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UNIVERSITY OF LISBON
INTERDISCIPLINARY STUDIES
ON SUSTAINABLE ENVIRONMENT AND SEAS

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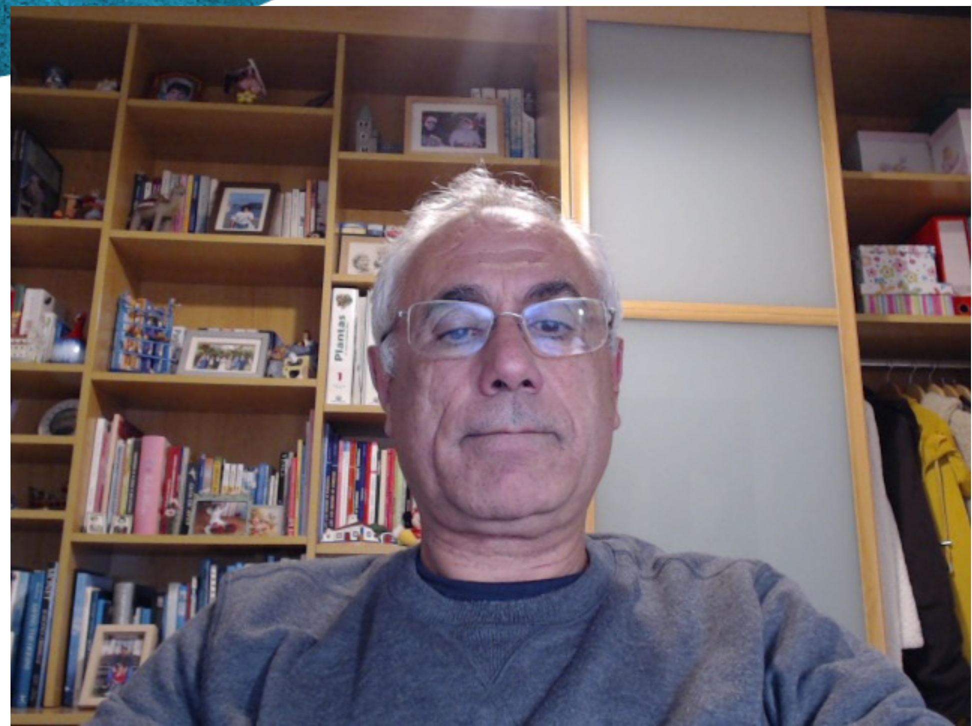

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Ocean Dynamics: Circulation, Biological productivity and Plastics Transport & fate

Ramiro.Neves@tecnico.ulilsboa.pt
www.tecnico.ulisboa.pt www.maretec.org www.mohid.com

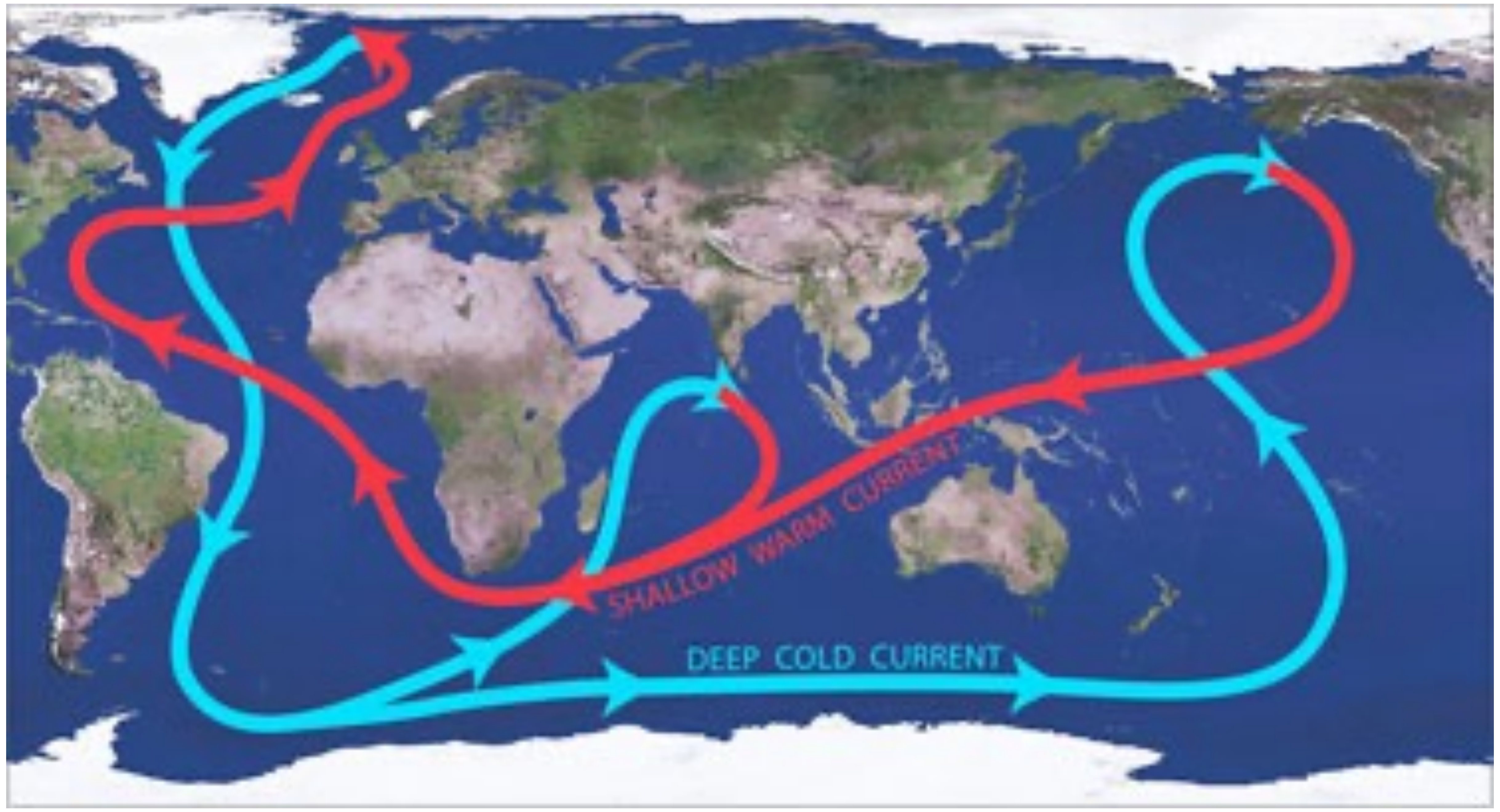
Ocean water is permanently moving, carrying energy (mostly heat), dissolved matter (salts) and particulate matter, floating (e.g., plastics) or in suspension (plankton, sediments).

This lecture will address the oceanic currents and the mechanisms (forces) that generate them

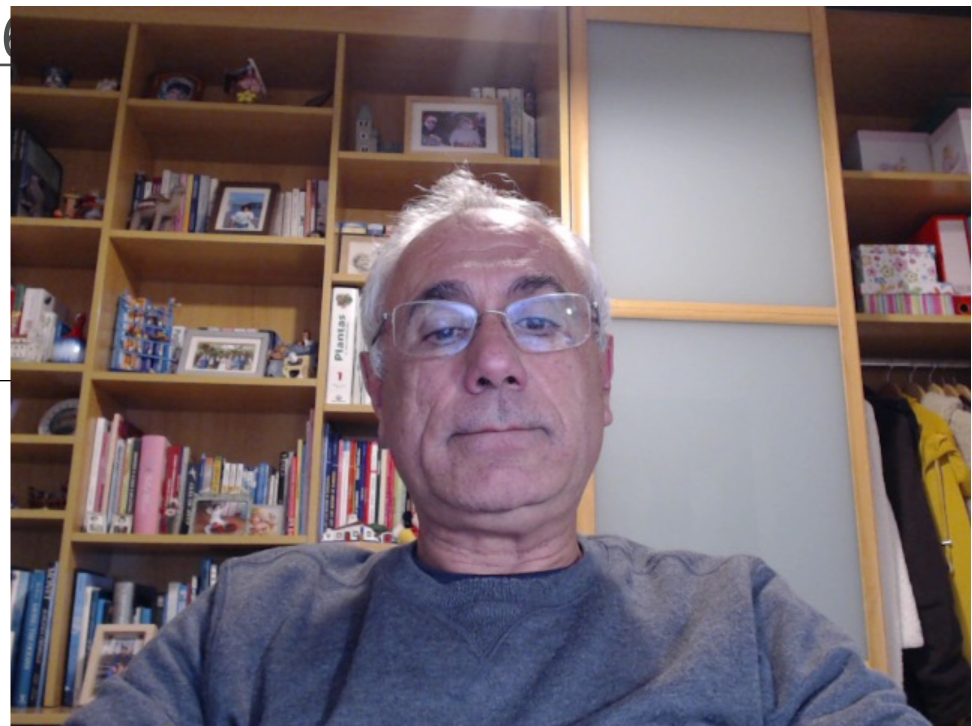
It will be shown that spatial variability of the vertical density gradient determines the biological productivity of oceanic regions as well as the locations of the regions of floating plastics accumulation.

Biological activity is more intense in regions where deep water can reach the upper ocean photic layer and plastics accumulate in regions were surface water sinks.

It will be also shown that the deep-water formation zones supply Dissolved Oxygen to the deep ocean assuring its health.



http://www.todayifoundout.com/wp-content/uploads/201



Plastics emitted in the Tagus Estuary

Plastics denser than water sink into the discharge zone and are trapped in the bottom. Others are transported by the currents.

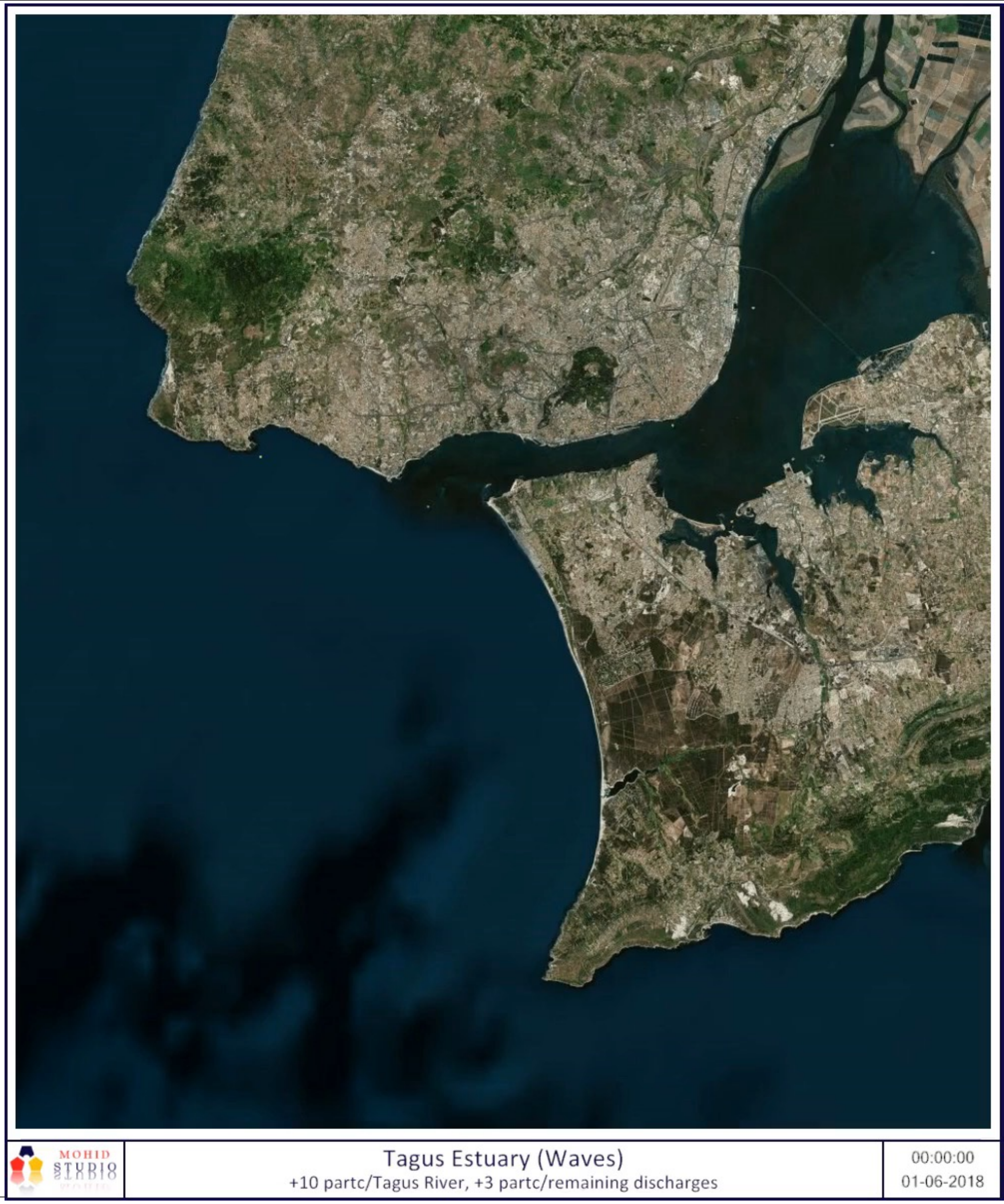
While moving along the coast Floating plastics can be stranded on the beaches, pushed by the waves and the wind, but most plastics will concentrate offshore in areas where surface water sinks.

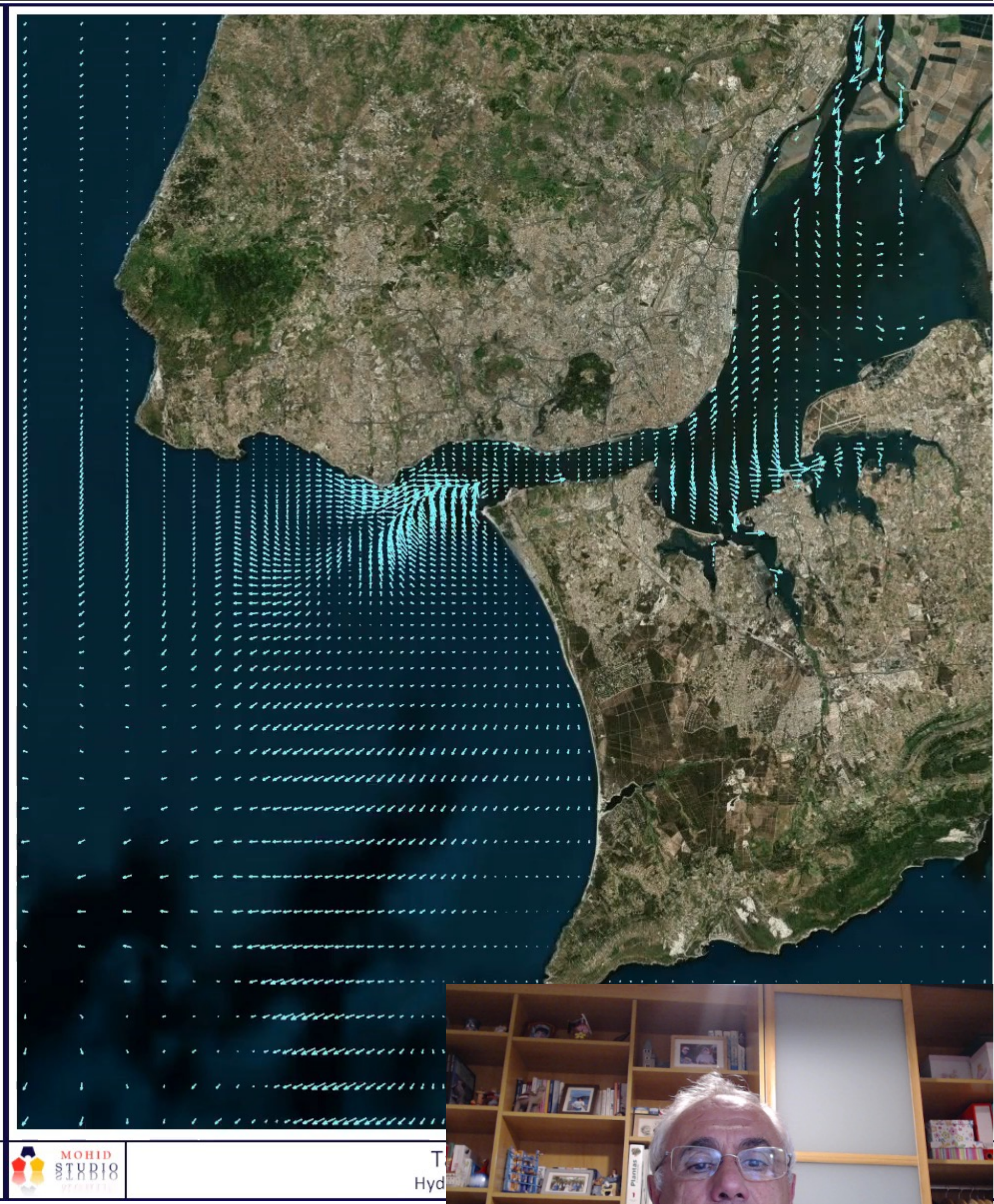
The next movies (click to start) show a 21 days simulation in June 2018 in the Tagus Estuary. The movie on the right shows the currents (dominated by the tide

The particles on the left movie represent floating plastic items. Particles have oscillatory movement, eventually leaving the estuary. Outside the estuary, particles move preferably south. Some are stranded on the coast.

