

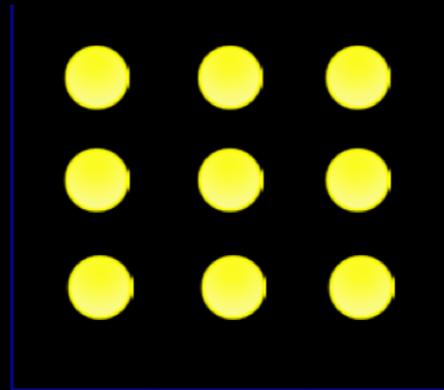
Climate Dynamics

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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

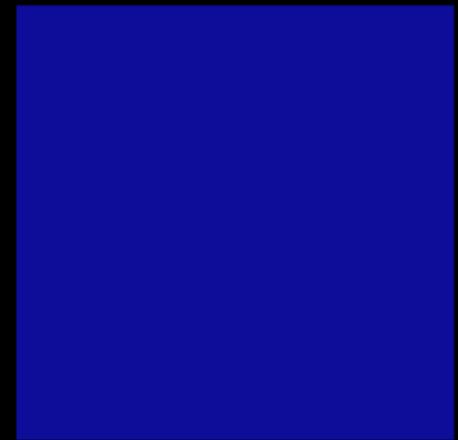
~9 lampadine da 40W
per metro quadrato



- e l'energia è la capacità di fare lavoro

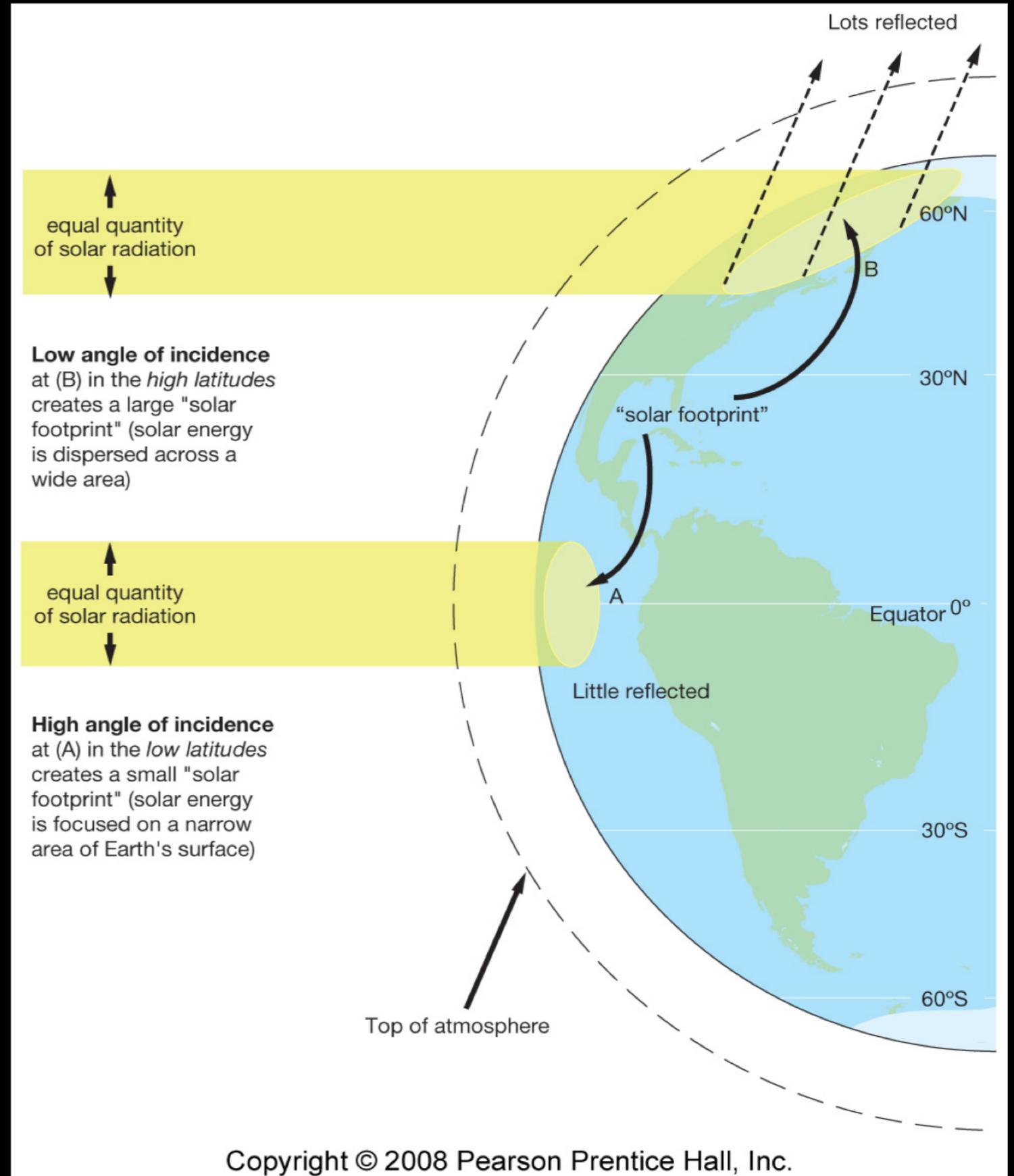
- la misuriamo in Joules (J)
- Il flusso di energia è $1 \text{ J/s} = 1 \text{ Watt}$

- e i W/m^2 sono l'energia (J) al secondo su un area di 1 m^2



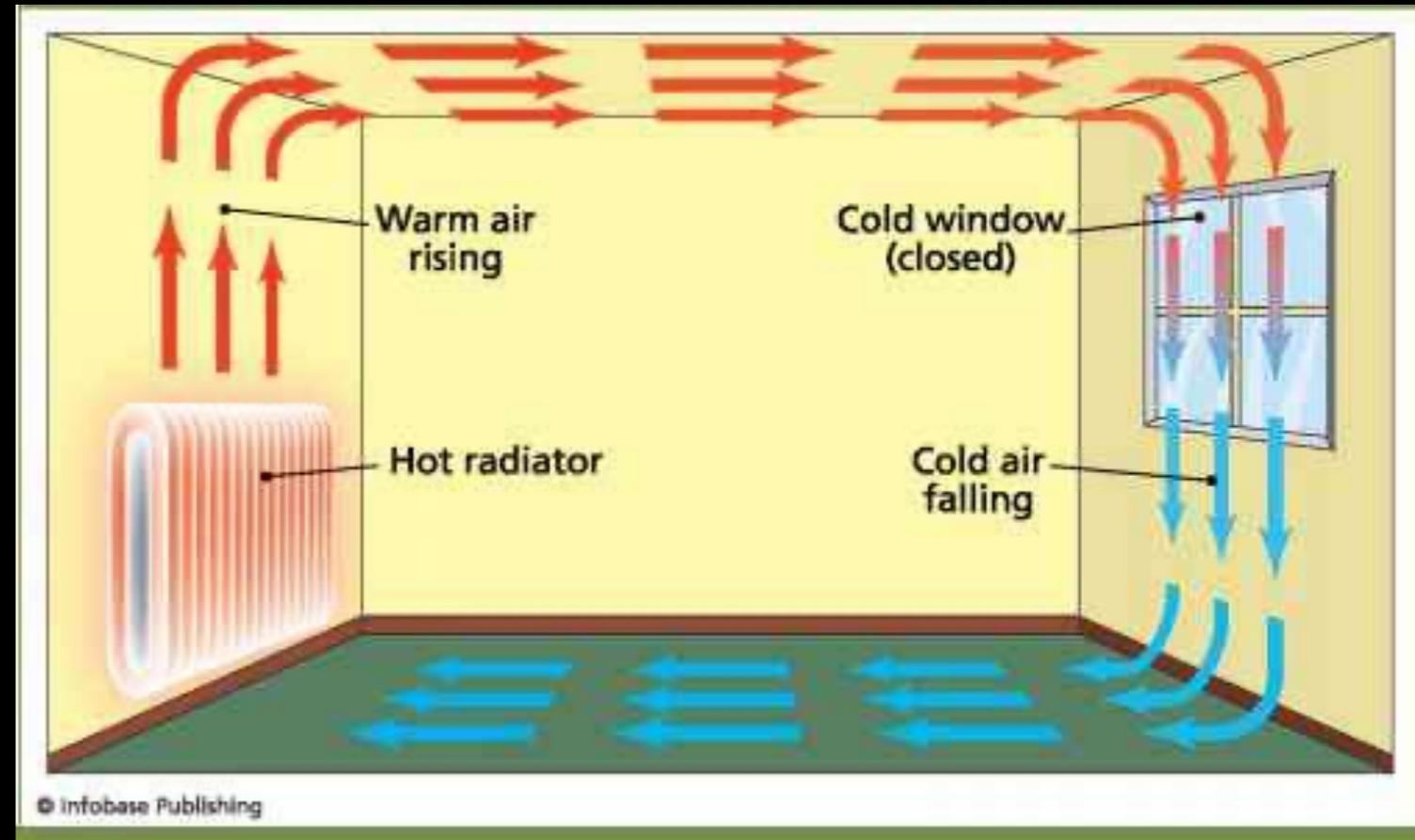
Riscaldamento solare non è uniforme

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



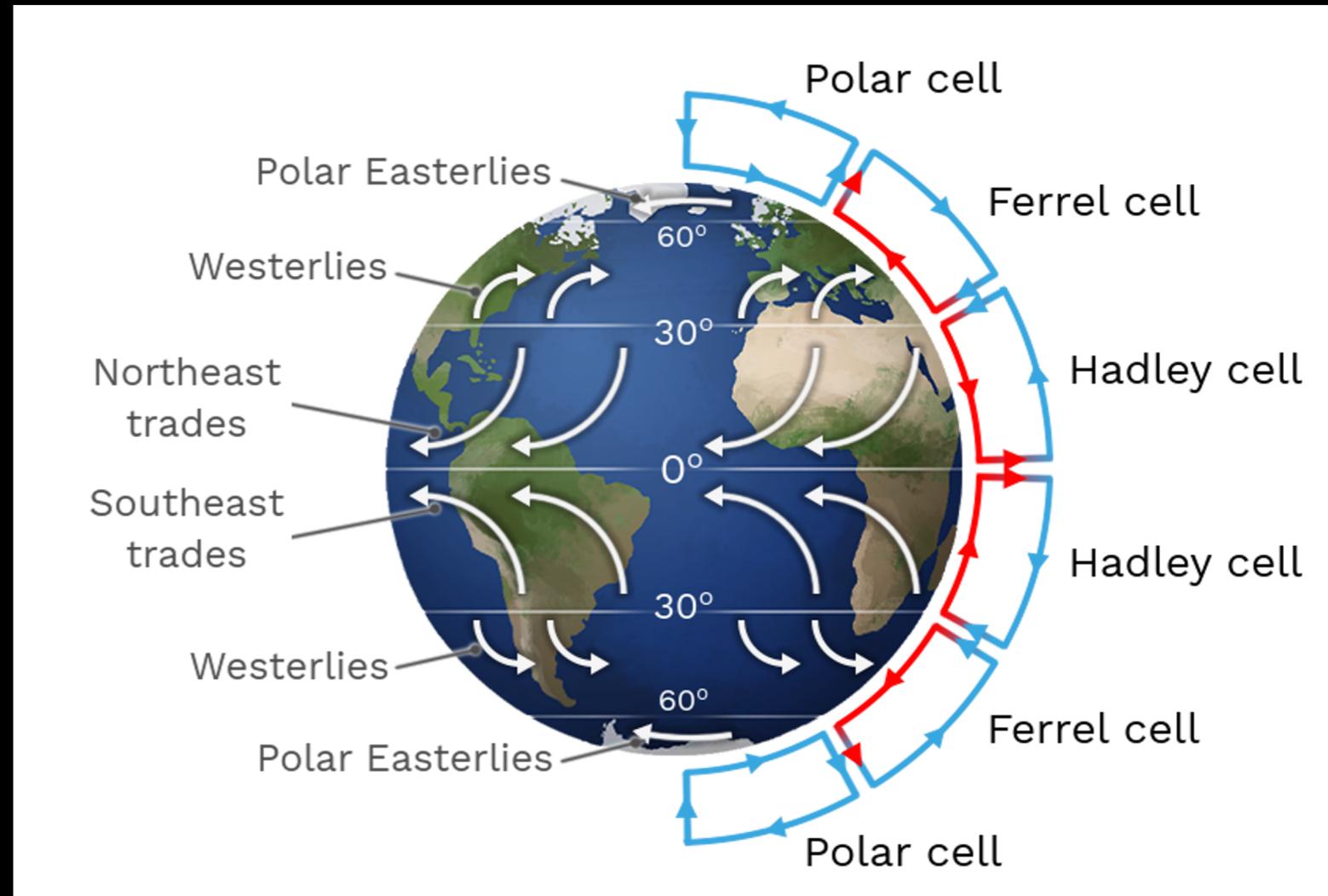
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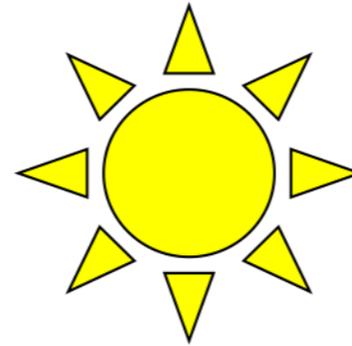


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Atmospheric Convection



Intense radiation at the equator warms the air

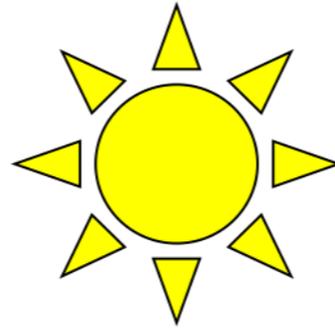
AAIW
Air expands and cools as it rises, vapor condenses and falls as rain



Warm air rises

Lots of rain in the tropics!

Hadley Circulation



Rising air is now dry...

