

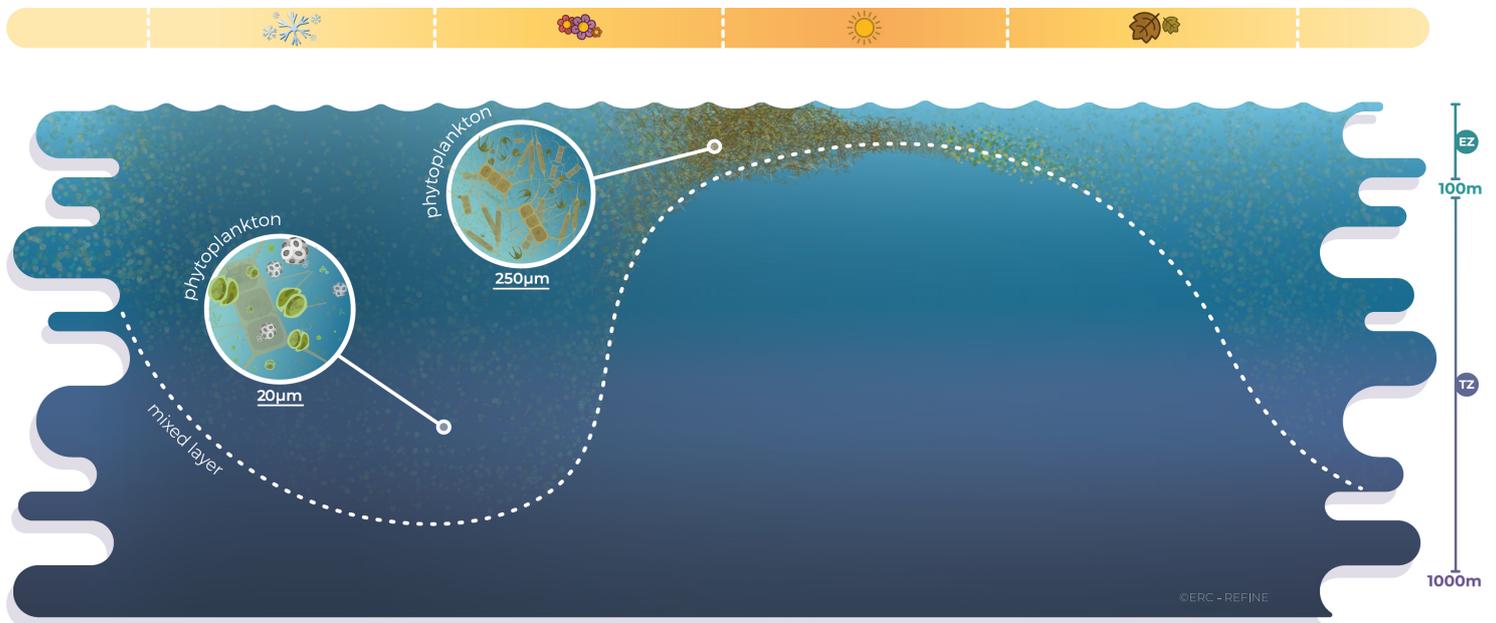


THE BIOLOGICAL CARBON PUMP

The ocean's carbon-sequestration capacity is largely controlled by the Biological Carbon Pump (BCP). The BCP is driven by processes that control both the downward export (pump strength) of biogenic carbon photosynthesized in the well-lit Euphotic Zone (EZ, between surface and ~100m), as well as the remineralisation (pump efficiency) of part of this sinking carbon in the underlying Twilight Zone (TZ between ~ 100m and 1000m).

According to a recently formulated paradigm, **the BCP is controlled by the cumulative and combined action of six different** biologically- or physically-mediated pumps, namely: **the Gravitational Pump, the Seasonal Migration Pump, the Diel Migration Pump, the Mixed Layer Pump, the Eddy Subduction Pump** and the Large Scale Subduction Pump (not specifically addressed here).

REFINE proposes a framework for an integrated observational approach of five of these Biological Carbon Pumps in the World Ocean.



The phytoplankton biomass cycle: typical seasonal evolutions in a temperate or subpolar environment.

