The ocean, a carbon pump

Laurent Bopp
Chris Bowler
Lionel Guidi

The ocean contains 50 times more carbon than the atmosphere and large amounts of carbon are exchanged each year between these two reservoirs. Over the past few decades, the ocean has slowed down the rate of climate change by absorbing nearly 30% of anthropogenic carbon dioxide emissions. While ocean absorption of anthropogenic carbon is the result of physical and chemical processes, marine biology plays a key role in the natural carbon cycle by sequestering large amounts of carbon in deep ocean waters. Changes in these physical, chemical, or biological processes may result in feedbacks to the climate system, thus accelerating or slowing down climate change. These feedbacks between climate, the ocean, and its ecosystems need to be better understood in order to more reliably predict how the ocean characteristics, atmospheric CO_2 and our climate will evolve in the future.

THE OCEAN'S MAJOR ROLE IN THE EVOLUTION OF ATMOSPHERIC CO_2

The carbon cycle involves a wide range of physical, chemical and biological processes, contributing to carbon exchanges between several reservoirs of the Earth system. While the global carbon cycle was roughly balanced before the industrial era began, atmospheric CO_2 has increased by almost 40% over the past 200 years, from less than 0.03% to more than 0.04% of the atmospheric reservoir. This increase is due to emissions generated by fossil fuel burning, cement production, deforestation and other land-use changes. Scientists now consider that such a rapid change is at least ten times faster than any other that has happened during the past 65 million years (Pörtner *et al.*, 2014; Rhein *et al.*, 2014.).

Since the beginning of the industrial period, the ocean has played a key role in mitigating atmospheric CO_2 by absorbing a significant fraction of the anthropogenic CO_2 emitted into the atmosphere. Over the past decade (2008-2017), the world ocean absorbed 2.4 billion tonnes of carbon per year, representing almost 30% of anthropogenic emissions over this period (Le Quéré *et al.*, 2018). Since 1870, the amount of carbon absorbed by the ocean has reached 155 billion tonnes – also 30% of anthropogenic emissions over this period. The ocean thus contributes to slowing down the anthropogenic climate change induced by increased emissions of this greenhouse gas.

A NATURAL OCEAN CARBON CYCLE INVOLVING PHYSICAL/ CHEMICAL AND BIOLOGICAL PROCESSES

Anthropogenic carbon absorbed by the ocean feeds an already considerable natural carbon reservoir. The ocean contains nearly 40,000 billion tonnes of carbon, mainly in the form of inorganic carbon dissolved in seawater. This quantity represents 50 times the size of the atmospheric reservoir. Every year, the ocean naturally exchanges nearly 100 billion tonnes of CO_2 with the atmosphere.

Carbon in the ocean, mainly present in the form of bicarbonate ions (HCO_3^-), is not evenly distributed. Concentrations are higher in deep waters than at the surface, and this uneven distribution of carbon controls atmospheric CO_2 levels. In fact, only the inorganic carbon present in the surface layer is in contact with the atmosphere and contributes to CO_2 exchanges with this reservoir.

This vertical carbon gradient in the ocean is due to both physical/chemical and biological processes.

Biological processes

Phytoplankton lives in the photic zone and uses the sun's energy to photosynthesize. These organisms take up nutrients present in seawater, as well as dissolved inorganic carbon, to produce organic matter. This production is called primary production.

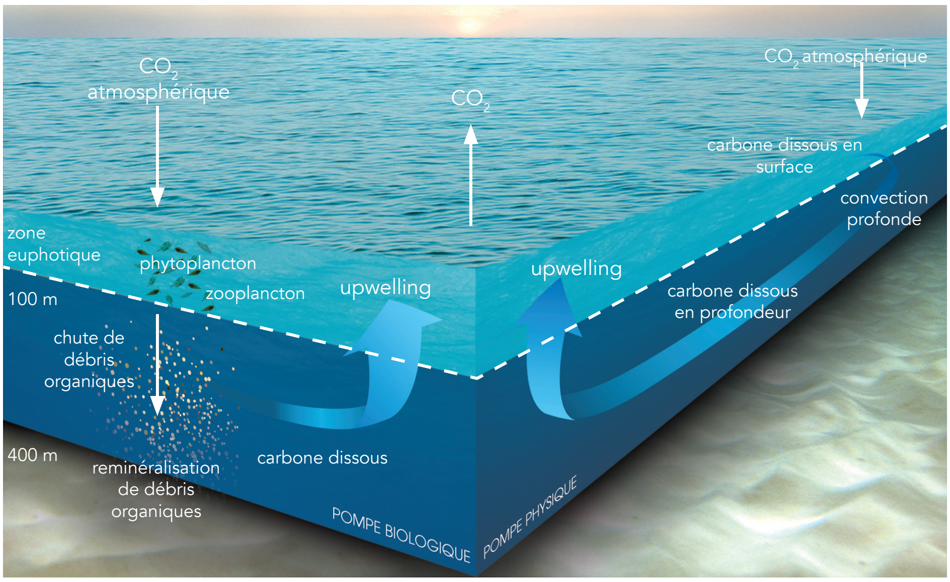
It represents the base of the ocean trophic chains, from which other non-photosynthetic organisms feed. This photosynthetic activity is therefore an effective mechanism for extracting CO_2 from the atmosphere and transferring it to living organisms. Surprisingly, the marine organisms contributing to primary production account for only a small fraction of dissolved carbon (~3 billion tonnes of carbon) in the ocean. However, they are able to generate large quantities of organic carbon each year (almost 50 billion tonnes per year or 50 PgC) to sustain the food chains, thanks to their fast turnover rate, ranging from a few days to a few weeks.

