CDRmare

Research Mission of the German Marine Research Alliance (DAM)
»Marine carbon sinks in decarboniation pathways«

FACT SHEET

Background II: The Earth's natural carbon cycle

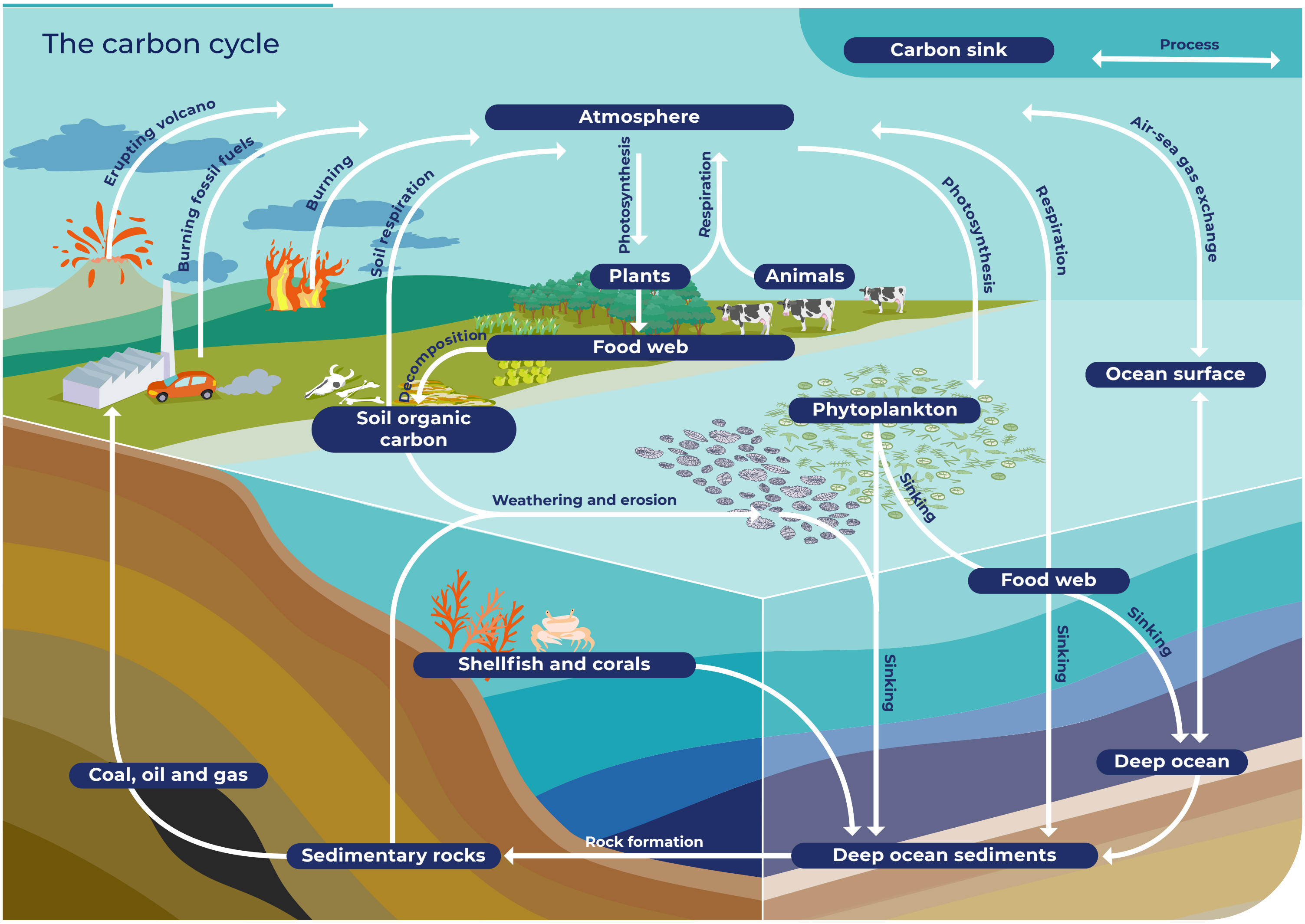
Carbon reservoir ocean: How the sea absorbs carbon dioxide

In the past decades, the world ocean has absorbed around 25 per cent of the carbon dioxide emissions caused by humans and thus significantly slowed down climate change. Humankind could boost this natural climate service of the ocean by enhancing the ocean's uptake processes in a variety of ways.

Carbon: An essential element

Carbon is a building block of life on our planet. Carbon-containing compounds make up all living tissue, including plants, animals and humans.

