6 Artificial upwelling – the idea of greening the ocean

> Algae, zooplankton and fish are prime drivers of what is termed the biological carbon pump. This natural process needs nutrients to function properly. Such nutrients, however, are lacking in many places, notably in sunlit surface waters. Pumping up nutrient-rich deep ocean water could remedy this nutrient deficiency. Whether such a step would actually increase the ocean's natural uptake of carbon is uncertain.

Kick-starting the biological carbon pump

> Phytoplankton growth is limited on about 75 per cent of the ocean surface, because in those regions the light-filled surface waters do not contain enough nutrients. Deep ocean water, in contrast, tends to be rich in nutrients. This knowledge gave rise to the idea to pump up ("upwell") nutrient-rich water from several hundred metres below the ocean surface in order to increase algal growth in the sunlit upper layers and thus boost the performance of the biological carbon pump. Whether artificial upwelling will prove useful is uncertain. Research investigating the concept has been presenting scientists with extraordinary technical challenges.

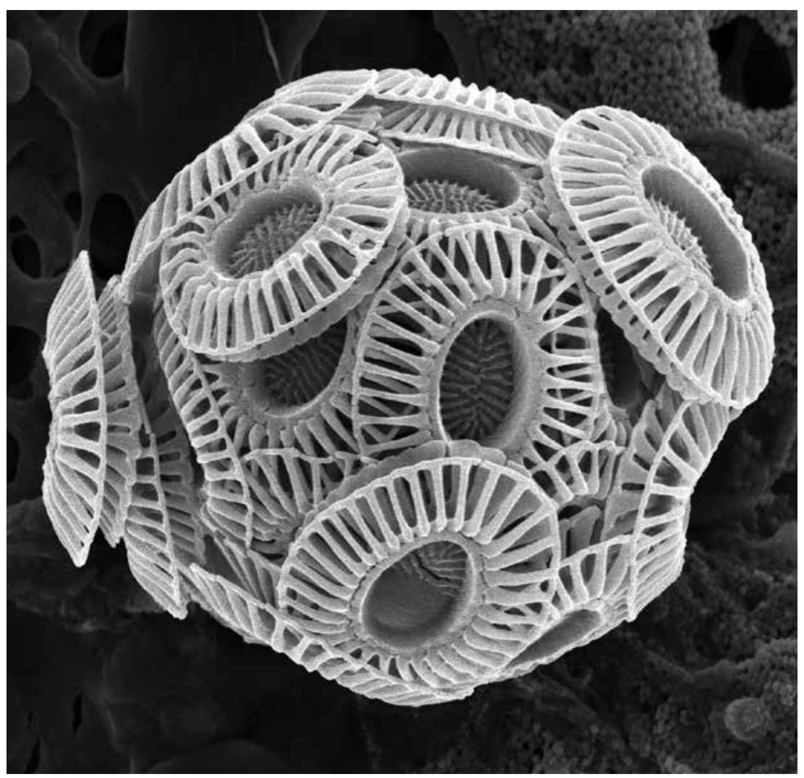
The role of microscopic marine algae

Protecting and expanding the highly productive plant communities of coastal regions (Chapter 5) would be one possible biological method to enhance the ocean's uptake of carbon dioxide. However, there is a second approach that relies on the ocean's biology. Its basic idea is to boost the natural organic biological carbon pump of the ocean. This is driven by the biotic communities in the oceanic surface waters, especially by single-celled, microscopic algae, the phytoplankton, whose representatives are just 0.0001 to 0.5 millimetres in size.

The most important groups of phytoplankton include the diatoms, the dinoflagellates, the haptophytes with their best-known subgroup, the coccolithophores, and the tiny picophytoplankton, which account for up to 80 per cent of the biomass in surface waters in the large nutrient-poor areas of the oceans. Together, the phytoplankton communities of the global ocean are currently responsible for about half of the global carbon dioxide uptake and carbon sequestration. It is estimated that they absorb about 50 gigatonnes of carbon per year. The unicellular marine algae thus have a critical influence on the carbon dioxide content of the global ocean and atmosphere and are important players in the ocean's carbon cycle.

