The Ocean: a Carbon Pump

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The ocean contains 50 times more carbon than the atmosphere and is exchanging large amounts of CO_2 with the atmosphere every year. In the past decades, the ocean has slowed down the rate of climate change by absorbing about 30% of human emissions. Whereas this absorption of anthropogenic CO_2 is today the result of physical-chemical processes, marine biology is playing an important role in the ocean carbon cycle by sequestering carbon in the deep ocean. Changes in any of these physical, chemical and biological processes may result in climate feedbacks that either increase or decrease the rate of climate change, although knowledge of such interconnections is today still limited. The feedbacks between climate, the ocean, and its ecosystems need to be better understood in order to predict the co-evolution of atmospheric CO_2 and climate change more reliably and also to understand the characteristics of a future ocean.

A MAJOR ROLE FOR THE OCEAN IN THE EVOLUTION OF ATMOSPHERIC CO_2

The cycling of carbon involves a wide range of physico-chemical and biological processes contributing to a series of interconnected carbon reservoirs in the Earth System. A schematic diagram of the global carbon cycle showing the relative importance of each of these processes is shown in Figure 1. The global cycle was roughly balanced before the industrial era. During the past 200 years, atmospheric CO_2 has increased from less than 0.03% to more than 0.04%, as a result of fossil fuel burning, cement production, deforestation and other changes in land use. It is considered that such a rapid change is at least ten times faster than any other that has happened during the past 65 million years (Portner *et al.*, 2014; Rhein *et al.*, 2014).

Since the beginning of the industrial era, the ocean has played a key role in the evolution of atmospheric CO_2 by absorbing a significant fraction of CO_2 emitted into the atmosphere by human activities, deforestation and burning of fossil fuels. During the past decade (2004-2013), the global ocean has absorbed 2.6 billion tonnes of carbon per year, representing nearly 30% of anthropogenic emissions over this period. Since 1870, the amount of carbon absorbed by the ocean has reached 150 billion tonnes – also representing 30% of anthropogenic emissions over this period. By absorbing this greenhouse gas, the ocean thus contributes to slow down human-induced climate change.

A NATURAL OCEAN CARBON CYCLE INVOLVING PHYSICO-CHEMICAL AND BIOLOGICAL PROCESSES

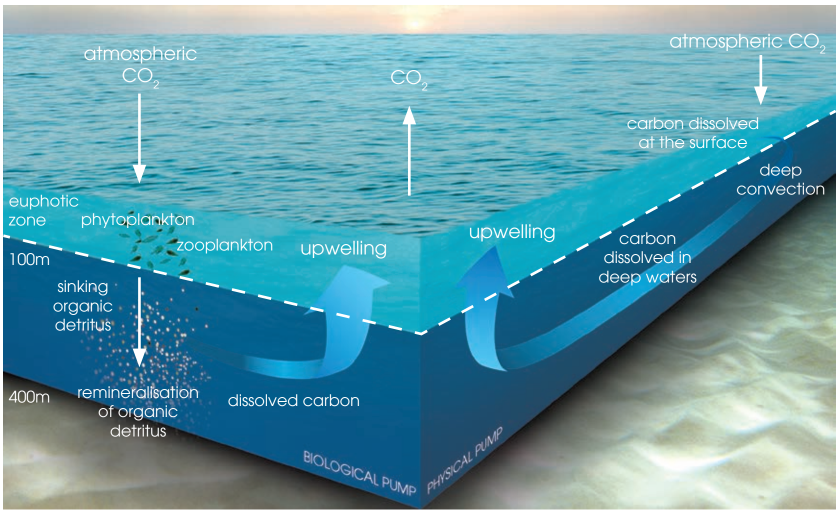
Anthropogenic carbon absorbed by the ocean feeds a considerable natural carbon reservoir. The ocean contains about 40,000 billion tonnes of carbon (40,000PgC), mainly in the form of inorganic carbon dissolved in seawater. This amount represents 50 times the size of the atmospheric reservoir. Each year, the ocean naturally exchanges with the atmosphere almost a hundred billion tonnes of carbon as CO_2.

In the ocean, this carbon, which prevails essentially in the form of bicarbonate ions (HCO_3^-), is not evenly distributed, as dissolved carbon concentrations are higher at depth than at the surface. The spatial distribution of carbon with depth controls atmospheric CO_2 levels, as only the inorganic carbon from the sea surface is in contact with the atmosphere and contributes to the exchange of CO_2 between the atmosphere and the ocean. This vertical gradient of carbon can be explained by both physico-chemical and biological processes.