Carbon is also found in wood and coal, in marble and limestone, and in petroleum-based plastics and fuels. This diversity of forms is due to the binding capacity of carbon atoms. Experts



The carbon cycle

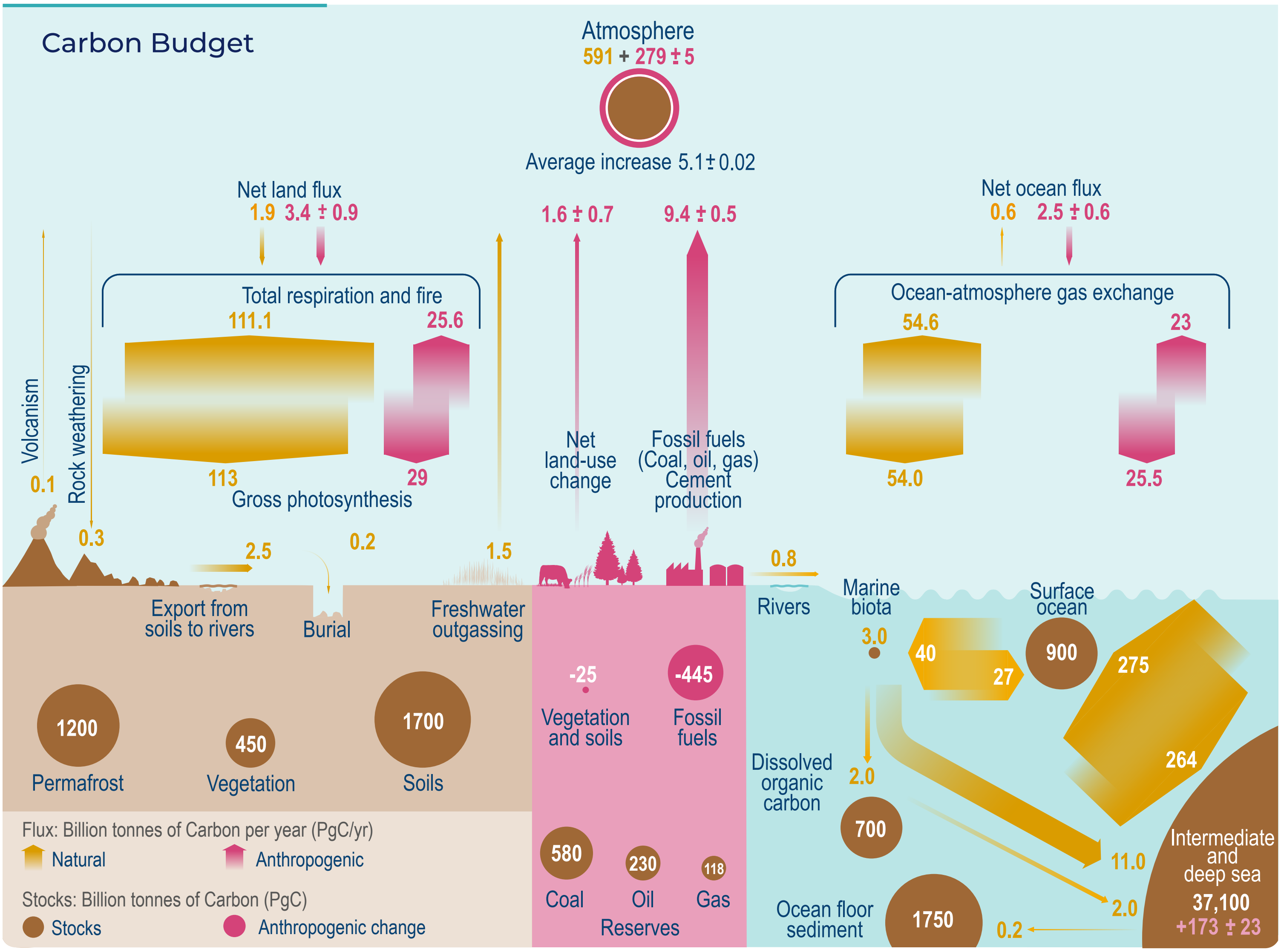
This overview shows the different stations and processes of the Earth's natural carbon cycle. All sections marked in blue indicate so-called carbon sinks or reservoirs, where carbon or one of its many compounds is stored. The white arrows indicate all exchange processes in which carbon or one of its many compounds is bound, shifted, exchanged or released

Graphic: Rita Erven/CDRmare

now know far more than a million different carbon compounds, and new ones are being added every year, so that their study forms a separate discipline in chemistry.

Due to its chemical properties and widespread distribution, carbon is naturally absorbed or released, chemically bound or else transformed at any given time anywhere in the world. This means that carbon is constantly on the move and travels through all components of the Earth system over time. For each step of this journey, carbon takes different amounts of time. Sometimes carbon or its compounds are released within a few minutes (respiration, combustion) or absorbed (photosynthesis, dissolution in seawater); sometimes it is stored in one place for thousands or millions of years (permafrost; formation of fossil raw materials).

The carbon dioxide concentration of the Earth's atmosphere, which is crucial for the climate, is controlled by various biogeochemical processes on land and in the ocean. In the course of these processes, the greenhouse gas is either removed from the atmosphere and stored (carbon sinks) or released into it (carbon sources).