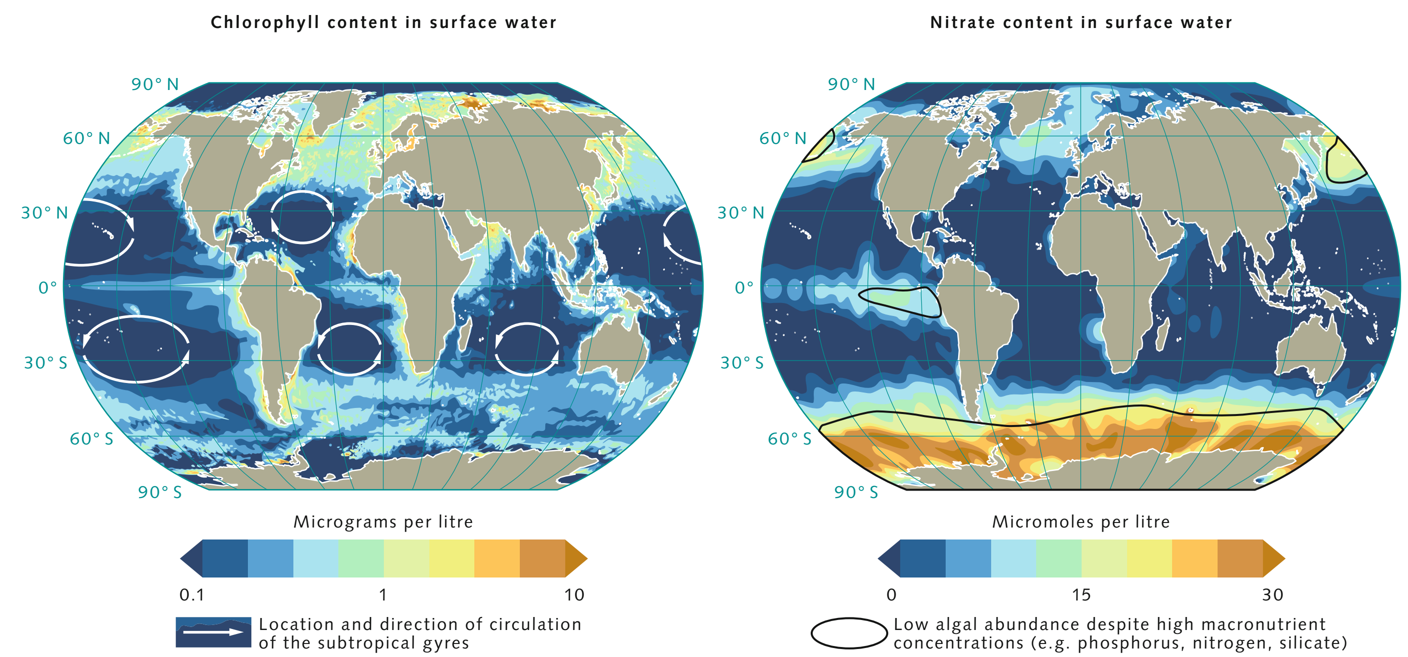
Phytoplankton needs sunlight in order to photosynthesize, which is why the algae are only active in the sunlit oceanic surface waters, at depths of not more than 150 metres, depending on the water's turbidity. How fast the algae grow and what species occur together depends primarily on which nutrients the surface water contains and in what quantities. It is not limited by the availability of dissolved carbon dioxide, as this basic ingredient for photosynthesis is always available in sufficient quantities. Diatoms, for example, which bind a comparatively large amount of carbon and are responsible for about 40 per cent of marine biomass production, primarily grow in areas where the surface water contains both the macronutrients phosphorus and nitrogen as well as micronutrients such as iron and dissolved silicic acids (silicon dioxide, also called silicate).

Phosphorus and nitrogen (often in the form of nitrate) are needed for the development of algal cells. Both nutrients enter the sea via rivers, from the atmosphere, or are released during microbial recycling processes, for example in the sediment layer on the ocean floor. The nitrogen then needs to be converted into nitrate by cyanobacteria – otherwise it's no use to the phytoplankton. The algae need iron to form enzymes and proteins – especially those that are essential for photosynthesis. Important sources of iron for marine phytoplankton communities are Arctic and Antarctic glacial meltwater, sediment-laden streams and rivers, dust clouds that rise above deserts and subsequently discharge sand over the ocean, as well as deep sea hydrothermal processes (such as black smokers, i.e. deep sea vents), in which iron-rich water escapes from the ocean floor. If there is a lack of silicate in the water, diatoms are unable to build up their silica shells, which among other things protect the protozoa from being consumed by smaller copepods. Under these conditions, other, mostly smaller algae species grow instead of diatoms.



6.1 > The unicellular alga *Emiliania huxleyi* is one of the ocean's keystone species. It forms huge algal blooms and thus contributes significantly to the oceanic biological carbon pump. Its conspicuous shell consists of microscopic calcite discs, to which the unicellular organism owes its name „calcareous algae".

