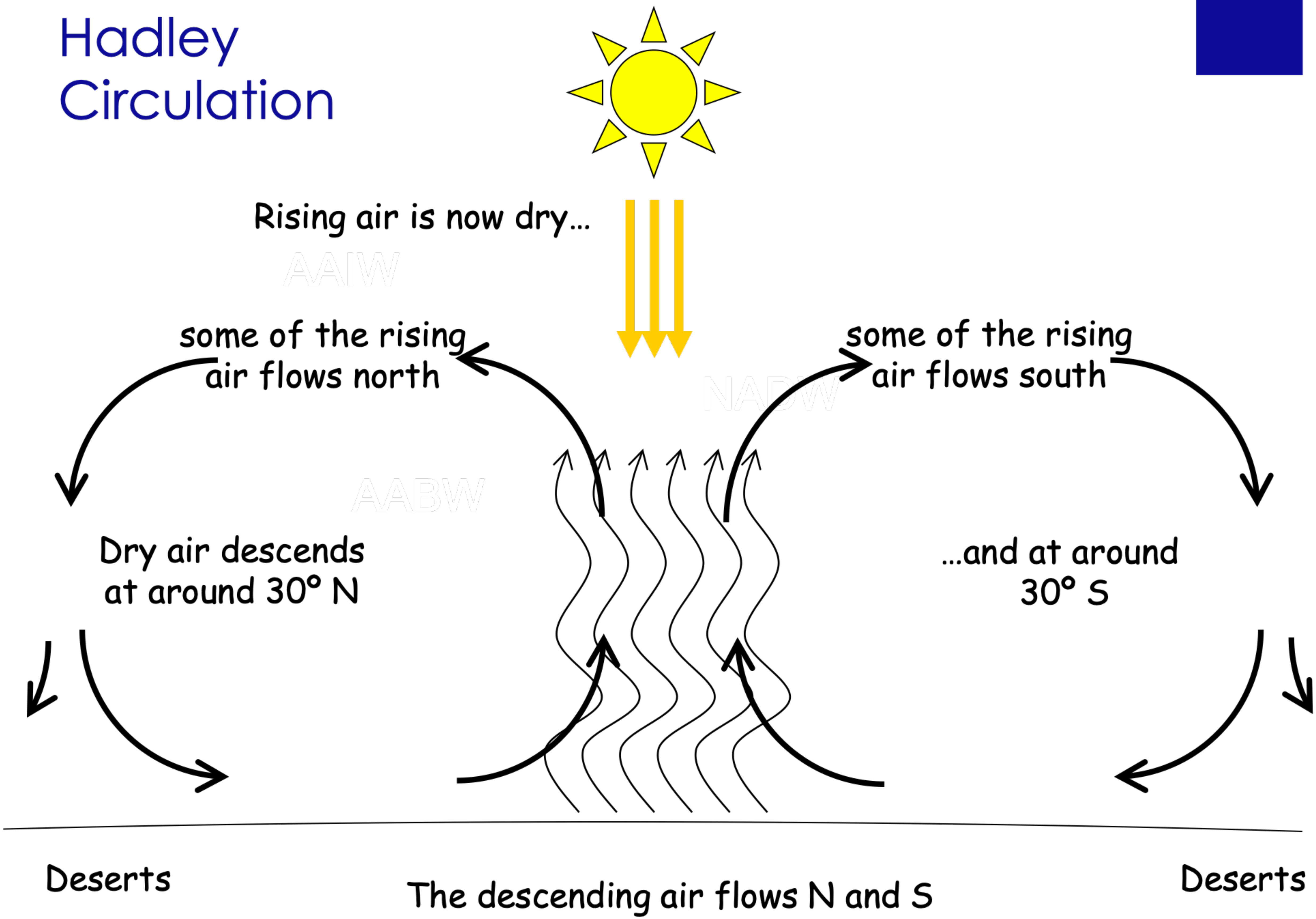
- Il riscaldamneto solare non è uniforme: l'equatore riceve più calore per unità di area delle alte latitudini
- L'Atmosfera (e l'Oceano) rispodono muovendo fluido caldo verso i poli e riportando fluido freddo verso l'equatore - riequilibrando l'input di calore



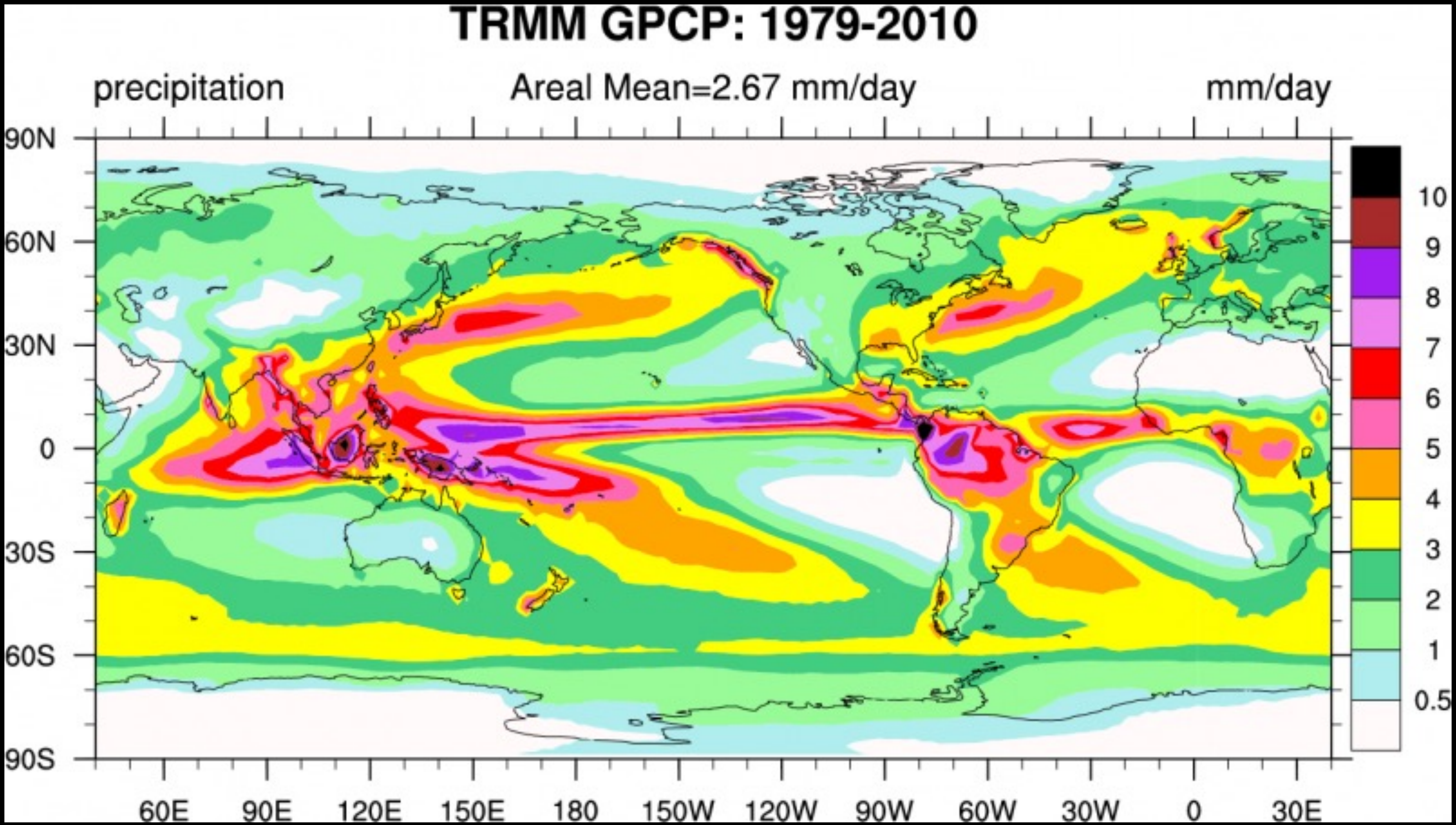
Atmospheric Convection



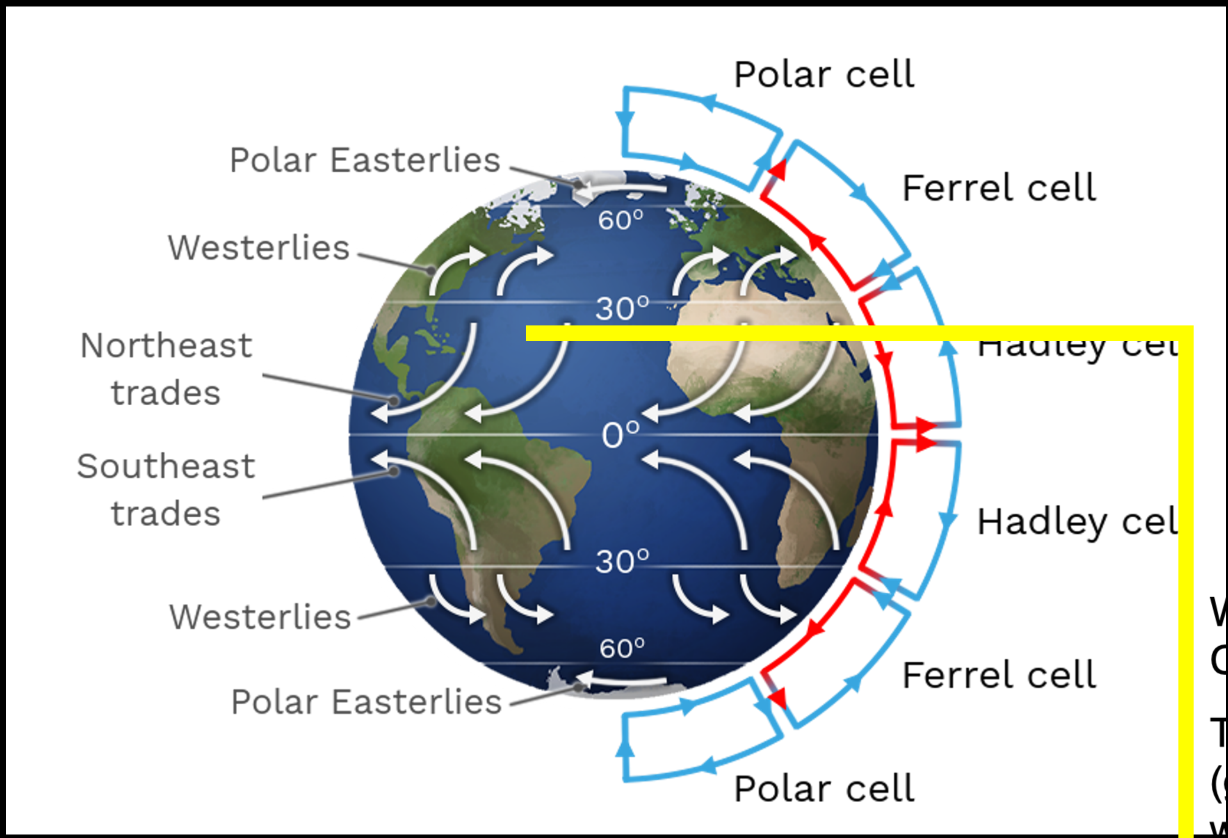
Hadley Circulation

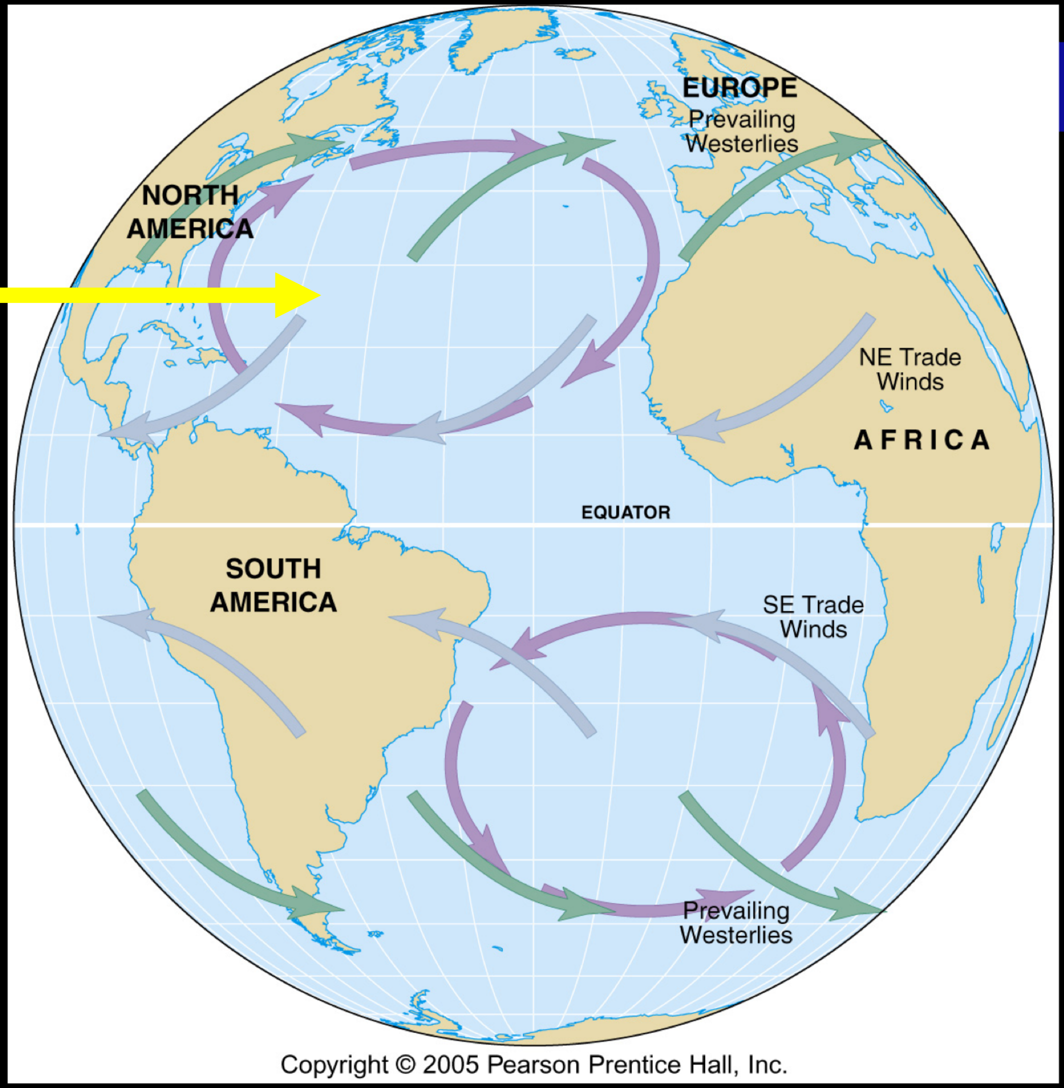


Precipitazione media è il risultato di questa circolazione



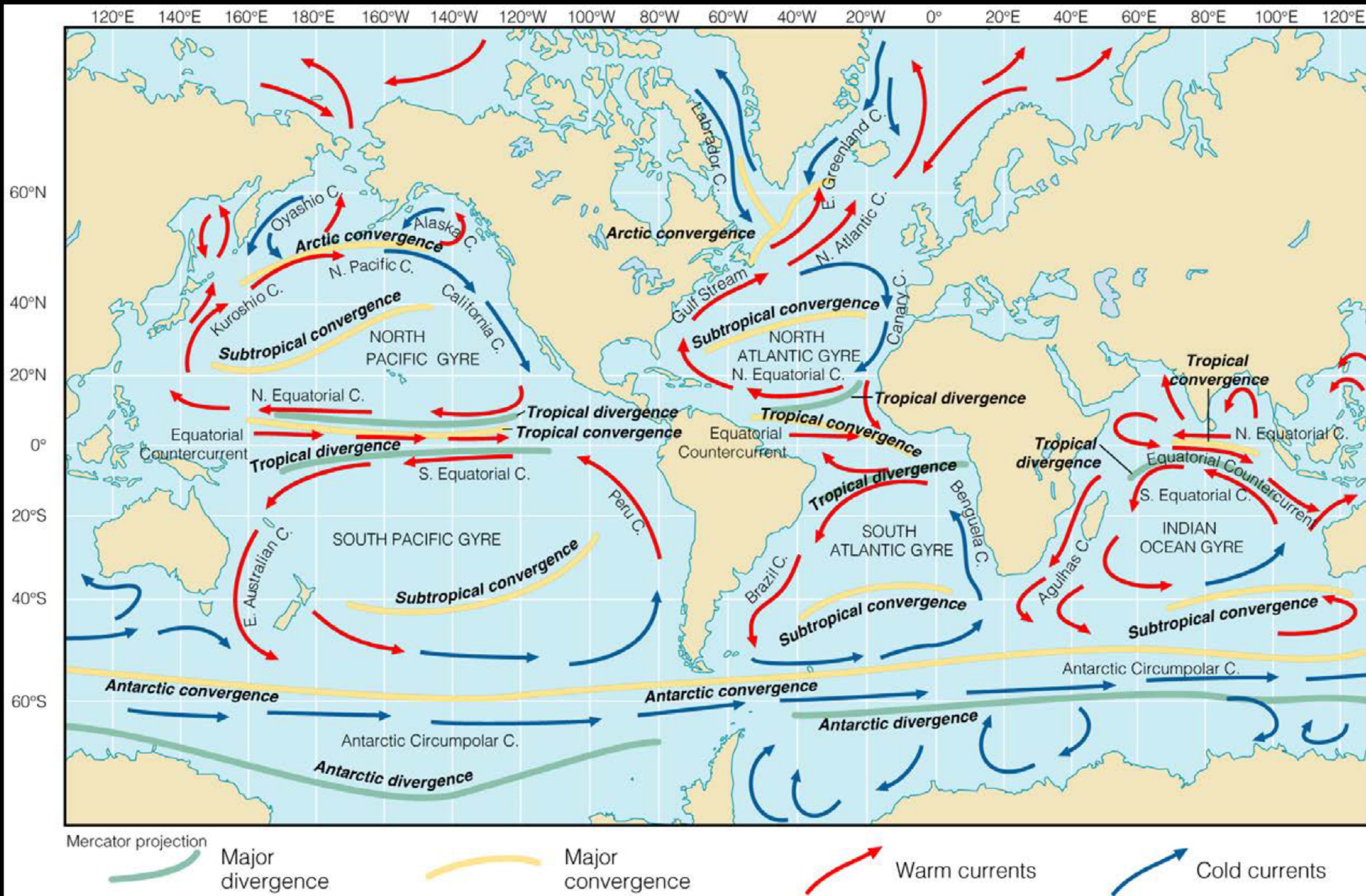
e i venti superficiali soffiano sull'Oceano