The global carbon budget in numbers:
The orange arrows represent the annual carbon fluxes in billions of tonnes of carbon associated with the natural carbon cycle for the period before industrialisation around 1750. The pink arrows with associated numbers represent the average annual human-induced carbon fluxes for the period from 2010 to 2019. Brown circles with white numbers represent the size of pre-industrial carbon stocks in billions of tonnes of carbon. The pink numbers in or on the circles represent the human-induced change in these stores since industrialisation.
Graphic: based on a template from IPCC WGI AR6, Chapter 5

Carbon reservoir ocean

The ocean contains about 40,000 billion tonnes of carbon, most of which is dissolved in seawater. With this carbon reservoir, the ocean exceeds the carbon content of the atmosphere by more than 50 times. Both systems are in constant carbon exchange. Every year, many billions of tonnes of carbon move back and forth between the ocean and the atmosphere in the form of the greenhouse gas carbon dioxide.

Because the concentration of carbon dioxide in the atmosphere is increasing due to human-induced emissions, the ocean is also absorbing more carbon dioxide. This means that, in contrast to pre-industrial times, it now absorbs more carbon dioxide from the atmosphere than it releases elsewhere. An imbalance has arisen. As a result, the world ocean has absorbed about 25 percent of man-made carbon dioxide emissions from the atmosphere in recent decades, thus significantly slowing down global warming.

Carbon dioxide uptake at the ocean surface

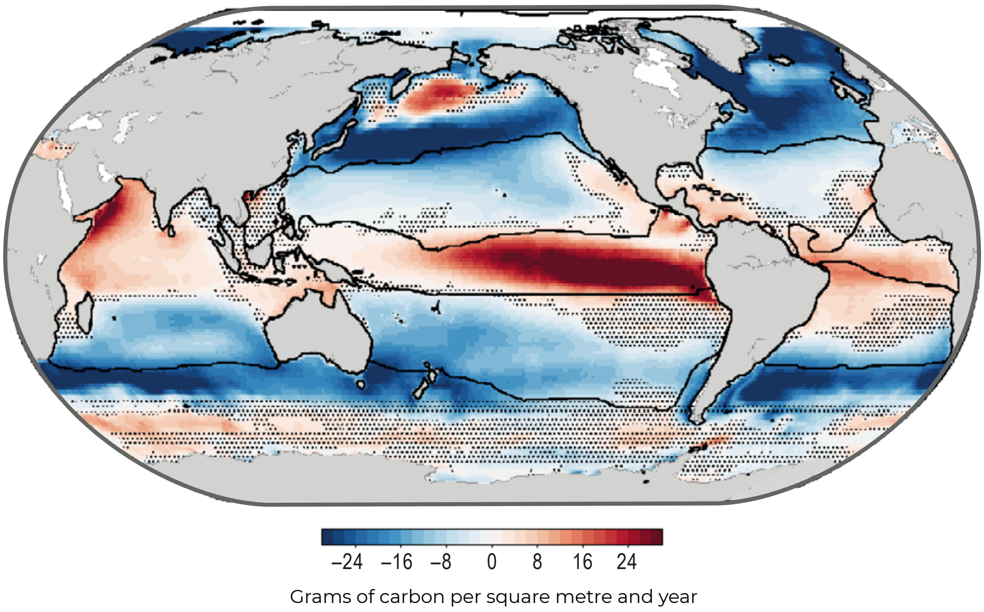
The ocean's carbon dioxide uptake takes place at the ocean surface, where carbon dioxide from the air dissolves in the seawater. Whether and how much atmospheric carbon dioxide is dissolved in the water depends primarily on the difference in the so-called carbon dioxide partial pressure between seawater and the atmosphere. Put simply, this is the pressure generated by the carbon dioxide dissolved in the surface water and the carbon dioxide in the atmosphere respectively. The natural gas exchange between seawater and the atmosphere always aims to balance these pressures. This means that surface water with a lower carbon dioxide partial pressure than the atmosphere above it absorbs carbon dioxide from the air until the pressure difference is equalised. The pressure equalisation also occurs in reverse from the water to the atmosphere.

Important for the ocean's carbon dioxide uptake are the water temperature as well as salinity, wind, waves and ocean currents. The temperature and salinity of the surface water influence how much gas can dissolve in the water – the warmer and saltier the water is or becomes, the less carbon dioxide it can absorb or store and the more likely it is to release carbon dioxide into the atmosphere. This physical law explains, among other things, why the world ocean in the warm, equatorial part of the Pacific releases carbon dioxide into the atmosphere, while in the cool North Atlantic it absorbs large amounts of carbon dioxide.

Wind and waves in turn mix the surface water and thus guarantee a carbon dioxide concentration balance within the uppermost water layer. The ocean currents keep the water masses in motion and ensure that, for example, in so-called upwelling zones, new deep water repeatedly reaches the sea surface and can enter into gas exchange with the atmosphere.