AAIW



some of the rising air flows north

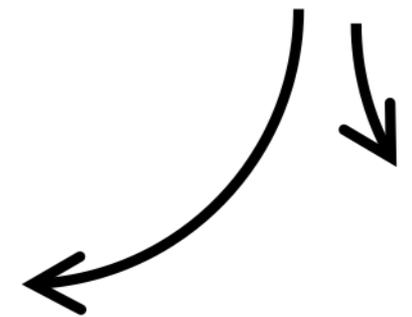
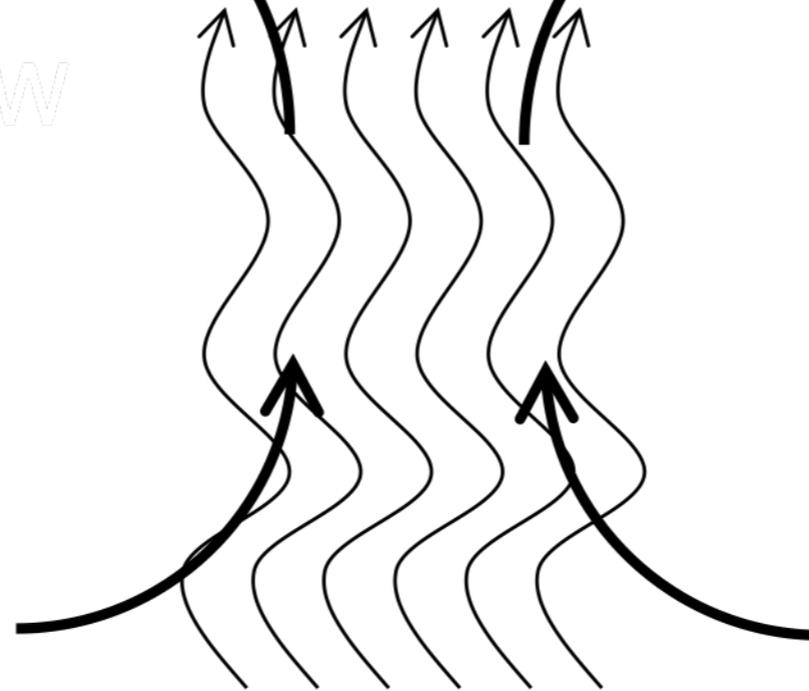
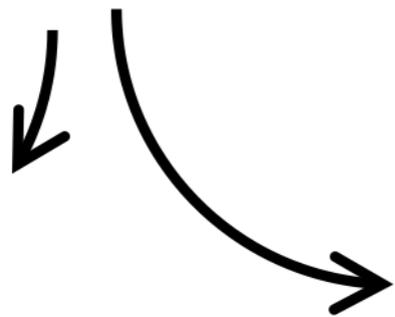
some of the rising air flows south

NADW

AABW

Dry air descends at around 30° N

...and at around 30° S

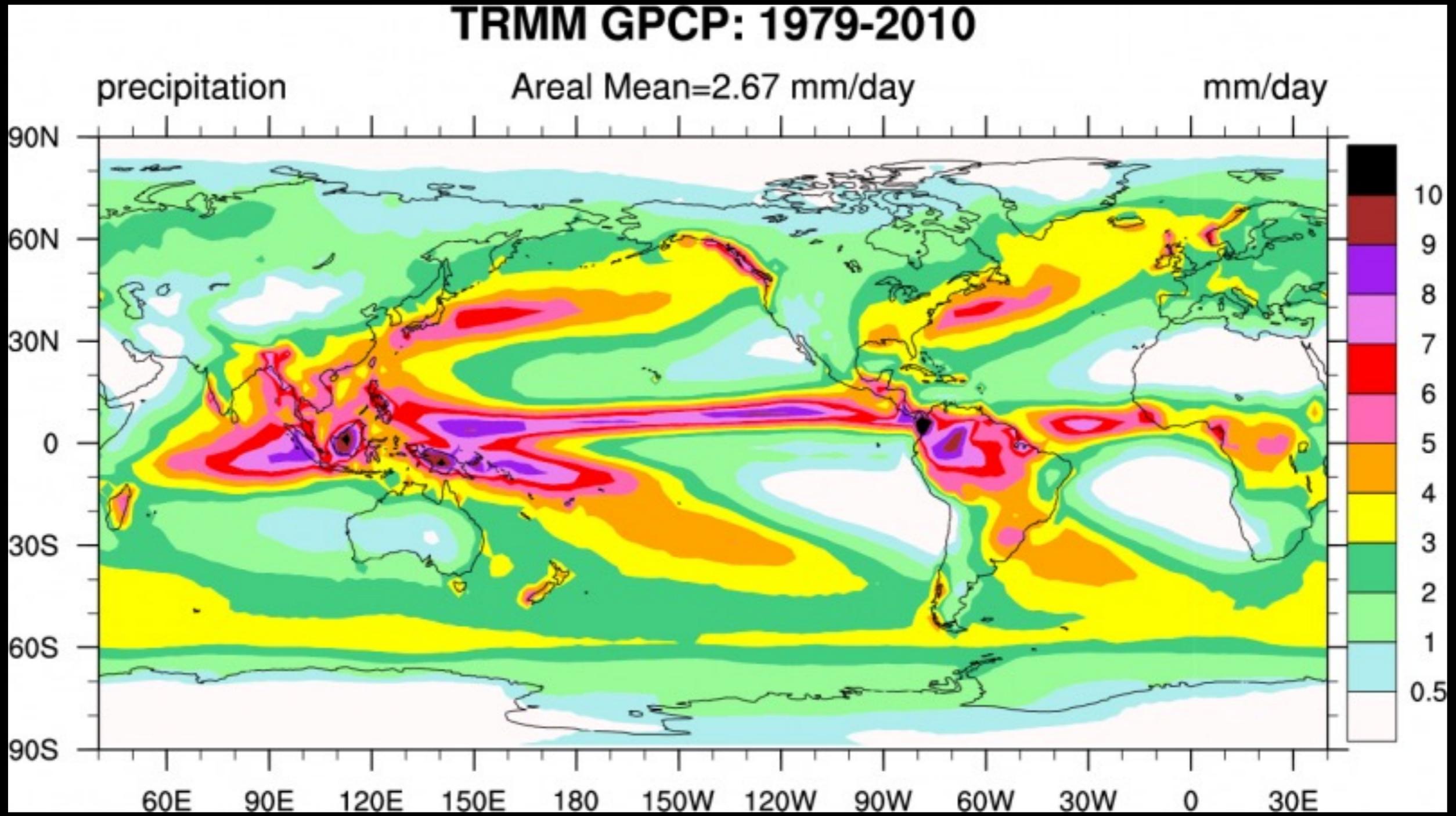


Deserts

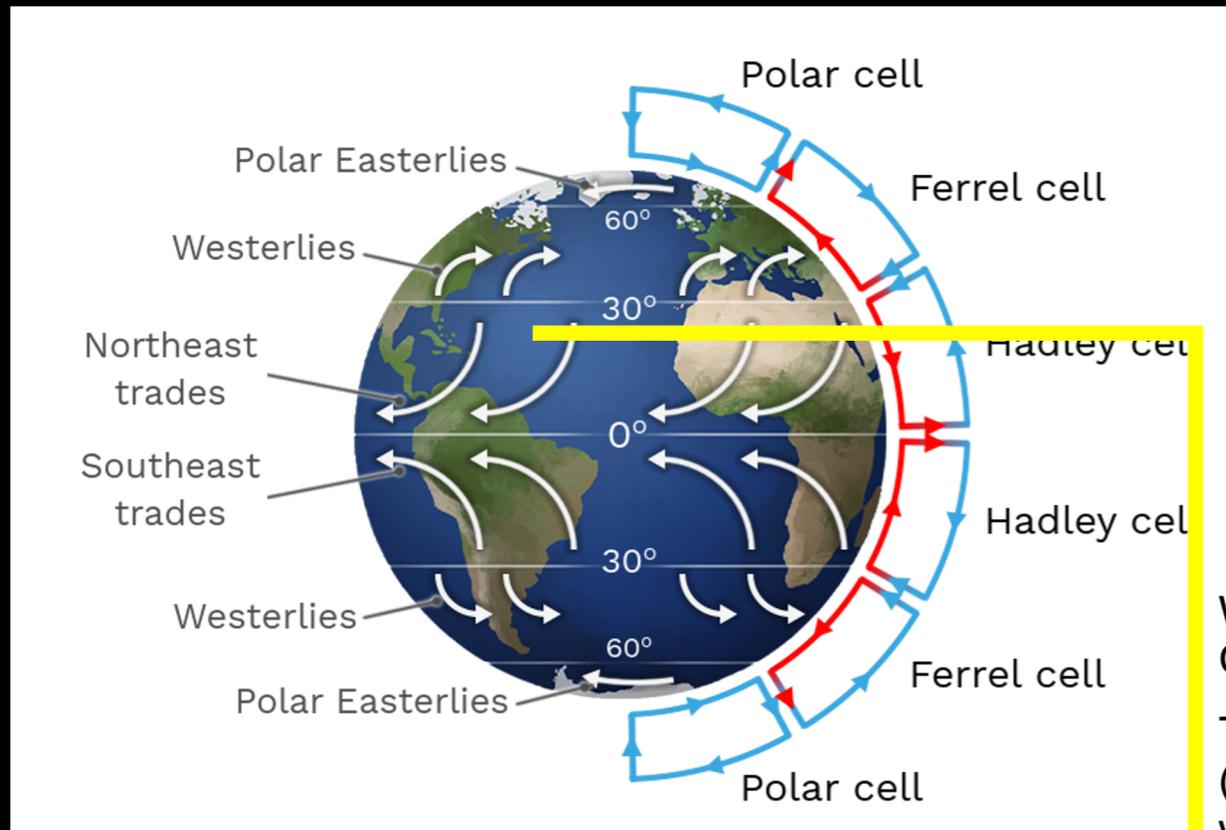
The descending air flows N and S

Deserts

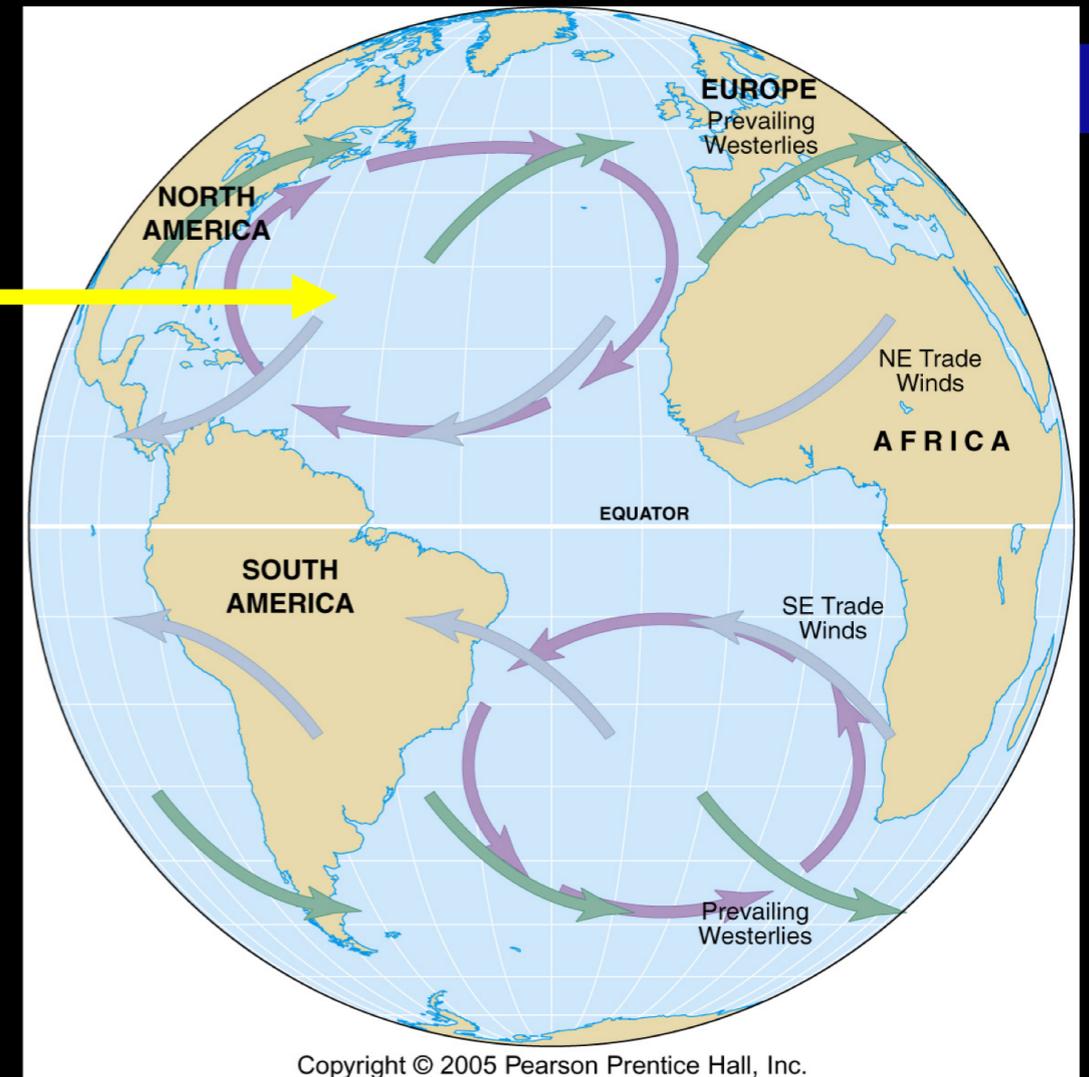
Precipitazione media è il risultato di questa circolazione



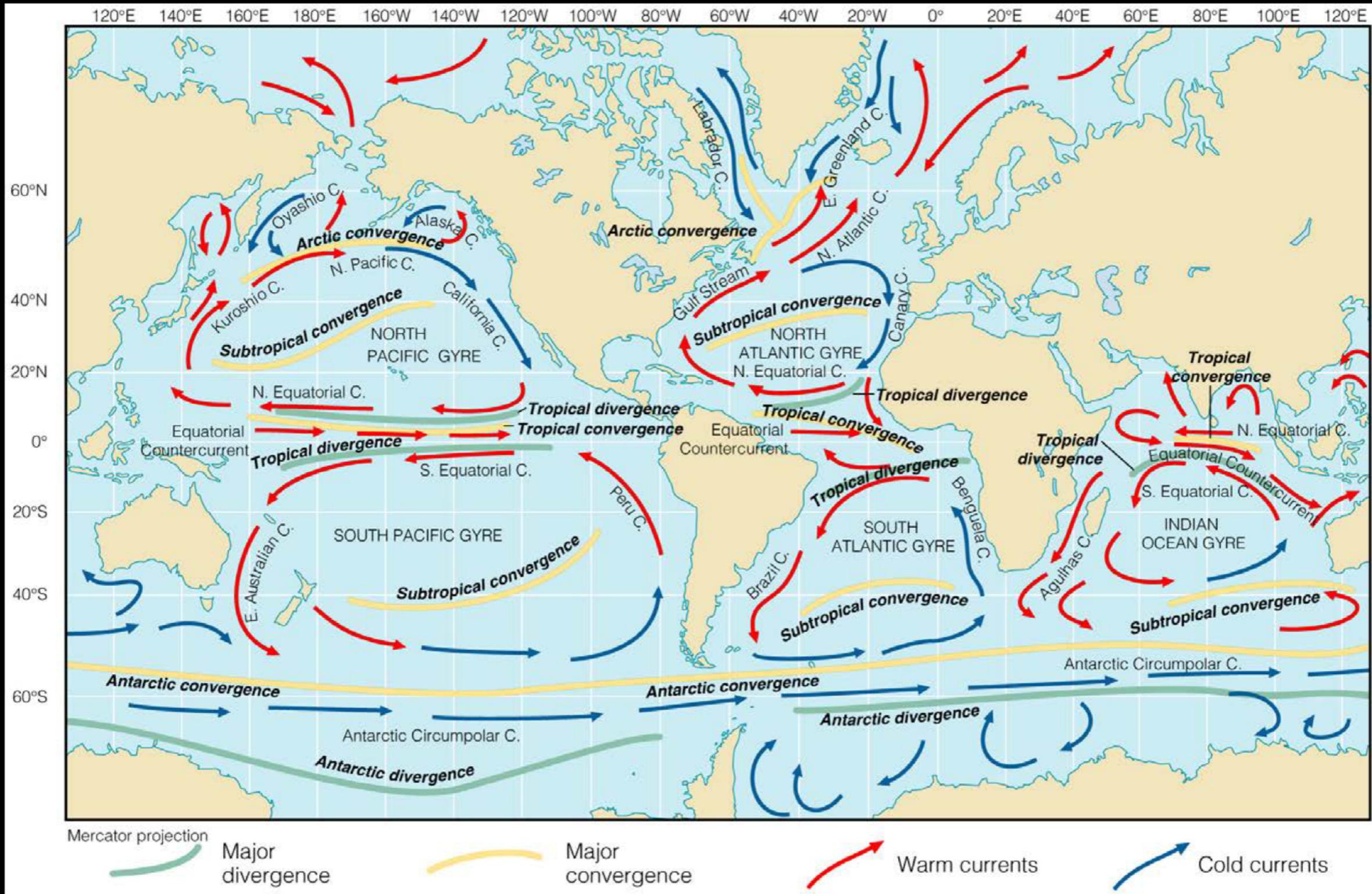
e i venti superficiali soffiano sull'Oceano