Globally, only 25 per cent of the ocean surface waters are considered to be nutrient-rich areas. These are mainly located in the higher latitudes (e.g. North Atlantic) and in the Earth's natural areas of upwelling. The remaining 75 per cent lack certain nutrients in the surface waters, so that algal growth is naturally limited. In deep ocean water, however, sufficient nutrients are available everywhere.



6.2 > The main nutrients of importance for algal growth, i.e. phosphorus, nitrogen (in the form of nitrate) and silicate, are unevenly distributed in the oceans. Therefore, only 25 per cent of the sea surface can be described as nutrient-rich areas. They are mainly located at higher latitudes as well as in the Earth's natural areas of upwelling.

Artificial upwelling – modelled on the ocean itself

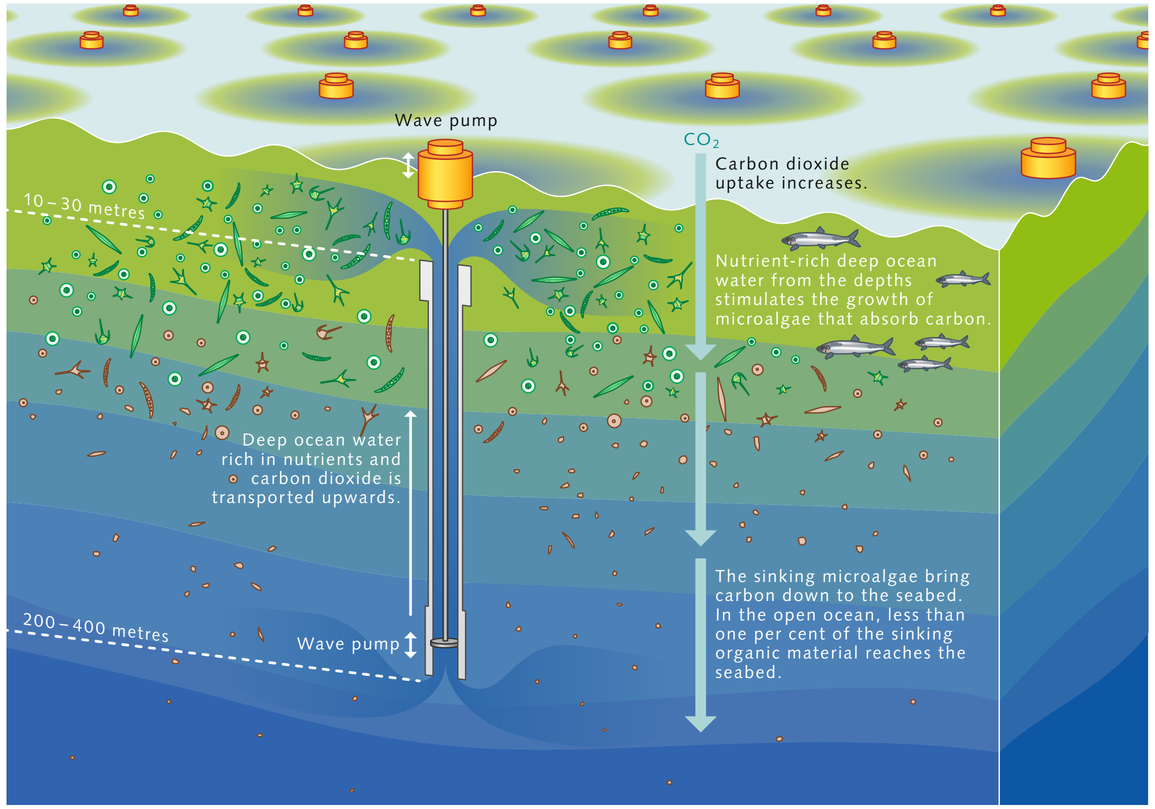
One must understand these connections to realize how the organic biological carbon pump could theoretically be cranked up. The plan is to pump nutrient-rich water from depths of 200 to 1000 metres up to the surface in nutrient-poor regions of the ocean where there is as yet not much algal growth, an approach termed "artificial upwelling". According to this idea, the function of deep ocean water brought up to the light-filled surface layer would be akin to fertilizer: Algal growth would increase, especially when it comes to diatoms, and in the course of photosynthesis the algae absorb more carbon dioxide from the water and incorporate the carbon it contains into their biomass. The carbon dioxide content of the surface water would consequently decrease, enabling the ocean to absorb new carbon dioxide from the atmosphere.