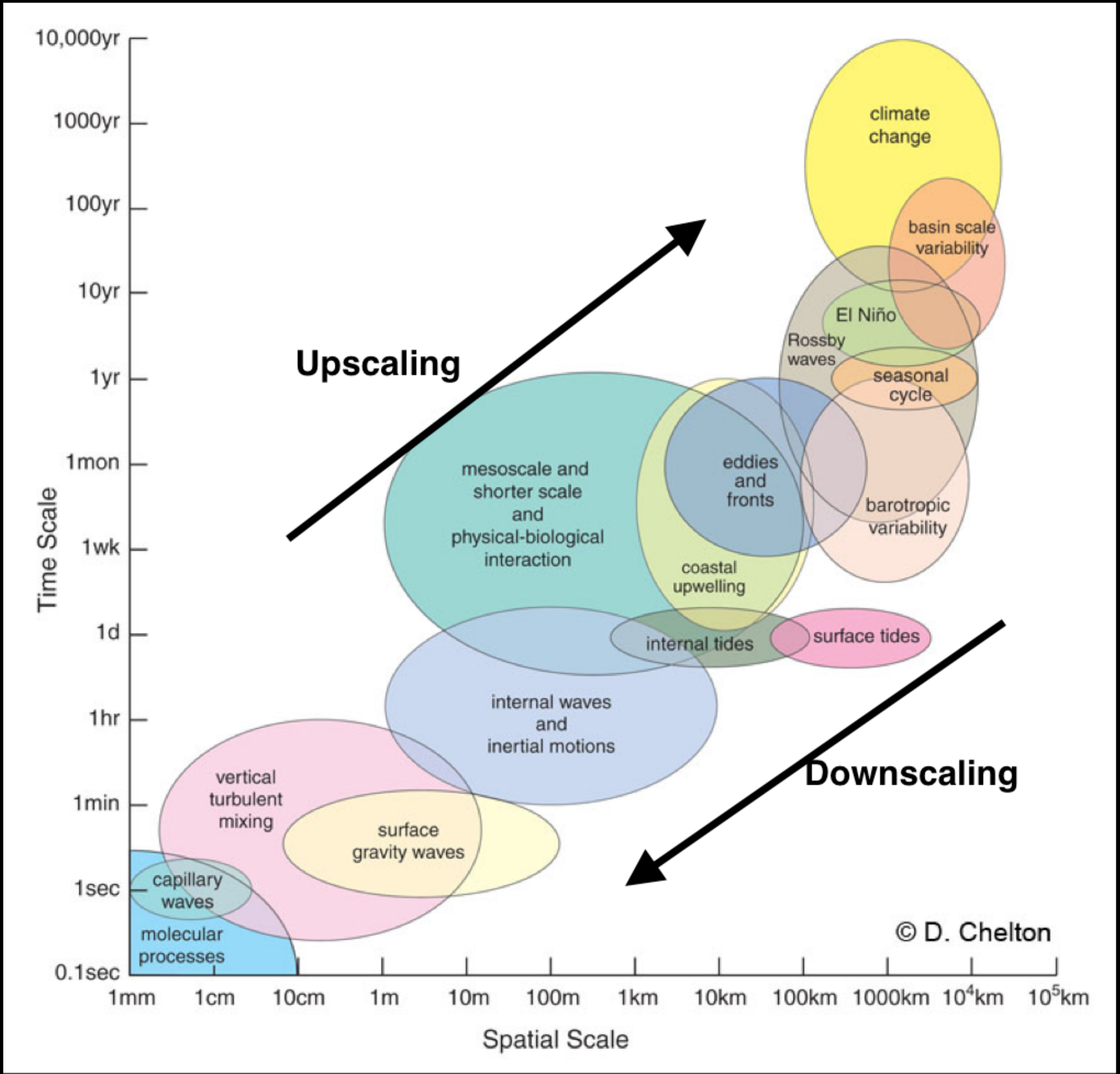


generando correnti superficiali indotte dal vento

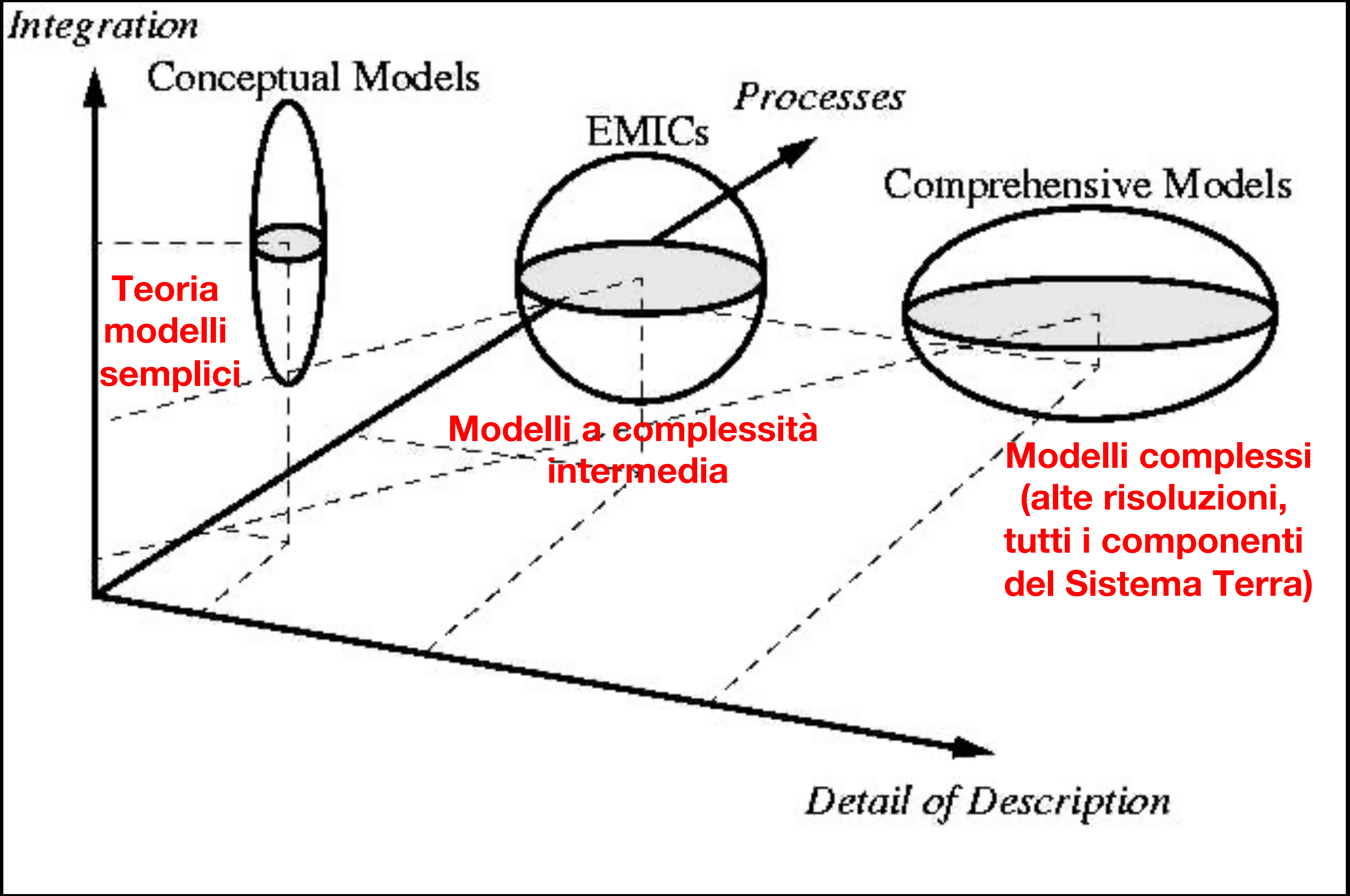
Che in realtà sono molto complesse e interagiscono fra loro



Processi fisici a diverse scale temporali e spaziali, interconnessi anche fra diversi componenti del Sistema Terra

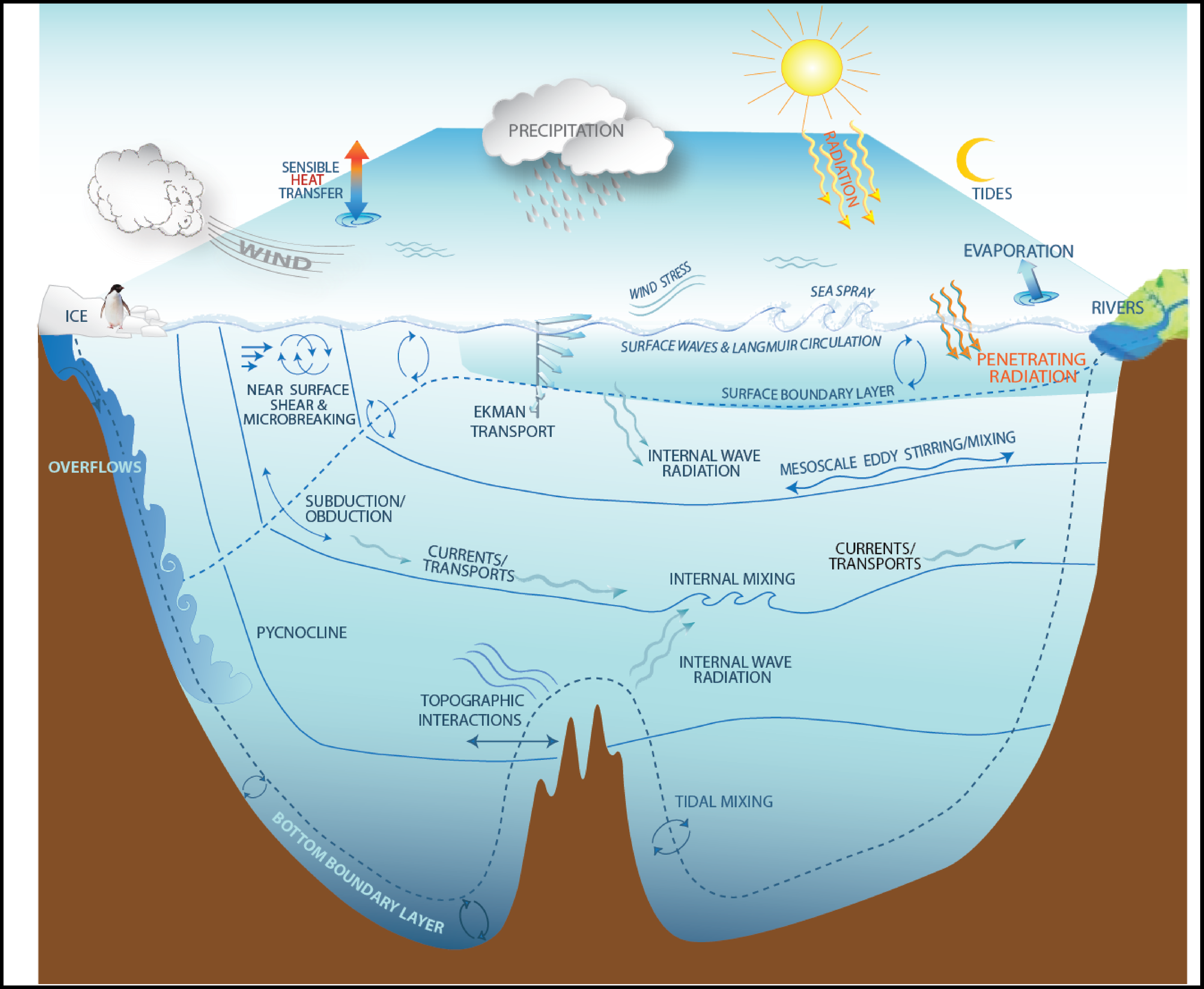


Come studiamo la Fisica della Terra (fluida)?

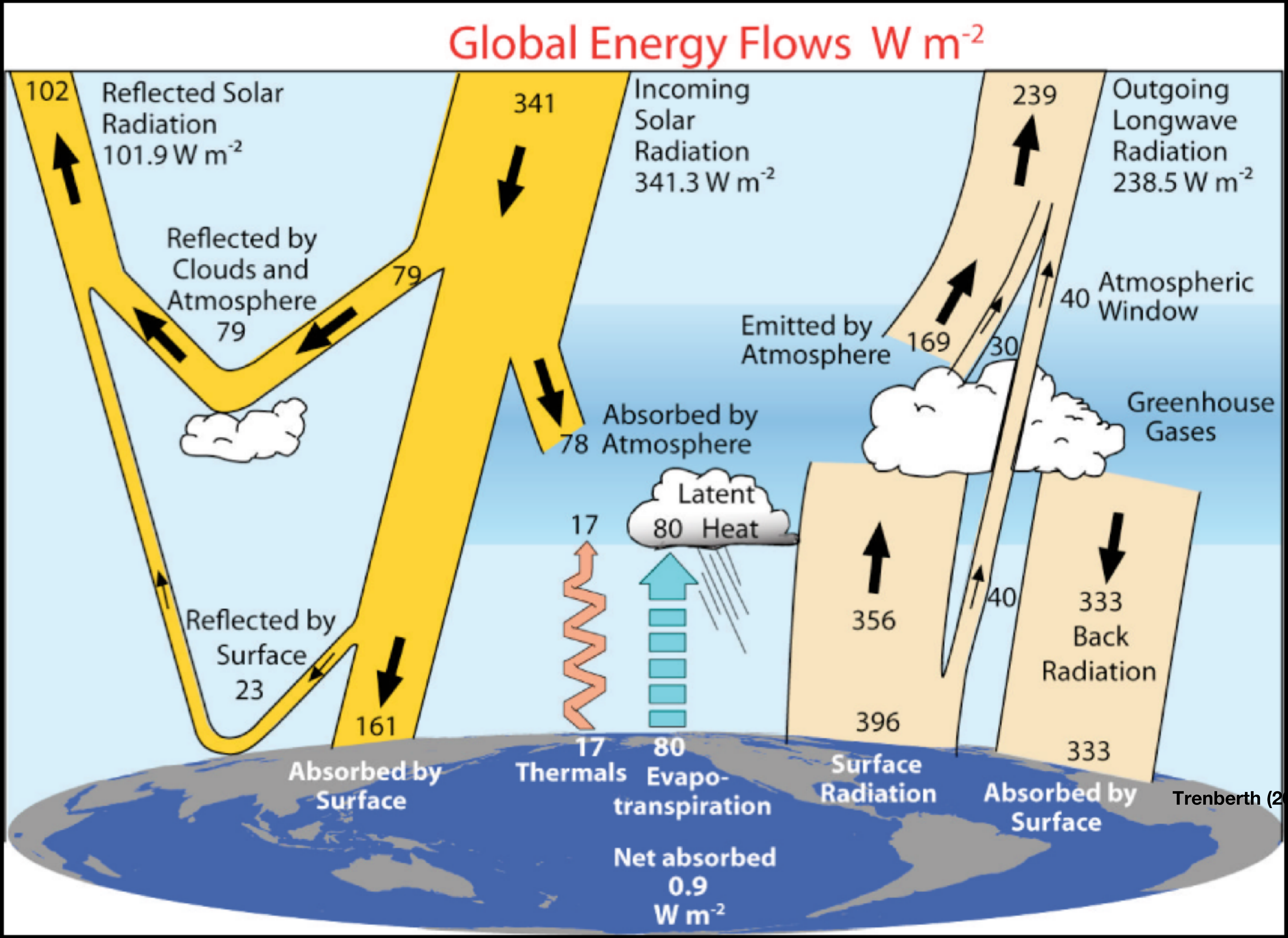


Come studiamo la Fisica della Terra (fluida)?

i Fluidi Geofisici sono un sistema molto complesso

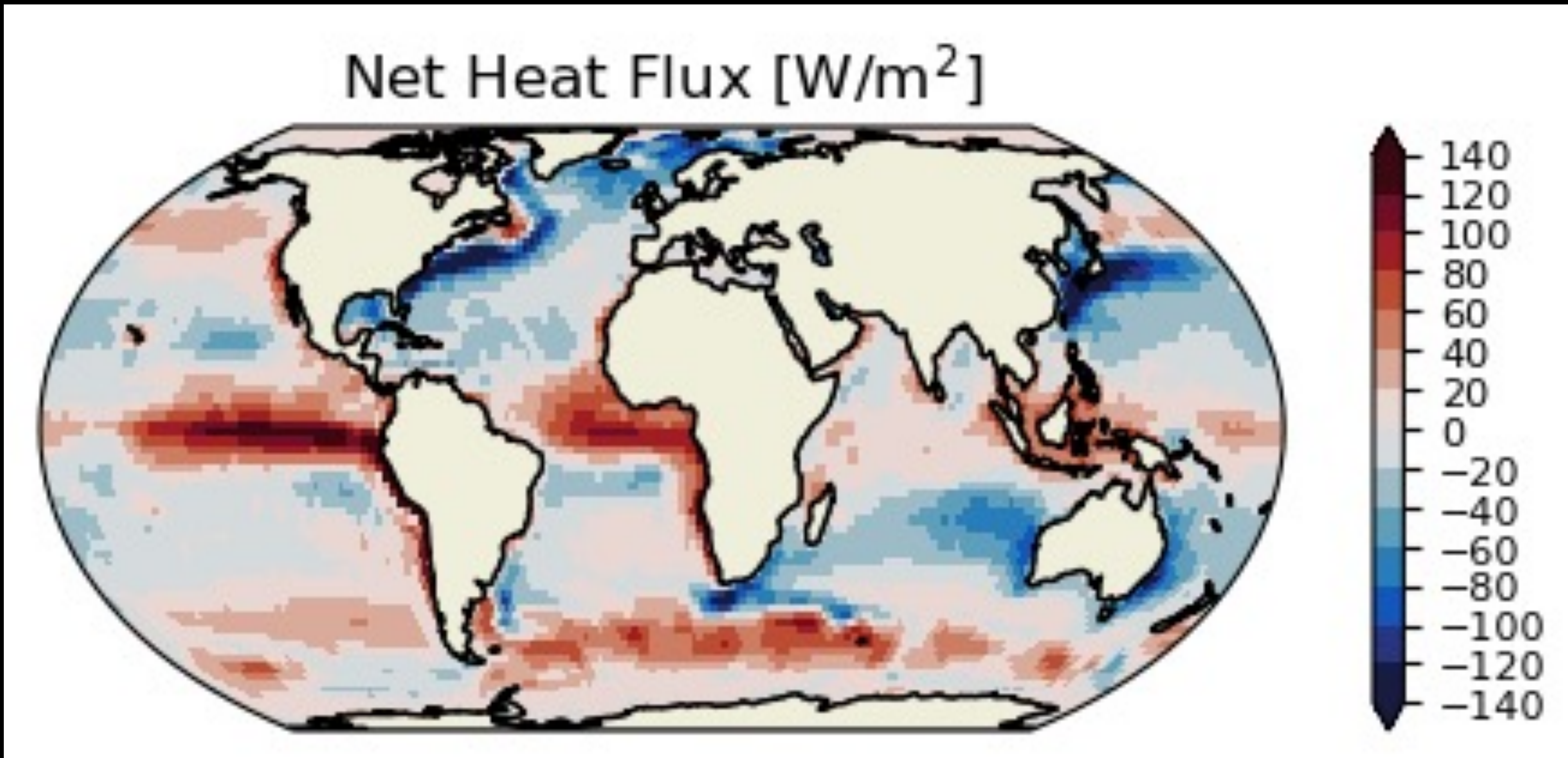


Bilancio energetico della Terra



Solo il 20% della insolazione che raggiunge la Terra è assorbita direttamente dall'atmosfera.
49% è assorbita dall'Oceano e dal suolo.

Air-sea exchange of heat



H_{solar} : represents the radiative heat flux from the incoming solar radiation minus that reflected. The net solar heat input at the sea surface ranges 250 W/m2 in the tropics to 50 W/m2 at high latitudes. This differential solar heating over the globe is the powerhouse of the atmosphere and ocean.

H_{long} : is the radiative heat flux over the range of wavelengths emitted from the sea surface, dominated by infrared radiation, so it is negative.

Total radiative flux : $H_{solar} + H_{long}$

The radiative heating into the ocean is offsetby air-sea transfer of heat through sensible and latent contributions.

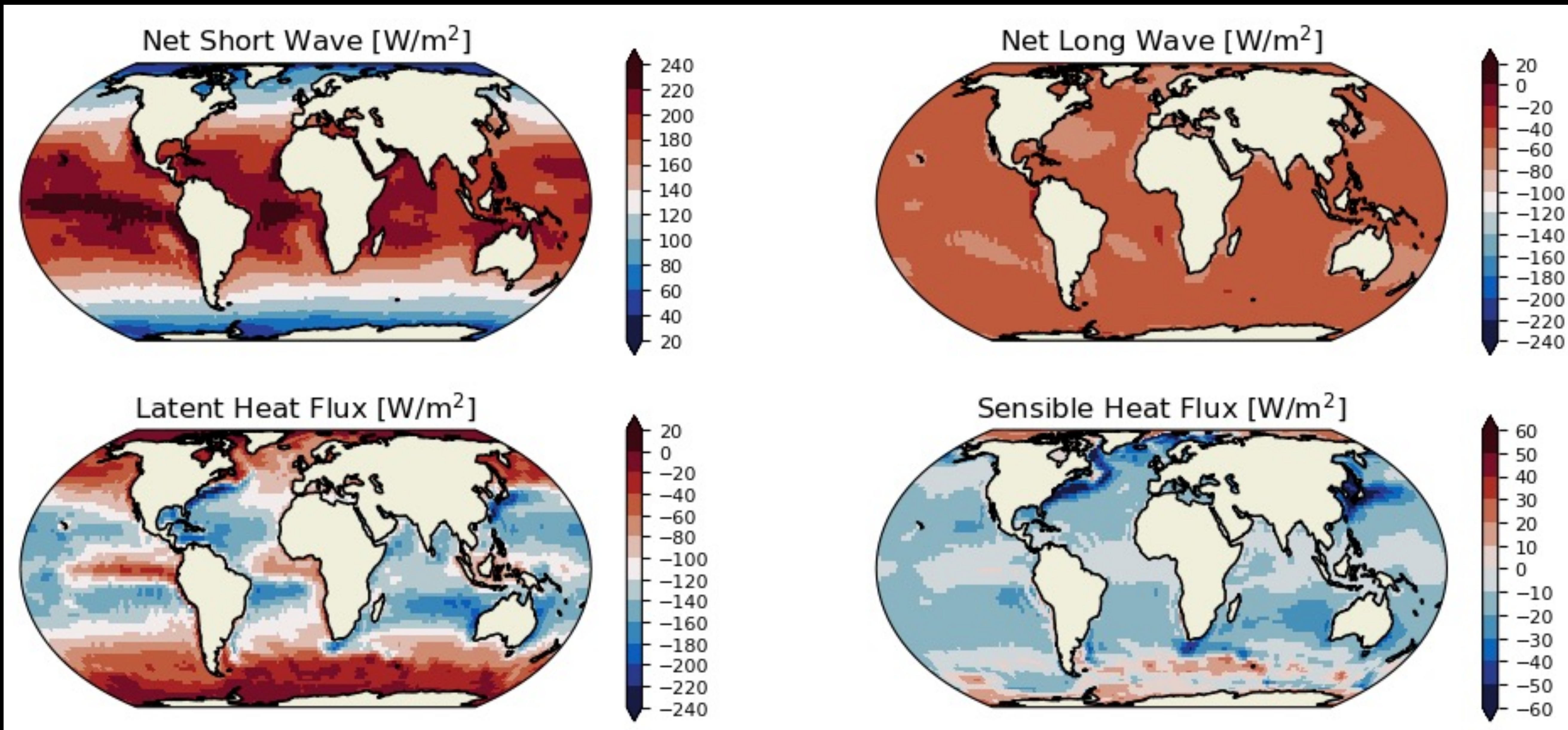
H_{sens} : turbulent transfer of heat across the sea surface as a function of the air-sea temperature difference.

H_{latent} : turbulent transfer of evaporated water, and heat is used to enable the phase change from liquid to vapour.

The latent exchange nearly always dominates over the sensible exchange.