Net carbon dioxide flux between atmosphere and ocean

in the period from 1994 to 2007



Not everywhere in the world does the ocean absorb the same amount of carbon dioxide from the atmosphere. This map shows that carbon dioxide uptake occurs mainly in the cold Southern Ocean and in the North Atlantic and North Pacific (blue colouring). In the warm tropical ocean regions, on the other hand, the ocean releases significantly more carbon dioxide into the atmosphere than it absorbs (red colouring). In the dotted areas, the situation is not clear.

Graphic: IPCC WGI AR6, Kapitel 5

A chemical equilibrium reaction

If the carbon dioxide concentration in the atmosphere increases, it usually leads to an increase in the carbon dioxide concentration in the surface water within a few months.

As carbon dioxide dissolves in seawater, there is a chemical change in the surface water, because unlike many other gases such as oxygen, carbon dioxide does not simply dissolve in the sea. A portion of the gas reacts with the water molecules and forms carbonic acid. Its molecules, in turn, split immediately, with very few exceptions, into hydrogen carbonate and a hydrogen cation, which is also called a proton. If the resulting hydrogen carbonate splits off another proton, carbonate is formed.

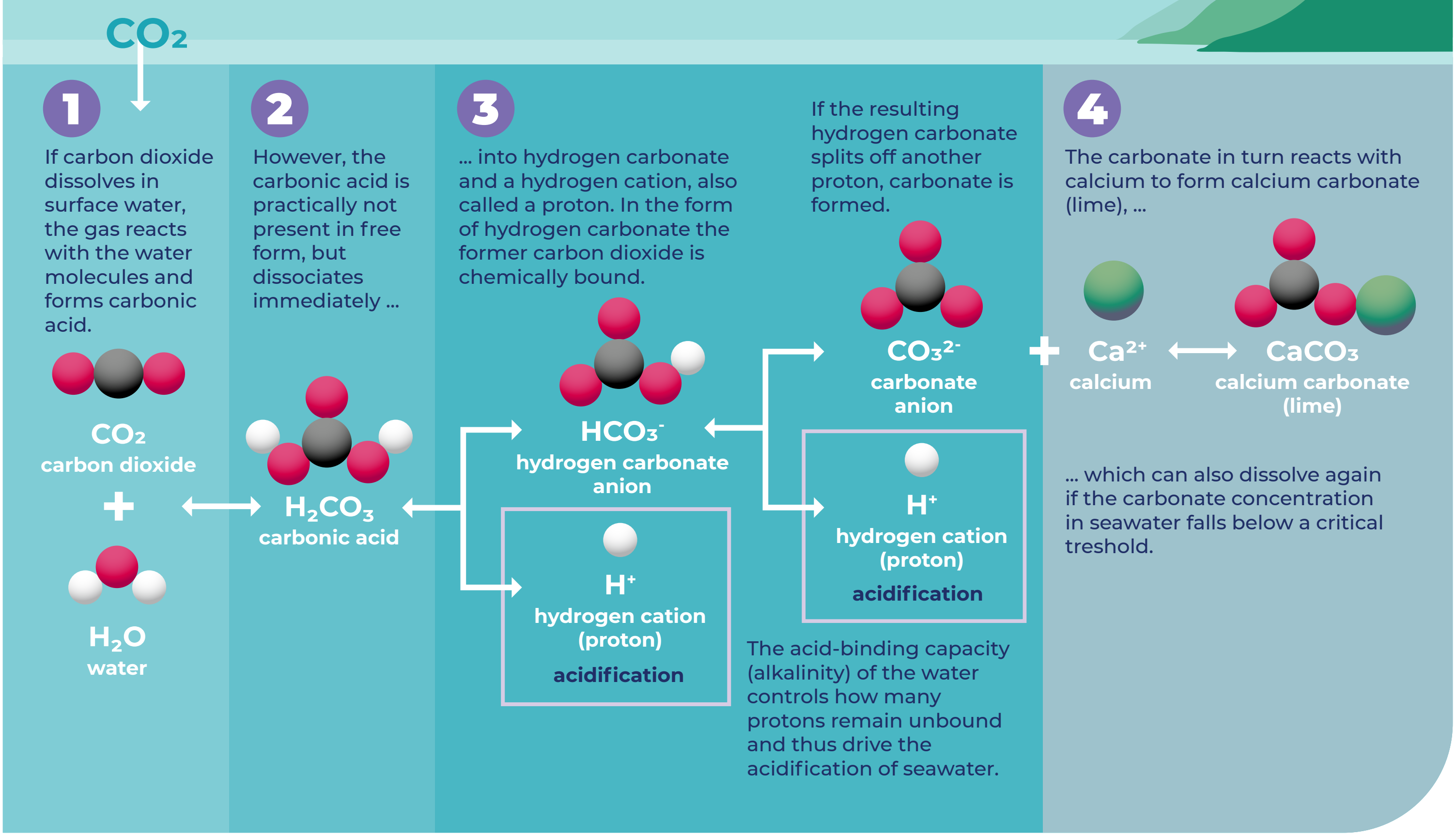
The surface water then contains carbon in three different dissolved forms:

- as carbon dioxide (CO_2), which can also escape back into the atmosphere. It accounts for only about one percent of the carbon stored in the ocean, but determines the carbon dioxide partial pressure of the seawater;
- as hydrogen carbonate, which accounts for about 90 percent of the carbon stored in the ocean;
- as carbonate, about which it is important to know that it is not only formed in the course of the carbonic acid chain reaction, but is also released by rock and mineral weathering on land (but more on this later).

