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Ocean and Geological Carbon Sequestration

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ABSTRACT

Carbon Sequestration is a natural or artificial process by which carbon dioxide is removed from the atmosphere and held in solid or liquid form. Carbon sequestration, ocean acidification, and global climate change: these are just a few complex processes associated with the carbon cycle and ultimately, the future of our environment. The carbon cycle is a system, an intricate web of parts working in relation to one another. When one part of a system is altered others may shift in an effort to restore balance. Through burning fossil fuels, humans are releasing massive amounts of carbon into the atmosphere that would otherwise be locked up and stored in the geosphere (mainly rocks and sediment). It is primarily excess carbon in our atmosphere that is giving the planet a high fever. A recent study conducted by the California Institute of Technology on the Southern Ocean has shown that higher phytoplankton efficiency, and therefore greater carbon sequestration, is actually associated with periods of colder climates over the past 40,000 years. A carbon sink is a natural or artificial reservoir that absorbs and stores the atmosphere's carbon with physical and biological mechanisms. Coal, oil, natural gases, methane hydrate and limestone are all examples of carbon sinks. After long processes and under certain conditions, these sinks have stored carbon for millennia. On the contrary, the use of these resources, considered as fossil, re-injects the carbon they hold into the atmosphere. Nowadays, other carbon sinks come into play: humus storing soils (such as peatlands), some vegetalizing environments (such as forming forests) and of course some biological and physical processes which take place in a marine environment. Each year, the global carbon budget is assessed to track how *well, or not, humanity is achieving any reductions in greenhouse gas emissions. This assessment involves calculating sources and sinks of CO2 across the world and determining the change in atmospheric CO2 concentrations. The oceans sequester carbon, but research suggests that oceans sequester carbon in different amounts. The International Panel on Climate Change report that an estimated 28% of anthropogenic carbon produced from 1750–1994 is stored in Earth's oceans (IPCC, 2013). Continued uptake of CO2 by the world's oceans is leading to ocean acidification. Changes to ocean chemistry will affect marine organisms, but the impact of large-scale ocean acidification is not fully understood. However, should marine flora and fauna be negatively affected by a change in ocean pH, their ability to sequester carbon could be affected.*

Keywords: *Ocean, Carbon, sequestration, carbon cycle, Phytoplankton, carbon sink, geological*

1. Introduction

If Amazonia is the Earth's green lung, the Ocean is undoubtedly its blue lung. Half of the oxygen we breathe comes from plankton, more specifically from the photosynthetic organisms that produce oxygen, as any land plant would do. Moreover, the impact of the global ocean on the climate system doesn't end there. These organisms emit a huge amount of oxygen in the atmosphere, but they also consume carbon dioxide, the famous CO_2. During the last decades, the ocean has thus slowed the pace of climate change by absorbing nearly 30% of anthropogenic emissions of carbon dioxide. Several mechanisms participate in this gigantic carbon pump:

1) The oceans naturally trap through their physical and chemical properties a portion of the atmospheric CO_2 that they carry into the depths; 2) Phytoplankton – the "vegetal" plankton – captures carbon dioxide and transforms it into oxygen during photosynthesis; 3) Droppings and remains of planktonic organisms slowly sink to the bottom of the ocean. This shower of carbon-rich organic particles – external skeletons, shells and calcareous envelopes of microorganisms – will end up buried in the sediment on the ocean floor and gradually be transformed into hydrocarbons. This process, known as carbon sequestration, is in other words a huge carbon sink. By observing this shower of organic fragments at various depths, a simple yet striking fact can be pointed out: the deeper the depth, the fewer particles there are. In the end, only a small proportion of fragments – in the range of 1 to 10% – will reach the ocean floor. In reality, a large part of these particles will be consumed on their way down by other planktonic organisms. Scientists speak of carbon remineralization, i.e., the transformation of organic matter into inorganic matter – in this case, CO_2. For instance, instead of ending up as oil, a fraction of algae will be eaten by a small crustacean. The carbon the algae contains will be assimilated by the crustacean and then be rejected as CO_2 through breathing.

Carbon Sequestration is a natural or artificial process by which carbon dioxide is removed from the atmosphere and held in solid or liquid form. Carbon sequestration, ocean acidification, and global climate change: these are just a few complex processes associated with the carbon cycle and ultimately, the future of our environment. More familiar and accessible to the general public, however, is the fact that the amount of atmospheric carbon, a primary driver of climate change, is steadily on the rise in today's world. Questions and concerns on the future of our planet develop when we begin to contemplate what consequences will arise as a result of this increased carbon. How will nature react? Before diving deeper, let's first try to understand the carbon cycle. Carbon is an element basic and vital to all life found in both living and non-living things. Carbon "sources" release the element either into the environment or into another form, whereas "sinks" take in and store carbon. This movement through sinks and sources creates a stop-and-start flow where time is inconsistent; carbon can be stored for millions of years in a rock or for only a day in a plant leaf before it may be eaten and released once again through animal respiration.