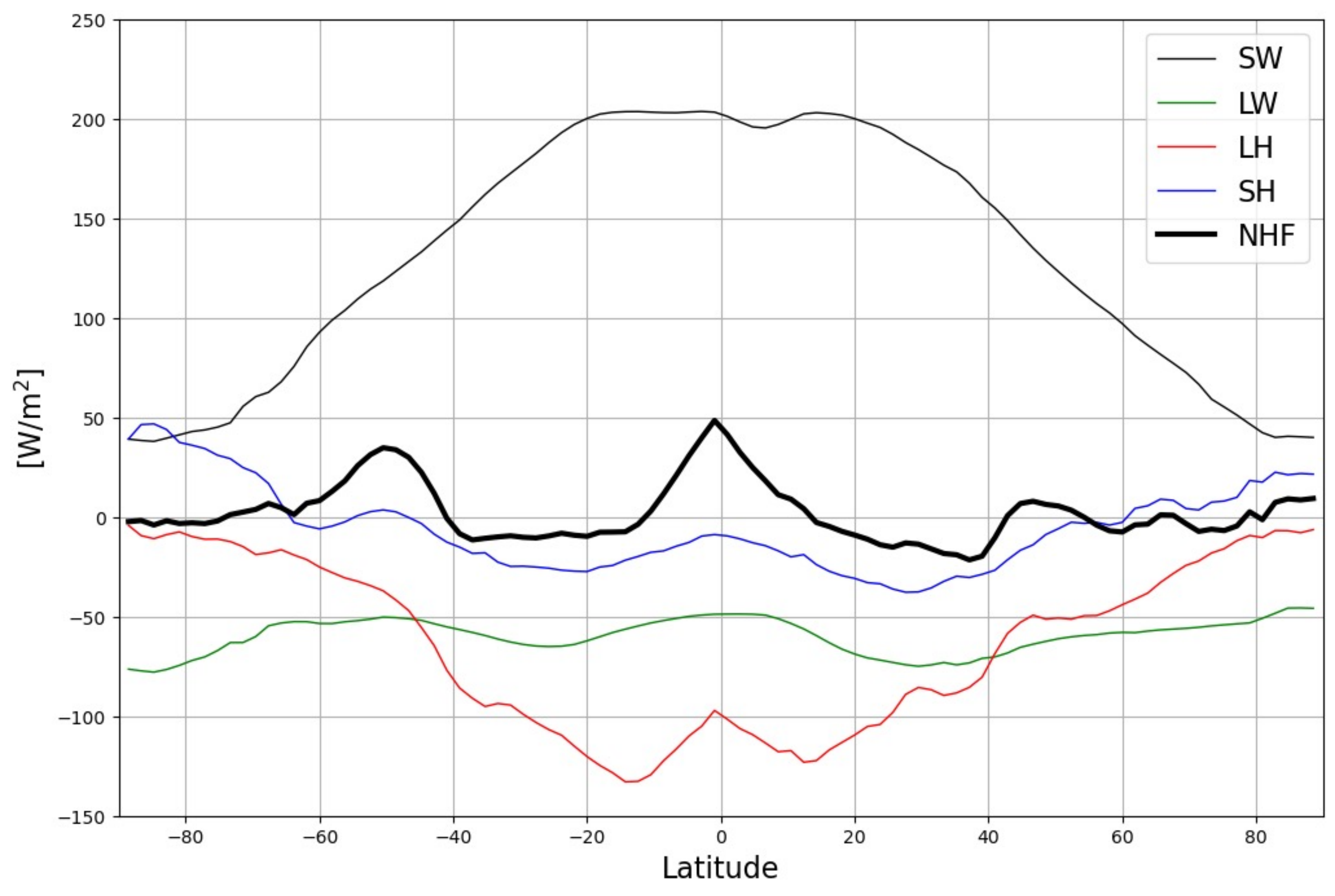
There is no local heat balance and the temperature change over a surface mixed layer is

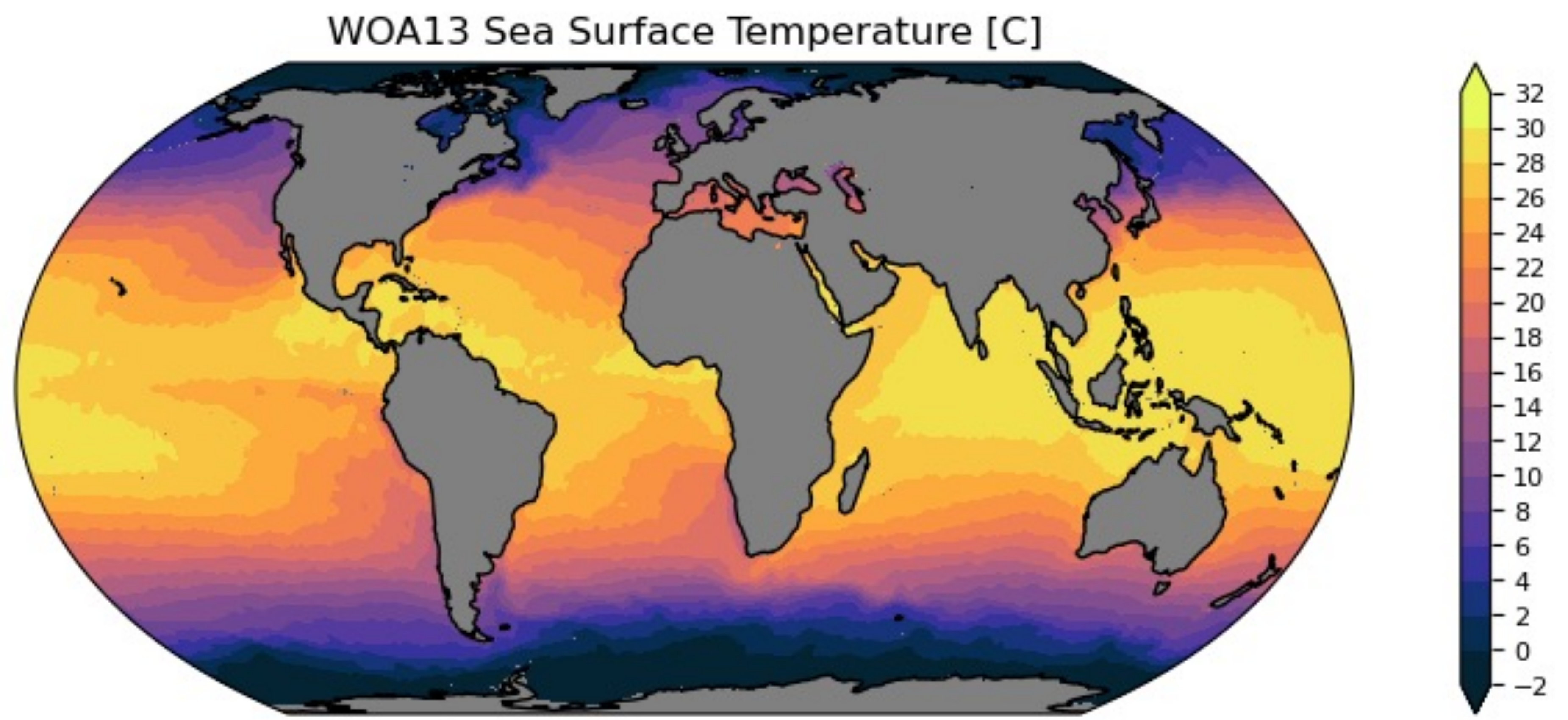
$$DT/Dt = 1/(\rho\ C_p)\ H/h$$

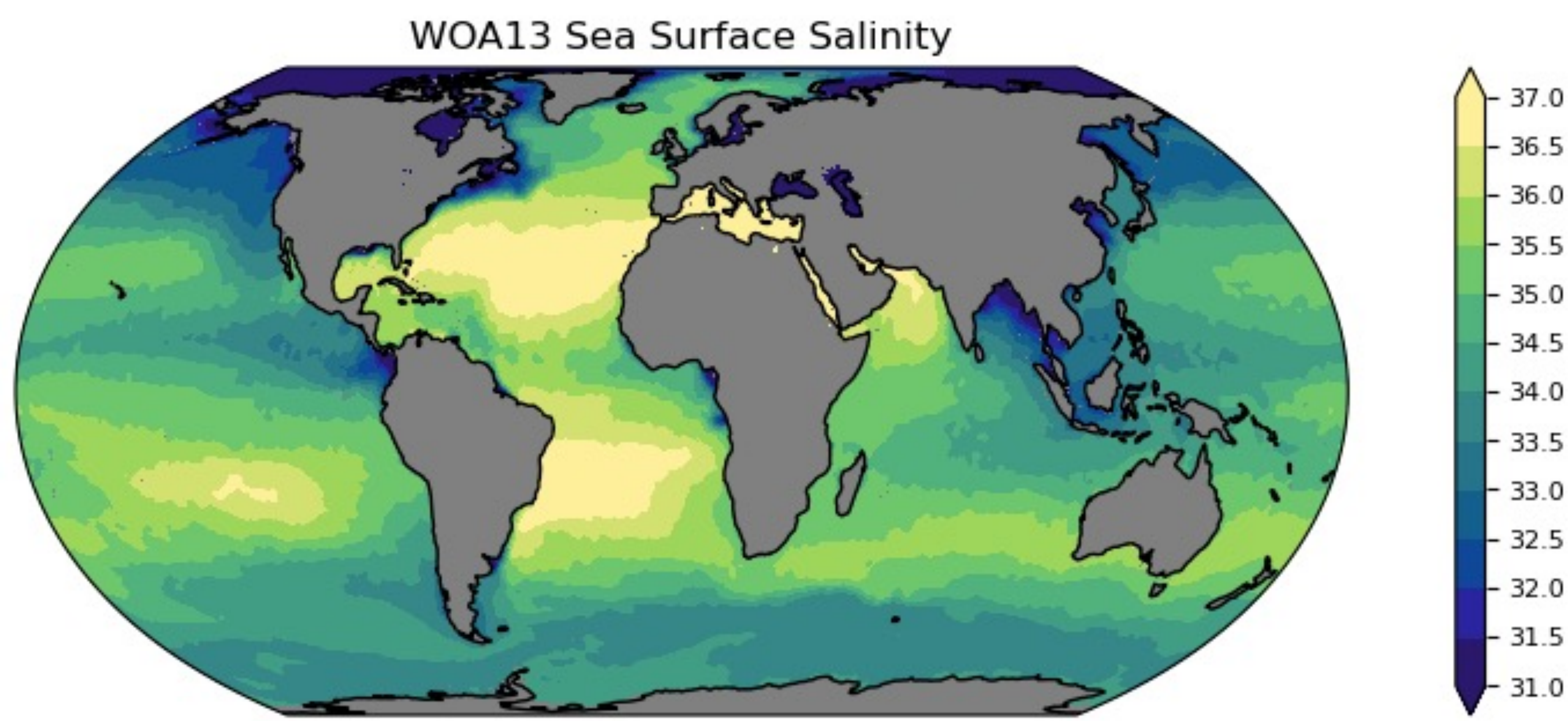


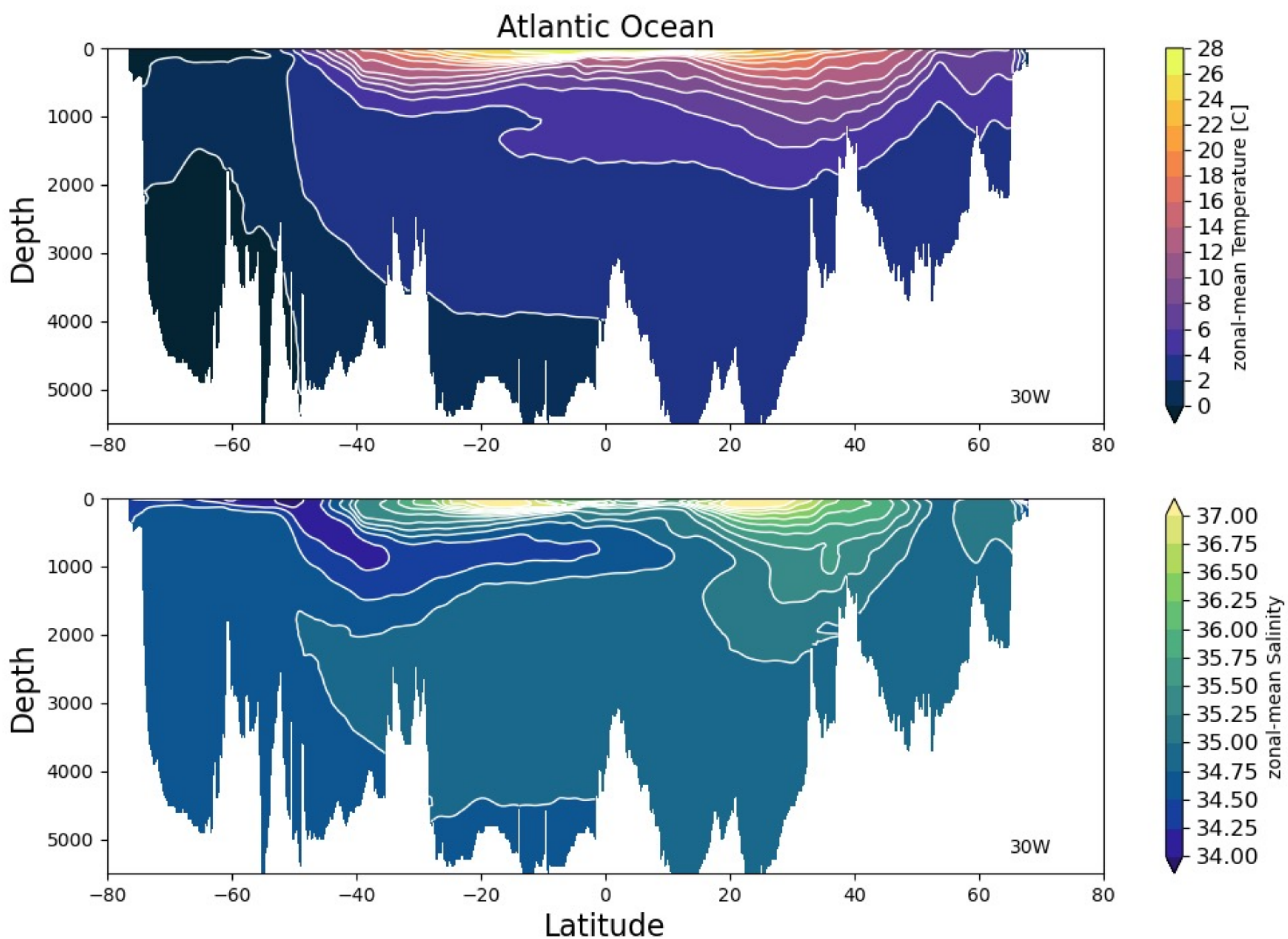
Net Short Wave [W/m^2]
240
220
200
180
160
140
120
100
80
60
40
20
Net Long Wave [W/m^2]
20
0
−20
−40
−60
−80
−100
−120
−140
−160
−180
−200
−220
−240
Latent Heat Flux [W/m^2]
20
0
−20
−40
−60
−80
−100
−120
−140
−160
−180
−200
−220
−240
Sensible Heat Flux [W/m^2]
60
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60

Zonal-mean heat flux components

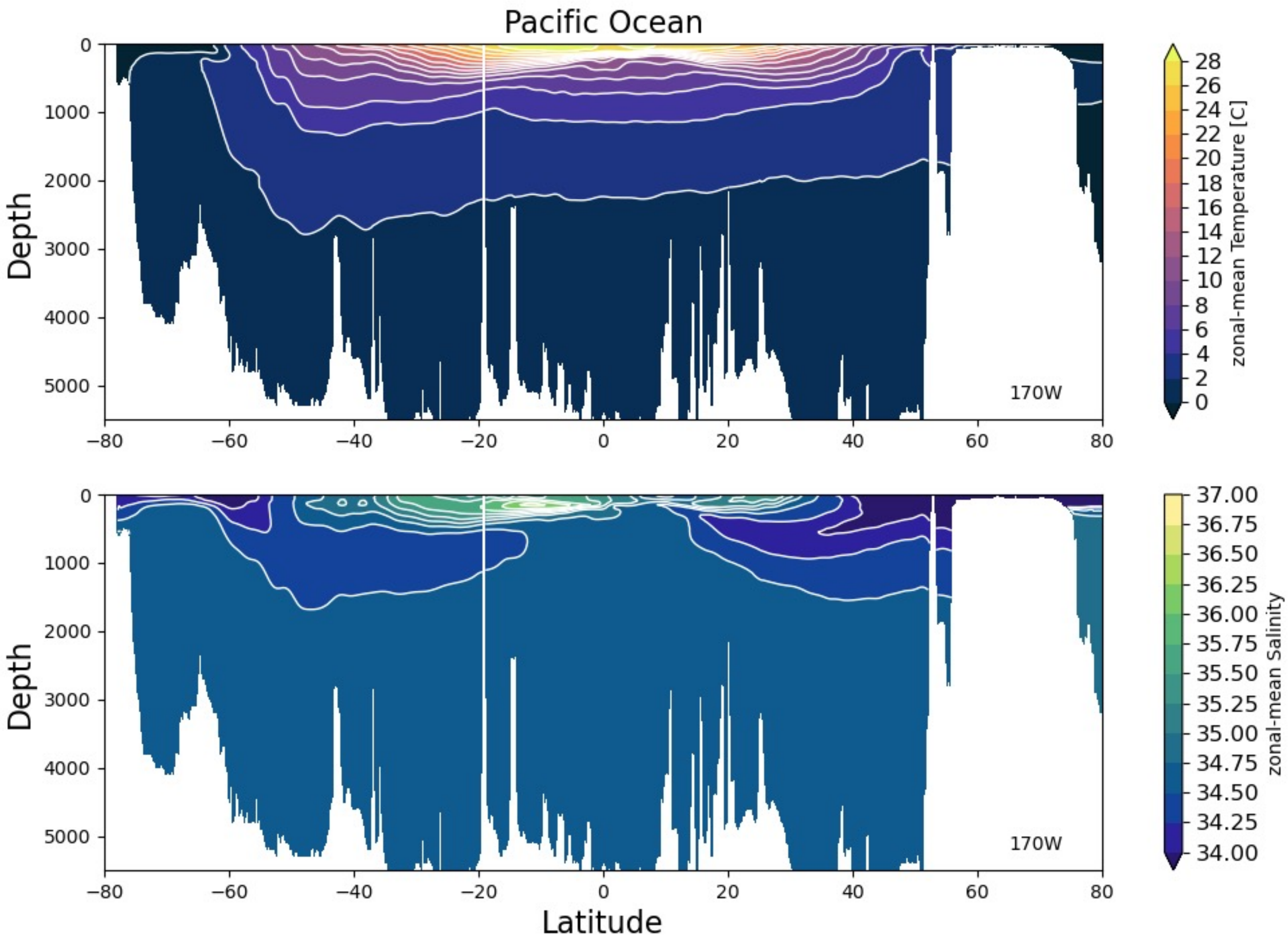



WOA13 Sea Surface Temperature [C]
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
−2


WOA13 Sea Surface Salinity
37.0
36.5
36.0
35.5
35.0
34.5
34.0
33.5
33.0
32.5
32.0
31.5
31.0



Atlantic Ocean
Depth
0
1000
2000
3000
4000
5000
30W
−80
−60
−40
−20
0
20
40
60
80
zonal-mean Temperature [C]
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
zonal-mean Salinity
34.00
34.25
34.50
34.75
35.00
35.25
35.50
35.75
36.00
36.25
36.50
36.75
37.00
Latitude


Pacific Ocean
Depth
0
1000
2000
3000
4000
5000
−80
−60
−40
−20
0
20
40
60
80
170W
zonal-mean Temperature [C]
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
zonal-mean Salinity
37.00
36.75
36.50
36.25
36.00
35.75
35.50
35.25
35.00
34.75
34.50
34.25
34.00
Latitude

Temperature, salinity and density in the ocean

Pressure and depth

Ocean ranges:

0-6000 meters (maximum depth of about 10,000 m)

0-6000 dbar (get to this unit below)

Pressure is a force per unit area

Newton's law: F = ma where F and a are 3-D vector force and acceleration, and m is mass.