This is the typical summer scenario. In some conditions, plastics can also go north, but end up resuming the displacement south and offshore (to the southwest).

http://www.cleanatlantic.eu/





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Plastics emitted by Atlantic European Rivers

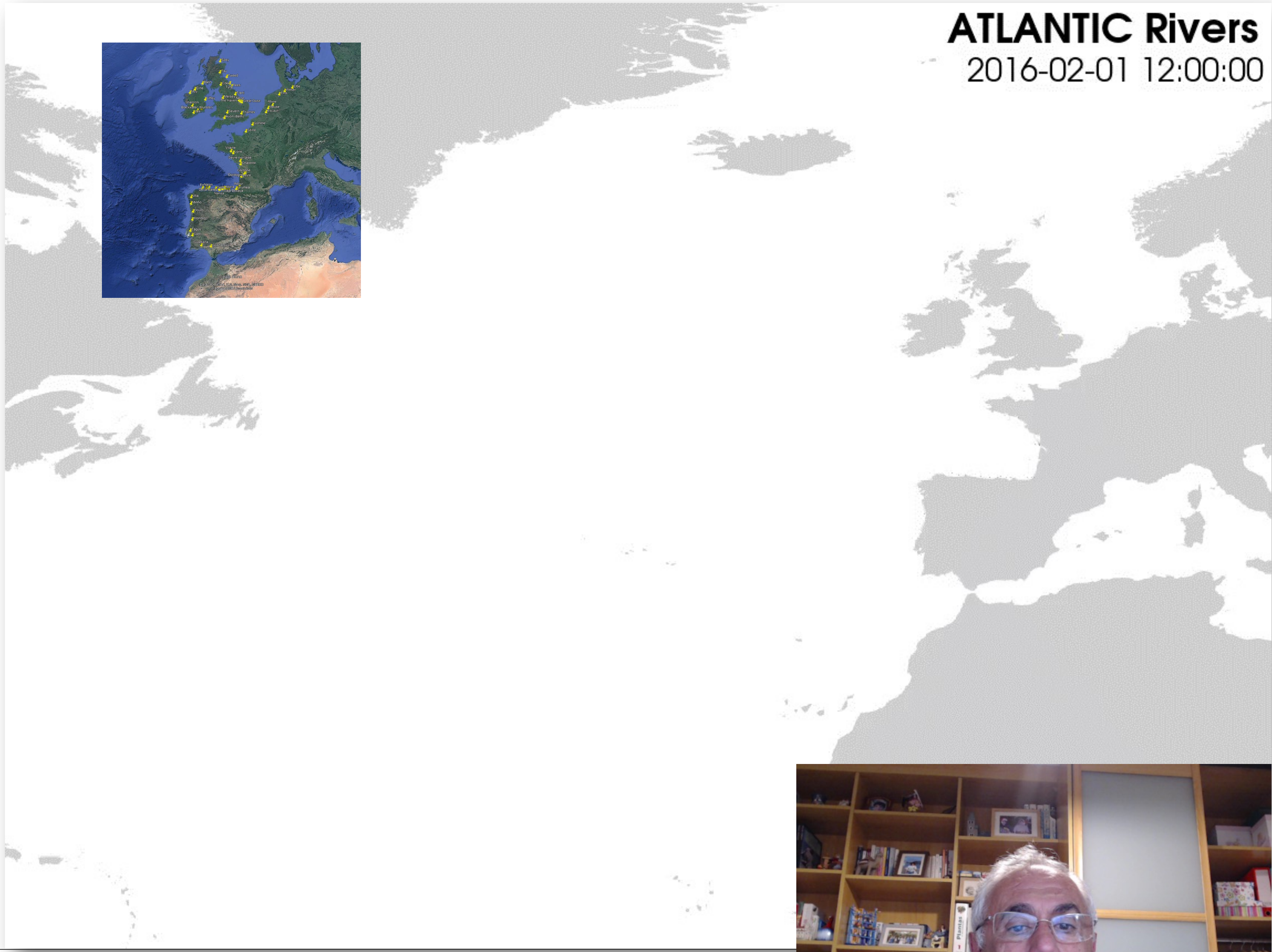
The next movie shows a simulation of the transport of plastics emitted in 68 rivers of Europe (yellow dots on the map) for about 4 years.

The simulation shows that plastics emitted south of the Bay of Biscay are preferably transported south. Some may enter the Mediterranean, but most will accumulate in the Sargasso Sea, taking about 2 years to get there. The plastics unloaded by the Tagus, shown in the previous slide, are transported by this flow.

The simulation shows that the west coast of Portugal is a zone of passage, and suggests it is not a zone of accumulation. The density of plastics varies throughout the year, being lower in the summer periods when the northern wind is more intense.

Plastics emitted north of the Bay of Biscay tend to move north, along the coast, toward the Arctic.

http://www.cleanatlantic.eu/

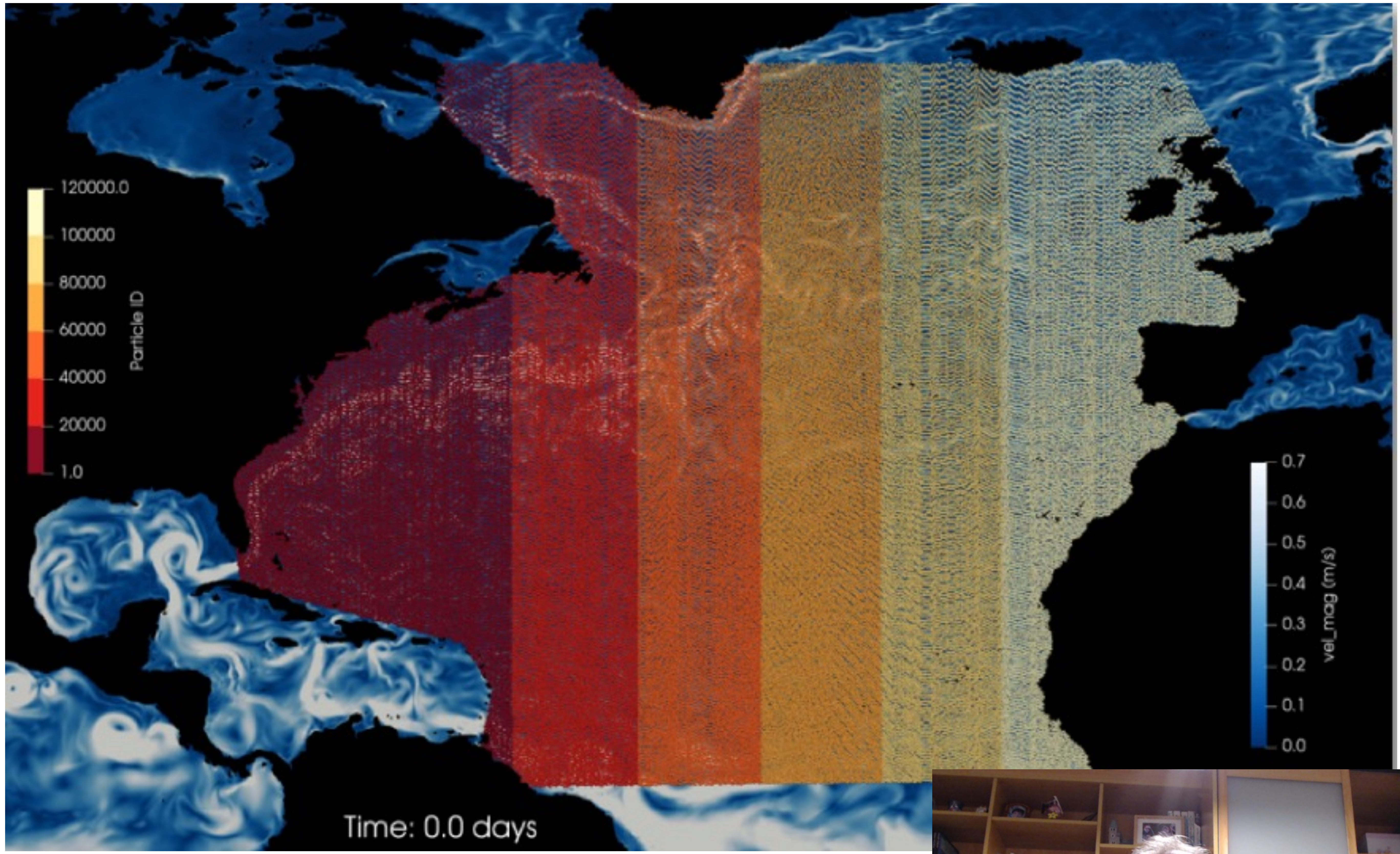


Instantaneous Plastic Emission: Accumulation zones in the North Atlantic

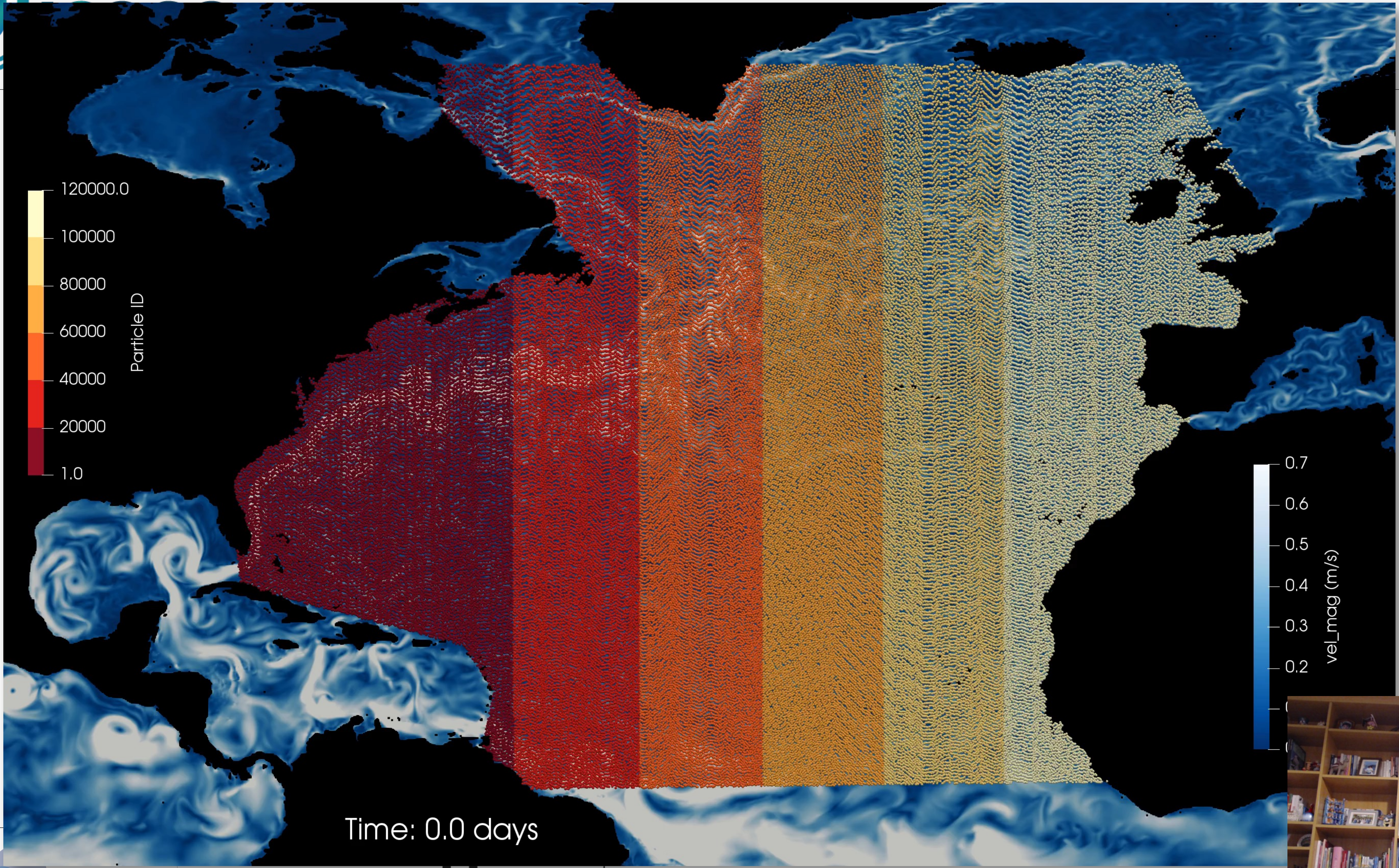
To identify the accumulation zones, the North Atlantic was covered with virtual plastics, which were followed over 2 years. To facilitate the identification of their origin, the particles were identified by colors, lighter to the east and darker to the west.

The simulation shows that the Iberian zone and the north Atlantic zone off Africa tend to clear. This means that they can be zones of passage, but they are not accumulation zones.

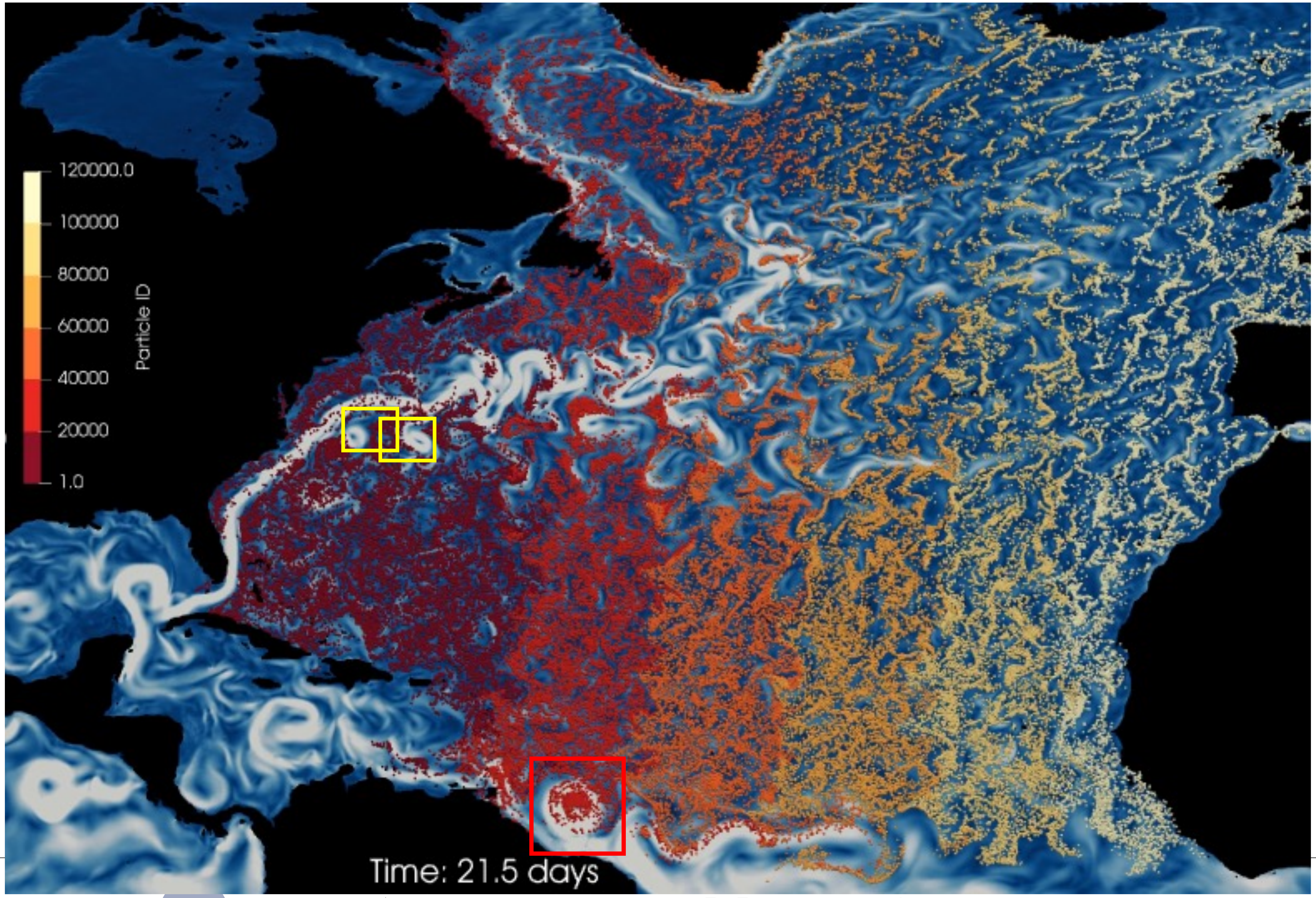
The Great accumulation zone is the Sargassos Sea, but the accumulation is in spots and is not continuous. The Gulf of Guinea is a smaller accumulation zone, but it also imports plastics.



http://www.cleanatlantic.eu/


120000.0
100000
80000
60000
40000
20000
1.0
Particle ID
0.7
0.6
0.5
0.4
0.3
0.2
vel_mag (m/s)
Time: 0.0 days

Interesting features



A uniform distribution becomes patchy because of eddies.

Patches tend to form in clockwise rotating eddies As the one inside the red square, where surface velocity converges due to Coriolis effect.

Eddies can be identified by the continuous background colour (white is maximum velocity). Eddies inside the yellow boxes are rotating counter-clockwise (diverging zones).

summary

The previous animations show that, as expected, the fate (and transport) of the plastics in the ocean is determined by the ocean circulation. The main currents are responsible for the global path.

A patchy distribution is formed, associated to the oceanic eddies. These patches can be important for satellite monitoring, because with present technologies sensors can identify floating plastics only if they occupy more that 50% of a pixel (minimum size 10x10 m^2).

These results show the importance of being able to know the detail of the velocity fields that, due to its spatial and temporal variability and to its tridimensionality can only be known using mathematical models.

Aim of the Lecture

This lecture aims to explain the Physical processes that are responsible for the fate of Plastics in the ocean and to show that accumulation zones are mostly the less biological productive zones.

