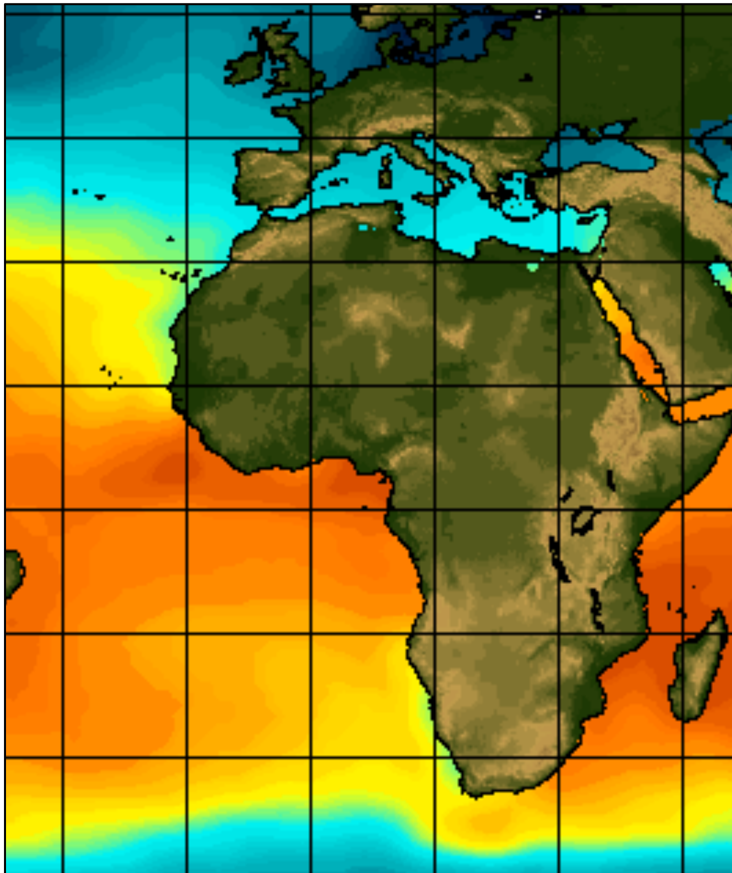
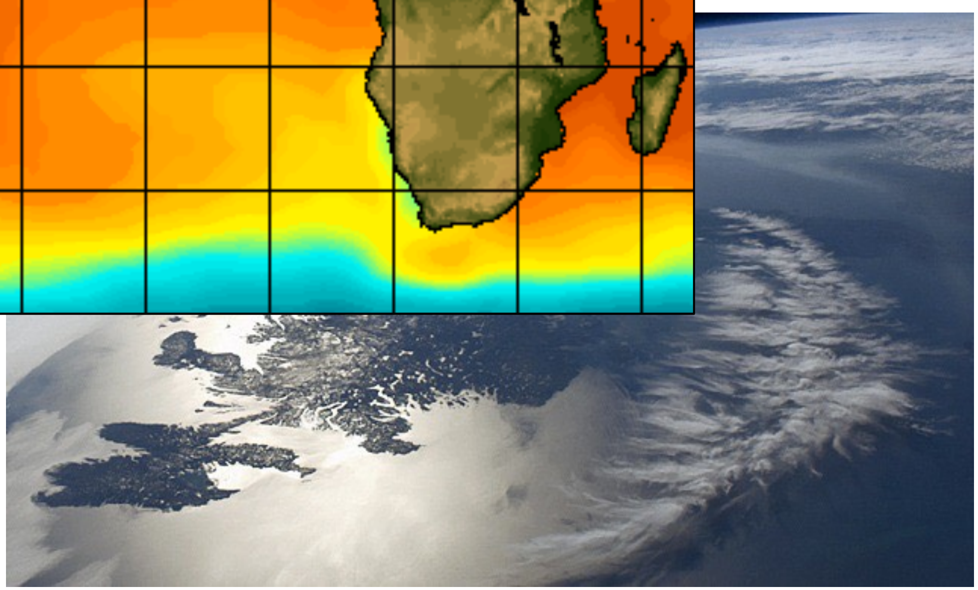
Department of Physics
University of Athens

1. Οι φυσικές ιδιότητες του θαλασσινού νερού και η κατανομή τους

1. Seawater properties





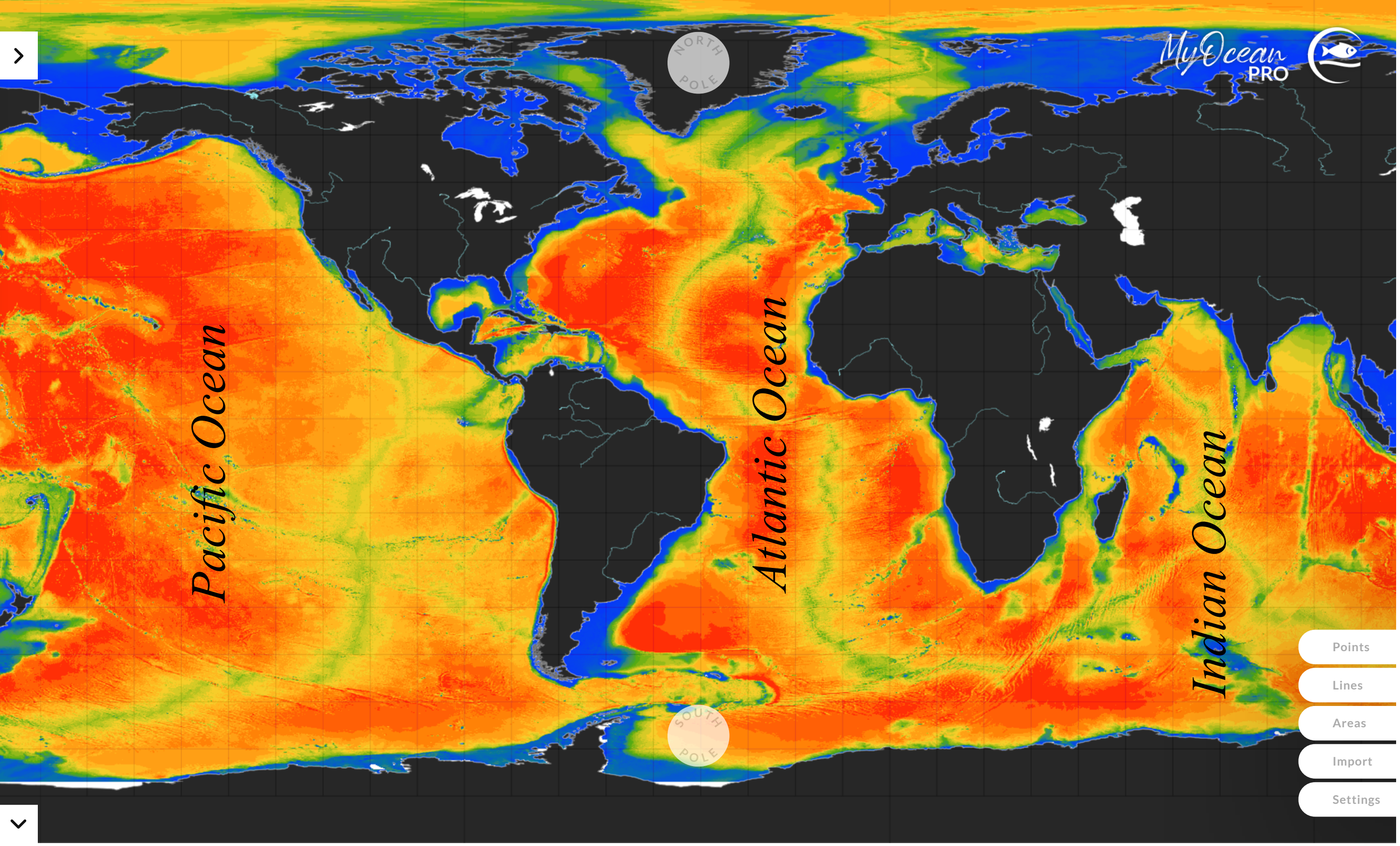
a. The physical characteristics of seawater:

- Αλατότητα - Salinity
- Θερμοκρασία -Temperature
- Πίεση - Pressure
- Πυκνότητα - Density

b. Στρωμάτωση - Stratification

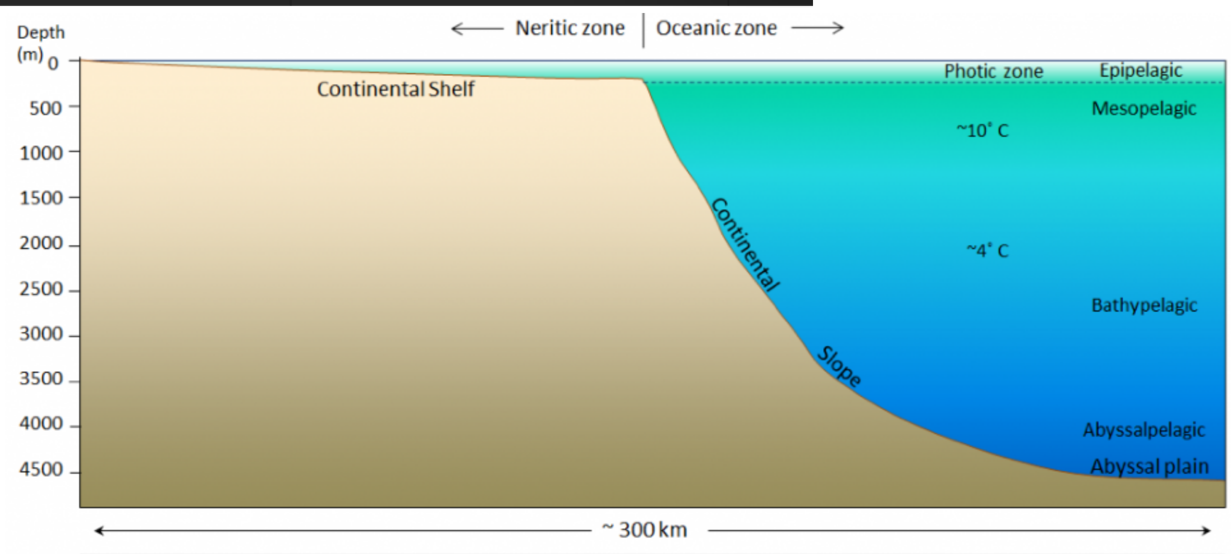
c. Υδάτινες Μάζες - Water masses in the ocean