- **Biological Processes**

Phytoplankton living in the sunlit layer of the ocean use light energy to perform photosynthesis. They take up nutrients as well as dissolved inorganic carbon to produce organic matter. The production of these carbon-based materials supported by solar energy is called primary production. It represents the base of the trophic chains from which other non- photosynthetic organisms can feed on. Photosynthetic activity is therefore an efficient mechanism for extracting CO_2 from the atmosphere and transferring the carbon into living organisms. Surprisingly, the organisms that contribute to primary production represent only a small organic carbon pool (~3PgC), but they are capable of generating large amounts of dissolved organic carbon (DOC: ~700PgC) to sustain the food chains because their turnover is very rapid, from a few days to several weeks.

A fraction of produced organic material exits the surface layer as sinking particles, thus transferring the surface carbon towards the deep layers of the ocean (Figure). Before being sequestered to the deep the atmospheric carbon fixed by photosynthetic organisms undergoes a series of transformations: phytoplankton can be directly consumed by zooplankton, or indirectly by heterotrophic bacteria, which will in turn be eaten by larger organisms. During this process, a fraction of the total carbon biomass (average value of 10%) ends up as detrital matter, fecal pellets or dead cells which compose the stock of marine particles. In turn, a fraction of these particles (in suspension or sinking) also undergoes a series of transformations before reaching the base of the mesopelagic layer (typically 1000m depth), thus sequestering atmospheric CO_2 for thousands of years. It is generally believed that 0.1 to 1% of the carbon-containing material at the surface finally reaches the base of the mesopelagic zone, then the sediment where it can turn into fossil fuel deposits. The remaining organic matter is remineralized through respiration, and CO_2 returns to the atmosphere. Each year, nearly 10 billion tonnes of carbon are exported from the surface layer and are responsible for most of the carbon vertical gradient. All of these



Natural carbon cycle and representation of biological and physical pumps (Bopp *et al.* 2002).

processes that contribute to the governing role of marine biology on the carbon cycle in the ocean are part of the so called biological carbon pump (Figure).

Although only a small fraction (~ 0.2PgCyr^{-1}) of the carbon exported by biological processes from the surface reaches the sea floor, the fact that it can be stored in sediments for millennia and longer (Denman *et al.*, 2007; Ciais and al., 2014) means that this biological pump is the most important biological mechanism in the Earth System allowing CO_2 to be removed from the carbon cycle for very long periods of time.

Over geological time-scales, the biological carbon pump has formed oil deposits that today fuel our economy. In addition, biochemical sedimentary rocks such as limestone are derived principally from calcifying corals, molluscs, and foraminifera, while the considerable reserves of deep sea methane hydrates (or clathrates) are similarly the result of hundreds of millions of years of activity of methanogenic microbial consortia. Considering that, each day, large amounts of CO_2 that have been trapped for millions of years are discharged into the atmosphere (the order of magnitude is now probably about a million years of trapped carbon burned by humankind each year), it is easier to understand the rapidity at which present climate change is taking place. Consequently, there is a dramatic difference between the rate of CO_2 sequestration by photosynthesis and rate of CO_2 discharge into the atmosphere. The anthropogenic emissions will therefore need to be redistributed by the global carbon cycle until a new steady state is reached.

- **Physico-Chemical Processes**

A second series of processes, comprising physico-chemical activities, also contributes to the increasing carbon distribution with depth. The cooling of surface waters at high latitudes favours their ability to dissolve atmospheric CO_2 (mainly by increasing the solubility of the gas) as well as increasing their density. These heavy surface waters plunge down to great depths, in this way exporting the CO_2 and preventing it from further contact with the atmosphere. This process that contributes to the vertical gradient of ocean carbon is known as the physical pump or solubility pump (Figure).

Despite the fact that biological processes are responsible for the majority of the vertical gradient of natural carbon in the ocean, the physico-chemical processes can nevertheless explain the anthropogenic carbon sink observed today. Indeed, excess CO_2 in the atmosphere will lead to a net carbon flux to the ocean due to the disproportion induced between atmospheric and oceanic CO_2 concentrations. Subsequently, once the anthropogenic CO_2 enters surface waters, it is transported by ocean currents and progressively mixed with the sub-surface waters.