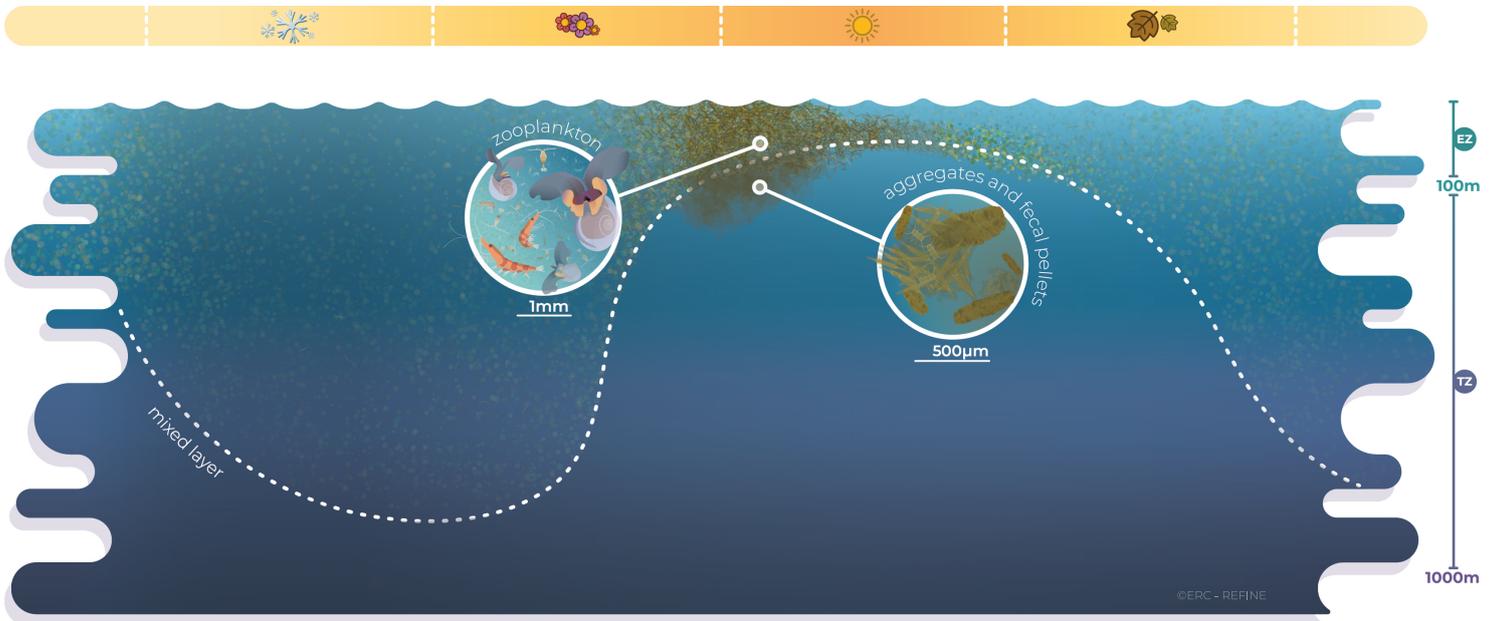
The depth domain covers the upper Euphotic Zone (EZ: ~0-100 m on average) and the Twilight Zone (TZ: ~100m-1000 m on average). The dotted white line identifies the bottom of the mixed layer which presents a marked seasonal evolution: deep in winter (up to 1000 m in some areas), shallow in summer, and transitioning between these two extremities in spring and fall.

In winter, despite the repletion of nutrients in the mixed layer, reduced light and temperatures limit phytoplankton growth. Phytoplankton biomass, dominated by flagellate-type nano-phytoplankton, remains low.

In contrast, spring stratification offers the conditions required for phytoplankton growth: nutrients are abundant and the light environment becomes favorable. As a result, a spring bloom develops, mainly characterized by micro-sized communities, generally diatoms.

Around mid-summer, a deep phytoplankton maximum eventually develops below the surface, generally at the level of the mixed layer where both light and nutrient conditions are suitable.

Fall storms and subsequent cooling contribute to destratification and the progressive establishment of conditions less apt for phytoplankton growth.