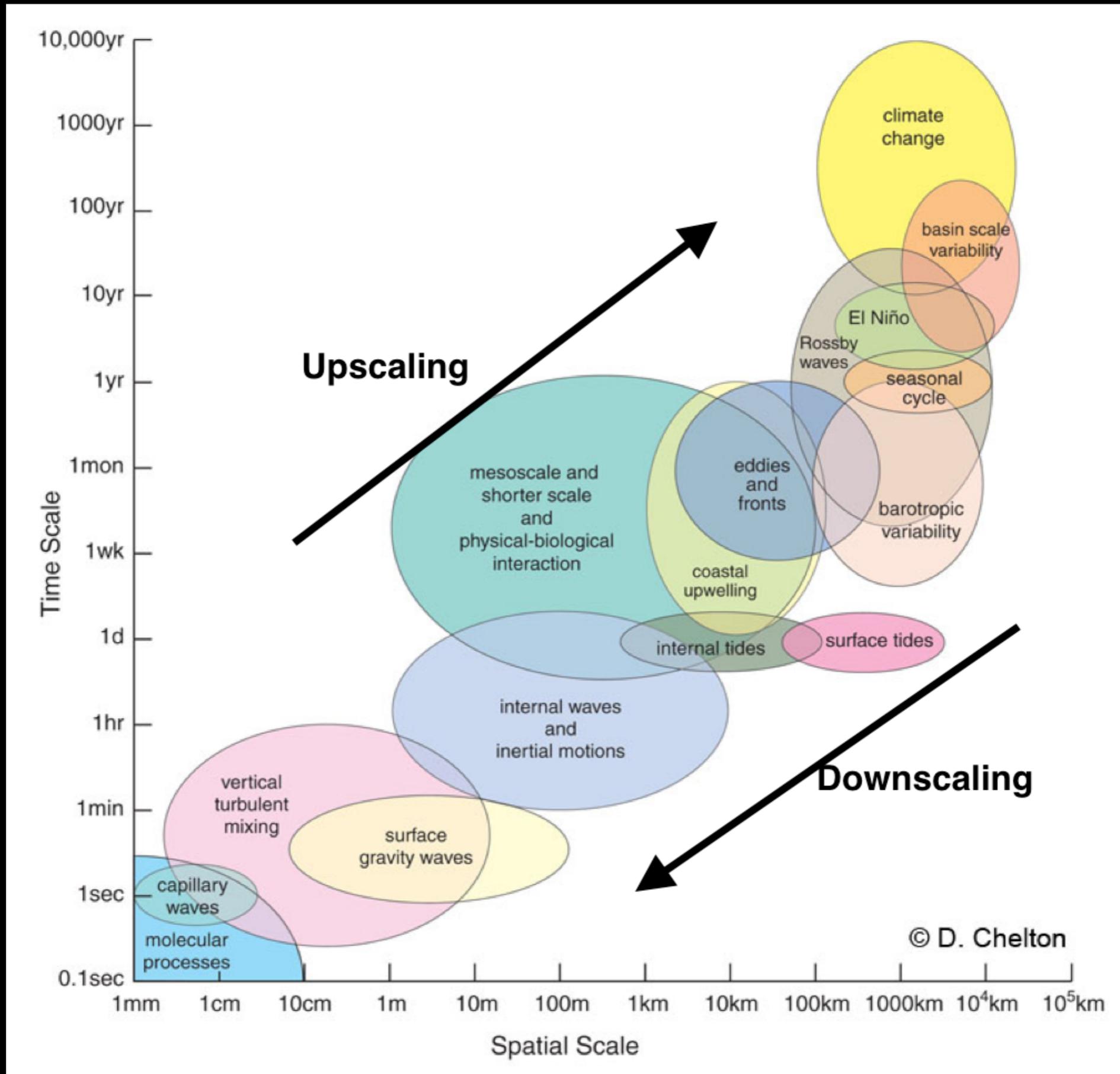
**generando correnti
superficiali indotte dal
vento**



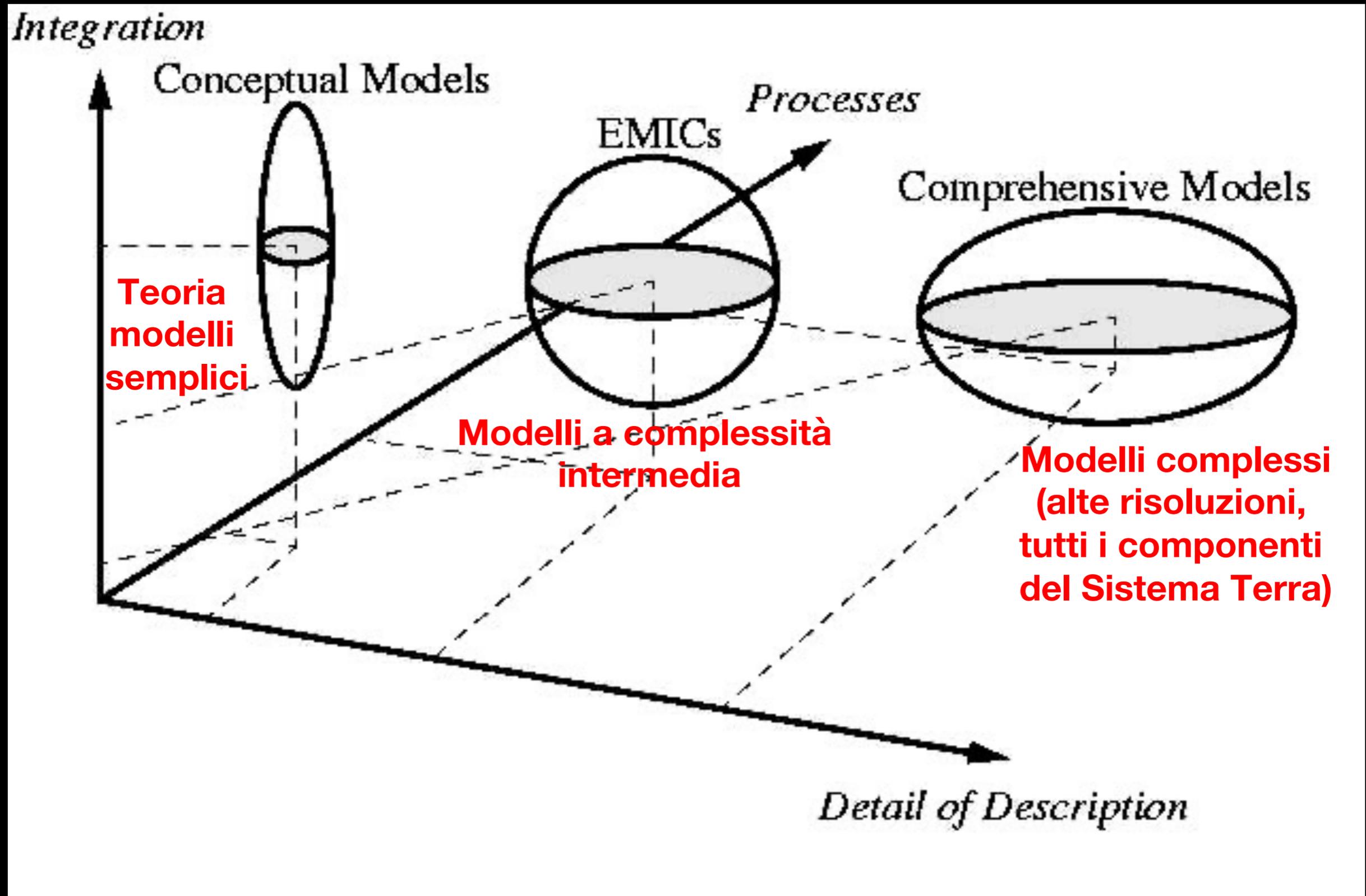
Che in realtà sono molto complesse e interagiscono fra loro



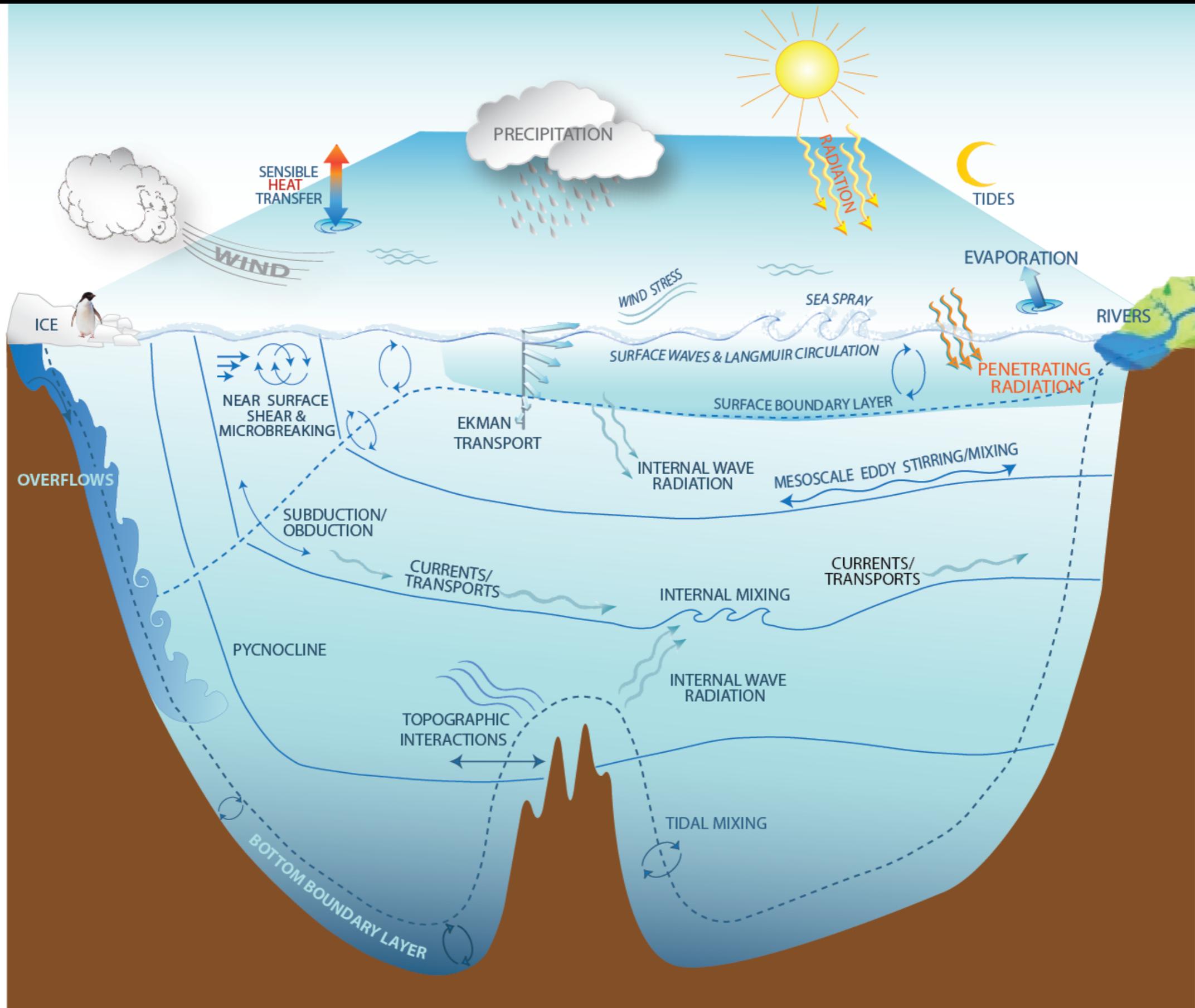
Processi fisici a diverse scale temporali e spaziali, interconnessi anche fra diversi componenti del Sistema Terra



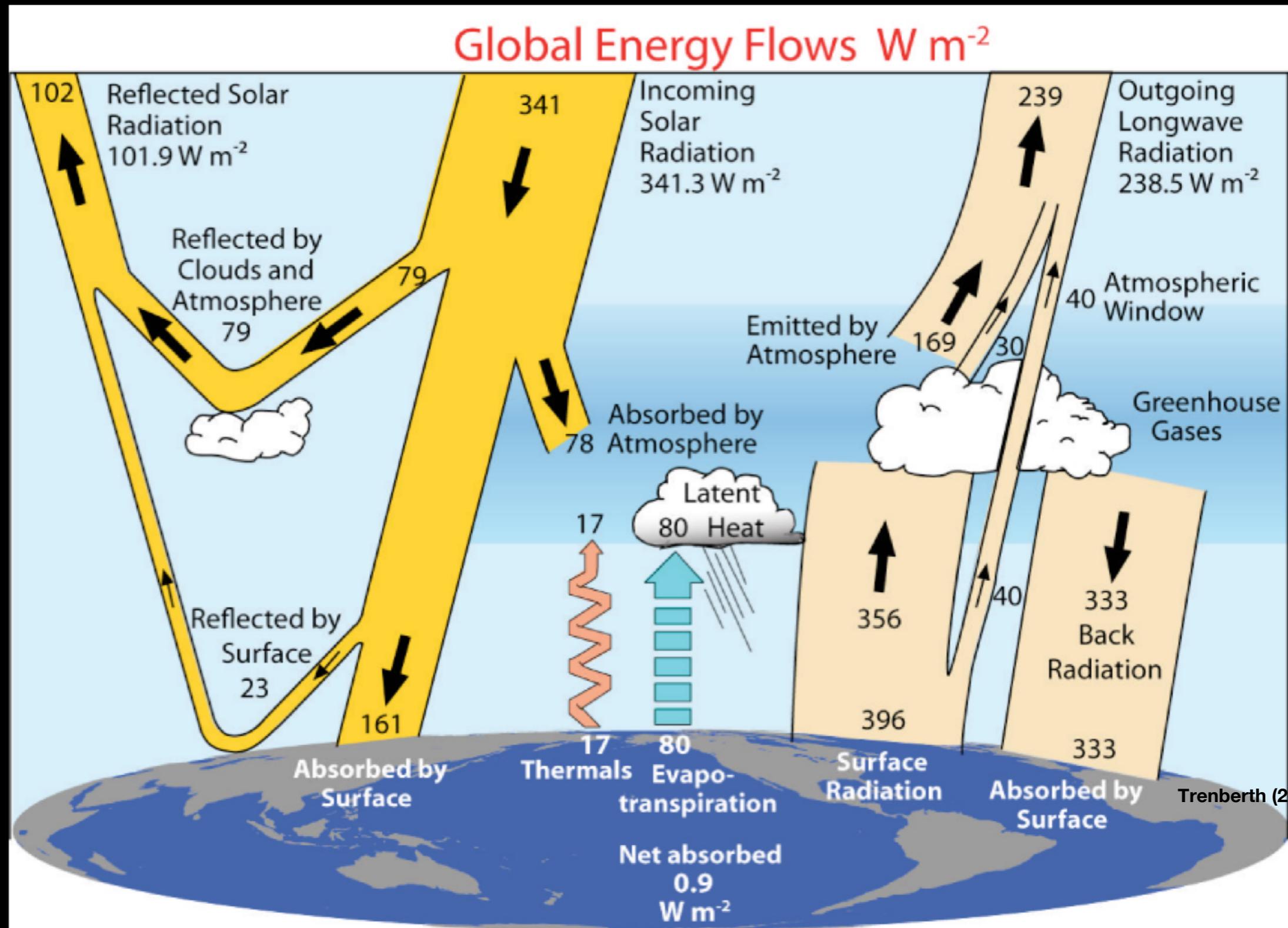
Come studiamo la Fisica della Terra (fluida)?



i Fluidi Geofisici sono un sistema molto complesso



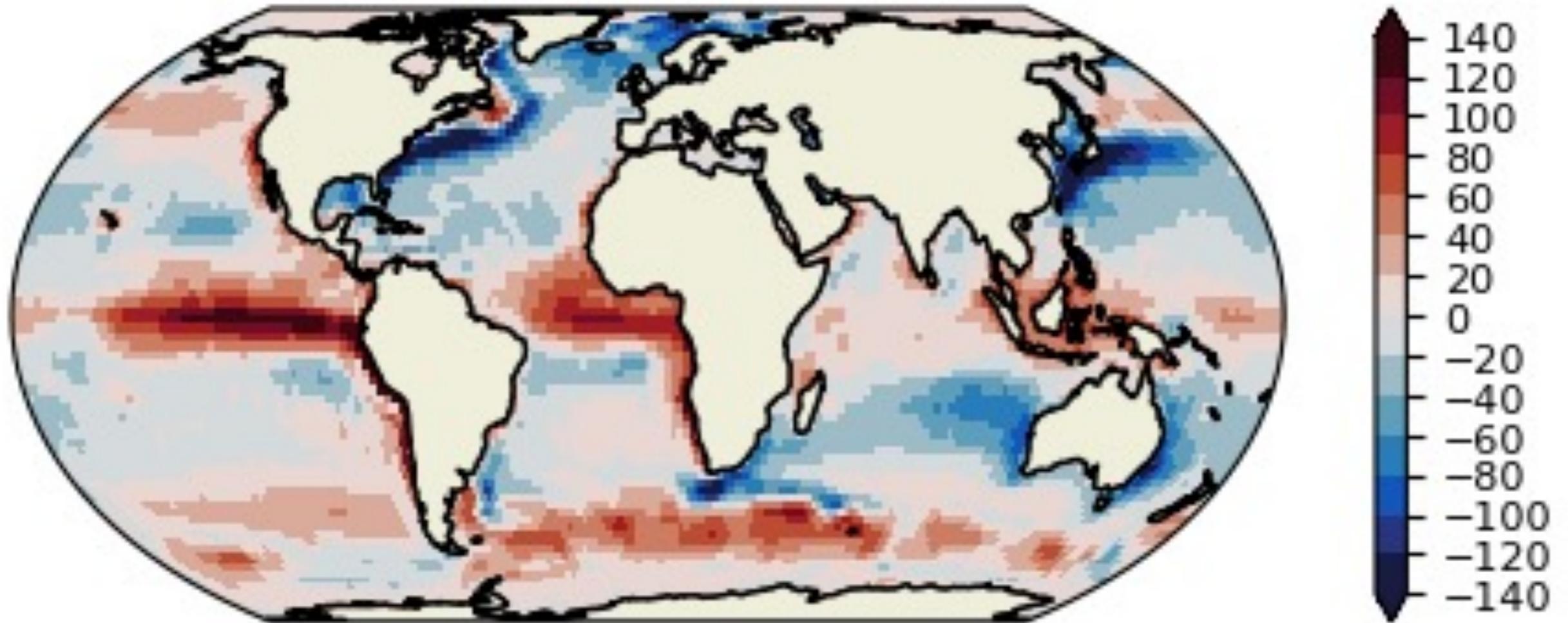
Bilancio energetico della Terra



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

Net Heat Flux [W/m^2]



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 : $H_{\text{solar}} + H_{\text{long}}$

The radiative heating into the ocean is offset by 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.