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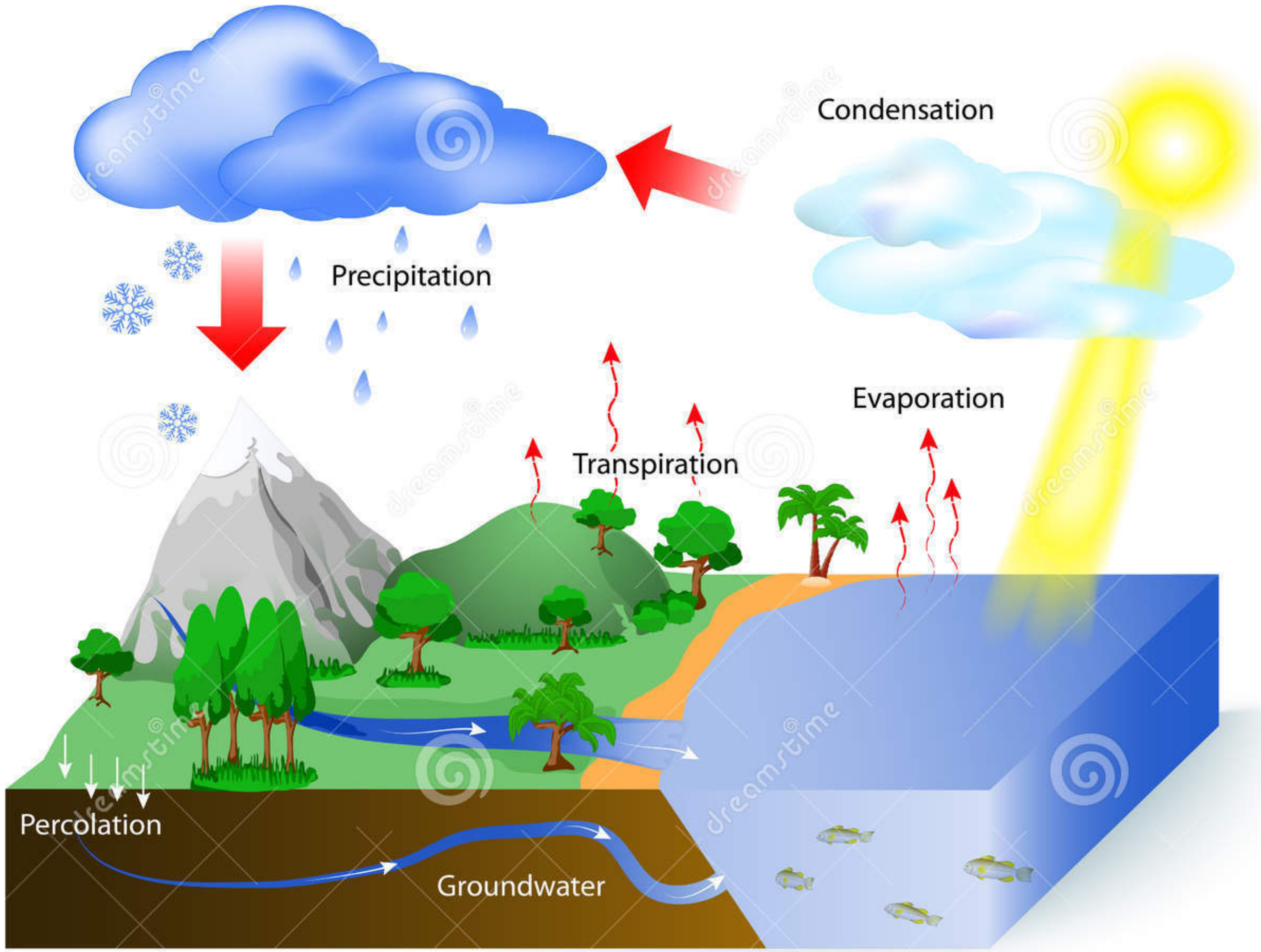
The Water Cycle. Why is the seawater salted?



Seas are salted because they keep accumulation salts. After precipitation, during its journey to the sea, freshwater dissolves salts that are carried by rivers and ground water to the sea/ocean. Subsequently the water is evaporated and goes, and salts remain. Salinity keeps increasing at a rate that depends on the local ratio evaporation/precipitation and on oceanic circulation.

The seas/oceans are the waterbodies with lower potential energy. Removing materials from there requires energy supply. Solar radiation is the main energy source. Promotes evaporation and generates horizontal transport, but no salts removal.

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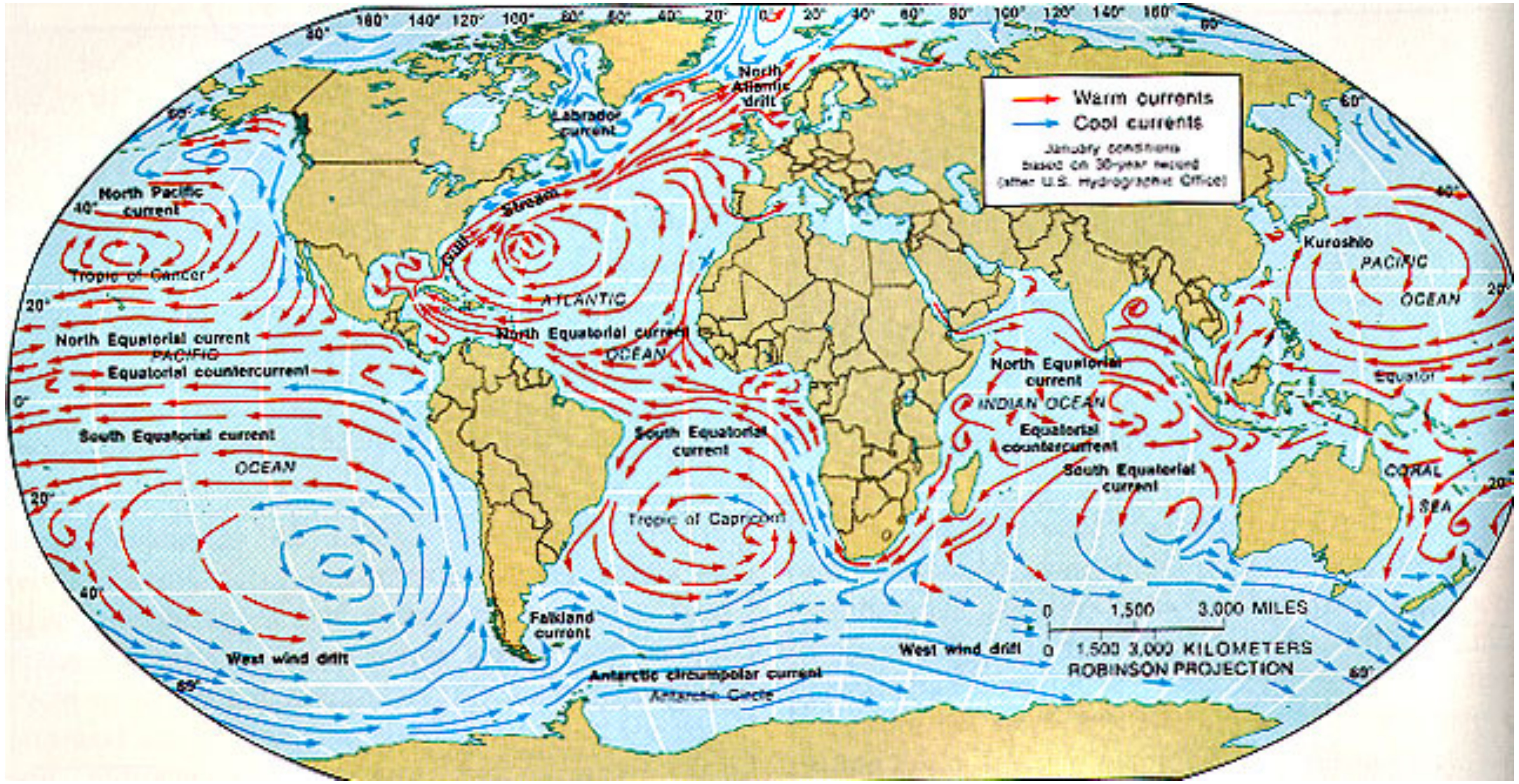
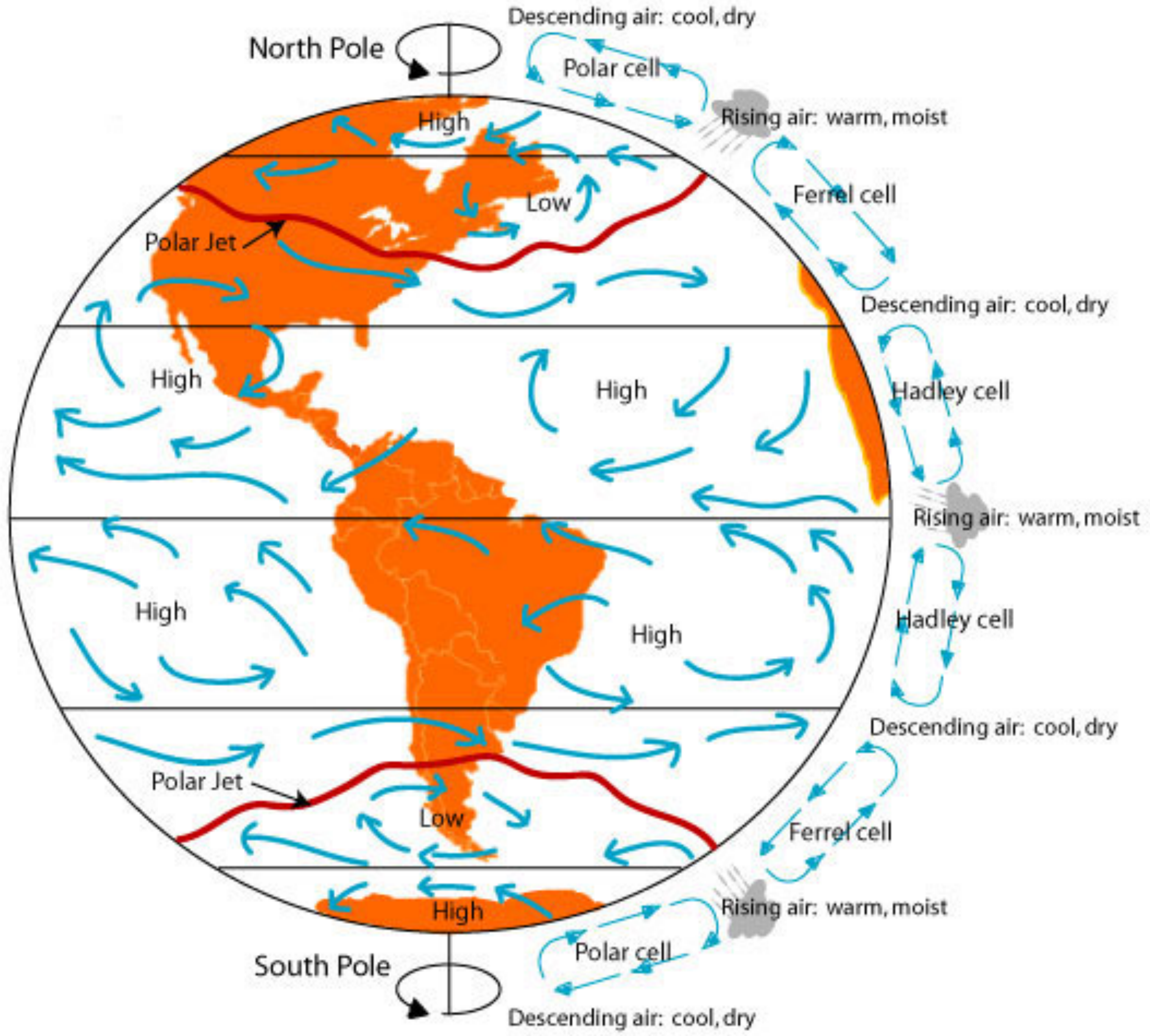
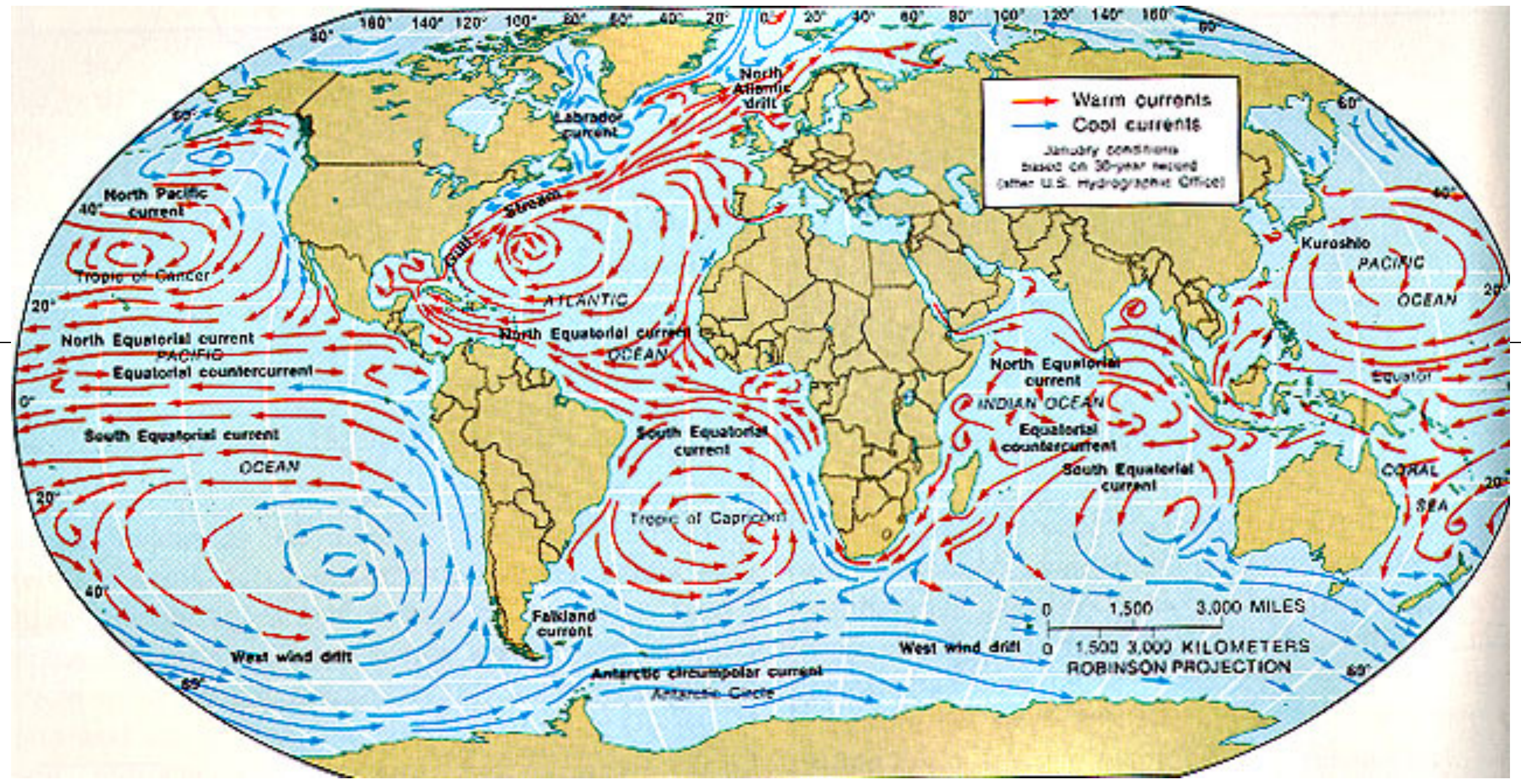
Ocean and Atmospheric Circulation Coupling

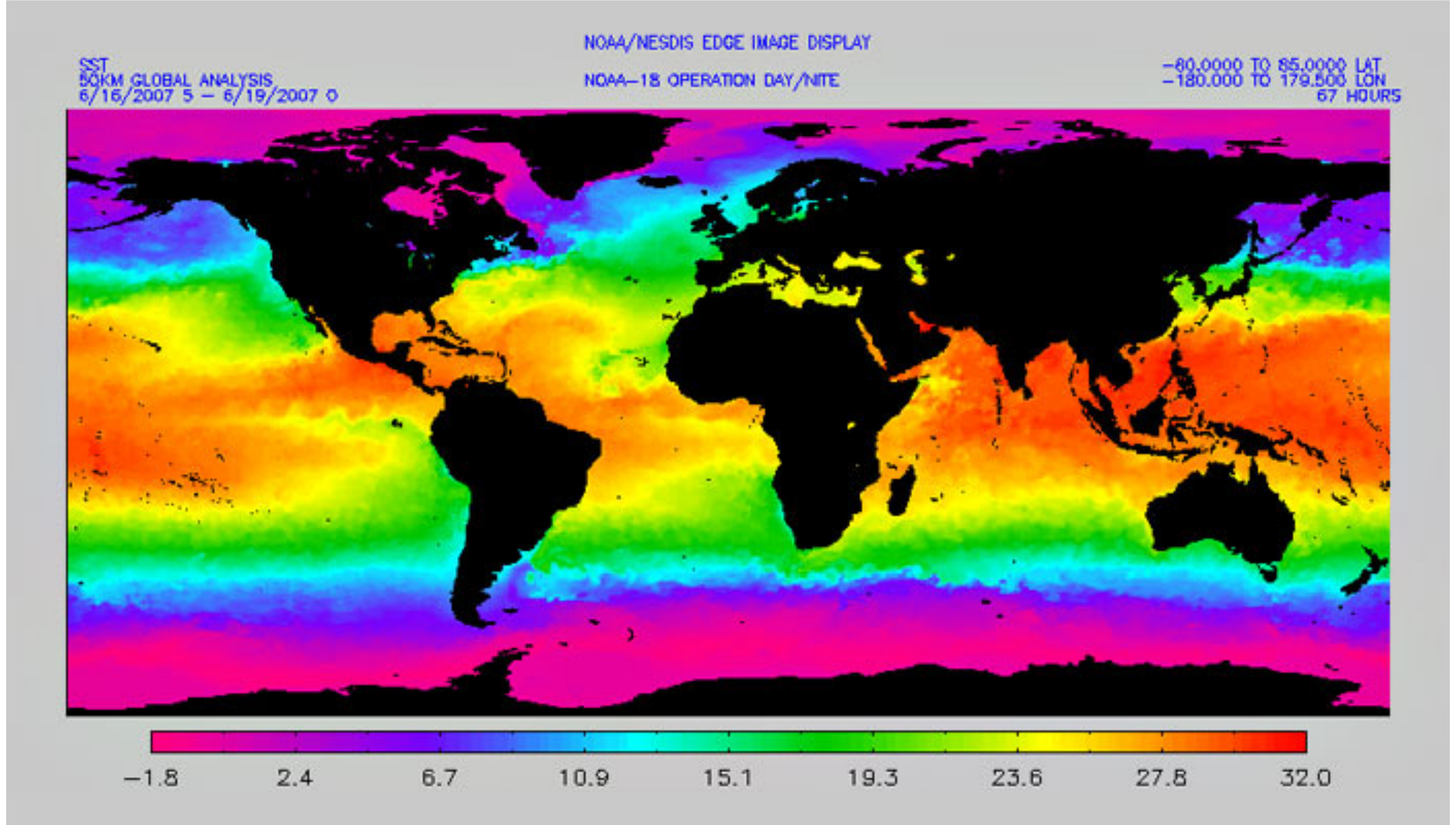




The left image shows the persistent ocean surface currents (warm currents on red and cold currents on blue) and the right-side image shows the persistent atmospheric circulation. There is a clear correlation between both images. Wind shear at the sea surface is in fact a major ocean circulation driver. Wind is forced by atmospheric pressure distribution, and this is a function of air density, which is a function of solar heating. Solar radiation drives the ocean circulation indirectly through the wind and directly, modifying the ocean-water density (salinity and temperature), generating the thermo-haline circulation.