2. The Carbon Cycle

The carbon cycle is a system, an intricate web of parts working in relation to one another. When one part of a system is altered others may shift in an effort to restore balance. Through burning fossil fuels, humans are releasing massive amounts of carbon into the atmosphere that would otherwise be locked up and stored in the geosphere (mainly rocks and sediment). It is primarily excess carbon in our atmosphere that is giving the planet a high fever. Considering that the ocean acts as a carbon sink and covers 71% of the earth's surface (and is 270 times greater in mass than the atmosphere!), the importance of understanding its role in regulating future changes in the environment becomes ever more apparent.

In the ocean, carbon sequestration, a fancy word for the process by which carbon dioxide is removed from the atmosphere, is achieved through various chemical and biological processes. Plankton at the ocean surface use photosynthesis to convert carbon dioxide into sugars in the same way trees and land plants do on land. Sea creatures consume this phytoplankton (photosynthesizing plankton), and therefore the carbon containing sugars, eventually dying and sinking to the bottom of the unfathomably deep ocean, locking the carbon away over millions of years as sediment. While chemical process can create calcium carbonate in the water and some organisms use carbon to build shells and skeletons, it is the "biological pump" initiated by surface-water plankton that is the primary driver of oceanic carbon sequestration.

3. Phytoplankton

A recent study conducted by the California Institute of Technology on the Southern Ocean has shown that higher phytoplankton efficiency, and therefore greater carbon sequestration, is actually associated with periods of colder climates over the past 40,000 years. Why? The answer is a seemingly unlikely candidate that begins with nutrients. A healthy population of phytoplankton relies on nutrients like nitrogen, phosphorus, and iron in order to thrive, essentially depleting these sources to run at optimal efficiency. In the modern Southern Ocean, researches have noted that the biological pump is not working at such "optimal efficiency" despite available nitrogen and phosphorus. The culprit: a limited source of iron. Through an additional analysis of over 10,000 fossils, an international team of researchers was able to look into the past, compare with the present, and conclude that colder climates have allowed more biomass to grow in the surface Southern Ocean, and it is likely because of the consequential stronger winds bringing more iron in from the continents to the ocean.

What makes this new finding so compelling is what it may imply for warmer climates as opposed to cold. Will an increasingly warmer climate experience decreasing levels of carbon sequestration if the opposite is true? Research has given us critical information in terms of how our biological pump, the photosynthesizing, carbon sequestering plankton, may change in response to a warmer climate. It seems that they may be less efficient at taking in the increasing amounts of carbon, which may heat the atmosphere further to create a vicious feed-loop.

Such research demonstrates the complexity of our ocean and its response to carbon, a building block of life. It sheds light on processes other than ocean acidification, which has been getting most attention in terms of oceanic and climate change research (as it should!). And while gaining insight on how the oceans will respond to the human derived influx of carbon to the atmosphere is imperative, it is equally important to conduct research on and devise methods to actively mitigate increased levels of atmospheric carbon.

Mangroves, sea grasses and tidal marshes (top to bottom) are promising solutions to mitigating climate change. Another recent scientific investigation published in the journal Frontiers in Ecology and the Environment has offered new information that may help us do just this, mitigate carbon influx. The team's analysis shows that shoreline environments, such as mangroves, sea grasses, and tidal marshes, show more promise for mitigating climate change than any other ecosystem. Our planet's coastline is extensive enough to wrap around the earth almost fifteen times (372,000 miles!). The study found that annually, such ecosystems could trap and store 2 to 35 times more carbon than even ocean phytoplankton. The major issue lies in current state of these ecosystems; within only the past 50 years, 50% of the world's mangrove forests have vanished due to anthropogenic action. With this information, the potential for positive change by human effort is clear. In addition to switching from reliance on fossil fuels, to driving fewer cars, there are other actions we can take. We push for habitat restoration and use research to help us combat our ecological footprint. The oceans cannot fight carbon alone- we must look into all aspects of our complicated, complex environment in order to find solutions. Are you willing to help take action?