All three parameters are in a balanced concentration equilibrium with each other, which means that changes in one parameter immediately lead to balancing reactions in the other two.

An important example: When water and dissolved carbon dioxide react to form carbonic acid, hydrogen carbonate is formed. In the process, the proportion of dissolved carbon dioxide in the seawater decreases and thus its carbon dioxide partial pressure. In response, the ocean takes up new carbon dioxide from the atmosphere to balance the partial pressure between the ocean and the atmosphere. The chemical reaction chain begins again. However, this process cannot repeat itself endlessly. The carbon dioxide uptake shifts the concentration balance between dissolved carbon dioxide, carbonic acid, hydrogen carbonate and carbonate in such a way that the carbon dioxide uptake of the surface water succumbs in the long term, unless other new processes disturb or shift the balance again.

Carbon dioxide uptake by the ocean – A chemical equilibrium reaction



1 If carbon dioxide dissolves in surface water, the gas reacts with the water molecules and forms carbonic acid.

2 However, the carbonic acid is practically not present in free form, but dissociates immediately ...

3 ... into hydrogen carbonate and a hydrogen cation, also called a proton. In the form of hydrogen carbonate the former carbon dioxide is chemically bound.

If the resulting hydrogen carbonate splits off another proton, carbonate is formed.

The acid-binding capacity (alkalinity) of the water controls how many protons remain unbound and thus drive the acidification of seawater.

4 The carbonate in turn reacts with calcium to form calcium carbonate (lime), ...

... which can also dissolve again if the carbonate concentration in seawater falls below a critical treshold.

Graphic: Rita Erven/CDRmare, text: Sina Löschke/schneehohl.net, translation: Anja Wenzel/CDRmare

Ocean acidification: A question of free protons

The protons released during carbonic acid splitting drive up the acidity of the water. If the ocean absorbs a lot of additional carbon dioxide, the sea therefore runs the risk of becoming acidic, with the result that the living conditions for many marine organisms deteriorate. However, how many protons are actually released during carbonic acid splitting depends on the acid binding capacity of the seawater. This is determined by mineral components (again, carbonates) in the water, which originate primarily on land. There, they were dissolved from weathered rock over millions of years and then washed into the ocean by rainwater, streams and rivers.

If the proportion of these minerals is high, the seawater has a high acid binding capacity. Experts speak of a high alkalinity of the water. In this case, many of the protons are not even released, but are immediately bound by the minerals during carbonic acid splitting. This reaction also produces hydrogen carbonate, while carbonate is broken down and the acidification of the water is buffered. However, if the water contains only a few carbonates, the acid binding capacity is limited. The number of free protons increases and the sea becomes increasingly acidic.

Viewed over a period of millions of years, the Earth's carbon cycle continually balances the carbon dioxide content of the ocean via the input of weathered minerals. If, for example, the carbon dioxide concentration in the atmosphere and in the ocean increases, the warming of both systems leads to more rock being weathered in the long term – both on land and on the seabed. As a result, larger quantities of minerals are introduced into the ocean, reducing the acidity of the water while the ocean takes up new carbon dioxide from the atmosphere again to restore the aforementioned concentration equilibrium. At the same time, the carbon dioxide concentration in the atmosphere decreases and warming slows down.

The idea of accelerated carbon dioxide uptake by the oceans

This process normally takes place over very long periods of time. In view of the dramatic effects of man-made climate change, however, scientists now investigate whether it could be accelerated, for example by the targeted input of many tonnes of mineral-rich rock flour (enhanced alkalinisation). The intention behind this is to be able to increase the carbon dioxide uptake of the ocean. If such an intervention succeeded, it could offset unavoidable man-made residual carbon dioxide emissions.

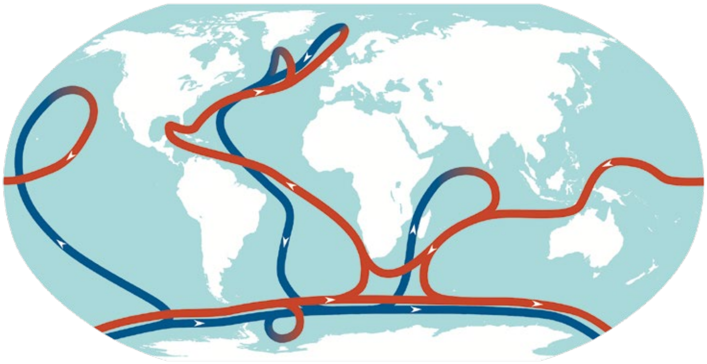
The three marine carbon pumps

As soon as the chemical equilibrium reaction in the surface water is complete and carbon is present in its three dissolved forms carbon dioxide, hydrogen carbonate and carbonate, it begins its journey through the marine carbon cycle. This journey can take place in three different ways, all of which are referred to as carbon pumps, but which differ significantly in their basic mechanisms. Experts speak of one ›physical‹ and two biological carbon pumps of the ocean – an ›organic‹ and an ›inorganic‹ pump.