Increased algal growth in the surface waters would in turn mean more food for krill, copepods, true conchs and other free-floating organisms (zooplankton) as well as fish, and would lead to an increased transport of carbon-containing material in the form of particles, faecal pellets and carcasses to greater water depths, ideally deeper than 1000 metres. The carbon contained in the sinking material would thus be locked away in the depths of the ocean for decades or even centuries – until such time as one day the carbon-rich water masses rise back to the surface.

Until then, the carbon stored in the depths can no ,longer escape into the atmosphere in the form of carbon dioxide. However, only those residual amounts of biomass are actually removed from the carbon cycle that trickle down to the ocean floor undamaged and are permanently stored in its sediment. Their share corresponds to less than one per cent of the carbon originally absorbed by the algae. If the carbon originated from other sources (wood, whale bones, etc.), this proportion can be higher (for more detailed information see Chapter 2).

Artificial upwelling mimics the functionality of the large natural areas of upwelling off the western coasts of Peru, Namibia, California and Mauritania (subtropical Africa and America). Driven by winds, nutrient-rich cold deep ocean water rises to the sea surface there and allows life to flourish in the surface waters. This nutrient input from the depths is the reason why upwelling areas are among the most productive and fish-rich ocean regions in the world. However, in order to imitate this successful oceanic strategy using technological means and apply it in previously less productive marine regions, tens to hundreds of thousands of upwelling pumps with a total delivery volume of one million cubic metres of water per second would be needed. Only then would the artificially generated upwelling effect be roughly equivalent to that in the natural areas of upwelling.

It is questionable whether it would be expedient and economically viable to deploy that many pumps. In a simulation study conducted in 2022, researchers concluded that the additional carbon dioxide removal and consequent storage at greater depths would merely



6.3 > A variety of methods can be used to generate artificial upwelling. One idea is to deploy tube-like wave pumps in the ocean. They have a surface buoy at the upper end that rises and falls, following the wave motion. The motion transfers to a pump in the upwelling tube which then lifts the deep ocean water to the surface.

6.4 > The beauty and variety of forms of diatoms only become apparent when viewed through an electron microscope. Many thousands of species have been discovered so far. They all live in a "house made of glass", or more precisely in a protective armour of hydrated silicate.

amount to approximately 150 million tonnes per year even if upwelling pumps reaching down to a depth of 500 metres were to be deployed to every square kilometre of surface across the tropical-to-subpolar ocean waters.

The envisaged ecosystem transformation

Artificial upwelling would have the greatest theoretical potential impact in nutrient-poor and consequently less productive marine regions such as the subtropical gyres. The biotic communities in their surface waters are perfectly adapted to the low nutrient status. For example, instead of many large diatoms, smaller species of algae grow in such regions; following their death they sink less quickly and also carry away less biomass (fixed carbon) into the ocean depths. The zooplankton is also comparatively small: It does not need large mouthparts to crack the diatoms' hard shells, and smaller organisms also need less food and energy to survive. After all, both are in short supply in the nutrient-poor surface waters of the subtropical gyres.

If the amount of available nutrients were to change permanently due to artificial upwelling, the biotic community of the surface waters would presumably adapt to this new situation over time. First, more diatoms would grow. These would be followed by larger zooplankton which is able to break down the diatoms' hard silicon shells. Large, nutritious zooplankton would in turn attract fish, which is why experts assume that artificial upwelling would boost fish stocks in the long term in the regions concerned. But just how well the envisaged adaptation processes would work in practice is the subject of current research projects.

Interplay of biological and physical carbon pump

The biological carbon pump is not the only process that determines whether or not artificial upwelling can in fact remove additional carbon dioxide from the atmosphere. In addition to high nutrient concentrations, deep ocean water also contains additional carbon dioxide, which has accumulated there by means of two processes: firstly via the biological carbon pump described above and secondly via the physical carbon pump.

The physical carbon pump is driven by sinking cold water masses in the polar regions. Since the solubility of gases is higher in cold water, i.e. the water can absorb more gases, the water masses that sink in the high latitudes and then slowly move at depth towards the equator contain a relatively high amount of carbon dioxide. If this cold, carbon dioxide-rich deep ocean water is pumped to the surface, it warms up. At the same time, its ability to dissolve gases decreases and the stored carbon dioxide outgasses back into the atmosphere. Therefore, if the oceanic carbon dioxide uptake is to be increased by means of artificial upwelling, the process must ensure that more carbon dioxide will be sequestered by algae and transported to great water depths than reaches the surface with the upwelled deep ocean water.