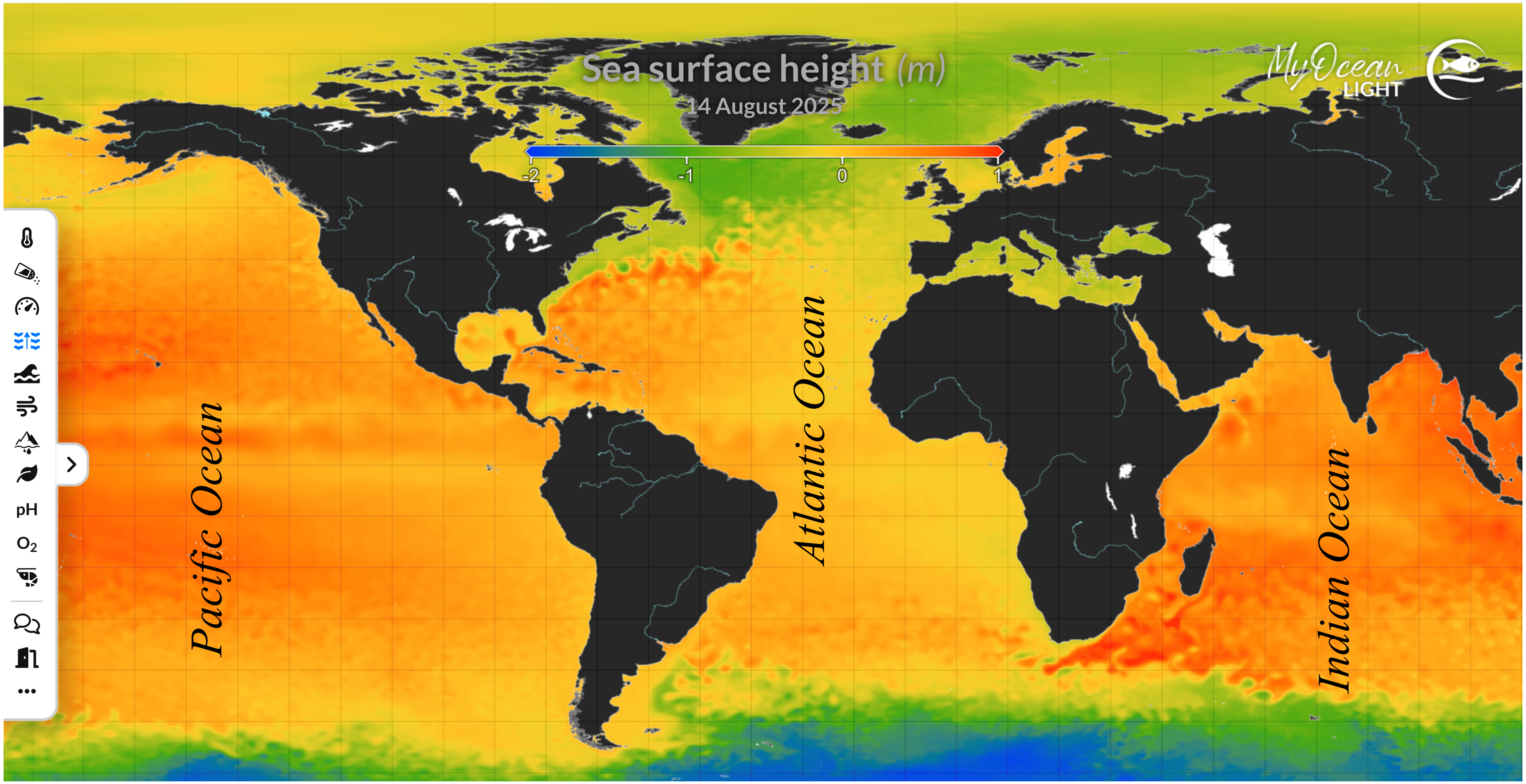
Σ. Σοφιανός & Β. Βερβάτης



Ocean Bottom Topography

Sea floor topography definitions





Oceans
1,350.0 x 10^{15} m^3

Land
33.6 x 10^{15} m^3

ATMOSPHERE
0.013 x 10^{15} m^3

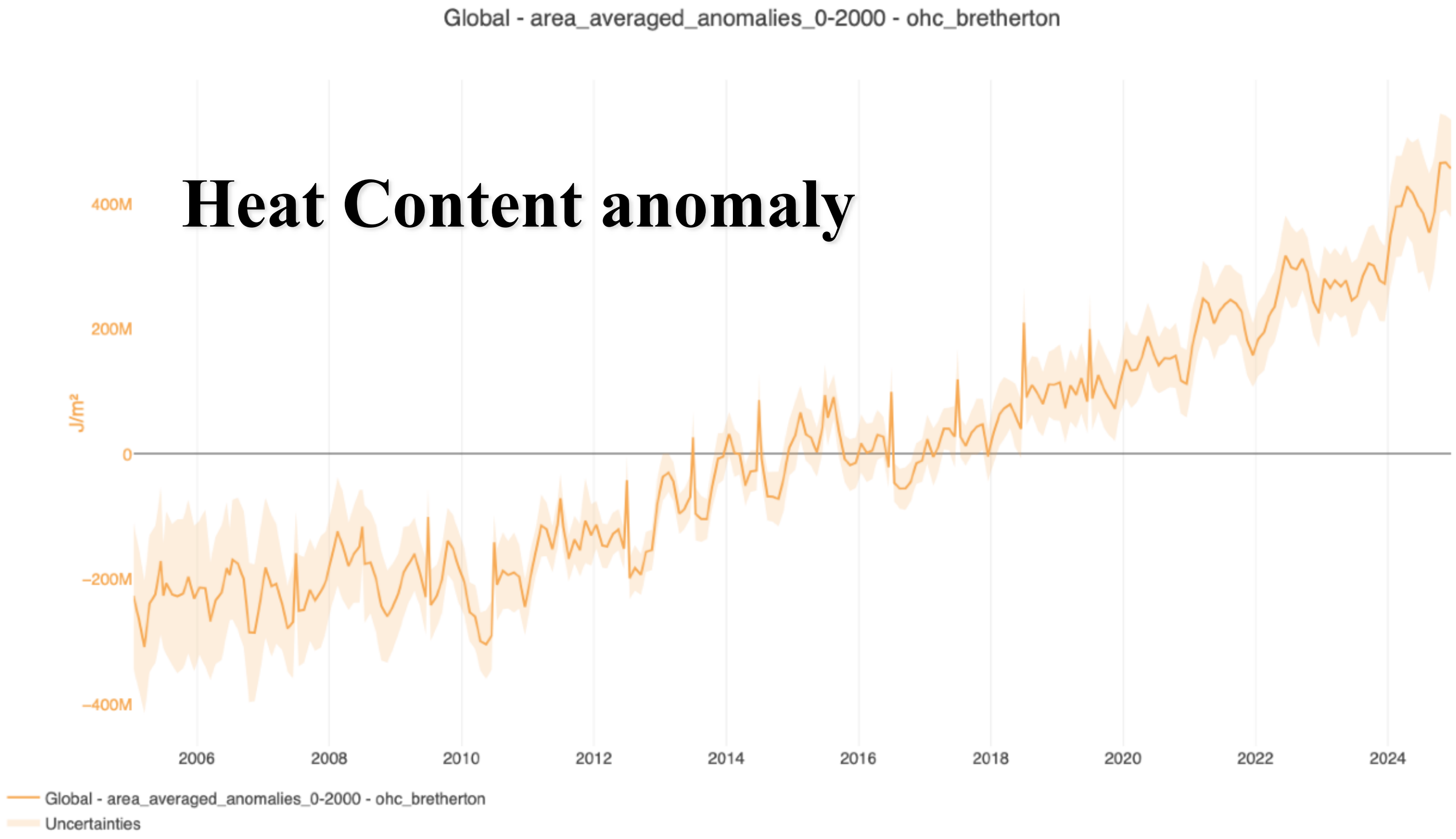
WATER: PHYSICAL PROPERTIES

Property	Comparison with other substances	Importance in physical–biological environment
Heat capacity	Highest of all solids and liquids except liquid NH_3	Prevents extreme ranges in temperature Heat transfer by water movements is very large Tends to maintain uniform body temperatures
Latent heat of fusion	Highest except NH_3	Thermostatic effect at freezing point owing to absorption or release of latent heat
Latent heat of evaporation	Highest of all substances	Large latent heat of evaporation extremely important in heat and water transfer of atmosphere
Thermal expansion	Temperature of maximum density decreases with increasing salinity; for pure water it is at 4°C	Freshwater and dilute seawater have their maximum densities at temperatures above the freezing point; this property plays an important part in controlling temperature distribution and vertical circulation in lakes
Surface tension	Highest of all liquids	Important in physiology of the cell Controls certain surface phenomena and drop formation and behavior
Dissolving power	In general dissolves more substances and in greater quantities than any other liquid	Obvious implications in both physical and biological phenomena
Dielectric constant	Pure water has the highest of all liquids	Of utmost importance in behavior of inorganic dissolved substances because of resulting high dissociation
Electrolytic dissociation	Very small	A neutral substance, yet containing both H^+ and OH^- ions
Transparency	Relatively great	Absorption of radiant energy is large in infrared and ultraviolet; in visible portion of energy spectrum there is relatively little selective absorption, hence is "colorless"; characteristic absorption important in physical and biological phenomena
Conduction of heat	Highest of all liquids	Although important on small scale, as in living cells, the molecular processes are far outweighed by eddy conduction

*After Sverdrup, H.U., M.W. Johnson and R.H. Fleming, 1942: *The Oceans*, Prentice-Hall, Englewood Cliffs, New Jersey.

The Oceans under Climate Change

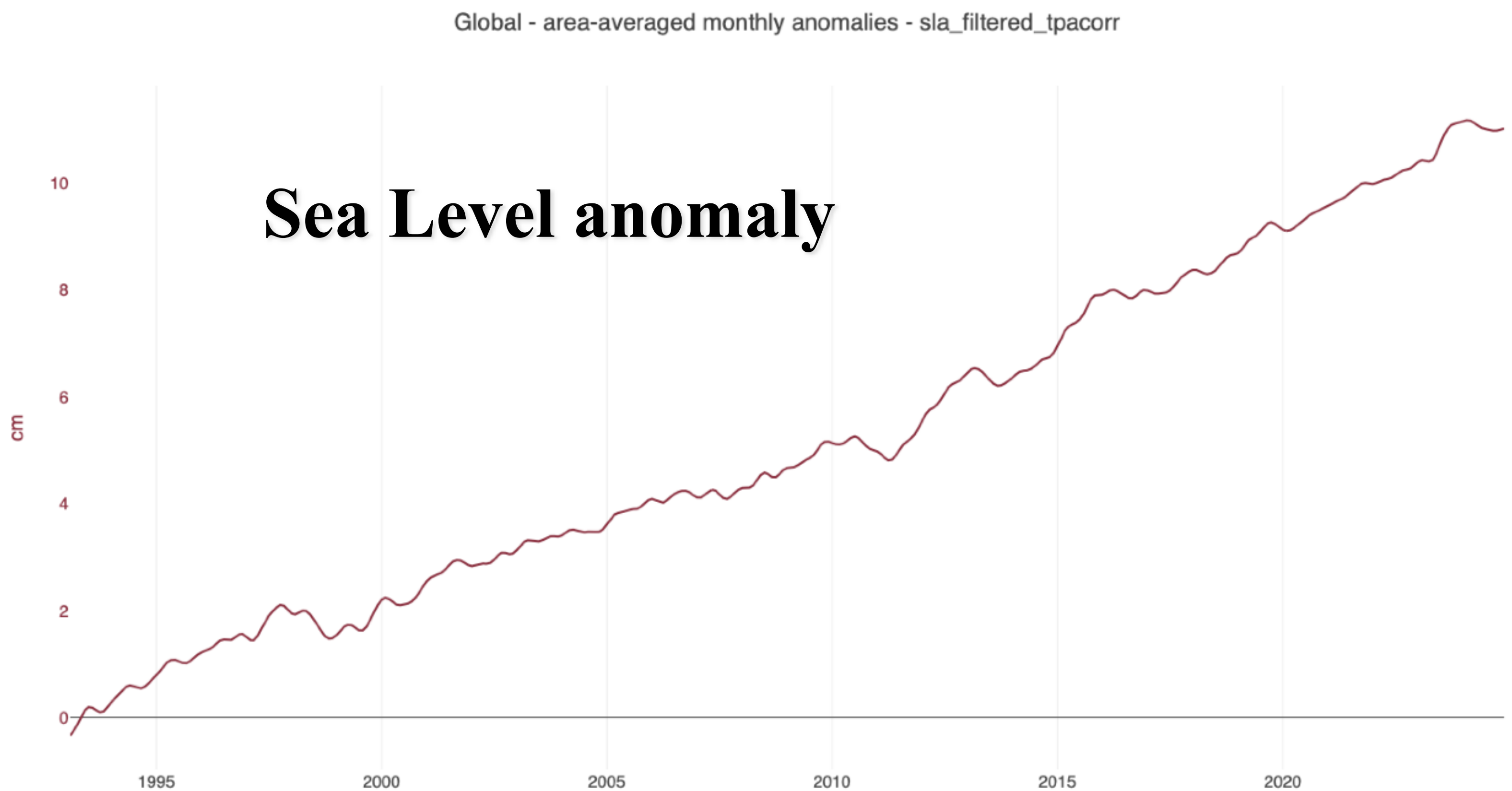
Heat Content anomaly



Copernicus Marine Service PROGRAMME OF THE EUROPEAN UNION Copernicus implemented by MERCATOR OCEAN INTERNATIONAL

The Oceans under Climate Change

Sea Level anomaly



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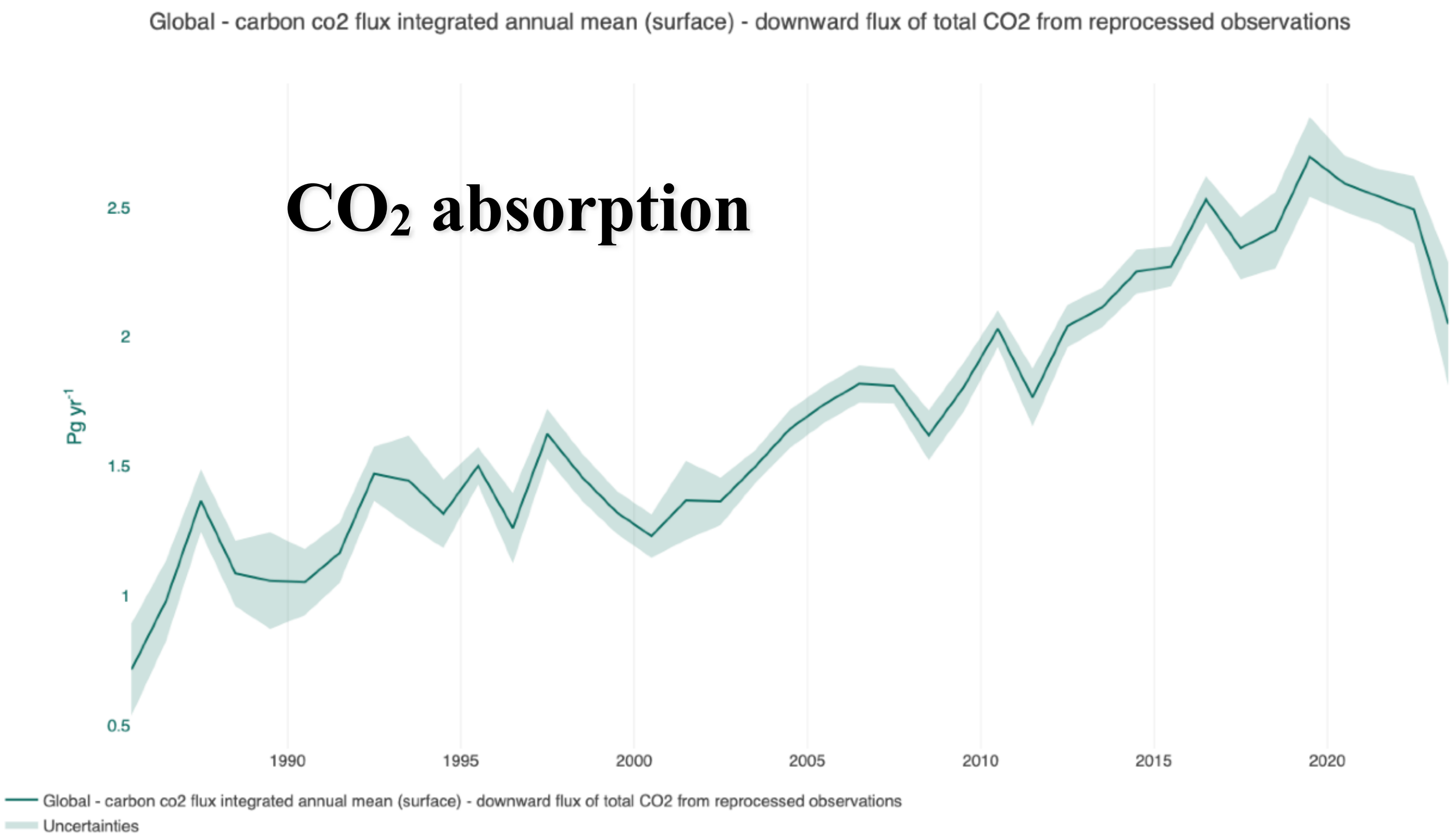

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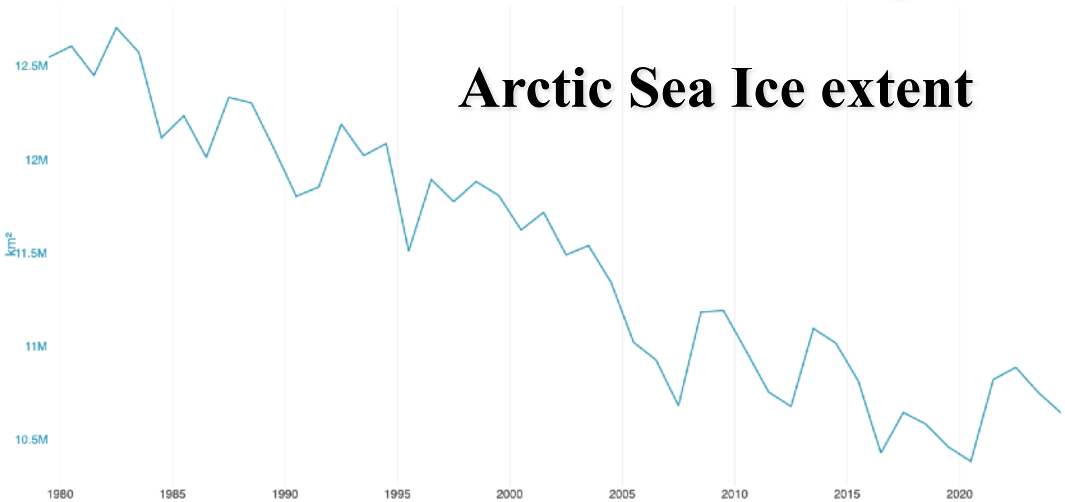
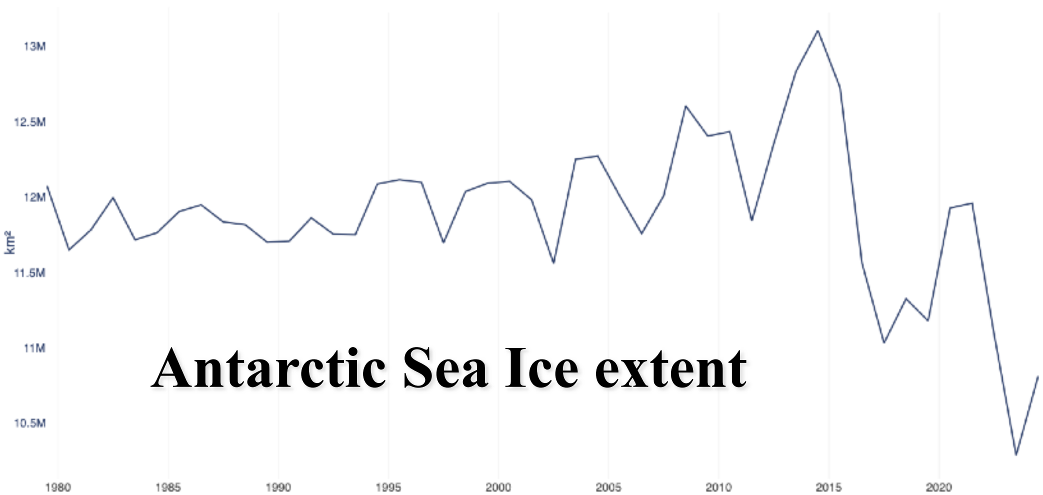
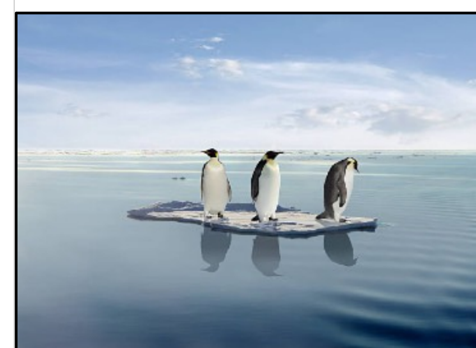






EUMETSAT OSI SAF | Copernicus Marine Service | PROGRAMME OF THE EUROPEAN UNION | Copernicus | implemented by MERCATOR OCEAN INTERNATIONAL

Part a. Οι φυσικές ιδιότητες του θαλασσινού νερού και η κατανομή τους (hydrography):

- Αλατότητα - Salinity
- Θερμοκρασία -Temperature
- Πίεση - Pressure
- Πυκνότητα - Density

- $$\frac{d\mathbf{u}}{dt} = \frac{\mathbf{F}}{m} = \frac{\mathbf{F}/V}{\rho} = \frac{\mathbf{F}^V}{\rho}$$
  $$\rho = \rho(T, q, P)$$
- **WHAT ARE WE OBSERVING**
- **HOW ARE WE OBSERVING**

Questions for PO

The "law" of constant proportions (Dittmar, 1884):

Although the total mass of ions dissolved in the seawater varies from place to place, the proportion of each ion in the total mass remains the same.