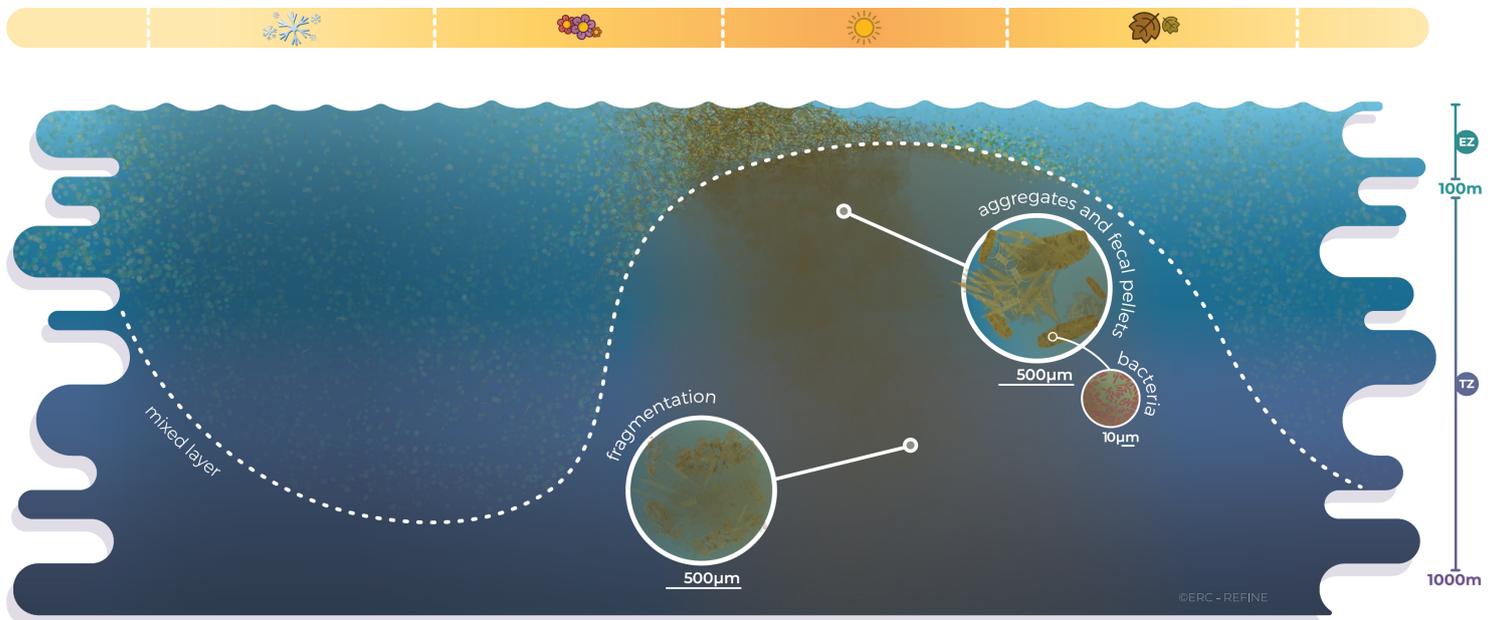


The spring bloom: the key trigger of the Gravitational Pump.

The sudden rise in availability of phytoplankton in spring is beneficial for herbivorous zooplankton (here, krill, pteropods, copepods) that graze on it and can subsequently develop massively.

This development of zooplankton biomass is associated with the production of fecal pellets. Being large, the pellets sink rapidly and contribute to the Gravitational Pump (GP), hence tracing an important route for the transfer of organic material from the EZ to the TZ and below. During their transit to deeper layers, fecal pellets are eventually accompanied by phytoplankton aggregates formed through the clumping of ungrazed phytoplankton cells.

Together, fecal pellets, phytoplankton aggregates and their by-products, all generated most abundantly during the spring bloom and its collapse, can be considered as the main drivers of the GP.



The Twilight Zone: the area where the Gravitational Pump's strength is regulated.

The journey of fecal pellets and phytoplankton aggregates towards the dark ocean is not necessarily untroubled. Despite sinking rapidly (~100 m per day), these large particles can have "unfriendly" encounters.

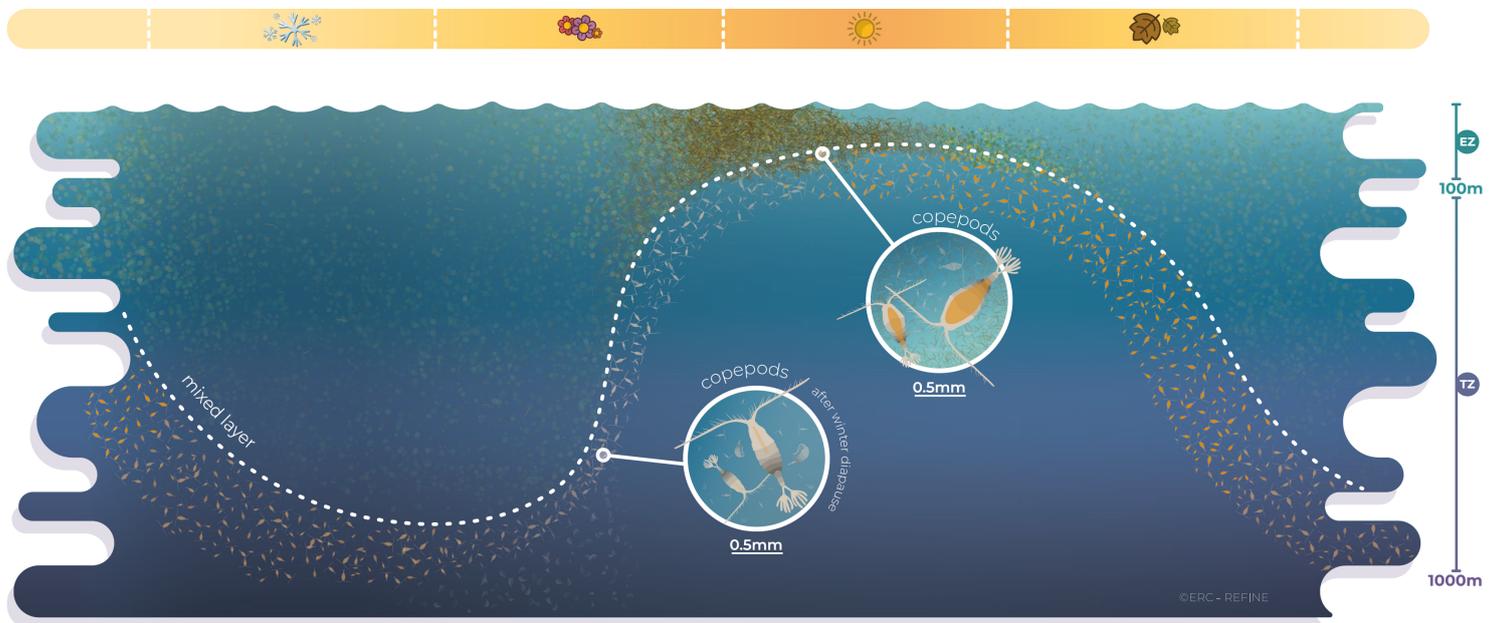
For example, bacteria can colonize them, consume their organic material for their own growth, and in return produce CO₂ through respiration. The result is that both fecal pellets and phytoplankton aggregates can become more fragile and progressively fragmented. This fragmentation can be further amplified by the grazing of animals living in the TZ.