Before being sequestered in deep waters, the atmospheric carbon fixed by photosynthetic organisms undergoes a series of transformations: phytoplankton can be consumed directly by zooplankton, or indirectly by heterotrophic bacteria, which, in turn, will be eaten by larger organisms. In total, only a fraction of the organic matter produced leaves the surface layer as sinking particles (dead cells, detritus, fecal pellets, etc.), thus transferring surface carbon to the deep ocean.

Every year, almost 10 billion tonnes of carbon are thus exported from the surface layer and are responsible for most of the carbon vertical gradient (approximately 90%). All the biological processes contributing to the ocean carbon cycle constitute the biological carbon pump (Figure 1).

Only a tiny fraction (~0.2 PgC/yr) of the carbon exported by biological processes reaches the ocean floor and can be stored in sediments for millennia or even longer (Denman *et al.*, 2007; Ciais *et al.*, 2014); this biological mechanism extracts carbon from the ocean-atmosphere system for very long periods of time.

Over geological timescales, the biological carbon pump has formed oil deposits that are now fueling our economy. Knowing that, every day, large amounts of CO_2 that have been trapped for millions of years are released into the atmosphere (about one million years of trapped carbon is burned each year) makes it easier to understand the current rate of climate change.



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

Physical and chemical processes

Physical and chemical processes also contribute to the uneven vertical distribution of carbon. The cooling of surface waters at high latitudes increases their ability to dissolve atmospheric CO_2 (mainly by increasing its solubility) while increasing their density. These waters then sink to great depths, carrying CO_2 away from the atmosphere and thus contributing to the vertical ocean carbon gradient. This is referred to as the physical or solubility pump. Despite the fact that biological processes are responsible for the majority of vertical natural carbon gradient in the ocean, physical and chemical processes nevertheless explain the current anthropogenic carbon sink.

In fact, excess atmospheric CO_2 will lead to a net carbon flux to the ocean, because of the induced imbalance between the atmospheric and ocean concentrations. Anthropogenic CO_2, once dissolved in surface waters, will be transported by marine currents and mixed with subsurface waters.

SATURATION OF THE OCEAN CARBON SINK?

Since the beginning of the industrial era, the ocean has been absorbing an almost constant share of anthropogenic CO2 each year. However, many studies, based on theoretical considerations, and conducted from *in situ* observations, controlled laboratory experiments, or simulated, suggest that several processes may lessen or slow down this natural carbon sink.

The first set of processes is related to carbonate chemistry (exchanges between CO_2, HCO_3^- and CO_3^{2-}) and eventually leads to saturation of the ocean carbon sink. In fact, dissolution of anthropogenic carbon dioxide reduces carbonate content and thus the ocean's buffering capacity, in turn, increasing the proportion of CO_2 in relation to other dissolved inorganic carbon gases and decreasing sink efficiency. This same phenomenon simultaneously causes ocean acidification and could potentially have consequences on ocean ecosystems.

The second set of processes is linked to climate-carbon cycle feedback. This feedback, induced by anthropogenic climate change, affects different carbon absorption mechanisms. Climate change leads to modifications in water temperature, marine currents, and ocean biological production. If these changes increase the carbon sink, in time, they will curb climate change and induce negative feedback.

On the contrary, in the event of decreased carbon sink, the changes will induce positive feedback, accelerating the phenomenon.

Once again, several processes are involved. Water warming, for instance, reduces the ocean carbon sink: a 2 or 3°C rise in surface water temperature decreases CO_2 solubility by a few percent, and thus the ocean's capacity to absorb carbon dioxide. Another effect could further increase carbon sink saturation: in response to rising temperatures, climate models predict an increase in ocean vertical stratification. In other words, vertical mixing, which homogenizes deep and surface waters, is expected to decrease. The resulting stratification will limit the ingress of anthropogenic CO_2 into the deep ocean.