The physical carbon pump

The physical carbon pump is driven by ocean currents and their differences in temperature and salinity and distributes dissolved carbon (carbon dioxide, hydrogen carbonate, carbonate) by the sinking or rising of water masses in the ocean. It is primarily responsible for the transport of man-made carbon dioxide emissions into the deep ocean.

In order to sink, water masses must cool down so that they become denser and heavier. This process is observed mainly in the polar regions, where the solubility of carbon dioxide in the water is particularly high at low temperatures and the surface water is correspondingly rich in carbon. The colder and saltier the water, the deeper it sinks and takes the dissolved carbon with it into depths. From there, the water masses then travel around the globe on the global conveyor belt of ocean circulation.



The global oceanic currents of warm surface water (red) and cold deep water (blue) form the global conveyor belt of the thermohaline ocean circulation.

Source: Robert Simmon, NASA, CC BY-SA 3.0

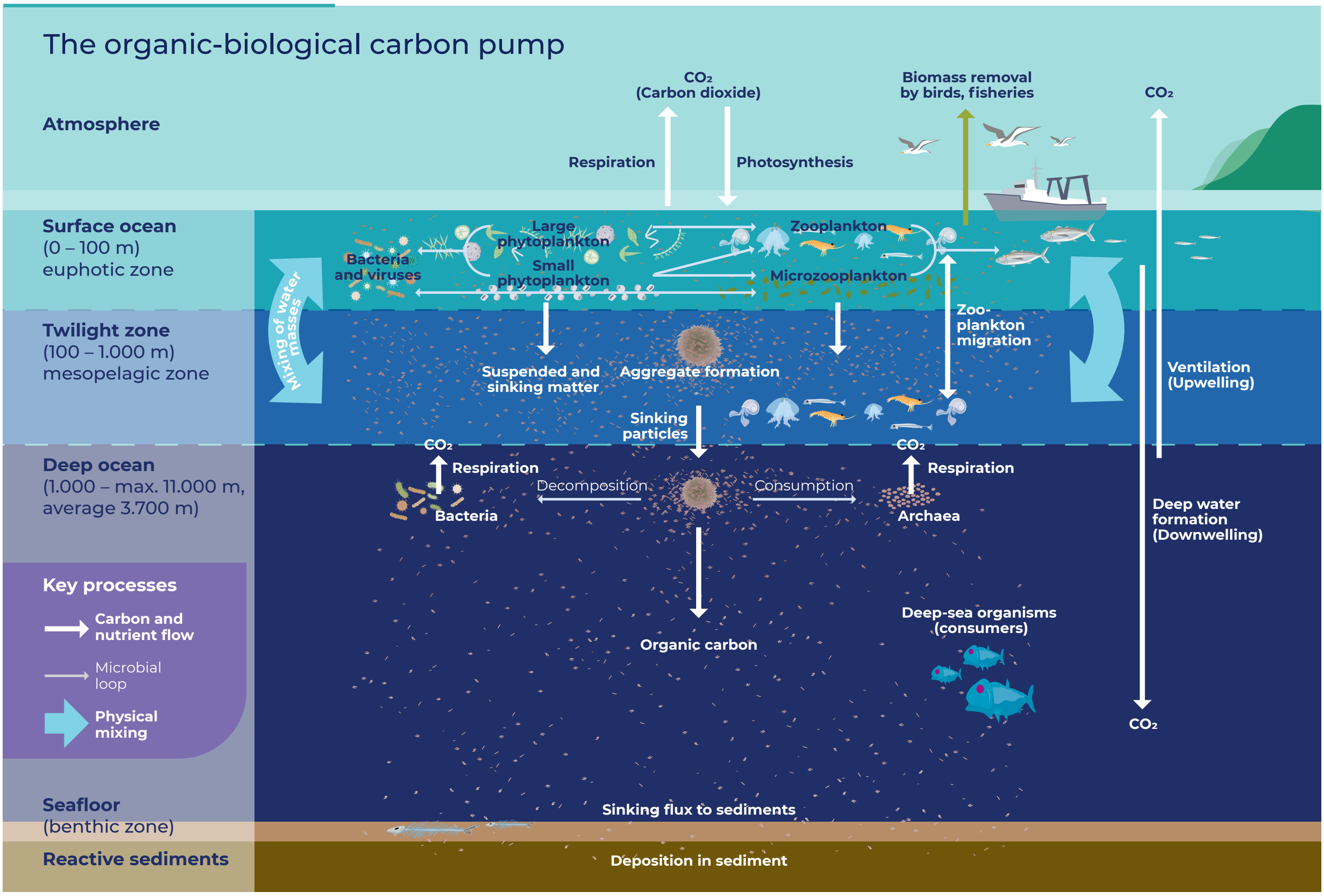
Decades to centuries pass before this carbon-rich deep water returns to the ocean surface and can once again enter into gas exchange with the atmosphere. One day, however, the water masses rise again – usually in one of the so-called coastal upwelling areas along the west coasts of Africa, South and North America, or along the equator, especially in the Pacific Ocean. Once it reaches the surface, the water warms up and releases some of its dissolved carbon dioxide back into the atmosphere as gas.