Units of force: mass x length / $(\text{time})^2$

mks: 1 Newton = 1 kg m / sec^2

Pressure

Units of pressure: N/m^2

1 Pascal = 1 N/m^2

1 bar = 10^5 N/m^2

approximately the atmospheric pressure at sea level

1 atmosphere = 1 bar

1dbar = 0.1 bar

Relation of pressure to depth

“Hydrostatic balance”

From **Newton’s law (F = m a), use the force balance in the vertical direction**

vertical acceleration = (vertical forces)/mass

vertical acceleration = vertical pressure gradient force + gravity

Pressure gradient (difference) force is upward due to higher pressure below and lower pressure above

PGF = - (Δpressure / Δdepth) = - (Δp / Δz)

Gravitational force per unit volume is downward = ρg

Where ρ is the density of seawater, $\rho \sim 1025$ kg/m^3

Relation of pressure to depth

We now assume vertical acceleration is approximately zero, so the vertical pressure gradient (pressure difference force) almost exactly balances the downward gravitational force. This is called "hydrostatic balance".

$$0 = \text{PGF} + \text{gravity}$$

$$0 = -(\Delta p/\Delta z) + \rho g$$

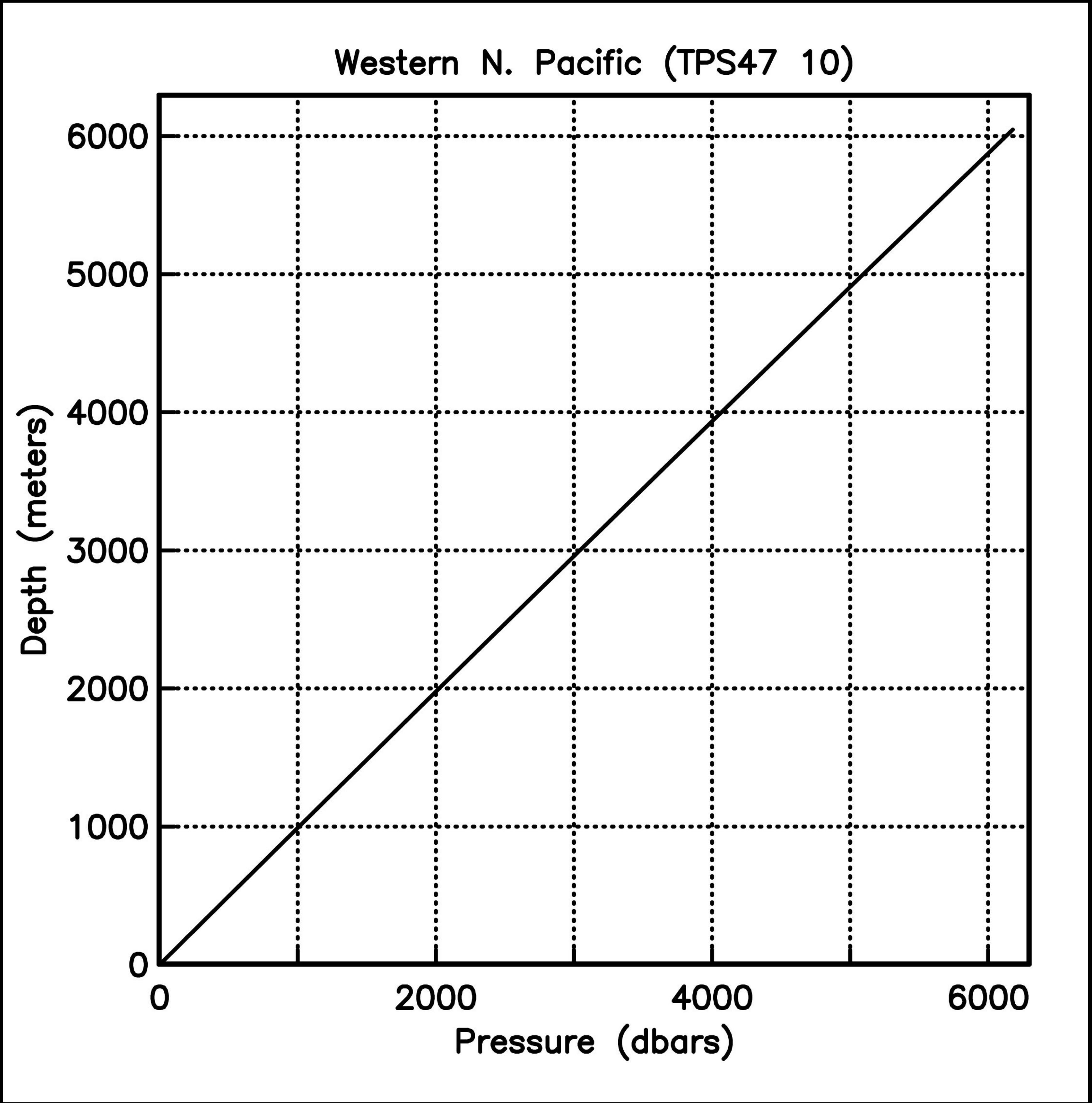
We can then solve for the change in pressure for a given change in depth.

For $\Delta z = 1$ meter, density $\rho \sim 1025\ \text{kg/m}^3$, and $g = 9.8\ \text{m/s}^2$, we get

$$\Delta p = \rho\, g\, \Delta z = (1025\ \text{kg/m}^3)(9.8\ \text{m/s}^2)(1\ \text{m}) =$$

$$10045\ \text{kg/(m s}^2) = 0.10045\ \text{bar} = 1.0045\ \text{dbar}$$

Pressure vs. depth



Temperature, heat and potential temperature

- Temperature units: Kelvin and Celsius
- Celsius 0° C at melting point at standard atmosphere (and no salt, etc)
- $T_K = T_C + 273.16°$
- Ocean temperature range: freezing point to about 30° or 31° C
- (Freezing point is < 0° C because of salt content)

Heat

Energy: 1 Joule = 1 kg m^2 / sec^2

Heat is energy, so units are Joules

Heat change per unit time: 1 Watt = 1 J/sec

Q = total amount of heat

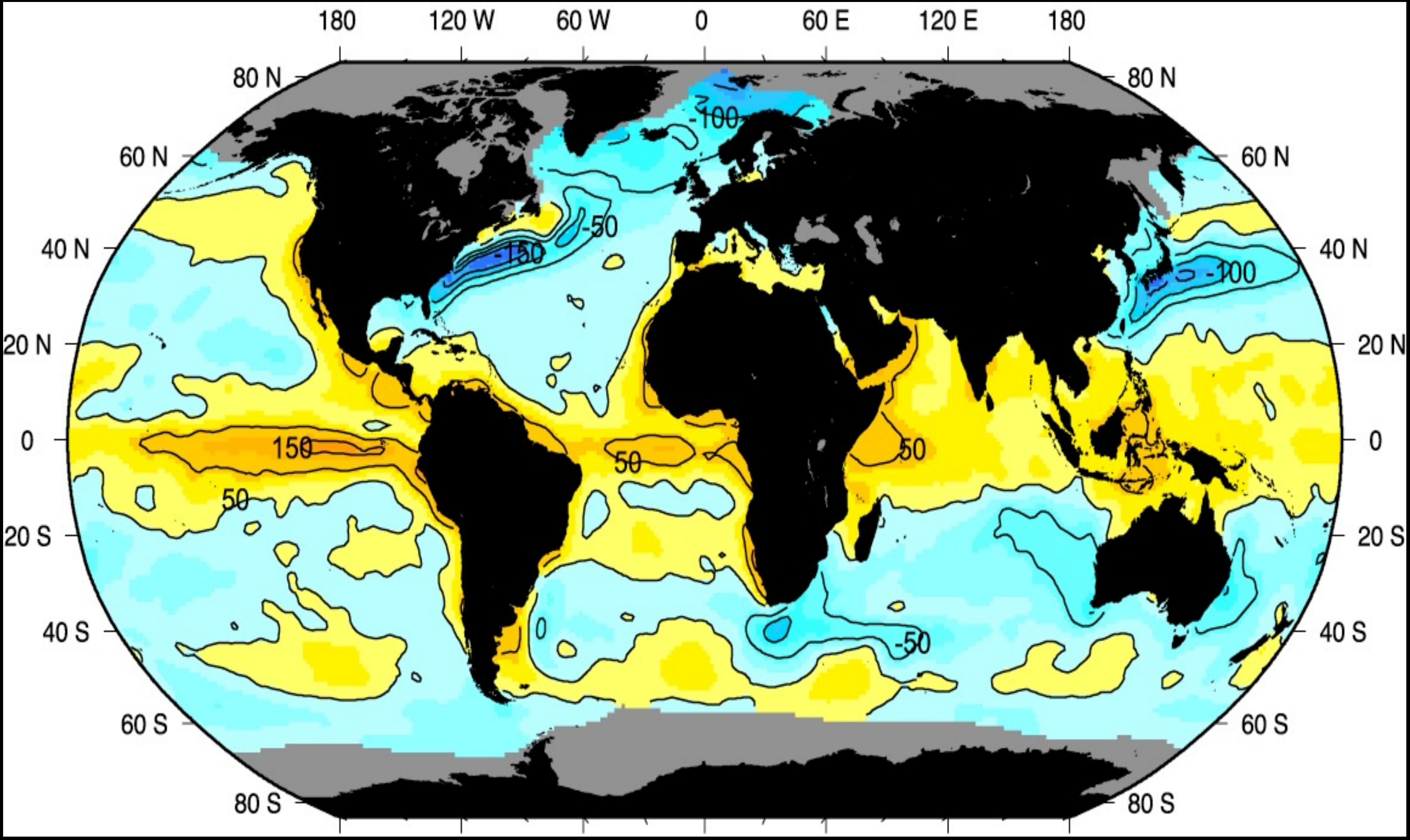
$dQ/dT = C_p$ where C_p is heat capacity

q= heat per unit volume = Q/V, units are J/m^3

$dq/dT = \rho\, c_p$ where c_p is specific heat = C_p/mass

For seawater, c_p ~3850 J/kg ˚ C and ρ ~ 1025 kg/m^3

Surface heat flux (W/m²) into ocean



This is the annual mean (total for all seasons)

Potential temperature

Water (including seawater) is compressible

If we compress a volume of water adiabatically (no exchange of heat or salt), then its temperature increases. ("adiabatic compression")

Define "potential temperature" as the temperature a parcel of water has if moved adiabatically (without exchanges or mixing) to the sea surface.

Use the Greek letter θ to denote potential temperature.

Potential temperature is always lower than measured temperature except at the sea surface (where they are the same by definition)

Potential temperature expressions

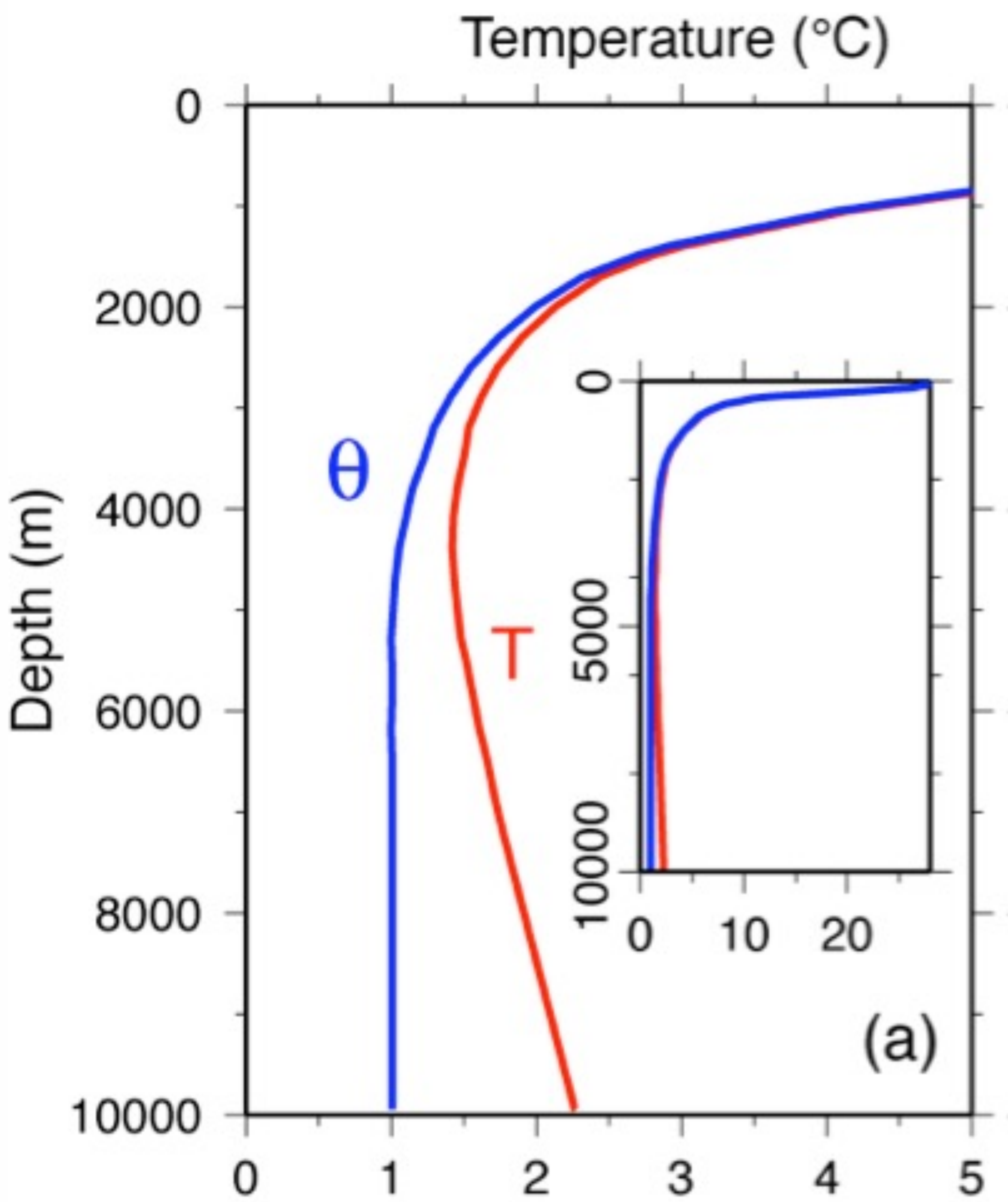
The change in temperature with pressure that is due solely to pressure is called the "adiabatic lapse rate"

In the atmosphere, the adiabatic lapse rate is 6.5° C per 1000 m altitude.
In the ocean, the adiabatic lapse rate is 0.1° C per 1000 m depth.

Again: potential temperature is always lower than measured temperature except at the sea surface (where they are the same by definition)

This makes observing the ocean a bit of a challenge ….

Pressure effect on temperature:
Mariana Trench (the most extreme example because of its depth)



Note the measured temperature has a minimum around 4000 dbar and increases below that.

Potential temperature is almost exactly uniform below 5000 m.
(This is because all of the water in this trench spilled into it over a sill that was at about 5000 m depth.)

The **Mariana Trench** is the deepest part of the world's oceans, and the lowest elevation of the surface of the Earth's crust. It is located in the western Pacific Ocean, to the east of the Mariana Islands. The trench is about 2,550 kilometres long but has a mean width of only 69 kilometres.
It reaches a maximum-known depth of about 11.03 kilometres

Salinity

- "Salinity" in the oldest sense is the mass of matter (expressed in grams) dissolved in a kilogram of seawater = Absolute salinity
- Units are parts per thousand (o/oo) or "psu" (practical salinity units), or unitless (preferred UNESCO standard, since salinity is mass/mass)
- The concept of salinity is useful because all of the constituents of sea salt are present in almost equal proportion everywhere in the ocean.

Salinity

•**Typical ocean salinity is 34 to 36 (i.e. 34 to 36 gm salt/kg seawater)**

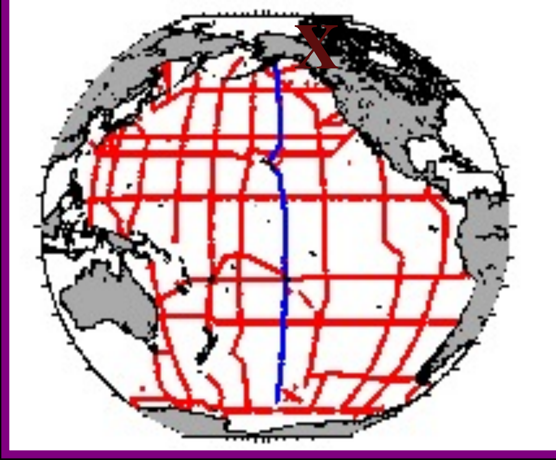
•**Measurements:**

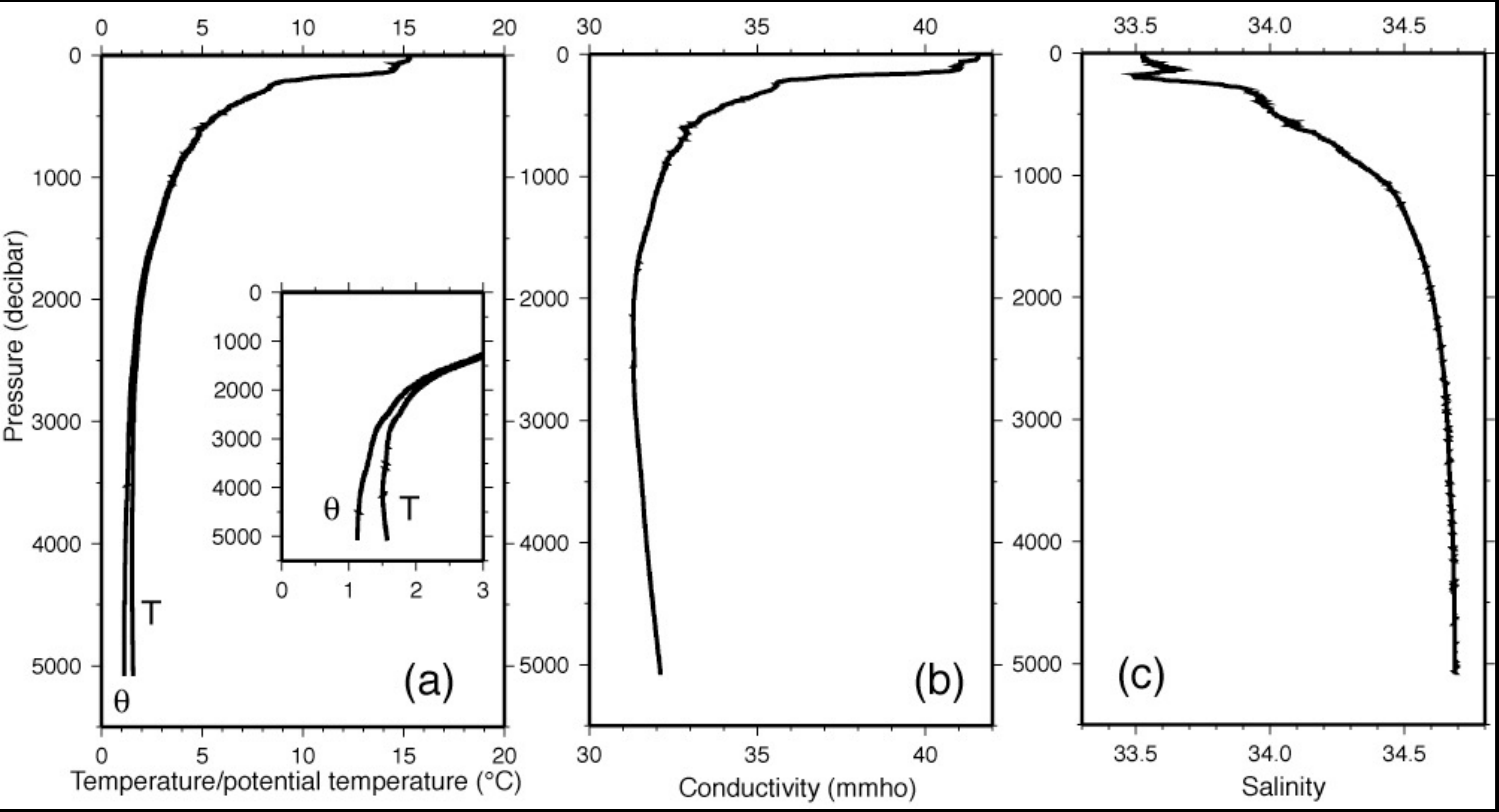
Oldest: evaporate the seawater and weigh the salts

Old: titration method to determine the amount of chlorine, bromie and iodine (prior to 1957)

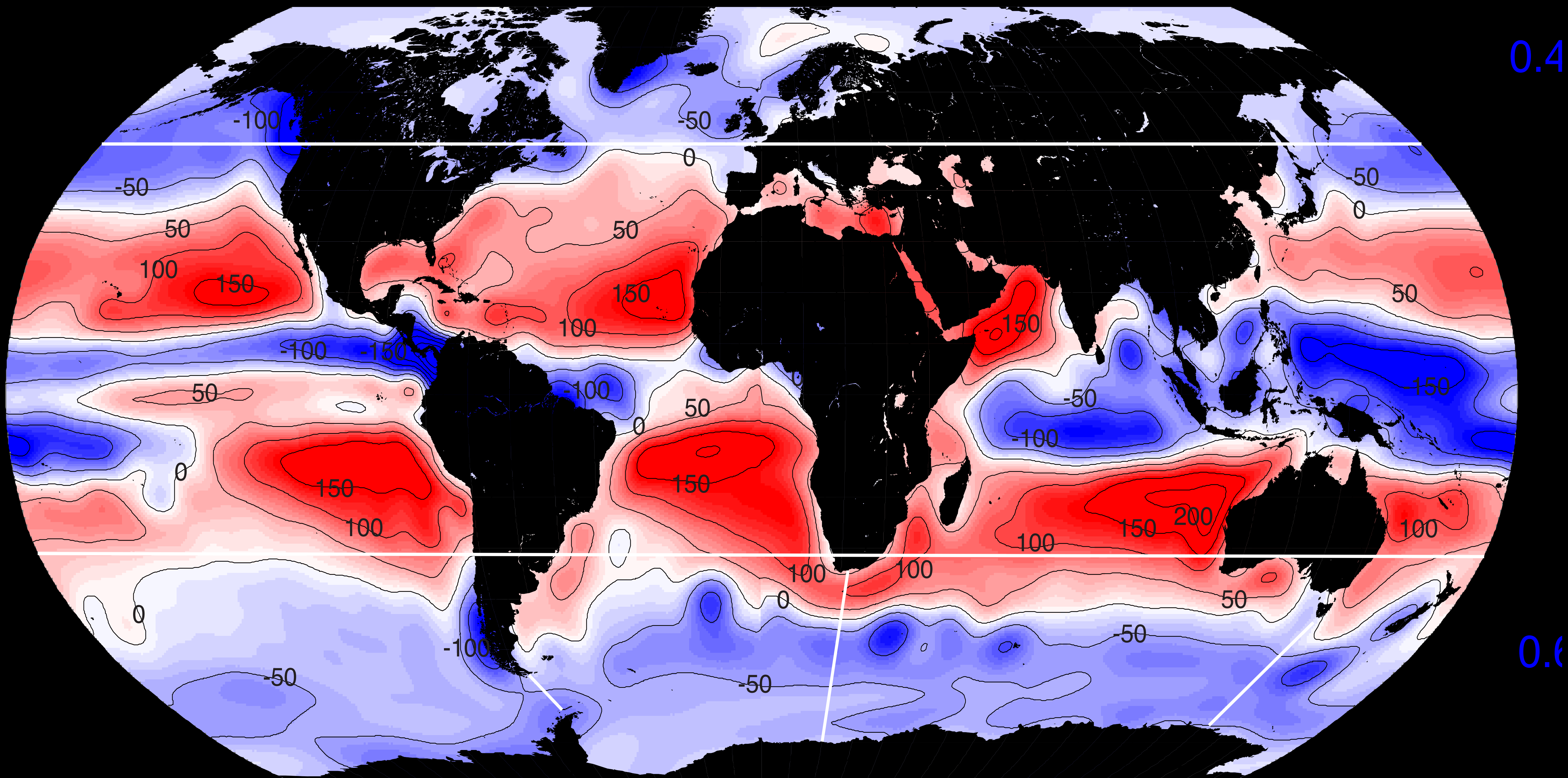
Modern: Use seawater conductivity, which depends mainly on temperature and, much less, on salinity, along with accurate temperature measurement, to compute salinity.