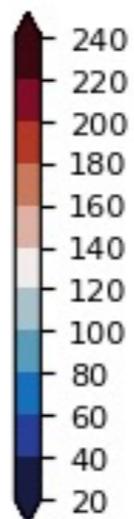
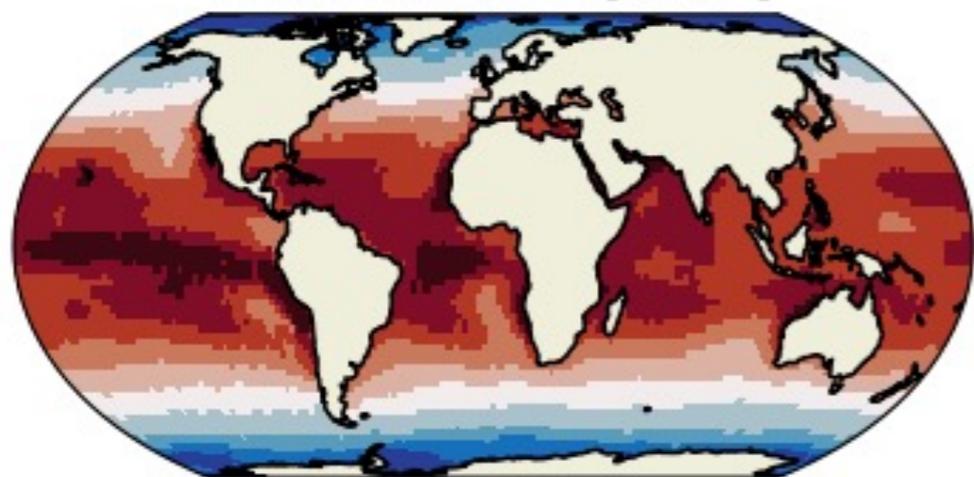
H_{latent} : turbulent transfer of evaporated water, and heat is used to enable the phase change from liquid to vapour.

The latent exchange nearly always dominates over the sensible exchange.

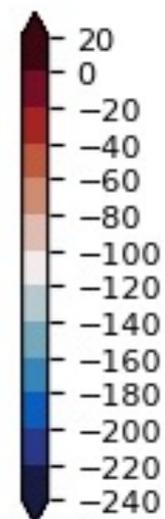
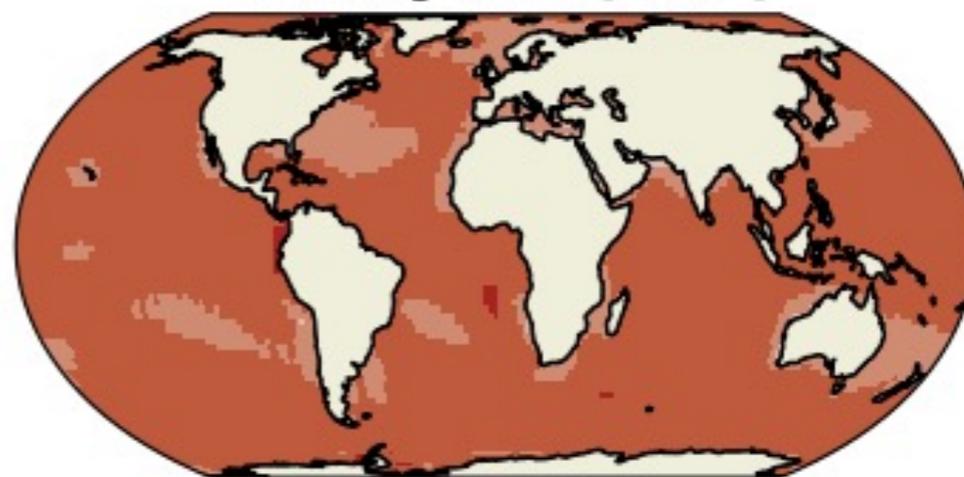
There is no local heat balance and the temperature change over a surface mixed layer is

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

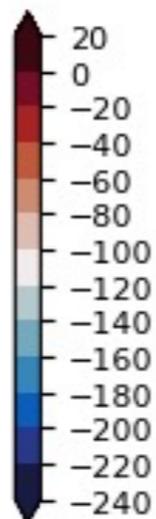
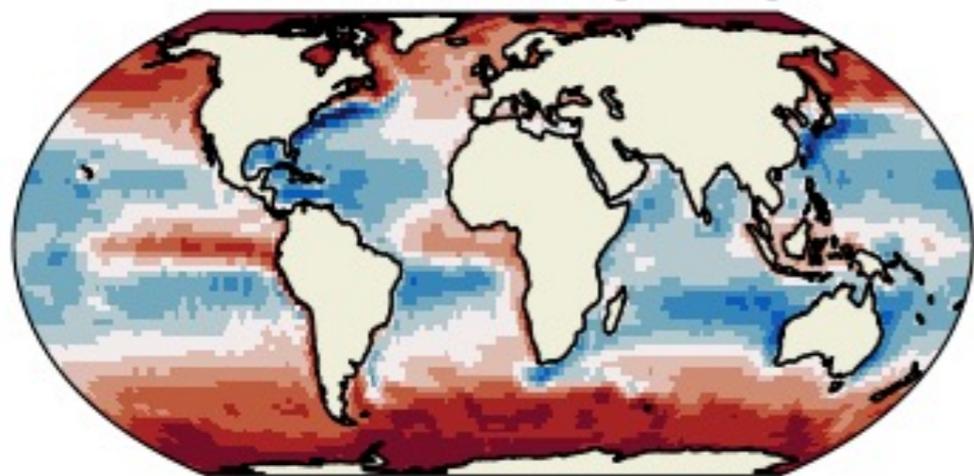
Net Short Wave [W/m^2]



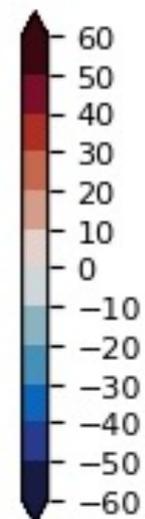
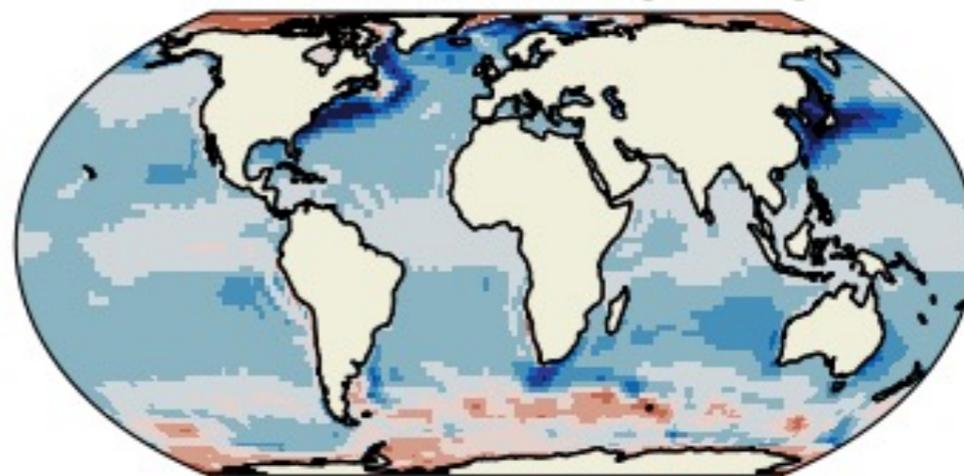
Net Long Wave [W/m^2]



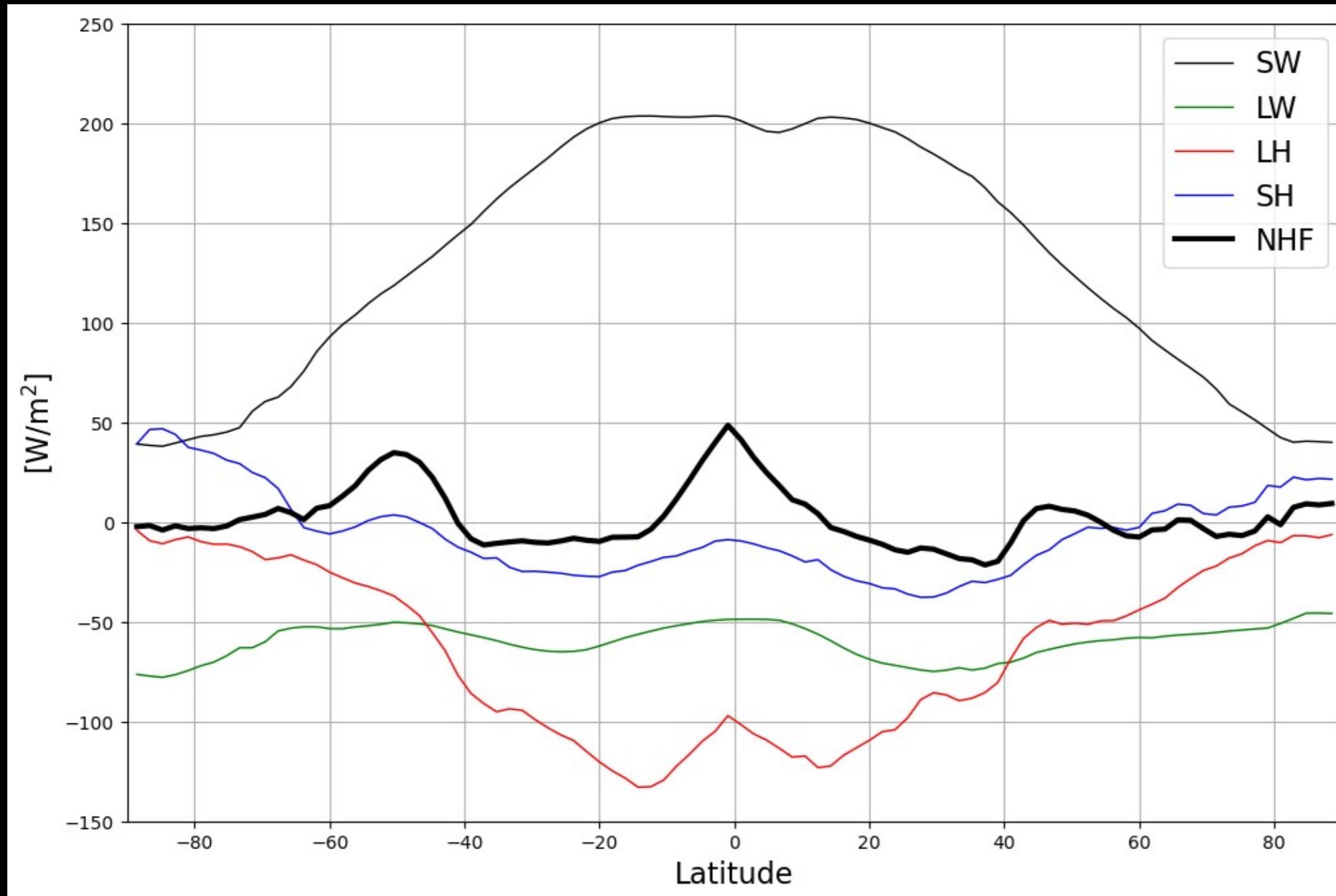
Latent Heat Flux [W/m^2]



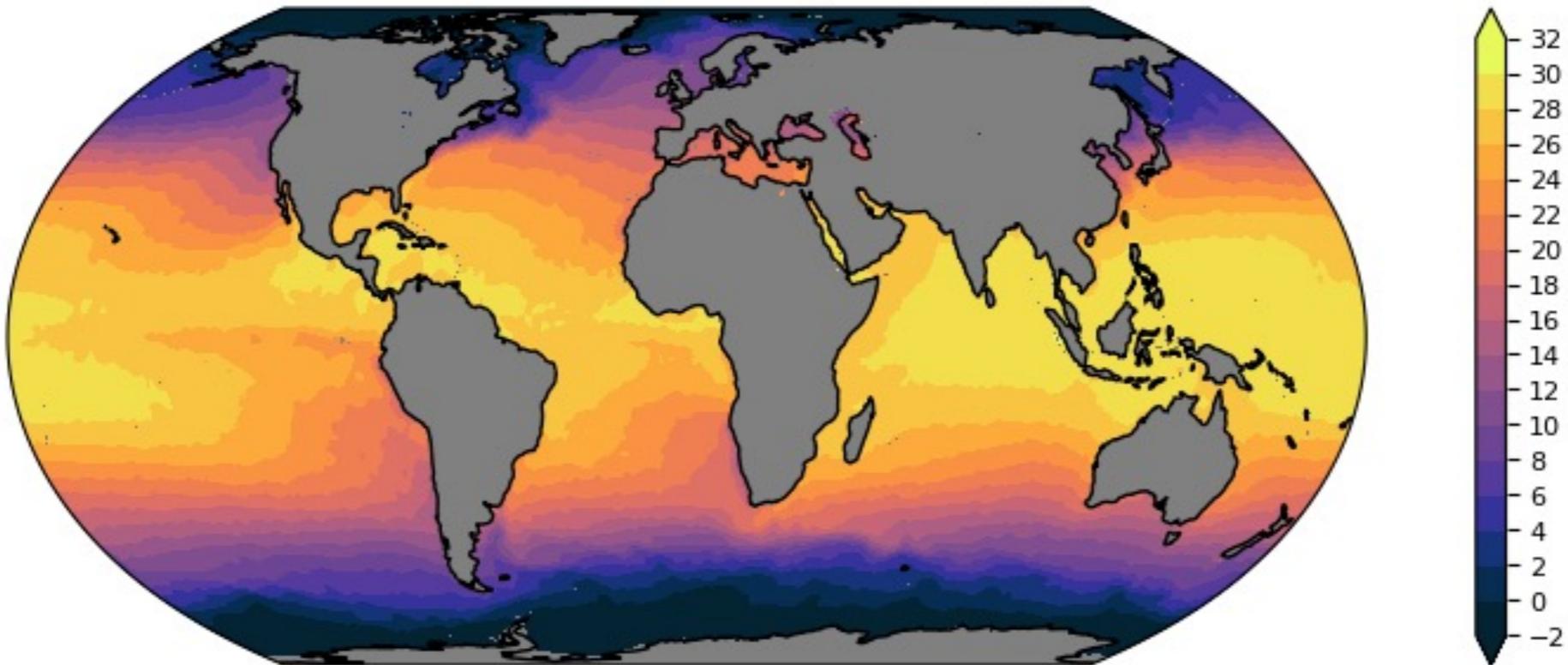
Sensible Heat Flux [W/m^2]