In addition, fragmentation reduces the particles' sinking velocity, so increasing their residence time in the TZ. As a consequence, they are more subject to bacteria colonization, ensuing further organic content loss and respiratory CO₂ release.

Overall, fragmentation of large into small particles influences the amount of organic carbon that will leave the TZ to reach the depths where carbon can ultimately be sequestered.

Note that in anoxic (oxygen-deficient) layers, which generally correspond to a similar depth domain to the TZ, the GP is usually more efficient in the transferal of organic carbon to depths, and hence in its sequestration. Indeed, animals can rarely survive in these environments, so large particles stay more protected from consumption and fragmentation.

THE SEASONAL MIGRATION PUMP



The Seasonal Migration Pump.

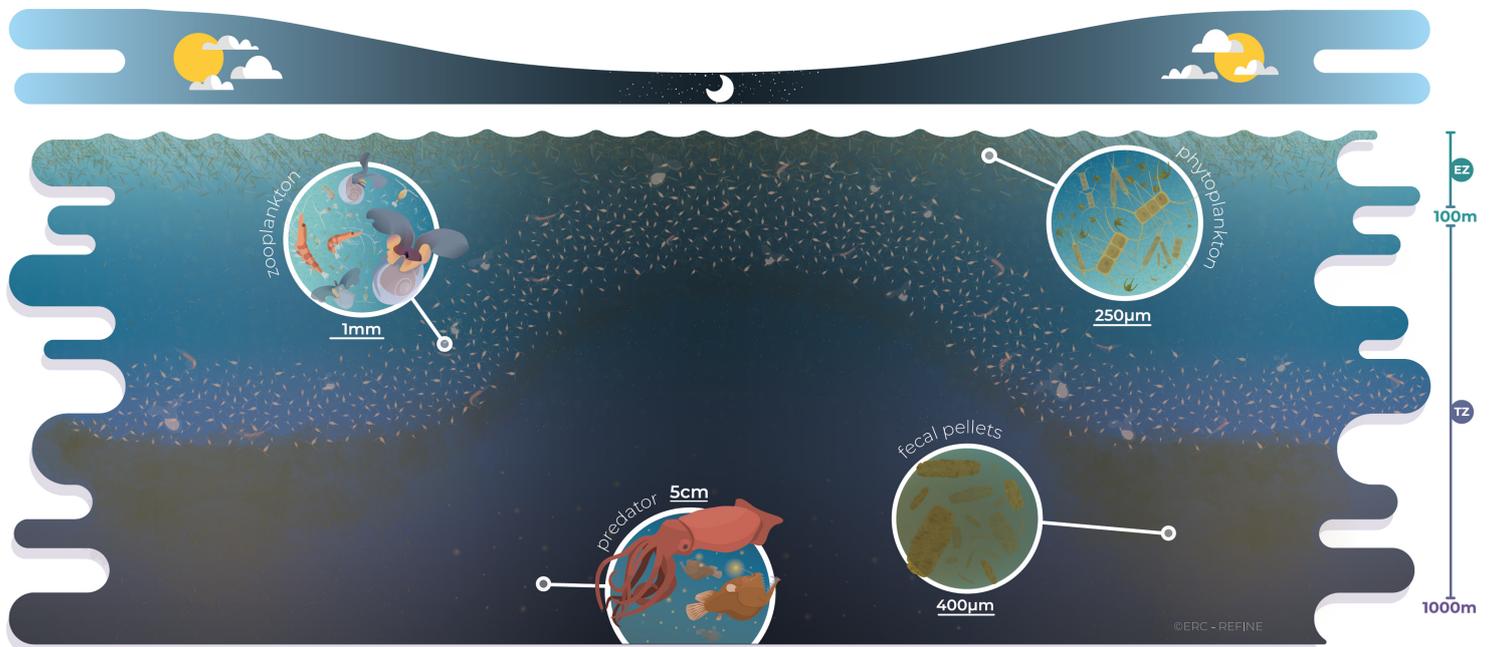
In high-latitude environments, certain zooplankton like copepods (e.g. *Calanus finmarchicus*) have a peculiar life cycle comparable to that of hibernating animals, creating an impact on the Biological Carbon Pump.