IS THE OCEANIC CARBON SINK GOING TO SATURATE?

To date, and since the beginning of the industrial era, the ocean has continuously absorbed a relatively constant part of the amount of CO_2 emitted by human activities. However, many studies based on theoretical considerations, in situ observations, controlled laboratory experiments, or supported by models, suggest that several processes may lessen or slow-down this natural carbon sink.

The first series of processes is related to the chemistry of carbonates (exchanges between CO_2, HCO^{3-} and CO_3^{2-}) and can eventually lead to a saturation of the oceanic carbon sink. Indeed, the dissolution of anthropogenic carbon dioxide decreases the ocean carbonate ion content and therefore the buffer effect of the ocean, which in turn increases the proportion of CO_2 in comparison to the other forms of dissolved inorganic carbon species and thus may reduce the efficiency of the natural carbon sink. This phenomenon occurs in parallel with the process of ocean acidification, and could potentially have serious impacts on life in the ocean.

The second series of processes is related to the feedback between climate and the carbon cycle. This concerns the feedback between anthropogenic climate change and different carbon absorption phenomena. As mentioned earlier, climate change leads to modifications in water temperature, ocean currents, and production of organic matter in the ocean. If these changes should boost the carbon sink, they would curb climate change and induce a negative feedback. On the contrary, in the event of a weakening of the carbon sink, the changes would lead to a positive feedback that would in turn accelerate the phenomenon.

Once more, different processes are involved. For example, the increase in the temperature of the ocean weakens the ocean carbon sink. An increase by 2 or 3°C in sea surface temperature decreases the solubility of CO_2 by a few percent, and thus the capacity of the ocean to absorb carbon dioxide. Another effect could accentuate this saturation of the carbon sink: in response to rising temperatures, climate models predict an increase in vertical stratification of the ocean. In other words, vertical mixing, which tends to homogenize the surface waters with the deep, would diminish and the resulting stratification would reduce the present penetration of anthropogenic CO_2 towards the ocean depths.

The future of the biological pump is difficult to predict. Even a qualitative estimate of the effect of changes in marine ecosystems on the ocean carbon sink remains highly speculative. More specifically, because the activity of the biological pump is likely to be strongly regulated by net primary production (NPP), it is important to consider the effects of climate change on photosynthetic activity. On land, as the CO_2 supply is generally limiting for photosynthesis, the increase in anthropogenic CO_2 tends to stimulate plant growth (known as the carbon dioxide fertilization effect). This does not appear to be the case in marine systems because Dissolved Inorganic Carbon (DIC) is not limiting for carbon fixation by photosynthesis. However, photosynthesis is also strongly affected by temperature, and the upper ocean has significantly warmed during the last 150 years. In addition to temperature, light, inorganic nutrients, and the density-dependent stability of the surface mixed layer (González-Taboada and Anadón, 2012; Portner *et al.*, 2014) are all likely to affect photosynthetic activity, as are oxygen, pH, and salinity. Environmental variability and the displacement of organisms by ocean currents cause variability in phytoplankton productivity, competitiveness, and natural selection, which are also likely to result in changes in carbon sequestration. It is therefore crucial to estimate how the production of organic material by phytoplankton is going to be affected by changes in environmental conditions of surface water: for example rising water temperature, melting of sea ice and changes in dissolved nutrient availability (nitrates, phosphates).

Modelling approaches predict an overall reduction in global mean NPP as a result of climate change, albeit with significant latitudinal variations. One of the factors leading to this reduction is the predicted expansion of oligotrophic gyres as nutrient availability decreases with the intensification of stratification. Predictions indicate increasing NPP at high latitudes (because the amount of available sunlight should increase as the amount of water covered by ice decreases). However this would be counterbalanced by a decrease of NPP in temperate and tropical latitudes (because of reduced nutrient supply). The types of plankton species that would dominate the ecosystem in altered conditions should also be estimated, as the composition of plankton can significantly affect the intensity of CO_2 absorption. The role of certain phytoplankton populations, such as diatoms, can be particularly significant. They are characterised by relatively large cell sizes (tens to hundreds of micrometers), which allows them to sink rapidly. They are therefore responsible for the export of a large fraction of carbon to the deep ocean. Nonetheless, diatoms cannot thrive in nutrient depleted conditions. In this case they could be replaced by other types of smaller (<10 microns) phytoplankton cells that are better adapted to poor nutrient conditions. Although such cells are abundant in the ocean, due to their small size they are principally recycled within the surface layer, and thus have a very minor role in carbon export to the deep. A decrease in the diatom/

small cell community ratio could thus greatly disrupt the intensity of the biological pump, especially in the polar regions.