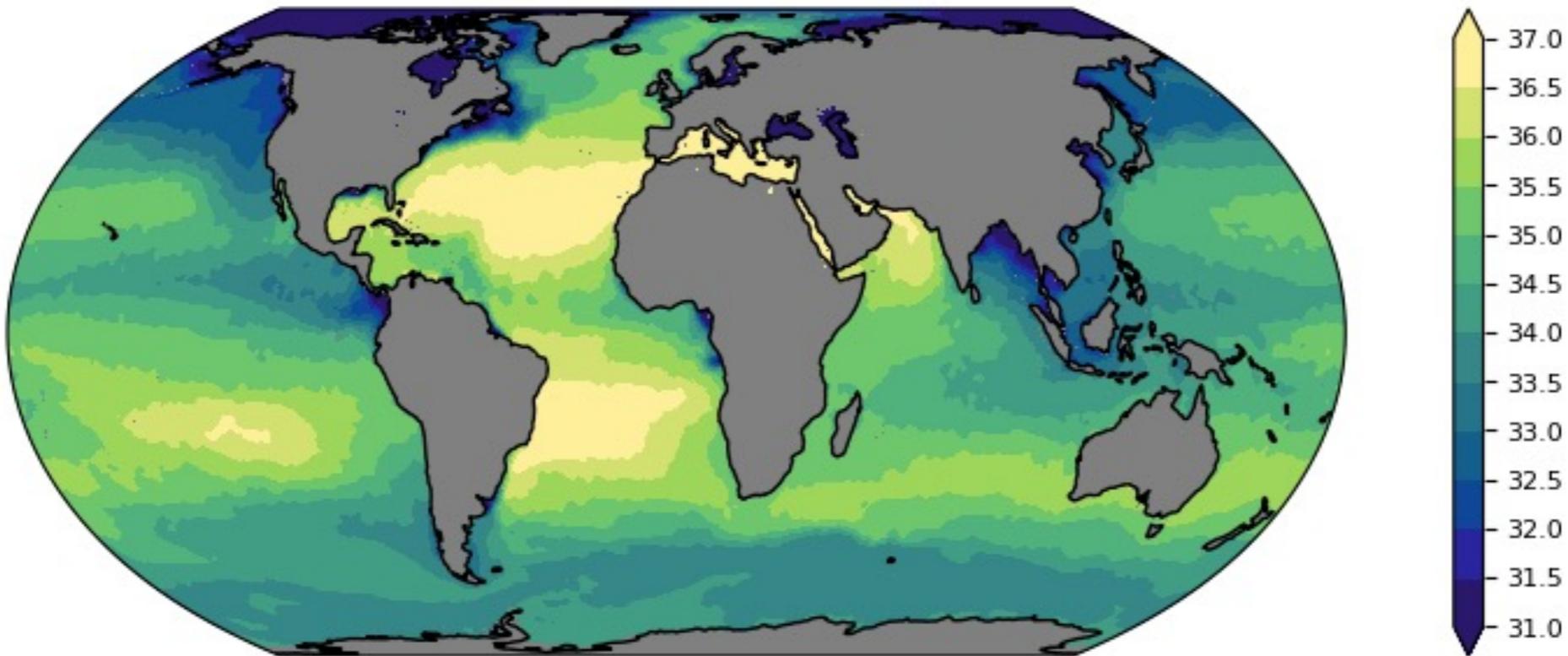
Zonal-mean heat flux components

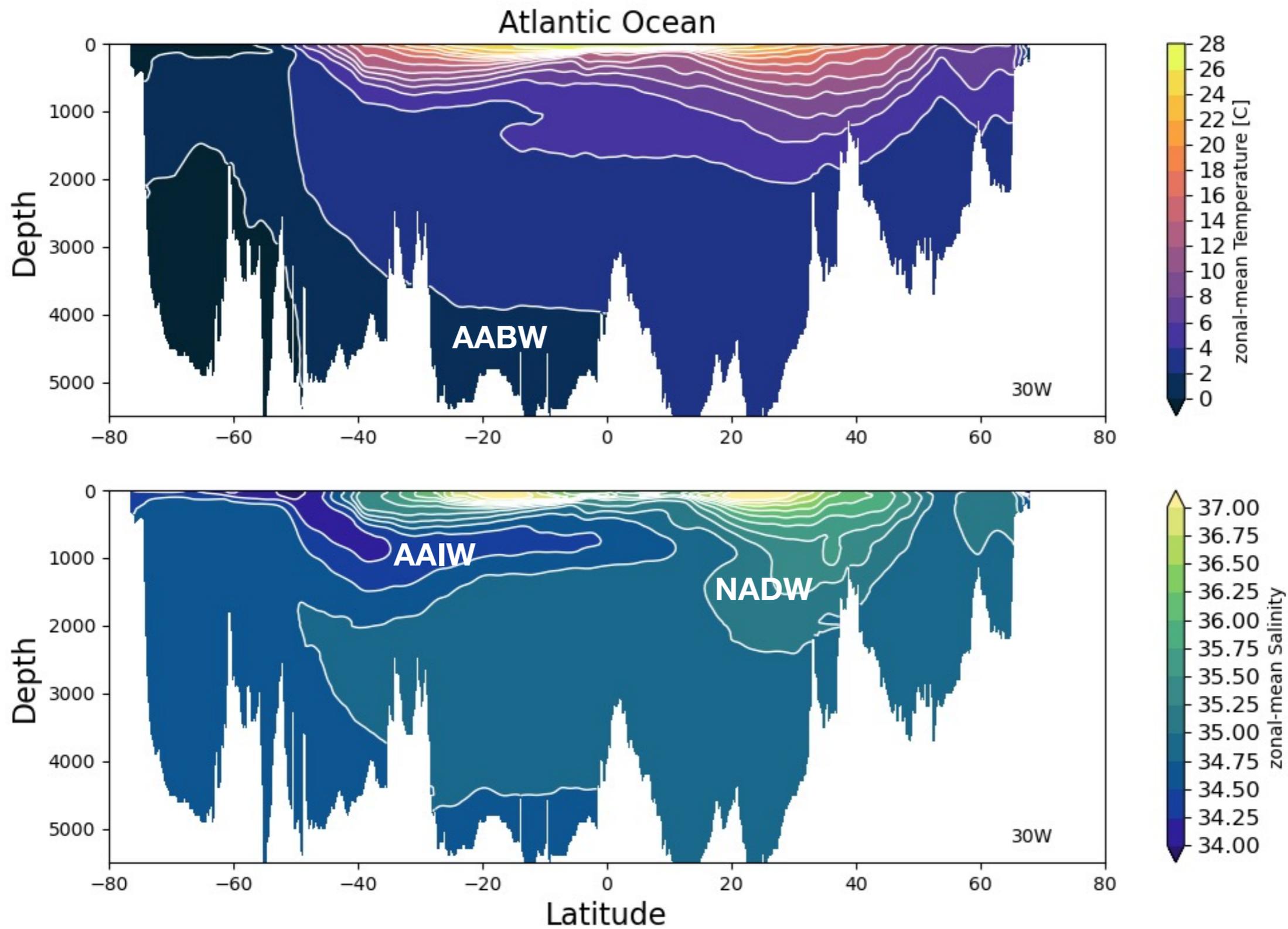


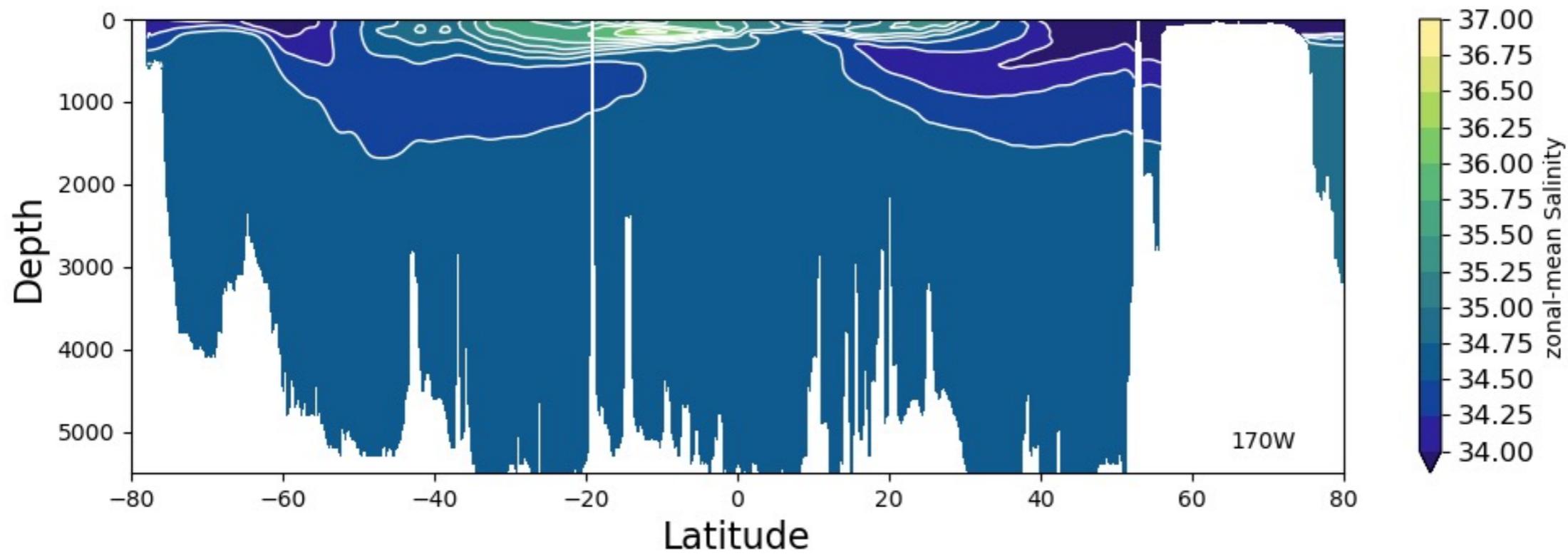
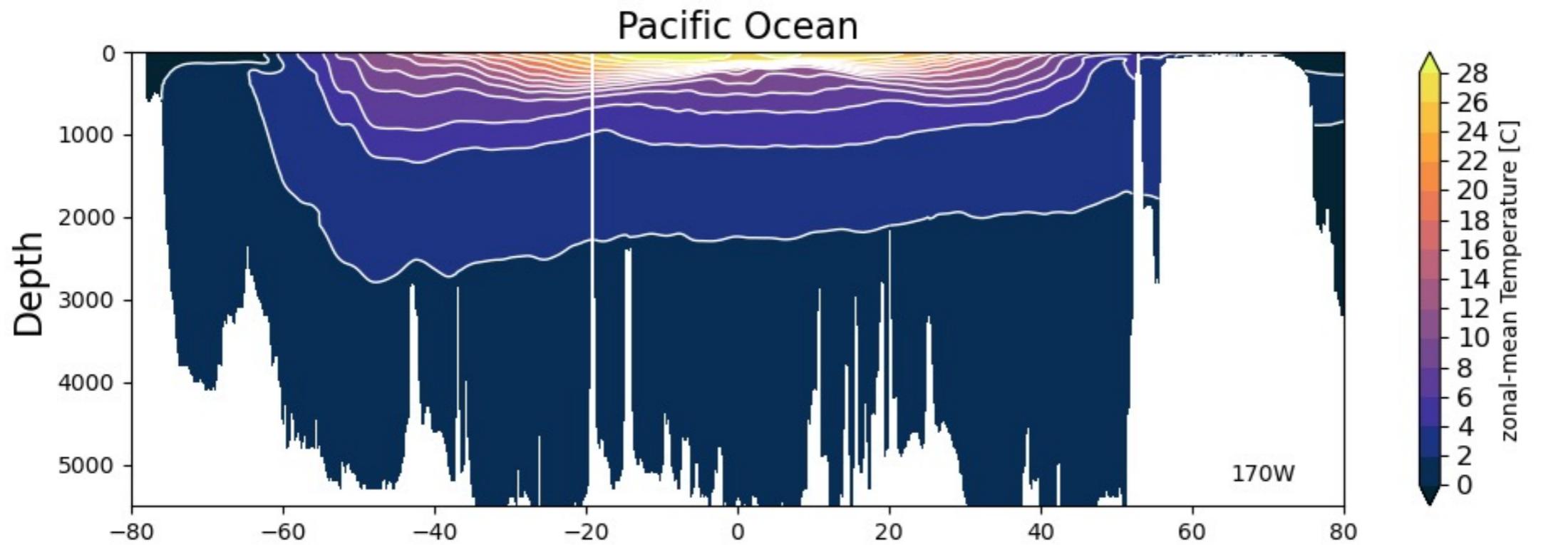
WOA13 Sea Surface Temperature [C]



WOA13 Sea Surface Salinity







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 / (time)²

mks: 1 Newton = 1 kg m / sec²

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

1 dbar = 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 force is upward due to higher pressure below and lower pressure above

$$\text{PGF} = - (\Delta \text{pressure} / \Delta \text{depth}) = - (\Delta p / \Delta z)$$

Gravitational force per unit volume is downward = ρg

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

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*”.

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

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

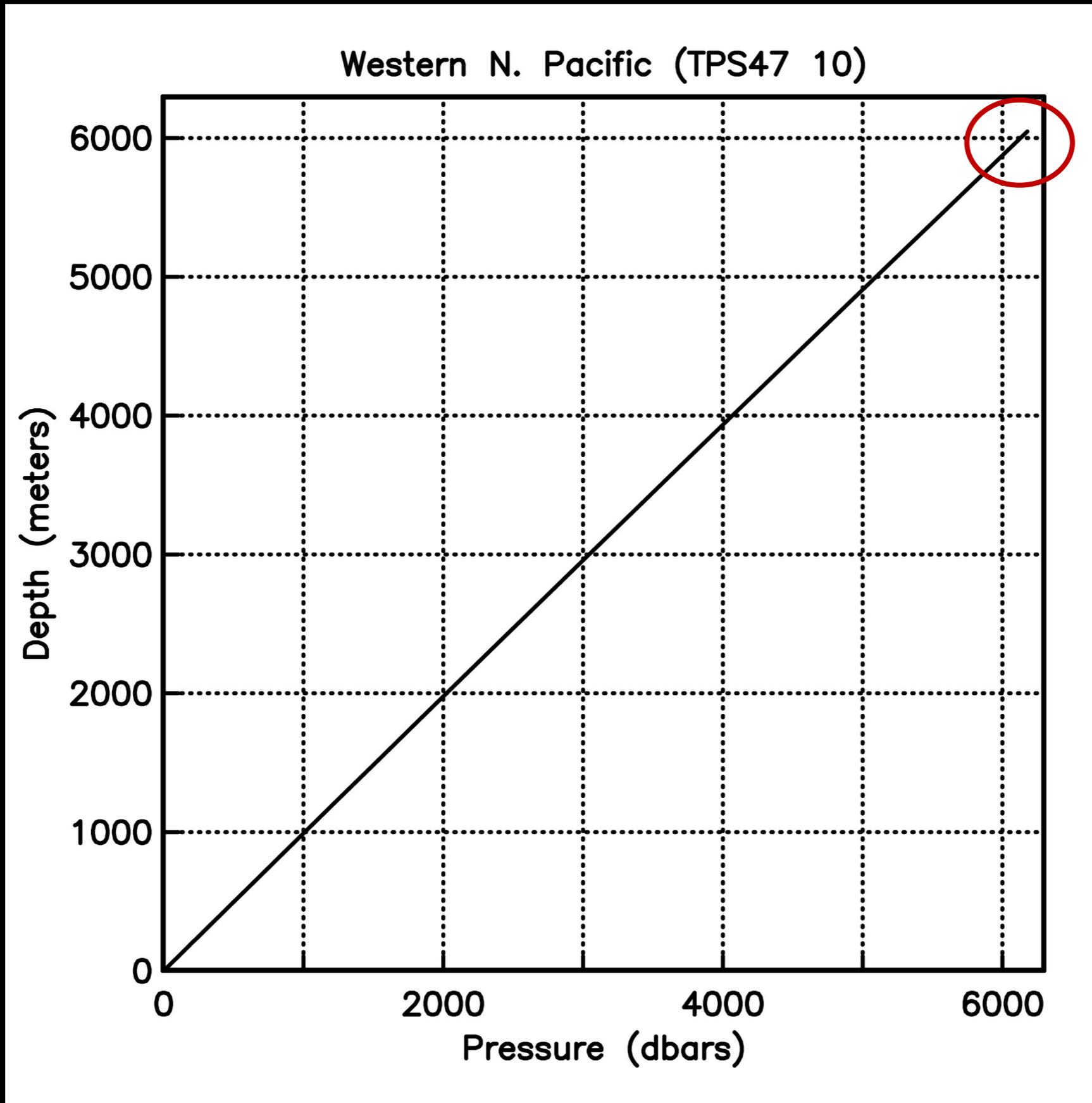
We can then solve for the change in pressure for a given change in depth.

