2 The role of the ocean in the global carbon cycle

> The world ocean is the second largest carbon reservoir on Earth. It stores around 40,000 billion tonnes of carbon. The amount of carbon contained in the ocean exceeds that in the atmosphere by a factor of greater than 50. The ocean and atmosphere, however, are constantly exchanging carbon. With increasing concentrations of carbon dioxide in the atmosphere, more carbon dioxide is absorbed by the ocean, which slows the rate of climate change.

How the ocean absorbs carbon dioxide

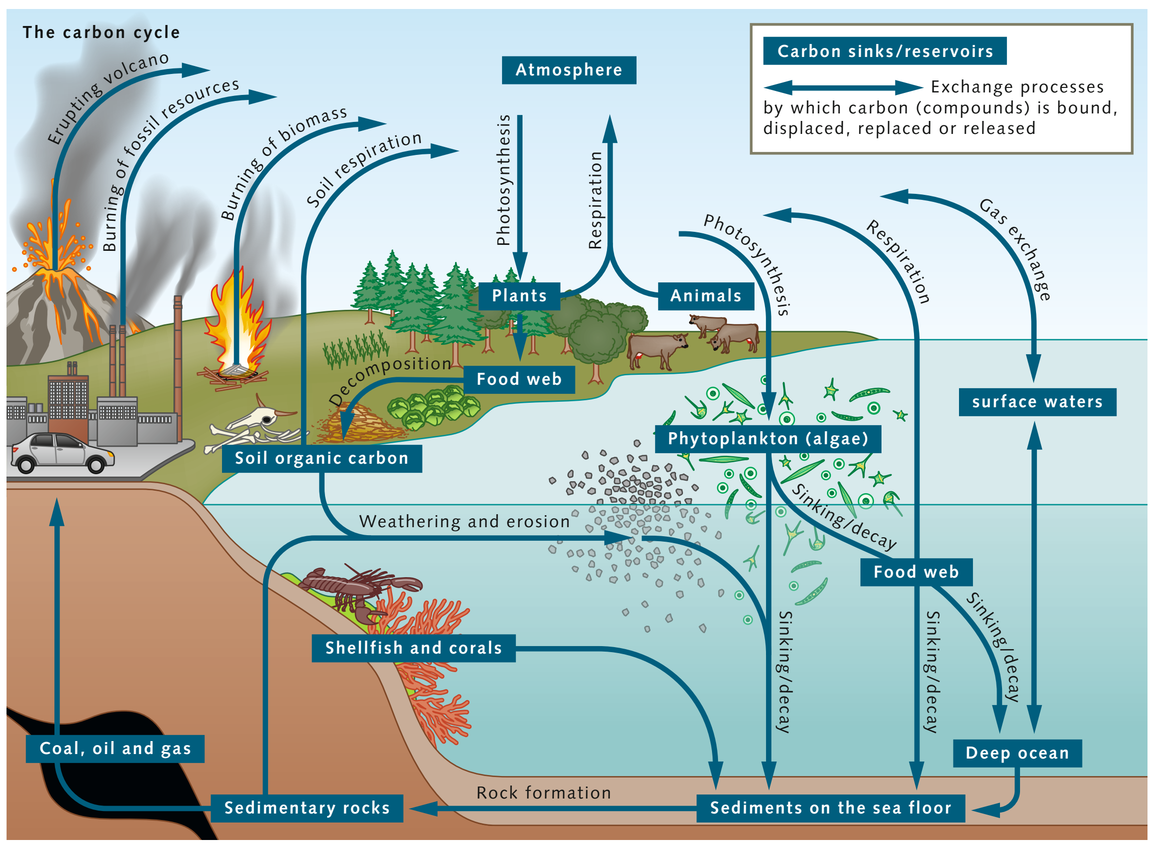
> In recent decades, the world ocean has absorbed around 25 per cent of the carbon dioxide emissions produced by human societies, thus retarding the progress of climate change significantly. This climate service is achieved through three natural carbon pumps whose functions may seem rather complex. Taken together, they are the reason that the world ocean is the second largest carbon sink on Earth. There is, however, a high price for this service in the form of ocean acidification.

Carbon – an essential element

Carbon is an essential building block for life on our planet. All of the tissues produced by living organisms, including plants, animals and people, are comprised of compounds that contain carbon. Carbon is required for animal and plant cells to function. It is in our food, in wood and coal, marble and limestone, as well as oil-based synthetic materials and fuels. This is due to the high bonding capacity of the carbon atom. In particular, it is often contained in compounds with hydrogen, oxygen, nitrogen and phosphorus. There are presently more than a million different carbon compounds known to science, and more are being added every year. These form the basis of the field of chemistry known as organic chemistry.

Because of its chemical properties and extensive distribution, carbon is constantly being naturally captured or released, chemically bonded or converted, everywhere around the globe. Furthermore, it is involved in almost all of the biological processes in which energy is either produced or consumed. These include, among others, photosynthesis, oxygen respiration and chemosynthesis. This means that carbon is in constant motion and, through time, migrates through all of the components of the Earth system. For the various steps of this journey, which is known as the carbon cycle, carbon requires different amounts of time. Sometimes it or its compounds are released (respiration, combustion, volcanic eruptions) or taken up (photosynthesis, dissolution in seawater) within a few short minutes, while in other situations it can be stored for thousands or even millions of years in one location (permafrost, formation of fossil resources). At the same time, its physical state also changes: Carbon and its compounds can occur in gaseous form, as carbon dioxide and methane, for example, or in the liquid or solid state.

The carbon dioxide concentration in the Earth's atmosphere, which is of crucial importance for the climate, is determined by various biogeochemical processes occurring both on land and in the sea. These determine whether this greenhouse gas is removed from the atmosphere and stored (carbon sinks) or is released into it (carbon sources).



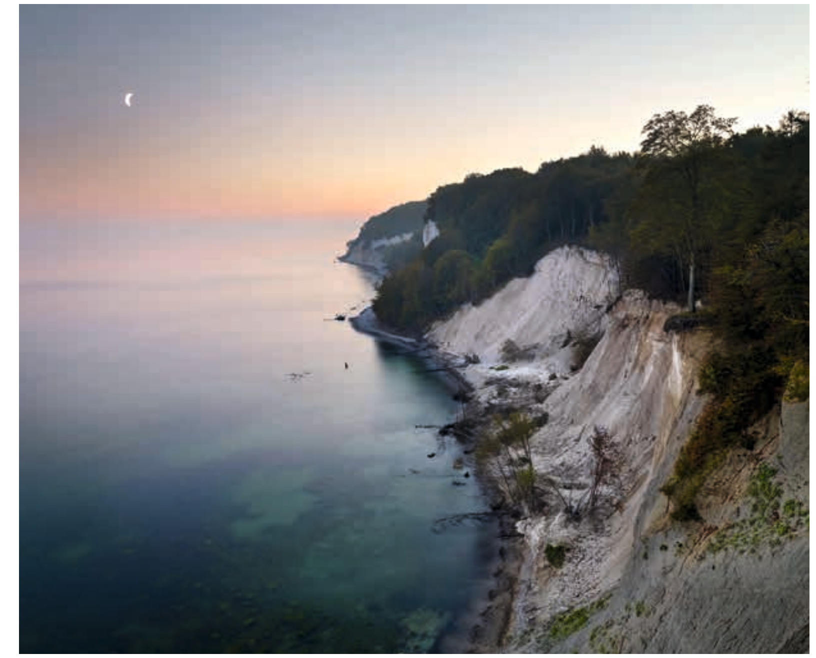
2.1 > The Earth's natural carbon cycle: Carbon sinks, or reservoirs, in which carbon or one of its many compounds are stored, are shaded in blue. The arrows represent exchange processes through which carbon or one of its many compounds are bound, stored, exchanged or released.