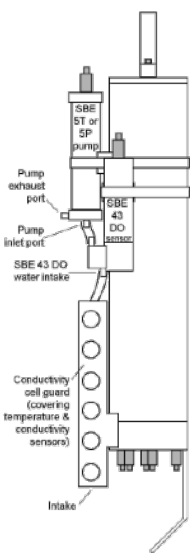
So, we measure the mass of one dissolved ion and we know the total mass of salt dissolved in the ocean. One property: **SALINITY**

Dissolved Ion	Chemical Formula and Charge	% by weight of dissolved ions	% by weight of seawater
Chloride	(Cl^-)	55.04	1.898
Sodium	(Na^+)	30.61	1.0556
Sulfate	(SO_4^{2-})	7.68	0.2649
Magnesium	(Mg^+)	3.69	0.1272
Calcium	(Ca^{2+})	1.16	0.04
Potassium	(K^+)	1.1	0.038
Bicarbonate	(HCO_3^-)	0.41	0.014
Bromide	(Br^-)	0.19	0.0065
Boric Acid	(H_3BO_3)	0.07	0.0026
Strontium	(Sr^{2+})	0.04	0.0013
Fluoride	(F^-)	0.002	0.0001
Total		**99.992**	**3.4482**

SALINITY

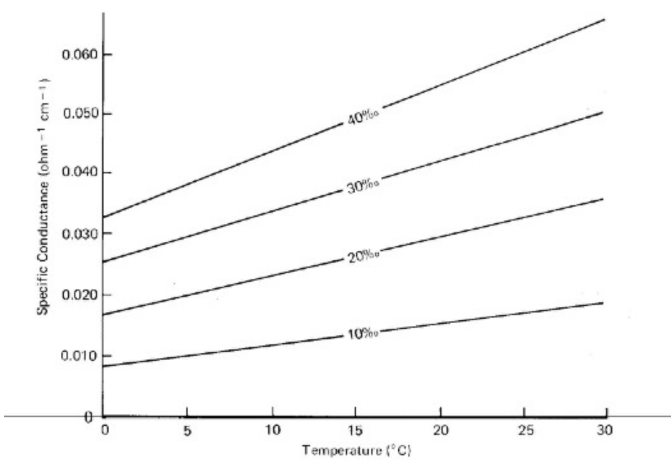
Older measurement procedures:

•Evaporate a sample to dryness and weigh the residue.
•Titrate seawater samples with $AgNO_3$, precipitate the halogens, determine the amount of *Cl*, then scale-up to *S* from the ratios of other constituents.
Units: g/kg (or ppt)

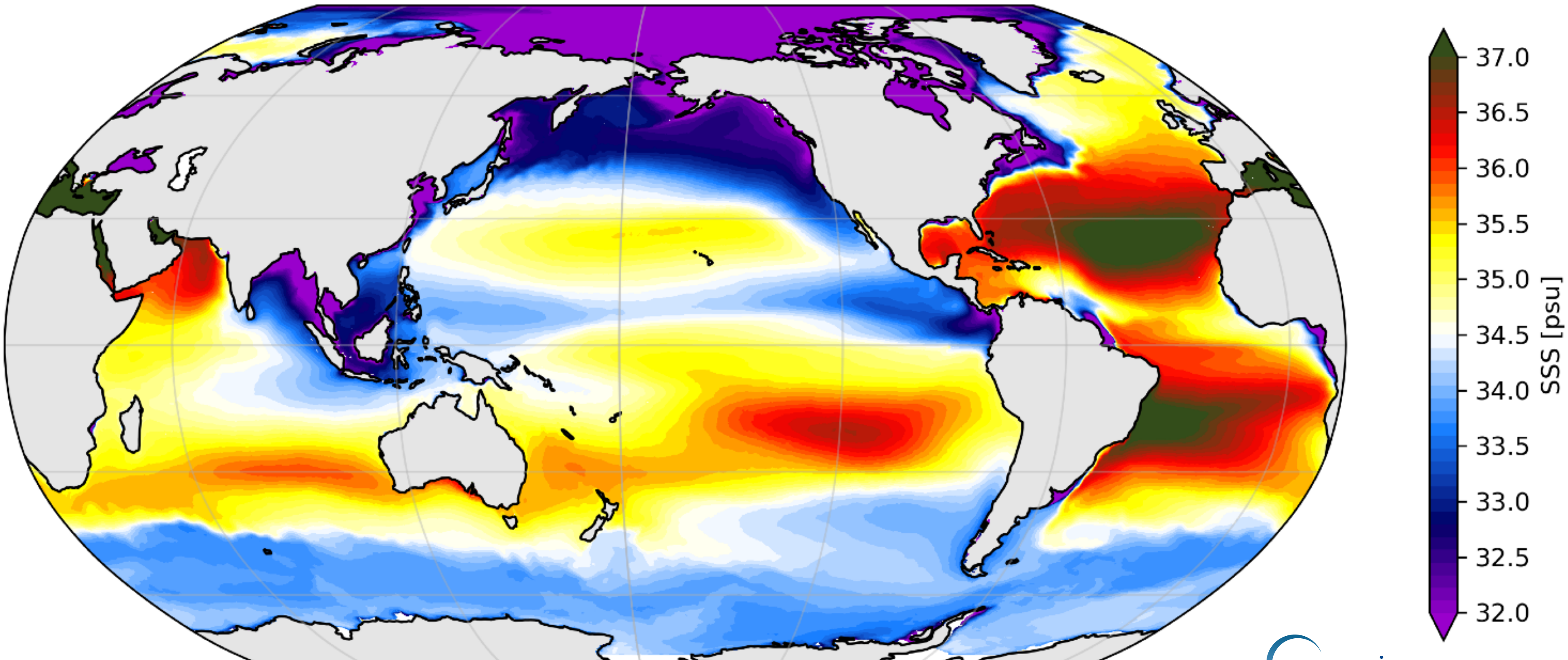


Current (since 1970s) measurement procedure:

•Determine the conductivity of a seawater sample relative to a known standard (“standard seawater”), add *T* and *p*, then infer *S* from the function.
Unit: PSU



Sea Surface Salinity (SSS)



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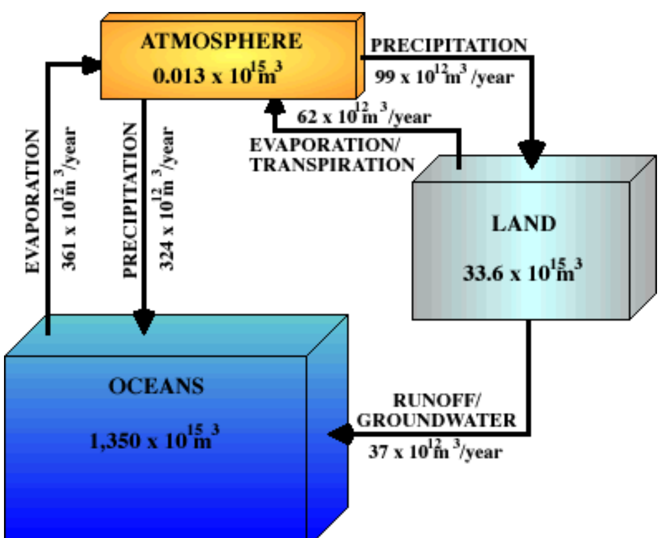
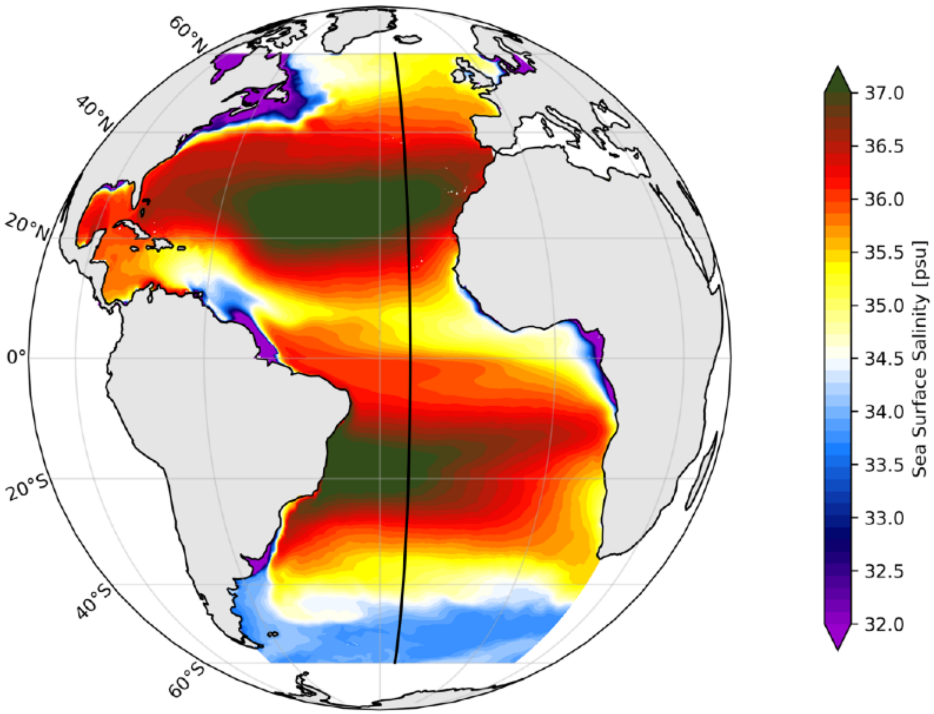
SALINITY



The HYDOLOGICAL CYCLE and OCEANIC MOTION/MIXING determines the oceanic salinity distribution. External forcing:

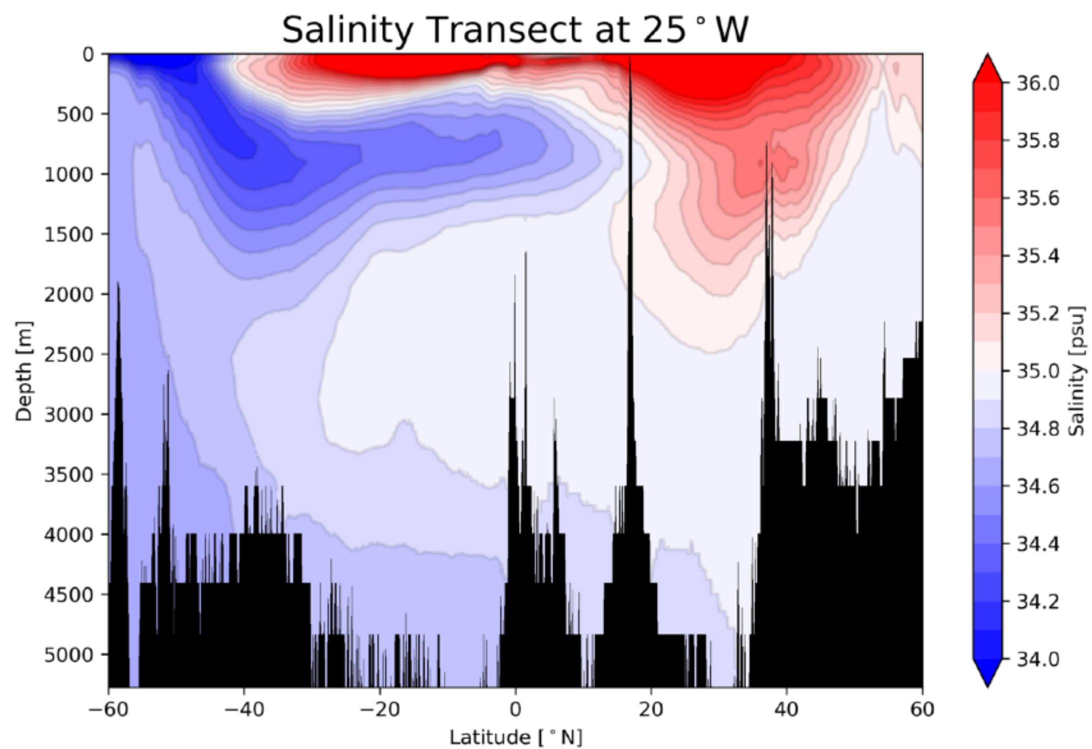
Evaporation – Precipitation – River/Ground Runoff

SALINITY



Horizontal and Vertical Distribution of Salinity:

Atlantic



For details:
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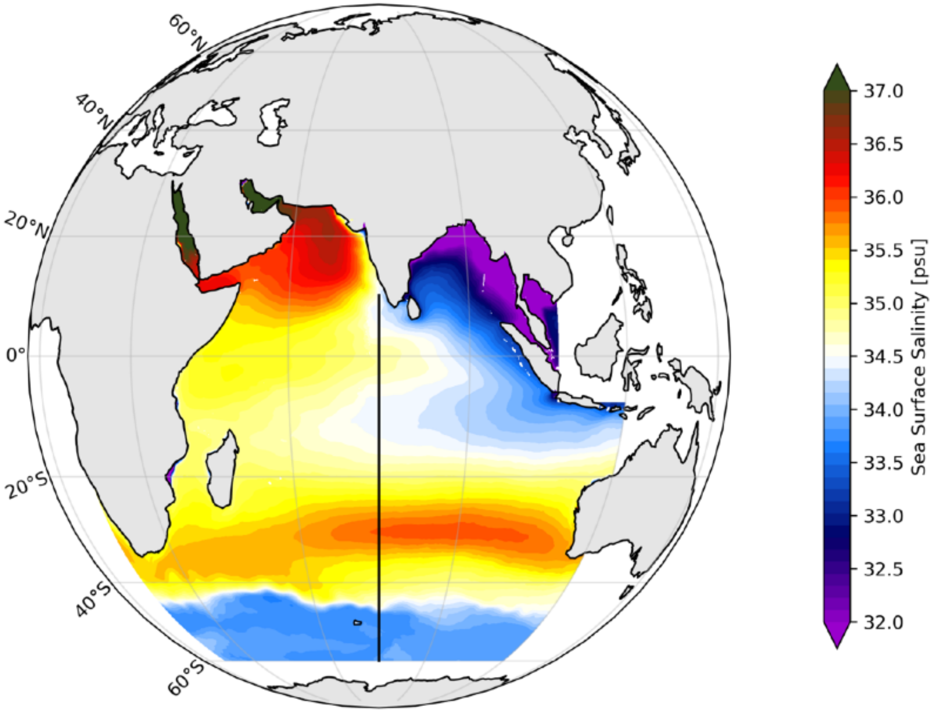
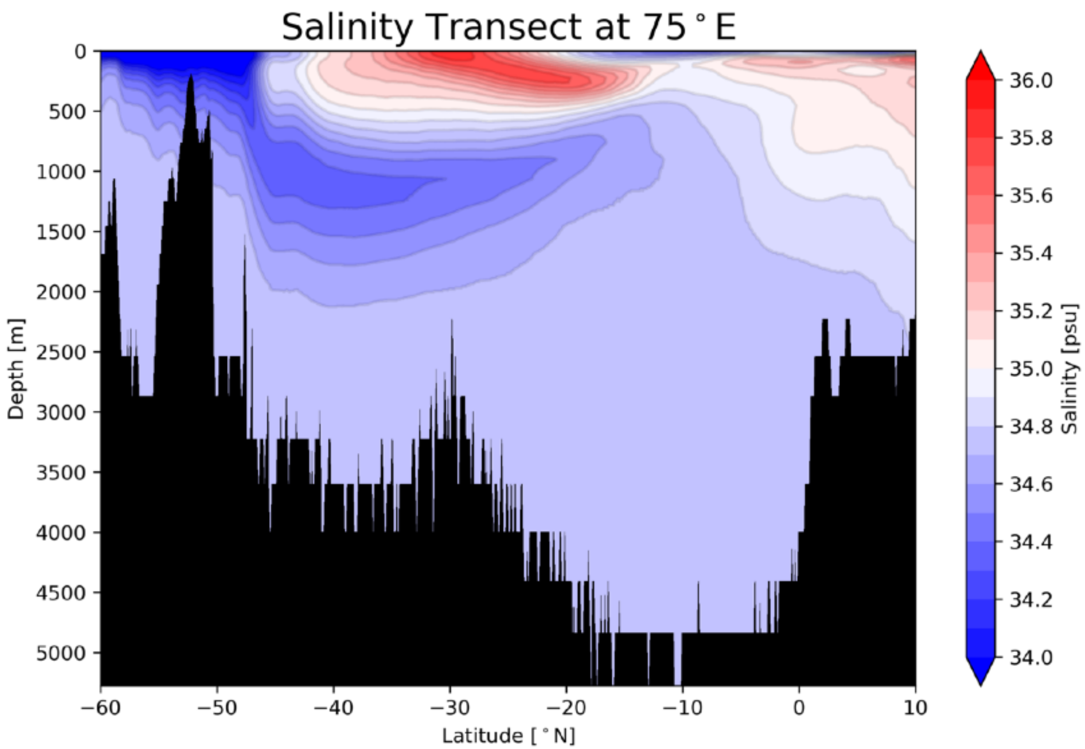
SALINITY



Horizontal and Vertical Distribution of Salinity:

Indian



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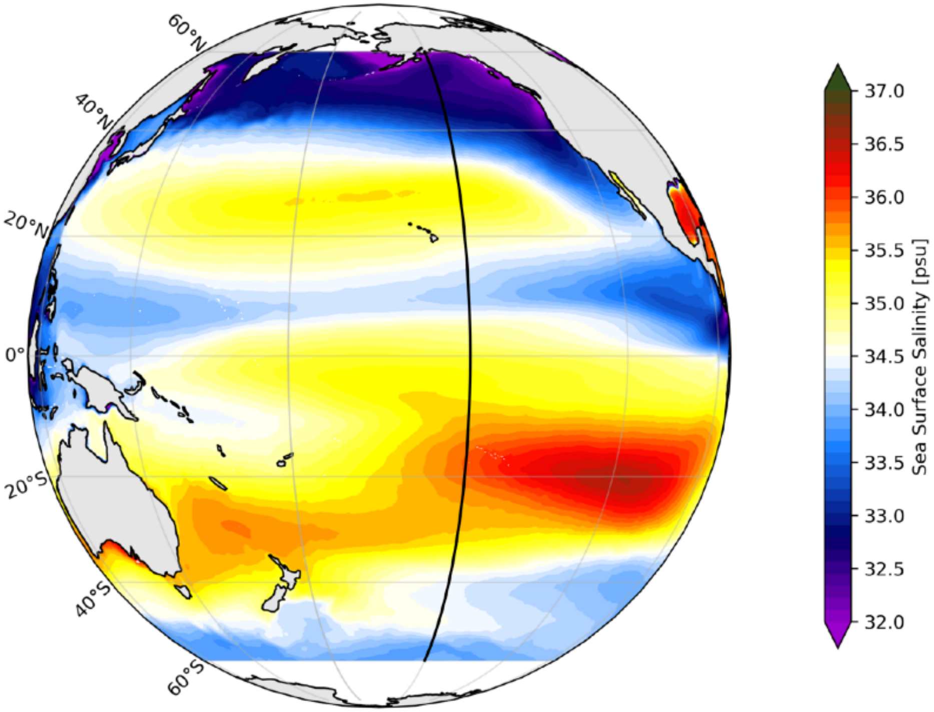
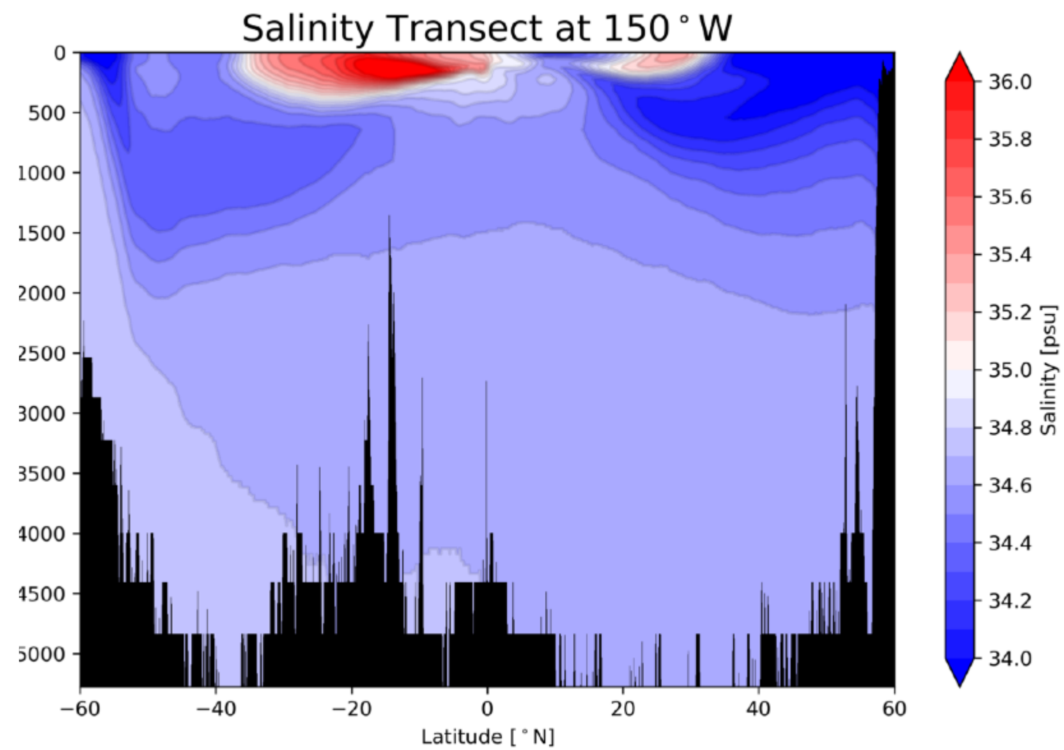
SALINITY



Horizontal and Vertical Distribution of Salinity:

Pacific



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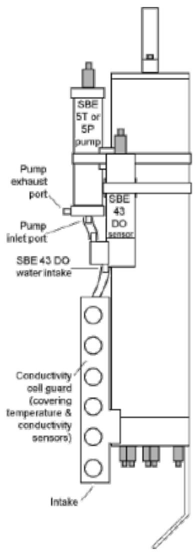
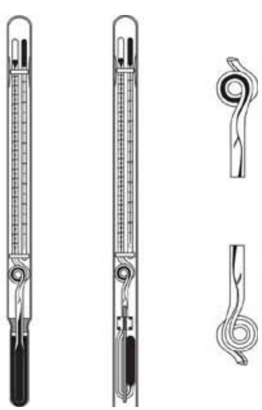
TEMPERATURE is a physical property of matter that quantitatively expresses the common notions of warm and cold. The temperature of a substance typically varies with the average speed of the particles that it contains.
Unit: ^{o}C

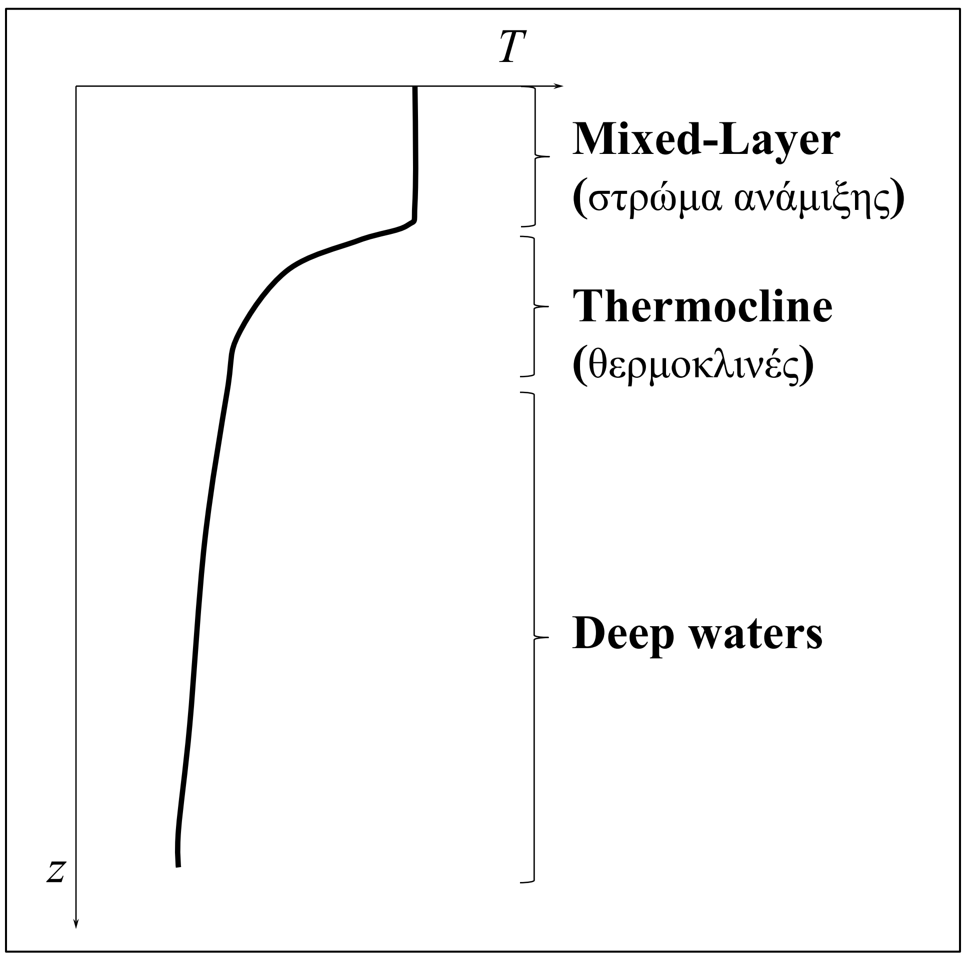
The **potential temperature** of a parcel of fluid at pressure P is the temperature that the parcel would acquire if adiabatically brought to a standard reference pressure P_0, usually the sea surface.

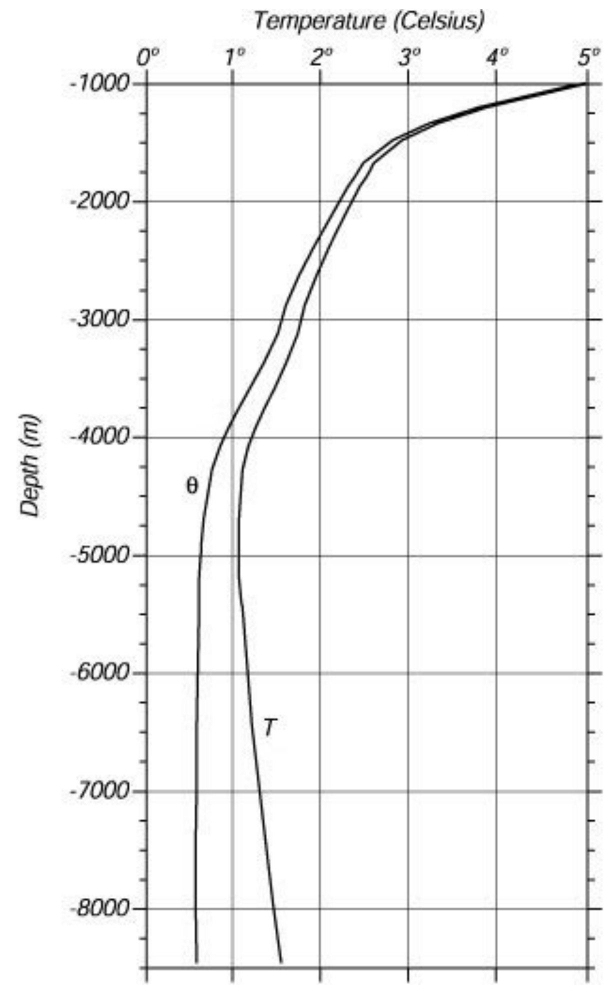
TEMPERATURE



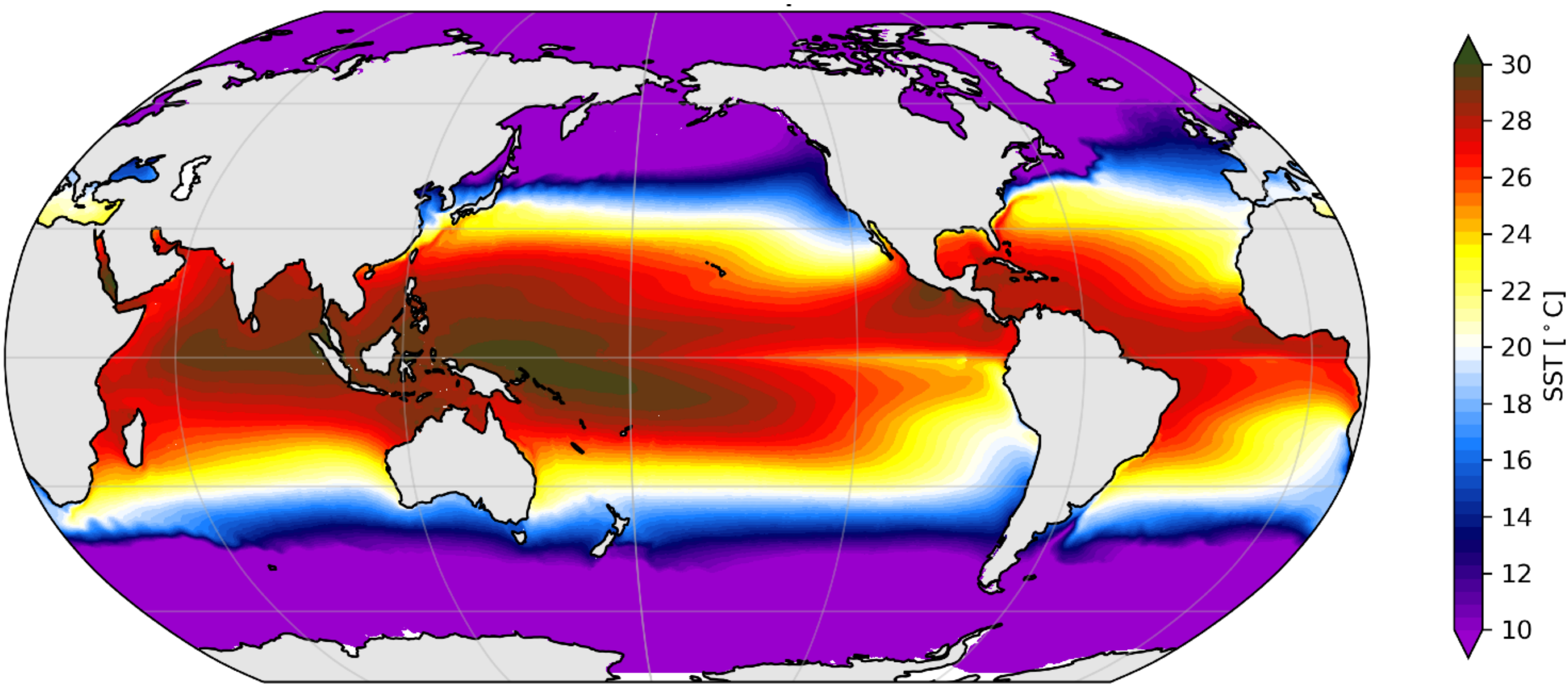


TYPICAL OCEANIC TEMPERATURE PROFILE

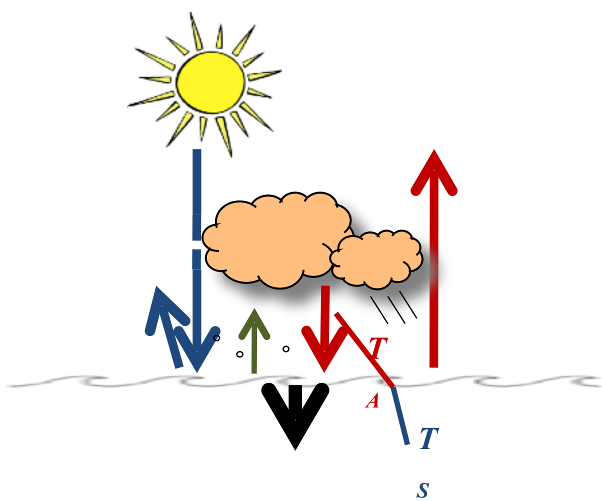




Sea Surface Temperature (SST)



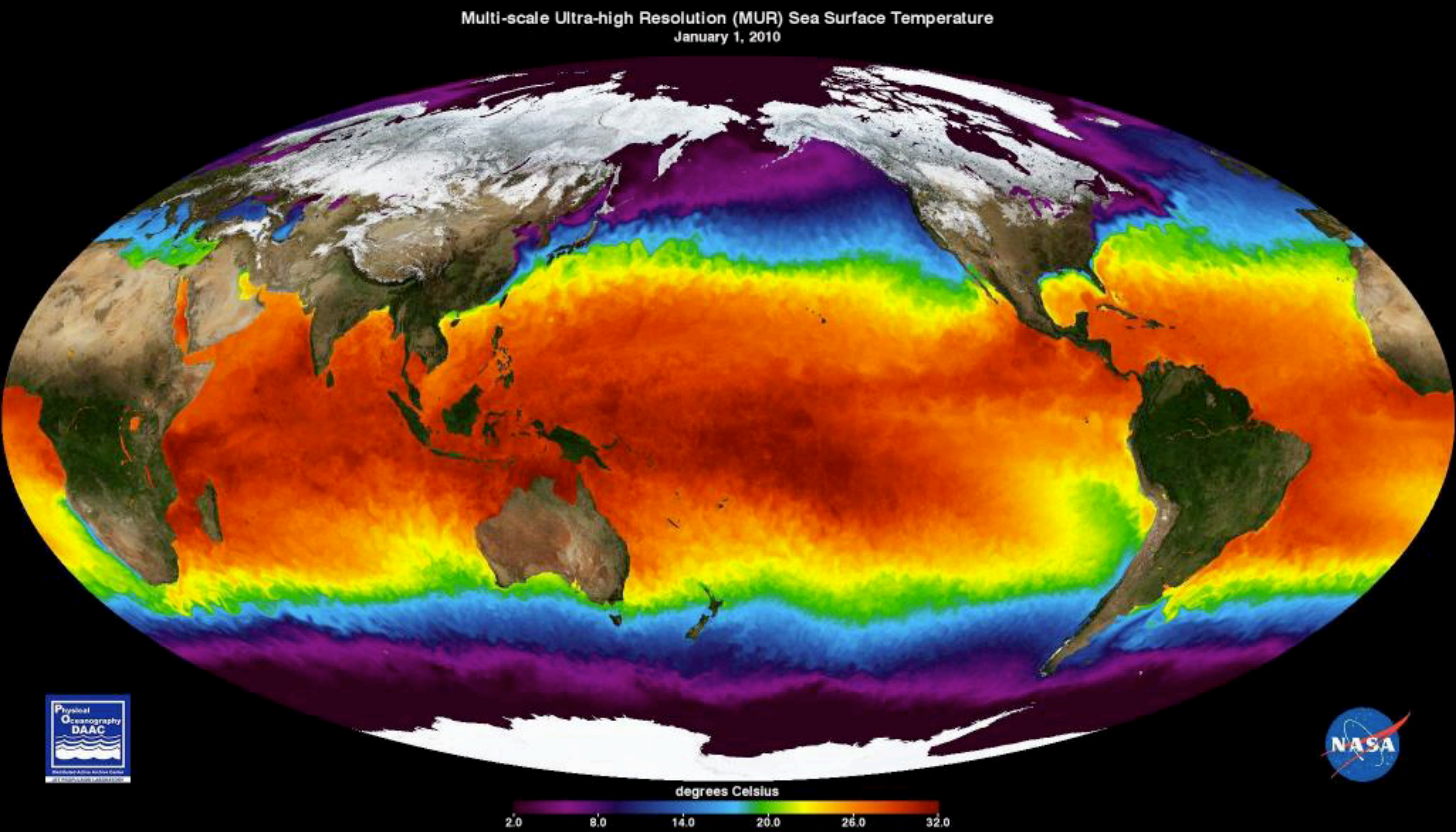
TEMPERATURE



RADIATION BUDGET, AIR-SEA INTERACTIONS and OCEANIC MOTION/ MIXING determines the oceanic temperature distribution. External Forcing:

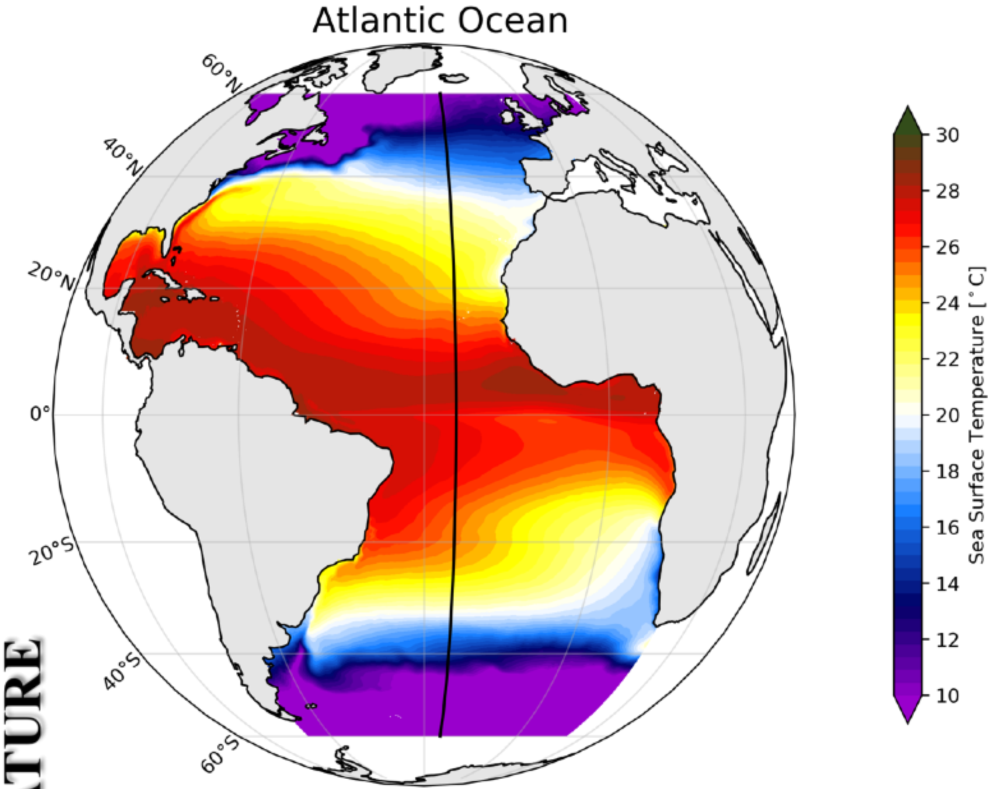
$$Q_{TOT}=R_S+R_L(up)+R_L(down)+Q_S+Q_L$$

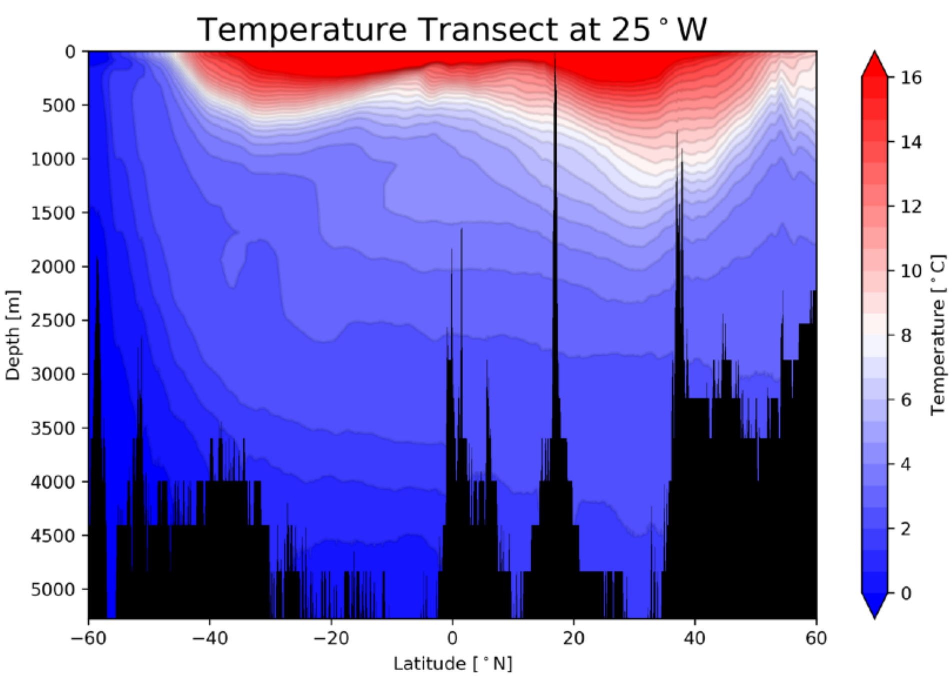
The distribution of Sea surface Temperature (SST) and its variability



(Satellite derived SST - NASA)

Horizontal and Vertical Distribution of Temperature: ***Atlantic***





TEMPERATURE

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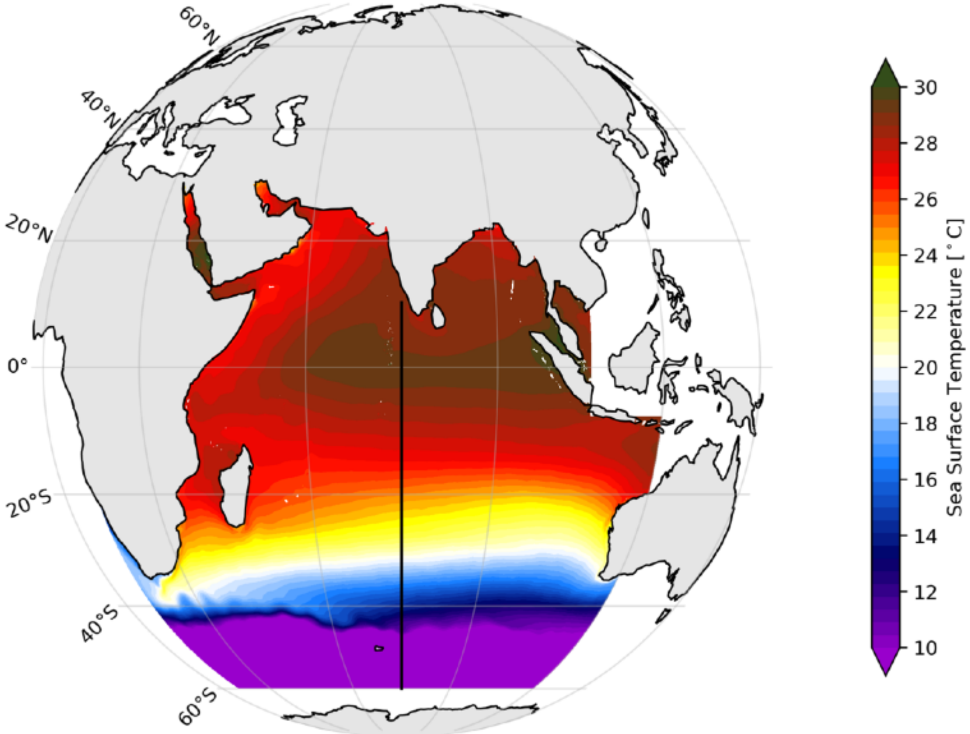
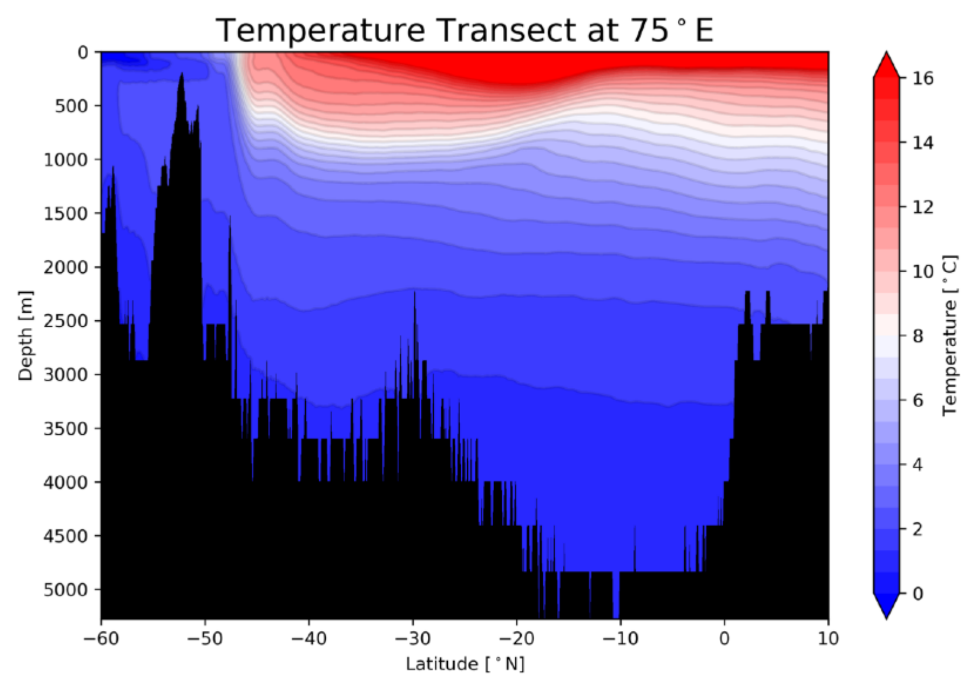
TEMPERATURE



Horizontal and Vertical Distribution of Temperature:

Indian



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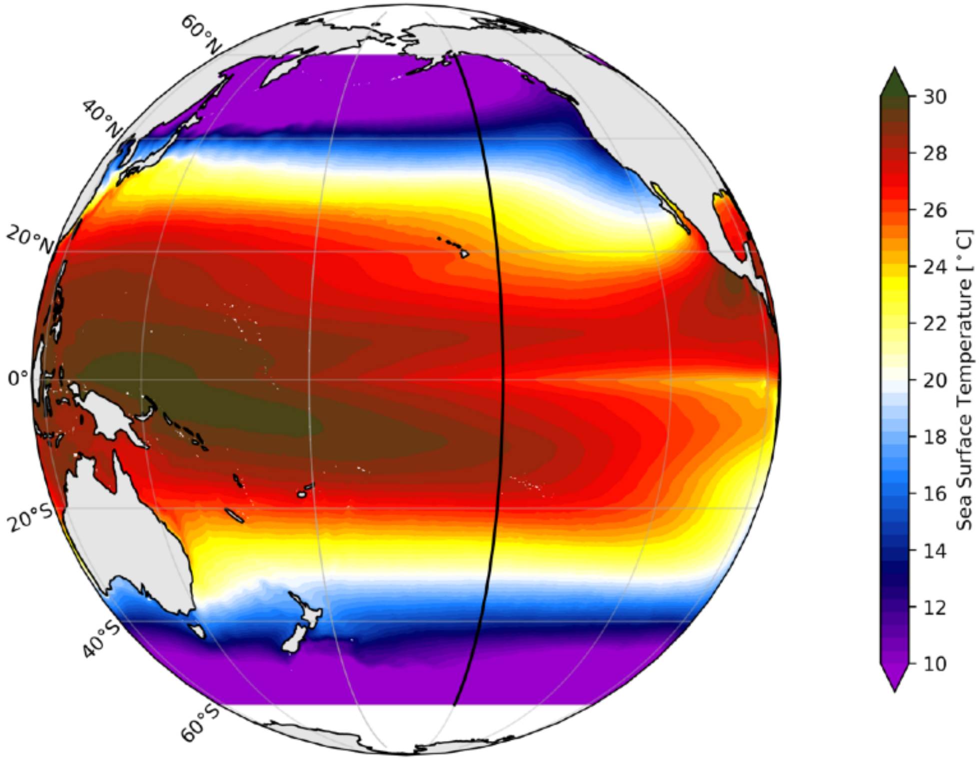
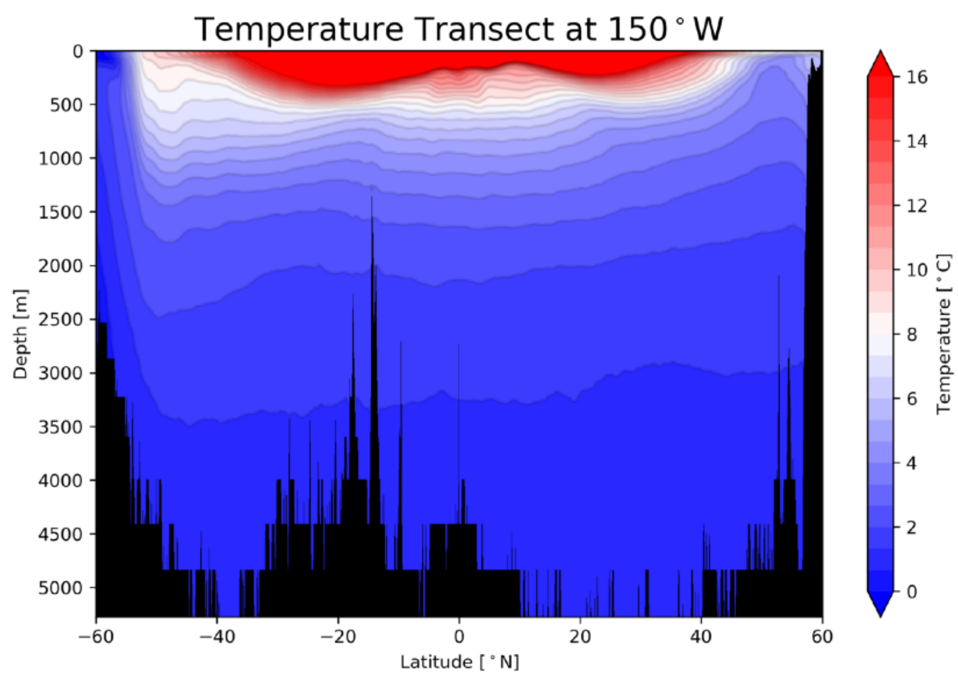
TEMPERATURE



Horizontal and Vertical Distribution of Temperature:

Pacific



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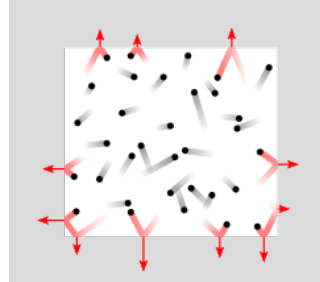
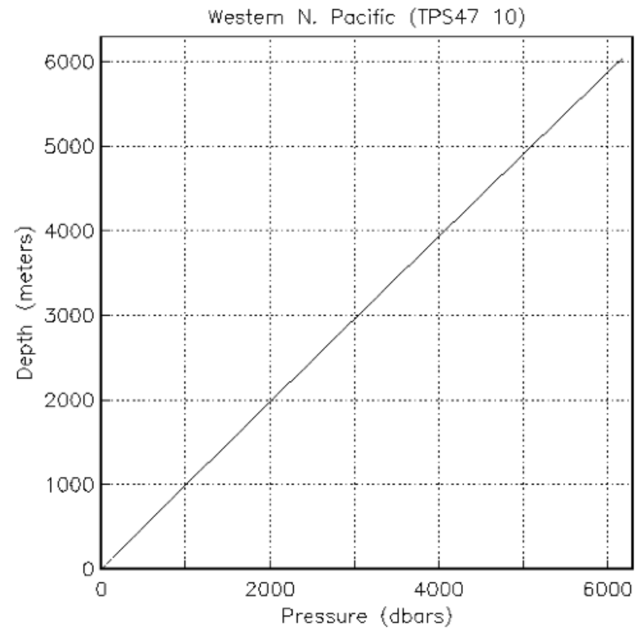
DENSITY

PRESSURE (p) is the force per unite area applied in a direction perpendicular to the surface of an object.



The force applied at point in a fluid due to pressure changes at this point (∇p) is called **pressure gradient**.

Units:
Pascal = Newton/m^2.
Atmospheric pressure is usually measured in bars:
1 bar = 10^5 Pascal
Ocean pressure is usually measured in decibars:
1 dbar = 10^{-1} bar = 10^4 Pascal



Pressure in open conditions usually can be approximated as the pressure in "static" or non-moving conditions (even in the ocean where there are waves and currents), because the motions create only negligible changes in the pressure. The pressure at any given point of a non-moving (static) fluid is called the **hydrostatic pressure**.

$$dp = -\rho g dz$$

We usually present the depth in pressure units: **1m ≈ 1dbar**

Measurements:
•Older procedure: Two reversing thermometers (one protected – one not).
•Today we use electronic sensors.