Conductivity and salinity profiles



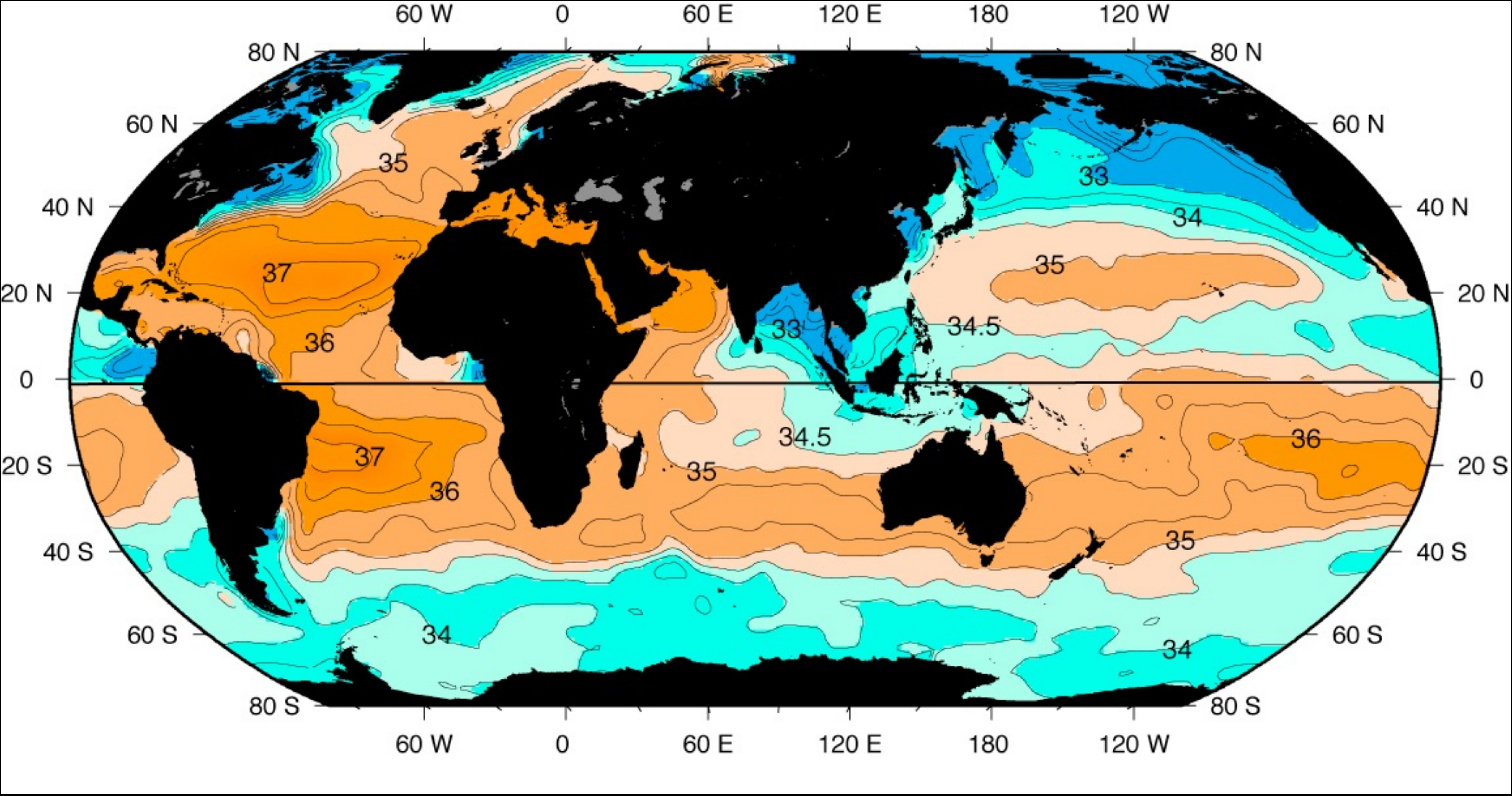


What sets salinity? Precipitation + runoff minus evaporation (cm/yr)

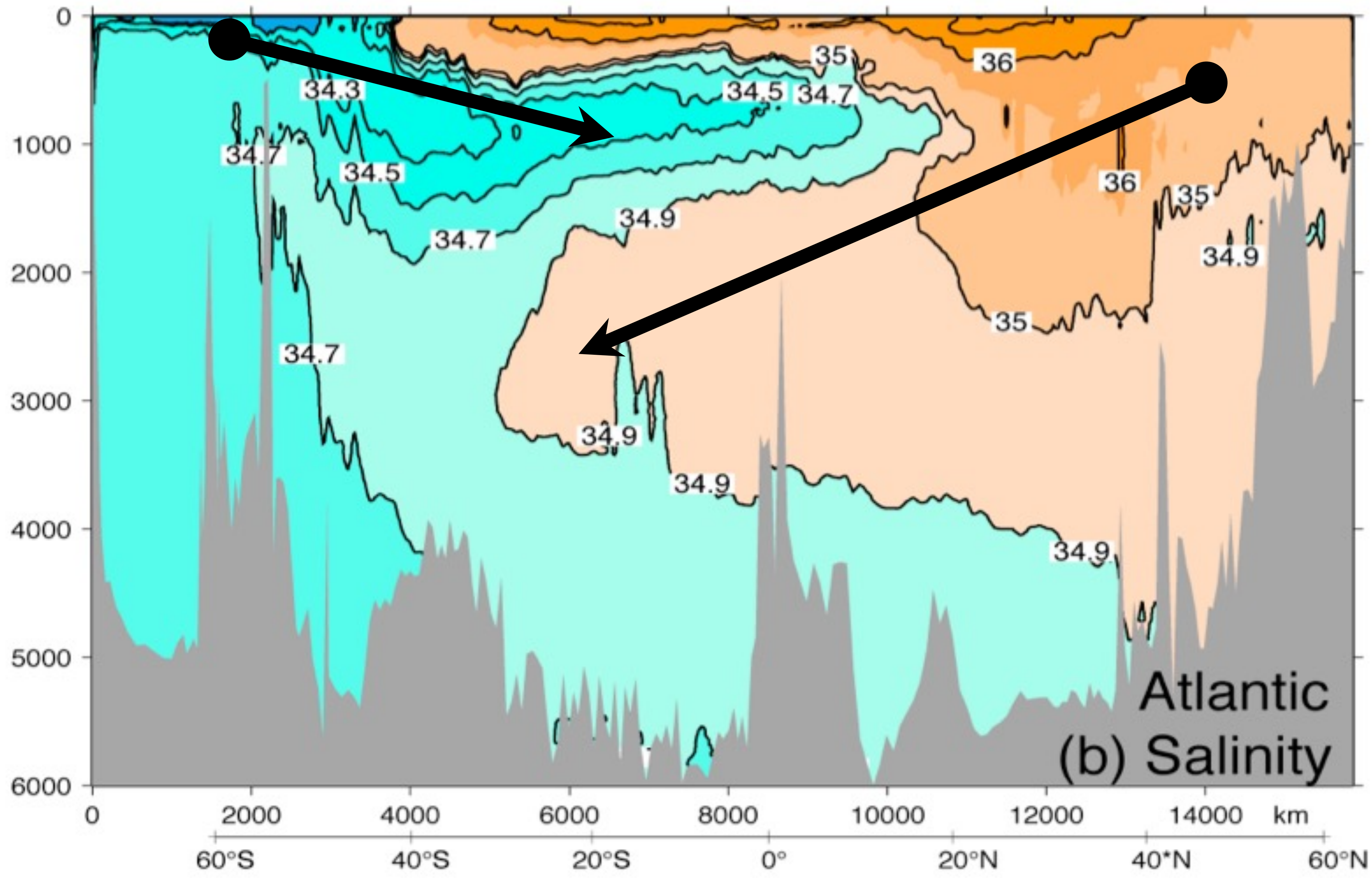


Salinity is set by freshwater inputs and exports since the total amount of salt in the ocean is constant, except on the longest geological timescales

Surface salinity
(note range of values)



Atlantic salinity section



Seawater density ρ

density is a non-linear function of T, S and P

$$\rho = \rho(S, T, p)$$

Units are mass/volume (kg/m^3)

- **When water warms, it expands, and its density cecreases. We measure thermal expansion as the relative change in density with respect to consevative temperature when pressure and salinity are held fixed**
- **When water gains salt, its density increases. We measure this with the haline contraction coefficient**
- **When conservative temperature and absolute salinity are held fixed as pressure is increased, the fluid is compressed. This property is quantified by the compressibility coefficient**

Pure water has a maximum density (at 4° C, atmospheric P) of

$$\rho(0, 4^\circ\ C, 1bar) = 1000\ kg/m^3 = 1\ g/cm^3$$

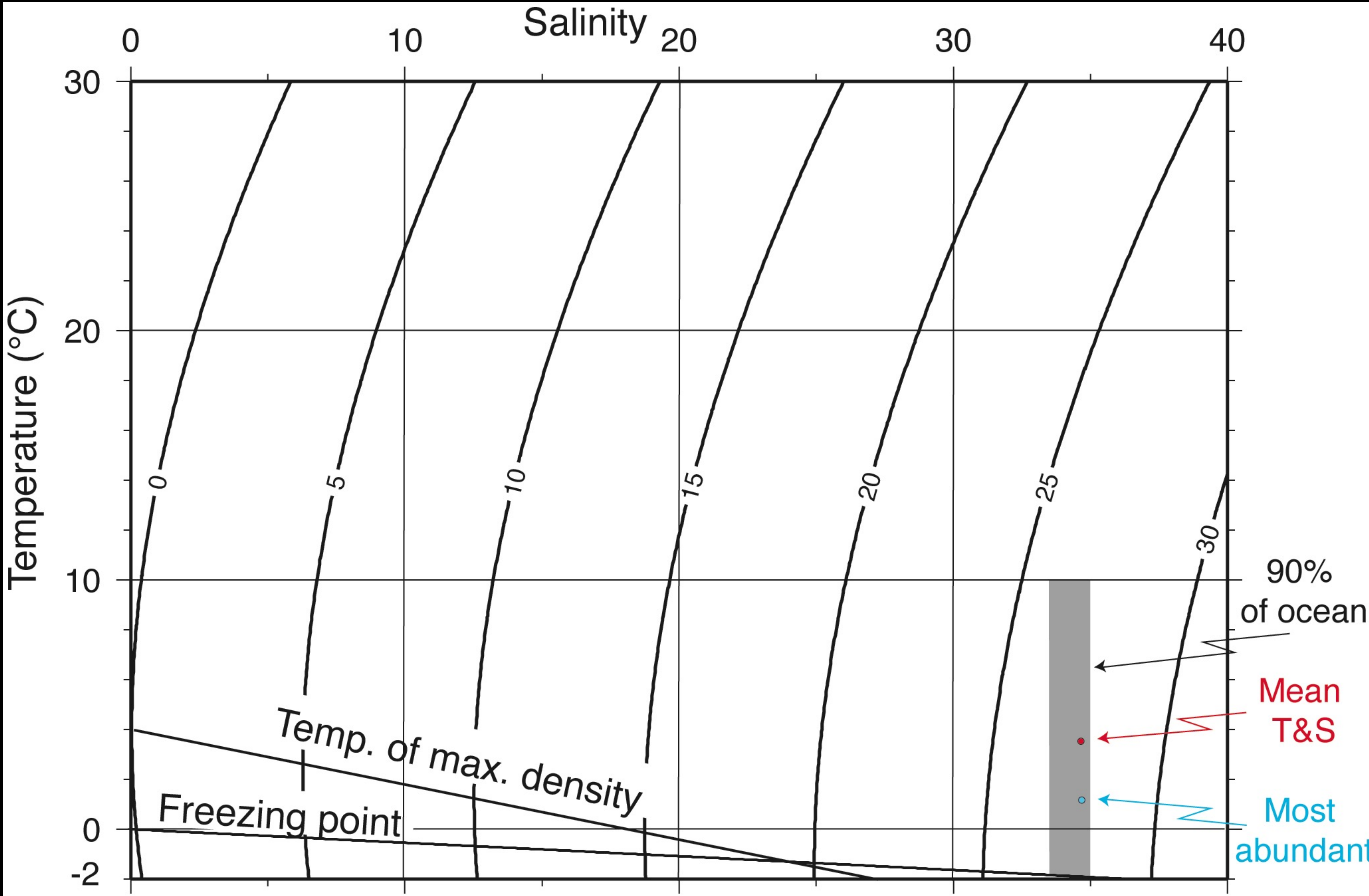
Seawater density ρ ranges from about 1025 kg/m^3 at the sea surface to 1050 kg/m^3 at bottom of ocean, mainly due to compression

Equation of state for seawater

- **The EOS is nonlinear**
- This means it contains products of T, S, and p with themselves and with each other (I.e. terms like T^2, T^3, T^4, S^2, TS, etc.)
- Common way to express density (used on next plot) is as

$$\sigma\,(S, T, p) = \rho(S, T, p) - 1000\ \mathrm{kg/m^3}$$

Seawater density, freezing point



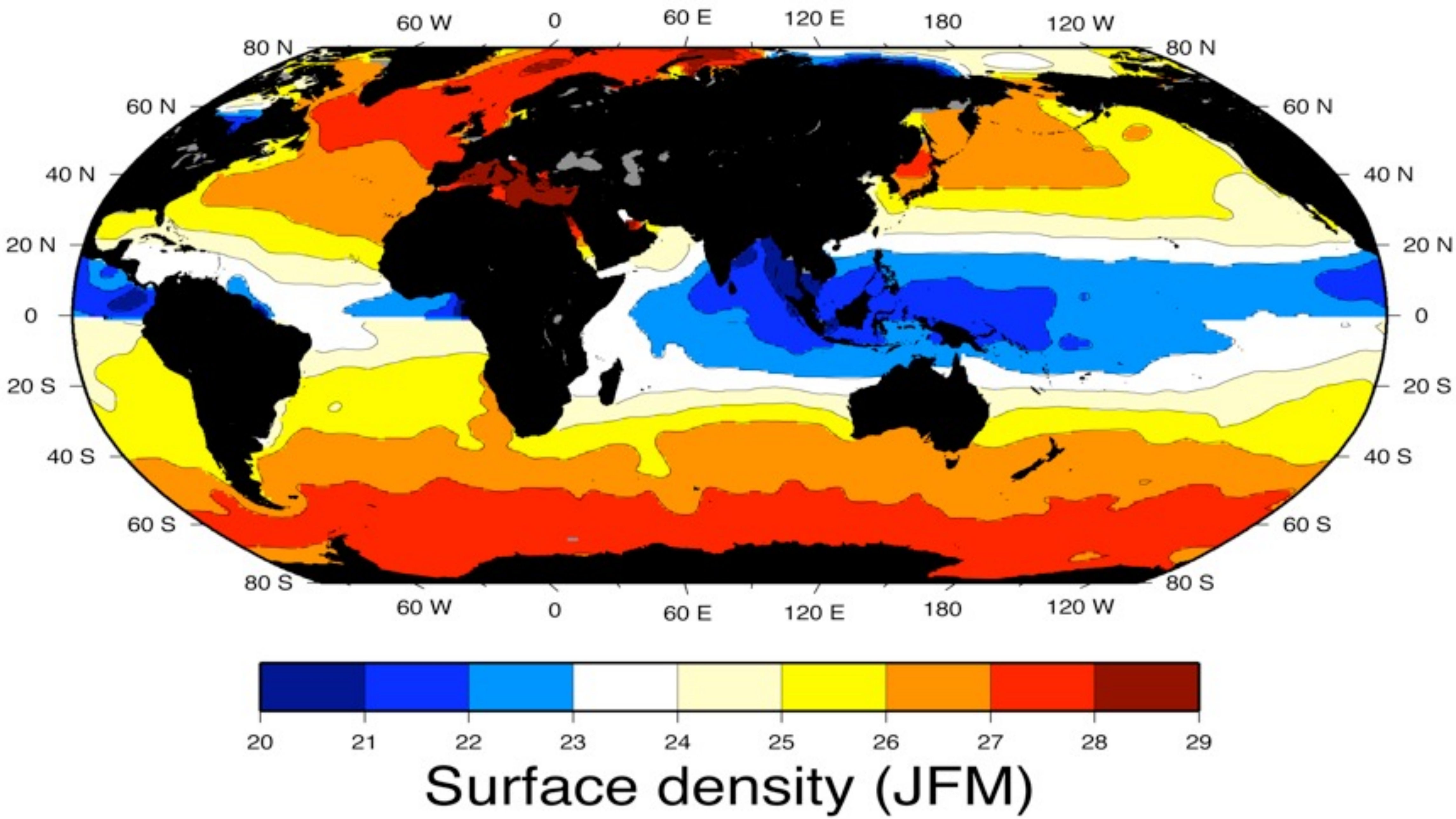
Digression to freezing point and sea ice

- Freezing point temperature decreases with increasing salinity
- Temperature of maximum density decreases with increasing salinity
- Most seawater has maximum density at the freezing point
- **Why then does sea ice float?**

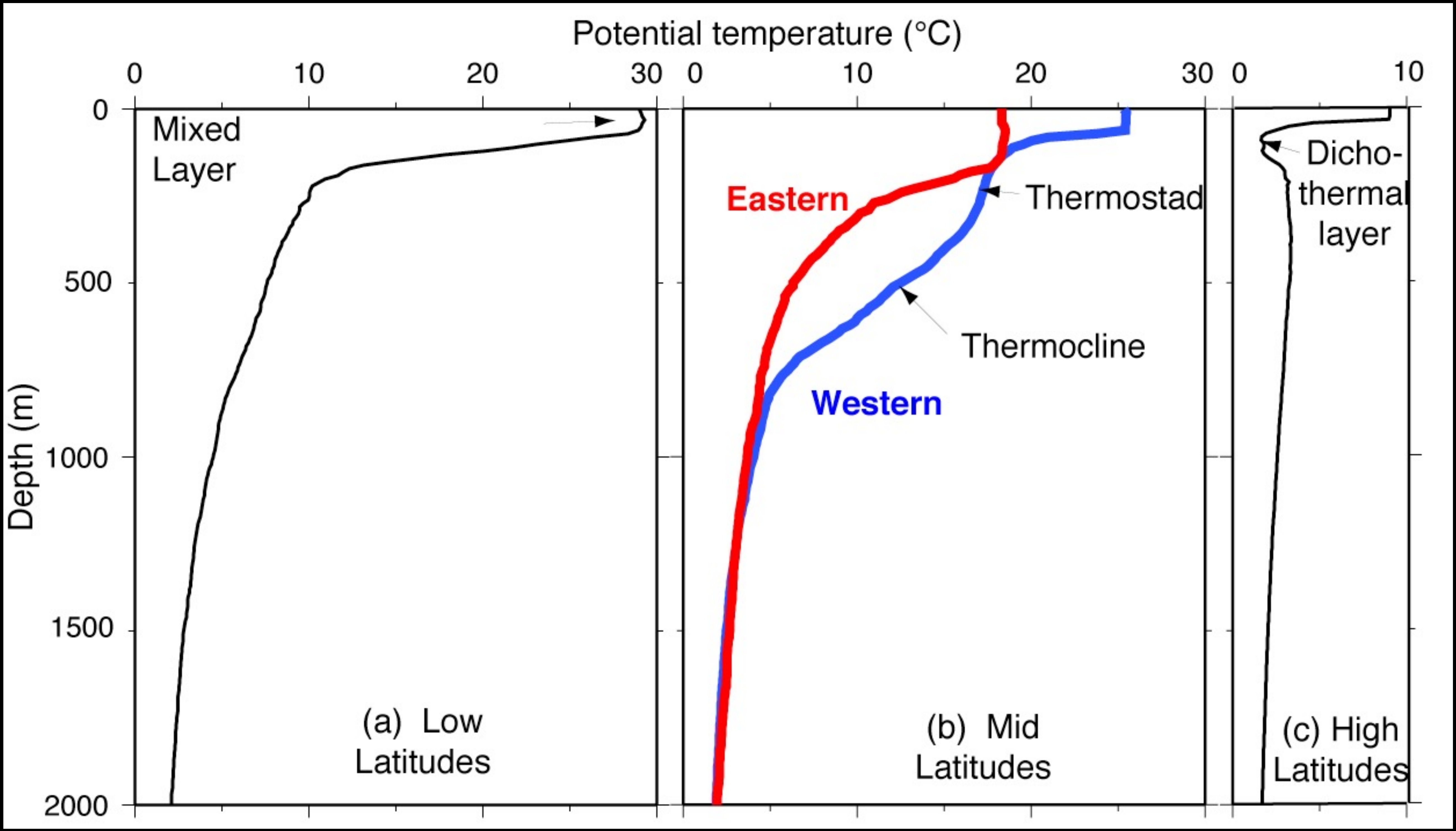
Sea ice and brine rejection

- Why then does sea ice float? (because it is actually less dense than the seawater…)
- **Brine rejection**: as sea ice forms, it excludes salt from the ice crystal lattice.
- **The salt drips out the bottom, and the sea ice is much fresher (usually ~3-4 psu) than the seawater (around 30-32 psu)**
- **The rejected brine mixes into the seawater below. If there is enough of it mixing into a thin enough layer, it can measurably increase the salinity of the seawater, and hence its density**
- **This is the principle mechanism for forming the densest waters of the world ocean.**

Surface density (winter)



Temperature profiles: definitions



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

Characterization: Surface mixed layer down through the main pycnocline.