4. A Carbon Sink

A carbon sink is a natural or artificial reservoir that absorbs and stores the atmosphere's carbon with physical and biological mechanisms. Coal, oil, natural gases, methane hydrate and limestone are all examples of carbon sinks. After long processes and under certain conditions, these sinks have stored carbon for millennia. On the contrary, the use of these resources, considered as fossil, re-injects the carbon they hold into the atmosphere. Nowadays, other carbon sinks come into play: humus storing soils (such as peat lands), some vegetalizing environments (such as forming forests) and of course some biological and physical processes which take place in a marine environment. These processes form the well-known "ocean carbon pump". It is composed of two compartments: a biological pump which transfers surface carbon towards the seabed via the food web (it is stored there in the long term), and the physical pump which results from ocean circulation. In the Polar Regions, more dense water flows towards the Deep Sea dragging down dissolved carbon. Actually, in high latitudes water stores CO2 more easily because low temperatures facilitate atmospheric CO2 dissolution (hence the importance of Polar Regions in the carbon cycle). It is difficult to determine the quantity of carbon stored by these mechanisms, but it is estimated that the ocean concentrates 50 times more carbon than the atmosphere. For some scientists, the Deep Sea and its water column may be the largest carbon sink on Earth but its large-scale future is still unknown. Also, with ocean acidification, this process could become less efficient because of a lack of available carbonates.

When talking about carbon storage, the notion of time is crucial. The biological pump is sensitive to disturbances. Consequently, it can be destabilized and re-emit carbon into the atmosphere.

The physical pump acts on another time-scale. It is less sensitive to disturbances but it is affected on a long-term basis. Once the machine is activated, it will be difficult to stop it. The carbon, transferred to the Deep Sea due to ocean circulation, is temporarily removed from the surface cycle but this process is rather poorly quantified. Also, after a journey of several hundred years, what will this carbon become when these waters resurface?

The biological pump is actually easier to assess. It relies on ecosystems' good health. In the high seas for instance, the planktonic ecosystem is a major player. All organic materials that reach the bottom participate in the biological pump and when conditions permit it, they also participate in oil formation. Calcium-containing materials such as coccolithophore, a microscopic one-celled alga, participate in subtracting carbon from the natural cycle. When they die, they generate a vertical net flux of carbon. This carbon can then be stored in the Deep Sea for long geological periods. These processes can leave traces. For instance, chalk cliffs are an accumulation of coccolithophores (micro algae covered with plating made of limestone) on the ocean seabed, which have later resurfaced to the continent due to geological movement.

Healthy coastal ecosystems play a mitigation role against climate change, especially by capturing carbon for their development. For instance, mangroves, sea grass beds and salt marshes are significant carbon sinks. These last three examples, store at least ten times more carbon than continental forests when they develop by capturing carbon in their calcium skeleton. However, these coastal ecosystems cover little surface on a global planet scale. Also, these ecosystems are weakened by coastal urbanization and coastal economic activities. Ecosystem restoration remains a priority to improve storage of carbon excessively released into the atmosphere and requires ambitious policies.

In order to combat climate change, geoengineering techniques to store CO2 artificially in the ocean carbon sink are under consideration. The scientific community is rather concerned because negative consequences of potential disequilibrium have not been explored yet. However, the concept of carbon sink is very controversial. The carbon cycle is rather complex as it is associated with other cycles which favour global warming. Consequently, storing CO2 also releases steam water, which plays an important part in the greenhouse effect. In addition, because of the increase in greenhouse gas concentration, the water temperature and its acidity are changing. This modifies physical, chemical and biological equilibriums and may affect the ocean pump. All of this data should encourage us to think about the future of marine ecosystems. This uncertainty should encourage us to be more careful and to preserve marine ecosystems.

5. Implications of a larger ocean carbon sink

A larger ocean sink could imply that CO2 emissions are larger than currently thought or that the land sink is smaller than we currently think. The sink seems to be increasing with time, especially in the last 20 years, and we believe this is because atmospheric CO2 has continued to rise rapidly, dissolving more every year into the surface waters.

Following convention, the uptake of CO2 into the ocean is shown as negative, so descending lines indicate that the ocean is absorbing more CO2. It means that the exchanges of carbon between the ocean and land – including those from large rivers like the Amazon, and that we currently consider to be relatively similar from year to year – are in fact more variable.

Each year, the Earth’s surface takes up billions of tonnes of CO2 from the atmosphere. These natural carbon sinks – oceans, plants and soils – help to buffer the continued emissions from human activity.

The ocean absorbs CO2 from the atmosphere because, as the atmospheric concentration increases, more is dissolved in the surface water. This water may then mix down, or sink as it is cooled, into the deep sea where the absorbed CO2 can stay locked up for hundreds of years as it slowly moves through the deep interior ocean and back to the atmosphere.