Ocean Surface Temperature

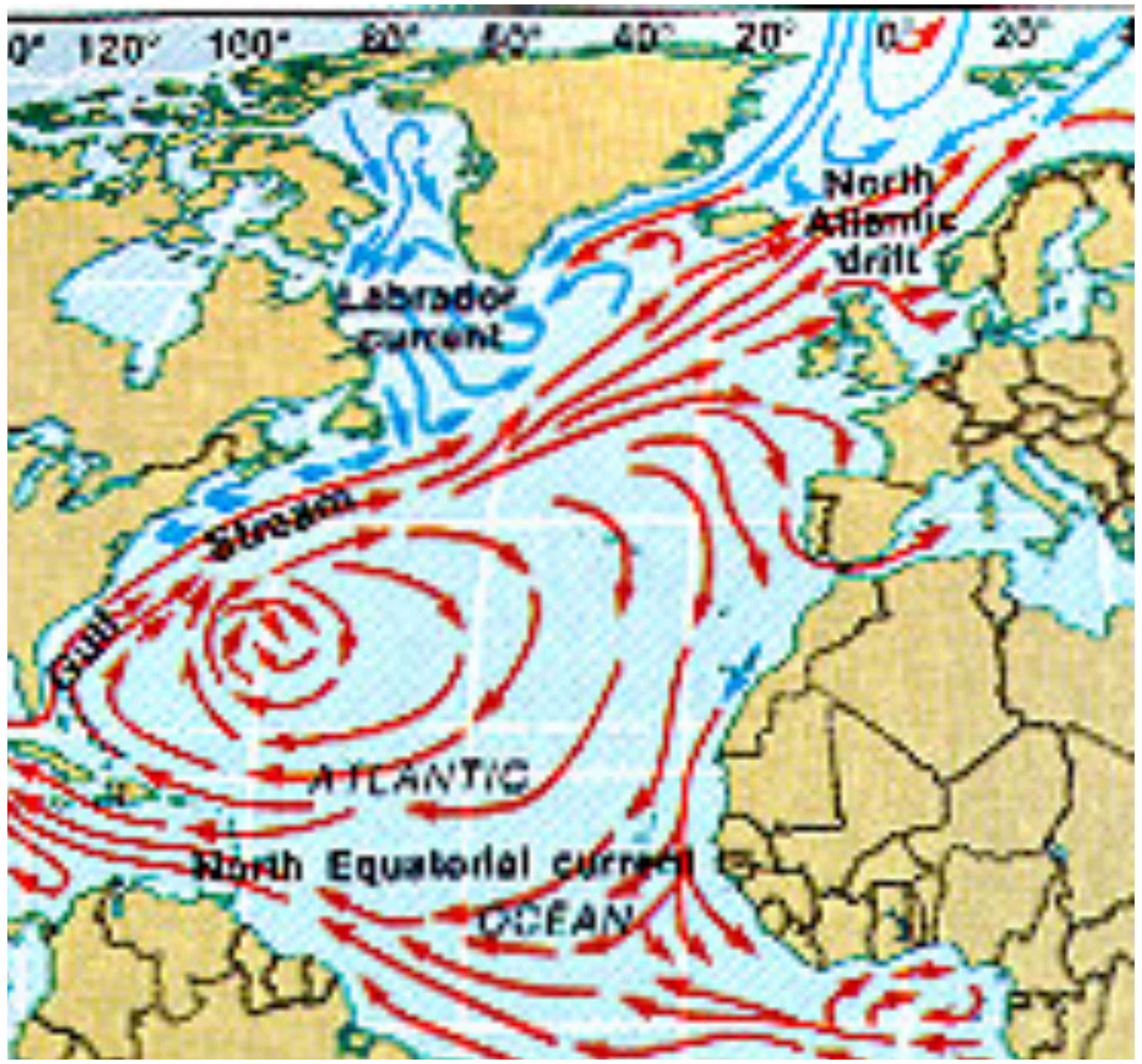




Surface, warm currents, carry heat to the higher latitudes and cold currents carry cold water equatorward, contributing to redistribute heat in the ocean.
The warm water tends to move along the western oceans coast and the cold water moves along the eastern coast because this is also the wind flow pattern due to the coriolis force generated by the earth rotation. Again, due to Coriolis Force, the surface water (warmer) tends to move to the centre of this eddy (carrying floating plastics).

Some anomalies appear (e.g., colder water along the equator but also along the Sahara, Namibia or California). This is due to upwelling of cold nutrients rich enhancing biological activity. On the contrary, downwelling regions concentrate surface water (warm) and accumulate plastics.

The Global circulation and the Plastics transport



This image shows the typical ocean surface velocity pattern. The big eddy is forced by the Azores Anticyclone. The northern part of the eddy is the Gulf-Stream current. This eddy generates a southward flow south of the Biscay Gulf, and northward flow, north of this Gulf. Theses flows are responsible for the transport of plastics emitted I Europe.

Through the Gibraltar straight there is a flow to the Mediterranean Sea and south of the eddy there is a flow oriented to the Gulf of Guinea. Plastics discharged along the northern coast of south-America also move to the Sargassos Sea!!

Forces responsible for the ocean Circulation

The surface wind shear stress,

Is a surface force and the main responsible for the flow field in the upper ocean layer

The thermo-haline circulation,

Is due to the density gradients, i.e., due to the Temperature and Salinity gradients. Acts along water column (thousands of meters) and consequently is the most important force driving the ocean circulation,

The tidal forcing,

Results from the attraction (gravitational) force between celestial bodies (Moon and Sun). It is the major driver of circulation in semi-enclosed water bodies (e.g., Estuaries Gulfs and some coastal seas).

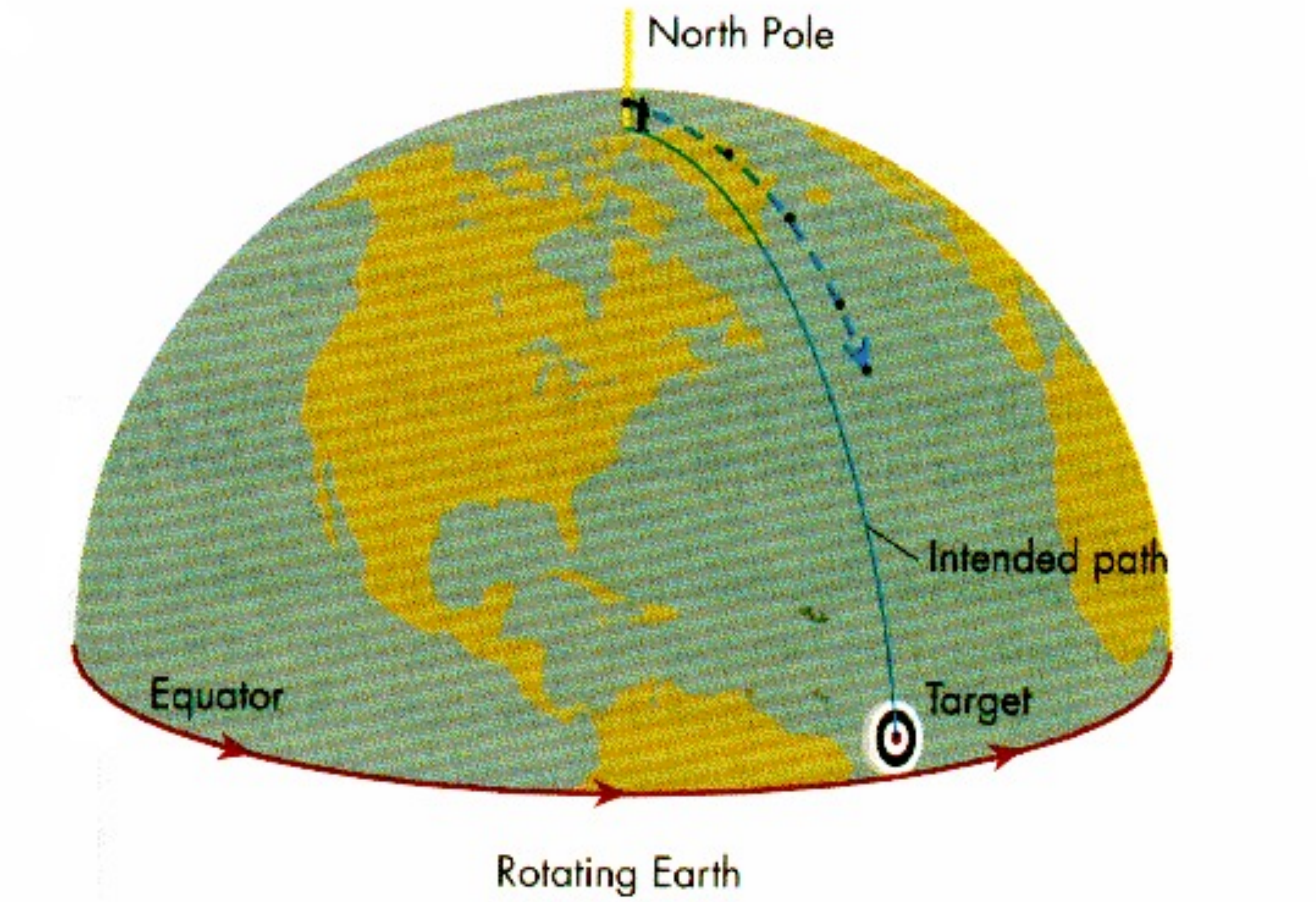
The Coriolis force,

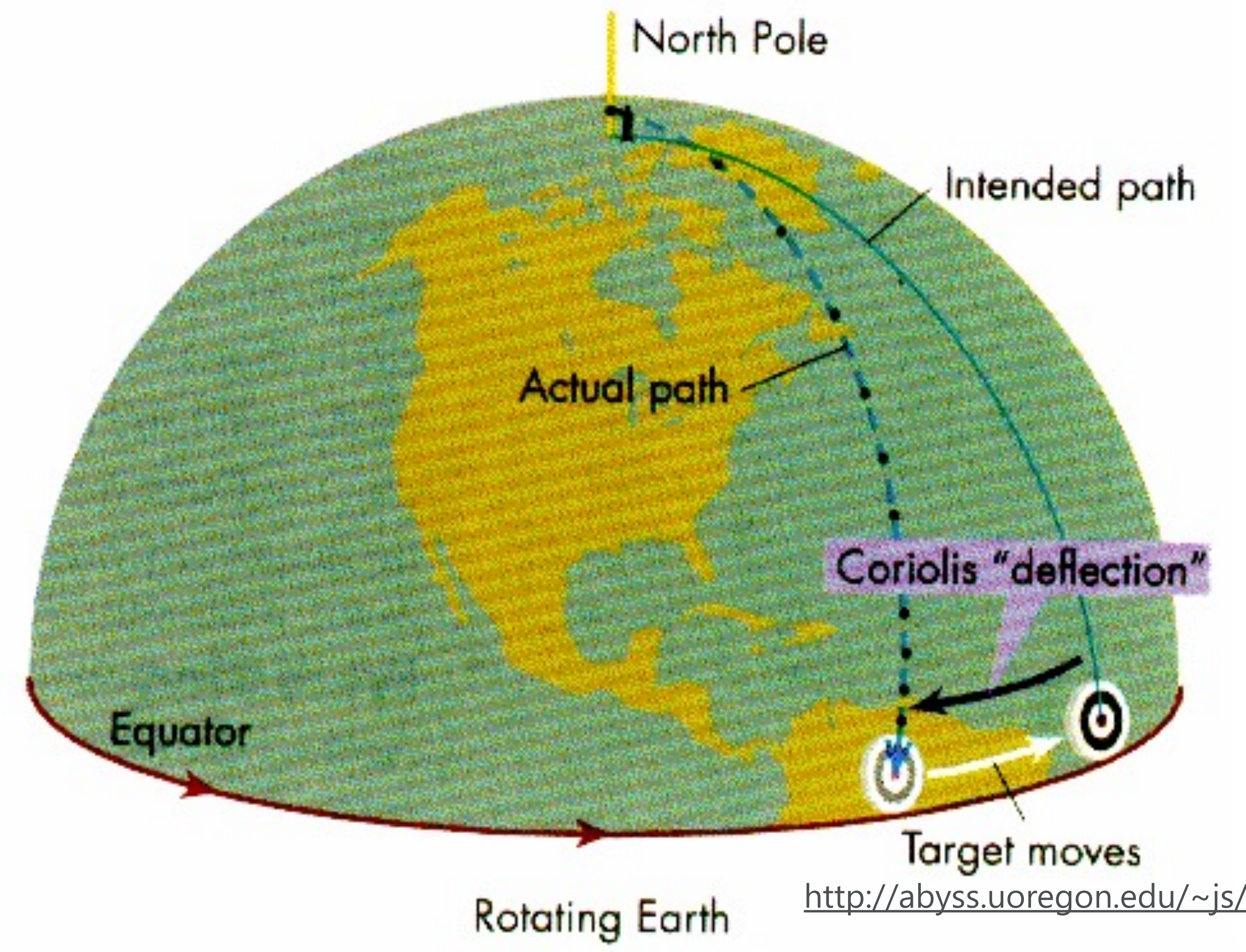
Is an inertial force due to the Earth Rotation. Deviates the flow originated by the driving forces to the right in the northern hemispheres and to the left in the southern hemispheres.

Free-surface level gradients,

Are a consequence of the null velocity divergence and tend to balance the external forces (and coriolis)

Earth Rotation: Coriolis effect





http://abyss.uoregon.edu/~js/glossary/coriolis_effect.html

What would happen if the stone was thrown along a parallel?