Ocean carbon reservoir

The ocean is our planet's second-largest carbon sink after the Earth's rocky shell (sedimentary rocks on land and the sea floor). It contains around 40,000 billion tonnes of carbon, the greatest share of which is dissolved in seawater. With this carbon reservoir, the ocean exceeds the carbon content of the atmosphere by a factor greater than 50. These two systems are in a state of constant carbon exchange. More than 150 billion tonnes of carbon in the form of the greenhouse gas carbon dioxide move back and forth between the ocean and atmosphere every year. Using an atomic weight conversion factor of 3.664, the annual global exchange of gases between the ocean and the atmosphere thus comprises more than 549 billion tonnes of carbon dioxide.

Because carbon dioxide concentrations in the atmosphere are increasing due to the emissions produced by human societies, the ocean is also absorbing more carbon dioxide. In contrast to preindustrial times, it is now taking up more carbon dioxide from the atmosphere than it releases elsewhere. The result is that the world ocean has absorbed around 25 per cent of the carbon dioxide released into the atmosphere by humans in recent decades, thus significantly inhibiting the progress of global warming. An estimated 40 per cent of the anthropogenic carbon dioxide emissions taken up by the world ocean were absorbed in the Southern Ocean. The especially great absorptive capability of the Southern Ocean, however, is subject to large natural fluctuations, which make a precise evaluation of the balance of the world ocean's carbon dioxide uptake very difficult.

Carbon dioxide uptake by the ocean occurs at the sea surface, where it is dissolved from the air into the seawater. Whether atmospheric carbon dioxide dissolves in the water, and the amount dissolved, depends primarily on the difference in carbon dioxide partial pressure between the seawater and atmosphere. Simply stated, this is the pressure generated by carbon dioxide dissolved in the surface water and that in the atmosphere. The natural exchange of gas between the seawater and the atmosphere always works towards a balance of these pressures. This means that surface waters with a lower partial pres-



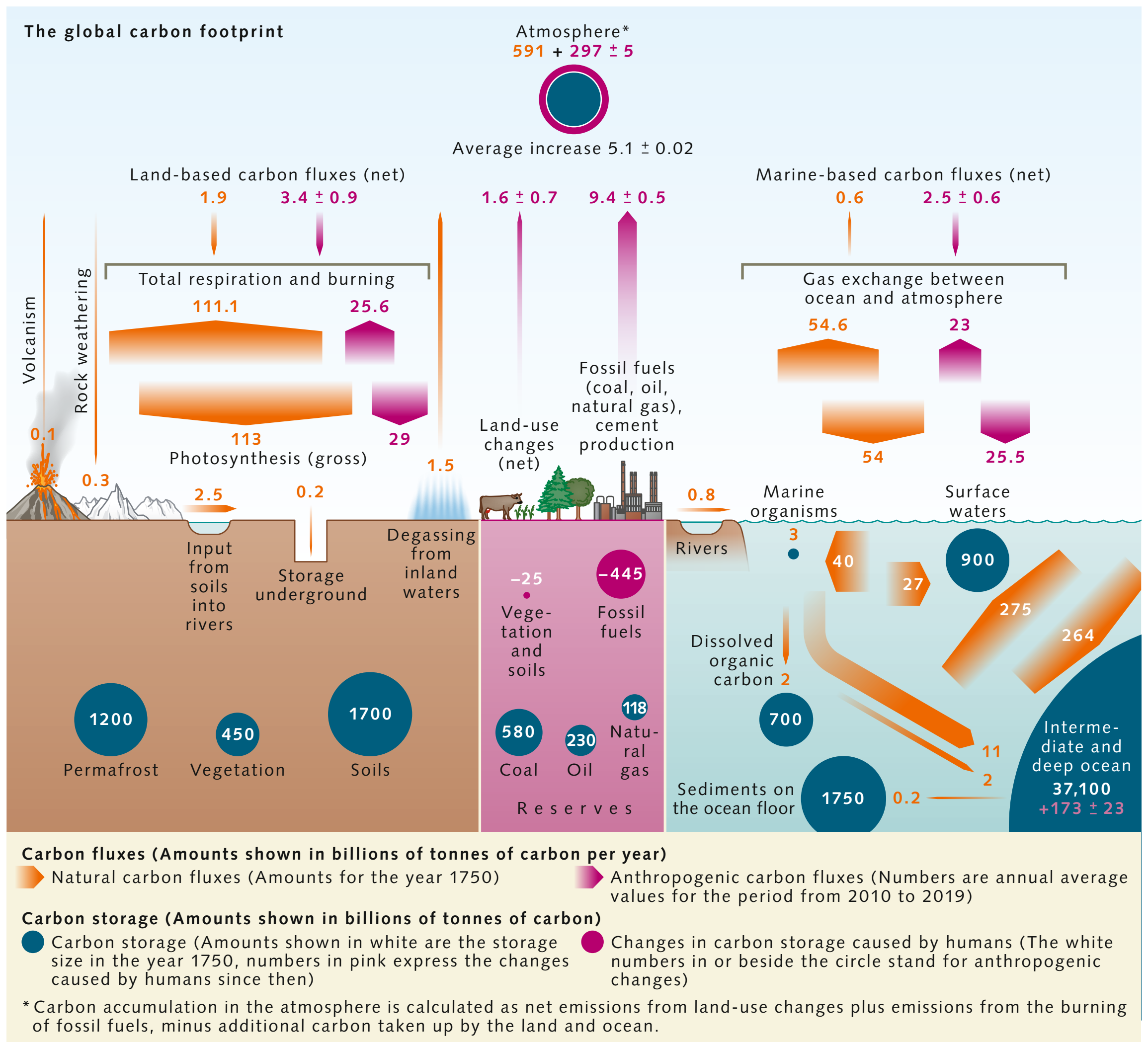
2.2 > The chalk cliffs on Germany's island of Rügen are composed of carbonate rocks. When carbon dioxide-rich rainwater falls on these rocks they weather readily, and acid-binding solution products are washed into the Baltic Sea. These react with free protons in the seawater and reduce its acidification.

sure of carbon dioxide than the overlying atmosphere will take up carbon dioxide from the air until the pressure difference is no longer present. The pressure-equilibration process also works in the opposite direction from the water into the atmosphere.

The water temperature, as well as salinity, wind, waves and currents, also affects carbon dioxide absorption by the ocean. The temperature and the salinity of the surface waters have an effect on the amount of gas that can be dissolved. The warmer and saltier the water is or becomes, the less carbon dioxide it can absorb or store, and the more it thus tends to release into the atmosphere.

This physical principle explains, among other things, why the world ocean releases carbon dioxide into the atmosphere in the warm, equatorial part of the Pacific, for example, while it absorbs large amounts of carbon dioxide in the cooler Southern and North Atlantic Oceans.

At the same time, wind and waves mix the surface waters, which effectively balances the carbon dioxide concentrations within the upper water layer. Marine currents keep the water masses in motion, and ensure, for example, that new deep water is constantly brought to the surface in upwelling zones, where it can engage in gas exchange with the atmosphere.



2.3 > Figures for the global carbon footprint: Anthropogenic carbon dioxide fluxes are shown in pink. They are the reason that carbon dioxide is being enriched in the atmosphere and why the Earth's temperatures are rising.