This life cycle hinges on their twice-yearly migration between the base of the TZ and the ocean surface, then back to depth. When these copepods wake up in spring from their winter diapause, they migrate to the surface where food is generally plentiful thanks to the phytoplankton bloom. They will stay there throughout the favorable summer period, eating and accumulating large quantities of lipids, extremely rich in organic carbon.

In fall, the first storms signal the end of the favorable season, and the mixed layer progressively deepens. The animals begin their migration back to depth. They will choose as their final destination for their winter diapause a depth below the mixed layer. There, the quieter waters mean that they do not risk being shaken and stirred by ocean turbulence during their winter rest. During this period of extremely weak activity, they survive on their lipid reserves and release CO₂ through respiration. Some may die, and their carcasses will gradually sink deeper.

Such seasonal migration below the winter mixed layer boosts the potential for carbon sequestration by allowing significant quantities of organic carbon to be actively transported from surface to deep layers. This pump is sometimes also referred to as the "ontogenic pump" or the "lipid shunt".

THE DIEL MIGRATION PUMP



The Diel Vertical Migration Pump.

Many zooplankton have developed diel vertical migration (DVM) behavior. In other words, they migrate to the EZ at dusk where they graze on phytoplankton, then migrate back to the TZ at dawn.

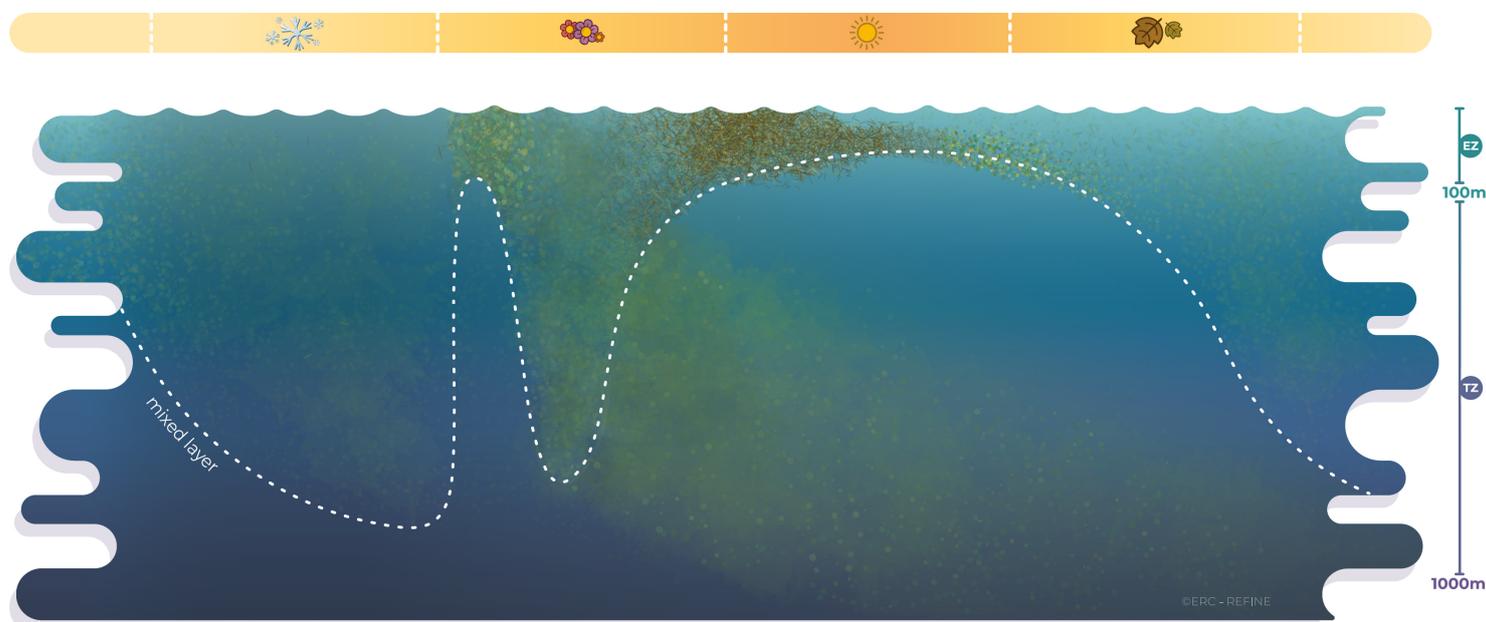
Reasons for this migration may vary but primarily come down to a trade-off between the need to feed vs predator avoidance (as fish hunt their zooplankton prey visually, they require sufficient light to detect them).