DENSITY

The non-linearity of the equation of state

The equation for ρ is obtained in a sequence of steps. First, the density ρ_w of pure water ($S = 0$) is given by

$$\rho_w = 999.842594 + 6.793952 \times 10^{-2}t - 9.095290 \times 10^{-3}t^2 + 1.001685 \times 10^{-4}t^3 - 1.120083 \times 10^{-6}t^4 + 6.536332 \times 10^{-9}t^5. \quad \text{(A3.1)}$$

Second, the density at one standard atmosphere (effectively $p = 0$) is given by

$$\rho(S, t, 0) = \rho_w + S(0.824493 - 4.0899 \times 10^{-3}t + 7.6438 \times 10^{-5}t^2 - 8.2467 \times 10^{-7}t^3 + 5.3875 \times 10^{-9}t^4) + S^{3/2}(-5.72466 \times 10^{-3} + 1.0227 \times 10^{-4}t - 1.6546 \times 10^{-6}t^2) + 4.8314 \times 10^{-4}S^2. \quad \text{(A3.2)}$$

Finally, the density at pressure p is given by

$$\rho(S, t, p) = \rho(S, t, 0)/(1 - p/K(S, t, p)). \quad \text{(A3.3)}$$

where K is the secant bulk modulus. The pure water value K_w is given by

$$K_w = 19652.21 + 148.4206t - 2.327105t^2 + 1.360477 \times 10^{-2}t^3 - 5.155288 \times 10^{-5}t^4. \quad \text{(A3.4)}$$

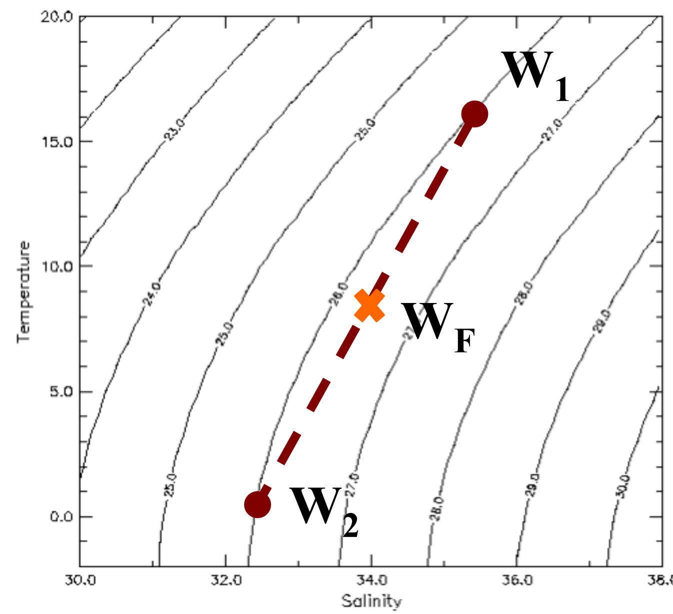
The value at one standard atmosphere ($p = 0$) is given by

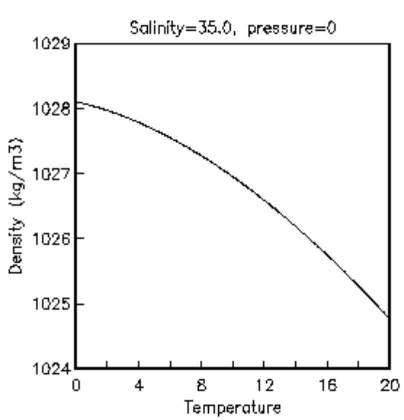
$$K(S, t, 0) = K_w + S(54.6746 - 0.603459t + 1.09987 \times 10^{-2}t^2 - 6.1670 \times 10^{-5}t^3) + S^{3/2}(7.944 \times 10^{-2} + 1.6483 \times 10^{-2}t - 5.3009 \times 10^{-4}t^2) \quad \text{(A3.5)}$$

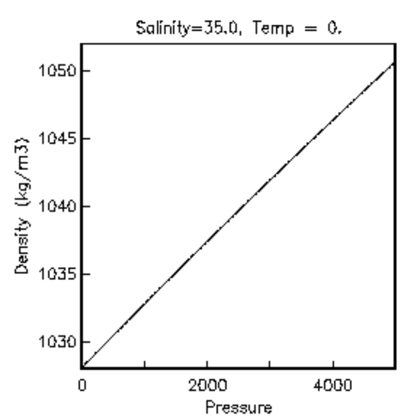
and the value at pressure p by

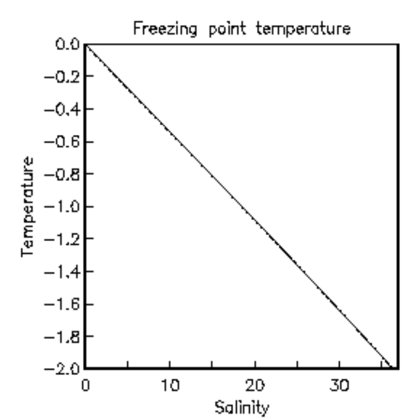
$$K(S, t, p) = K(S, t, 0) + p(3.239908 + 1.43713 \times 10^{-3}t + 1.16092 \times 10^{-4}t^2 - 5.77905 \times 10^{-7}t^3) + pS(2.2838 \times 10^{-3} - 1.0981 \times 10^{-5}t - 1.6078 \times 10^{-6}t^2) + 1.91075 \times 10^{-4}pS^{3/2} + p^2(8.50935 \times 10^{-5} - 6.12293 \times 10^{-6}t + 5.2787 \times 10^{-8}t^2) + p^2S(-9.9348 \times 10^{-7} + 2.0816 \times 10^{-8}t + 9.1697 \times 10^{-10}t^2). \quad \text{(A3.6)}$$

(see Gill, 1982: Atmosphere-Ocean Dynamics)









DENSITY

DENSITY is defined as the mass per unit volume

$$\rho = m/V$$

It depends on the temperature, salinity and pressure characteristics:

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

Equation of state (Καταστατική εξίσωση)
Density is not measured but is computed by the equation of state.

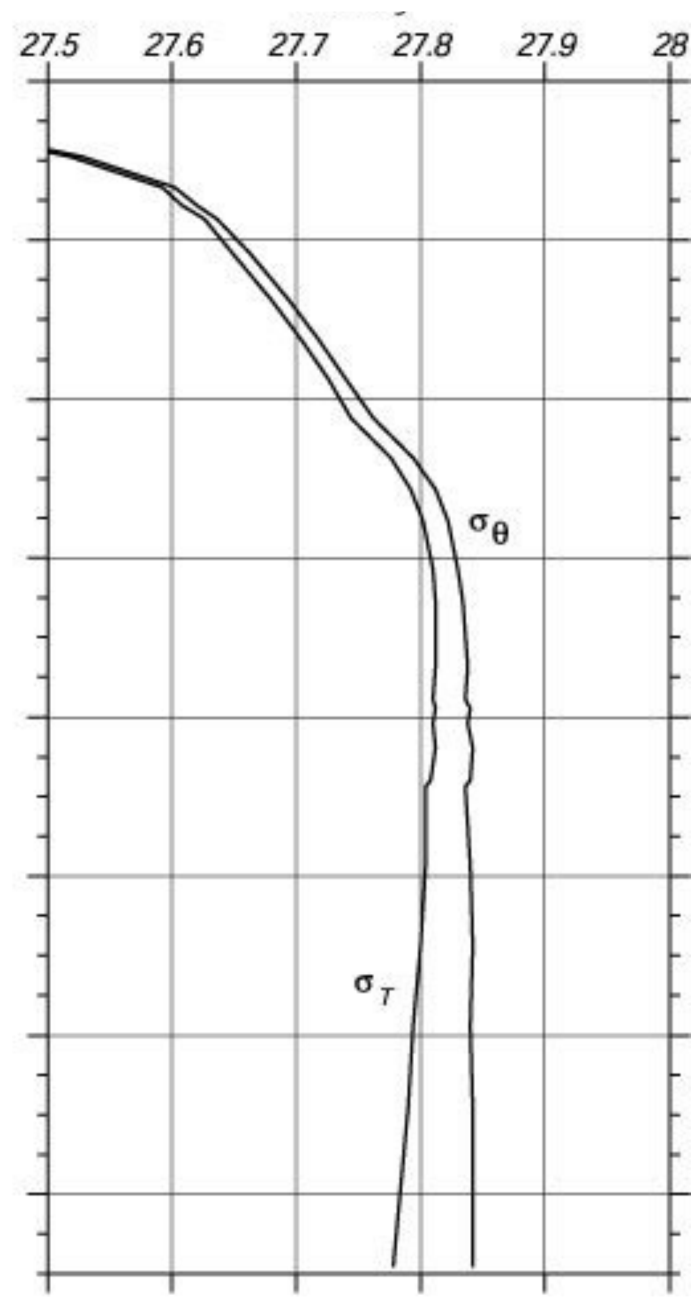
Units: Kg m^{-3}

We usually use **density anomaly** (or sigma):

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

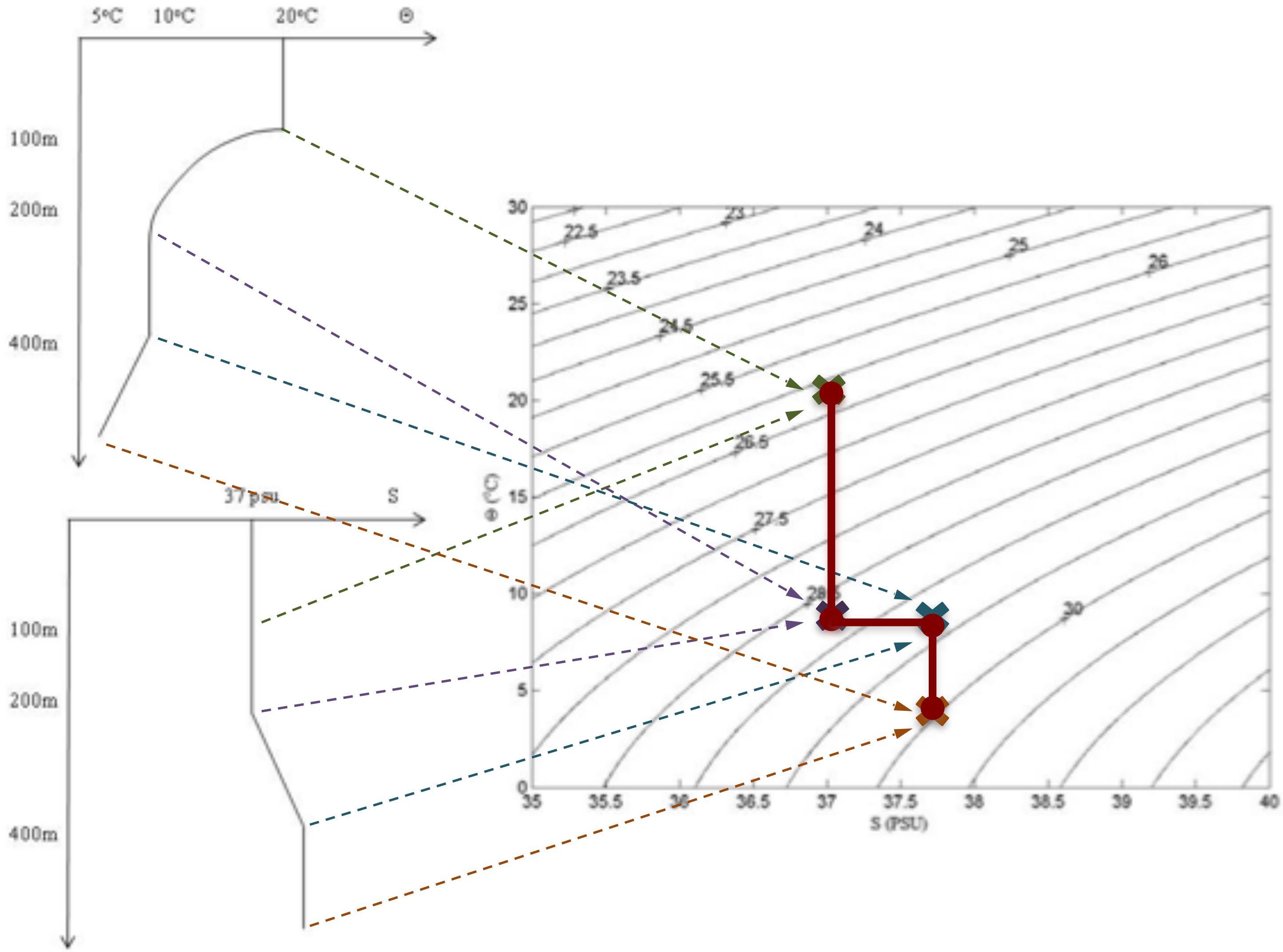
Potential density and **density anomaly**

$$\sigma_\theta = \rho_0(S,\theta,0) - 1000 \text{ kg/m}^3 = \sigma(S,\theta,0)$$



The Θ/S (potential temperature – salinity) diagram

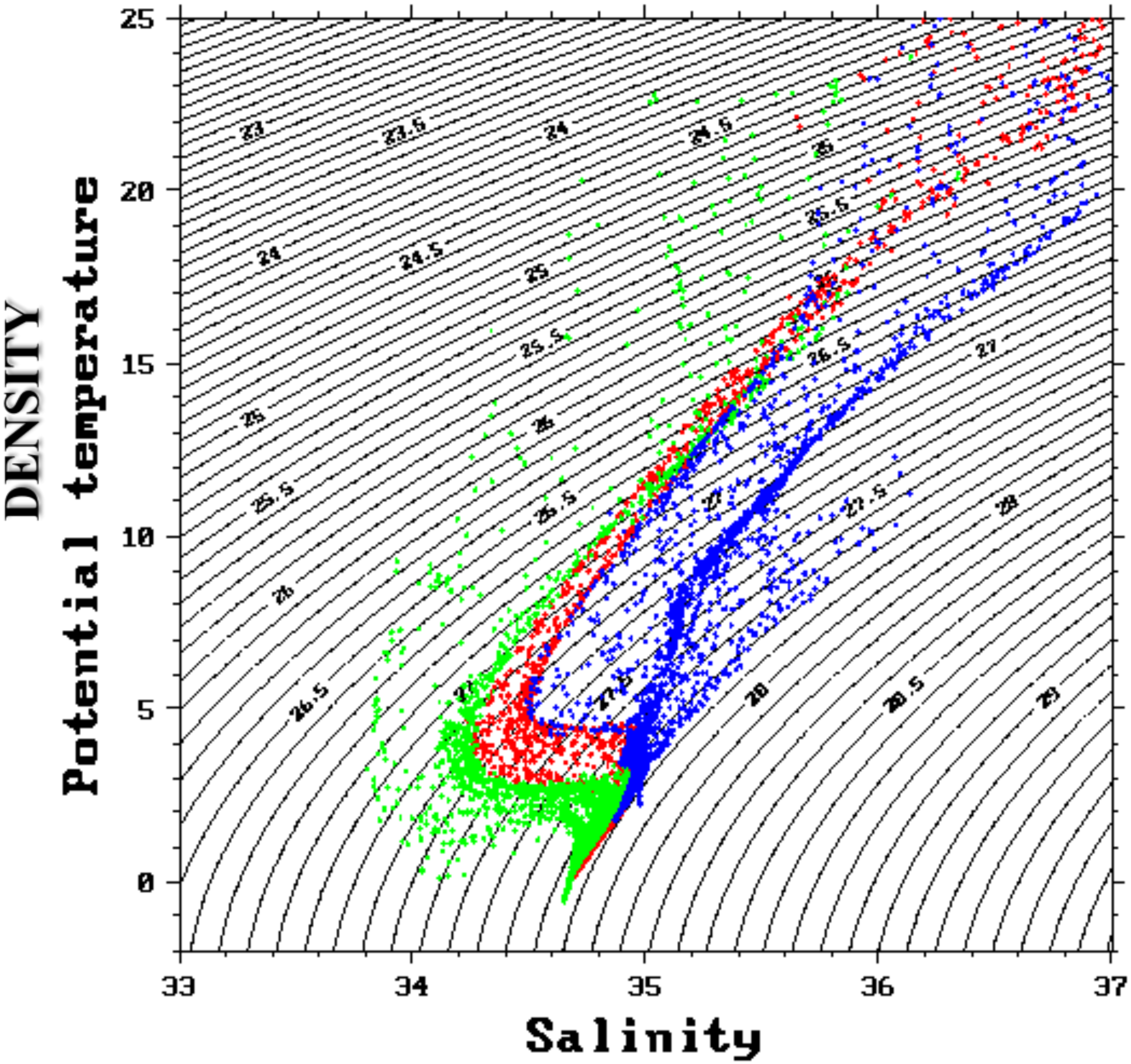
DENSITY



measured → **derived**

Θ/S characteristics:

Atlantic



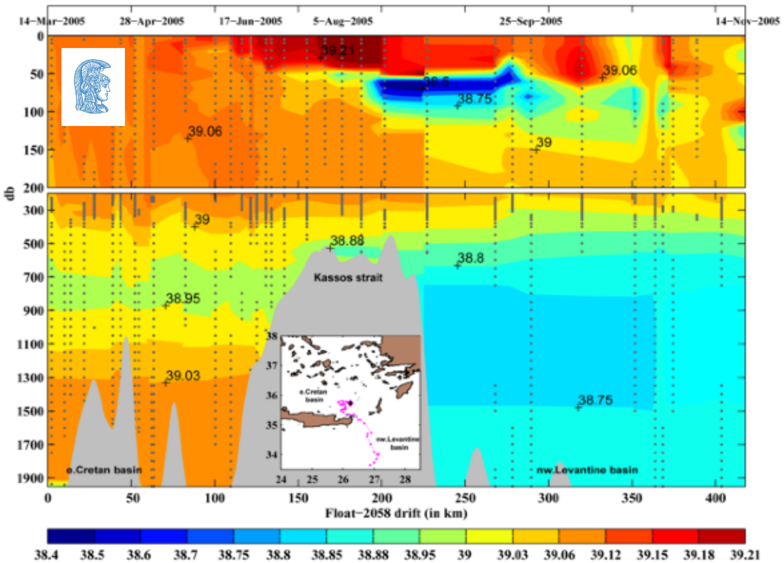
Blue: equator to Iceland.