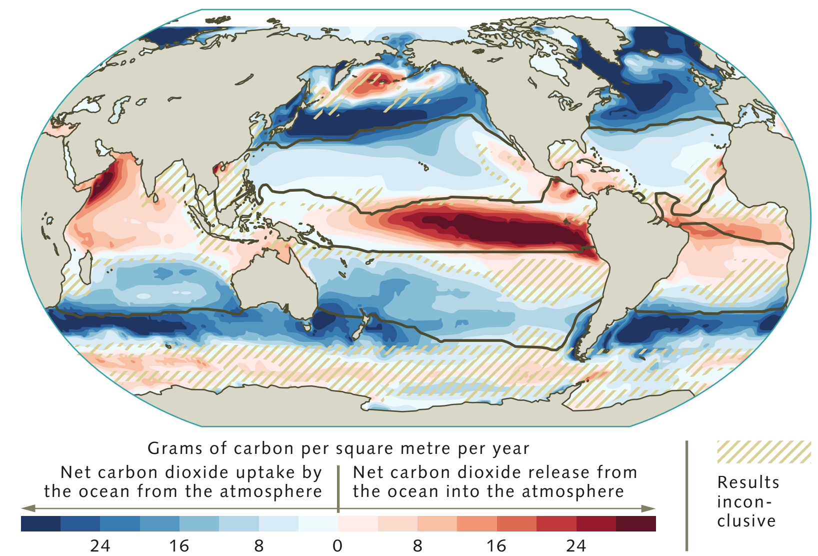
A chemical equilibrium reaction

When the carbon dioxide concentration in the atmosphere increases, it usually leads to a rise in the carbon dioxide concentration in the surface waters of the ocean within a few months. As carbon dioxide dissolves in seawater, a chemical change occurs in the surface waters because, unlike oxygen for example, carbon dioxide does not simply dissolve in the sea. A certain proportion of the CO_2 reacts with the water molecules to form carbonic acid. With very few exceptions, these molecules, in turn, immediately split into hydrogen carbonate plus one hydrogen cation (which is a proton). If the hydrogen carbonate loses another proton, a carbonate anion is formed.

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

- as carbon dioxide (CO_2), which can also be released into the atmosphere again. It makes up only about one per cent of the carbon stored in the ocean, but it determines the partial pressure of carbon dioxide for the seawater;
- as hydrogen carbonate, which accounts for around 90 per cent of the carbon stored in the ocean;
- as carbonate, which, it should be noted, is not only formed as a result of the carbonic acid chain reaction, but is also released as a result of rock and mineral weathering on land (more on this later).

These three forms exist in a balanced state of concentration equilibrium with each other, which means that a change in one parameter immediately leads to compensating reactions in the other two. As an important example, when water and dissolved carbon dioxide react to form carbonic acid, hydrogen carbonate is also formed. This results in a decrease in the proportion of dissolved carbon dioxide in the seawater and thus the partial pressure of carbon dioxide. As a result, the ocean takes up more new carbon dioxide from the atmosphere in order to balance the partial pressure between the ocean and atmosphere. The chemical chain reaction then starts again from the beginning. This process, however, cannot be continued indefinitely. Carbon dioxide absorption shifts the concentration equilibrium between dissolved carbon dioxide, carbonic acid, hydrogen carbonate and carbonate to such an extent that carbon dioxide uptake by the surface water will eventually come to a standstill, unless other additional or new processes disturb or shift the equilibrium again.



2.4 > The ocean does not absorb the same amounts of carbon dioxide from the atmosphere everywhere in the world. As this map illustrates, carbon dioxide uptake occurs primarily in the cold Southern Ocean and in the North Atlantic and North Pacific Oceans (blue shading). In the warm tropical regions, on the other hand, the ocean releases considerably more carbon dioxide into the atmosphere than it absorbs (red shading). In the hatched areas, the situation is inconclusive.

Ocean acidification – a matter of free protons

The protons released by carbonic acid increase the acidity of the water. If the ocean absorbs large amounts of additional carbon dioxide, the sea is in danger of acidifying, which results in deteriorated living conditions for many marine organisms. The number of protons actually released by the carbonic acid reaction, however, depends on the acid-binding capacity of the seawater. This is determined by acid-binding components of mineral origin (again, carbonates) in the water that originate primarily on land. They have been dissolving there over millions of years through the weathering of rocks, and were eventually washed into the sea by rainwater, brooks and rivers.

If the proportion of this influx of acid-binding solution products of rock weathering is large, the seawater has a

Ocean acidification – the great carbon dioxide problem

When the ocean absorbs carbon dioxide from the atmosphere, fundamental changes occur in the carbonate budget of the ocean. Carbonates are consumed in the surface waters through the carbon dioxide reactions, and hydrogen cations (protons) may be released. The number of free hydrogen cations, in turn, determines the acidity of the seawater. The greater their number, the more acidic the water is.

The concentration of hydrogen cations in a solution is measured using a number known as the pH value. It indicates how acidic or basic a liquid is. The scale of the pH value ranges from 0 (very acidic) to 14 (very basic). This means that the more hydrogen cations a solution contains, the smaller its pH value is.

The average pH value at the ocean surface has decreased since the onset of industrialization from 8.2 to 8.1. This seemingly small step on the logarithmic pH scale represents a real acidity increase of about 26 per cent, a change in magnitude that has not been experienced by the world ocean or its inhabitants in millions of years. The acidification signal now reaches depths of up to 2000 metres, and even deeper in the North Atlantic and Southern Oceans. If humans continue to emit as much carbon dioxide as they have in the past, the pH value of the oceans is predicted to fall by another 0.44 units by the year 2100. This does not mean that the oceans are actually acidic technically speaking, because values of 7.6 to 7.7 are still considered to be chemically basic, but relatively speaking they are more acidic than before.

Together with the pH values, carbonate concentrations in the ocean are also falling with increasing carbon dioxide absorption. The saturation of seawater with carbonate ions, however, is a vital parameter for all marine organisms that construct their shells or skeletal structures with calcium carbonate. Marine organisms use carbonate primarily in the forms of aragonite and calcite, whereby aragonite is particularly susceptible to dissolution. Carbonate-saturated water masses possess a carbonate saturation state (Ω) of 1. This corresponds to a carbonate concentration of 66 micromoles per kilogram of water. If the concentration is slightly higher than this value, the seawater is considered to be supersaturated. If a water mass falls below that, however, it is referred to as undersaturated and the aragonite formed by the organisms will dissolve in the water.

Undersaturated seawater is present in all of the oceans because, due to the increasing solubility of carbonate with decreasing water temperature and increasing pressure, the deeper layers of the oceans, as a rule, are undersaturated. The boundary between the undersaturated and supersaturated water layers is called the saturation horizon. According to reports by the Intergovernmental Panel on Climate Change, the increasing inflow of carbon-rich surface waters at intermediate and greater water depths is shifting this boundary, below which the carbonate dissolves, further and further toward the ocean's surface. In some regions of the western Atlantic Ocean, for example, the calcite saturation horizon has risen by around 300 metres since the onset of industrialization. In the Arctic Ocean, the depth of the aragonite saturation horizon has shifted upward towards the surface by 270 metres during the period from 1765 to 2005. This means that ever larger portions of the water column there are being affected by carbonate deficiency.