As for the biological pump, its fate is hard to predict. Even a qualitative estimate of the impacts of changes in marine ecosystems on the ocean carbon sink remains highly speculative. Because the functioning of the biological pump is strongly linked to primary production, it is important to consider the impacts of climate change on photosynthetic activity. On continents, CO_2 concentration is generally a limiting factor in photosynthesis. The increase in anthropogenic CO_2 therefore tends to stimulate plant growth (known as the carbon dioxide fertilization effect). This does not appear to be the case in marine systems because of high dissolved inorganic carbon (DIC) concentrations. However, photosynthesis is strongly affected by changes in water temperature, which has increased significantly over the past 150 years. In addition to temperature, light and nutrient limitation (Gonzalez-Taboada & Anadón, 2012; Pörtner *et al.*, 2014) are likely to affect photosynthetic activity, as will oxygen, pH, and salinity.

Models predict an overall reduction in oceanic primary production in response to climate change, though with significant variations depending on latitude. One of the factors leading to this reduction is the predicted expansion of oligotrophic gyres and the decrease in surface nutrient concentrations due to an intensification of ocean stratification. Climate projections, however, show an increase in primary production at high latitudes due to ice melt.

Finally, it is also necessary to assess which types of planktonic species will dominate the ocean ecosystem in response to these changes, since plankton composition can considerably affect CO_2 absorption. The role of some phytoplankton algae, such as diatoms, is particularly significant. Because of their relatively large size compared with phytoplankton cells (ranging from a few tens to a few hundred micrometers), these cells sink quite easily and are therefore responsible for the export of a large fraction of carbon to the deep ocean in productive regions. Nonetheless, diatoms are particularly sensitive to a decrease in mineral salt concentrations. Other phytoplankton cells, abundant in the ocean, but very small in diameter (<10 µm)[1], consume less and could replace them. Due to their size, they are mostly recycled in the surface layer, and thus contribute little to carbon storage in the depths. An imbalance in the diatom/small cell ratio could thus greatly disrupt the biological pump intensity.

Despite these multiple levels of uncertainty — the most important being the biological response to climate change — the different projections produced by numerical models that couple the climate system and the carbon cycle all show a reduction in the ocean sink due to the ongoing warming. Even though this ocean sink is unlikely to become a source, this decrease will affect atmospheric CO_2 concentrations and, ultimately, climate change. By 2100, climate/carbon cycle feedbacks (including the response of the terrestrial biosphere to climate change) could be responsible for an "additional" increase in atmospheric CO_2 concentrations by several tens of ppm2!

The future evolution of the ocean carbon sink, as predicted by models coupling climate-carbon cycle at a global scale, remains very uncertain. The IPCC's latest report points to a number of poorly constrained processes that explain the wide range of uncertainties associated with these projections: these primarily include the living world's response to climate change and changes in the biological pump, but other processes related to the representation of small-scale features (eddies) and to the consideration of particularly complex coastal areas are also mentioned.

MANAGING THE CARBON PUMP TO OFFSET CLIMATE CHANGE

Human activities have disrupted the carbon cycle balance and considerably contributed to changes in the composition of the Earth's atmosphere, just as bacteria, protists and the biosphere in general t have played a role in shaping the Earth's atmosphere in the past.

Like other events that have marked our planet's history in the past, these changes caused by human activities significantly affect the Earth system. Our duty as inhabitants of the planet Earth is now to make the most reliable predictions possible of future changes, react in the best possible way to limit the upcoming disruptions and adapt to inevitable changes.

Studies have suggested that an artificial increase in the ocean carbon pump might improve oceanic carbon sequestration, thus offsetting CO_2-induced climate change. For instance, primary phytoplankton productivity could be stimulated by adding nutrients, such as iron, to waters where this nutrient limits phytoplankton productivity. There is currently no consensus on the effectiveness of these methods, so far limited to a few field experiments. Other geoengineering approaches,

1 1 micrometer (µm) is 0.001 millimeter.

designed to artificially alter the incoming solar radiation by sending particles into the upper atmosphere, for instance, are equally controversial, and cannot solve the problem of ocean acidification.

In conclusion, just as we should protect forest areas on our continents, it is essential to protect the ocean carbon sink. This can only be done by preserving the oceans, marine life and planktonic ecosystems. To better assess the ocean-climate interactions, it is also necessary to better understand the footprint of each component of the carbon cycle, by conducting further fundamental research on the functioning of physical and biological carbon pumps.

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