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)
- $T_K = T_C + 273.16^{\circ}$
- Ocean temperature range: freezing point to about 30° or 31° C
- (Freezing point is $< 0^{\circ}$ C because of salt content)

Heat

Energy: 1 Joule = 1 kg m² / sec²

Heat is energy, so units are Joules

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

Q = total amount of heat

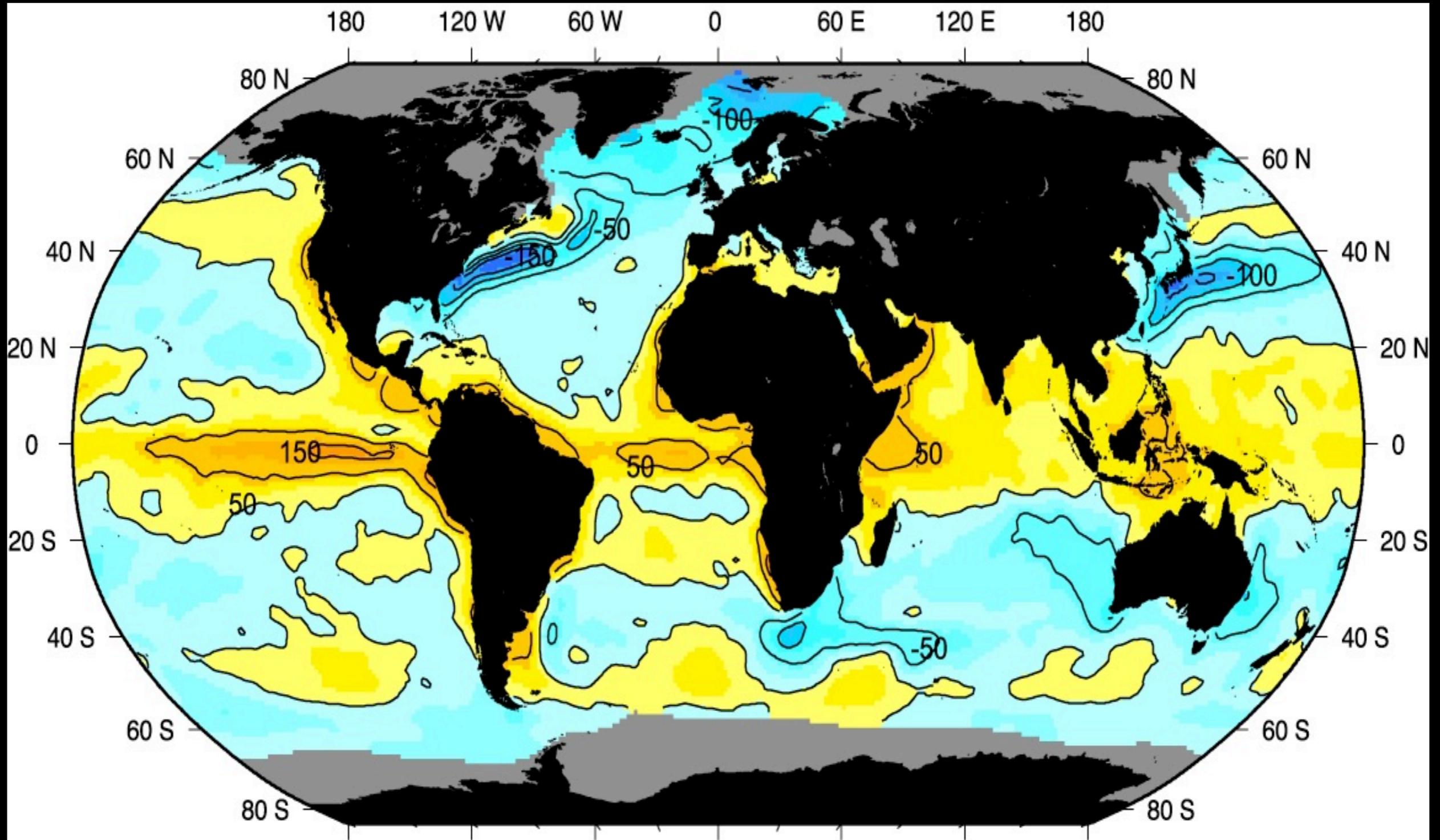
dQ/dT = C_p where C_p is heat capacity

q = heat per unit volume = Q/V, units are J/m³

dq/dT = ρ c_p where c_p is specific heat = C_p/mass

For seawater, c_p ~ 3850 J/kg ° C and ρ ~ 1025 kg/m³

Surface heat flux (W/m^2) 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 that is due solely to pressure is called the “*adiabatic lapse rate*”

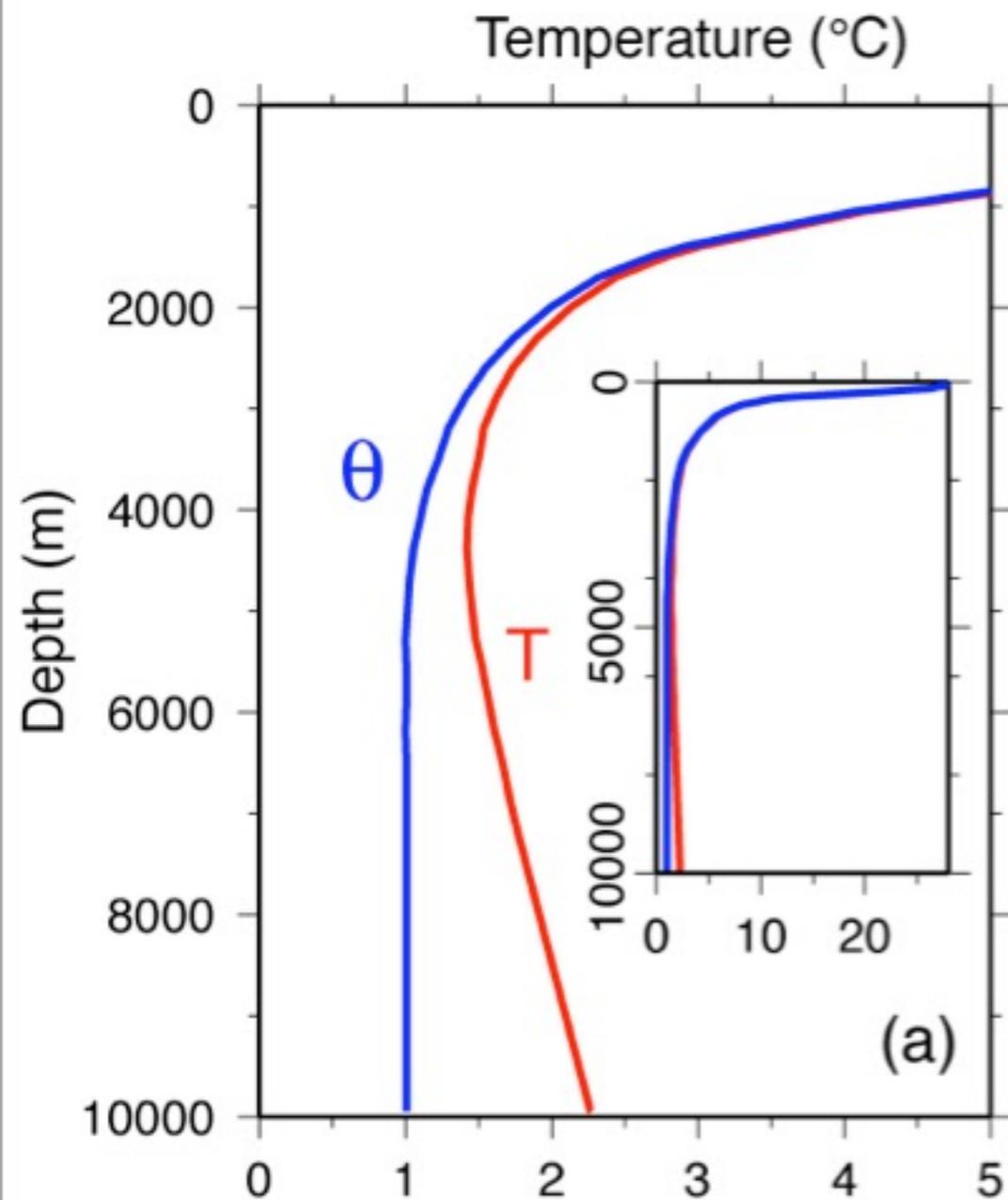
In the atmosphere, the adiabatic lapse rate is 6.5° C per 1000 m altitude.

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)**

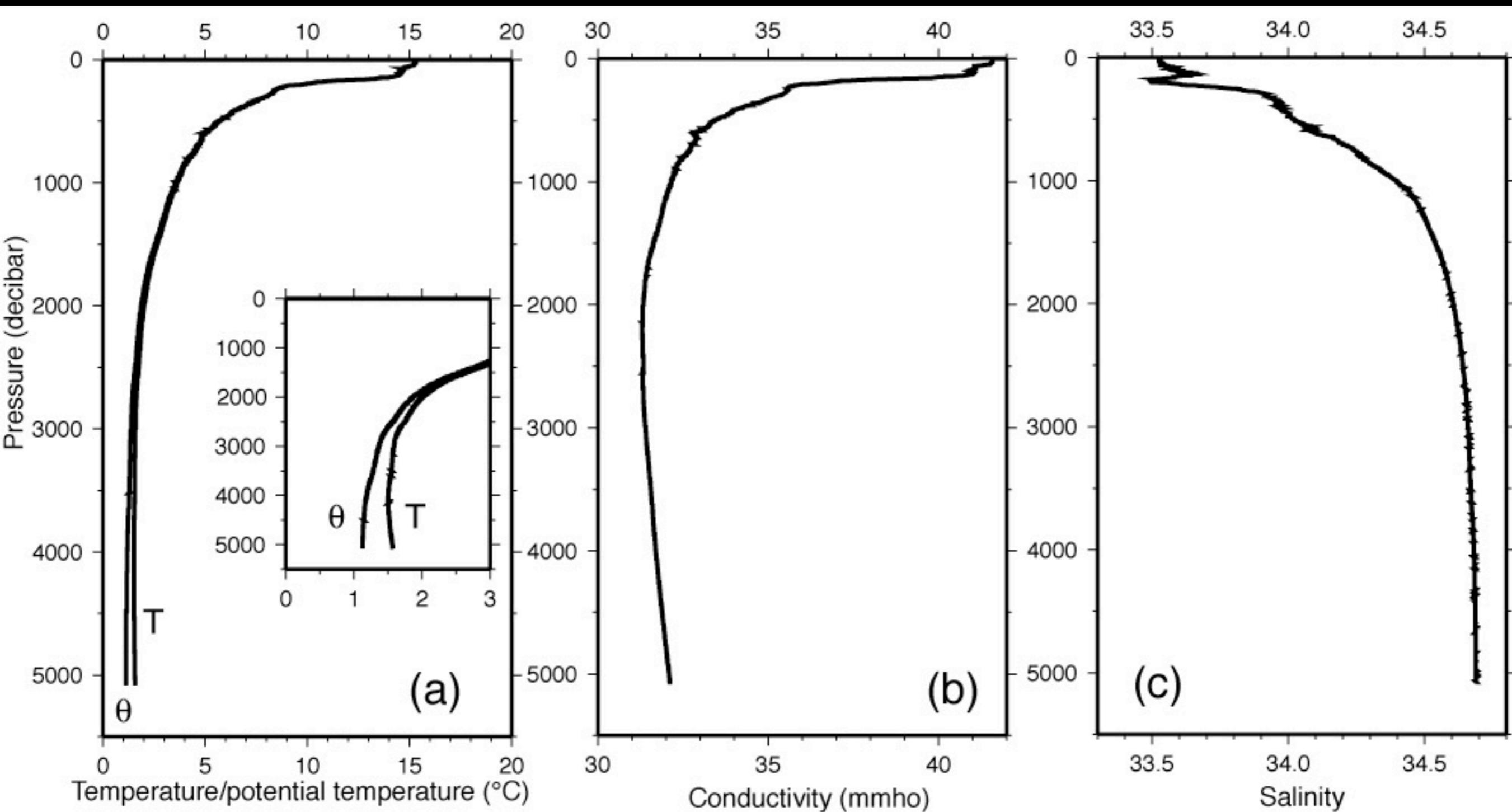
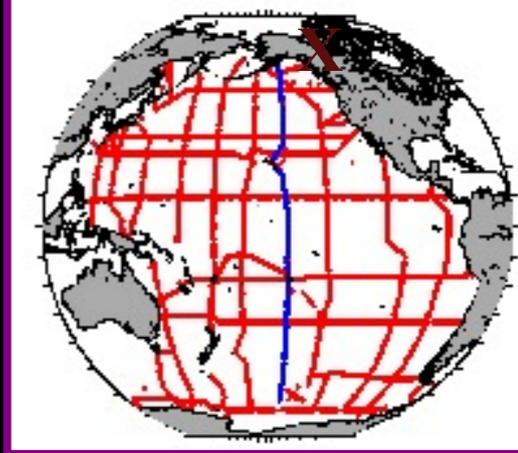
- **Measurements:**