Uncertainty about adaptability

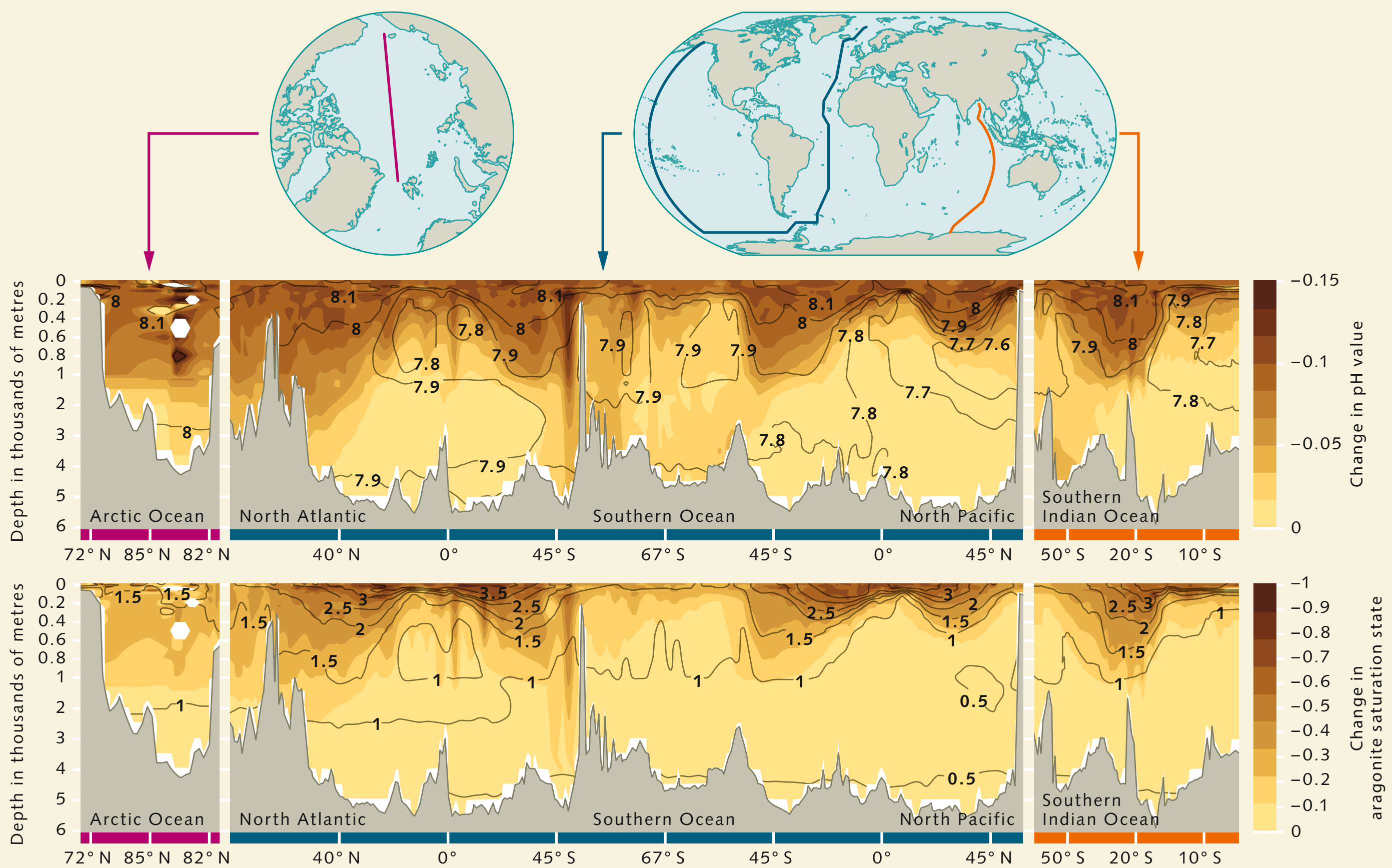
Increasing acidification of the seas has an impact on a variety of biological processes, and thus on the lives of many marine organisms. Due to the decreasing availability of carbonates, it is becoming more difficult for carbonate-forming organisms such as corals, bivalves, conchs and foraminifera to build their calcareous shells or skeletons. They are becoming thinner and more delicate. Evidence from echinoderms such as sea urchins and starfish indicates that they grow less and die earlier as acidification increases.

The degree to which inhabitants of the sea are endangered by acidification and increasing carbon dioxide concentrations, however, depends on the species and the family. For corals, molluscs and echinoderms, for example, the risks are greater than for crabs and shrimps. The danger for fish is primarily in the embryo or egg stage, or for the larvae. In these early development stages, the animals do not yet have a functioning system for acid-base regulation. This system prevents or minimizes damage later when the body liquids of the fish also gradually acidify in carbon dioxide-rich water. As a result, a portion of the young animals die, others experience growth difficulty or develop abnormally. There is also evidence that ocean acidification influences the behaviour of marine animals in complex ways, for example by affecting neural processes or the learning or visual abilities of the organisms.

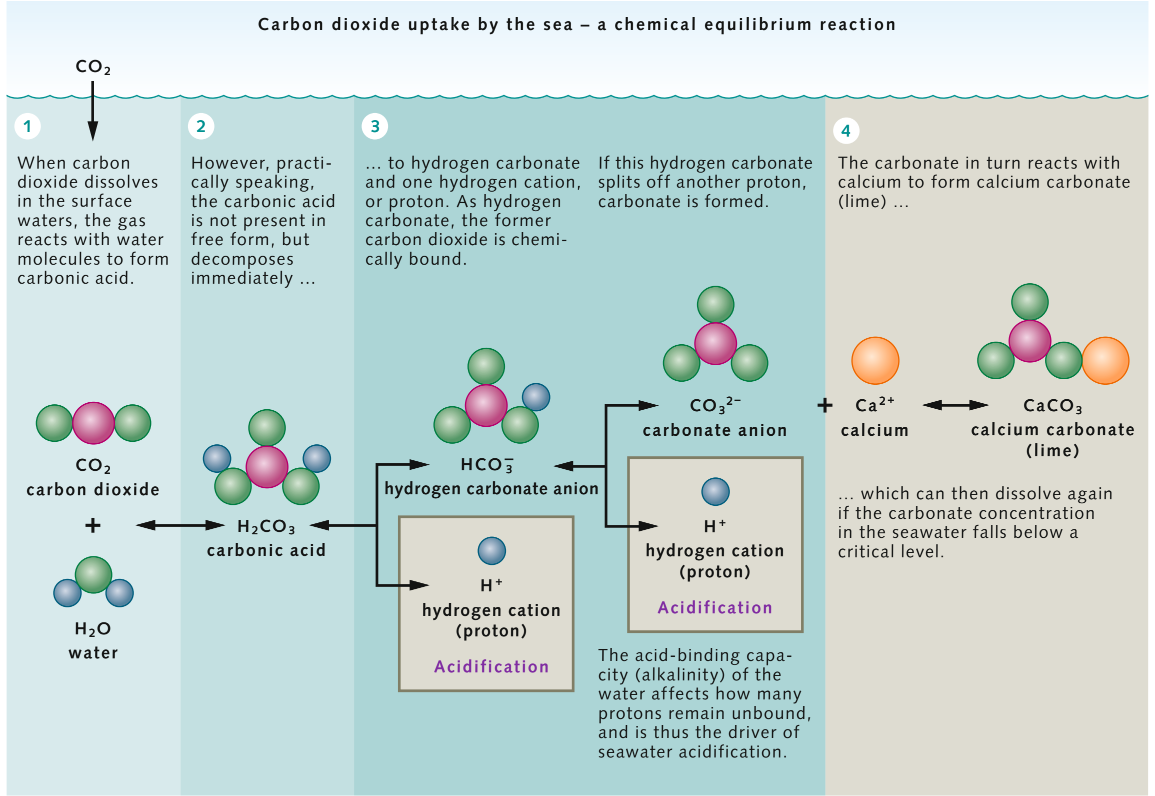
Some algae and sea grasses, on the other hand, actually benefit from carbon dioxide-rich water. During photosynthesis they are able to take up more carbon dioxide and transform it to biomass. That means that the organisms grow faster, and in some cases are able to cope better with heat stress. It is still uncertain to what extent the various marine organisms are able to adapt to ocean acidification. Single-celled algae and small zooplankton with short reproductive cycles appear to be better equipped than larger organisms with longer reproductive cycles. Additionally, researchers are becoming more convinced that increased ocean acidification combined with the declining oxygen content in the seas has a negative influence on the temperature tolerance of the individual species, especially in tropical and polar waters. This means that the temperature range in which these species can survive is shrinking with the falling pH value of the water. This development, in turn, has an effect on the geographical distribution of species and populations, and even on their basic chances of survival.

Important to know: The acidification of the seas is a development that can be attributed exclusively to the increase in carbon dioxide in the atmosphere. Other greenhouse gases are not involved in this. For an effective protection of the oceans, therefore, the prevention of anthropogenic carbon dioxide emissions and a targeted reduction of carbon dioxide concentrations in the Earth's atmosphere are doubly important. Such action would help to limit both global warming and ocean acidification.