Despite these multiple levels of uncertainty - the most important being the biological response to climate change - the different predictions produced by numerical models that couple the climate system and the carbon cycle all point to a declining ocean carbon sink due to global warming. Even though this ocean sink is unlikely to become a source there is no doubt that a decrease will affect the evolution of the CO_2 in the atmosphere and, ultimately, climate change itself. By 2100, the feedback between the climate and the carbon cycle (including the response of the terrestrial biosphere to climate change) could even be responsible for an additional increase in atmospheric CO_2 of several tens of ppm!

The future evolution of the oceanic carbon sink, as predicted by models coupling the climate and carbon cycle at a global scale, still remains very uncertain. The last IPCC report points to a number of poorly constrained processes that explain the wide range of uncertainties associated with the predictions: these primarily include biotic responses to climate change and the changes in the biological pump (the complexity of biological processes being extremely difficult to include in climate models). Other processes related to the representation of small-scale features (eddies) and to the consideration of particularly complex coastal areas are also mentioned in this report.

A ROLE IN OTHER BIOGEOCHEMICAL CYCLES

Besides its role in both the carbon cycle and the evolution of atmospheric CO_2, it must be emphasized that the ocean also plays a key role in other major biogeochemical cycles, including nitrogen, phosphorus and sulphur that are liable to affect the biogeochemical balance of our planet.

In the mid-1980s, several scientists including James Lovelock suggested that ocean ecosystems, especially phytoplankton, are able to regulate the world climate by releasing the sulphurous gas dimethyl sulphide or DMS. Once in the atmosphere, this gas favours the formation of tiny sulphate particles which play a role as condensation nuclei for clouds, thus contributing to an increase in cloud cover. This hypothesis, which is still called the CLAW hypothesis (based on the first letter of the surname of each of the authors; Charlson *et al.*, 1987), states that the ocean ecosystem reacts to an increase in temperature by increasing productivity. This in turn leads to increased emissions of DMS, resulting in a temperature drop due to the enhanced cloud cover. This would be a self-regulating negative feedback loop. It is an example of regulation that allowed Lovelock to build the Gaia theory, stipulating that several self-regulatory processes, including the sulphur cycle, allow the planet Earth to be considered as a living organism.

More than 20 years later, research projects have revealed the complexity of the sulphur cycle in the ocean, but have neither confirmed nor refuted this hypothesis. It is not yet known how, why and what species of phytoplankton can release the precursory sulphur compounds for the formation of DMS. Knowledge is therefore still lacking to determine whether anthropogenic climate change will result in a decrease or an increase in DMS emissions from the ocean.

MANIPULATION OF THE CARBON PUMP TO OFFSET CO_2-INDUCED CLIMATE CHANGE

Humankind has disrupted the steady state balance of the global carbon cycle and has brutally contributed to the modification of the composition of Earth's atmosphere, just as bacteria, protists and the biosphere in general have played a role in the shaping of the Earth's atmosphere in the past. As other events have marked the history of our planet in the past, these present changes provoked by human activities will significantly affect the Earth System. Our duty as inhabitants of the planet Earth is now to formulate predictions and to react in the best possible way to avoid disaster.

Studies have suggested that an artificial enhancement of the ocean carbon pump might improve carbon sequestration in the ocean, thus counterbalancing CO_2-induced climate change. For example, primary productivity of phytoplankton could be stimulated by adding nutrients such as iron to surface waters where they are limiting. There is currently no consensus on the efficiency of such methods, which are limited to a few field experiments. Moreover, alternative geoengineering approaches focusing on solar radiation management are not capable of resolving the issue of ocean acidification.

To conclude, it remains essential to protect the ocean carbon pump that contributes to more than half of the CO_2 sequestered each day. This can only be done by preserving the oceans, their marine life and their planktonic ecosystems. The carbon balance of the different parts of the carbon cycle also needs to be better characterised by carrying out further fundamental research in this field.

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