While the long migration of carbon-rich water through the deep ocean is highly desirable from an emissions point of view, it brings with it a decisive disadvantage: Should the water masses at the ocean surface acidify – a development that can currently be observed worldwide – their long circulation at great depths means that this acidification is irreversible when viewed on human time scales.

The organic-biological carbon pump

The organic-biological carbon pump is driven by the biotic communities in the surface water of the ocean. There, single-celled algae (phytoplankton), macroalgae and sea grasses carry out photosynthesis. This means that they use the energy of the sun to build up biomass. To do this, they need carbon dioxide as a building material, most of which they take from the surface water in dissolved form (mainly as carbon dioxide). They incorporate the carbon it contains into their biomass.

If the algae or sea grasses are eaten, the consumers automatically absorb the carbon they contain. They respire a part of it: This means that the carbon is released back into the ocean in the form of carbon dioxide. The rest is stored, for example in the form of muscle mass or body fat, and some is excreted as faecal matter. Following the natural laws of the ocean, the carbon may thus migrate through the entire marine food web: from small crustaceans to various species of fish to marine mammals such as whales – and at each step carbon is respired, converted into biomass or excreted in the form of faeces.



The organic-biological carbon pump of the ocean are the processes by which algae and plants absorb carbon dioxide from the light-flooded surface water and convert it into biomass. This biomass then travels towards the ocean floor. The critical factor for the global emissions balance and the further course of climate change is how much of the biomass sinks into water layers below the surface layer mixed by wind and waves. In the intermediate and deep water, both the organic material and the carbon it contains are trapped for decades to centuries – regardless of whether the biomass is eaten and respired or continues to sink towards the seabed..

Graphic: Rita Erven/CDRmare based on atemplaet by the Office of Biological and Environmental Research of the U.S. Department of Energy Office of Science..

However, the plants and algae can also die directly. In this case, they sink to depths together with the faeces and the remains of their consumers. On their way to the seabed, bacteria and other microorganisms pounce on the dead biomass and decompose a large part of it even before the material has reached great water depths or the seabed. In the process, the stored carbon is once again released into the seawater in the form of carbon dioxide. The remaining remnants trickle into the deep ocean as so-called »marine snow«.

Once they reach the deep seabed, the carbon-containing particles, no matter whether protozoa, faecal particles or whale carcasses, are almost completely consumed by the deep-sea inhabitants. What remains is a residual amount of significantly less than one percent of the carbon originally absorbed by the algae. If the carbon comes from other sources (wood, whale bones, etc.), the proportion can be higher. The residual amounts are stored in the sediment and the carbon contained is thus removed from the natural cycle for a very long time.

The storage in the sediment is a critical factor when considering the carbon cycle over geological periods, i.e. over millions of years. For the current development of climate change, however, it is already essential how much of the carbon bound by algae and plants sinks into water layers below the so-called mixed surface layer. This is the term used to describe the layer of water at the ocean surface whose water masses are regularly mixed by wind and waves.

Once carbon-containing particles have left the surface layer, decades or centuries pass before they or their respired residual products return to the ocean surface and can escape into the atmosphere again as carbon dioxide. Science therefore regards all carbon sequestered (taken up and stored) that the biological-organic carbon pump transports to depths that are no longer mixed by wind and waves.

The special roles of coasts, shelves, marine meadows and forests

On the coasts and continental shelves (0 – 200 metres water depth), a large part of the plankton biomass is not decomposed in the water column, but sinks to the seabed. There, the biomass is partly embedded in the sediment. The shelf sediments are much larger carbon reservoirs than the deep-sea sediments. More than 90 percent of permanent carbon embedding takes place in shelf sediments. The biomass in these sediments then transforms into oil and natural gas on geological time scales. A large part of man-made greenhouse gas emissions is thus caused by humans extracting the carbon that was trapped there long ago as oil and gas, burning it and releasing it into the atmosphere as carbon dioxide.

Another special role in the ocean's carbon cycle is played by coastal vegetated ecosystems such as salt marshes, seagrass beds and mangrove forests. Although They grow on less than one percent of the ocean surface, they are responsible for a significant part of the natural carbon storage in the seabed and are therefore key players in the Earth's carbon cycle.