Expansion of ocean acidification from the surface to the inner ocean (2002) since preindustrial times



2.5 > Water chemistry changes as a result of CO_2 uptake at the ocean surface. Its pH value decreases as does the aragonite saturation state. The measurement profiles show the changes in these two parameters during the period from 1800 to 2002. The black lines and numbers indicate values measured in 2002.



2.6 > Seawater stores carbon in three dissolved forms: as carbon dioxide, hydrogen carbonate, and carbonate. These three types maintain a balanced state of concentration equilibrium with each other, which means that a change in one results in an immediate compensating reaction in the other two. Scientists refer to these as equilibrium reactions.

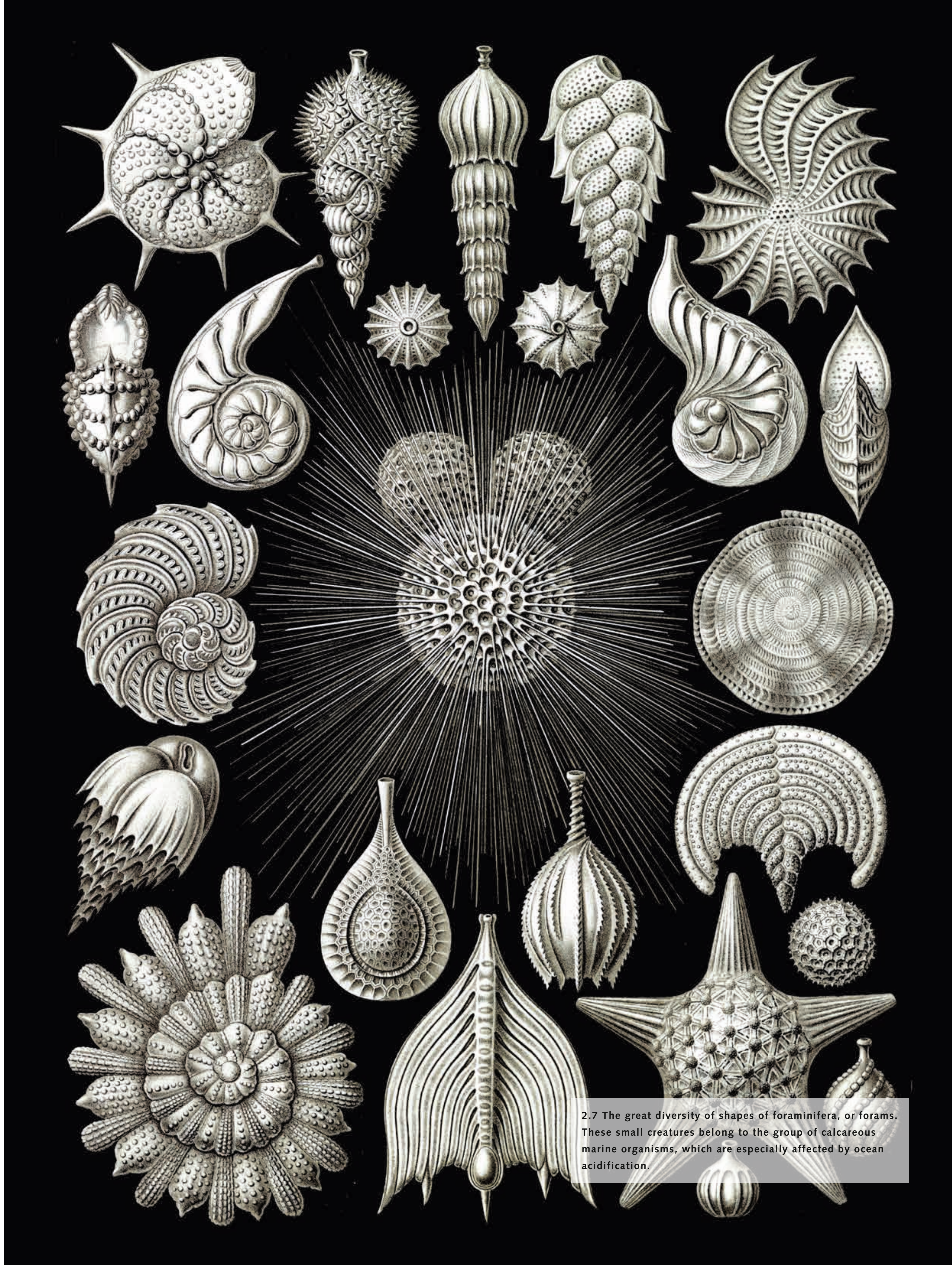
Mineral
In contrast to rocks (mixtures of various minerals), a mineral is an individual element or a single chemical compound that as a rule is crystalline and is formed by geological processes. At room temperature minerals are usually solids, with the element mercury being an exception.

high acid-binding capacity. Scientists also refer to this water as having a high alkalinity. In this situation, a large number of protons are not even actually released, but in the course of the carbonic reaction are immediately bound by the introduced solution products. Hydrogen carbonate is produced in this reaction as well, while the carbonate mineral is broken down and the acidification of the water is buffered. If the water only contains small amounts of acid-binding components of mineral origin, however, the acid-binding capacity is limited. The number of free protons increases and the sea becomes increasingly acidified.

When considered over periods of millions of years, the Earth's carbon cycle always compensates for the carbon dioxide content of the sea by the influx of weathered acid-binding minerals. For example, if the carbon dioxide concentration increases both in the sea and the atmosphere, the warming of the two systems will lead, in the long term, to an increase in the weathering of rocks, both on land and on the sea floor. This results in larger amounts of minerals being carried into the sea, reduction of the acidity of the water, and the ocean again taking up more CO_2 from the atmosphere in order to re-establish the concentration equilibrium discussed above. This decreases the carbon dioxide concentration in the atmosphere, and the warming slows down. But this process requires millions of years.

The three carbon pumps of the sea

When the chemical equilibrium reaction is completed in the surface waters and carbon is present in its three dissolved forms of carbon dioxide, hydrogen carbonate and carbonate, it begins its journey through the marine carbon cycle. This trip can happen in three different ways, all of which are designated as carbon pumps, but which are significantly different in their basic mechanisms. Scientists differentiate these as a "physical" ocean carbon pump and two biological ocean carbon pumps, one "organic" and one "inorganic".



2.7 The great diversity of shapes of foraminifera, or forams. These small creatures belong to the group of calcareous marine organisms, which are especially affected by ocean acidification.

The physical carbon pump

The physical carbon pump is driven by the ocean currents and their differences in temperature and salinity. It distributes the dissolved carbon (carbon dioxide, hydrogen carbonate, carbonate) through the sinking or upwelling of water masses in the ocean. This process is the primary mechanism for transporting anthropogenic 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 occurs mainly in the polar regions because the solubility of carbon dioxide in colder water is particularly high, and the surface water is thus carbon-rich. The colder and more saline the water is, the deeper it sinks, taking the dissolved carbon with it to greater depths. Once there, the water masses subsequently spread around the entire world on a global conveyor belt of marine circulation.

Decades or centuries pass before this carbon-rich deep water returns to the ocean surface to take part in the gas exchange with the atmosphere once more. But eventually the water masses rise again, usually at one of the coastal upwelling zones along the western coasts of Africa, South or North America, or along the equator, primarily in the Pacific Ocean. When it reaches the sea surface, the water is warmed and releases a portion of its dissolved carbon dioxide into the atmosphere as a gas again.

Although the long journey of the carbon-rich water through the deep ocean can be seen as beneficial from the perspective of CO_2 emissions because it sequesters the dissolved carbon in the deep sea, it also comes with a significant drawback: If the water masses at the sea surface become more acidic – a development that is now observable globally – their long-term circulation at great depths means that this acidification would have to be considered irreversible on human time scales.