- Oldest: evaporate the seawater and weigh the salts**

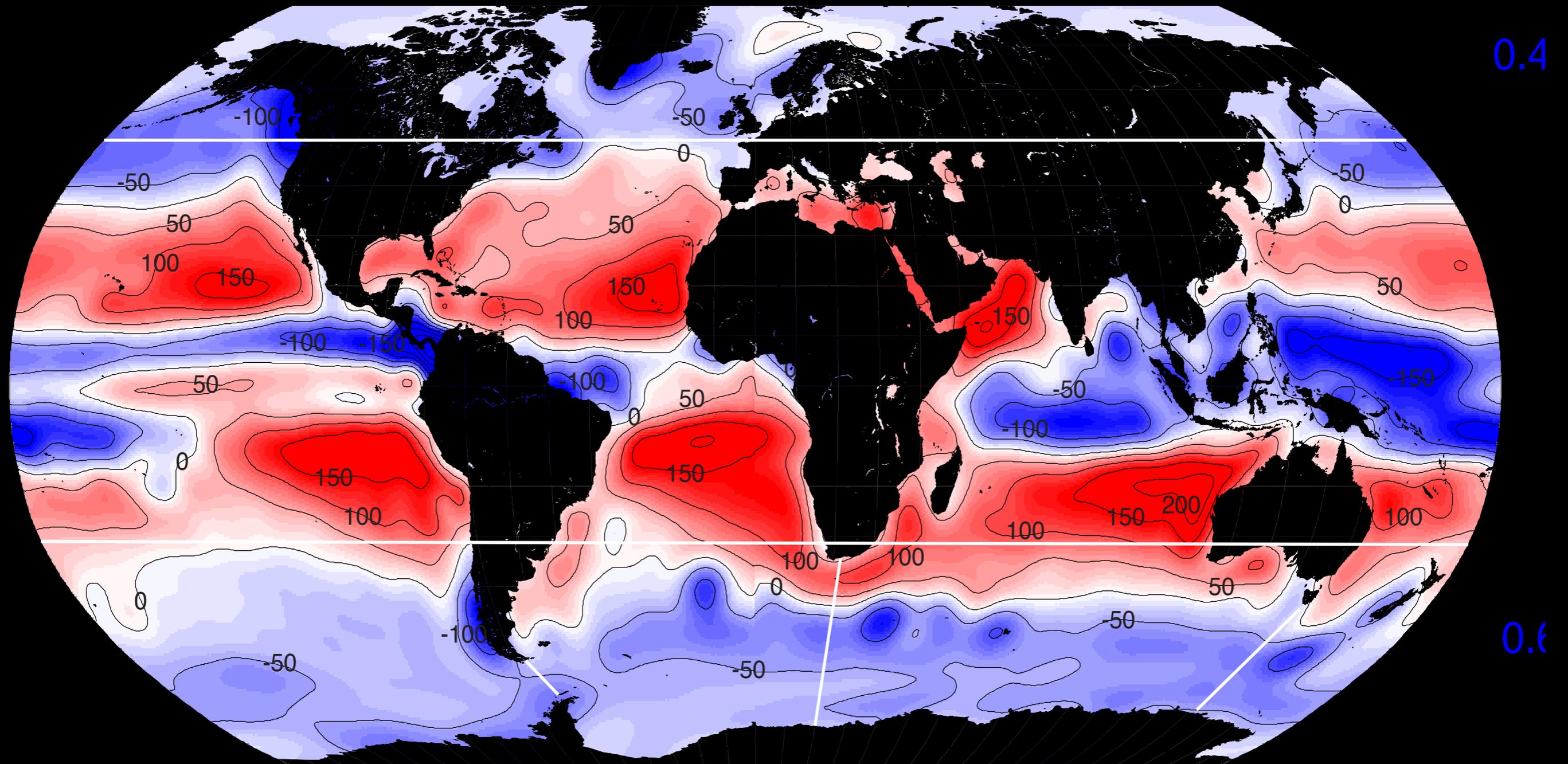
- Old: titration method to determine the amount of chlorine, bromine and iodine (prior to 1957)**

- 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



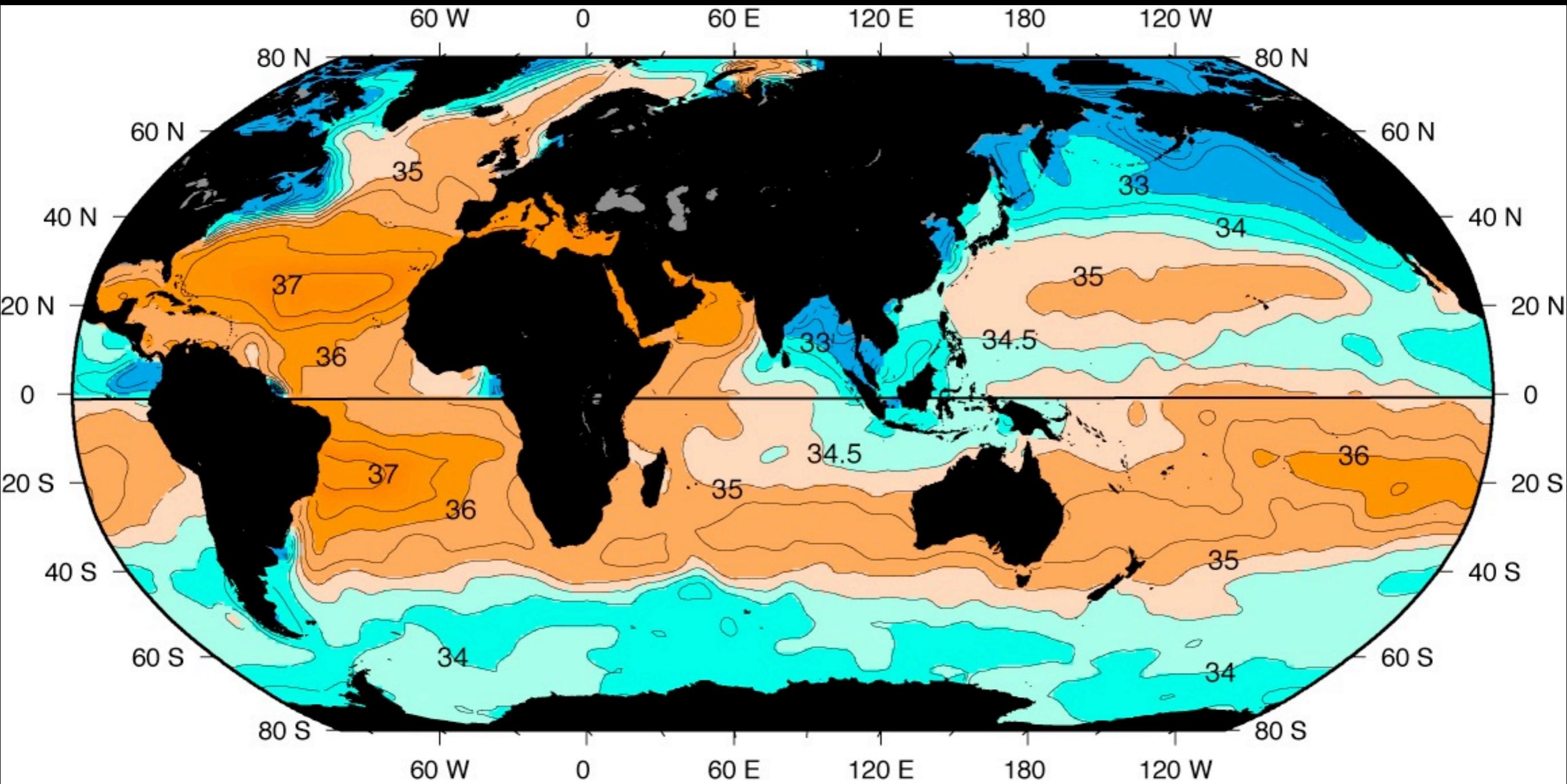
What sets salinity? Precipitation + runoff minus evaporation (cm/yr)



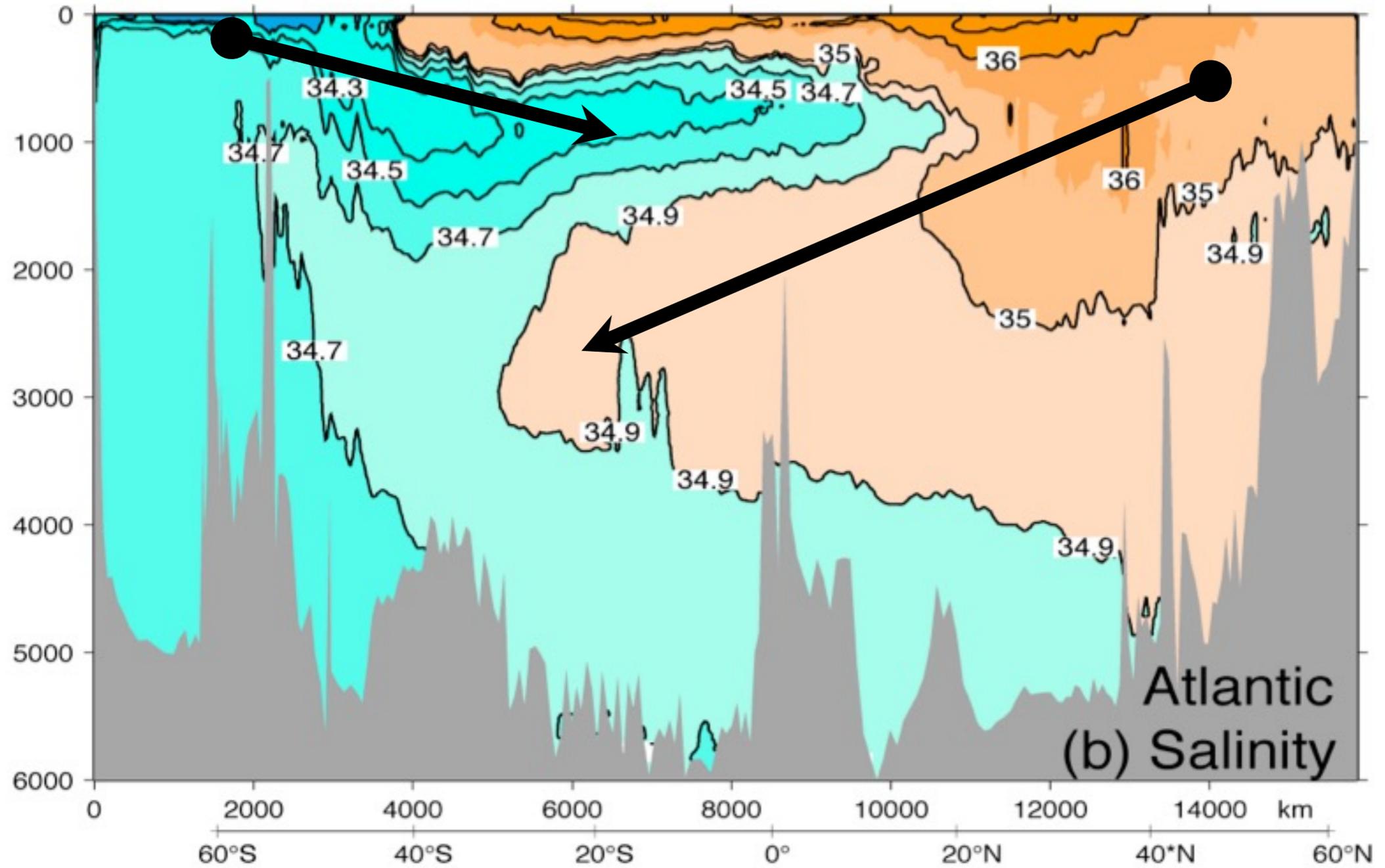
Salinity is set by freshwater inputs and exports since the total amount of salt in the ocean is constant, except on the longest geological timescales

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)

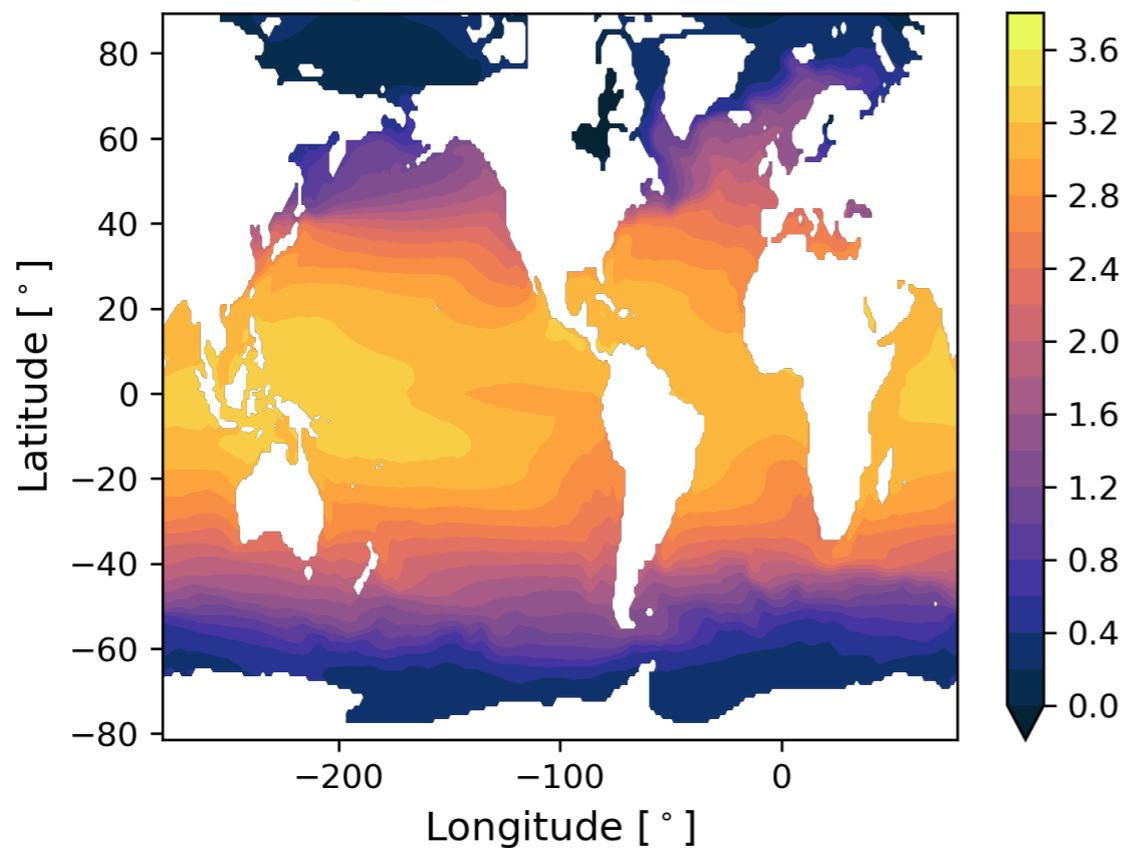
- When water warms, it expands, and its density decreases. We measure thermal expansion α as the relative change in density with respect to conservative temperature when pressure and salinity are held fixed
- When water gains salt, its density increases. We measure this with the haline contraction β coefficient
 - A linear Equation of State

$$\rho = \rho_0 (-\alpha \delta T + \beta \delta S)$$

- 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

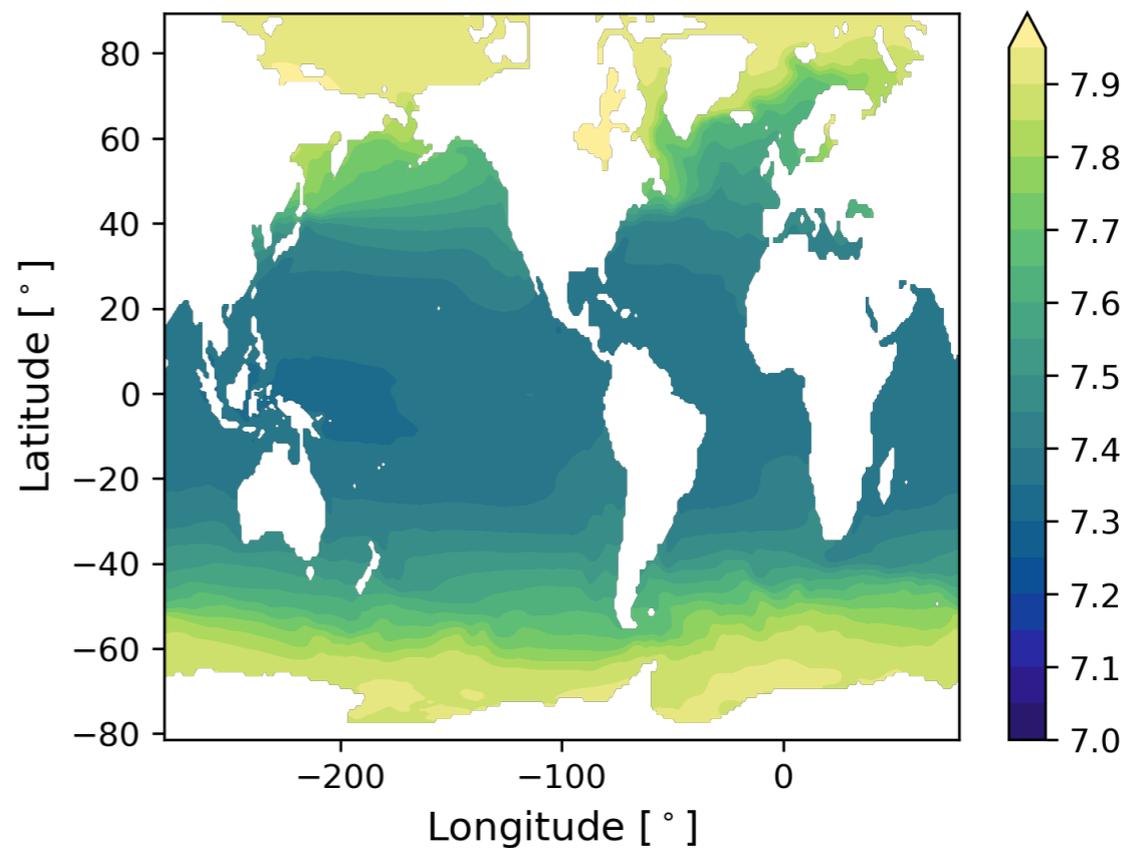
$$\alpha = \rho^{-1} \partial_{\theta} \rho$$