But the oceans have not always been a carbon sink. Before the industrial era, the ocean was actually a net source of CO2. However, the increasing atmospheric CO2 concentrations, driven by human-caused emissions are forcing the ocean to now absorb this gas.

While the ability of the ocean to capture and store carbon has helped to slow the accumulation of atmospheric CO2 – and, hence, the pace of global warming – it has come at a cost. Increasing CO2 in the ocean alters the chemistry of seawater – an effect known as ocean acidification – which has negative impacts on marine life.

6. New Observations

Each year, the global carbon budget is assessed to track how well, or not, humanity is achieving any reductions in greenhouse gas emissions. The assessment involves calculating sources and sinks of CO2 across the world and determining the change in atmospheric CO2 concentrations. Estimating the ocean sink is clearly needed to complete this assessment, but its importance has a knock-on impact for other parts of the overall budget. The huge variations in land cover, vegetation, terrain and their year-to-year variations mean that it is currently very difficult to measure the total global land sink accurately. Solving this issue is complex and complicated. However, it can be estimated indirectly.

Scientists can calculate the total human-caused emissions and observe how much of this CO2 stays in the atmosphere. The remainder must have been absorbed by either the land or the ocean. So a good estimate of the ocean sink also enables calculation of how much is being taken up by the vegetation on land. Put simply, the CO2 that goes missing that doesn't go into the ocean, must go into the land.

Nonetheless, quantifying the carbon absorbed by the vast oceans – whilst they are less variable when compared to the land – is still a complex problem. It requires measurements and observations from a range of sources including ships, buoys and even satellites. Thankfully, satellite measurements are now becoming much easier to access as European and international agreements have made these widely available to scientists. Such satellites have many uses, including ocean weather forecasting, so they are well maintained. The situation is a little different for measuring how much CO2 seawater contains, as these measurements are collected by researchers and then voluntarily collated into the Surface Ocean CO2 Atlas (SOCAT). These – along with the other observations – form a critical part of our ability to determine the oceanic sink. Each year more than a million new measurements are added to SOCAT; a herculean effort involving scientists throughout the world.

7. Carbon sequestration in different oceans

The oceans sequester carbon, but research suggests that oceans sequester carbon in different amounts. The International Panel on Climate Change report that an estimated 28% of anthropogenic carbon produced from 1750–1994 is stored in Earth's oceans (IPCC, 2013). Continued uptake of CO2 by the world's oceans is leading to ocean acidification. Changes to ocean chemistry will affect marine organisms, but the impact of large-scale ocean acidification is not fully understood. However, should marine flora and fauna be negatively affected by a change in ocean pH, their ability to sequester carbon could be affected (Stocker, 2015).

An inventory of CO2 by Sabine *et al*. (2004) looked at different oceans and found an uneven distribution of CO2 within and between oceans (Fig. 5). Vertical integration of water from the surface with water from deeper regions can take centuries. The concentration of CO2 in different depths of an ocean or sea can vary substantially (Sabine *et al*., 2004). Because atmospheric CO2 is absorbed into the sea at the surface, higher concentrations of CO2 are found in surface waters. Most of the anthropogenic CO2 in the world's oceans is found in the thermocline, which is a region in the mesopleagic zone of the oceans in which warm surface sea water mixes with cold water from the deep zone: 50% of anthropogenic CO2 is found in water up to 500m deep. Only 7% of anthropogenic CO2 is found at depths greater than 1,500m (Sabine *et al*., 2004).

The solubility pump is more efficient in Polar Regions because CO2 is twice as soluble in cold water as in warm tropical waters. The ocean currents (Fig. 6) transport warm water from Tropical regions towards colder areas at the poles, during which time the sea water cools and absorbs atmospheric CO2. Then the cool water sinks, taking with it the dissolved CO2 (Feely *et al.,* 2001).

North Atlantic

The North Atlantic Ocean has high vertical integration, which refers to water from the surface meeting with water from deeper zone. The North Atlantic stores 23 % of anthropogenic CO2, yet it covers 15 % of the global ocean area. This is the only area in which large concentrations of anthropogenic CO2 are found in the deep ocean – this is because of ocean currents in the region (Sabine *et al*., 2004).

Southern Ocean

The Southern Ocean is important in dissolving atmospheric CO2. Hoppema (2004) suggests that the Weddell Sea, and maybe other sub-polar gyres or seas, are important in carbon sequestration into the deep sea. The amount of CO2 remineralised in the subsurface Weddell Sea that is sequestered into the deep sea is approximately 6% of global CO2 sequestration in the deep oceans – this is a significant amount considering that the Weddell Sea is 0.4 % of the world's ocean (Hoppema, 2004). The Southern Ocean contains in total 9% of the global anthropogenic CO2 concentration (Sabine *et al*., 2004).