The special roles of the shelf seas and vegetation-rich coastal ecosystems

On the coasts and the continental shelves (0 to 200 metre water depths) a large portion of the plankton biomass is not broken down in the water column but sinks to the sea floor. There, in part, the biomass is incorporated into the sediments. The shelf sediments are therefore much larger carbon reservoirs than the deep-sea sediments. More than 90 per cent of the permanent carbon burial occurs in the shelf sediments. On geological time scales, oil and natural gas are formed from the biomass in these sediments. A large portion of human-induced greenhouse gas emissions results from the fact that, by extracting oil and gas, we remove carbon that was sequestered there long ago. We then burn the fuel and release the carbon into the atmosphere as carbon dioxide.

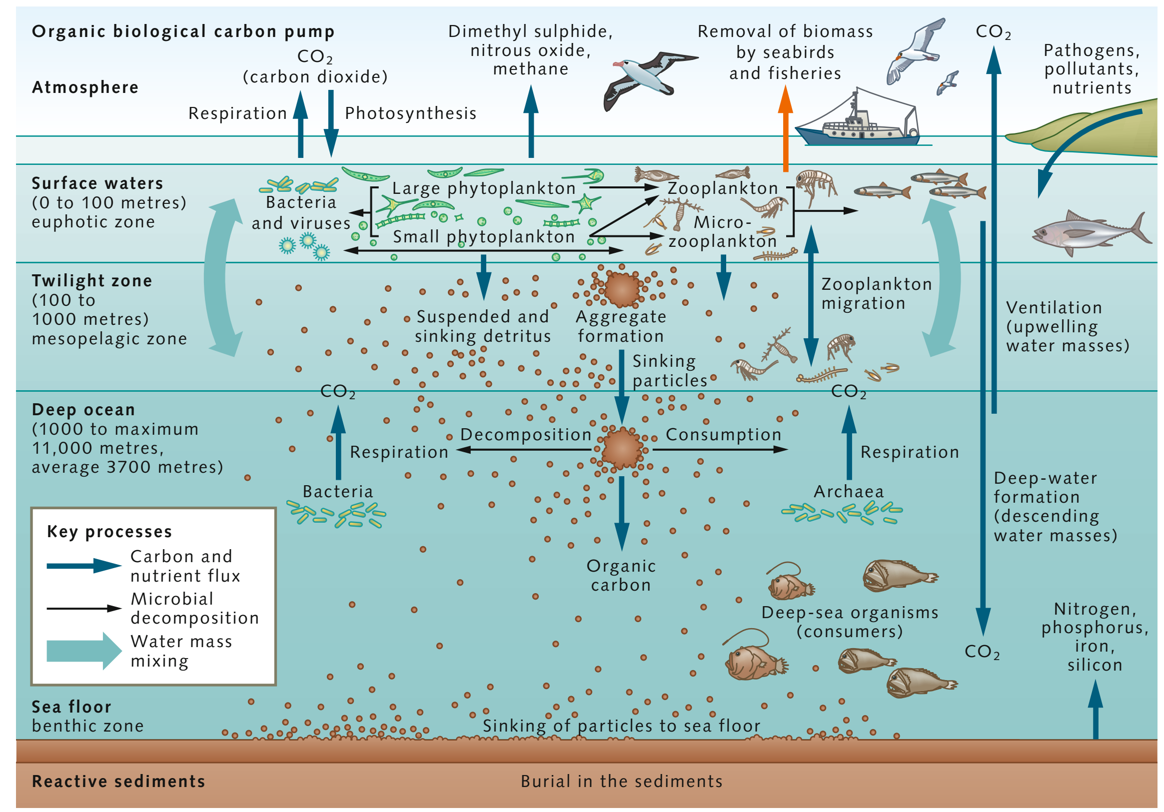
Vegetation-rich coastal ecosystems such as salt marshes, seagrass meadows and mangrove forests also play special roles in the carbon cycle of the sea. Although they cover only less than one per cent of the total marine area, they are responsible for a significant portion of the natural carbon sequestration in the sea floor, and are thus key components in the Earth's carbon cycle.

These plant communities flourish in tidal and shallow-water areas and take up carbon dioxide from the surface waters as well as from the air. They subsequently store the carbon bound by photosynthesis predominantly in the subsurface – partly in their dense root systems, and partly directly in the coastal sediments as dead plant material (foliage, deadwood, etc.).

Because the marine meadows and forests also filter large amounts of suspended material out of the water and these particles are deposited between their stems and roots, the plant communities grow steadily upwards. Through the deposition of the particles abundant washed-in animal and plant material is incorporated in the sea floor. These two processes lead to an accumulation of large amounts of carbon beneath the salt marshes, mangroves and seagrass meadows. These deposits can be more than ten metres thick and they continue to grow as long as the ecosystems are healthy. In ideal situations they are preserved for hundreds, and sometimes even thousands of years.

The organic biological carbon pump

The organic biological carbon pump is driven by the biological communities in the surface waters of the ocean. This is where photosynthesis is carried out by single-celled algae (phytoplankton), macroalgae and seagrasses. They use the sun's energy to produce biomass. For this, the plants require carbon dioxide as a building material, which they obtain mostly from the surface waters in its dissolved form. They incorporate the carbon contained in the CO_2 into their biomass.



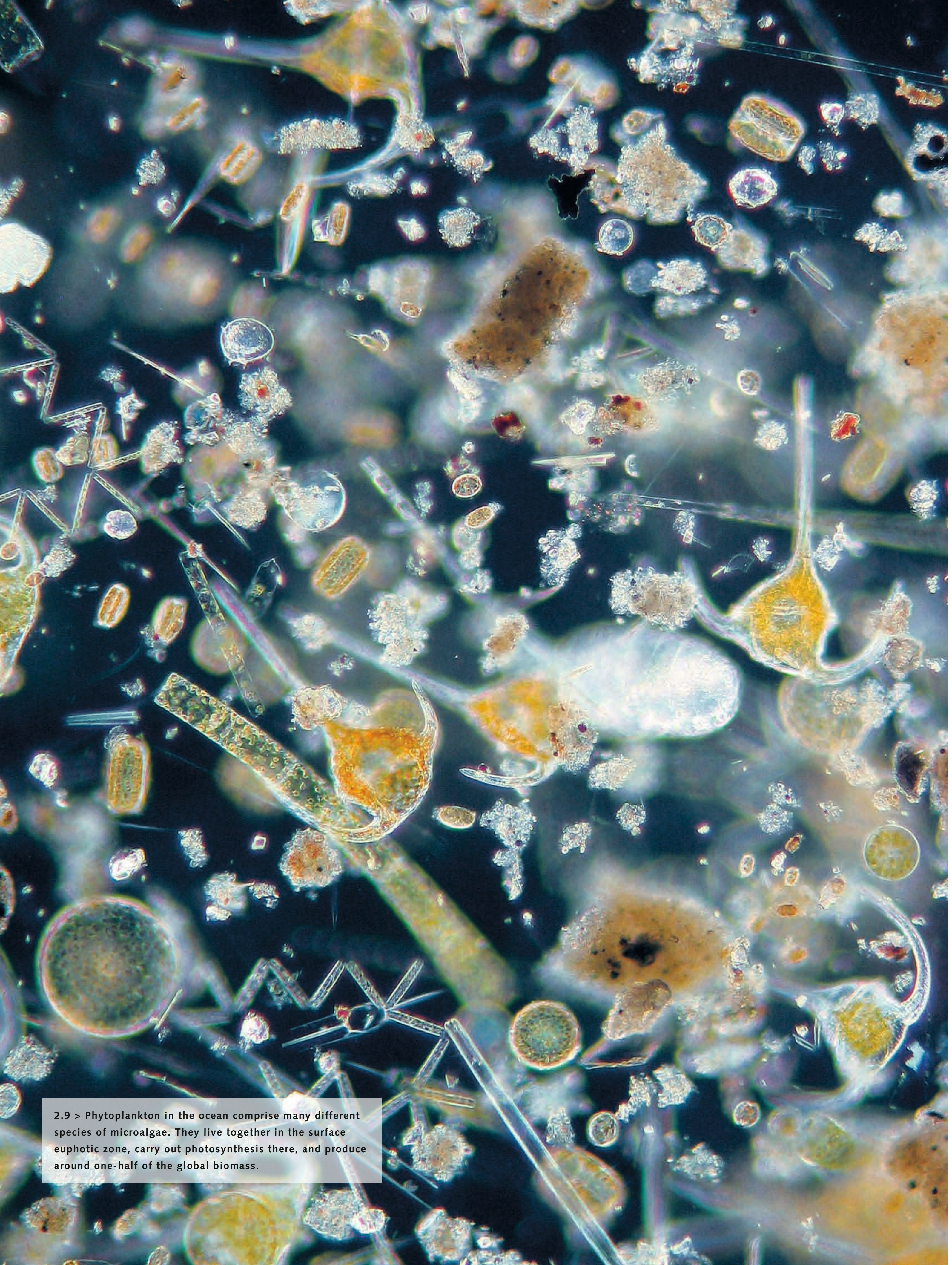
2.8 > The organic biological carbon pump of the sea involves the processes by which algae and plants absorb CO_2 from the well-lit surface waters and convert it into biomass, which then sinks towards the seabed. The crucial question for the balance of global emissions and the continued progress of climate change is how much of the biomass sinks to the water levels below the surface layer mixed by winds and waves. In the intermediate and deep waters (twilight zone/deep ocean), in fact, the organic material along with the carbon it contains is trapped for decades to centuries, regardless of whether the biomass is eaten and respired or continues to sink toward the sea floor.