DVM obviously has an effect on the Biological Carbon Pump. Indeed, this migration is an efficient mechanism for actively transporting organic material from the surface to the depths of the TZ where it can be released e.g. in the form of fecal pellets.

As these fecal pellets may subsequently undergo gravitational sinking, DVM can be considered as an accelerator of the Gravitational Pump. Ubiquitous throughout the global ocean, DVM is considered as the vastest migration phenomenon on our planet.

THE MIXED LAYER PUMP

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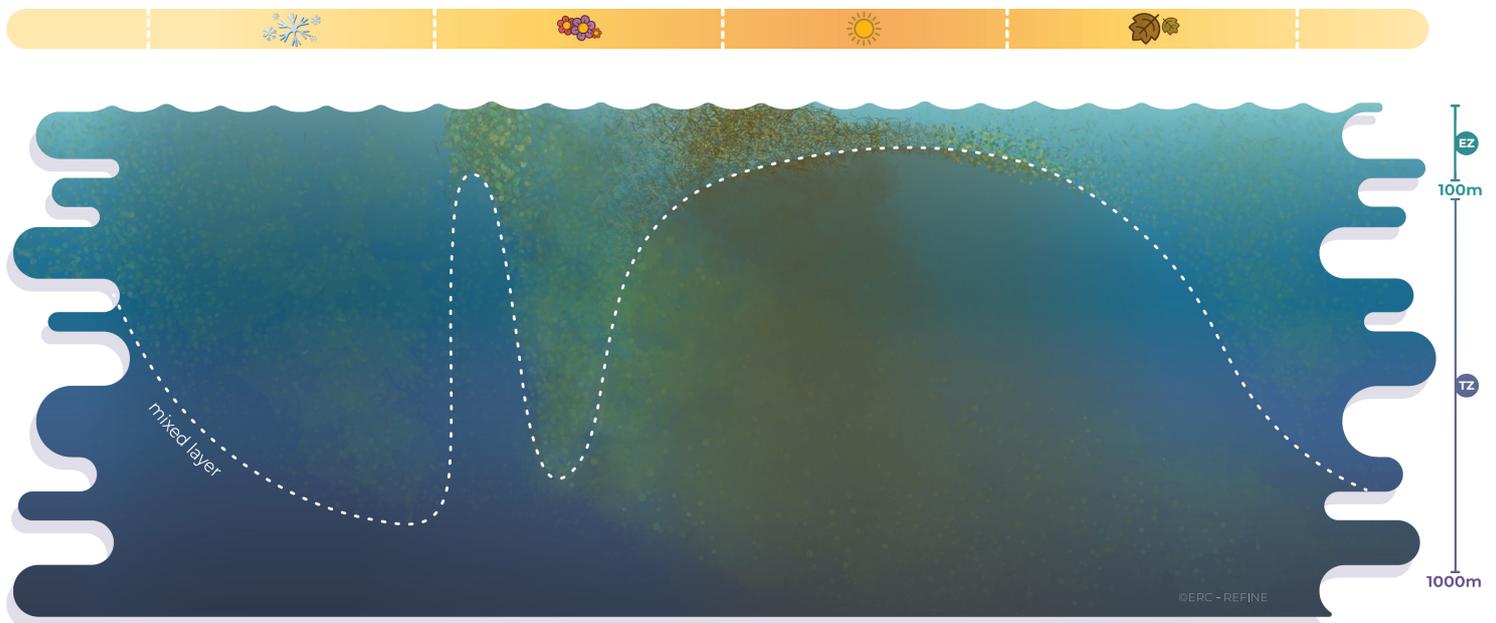


The Mixed Layer Pump.

The Mixed Layer Pump (MLP) corresponds to mechanisms whereby organic carbon, produced photosynthetically at the ocean surface, is physically transported and subsequently isolated in deeper layers via the alternation of mixing and stratification periods.

In subpolar environments as illustrated here (e.g. Labrador Sea), the MLP is essentially at work during the winter to spring transition. Even during the period of intense deep winter mixing (up to 1000 m and sometimes more), calm meteorologic periods (low wind stress and reduced loss of heat by the ocean) can initiate a temporary stratification, characterized by a shallow mixed layer. This transient situation creates light and nutrient conditions conducive to phytoplankton growth at the ocean surface, resulting in ephemeral blooms. Storms will then eventually destroy stratification and dilute this newly formed phytoplankton biomass within a larger mixed layer. Subsequent stratification will isolate part of this organic material under the new mixed layer, possibly permanently (*i.e.* in favor of carbon sequestration) if no new mixing intervenes before spring-summer stratification finally sets in place.

Note that this description traces only one stratification-mixing cycle but the winter to spring transition is obviously characterized by numerous successions of cycles. In low-latitude environments (e.g. subtropical gyres) the MLP can operate on a daily-scale cycle with diurnal stratification following nocturnal convection, so acting as a recurrent mechanism for pushing organic matter below the mixed layer.