It would also move to the right (in the Northern Hemisphere)!!!

$$V_\theta = \omega R$$

$$F_{coriolis} = 2\left(\frac{2\pi}{T}\right) V \sin\theta = fV$$

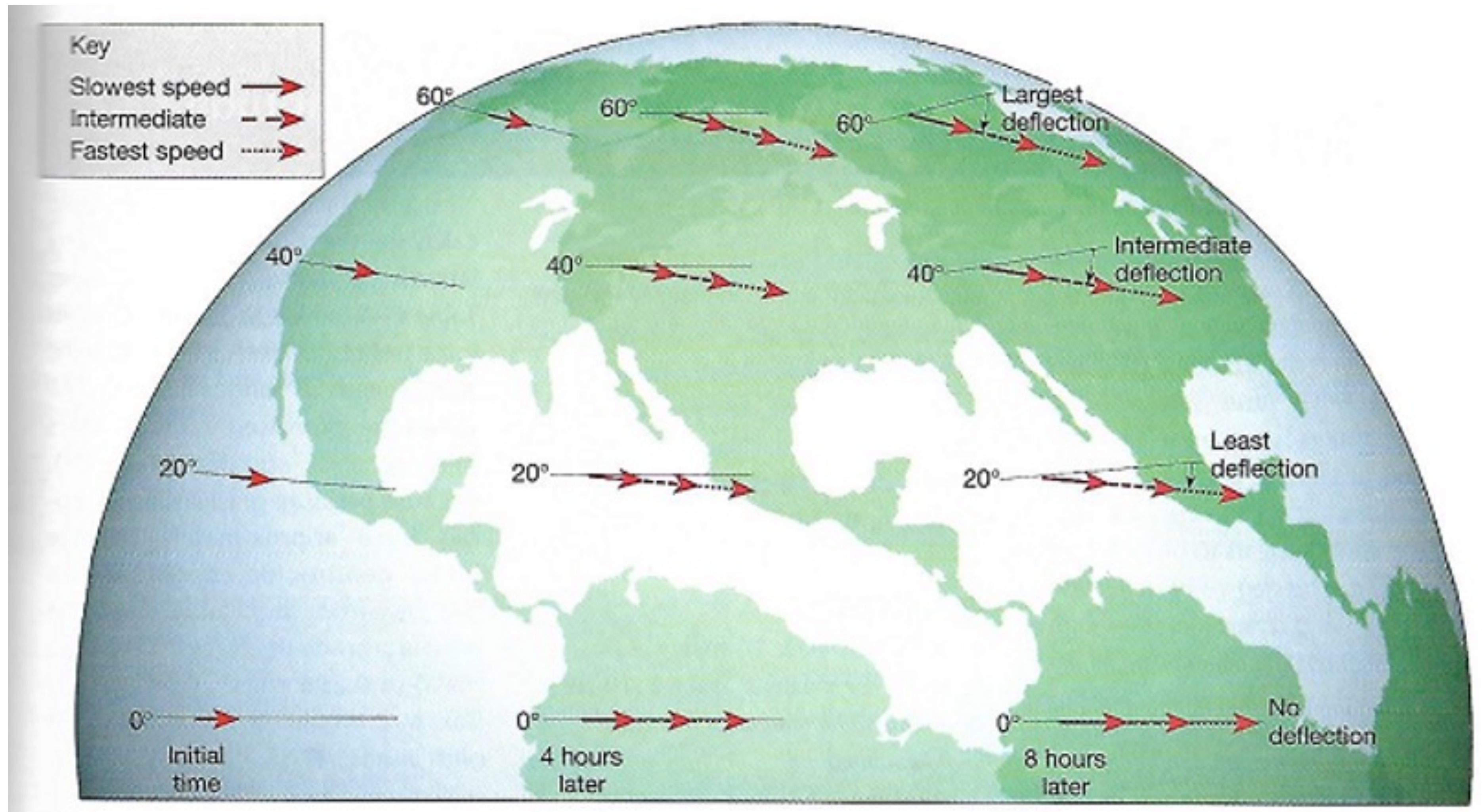


Figure 6–12 Coriolis deflection of winds blowing eastward at different latitudes. After a few hours, the winds along the 20th, 40th, and 60th parallels appear to veer off course. This deflection (which does not occur at the equator) is caused by Earth's rotation, which changes the orientation of the surface over which the winds are moving.

R is maximum at the equator. When we move away from the equator one have a tangential velocity higher than the ground.

Coriolis effect (zonal movement)

If the stone was sent eastward, it would have a tangential velocity higher than the earth tangential velocity at the same place. Therefore, it would be submitted to a higher centrifugal force, and it would be deviated towards the equator, i.e., to the right in the northern hemisphere and to the left in the southern one.

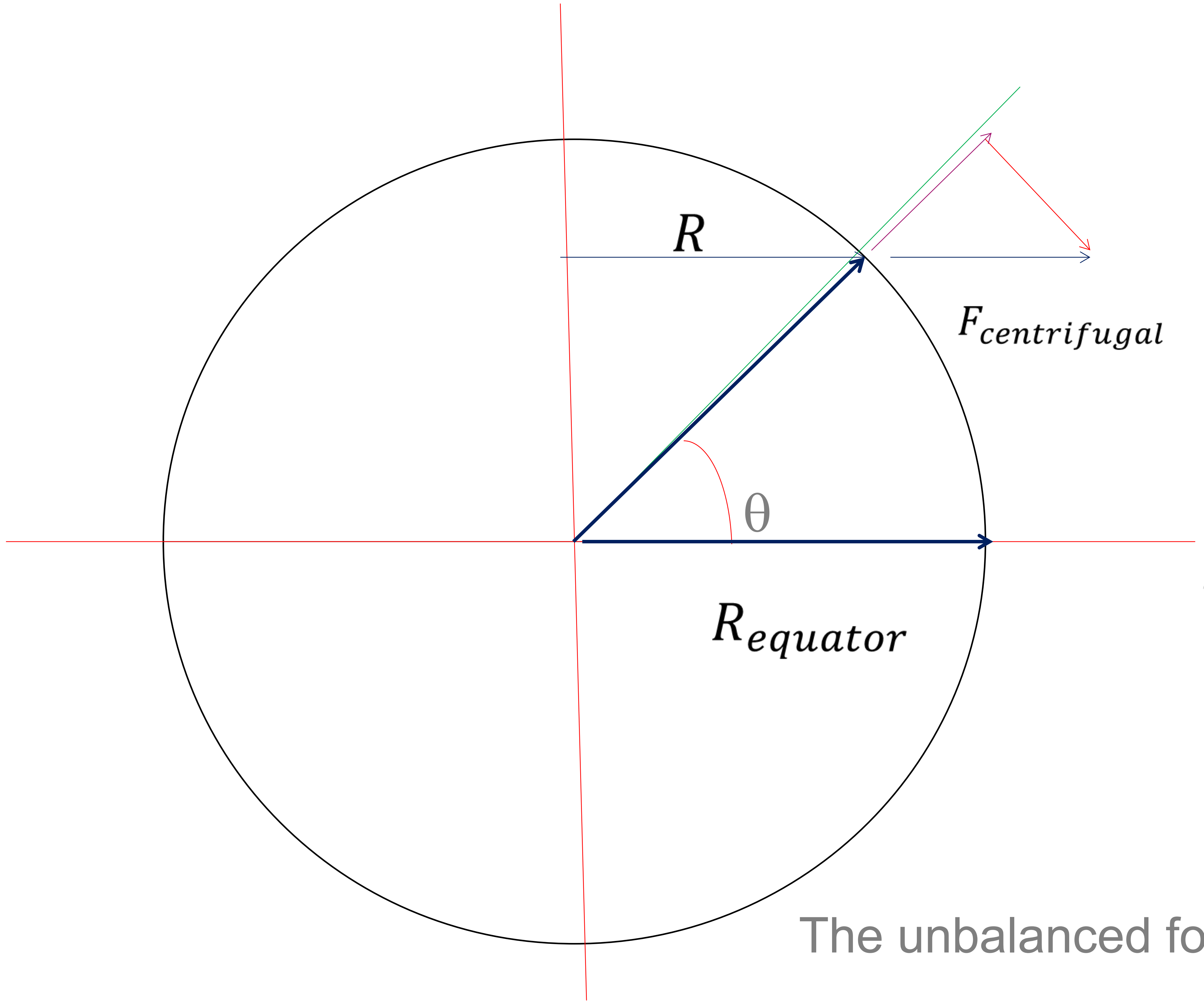
If the stone was thrown westward its tangential velocity would be smaller, and then the centrifugal force would me smaller and the stone would be deviated towards the pole.

The stone only feels the difference between its own velocity and the earth velocity because the earth is deformed due to the centrifugal force. Due to this deformation the gravity force that acts along a line linking the place to the center of the earth can be decomposed in two forces, one perpendicular to the earth surface and another pointing to the pole This two forces and the centrifugal force balance. Additional movement tangential movement deviates the system from equilibrium.

Anticyclonic and cyclonic movement in the high and low atmospheric pressure regions is a consequence of coriolis and the coastal upwelling in the ocean generated by the wind is also a consequence of the atmospheric pressure.

The high and low temperatures in oceanic eddies according to the sense of rotation and its size variation when submit to meridian movement as well.

Coriolis in case of zonal movement



A body rotating with the earth suffers a centrifugal force (per unit of mass):

$$R = R_{equator}\cos\theta$$
$$V_\theta = \omega R = \omega R_{equator}\cos\theta$$
$$F_{centrifugal} = \frac{(V_\theta)^2}{R} = \left(\frac{2\pi}{T}\right)^2 R_{equator}\cos\theta$$

The centrifugal force can be decomposed into a radial and a tangential component:

$$F_{tangential} = \left[\left(\frac{2\pi}{T}\right)^2 R_{equator}\cos\theta\right]\sin\theta$$
$$F_{tangential} = \frac{(V_\theta)^2}{R}\sin\theta$$

This tangential force is balanced by an oval deformation of the earth. The earth cannot be spherical!!!

A body with velocity (V) rotating with the earth suffers a centrifugal force:

$$V_\theta = (\omega R + V) =$$
$$\left(F_{centrifugal}\right)_{mov} = \frac{(V_\theta + V)^2}{R} = \frac{(V_\theta)^2}{R} + \frac{2(V_\theta * V)}{R} + \frac{(V)^2}{R}$$

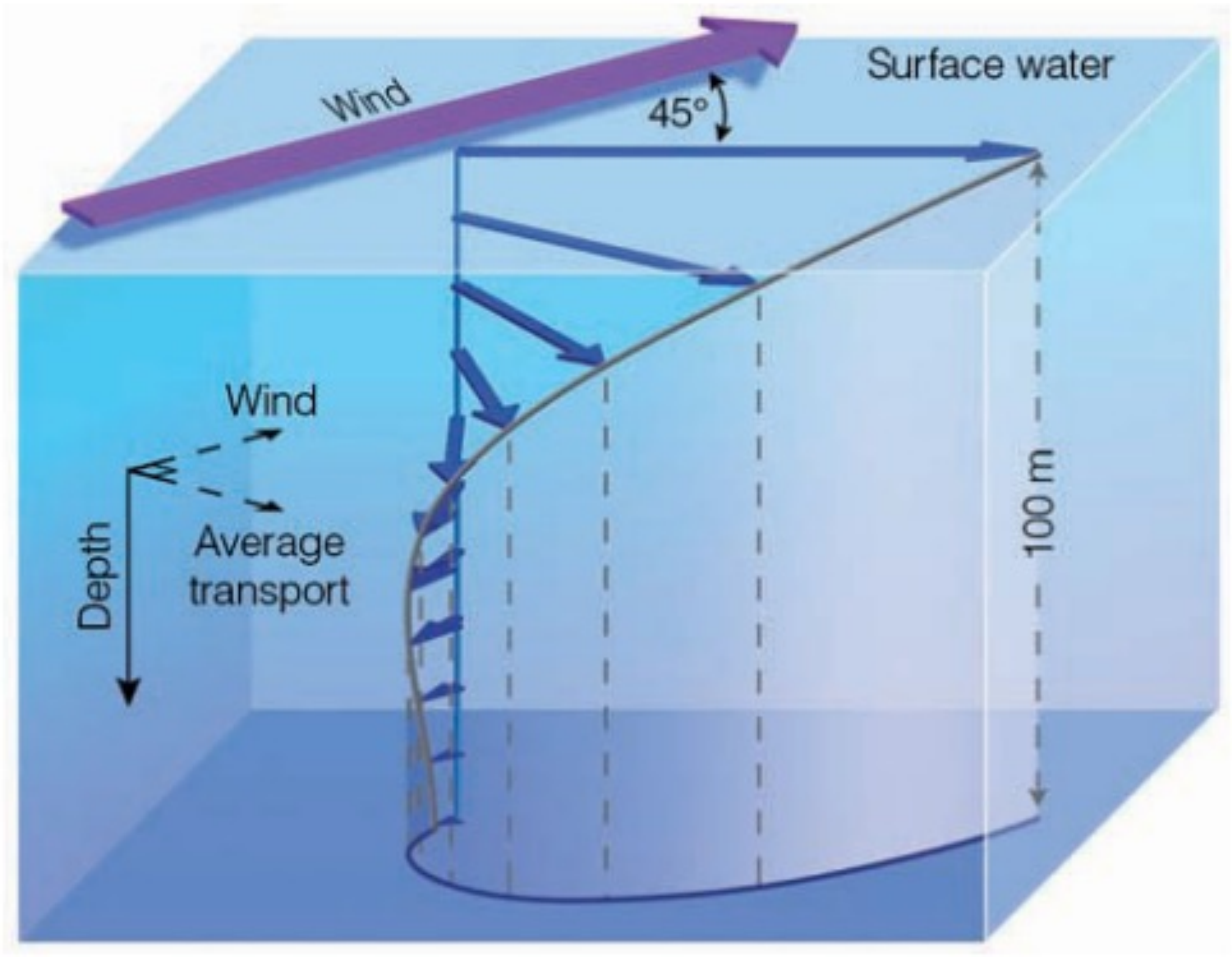
The unbalanced force is: $$(F_{cent})_{mov} - F_{cent} = \frac{(V_\theta + V)^2}{R} - \frac{(V_\theta)^2}{R} = + \frac{2(V_\theta * V)}{R} + \frac{(V)^2}{R} \approx \frac{2(V_\theta * V)}{R}$$

$$F_{tangential} = \frac{2(V_\theta * V)}{R}\sin\theta = 2\left(\frac{2\pi}{T}\right)V\sin\theta = fV$$

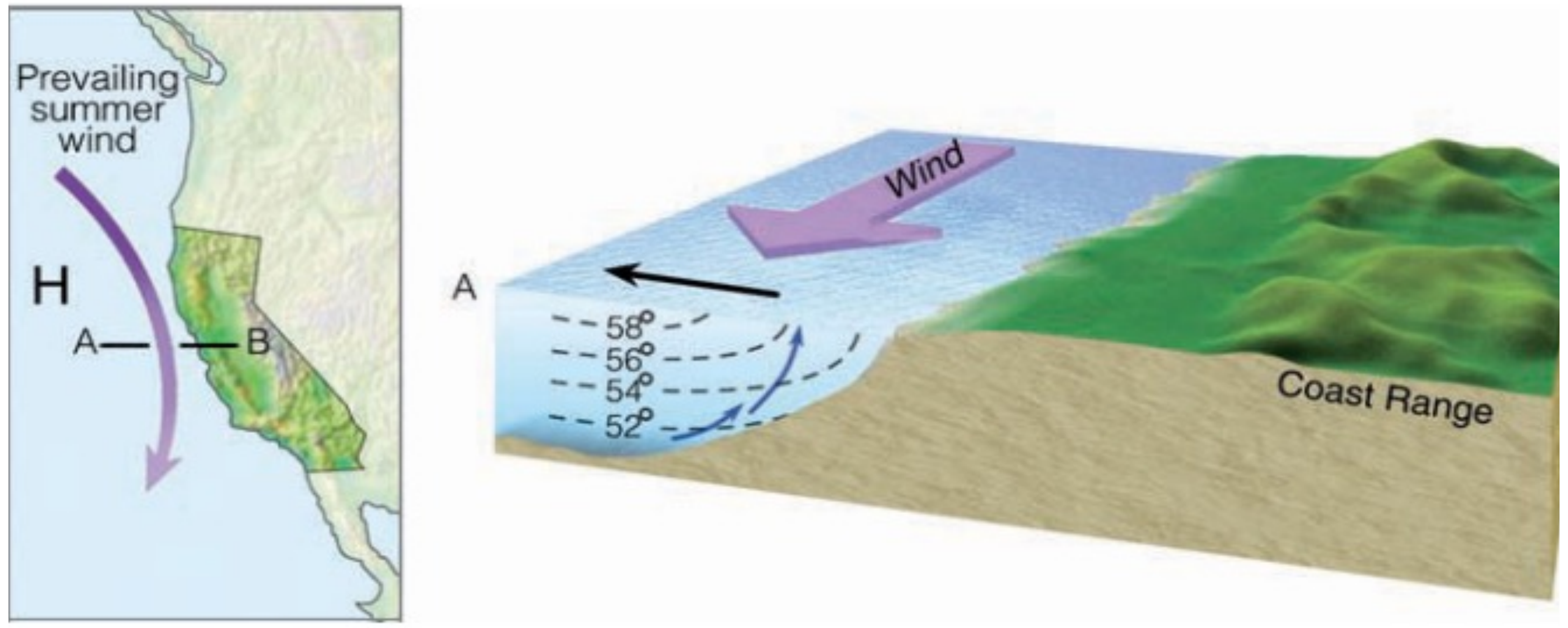
A body moving over the earth, whatever is the movement, will feel the coriolis force!!!

Upwelling: The Ekman Spiral

When the wind blows over the ocean creates movement in the sea surface layer.
If there was no Coriolis (no earth rotation) the sea water would follow the wind flow. Because of Coriolis, the water gets a velocity component perpendicular to the wind and rotates to the right.
When the surface layer of the ocean starts moving, a force will be applied on the water below and then a second layer will start moving. Because of Coriolis, the second layer will rotate further to the right and then the third, the others below and a spiral (Ekman spiral) is formed.
The equilibrium flow happens when at the surface the angle between the wind speed and the sea surface water velocity is 45 degrees and integrating along the vertical, the average velocity makes an angle of 90 degrees with the wind and, globally, the sea water displacement is perpendicular to the wind.
In the northern hemisphere, wind blowing from north along the eastern Atlantic coast will push the coastal water off the coast, decreasing the water level. This water-level decrease will generate a upward movement (upwelling) that pushes surface water off the coast (carrying plastics away) and brings deep water nutrients' rich to the surface enhancing biological productivity.



Coastal Upwelling



A wind blowing from north along the eastern northeast Atlantic coast will push the coastal water off the coast generating upwelling. For the same reason, the upwelling appears in the north pacific along the Californian coast as represented in the Figure.

The northern wind pushes the surface water to the right. This movement decreases the surface level along the coast and tends to increase it off the coast, creating a pressure gradient that affects the whole water column. Consequently, the water below the surface not acted by the wind will move towards the coast pushed by the pressure gradient and can reach the surface. Stronger is the wind, stronger is the pressure gradient and deeper is the water that can move upwards (temperature of the lower layers is lower and consequently the density is higher).