Location: 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)

Formation mechanisms: 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

Characterization: large-scale salinity maximum and minimum layers.

Location: 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.

Formation mechanisms: 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" 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" 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" 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”

“Lower Circumpolar Deep Water”

Formation mechanism: brine rejection close to Antarctica

Water masses and water types

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

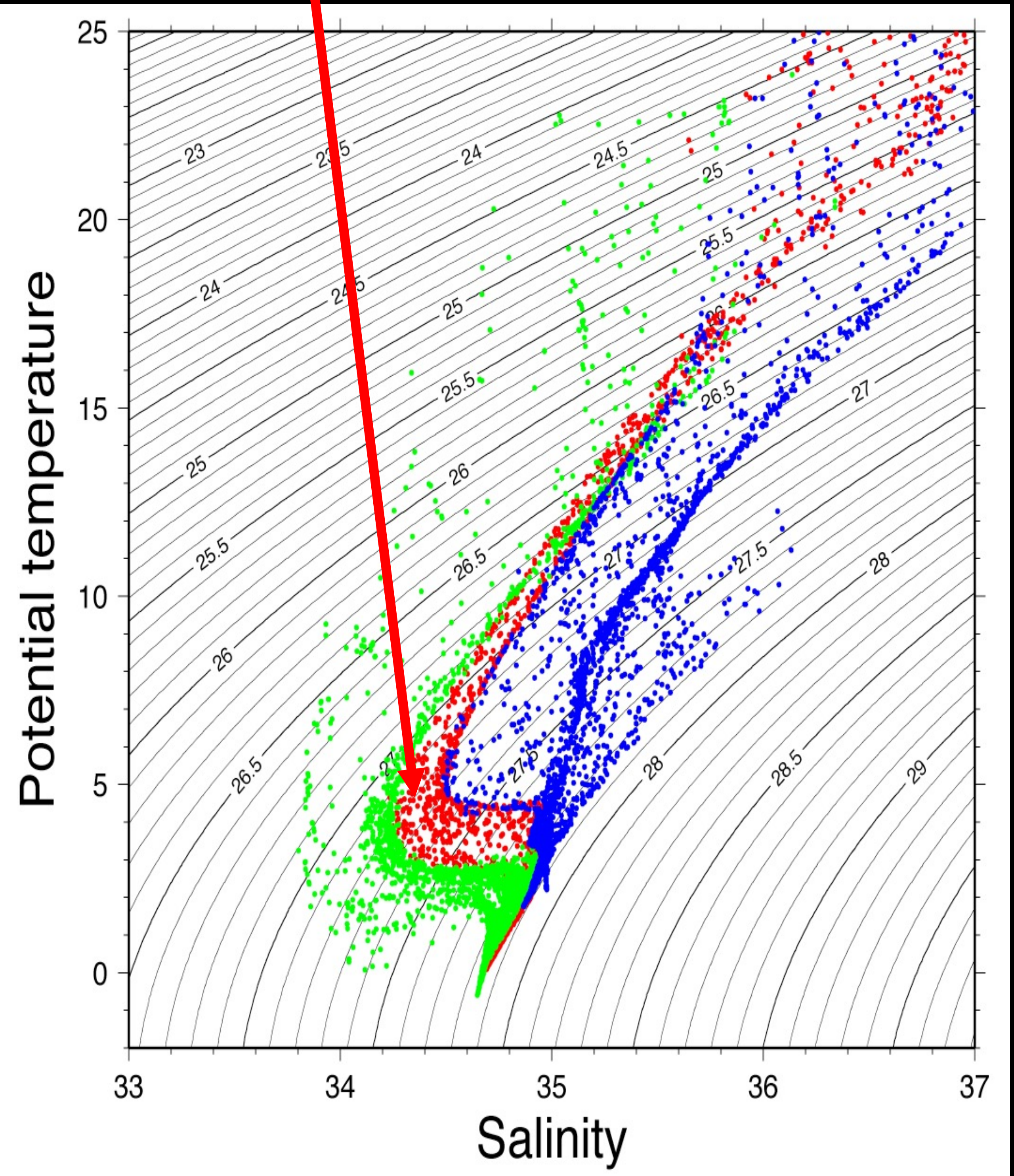
Water type: point on a temperature-salinity diagram

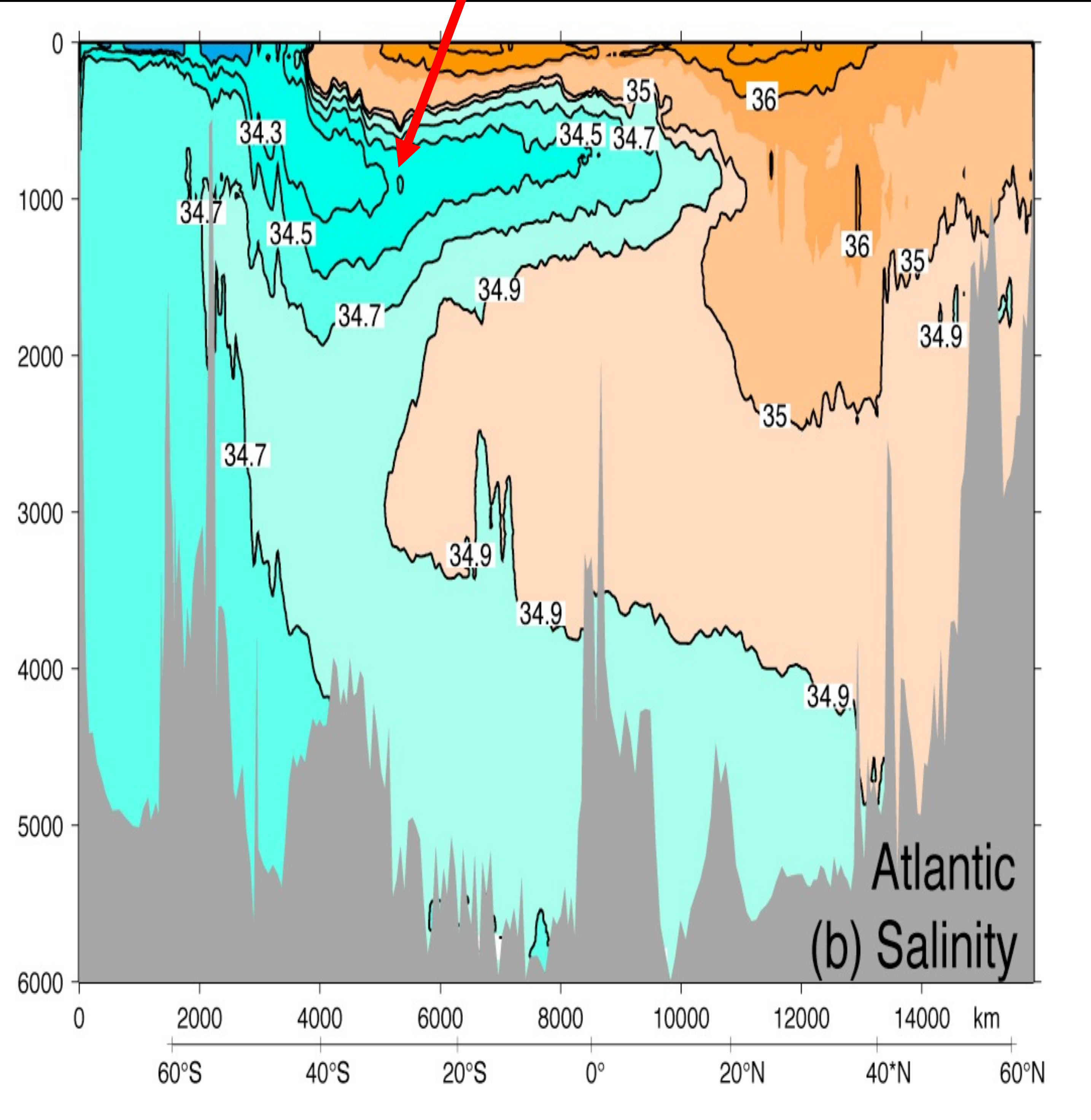
Source water type: water type at the source of a water mass

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

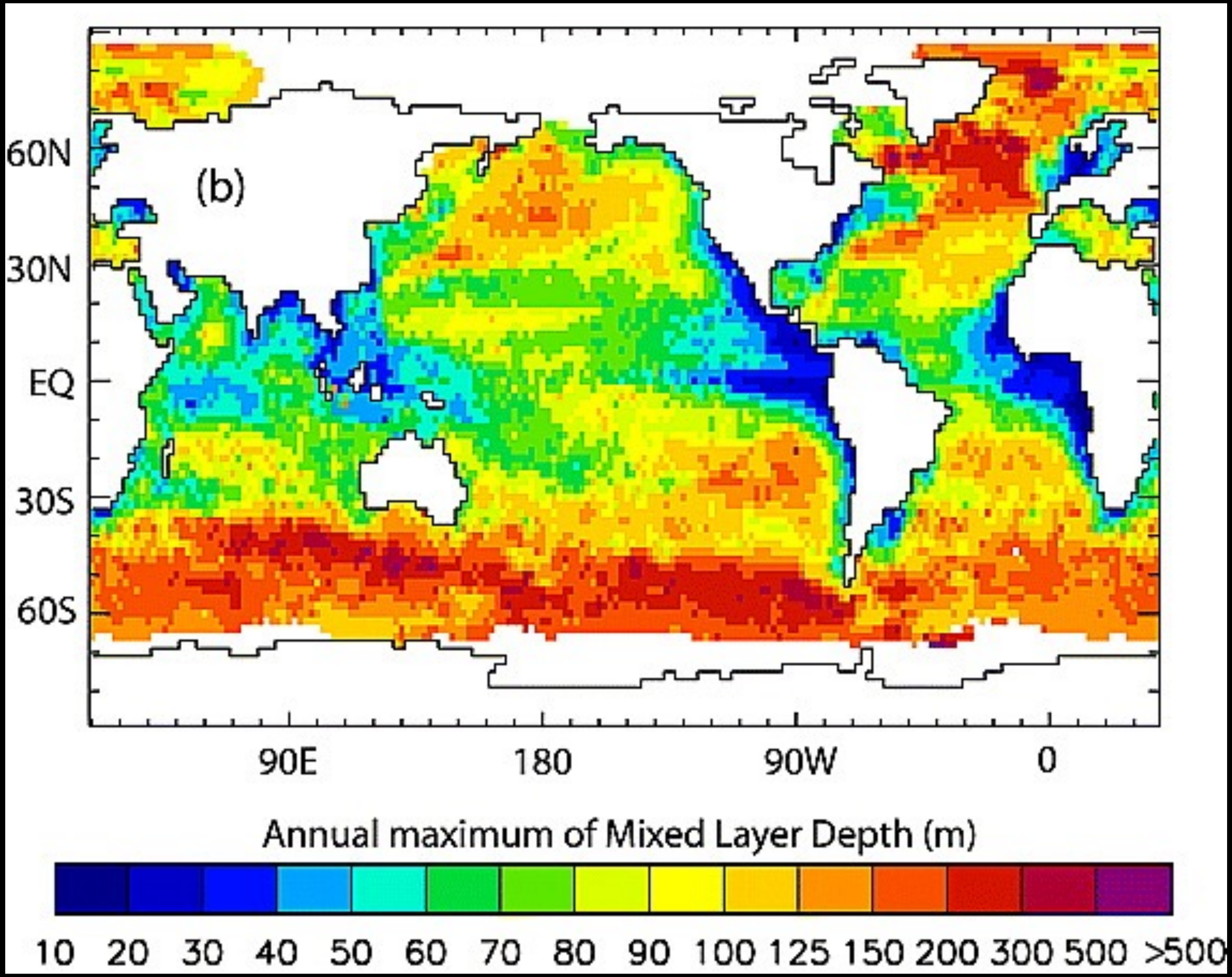




Mixed layers

- 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.

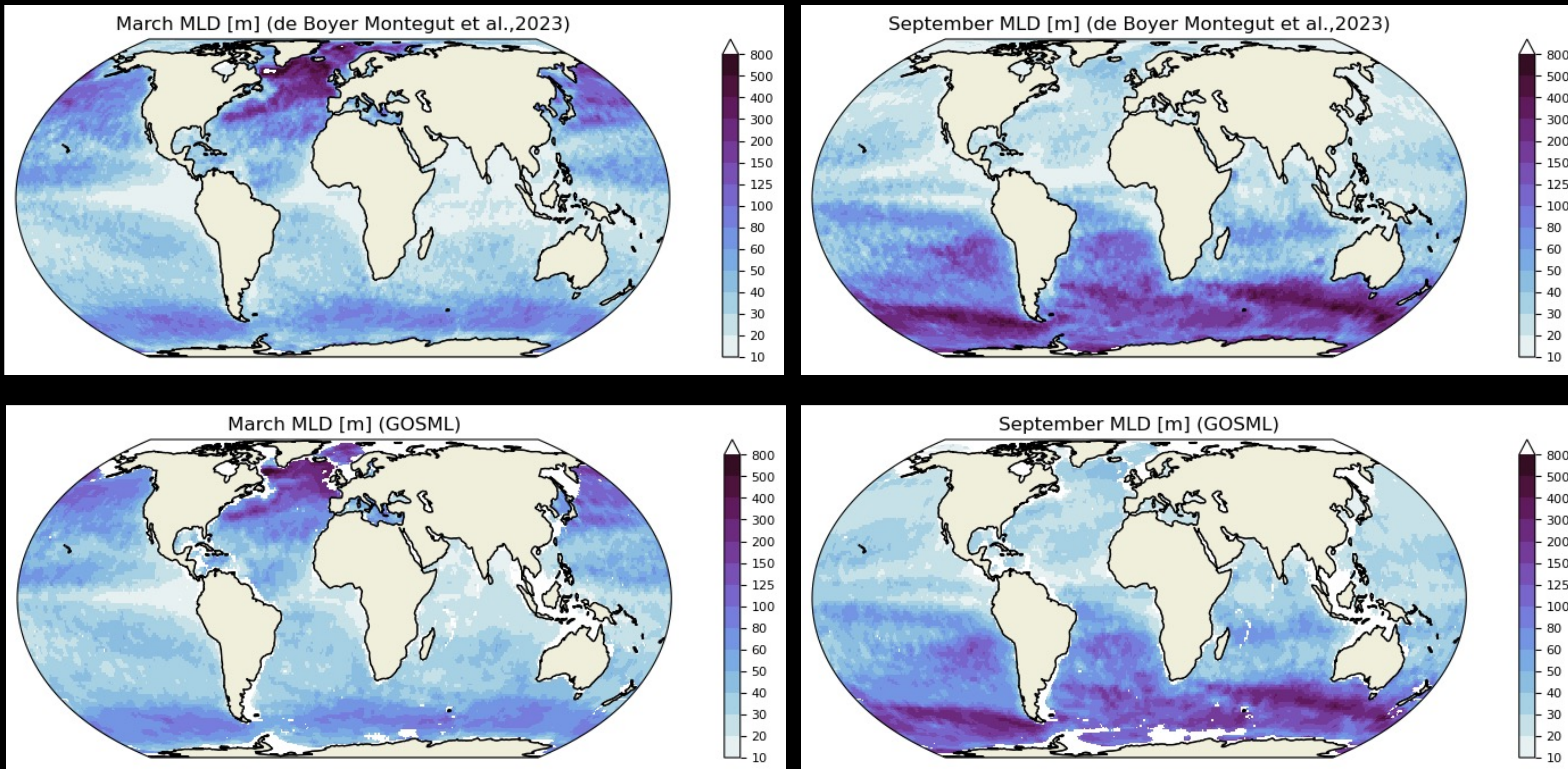
Maximum mixed layer depth (mainly late winter in each location)



Using delta T = 0.2° C

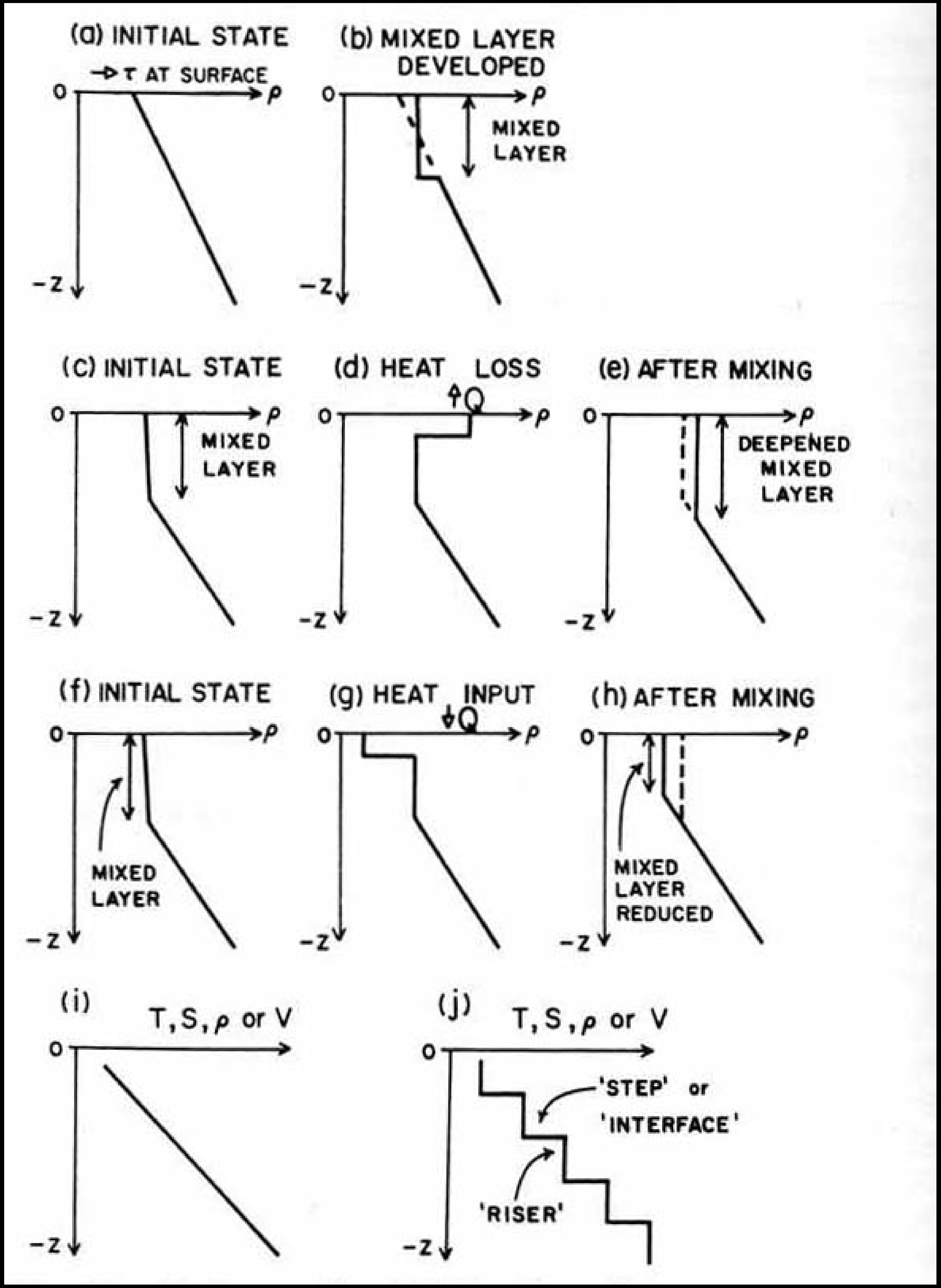
deBoyerMontegut et al. (JGR, 2004)

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



deBoyerMontegut et al. (JGR, 2004) & GOSML

Mixed layer development



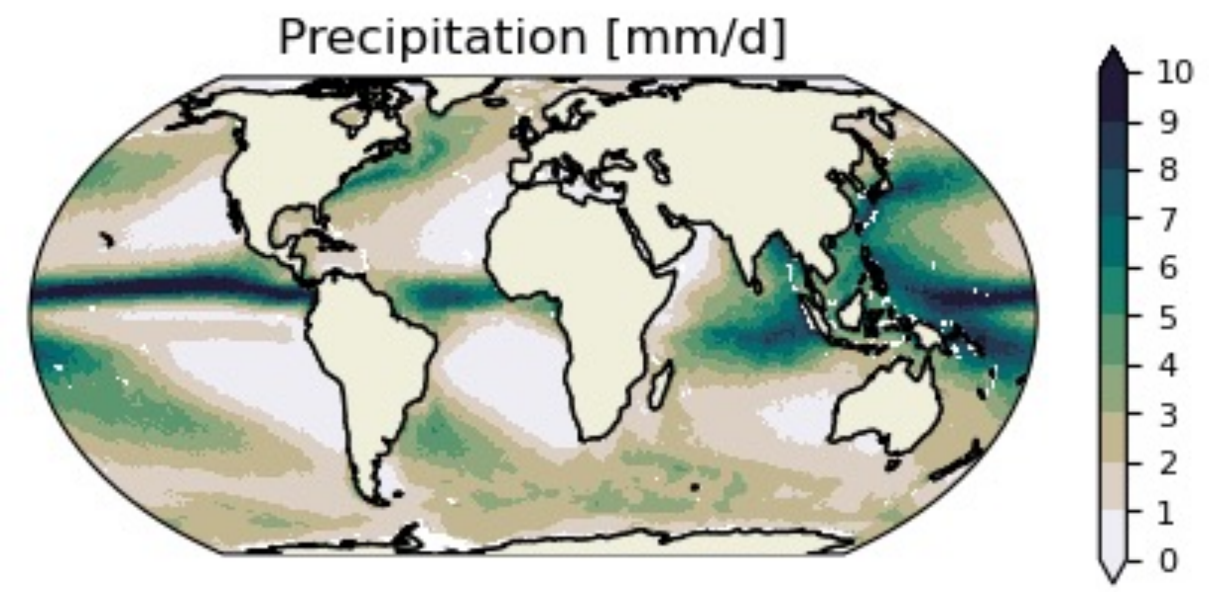
Winter development of mixed layer:

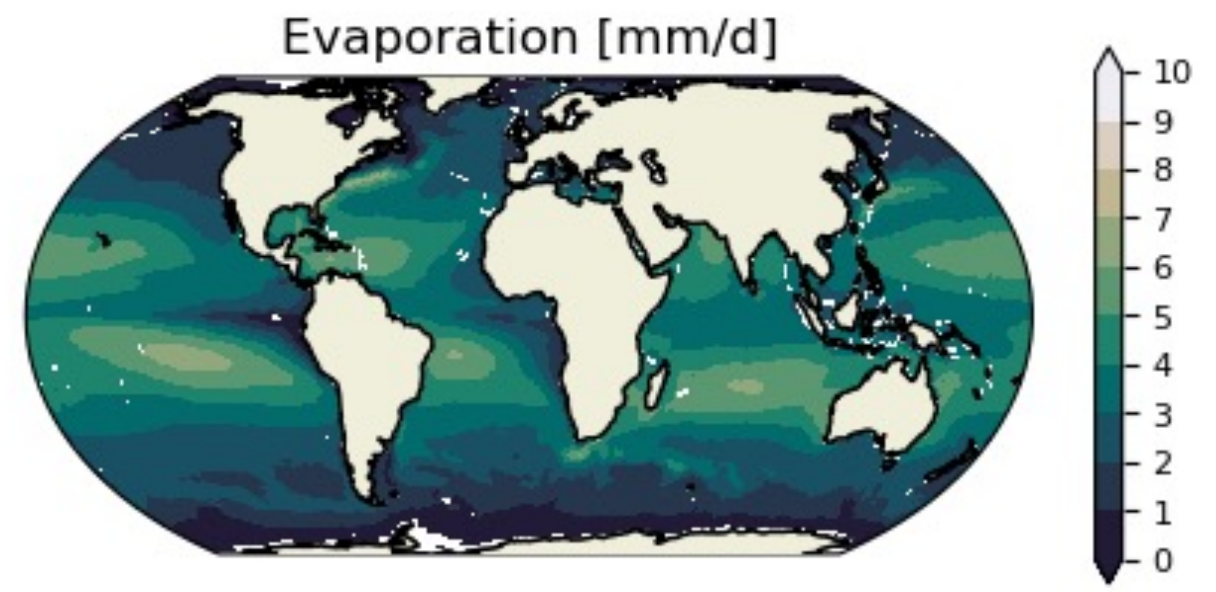
Wind stirring and cooling erode stratification, gradually deepening the mixed layer to maximum depth at the end of winter (Feb. to April depending on location)

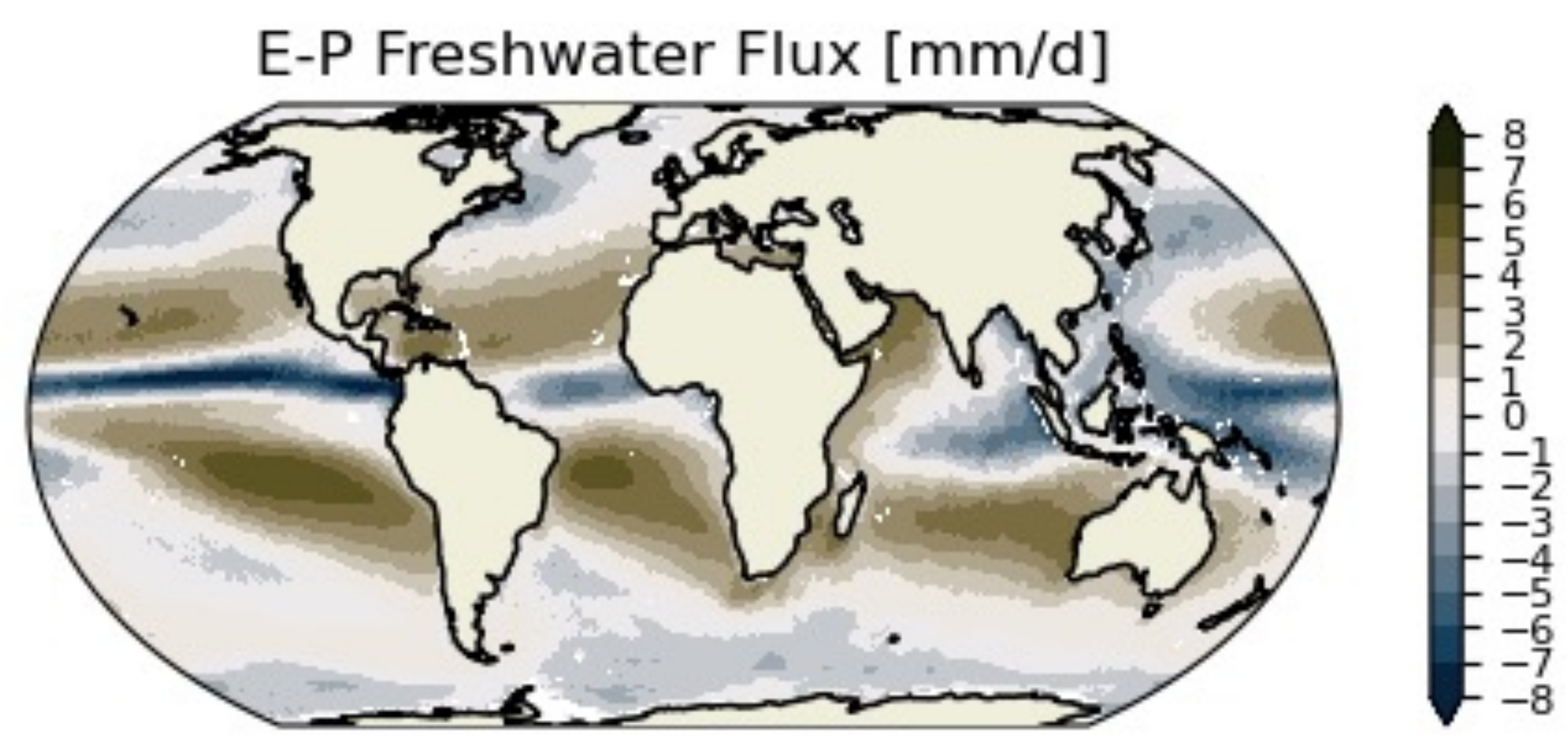
Summer restratification:

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

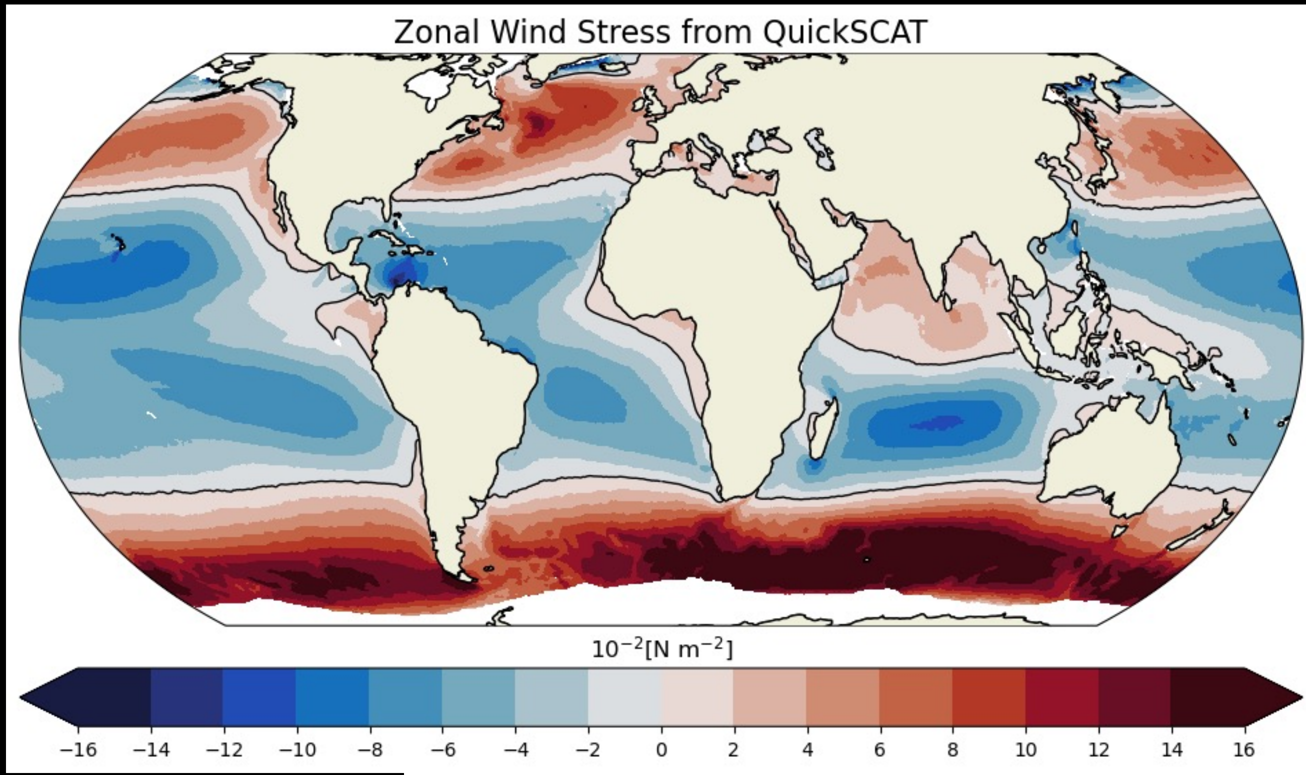
Air-sea freshwater flux and surface salinity