Their plant communities thrive in tidal and shallow water areas and absorb carbon dioxide both from the surface water and from the air. They then store the carbon bound by photosynthesis mainly underground – on the one hand in their dense root system, and on the other hand directly in the coastal sediment via dead plant material (leaves, deadwood, etc.).

As the marine meadows and forests simultaneously filter lots of suspended matter from the water and deposit these particles between their stalks and roots, the plant communities grow steadily upwards. The particle rain also traps a lot of washed-up animal and plant material in the seabed. Both processes cause the salt marshes, mangroves and seagrass beds to accumulate large amounts of carbon beneath them. These deposits are sometimes more than ten metres thick and grow as long as the ecosystems are healthy. Ideally, they remain intact for many centuries, sometimes even millennia.

Photo: Ocean Image Bank / The Ocean Agency

The inorganic-biological carbon pump

In addition to photosynthesis, there is a second process by which marine organisms biologically bind carbon dissolved in the water and ultimately transport it into depths – the formation of calcareous shells or skeletons.

Calcifying organisms such as calcareous algae, mussels, corals, winged snails or chambered molluscs extract the dissolved hydrogen carbonate from the seawater, convert it into calcium carbonate and use this as a building material for the structures mentioned. When the organisms die, the calcium carbonate shells sink to the seabed and are deposited there in the sediment.

In this way, the carbon contained is removed from the natural cycle for millions of years.

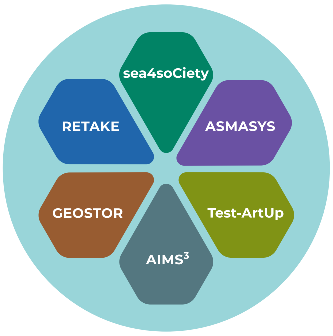
However, the inorganic-biological carbon pump is of little help when it comes to increasing the ocean's carbon dioxide uptake. In sum, its carbon dioxide balance in relation to the atmosphere is negative. The explanation for this is that when lime is formed, hydrogen carbonate is taken from the water. One of the products of the corresponding chemical reaction is carbon dioxide dissolved in the water. This in turn increases the partial pressure of carbon dioxide in the sea and thus promotes the outgassing of carbon dioxide into the atmosphere. If, on the other hand, lime dissolves – which does happen under certain chemical conditions in the sea – carbonic acid is consumed and the seawater tends to absorb more carbon dioxide from the atmosphere.

Research mission CDRmare: How can the ocean's carbon uptake be enhanced?

Even with ambitious climate policies and maximum efforts to reduce man-made greenhouse gas emissions, optimistic forecasts predict that Germany will still be releasing 10 to 20 per cent of current emissions in three decades' time and will continue to drive global warming. One possible way out: offsetting these unavoidable residual emissions through targeted carbon dioxide removal and storage.

In the research mission CDRmare, scientists investigate whether and to what extent the ocean and its coastal ecosystems can play an essential role in removing and storing carbon dioxide from the atmosphere. The researchers do not only test the technical feasibility of various approaches and processes, but also investigate the interactions with and impacts on the marine environment, the Earth system and on humans and society.

At the same time, they develop methods with which marine carbon storage can be monitored, balanced and traced back to specific measures – all this against the backdrop of a marine environment that is already undergoing fundamental changes due to man-made climate change.



Within the research mission CDRmare of the German Marine Research Alliance (DAM), which involves about 200 researchers in 6 consortia, different methods of marine CO_2 removal and storage (alkalinisation, blue carbon, artificial upwelling, CCS) are investigated with respect to their potential, risks and trade-offs and brought together in a transdisciplinary assessment framework. CDRmare has been funded by the German Federal Ministry of Education and Research with 26 million euros since August 2021 and will run for three years.

CDRmare www.cdrmare.de
twitter.com/cdrmare
linkedin.com/company/cdrmare/
CDRmare Knowledge Transfer
transfer@cdrmare.de

DAM GERMAN MARINE RESEARCH ALLIANCE

SPONSORED BY THE
Federal Ministry of Education and Research

IMPRINT
GEOMAR Helmholtz Centre for Ocean Research Kiel // Wischhofstr. 1-3 // 24148 Kiel // Germany // **Responsible for content:** Andreas Oschlies, Gregor Rehder, Achim Kopf, Ulf Riebesell, Klaus Wallmann, Martin Zimmer // **Editorial office:** Ulrike Bernitt (ubernitt@geomar.de) // **Text:** Sina Löschke (schneehohl.net) // **Design & graphics:** Rita Erven // **Translation:** Anja Wenzel // June 2023

Text and Infographics on page 1/4/6: **CC BY 4.0** // **Cite as:** CDRmare (2023): *The Earth's natural carbon cycle – Carbon reservoir ocean: How the sea absorbs carbon dioxide*, CDRmare Research Mission, pp. 1-8, DOI 10.3289/CDRmare.24_V2