This process is called coastal upwelling and is responsible for the decreasing of the temperature along the coast. Typical summer winds can rise water 200-300 meters deep and are responsible for temperatures along the Portuguese coast of the order of 15ºC in summer. This water immerge from a dark layer of the ocean where there is no photosynthesis and is reach on mineral nutrients necessary to phytoplankton growth. This is why upwelling regions are biologically reach, producing more fish than other oceanic regions.
In winter, when the wind blows from the south for long periods, the opposite happens, and upwelling regions become downwelling regions.
The next slide shows the results for the Iberian coast and the subsequent shows the solution for the whole world, including the southern hemisphere. The third slide shows the global circulation induced by the wind, that can be easily correlated with the ocean anticyclones.

Upwelling/downwelling off Iberia

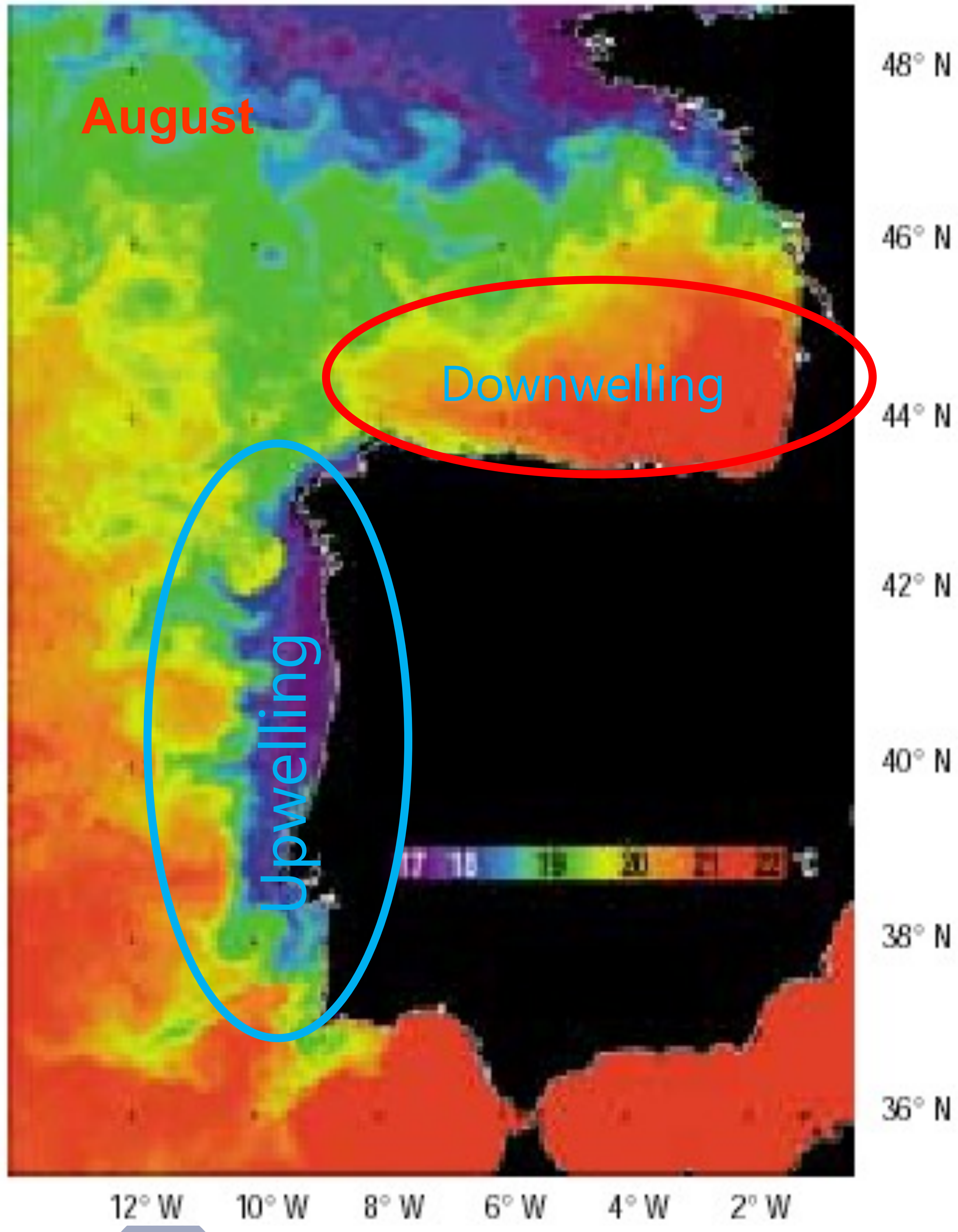
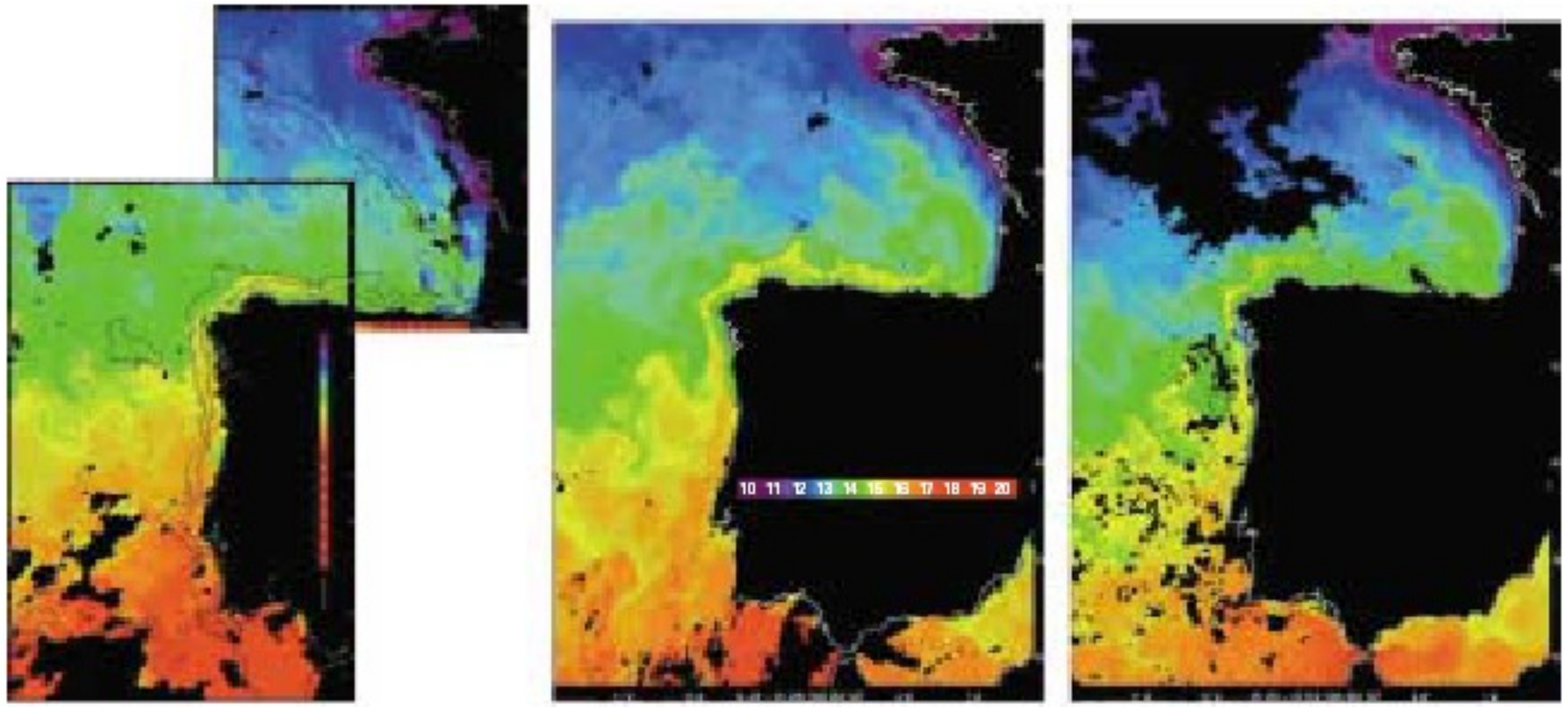
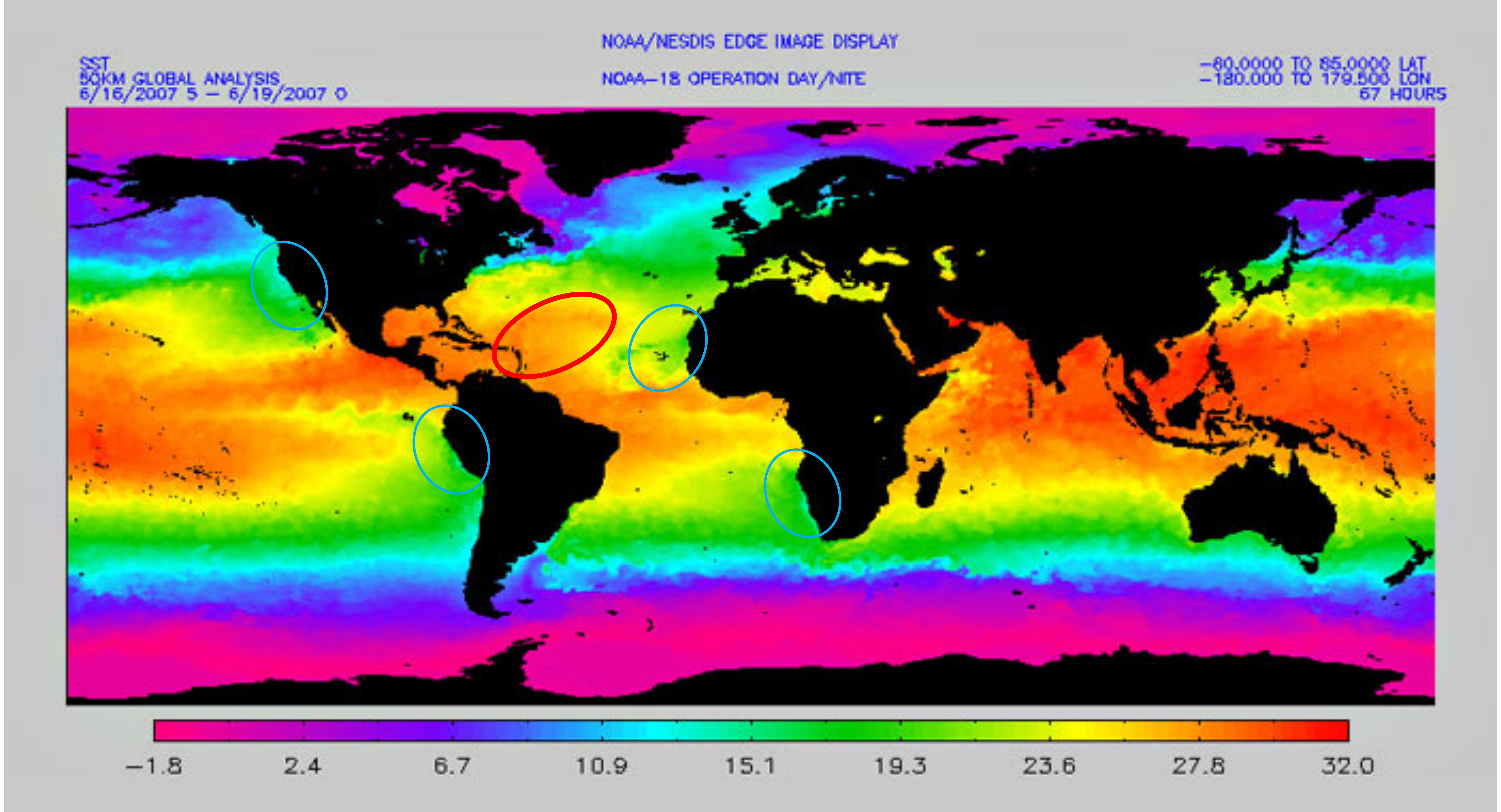


Figure 2.9 Weekly composite sea surface temperature images, winter 1995/6. Land and cloud covered areas appear black. Source: CCMS.

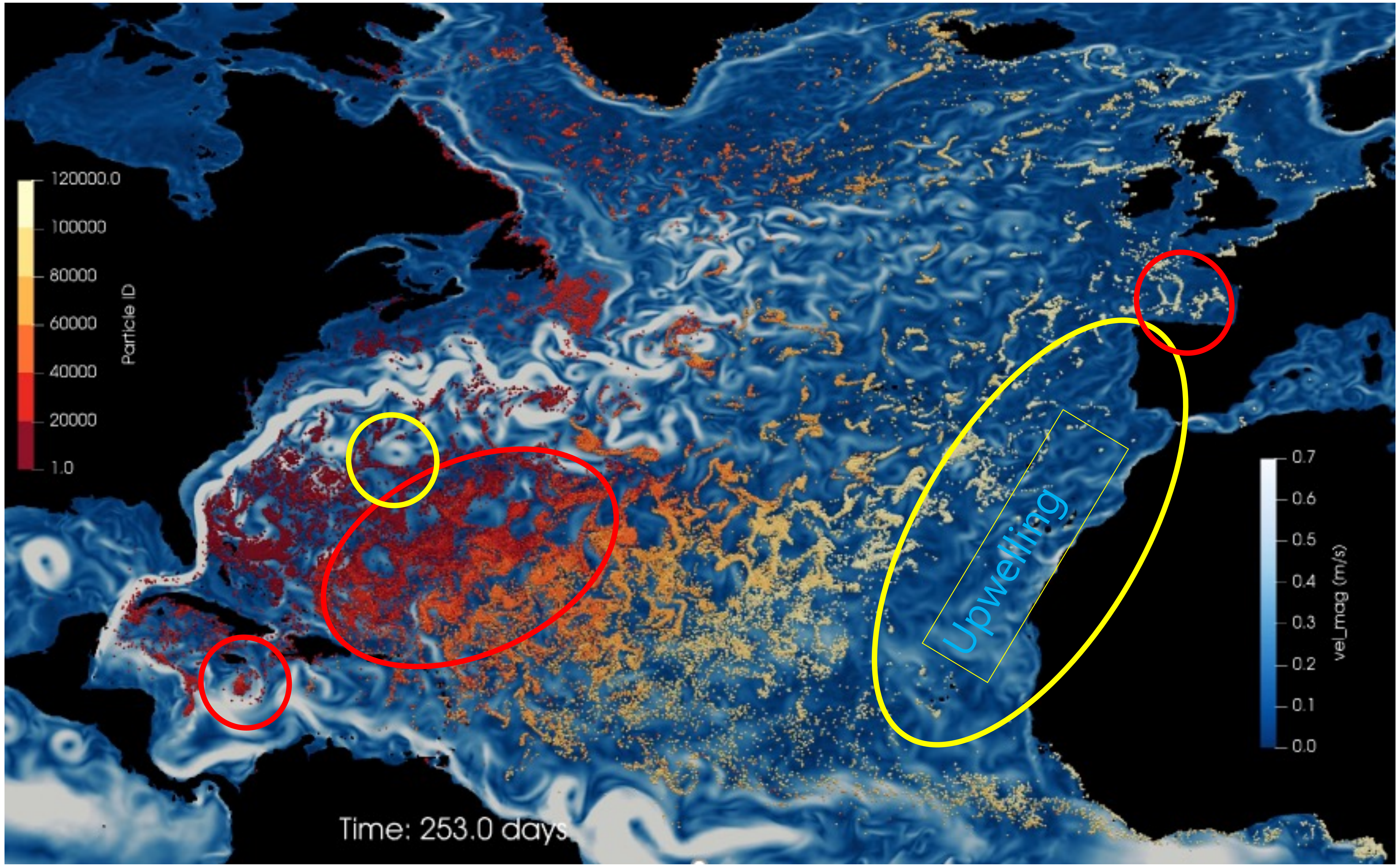


31 Dec 1995 – 6 Jan 1996   14 – 20 Jan 1996   28 Jan – 3 Feb 1996

Major world upwelling regions



Upwelling and Plastic divergence



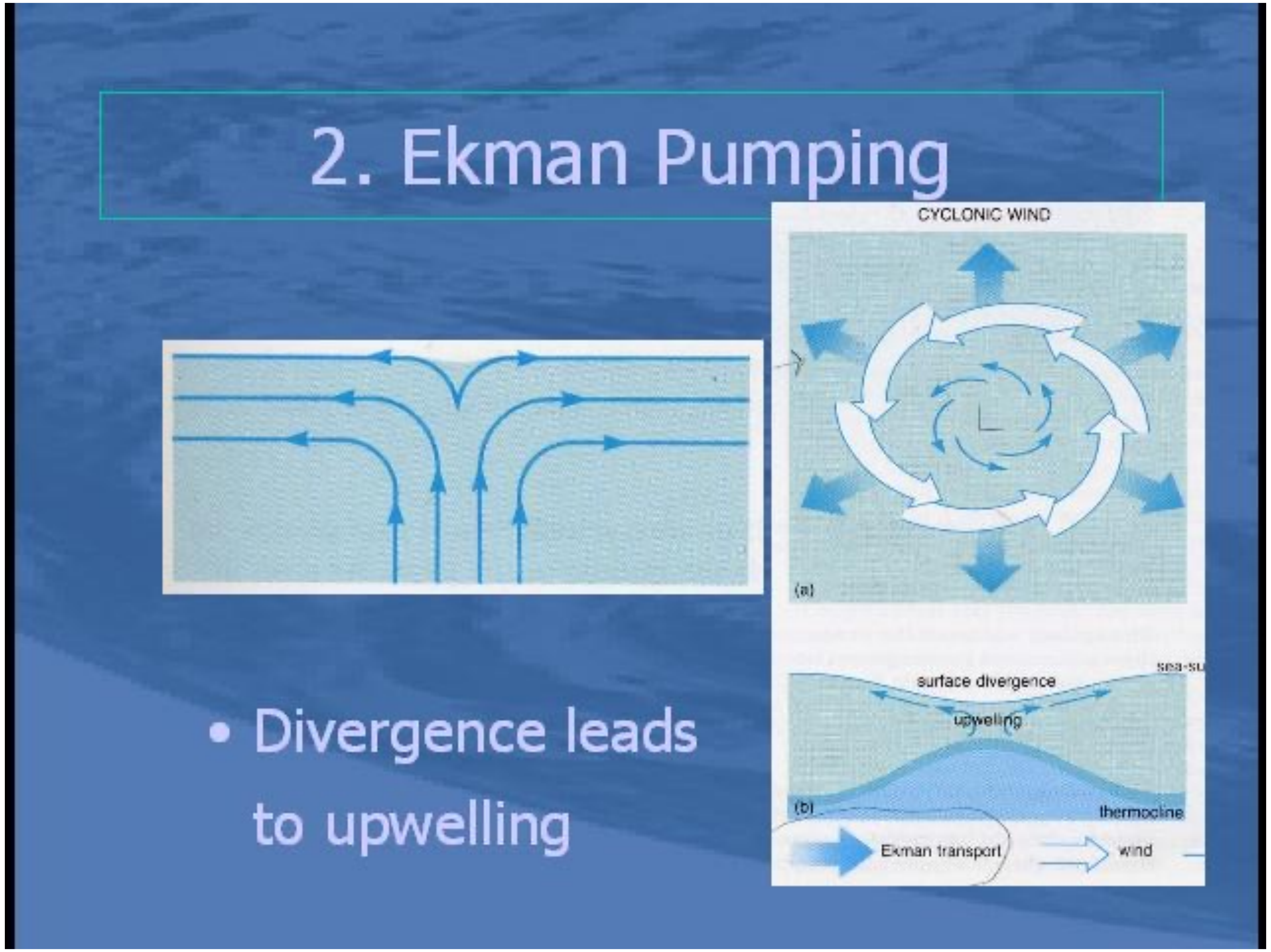
Surface flow in upwelling regions is "divergent" supplied by rising (deep) water. Plastics do not accumulate (and biological activity is high).