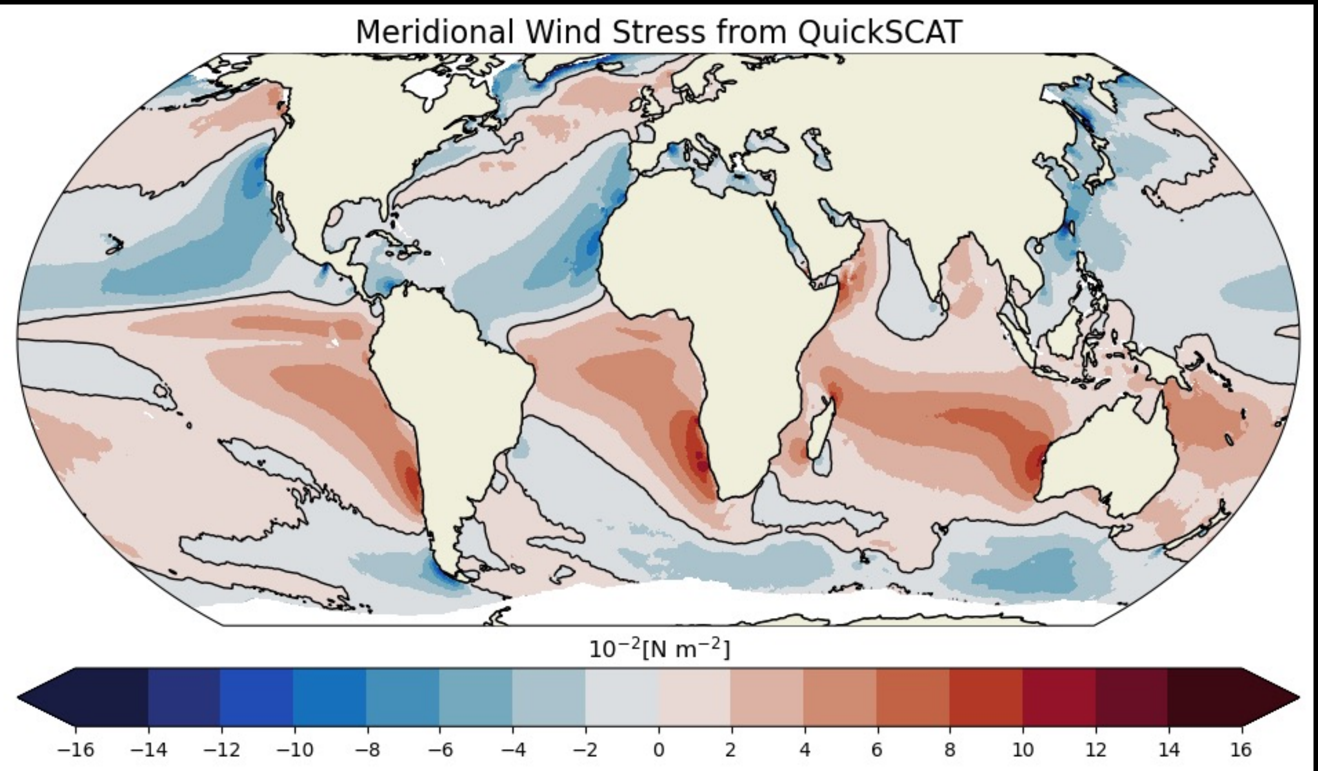


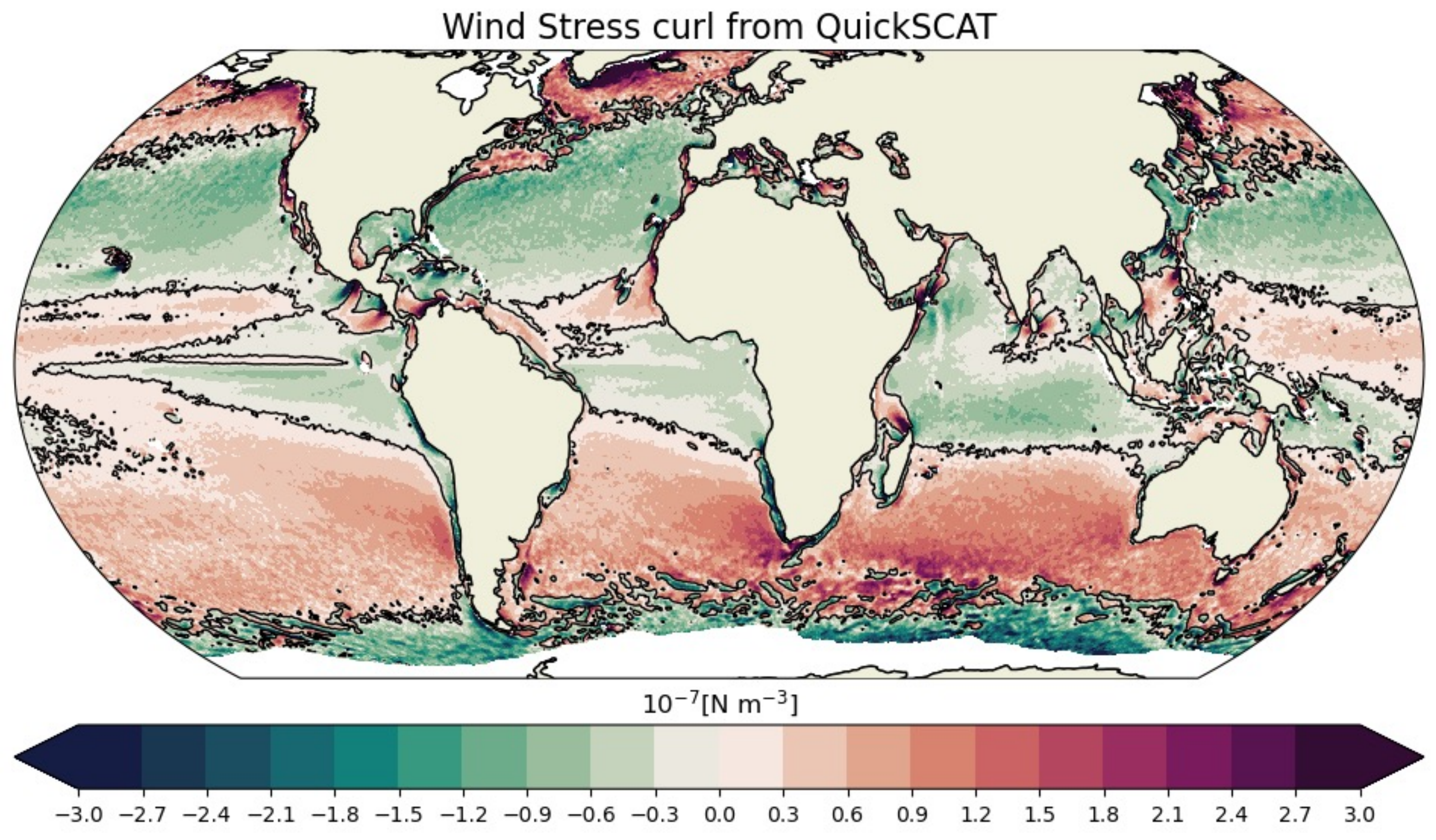




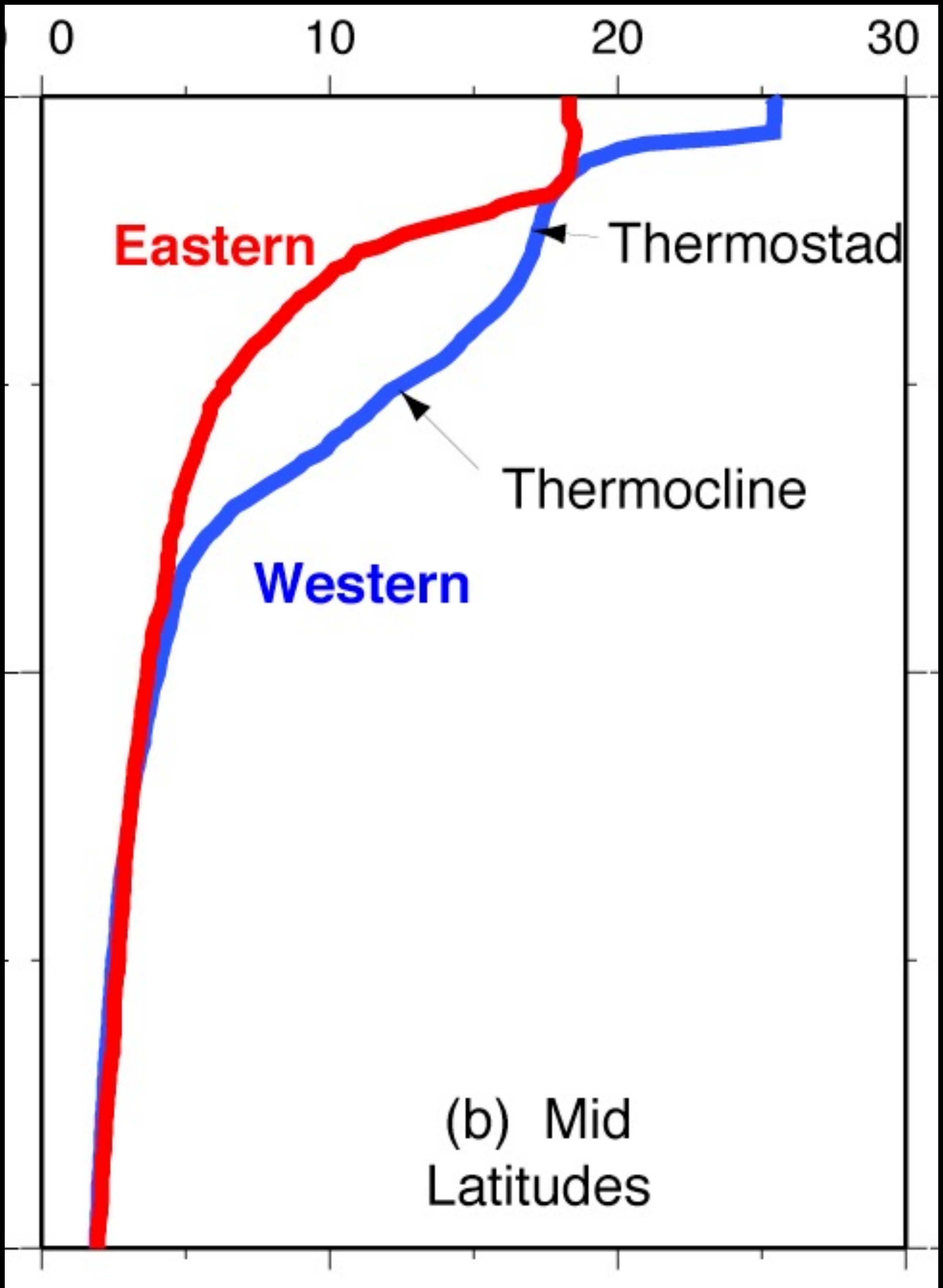
Momentum flux





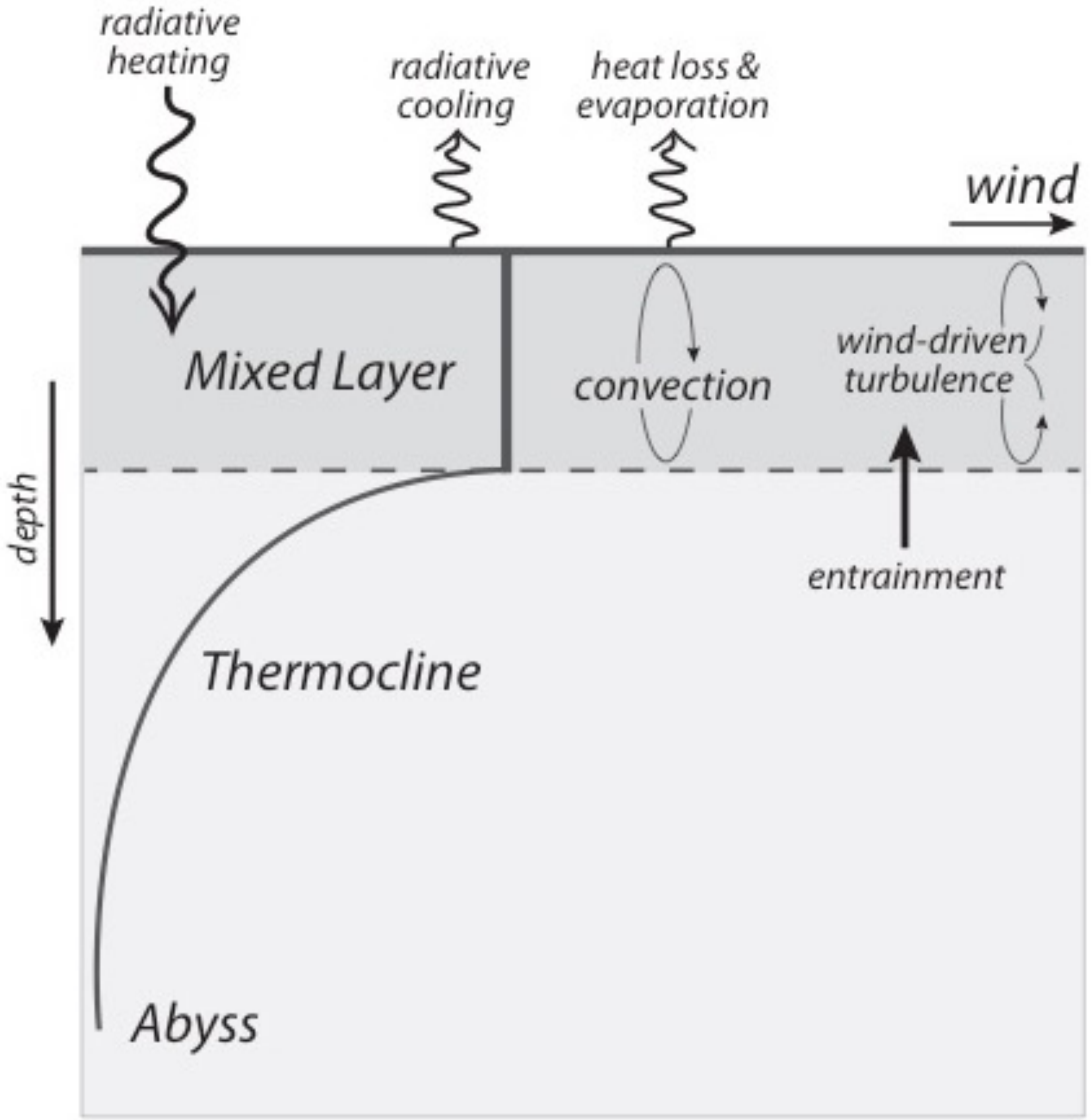


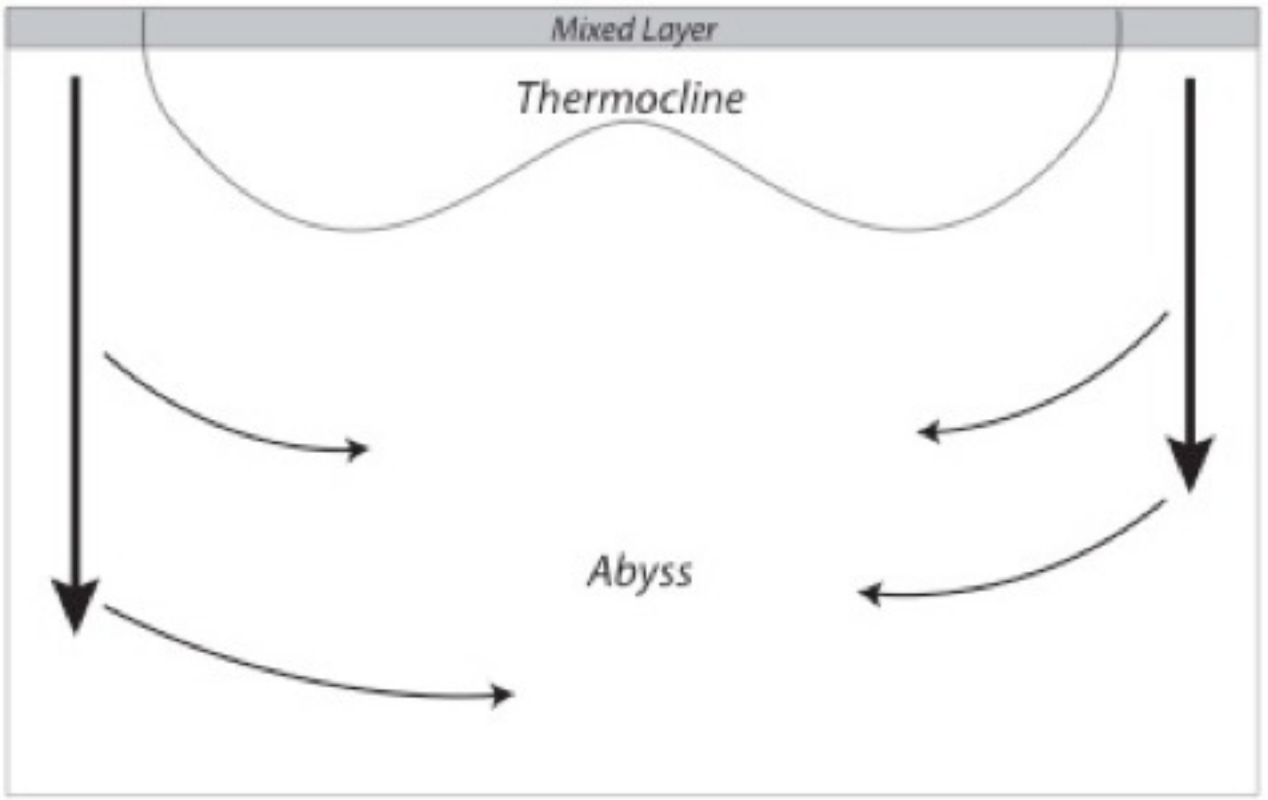
Thermocline (pycnocline)



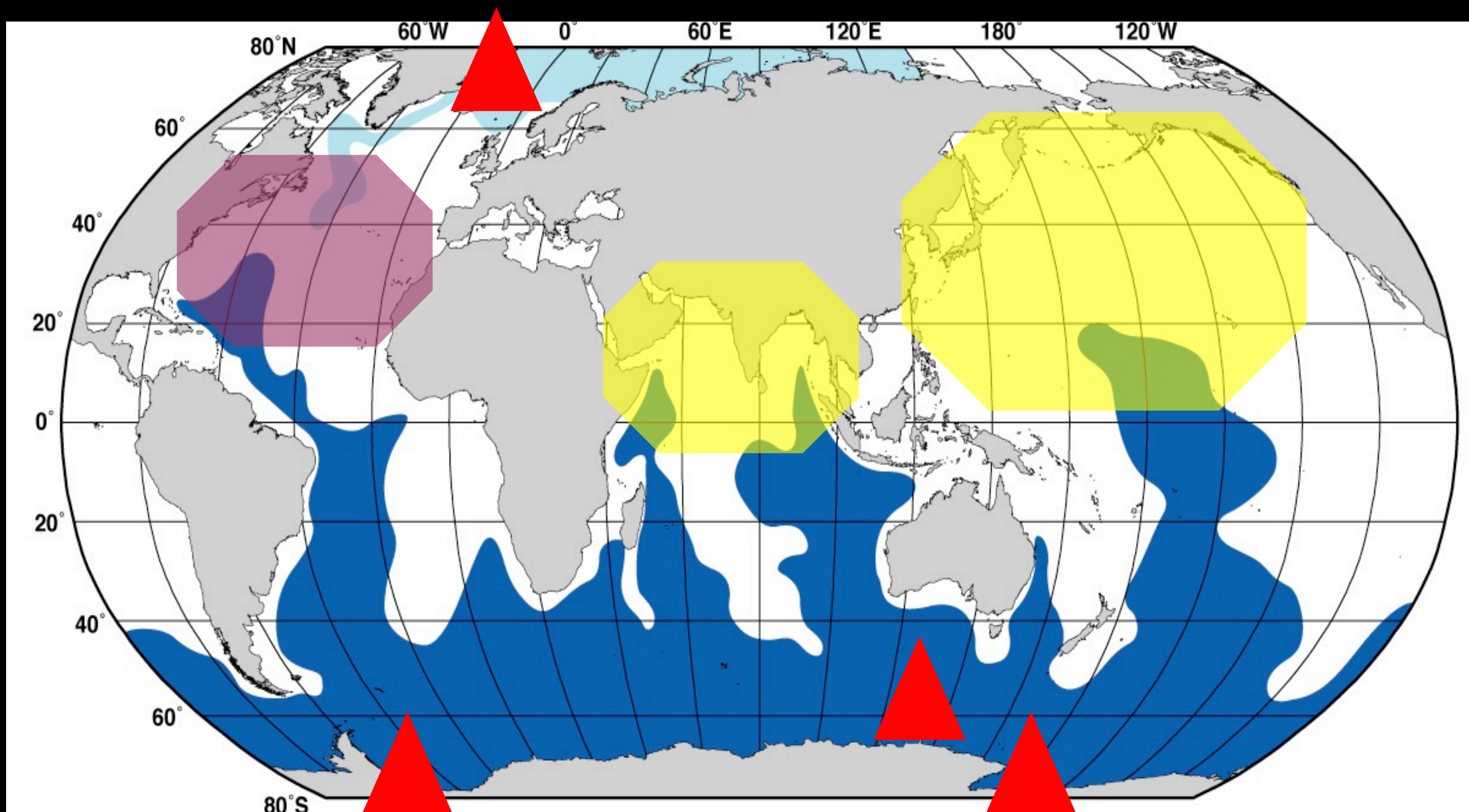
Two physical processes:

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**


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


Mixed Layer
Thermocline
Abyss

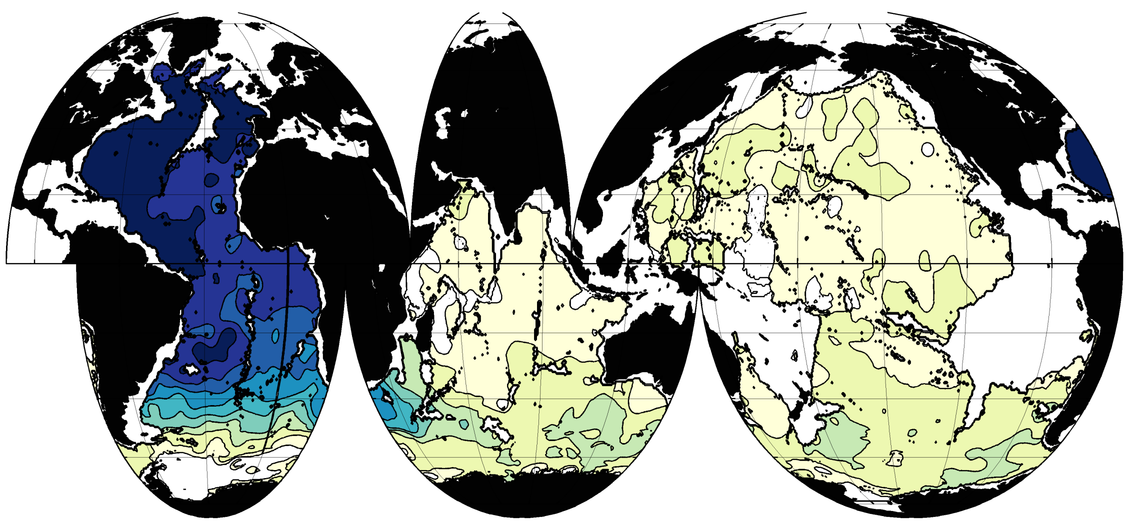
Deep and bottom water



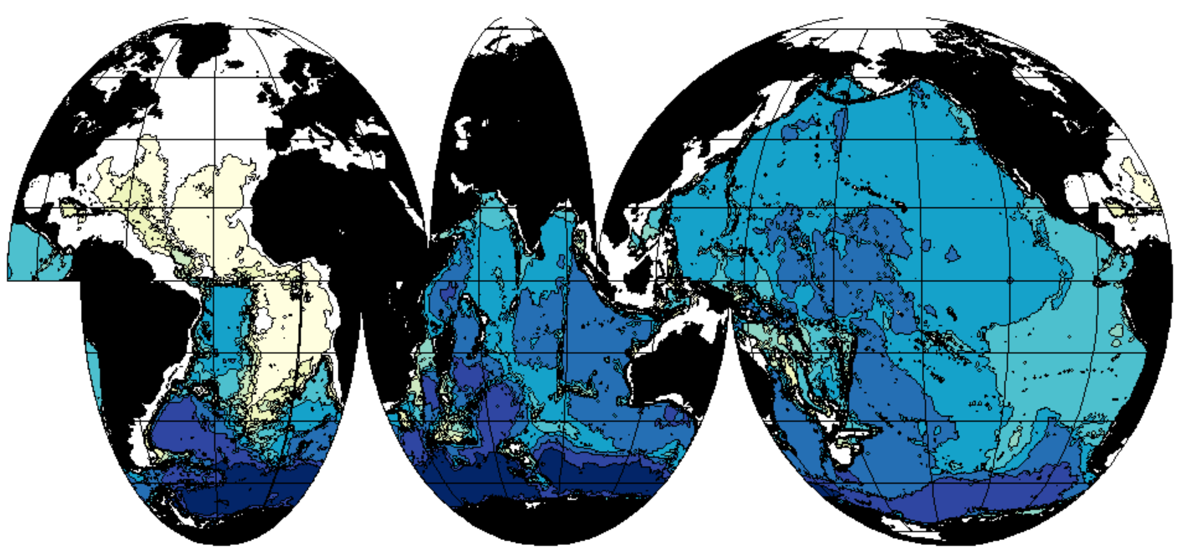
Deep and bottom water production sites

- 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

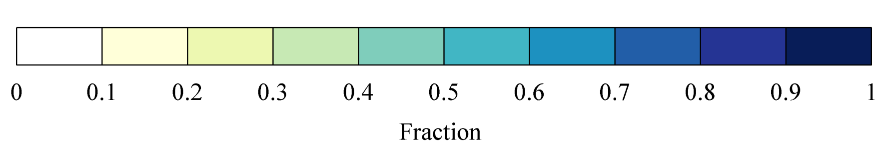
NADW and AABW in the abyssal



(a) Fraction of NADW at γ^N=28.06 kg/m^3 (2500-3000 m)



(b) Fraction of AABW at ocean bottom



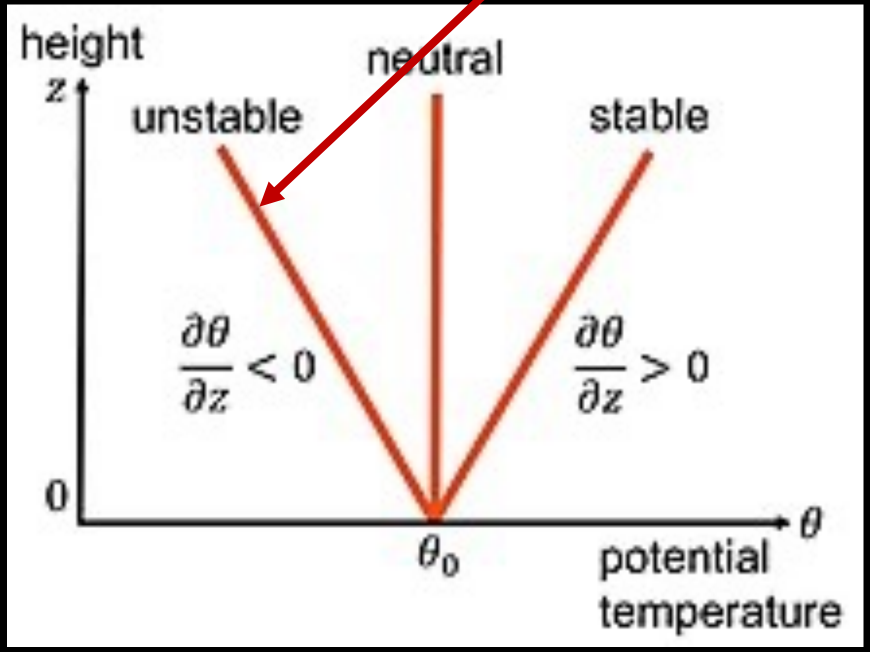
NADW and AABW both occupy the deep and bottom layers, although AABW clearly dominates at the bottom.

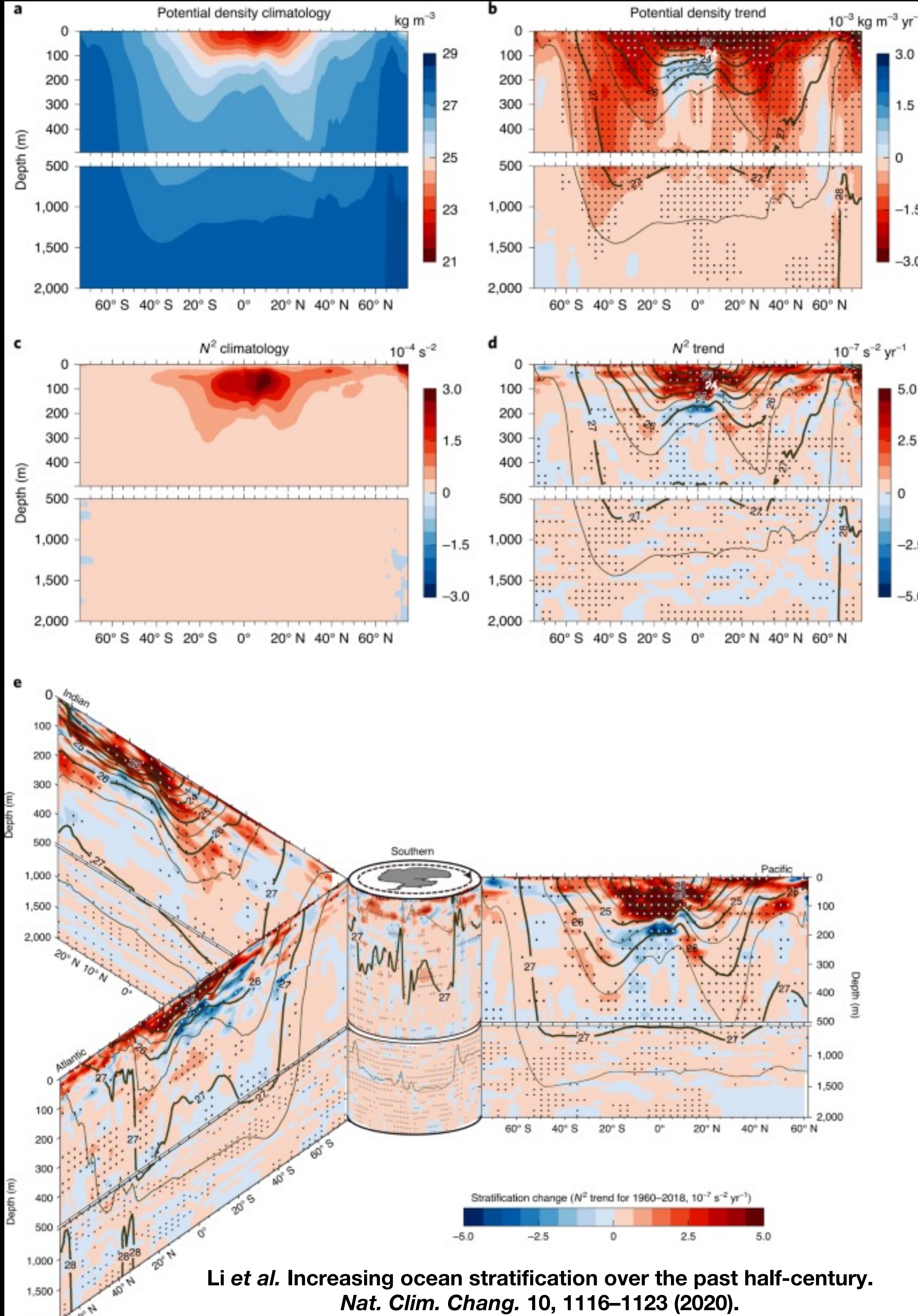
Maps of the fraction of water at mid-depth and at the bottom that are NADW or AABW. (Only two water masses were included in the analysis: these are the surface source waters.)

Static stability and Buoyancy Frequency

- **Static stability of the ocean (atmosphere)**
- **Static stability of the environment can be measured through the vertical changes in temperature (density)**
- **A parcel of fluid that is displaced vertically adiabatically tends to oscillate within a stable environment**
- **The frequency of those oscillations is called Brubt-Vaisala frequency or buoyancy frequency N^2.**

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 barrier to water mixing that impacts the efficiency of vertical exchanges of heat, 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 decrease in ocean ventilation could affect ocean heat and carbon uptake, water mass formation.

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