When the algae or seagrass is eaten, the consumers naturally also ingest the carbon contained in it. A portion of the carbon is returned to the sea as carbon dioxide through respiration by the animals. The remaining amount is retained in the form of muscle mass or body fat, for example, and some is excreted as faecal pellets. Subject to the natural processes of the ocean, 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 seals – and at each step carbon is respired, converted into biomass, or released in the form of faeces.

But the plants and algae may also simply die. When this happens, they descend through the water column, along with the mortal remains of their consumers and their faecal matter. On the way towards the sea floor the dead biomass encounters bacteria and other microorganisms, which break down a large proportion of the material before it can reach great water depths or the sea floor. Through this process, the stored carbon is again released into the seawater in the form of carbon dioxide. The remaining material settles into the deep sea as "marine snow". It is estimated that only ten to 30 per cent of the carbon bound up in biomass reaches a water depth of 1000 metres or more. The rest will be consumed before that.

Upon reaching the sea floor, the remaining carbon-bearing material, whether unicellular organisms, faecal particles or whale carcasses, is almost entirely consumed by the inhabitants of the deep sea. What remains is significantly less than one per cent of the original carbon that was taken up by the algae. If the carbon originates from other sources (wood, whale bones, etc.) the proportion may be higher. The ultimate remaining amount is incorporated into the sediments, which removes the carbon from the natural cycle for a very long time.

Sequestration in sediments becomes a significant quantity when considering the carbon cycle on a geologi-



2.9 > Phytoplankton in the ocean comprise many different species of microalgae. They live together in the surface euphotic zone, carry out photosynthesis there, and produce around one-half of the global biomass.

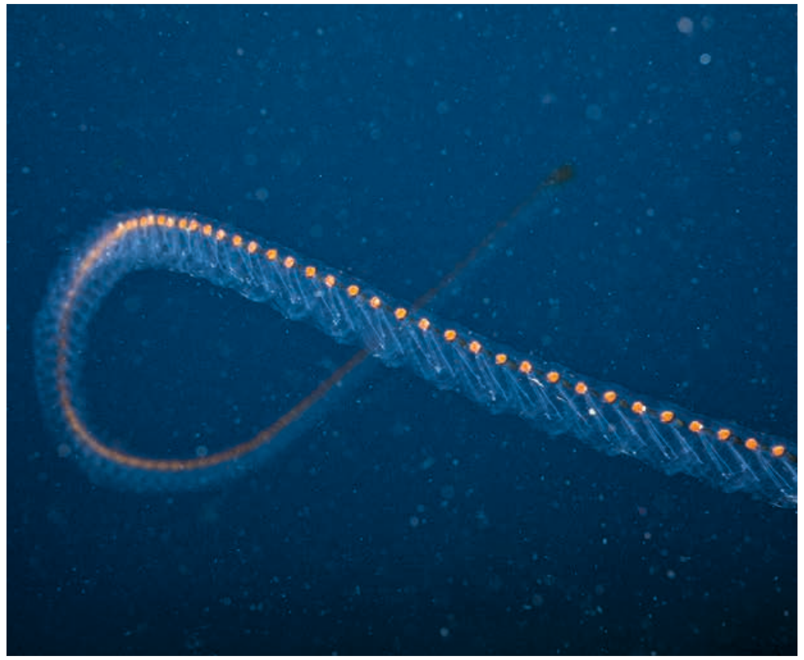
cal time scale, i.e., over millions of years. For the current development of climate change, however, it is the amount of carbon bound up in algae and plants that sinks to water depths below the surface mixed layer that counts. This is the layer near the sea surface in which the water masses are regularly mixed by winds and waves.

Once carbon-bearing particles have left the surface layer, decades or even centuries may pass before they or their respired products can return to the sea surface and are able to escape into the atmosphere again as carbon dioxide. Scientists therefore use the term "sequestered" (taken up and stored) to refer to all carbon that is transported by the organic biological carbon pump to depths that are no longer mixed by wind and waves.

The inorganic biological carbon pump

In addition to photosynthesis, there is a second process by which marine organisms biologically fix dissolved carbon from the water and ultimately transport it to greater depths. This is achieved through the construction of calcareous shells or skeletons. In this process, carbonate-forming organisms such as calcareous algae, bivalves, corals, conchs and foraminifera extract the dissolved hydrogen carbonate from the seawater, and transform it into calcium carbonate to use as their building material. When the organisms die, their calcareous shells sink to the sea floor where they are incorporated into the sediments. In this way, the carbon contained in them is removed from the natural cycle for millions of years.

With respect to the carbon dioxide balance in the atmosphere, however, the inorganic biological carbon pump of the ocean is negative. The explanation for this is that during calcite formation hydrogen carbonate is removed from the water. As a product of the accompanying chemical reaction, dissolved carbon dioxide is formed in the water. This, in turn, increases the carbon dioxide partial pressure of the seawater, thus facilitating the release of carbon dioxide into the atmosphere. If, on the other hand, the carbonate dissolves – which does happen under certain chemical conditions in the sea – carbonic acid is consumed and the seawater then tends to absorb more carbon dioxide from the atmosphere.



2.10 > Salps are cylinder-shaped tunicates that often live in colonies. The colony of animals forms a long chain that goes hunting for plankton.

Climate change as a constraining factor

With the acceleration of climate change and the accompanying warming of the seas, the ocean's capacity to take up carbon dioxide and store it will decrease. There are two primary reasons for this. The first is physical in nature: Warm water cannot store as much dissolved carbon dioxide as cold water. The second is related to the biological carbon pump. One effect of climate change is that the density-related stratification of water masses in the water column is strengthened. As a consequence, the layer of warm, light, and often nutrient-poor surface water becomes less prone to mix with the underlying nutrient-rich intermediate and deep waters. To a certain extent it is cut off from the nutrient supply from below. Due to the paucity of nutrients in the well-lit surface water, there is more of a tendency for the growth of smaller algal species instead of abundant large and more productive diatoms. The smaller species produce less biomass than the diatoms and are therefore also able to store less carbon.

In addition, rising water temperatures accelerate the metabolic processes of marine organisms. They all need more food, which means that organic material is more

2.11 > As a consequence of climate change the abundances and distributions of phytoplankton and zooplankton will change. In tropical and subtropical marine regions they will decrease, and in the temperate and polar latitudes they will increase.

rapidly consumed, broken down and recycled, and usually at shallower water depths. The carbon dioxide released through these processes is then returned by the organisms to the surrounding seawater. The carbon-dioxide partial pressure of the water thus increases, enhancing the tendency of the carbon dioxide to escape from the sea into the atmosphere.