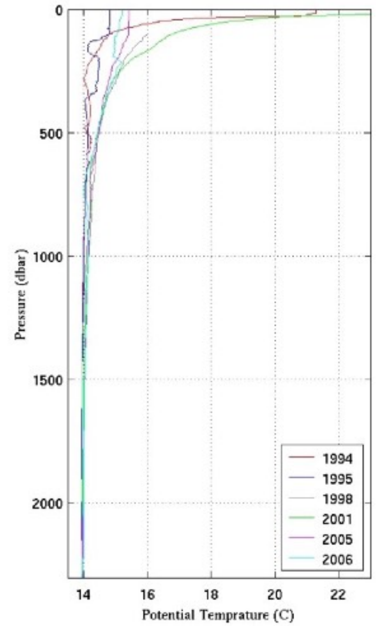
Red: equator to about 30S.

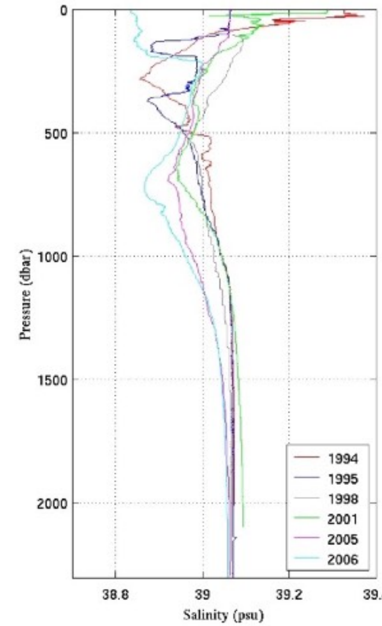
Green: 30S to South Georgia Island

WATER MASSES

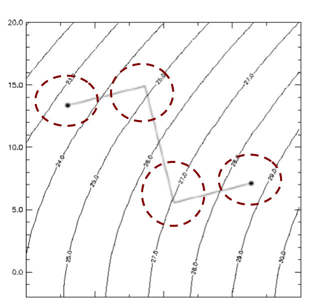
A regional example (Cretan Sea)

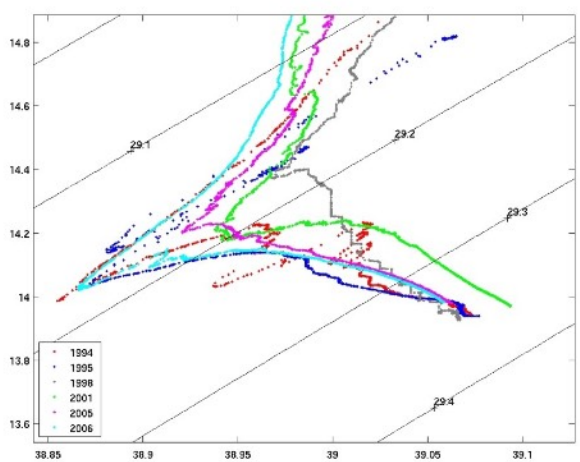


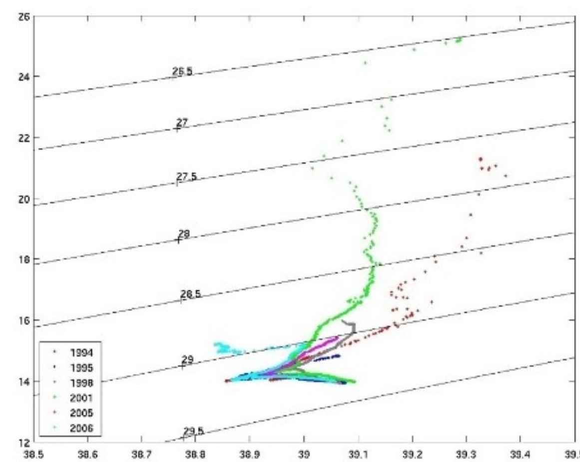




Definition of water masses on the θ/S diagram





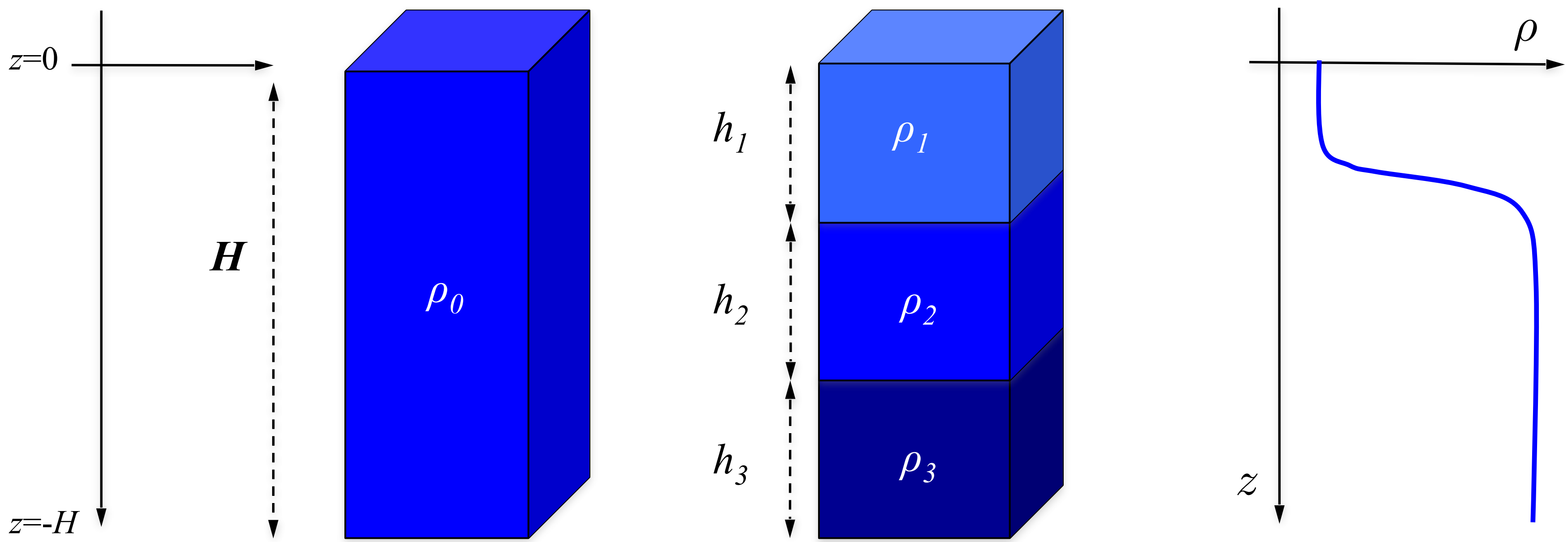


Part b. Στρωμάτωση - Stratification $\frac{\partial \rho}{\partial z}$

The stratification of the oceanic water column

STRATIFICATION

1) Homogeneous | 2) Stratified | 3) Continuously Stratified



Hydrostatic pressure at z = -H } $p = \rho_0 g H$ $\quad p = \rho_1 g h_1 + \rho_2 g h_2 + \rho_3 g h_3$ $\quad p = -\int_{-H}^{0} \rho(z) g dz$

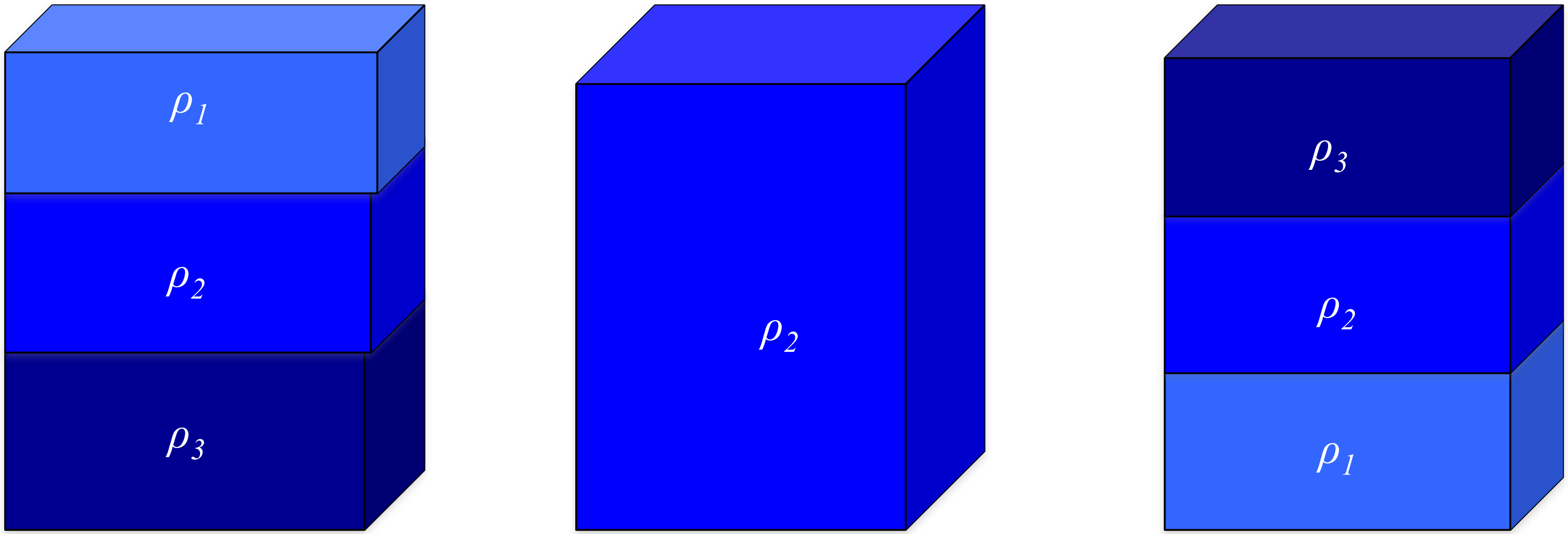
Higher dynamic complexity →

← Simpler solutions

Static Stability $\rho_1 < \rho_2 < \rho_3$

STRATIFICATION

Stable | Neutral | Unstable



Stratification resists vertical motion

Density has no influence on vertical motion

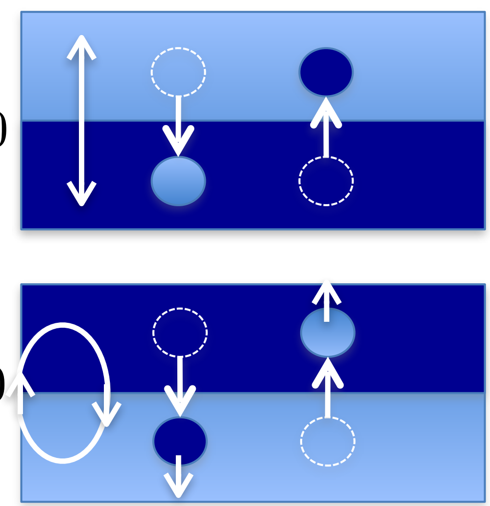
Density distribution causes vertical motion

Brunt Väisälä Frequency

One way of expressing stability is with the Brunt-Väisälä frequency (or buoyancy frequency)

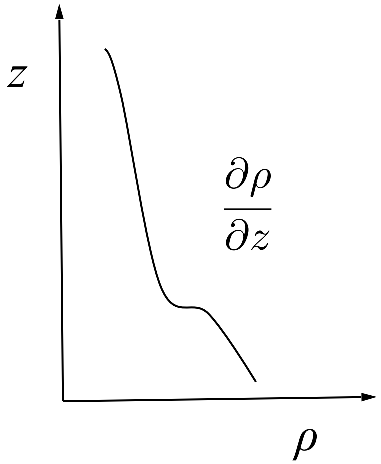
$N^2 > 0$

$N^2 < 0$



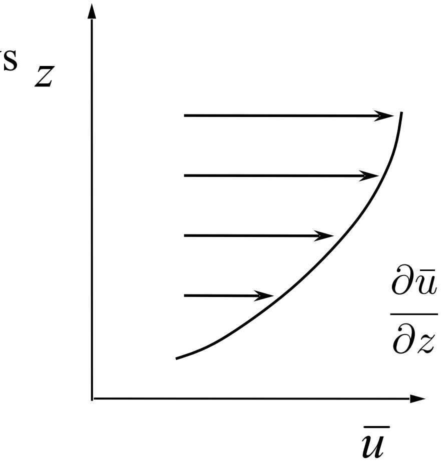
$$N^2 = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}$$

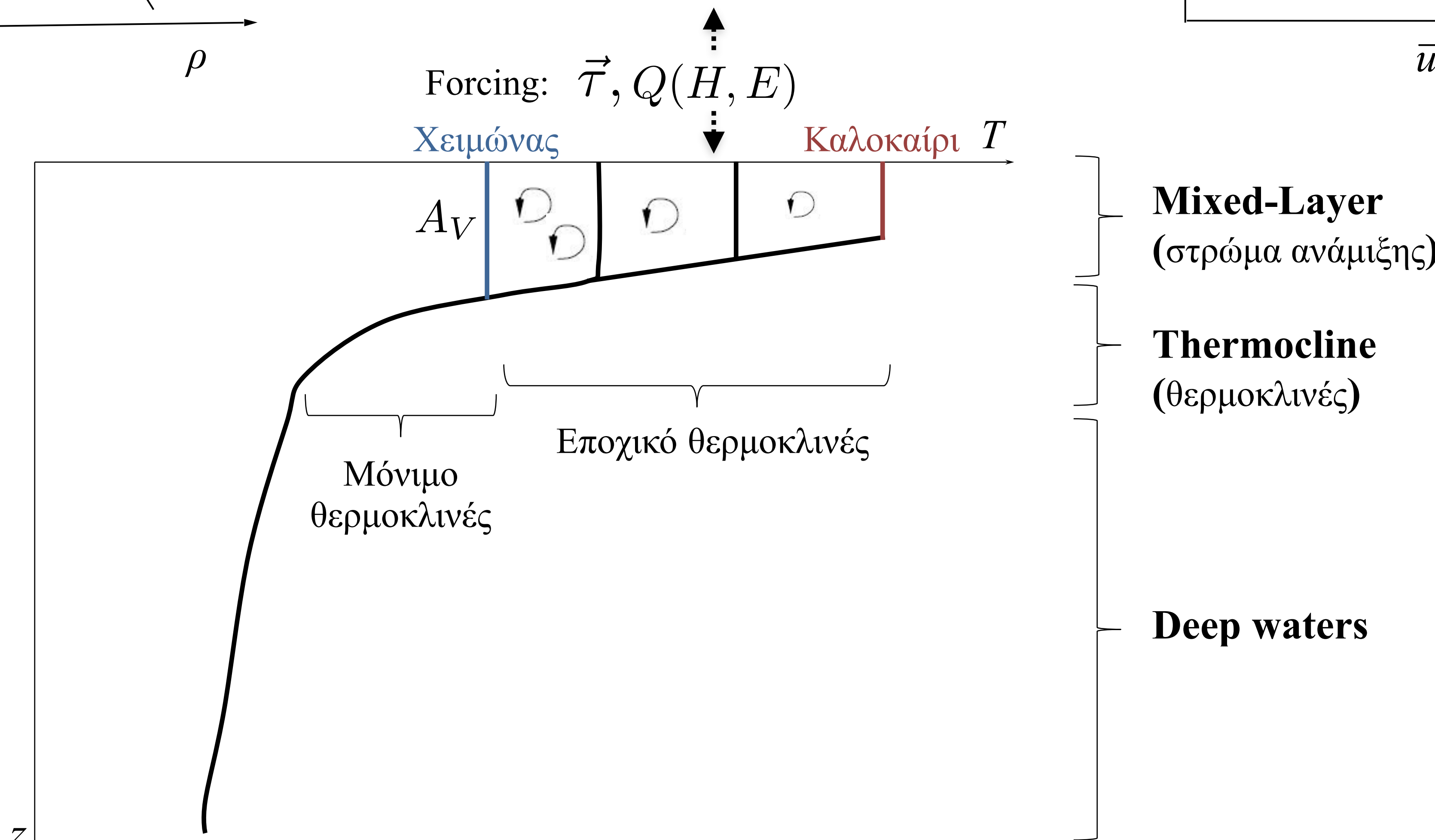
$$N = \sqrt{-\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}}\,(\mathrm{s}^{-1})$$