In downwelling regions flow is "convergent" supplied by descending surface water. Plastics accumulate (and biological activity is low). This happens at regional scale in the Sargassos Sea and locally in clockwise rotating eddies.

Vertical transport (induced by horizontal transport) is the major cause of marine regions specificity because most oceanic regions are density stratified.

The Coriolis force and the Surface Ocean Dynamics

The dynamics of the ocean surface layer (200 meters) is dominated by the wind forcing plus coriolis. The shear stress drives the movement and Coriolis deviates it to the right (in the northern hemisphere), generating convergence or divergence according to the sense of the movement. Convergence generates downward movement concentrating floating material (e.g., Plastics, but also warm water) and divergence generates upward movement (Ekman pumping) pulling cold water (nutrient rich) upwards enhancing biological activity.



https://www.ias.ac.in/public/Resources/meetings/myrmeet/pjm1_talks/pnvinayachandran/img4.html

Summary of Ocean Dynamics Controlling Processes

Ocean Dynamics is controlled by forces (Newton law). When the application point of a force moves, work is produced and therefore energy must be supplied to the system. In the ocean that energy is provide mostly by solar radiation. A smaller part is provided by the tidal movement, that extracts energy from earth rotation (the rotation kinetic energy of earth is decreasing, and days are getting longer….).

The solar energy is provided to the ocean directly through surface layer heating and indirectly through wind shear stress and through river discharges (that increase the surface level close to the mouth). Solar heating increases the water temperature, that expands and creates a surface level gradient and generates movement.

But solar heating also creates vertical density stratification, that stabilises the denser water in the deeper layers. To pump this water to the surface, energy must be supplied because the potential energy of the ocean increases. Surface lighter water cannot sink because to keep the free surface horizontal, sinking lighter water implies rising of colder deep water and consequent potential energy increase.

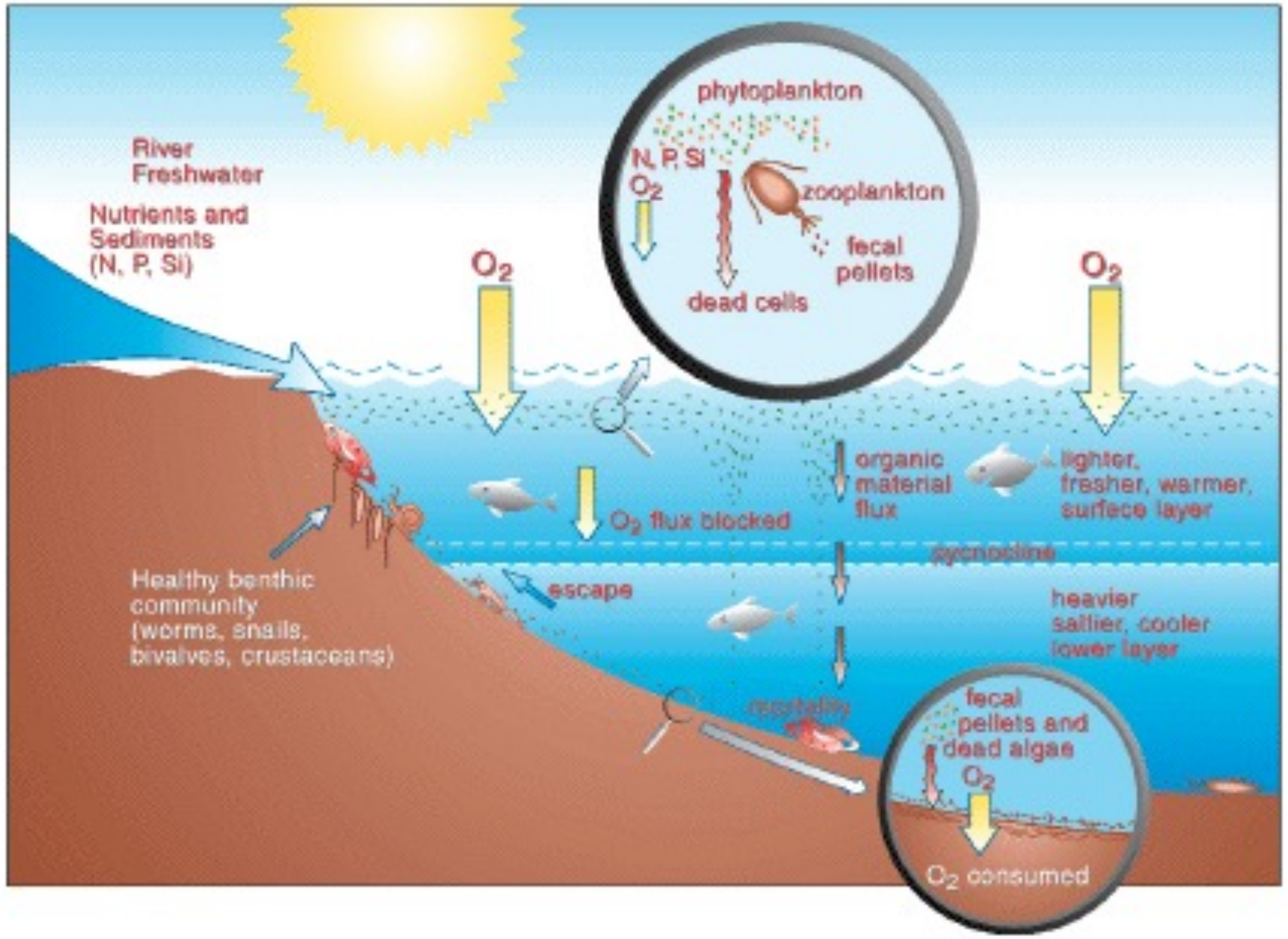
In the next slides we will see that vertical density stratification associated to the need of light by primary producers turns vertical transport processes critical for marine biological activity.

Vertical density stratification and Marine Ecosystems

The next image shows a pycnocline (line of separation of water masses with different density due to temperature or to salinity gradients) inhibiting vertical diffusion. The figure also shows the biological pump and the higher benthic activity on the bottom above the thermocline (i.e., in the shallow areas) where bottom nutrient recycling can generate “recycled production”.

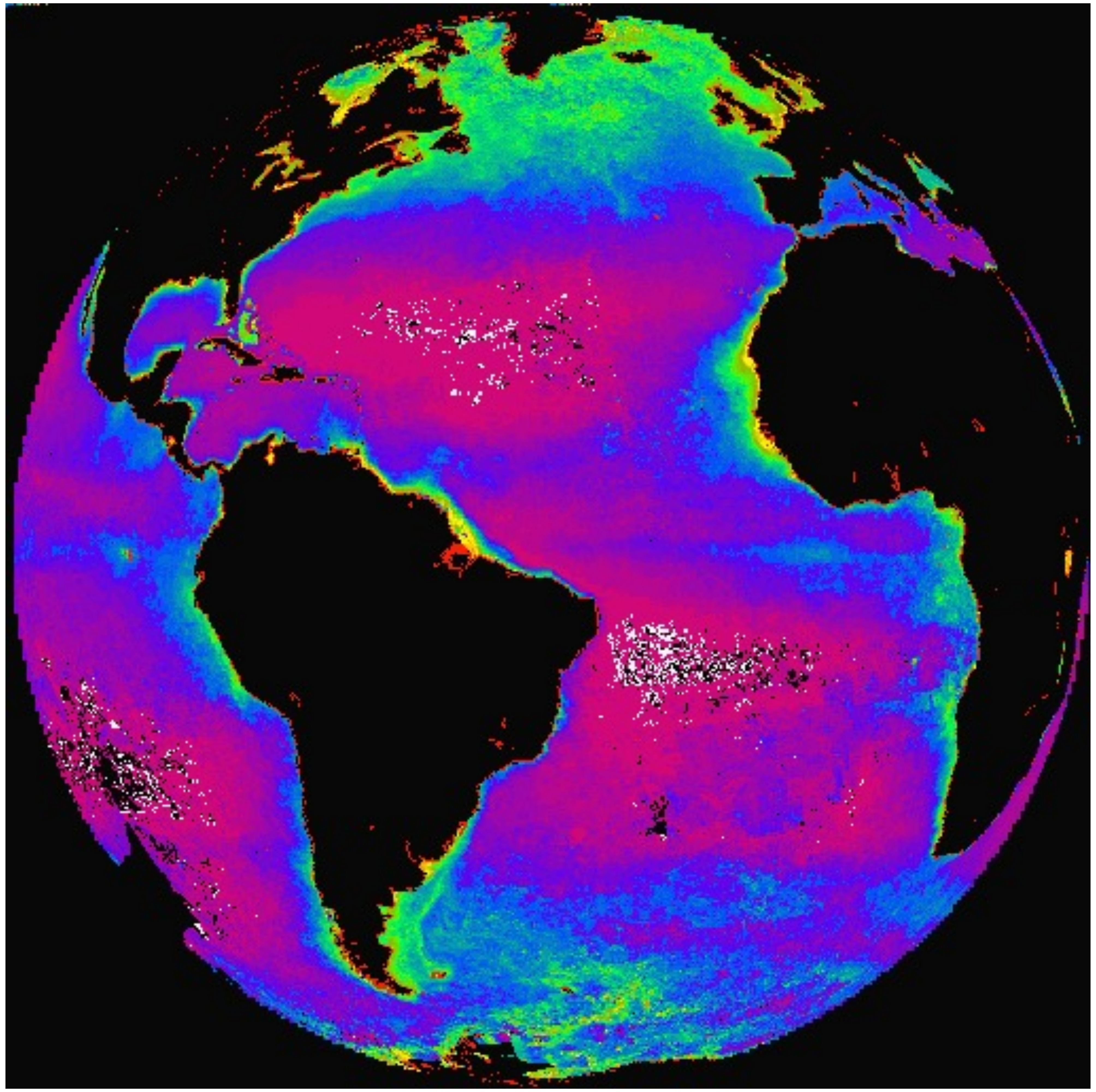
The thermocline depth is the depth up to which the wind generated turbulence can mix water. The actual depth depends on the year’s season, but typically is located at the continental shelf depth (~200 meters) and thus stratification over the shelf is low, easing nutrient recycling.

The image suggests the transformation of mineral nutrients discharged by a river into phytoplankton and its subsequent consumption by zooplankton and of both by fish and the subsequent settling of these organisms and mineralization below the thermocline and consequent pumping of nutrients (and carbon) from the surface layer to the deep layers known as “Biological Pump).



The biological pump has been so effective during the ocean lifetime that nowadays the most productive zones in the ocean only very seldom are associated to river plumes!

Chlorophyll in the Ocean



The image slide shows ocean primary production distribution. It shows that primary production is higher in the cold polar regions and in upwelling regions located along the eastern ocean borders, both in the northern and in the southern hemispheres.

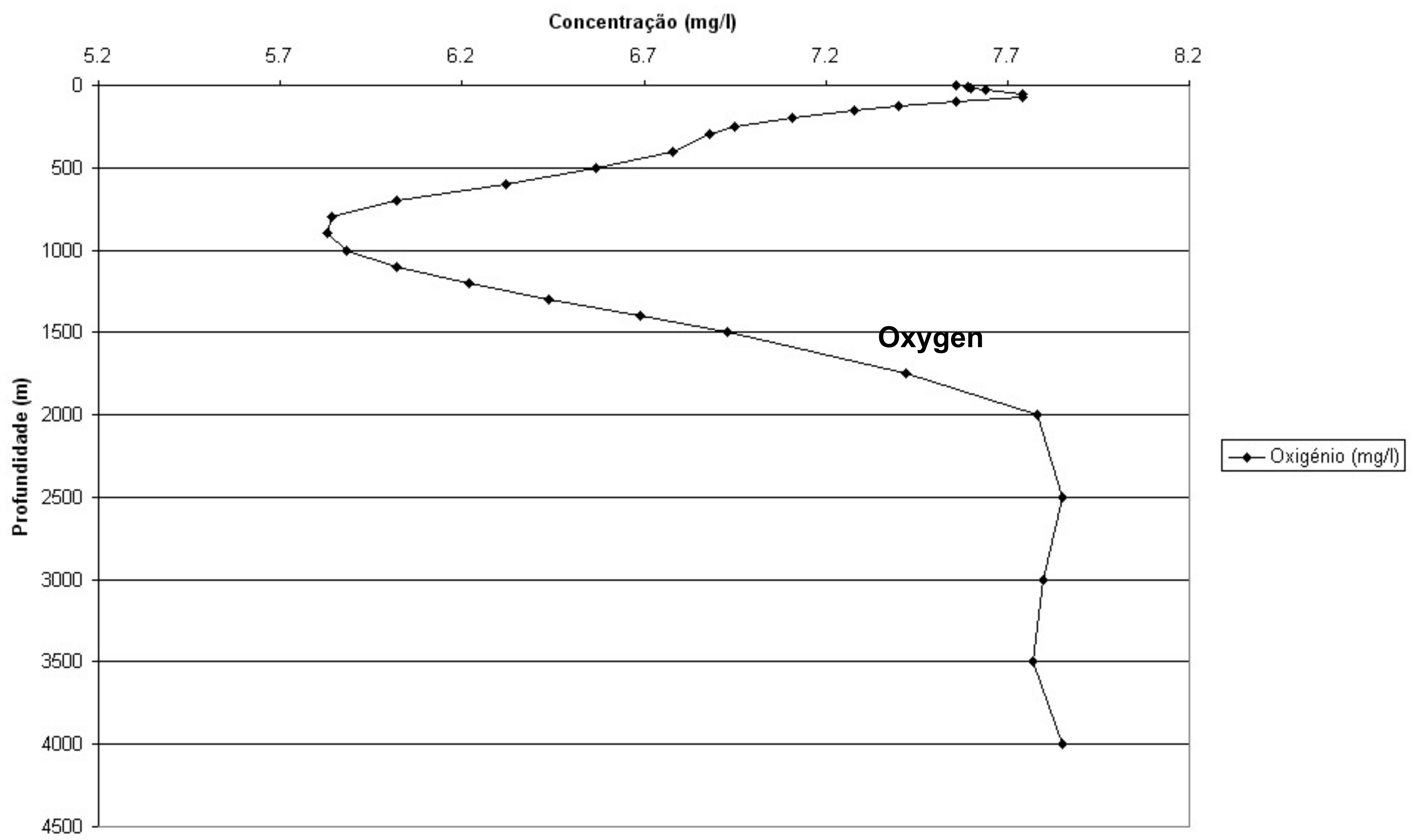
Effects of Land discharges are seen only in Shallow, semi-enclosed seas as the Northern Sea or the Baltic sea and close to the Amazonas mouth or the estuary “Mar de la Plata”.