Furthermore, climate-induced changes in species compositions can also have a negative impact on the transport of carbon to the deep ocean. Research off the coast of the Antarctic Peninsula, for example, has shown that the faecal pellets of Antarctic krill *(Euphausia superba)* generally sink to greater water depths than the excrement of salps. In the course of ocean warming the latter are advancing further and further into the krill's home waters while the crustaceans retreat southwards.

Unlike the krill, however, salps do not pack their comparatively large faecal pellets in a protective membrane. This makes the faeces easy game for other zooplankton and for microorganisms. Within the time frame of the investigation, these had consumed around 80 per cent of the carbon-rich salp excrement before it reached a water depth of 300 metres. Of the well-packed krill faeces, on the other hand, 72 per cent was still preserved at that depth. The researchers were thus able to conclude that if the retreat of the Antarctic krill continues and salps become the dominant species throughout the area, the waters along the Antarctic Peninsula will store significantly less carbon in their depths than previously.

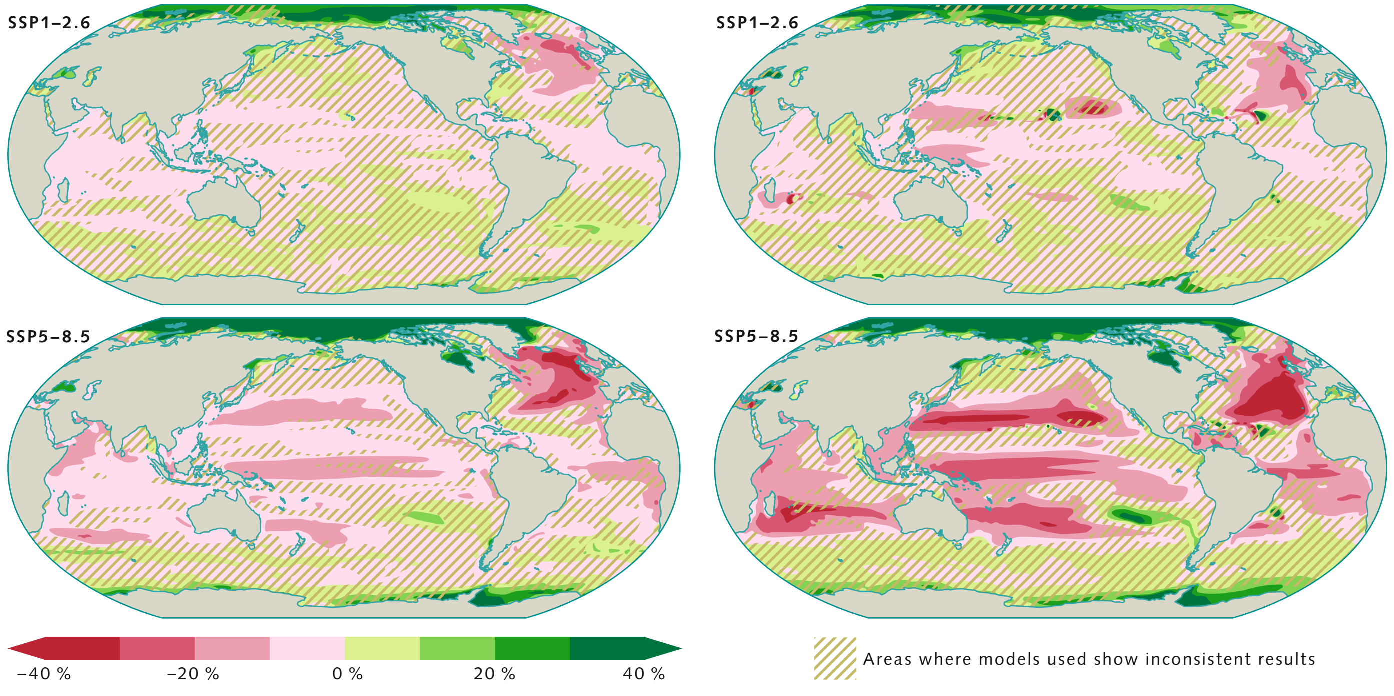
It could look very different in marine regions where both the biomass production of phytoplankton and the abundance of zooplankton increase in the coming decades as a result of climate change. According to the Intergovernmental Panel on Climate Change, this would be the case in the Arctic Ocean, for example. On a global scale, however, scientists anticipate that biomass production by phytoplankton will decline in most parts of the world ocean as a consequence of climate change, and with it the carbon export to the deep ocean.

Projected change in marine phytoplankton biomass

Average change for the period from 2090 to 2099 compared to the period from 1995 to 2014

Projected change in marine zooplankton biomass

Average change for the period from 2090 to 2099 compared to the period from 1995 to 2014



Conclusion

The ocean as a carbon reservoir – huge, efficient and endangered

The Earth's climate system uses physical, chemical and biological processes to extract carbon dioxide (CO_2) from the atmosphere and store it on land, in the seas or in the geological subsurface. The world ocean employs these processes so extensively that it has been able to moderate major changes in atmospheric CO_2 concentration throughout the course of the planet's history. These equilibration processes, however, occur over time spans of millions of years.

Because of its natural ability to absorb carbon dioxide, the ocean plays a major role in the global carbon cycle. It contains around 40,000 billion tonnes of carbon, the largest proportion of which is dissolved in the seawater. The ocean is thus the second largest reservoir of carbon on the planet. Its carbon reserve exceeds that of the atmosphere by a factor of more than 50.

There is a continuous exchange of carbon between the ocean and atmosphere. Every year, more than 150 billion tonnes of carbon pass back and forth in the form of the greenhouse gas CO_2. Because CO_2 concentrations in the atmosphere are increasing due to anthropogenic emissions, the oceans are absorbing more CO_2. In recent decades, the world ocean has absorbed around 25 per cent of the anthropogenic CO_2 emissions from the atmosphere, thus significantly inhibiting the progress of global warming.

CO_2 uptake by the ocean occurs at the sea surface, where CO_2 in the air is dissolved in the seawater. A chemical equilibrium reaction is consequently initiated in the surface waters that leads to the carbon from the carbon dioxide being chemically fixed to a large extent. The surface waters then contain carbon in three dissolved forms: as carbon dioxide, as hydrogen carbonate, and as carbonate anions.

The carbon then begins its journey through the sea and may be stored for millennia at great water depths. The journey can occur in different ways: through the ocean currents (physical carbon pump), through the food web (organic biological carbon pump), or by the formation of calcareous shells and skeletons (inorganic biological carbon pump). In the latter two, a portion of the carbon is even stored in the sea-floor sediments, which means it is locked away for millions of years.

The ocean carbon cycle, however, is not a one-way street because the three forms of dissolved carbon exist in a state of balanced concentration equilibrium with one another. Changes in one parameter lead immediately to compensating reactions by the two others.

One of the most important chemical changes that results from the increasing uptake of carbon dioxide by the world ocean is increasing acidification. Since the beginning of industrialization, the acidity of the ocean has increased by 26 per cent, a change not experienced in the seas over the past millions of years. In some regions the acidification signal now extends to depths of greater than 2000 metres, and impacts the lives of many organisms. It is not yet clear to what extent they will be able to adapt to ocean acidification.

What is certain, however, is that with increasing climate change the CO_2 uptake and storage capacity of the ocean will decrease. This is firstly because warmer water cannot store as much dissolved carbon dioxide as cold water can. And, secondly, it will occur because increasing water temperatures strengthen the stratification of water masses and enhance the metabolic rates of marine organisms. Both of these processes inhibit the biological carbon pump, with the result that less carbon can be exported to the deep sea.