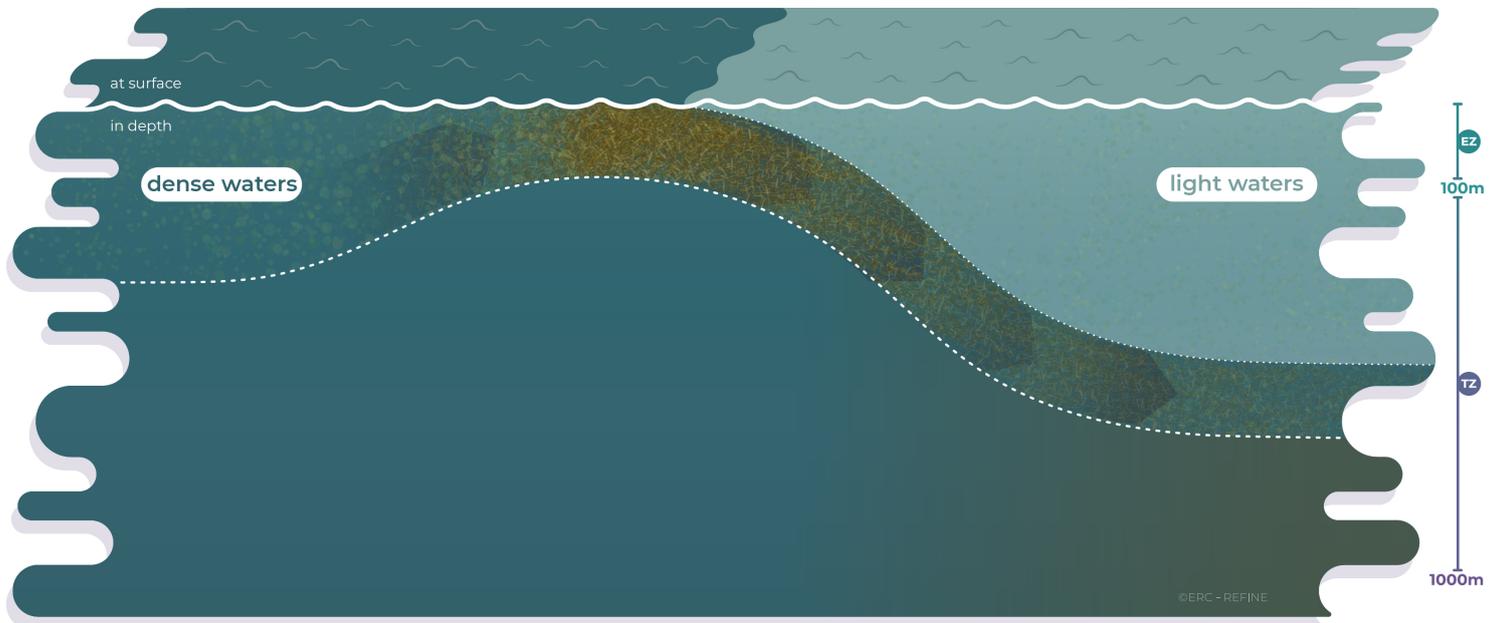
Where and when Mixed Layer and Gravitational Pumps overlap.

Phytoplankton and associated particles transported downward by the MLP will continue their journey onward to lower depths through gravitational sinking. This way, they will subsequently contribute to the GP. Additionally, they will encounter in the TZ particles issuing from the spring bloom and also escaping from the EZ thanks to the GP.

The two types of particles arriving in the TZ diverge in their residence time and their potential for carbon sequestration. On the one hand, ephemeral blooms associated with the MLP are dominated by phytoplankton such as flagellates, likely to be grazed by microzooplankton — conditions that favor the injection of suspended particles with a low sinking speed into the TZ, where they tend to reside for a considerable period.

On the other hand, the spring bloom is generally dominated by diatoms grazed by large zooplankton, which generate large particles with a high sinking speed that will cross the TZ more rapidly, hence increasing their potential for carbon sequestration.