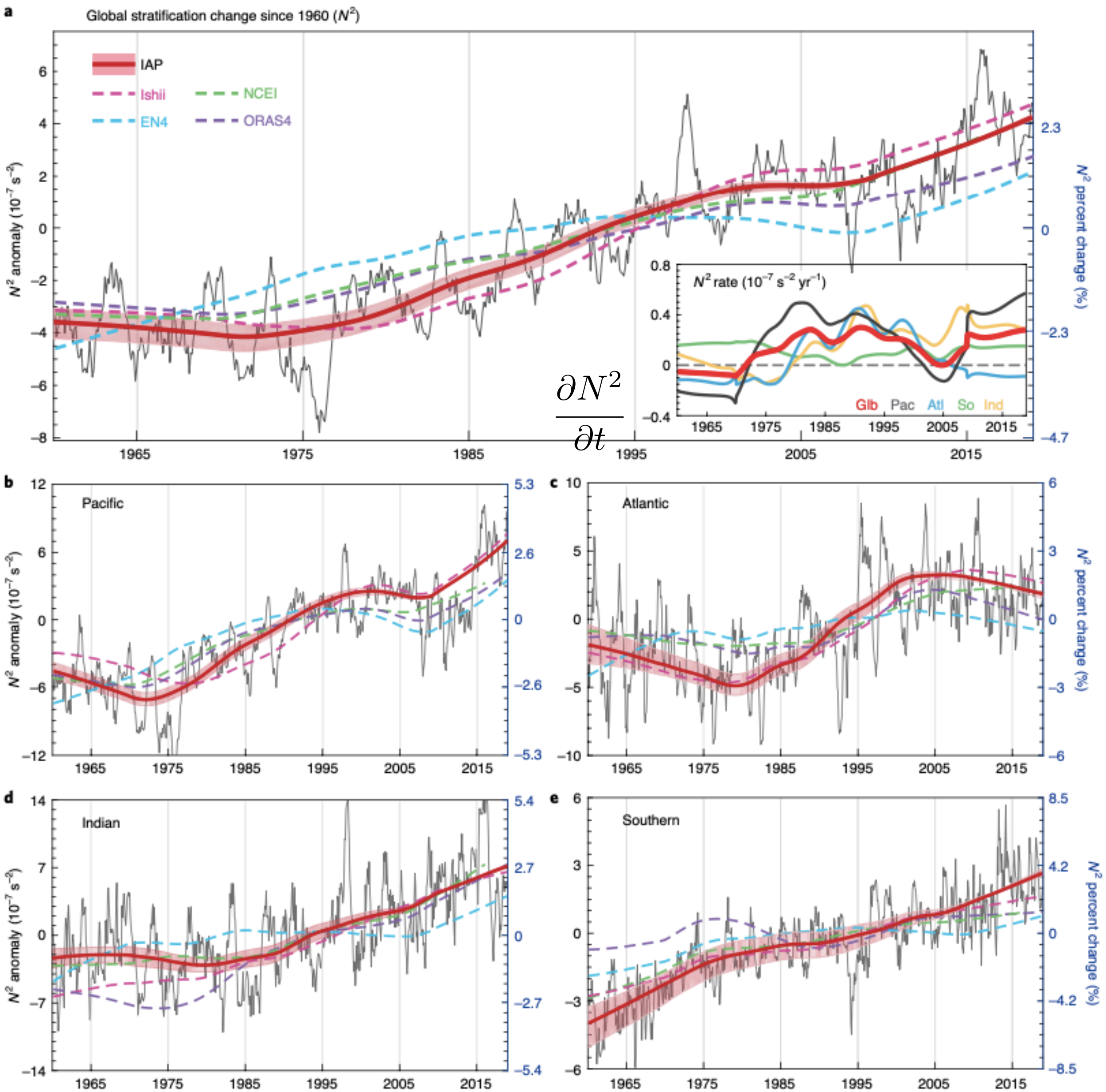
In general, in the presence of stratified and sheared flows (*Miles-Howard Theorem**) turbulence grows when:

$$Ri = \frac{g}{\rho_0} \frac{\partial \rho / \partial z}{(\partial u / \partial z)^2} = \frac{N^2}{(\partial u / \partial z)^2} < \frac{1}{4}$$





*δες σημειώσεις Δυναμικής των Ρευστών



$$\frac{\partial N^2}{\partial t}$$

$$N^2 = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}$$

$$N = \sqrt{-\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}}\,(\mathrm{s}^{-1})$$

Some consequences:

Weaker mixing

Stronger Thermocline

Reduction of nutrients in the surface layer

Weaker biological pump

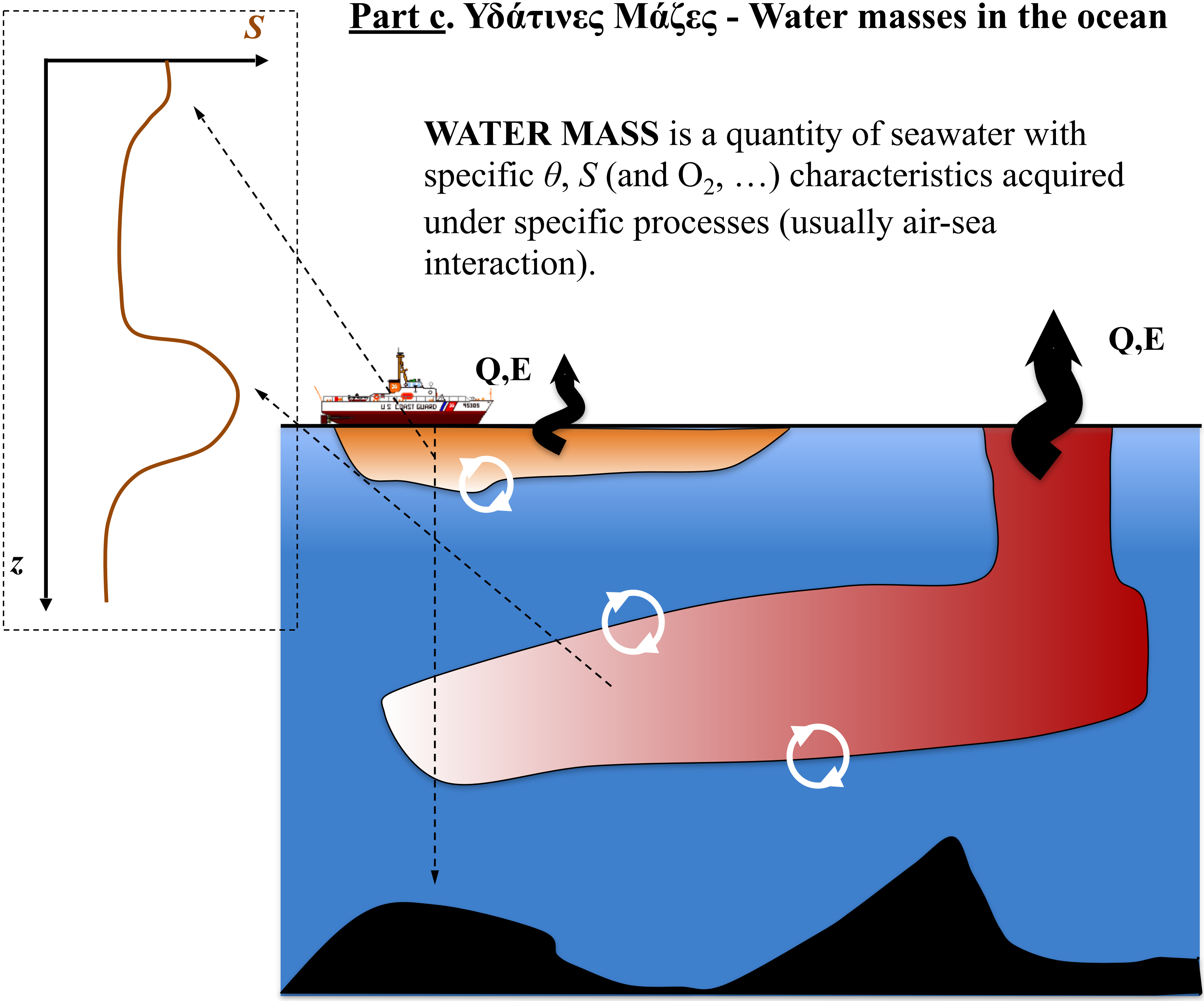
De-oxygenation and hypoxia of benthic environment

Li, G., Cheng, L., Zhu, J. *et al.* Increasing ocean stratification over the past half-century. *Nat. Clim. Chang.* **10**, 1116–1123 (2020). https://doi.org/10.1038/s41558-020-00918-2

WATER MASSES

<u>Part c</u>. Υδάτινες Μάζες - Water masses in the ocean

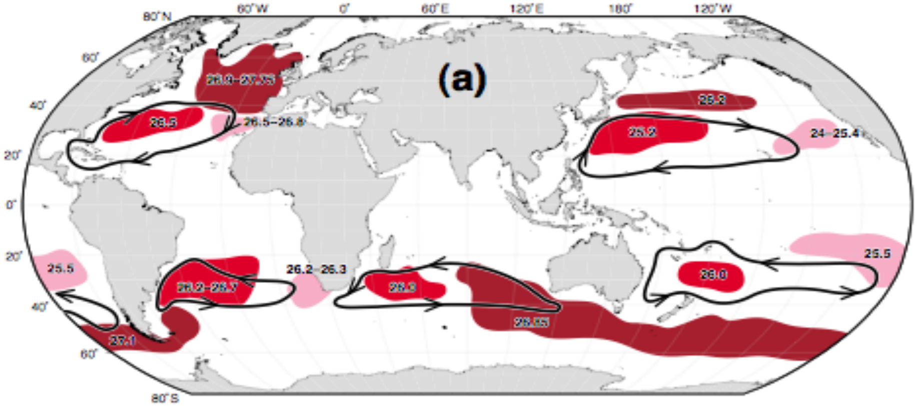
WATER MASS is a quantity of seawater with specific θ, S (and O_2, …) characteristics acquired under specific processes (usually air-sea interaction).

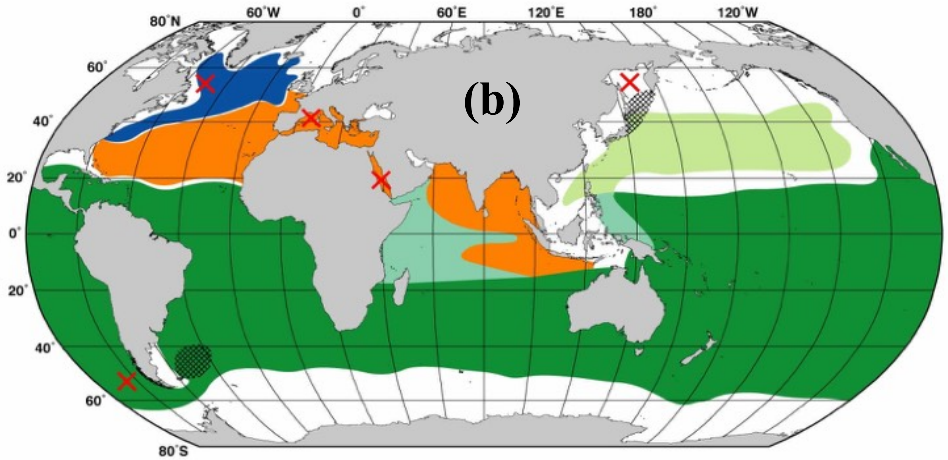


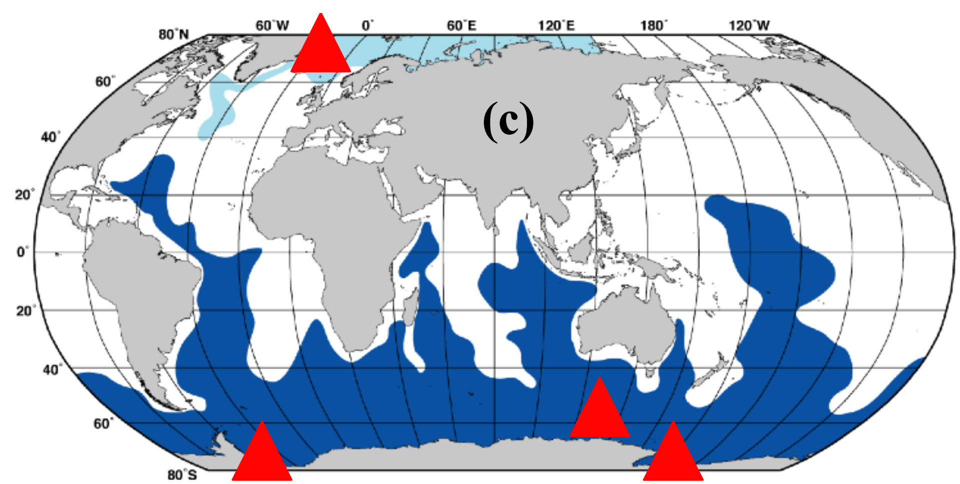
WATER MASSES

Water mass formation areas and major water masses of the world ocean:

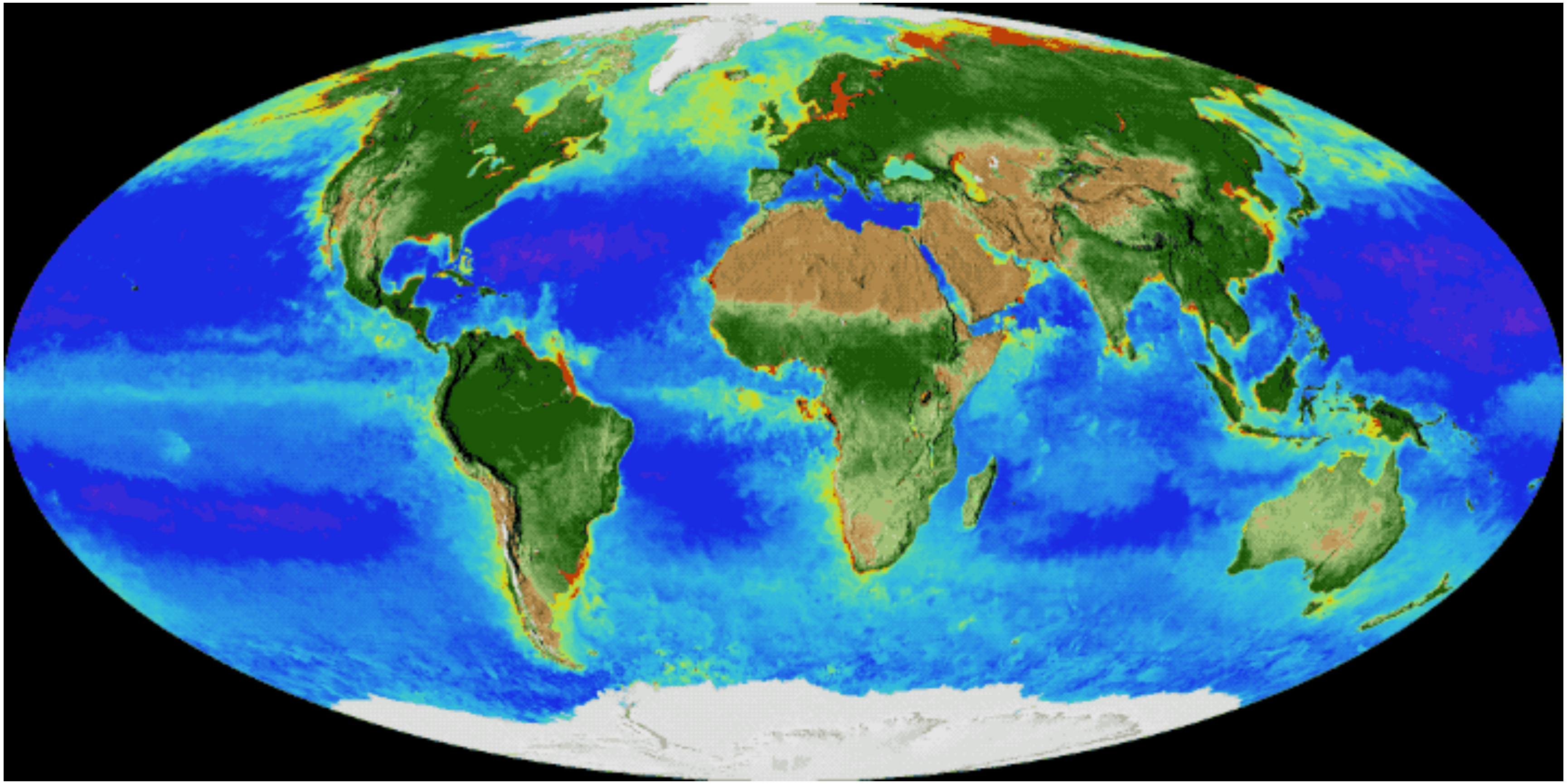
(a)Surface
(b)Intermediate/Deep
(c)Bottom







Ocean Productivity



and its connection to ocean circulation activity