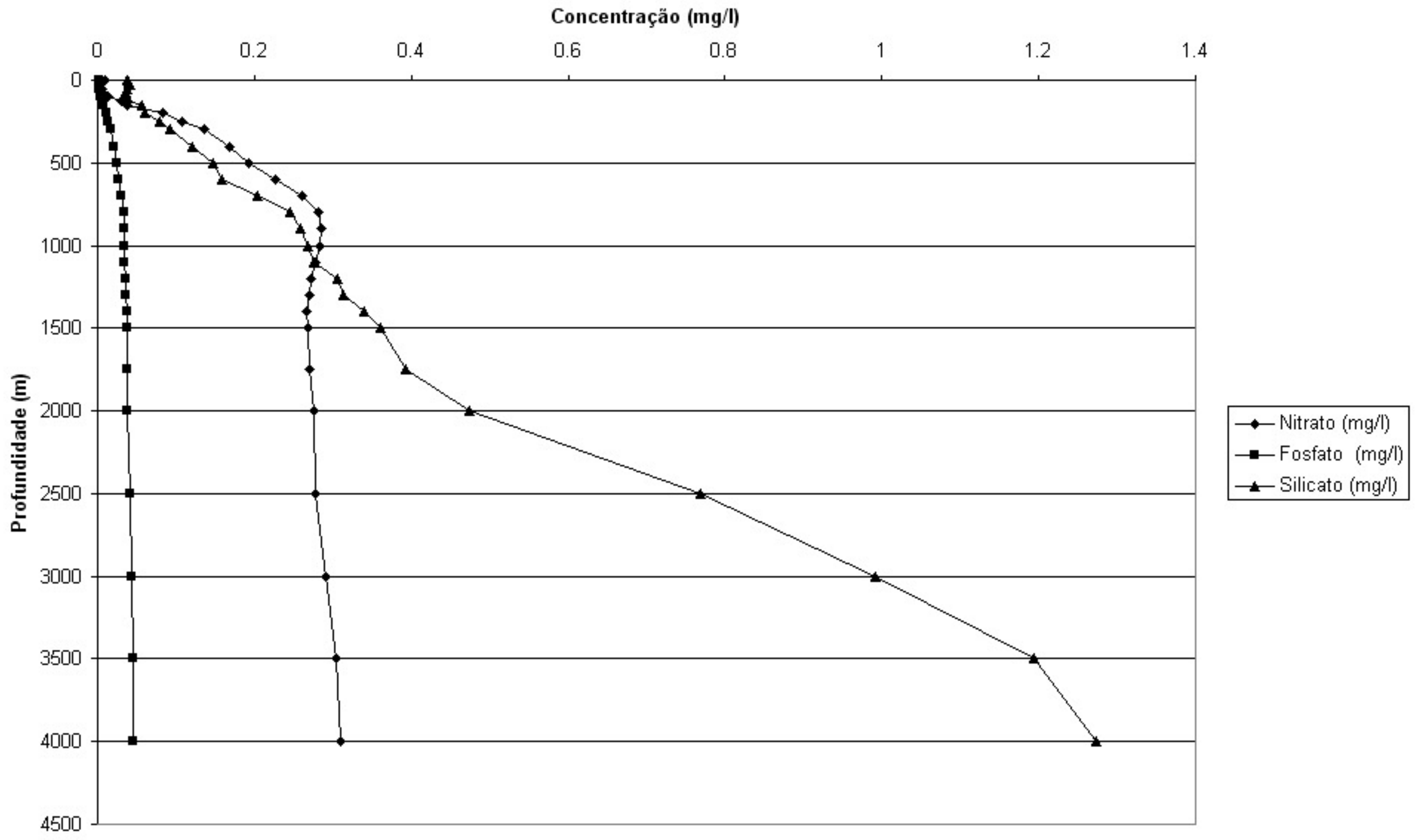
One can thus say that globally ocean primary production is nourished by nutrient recycling in regions where physics allows deep nutrients to reach the surface, this includes the continental shelf, although it is higher if there is upwelling.

http://public.wsu.edu/~dybdahl/lec10.html
http://public.wsu.edu/~dybdahl/globeprod.gif
http://public.wsu.edu/~dybdahl/tasmania.gif

O2 and Nutrients' profiles off Madeira Archipelago WOA05 data (NOAA)

http://www.nodc.noaa.gov/cgi-bin/OAS/prd/text/query





The Oxygen profile shows a small increase between the surface and 100 meters and then it decreases up to 800 meters deep, to increase again towards the bottom. The concentration closer to the bottom. At the free surface the concentration is in equilibrium with the atmosphere. The maximum at 100 meters is a consequence of primary production that is maximum at the lower limit of the photic zone as a consequence of the nutrient limitation. The decrease up to 800 meters is a consequence of the consumption (respiration) of the settling organic matter produced at the surface. The higher concentration below 2000 meters must be due to deep water formation in regions where the surface water density is higher than the bottom density (grosso modo in areas where surface temperature is lower than bottom temperature). This occurs in the polar regions for the Oceans and in specific areas of other seas, as is the case of the Gulf of Lyons in the Med Sea).

Thermo-haline Circulation

The next slide illustrates the thermohaline circulation in the ocean. Even if the ocean was horizontal in the "beginning of the times", heating in the tropical zones and cooling in the polar regions would create a surface gradient responsible for a surface flow from the tropical regions to the polar regions.

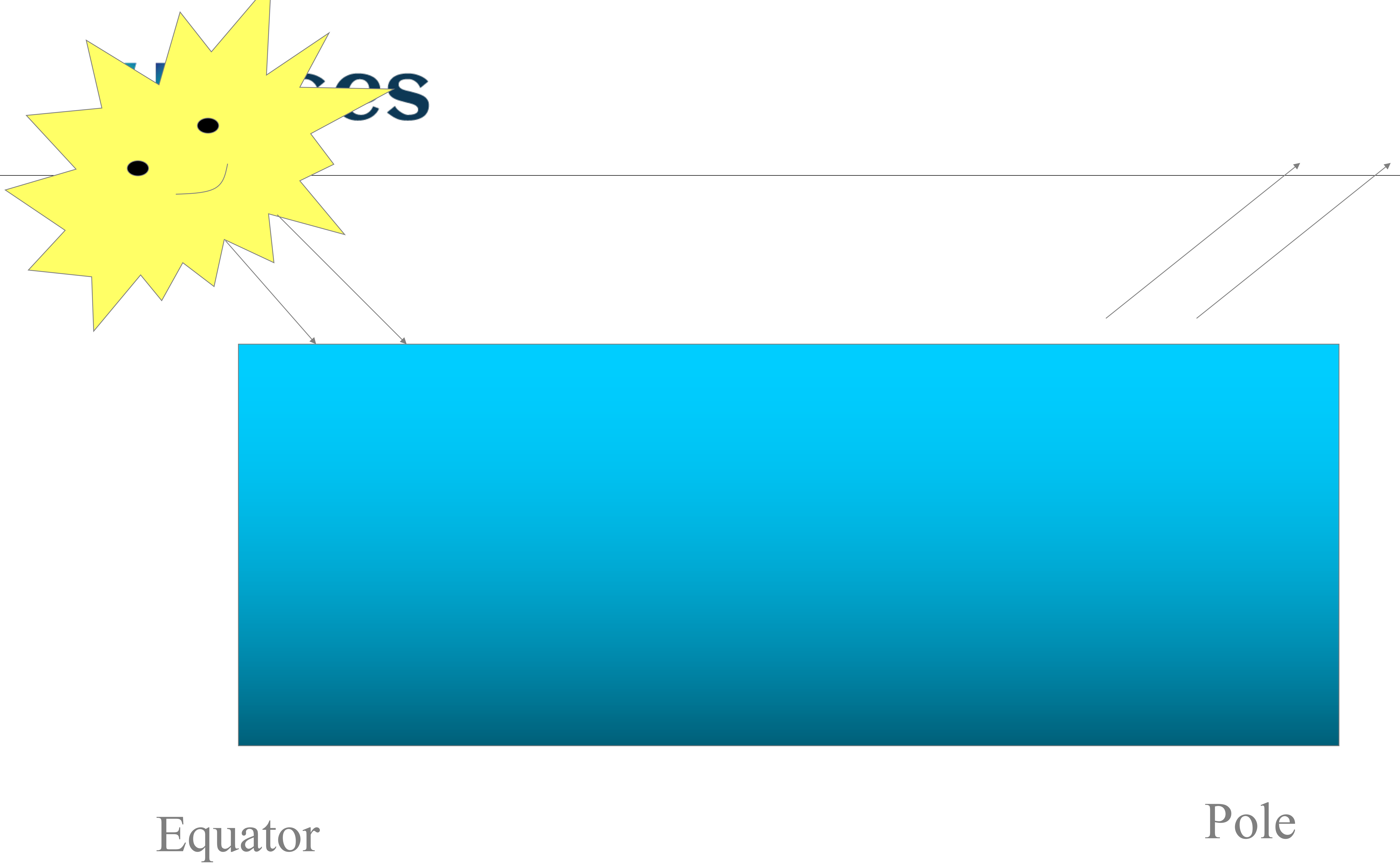
This flow would increase the level in the polar regions, would increase the pressure below and would generate a return flow at a lower depth.

In this area of small vertical density gradients vertical diffusion is possible. Therefore, nutrients concentration close to the surface will increase and primary production will be enhanced.

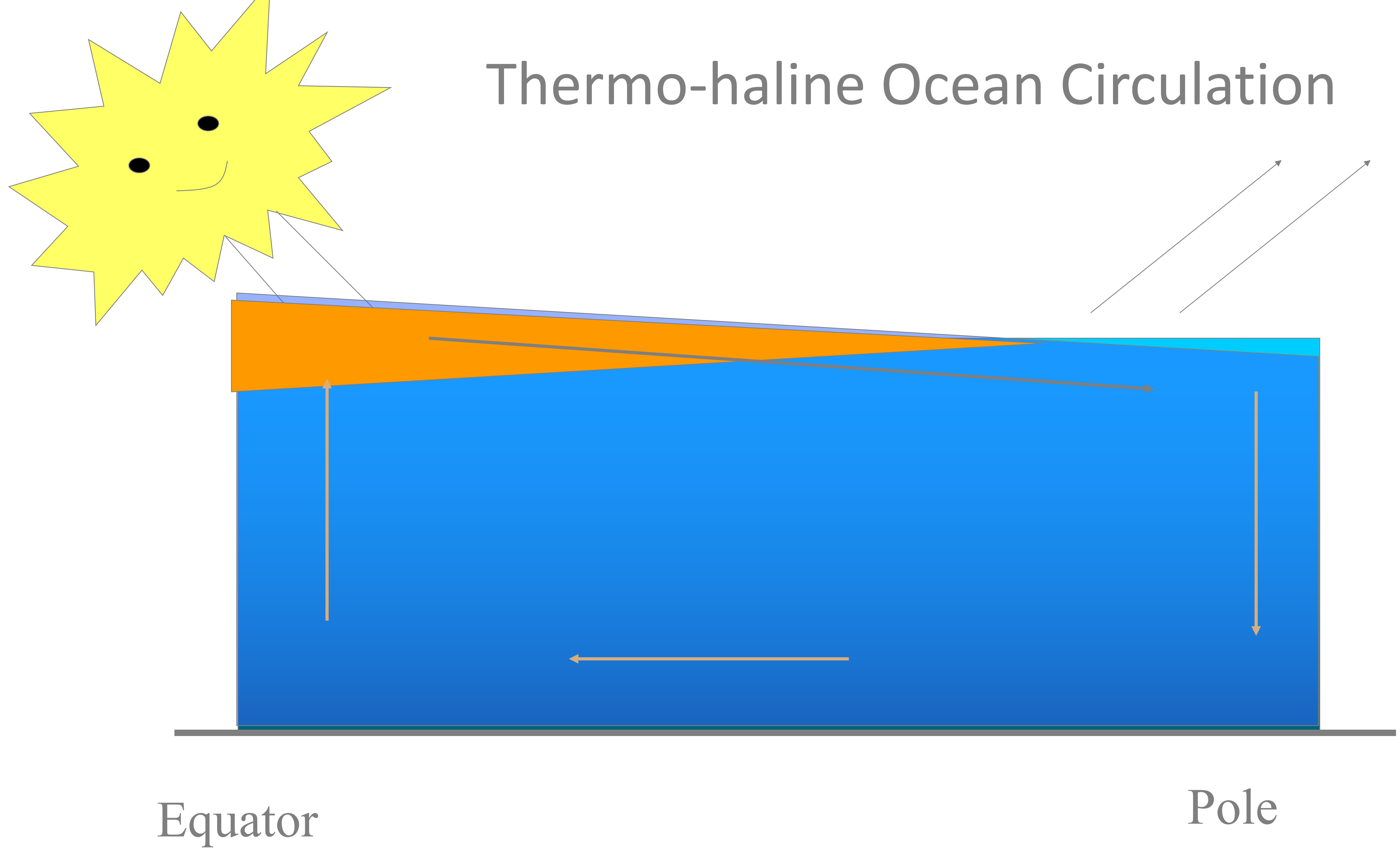
The sinking water is saturated in oxygen and has higher concentrations than in warmer regions because oxygen solubility increases when temperature decreases. This explains the high oxygen concentration in the deep ocean and the fact that in the Region of Madeira the bottom concentration is higher than the surface concentration.

Equator

Pole


Equator
Pole

Thermo-haline Ocean Circulation



The Oxygen profile shows a small increase between the surface and 100 meters and then it decreases up to 800 meters deep, to increase again towards the bottom. The concentration closer to the bottom.

At the free surface the concentration is in equilibrium with the atmosphere. The maximum at 100 meters is a consequence of primary production that is maximum at the lower limit of the photic zone as a consequence of the nutrient limitation.

The decrease up to 800 meters is a consequence of the consumption (respiration) of the settling organic matter produced at the surface.

Up to 2000 meters the oxygen concentration increases again and then it becomes constant and higher than the surface concentration. The detail of the oxygen profile depend on the consumption and on the vertical diffusion but suggests that most organic matter is mineralized above the 2000 meters.

The higher concentration below 2000 meters must be due to deep water formation in regions where the surface water density is higher than the bottom density (grosso modo in areas where surface temperature is lower than bottom temperature). This occurs in the polar regions for the Oceans and in specific areas of other seas, as is the case of the Gulf of Lyons in the Med Sea).

Summary of relation between physical and biological processes

Vertical Stratification inhibits vertical movement of water (and of dissolved materials) but particulate matter denser than the water can still sink.

Primary producers transform dissolved (mineral) nutrients into particulate material and the food web transforms small organisms into larger organisms. It starts into phytoplankton and can end into whales.

When organisms die, they are mineralized in the water column while they sink. The sinking velocity increases with the size of the organisms and consequently some of them (the larger) can be mineralized below the pycnocline and the dissolved products resulting from their mineralization remain there. This is the biological pump responsible for the very high concentrations of mineral nutrients in the deep layers.

In upwelling regions, water from below the photic zone is pumped to the photic zone enhancing primary production. In regions of strong cooling (in polar zones, but not only) the temperature of surface water can decrease below the temperature of deeper layers. This will generate sinking of surface water and rising of deep water mixing the water column and carrying nutrients up to the surface and enhancing primary production.

Nutrients discharged by river are a large part of the nutrients stored in deep marine waters, but new nutrients are important only in particular conditions (large discharges and/or shallow coastal zones).

The degrees of freedom of the marine system require the use of complex 3D models to quantify the processes that determine the functioning of the marine systems t0o forecast their evolution and the impact of anthropogenic pressures.

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What is an oceanic model

An Ocean Circulation model solves equations for the basic conservation principles:

- Mass conservation
  - Null velocity divergence
  - Salinity conservation
- Momentum conservation
  - Newton law or
  - Navier-Stokes equations or
  - Shallow water Equations
- Energy Conservation
  - Temperature Equation
- Turbulent closure, to compute diffusivity
- State Equation, to compute density

A Global Ocean Circulation Model

- Uses grids of the order of 10 km to describe the whole ocean and 50 layers to describe the whole water column and computes:
  - Free surface levels (2D)
  - 3D distributions of:
    - Velocity & Diffusivity,
    - Temperature & Salinity.
- Based on these results other models can be developed, e.g.,
  - Nested models can be developed to refine the solution at regional and local scale,
  - Lagrangian tracking Models as those used to simulate plastics,
  - Ecological models to describe the Marine ecosystems at global, regional or local scale.

Summary

- The Ocean receives solar energy from above and looses heat and mass (water/gas) also through the free surface. Most solar energy is received between the tropics while energy is lost along the whole surface. Consequently, in the inter-tropical zones the heat budget is positive, while in the polar zones is negative and globally, the ocean temperature decays between the equator and the polar regions.
- Because the ocean is heated from the top and water density decays with temperature, the water column is stratified along most of the ocean and the vertical gradient of density inhibits vertical mixing. Polar zones are the exception because the water density is maximum at about 4ºC and consequently water sinks before reaching the ice interface. When ice is formed, salts' concentration increase in the liquid phase increasing water density. These mechanisms increase vertical water mixing and vertical density gradients are minimum along the polar regions.
- In the ocean primary producers (mostly phytoplankton) transform dissolved (mineral) nutrients into organic matter (their own biomass). The phytoplankton enters the food web being consumed by the zooplankton and higher animals entering a chain of bigger and bigger animals. When these large animals die, their bodies sink and are mineralised in the ocean deeper layers, below the thermocline. The products of their mineralisation are mineral nutrients and CO_2. The vertical stratification inhibits the return of those nutrients to the photic zone.
- Deep water nutrients return to the photic zone only in the upwelling regions driven by the work of the wind shear or in the polar regions due to the destruction of vertical stratification by surface cooling. Those are the most productive zones and consequently the main fishing areas. Shallow coastal water zones and especially coastal seas that are on the pathway of nutrients discharged by rivers and therefore are also nutrients rich (some are event eutrophic) and are also important fishing zones.
- The first challenge of ocean models is to simulate the vertical water movement and mixing. This process controls the accumulation of floating material as is the case of plastics, but also the availability of nutrients in the photic zone and therefore the primary production. Vertical movement of the ocean water also determines the availability of O_2 in the deep ocean, necessary for mineralization of sinking organic matter. If the deep ocean would become anoxic, anaerobic respiration would take place and the ocean would become a huge factory of methane. This is one of the dangers of global warming!!!


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