THE EDDY SUBDUCTION PUMP



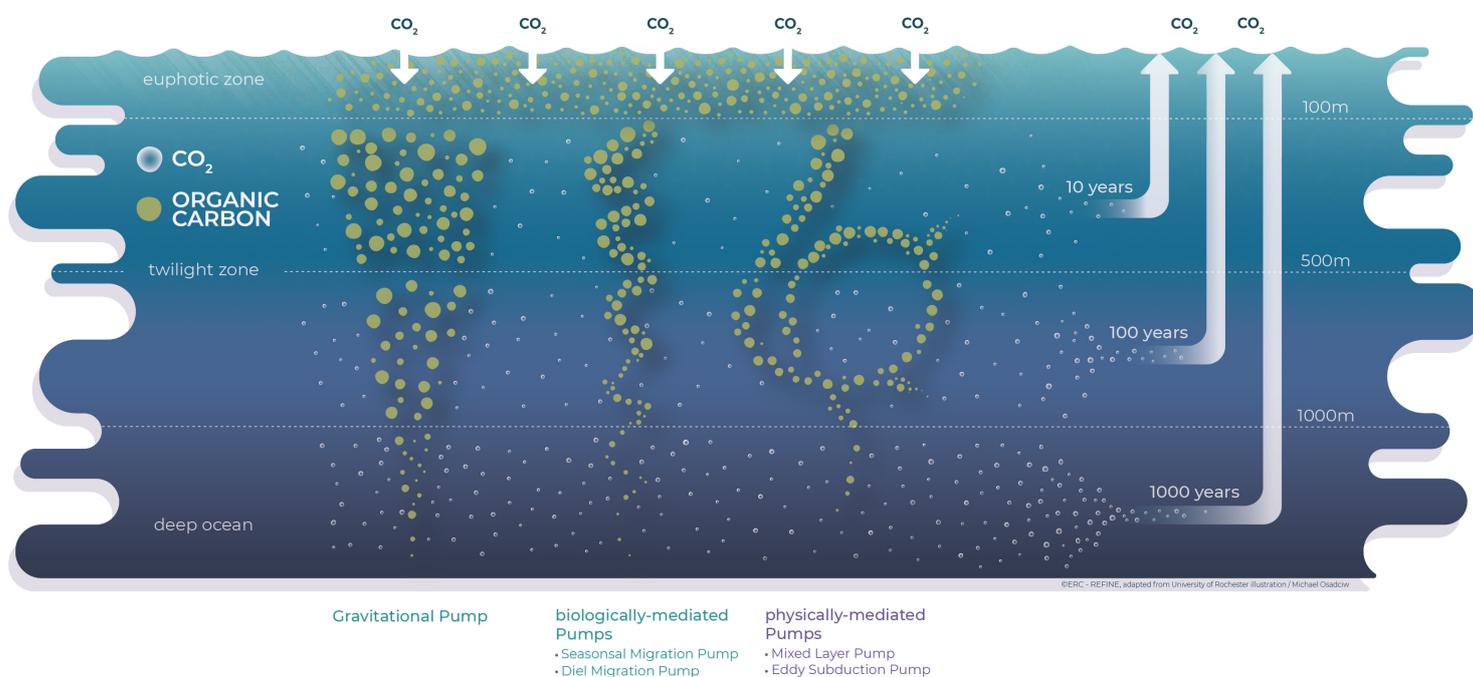
The Eddy Subduction Pump.

The Eddy Subduction Pump is a physical mechanism injecting surface biogenic material deeper in the water column. This injection mechanism occurs at fronts which result from abutting between dense and less-dense waters. The mechanism is accentuated by atmospheric forcing which inhomogeneously mixes the upper ocean through the actions of winds and the exchange of heat and freshwater with the atmosphere.

The density gradients between waters of different densities trigger variations in water movement over the vertical dimension (so-called cross-front circulation) and occurring over sub-mesoscale spatial scales of 1-10 kilometers. Movements with positive velocities (known as obduction) bring dense waters to the surface; from there they will later flow under less dense waters via water movements with negative velocities (known as subduction). Such subduction can carry surface biogenic content to depths as deep as 500 m.

Very often, subducted waters are also enriched with biogenic material (the situation represented here). This enrichment results from obducted waters originating from a nutrient-rich depth horizon. When these waters reach the illuminated surface layer, environmental conditions hence become favorable for phytoplankton growth and the development of biomass hotspots which will be subsequently carried to depths from which they can also further sink through the Gravitational Pump.

SYNTHESIS



Joint pump action and the oceanic biogeochemical cycle of carbon.

At the ocean surface, photosynthesis allows the production of organic carbon from its inorganic form CO₂.

All five pumps will then join forces to deliver this organic material at various depths of the TZ and below. In the course of this delivery, the organic carbon will progressively return to its mineral phase CO₂ due to bacterial remineralization. The intensity of this CO₂ release essentially depends on the balance between the velocity at which organic carbon is vertically transported, and the strength of bacterial remineralization.

Ultimately, all pumps contribute to an increasing gradient of CO₂ from the surface to depth. This major process has always existed and worked to significantly reduce CO₂ from the atmosphere. What is now critical to understand is :

At which specific oceanic layers does the back-release of CO₂ operate, and how do the various pumps contribute to this ? Indeed, the deeper this release occurs, the longer CO₂ will be stored away from contact with the atmosphere.

How will climate change and its resulting evolving constraints on oceanic environment (stratification, nutrient availability, light, temperature) impact the biological and physical processes underlying these pumps ?

REFINE aims to help answer these questions.

REFINE

ROBOTS EXPLORE PLANKTON-DRIVEN FLUXES IN THE MARINE TWILIGHT ZONE

The ERC REFINE project focuses on the **Ocean Carbon Pump** with a particular emphasis on the **Ocean Twilight Zone**.

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