Thermal expansion at ocean surface [10^{-4} C^{-1}]

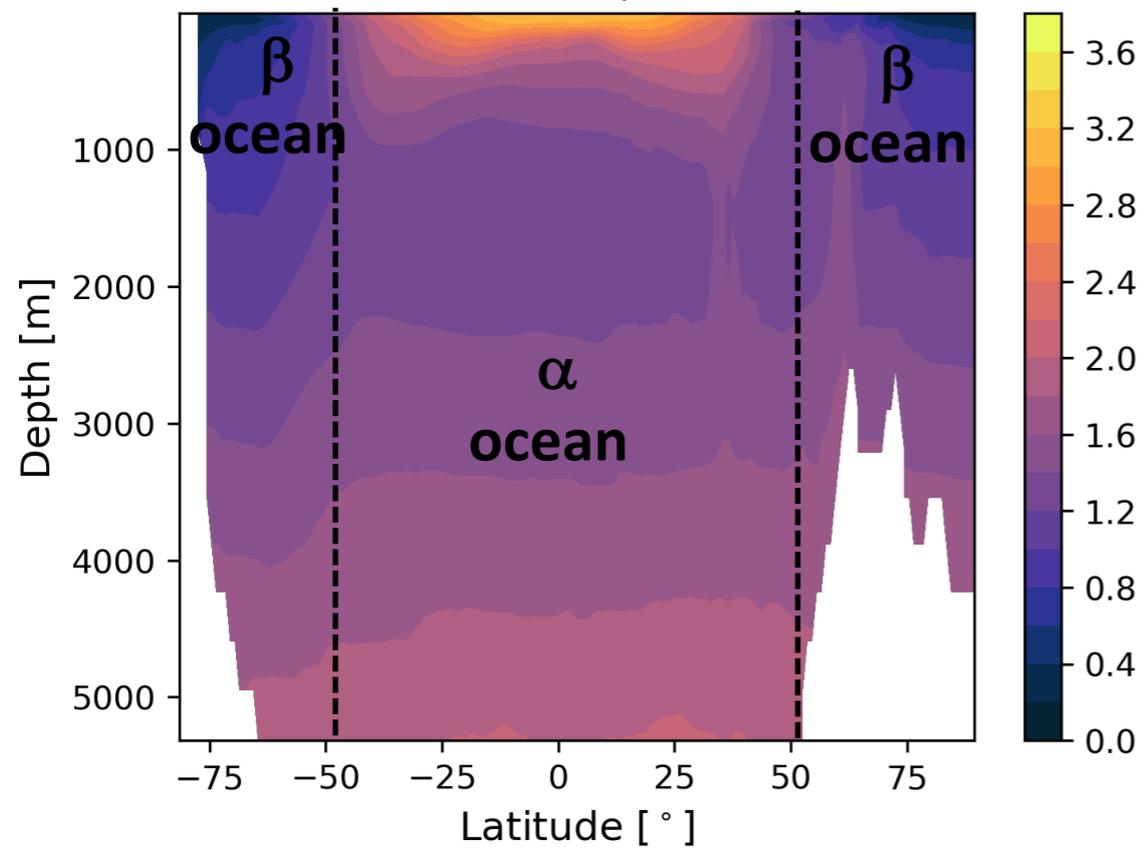


$$\beta = \rho^{-1} \partial_S \rho$$

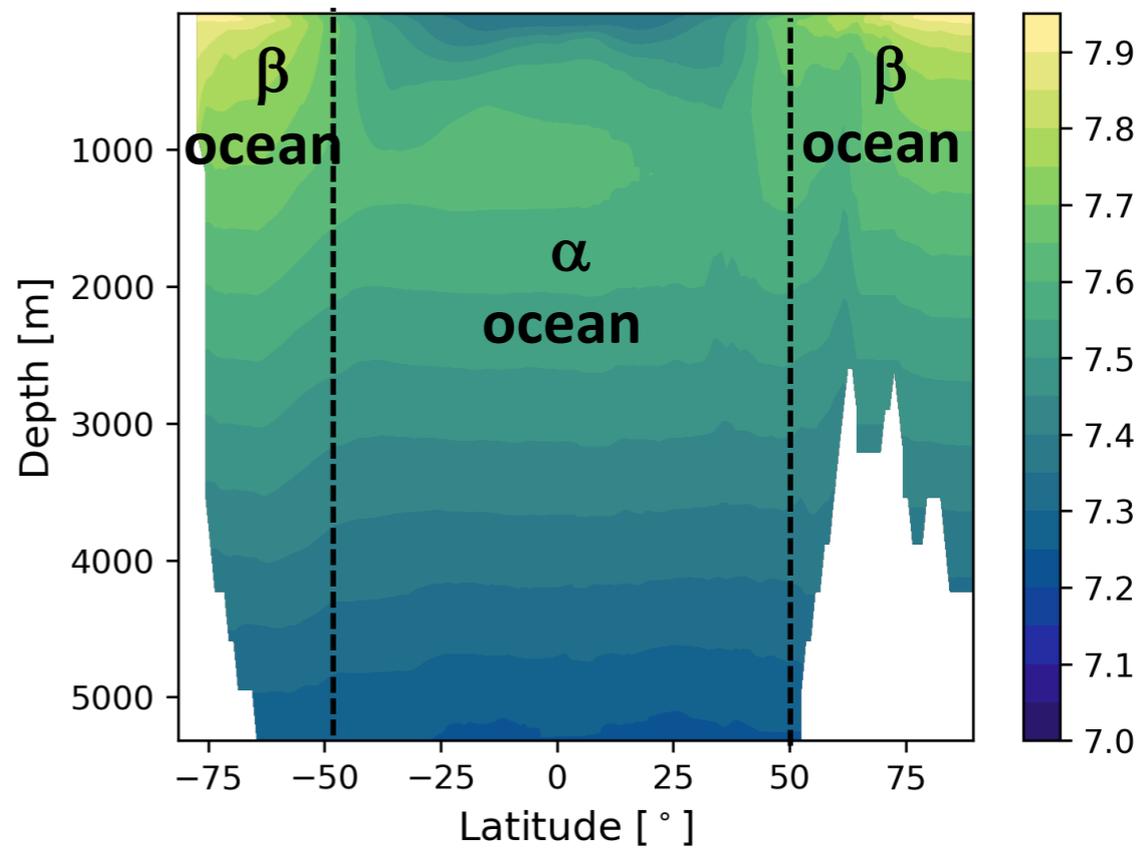
Haline contraction at ocean surface [10^{-4} PSU^{-1}]



Zonal mean Thermal expansion [10^{-4} C^{-1}]



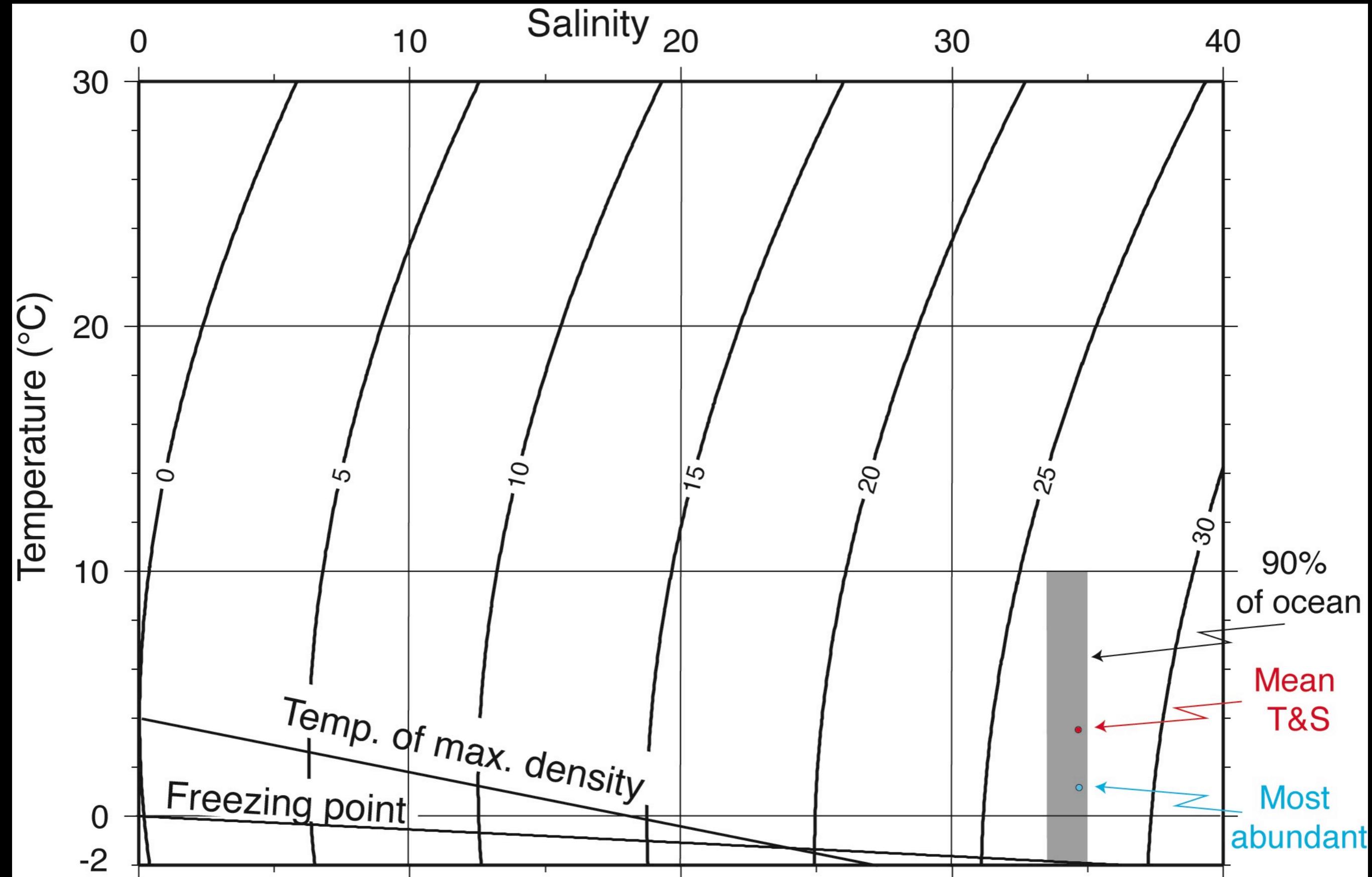
Zonal mean Haline contraction [10^{-4} PSU^{-1}]



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

Seawater density, freezing point



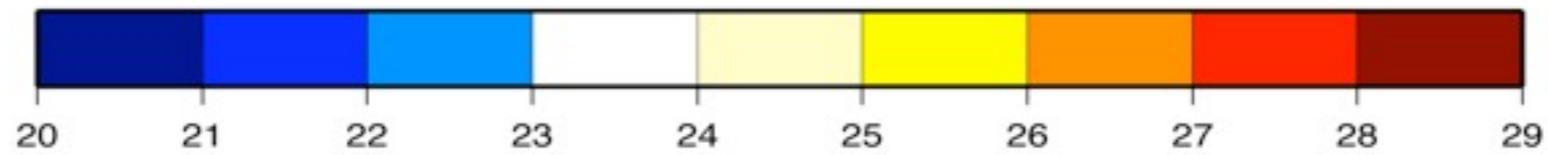
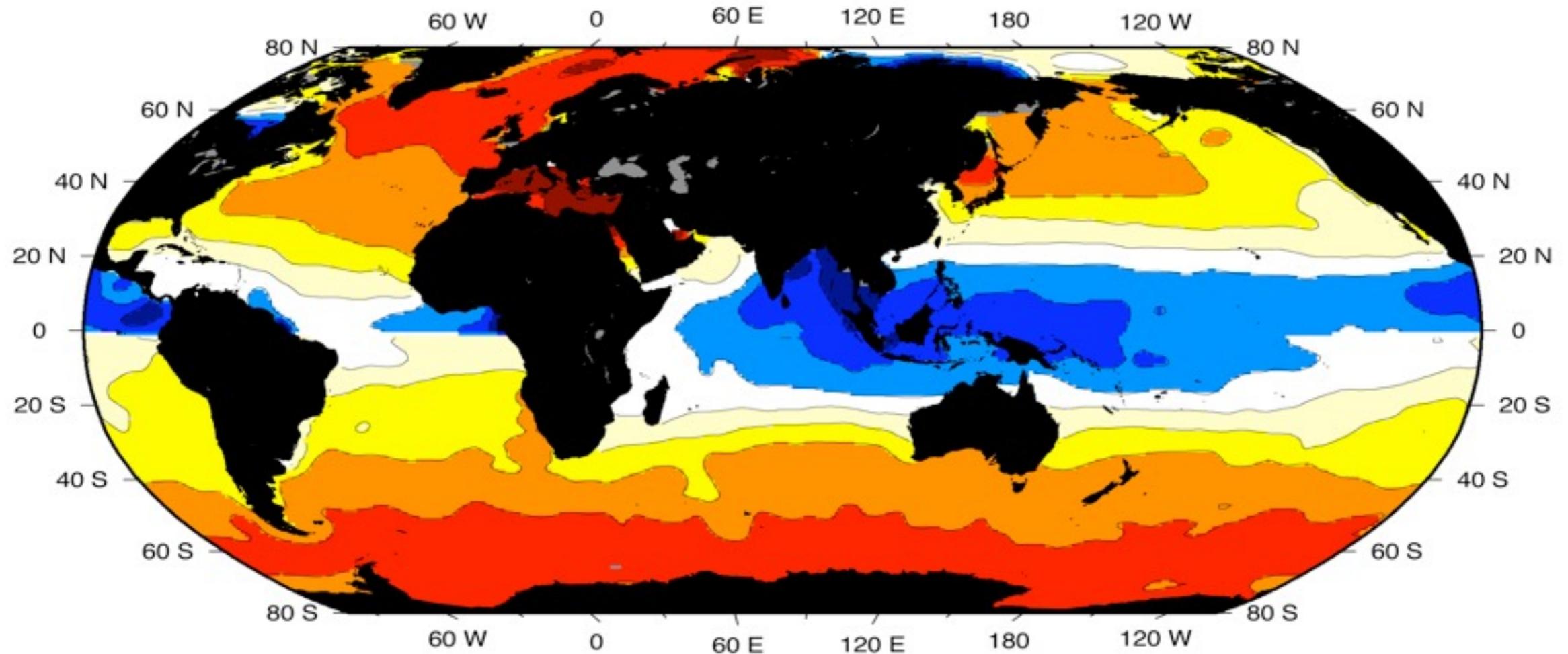
Digression to freezing point and sea ice

- 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 $\sim 3-4$ 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 one of the main mechanisms for forming the densest waters of the world ocean.**

Surface density (winter)



Surface density (JFM)

Temperature profiles: definitions