Caldeira & Duffy (2000) suggest that most of the anthropogenic CO2 entering the Southern Ocean is not sequestered in that region because it is transported north to the subtropical convergence by ocean currents. Caldeira & Duffy (2000) conclude their modelling study by suggesting that uptake of CO2 in the Southern Ocean is large but that sequestration of carbon is low. They suggest factors that would affect oceanic CO2 uptake in the future as changes to the ocean circulation, changes in the coverage of sea ice, and changes in biological activity.

The relevance of deep-sea carbon sequestration is that the carbon stored in the deep sea – the area known as the abyss – is released in upwelling zones. The carbon stored in such zones might have been stored for decades (Canu *et al.*, 2015).

Arctic Ocean

The Arctic Ocean is an atmospheric CO2 sink, although its role in the carbon cycle may alter as a result of climate change. However, the Arctic Ocean's part in the carbon cycle is poorly quantified (MacGilchrist *et al.*, 2014).

Red Sea and Persian Gulf

These waters are high in anthropogenic CO2. The high air temperature causes seawater to evaporate, which increases the salinity of the water and makes it denser than less salinated water. The dense water sinks and carries dissolved CO2 towards the equator and across the Indian Ocean (Sabine *et al*., 2004).

Pacific Ocean

The Pacific Ocean is the world's largest ocean, covering approximately half of the world's marine area. Yet it is a store for just 18% of anthropogenic CO2 (Feely *et al.*, 2001).

Chu *et al*. (2016) found that storage of anthropogenic CO2 is increasing in the Northwest Pacific. The team compared data collected on a cruise in 2001 with data collected along the same route in 2012 and found elevated levels of anthropogenic CO2 in the surface water of the section studied. The increased CO2 has contributed to acidifying the ocean water in that region.

8. Geological sequestration

Geological carbon sequestration involves the separation and capture of carbon dioxide (CO_2) at the point of emissions followed by storage in deep underground geologic formations. This is also referred to as carbon (or CO_2) capture and storage (CCS).

Physical

Physical mechanisms usually involve trapping CO_2 within a cavity in the rock underground. These cavities are either large man-made cavities, such as caverns and mines or the pore space present within rock formations such as the structural traps in depleted oil and gas reservoirs and in aquifers.

Enhanced oil recovery

CO_2 injection into oil and gas reservoirs is sometimes used to help push out the product and extend the amount of oil and gas that can be recovered from the site. This is called enhanced oil recovery. The United States is the world leader in enhanced oil recovery technology, using about 32 million tons of CO_2 per year for this purpose. (2) In this way, there is an economic benefit to CO_2 capture and storage for the oil and gas industry.

Concerns about geological sequestration

Much of the current work on geological sequestration involves capturing the CO_2 from large emitters such as the oil sands and coal-burning electrical plants and injecting the CO_2 underground. However, these producers are usually a long distance from suitable geological formations required for potential sequestration sites. So, the CO_2 often needs to be piped or trucked from the source to the injection site. This takes a lot of energy which usually involves production of more CO_2.

Many consider geological carbon sequestration to still be experimental and controversial. There are some key unanswered questions:

- How long will the sequestered CO_2 remain captured?
- Are there other consequences or risks that need to be considered?
- Will this prevent us from reducing our consumption of fossil fuels (esp. coal)?

It takes a lot of energy and resources to build and operate sequestration facilities. Is this type of CO_2 sequestration cost effective? Wouldn't we be better to eliminate CO_2 production in the first place?

Biological / terrestrial sequestration – the net removal of CO_2 from the atmosphere by plants and micro-organisms and its storage in vegetative biomass (biological) and in soils (terrestrial).

Carbon sequestration is the process by which natural and artificial carbon dioxide sinks remove CO_2 from the atmosphere that would otherwise persist for a long time.

Chemical

Chemical mechanisms of trapping CO_2 involve transforming the CO_2 or binding it chemically to another substance in the ground. This can be done in the following ways:

- dissolving CO_2 in underground water or reservoir oil
- decomposing CO_2 into its ionic components
- locking CO_2 into a stable mineral precipitate
- adsorption trapping

The fundamental mechanisms for CO_2 storage in underground geological media basically translate into the following trapping means:

i. CO_2 is dissolved into fluids, such as formation water and reservoir oil, that saturate the pore space within rock formations

ii**.** Gaseous CO2 is adsorbed onto a coal matrix underground because CO_2 has a higher affinity to coal than does the methane that is usually found in coal beds.

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