One of the arguments in favour of using artificial upwelling is that progressive climate change increases the stratification of oceanic water masses. As a result, the surface water and the water in the twilight zone below mix to a lesser extent, which is why the natural nutrient supply from the deep ocean decreases, and along with it, in the long term, biomass production in the sunlit part of the water column. Artificial upwelling could counteract this development to some extent.

Using computer simulations, researchers also discovered that the carbon dioxide removal potential through artificial upwelling increases with each degree of additional warming, regardless of the decreasing biomass production due to ocean warming, acidification and oxygen loss. Once again, this is due to the physical carbon pump. Model calculations indicate that the physical carbon pump would benefit threefold in a warmer world from large-scale deployment of artificial upwelling:

- Firstly, the upwelling of cold deep ocean water would lead to a cooling of the air layers near the surface and simultaneously reduce the temperature of the surface water.
- Secondly, a large proportion of today's deep ocean water was formed before the onset of industrialization. This means that these water masses so far only contain carbon from natural carbon dioxide sources and not yet from man-made emissions. For this reason, the deep water still has sufficient buffer capacities to absorb additional carbon dioxide and contribute to compensating for hard-to-avoid anthropogenic carbon dioxide emissions (for further explanations please refer to Chapter 2).
- Thirdly, the acid-binding capacity of deep ocean water – its alkalinity – is higher than that of the surface water in some marine regions. There, artificial upwelling would lead to an increase in alkalinity in the surface water, which would allow for an increased uptake of carbon dioxide, while also buffering the associated acidification (for further explanations please refer to Chapter 2).

However, it is not yet clearly understood which of the two carbon pumps is the more significant in terms of artificial upwelling, and how their carbon dioxide removal potential will change in the course of climate change. Research into the feasibility of artificial upwelling processes and their impacts and risks is still in its infancy.

The search for the optimal pumping technology

One open research question, for example, is which pumping technique would be the most efficient way to generate artificial upwelling. The methods discussed so far differ in pumping technique and upwelling mode. The critical factor for the pumping technique is where the pumps get the energy they would need to transport large masses of water to the ocean surface. German marine scientists have already gained experience with a "wave pump". Pumps of

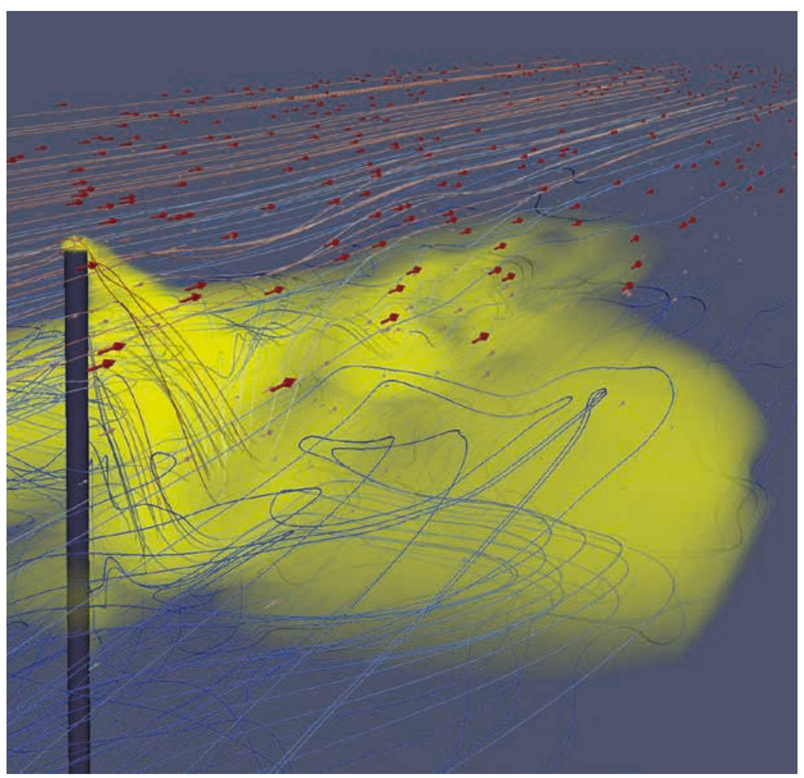
6.5 > The Spanish research vessel *Sarmiento de Gamboa* at sea with a wave pump. The pump was deployed in November 2022 for testing and research purposes in the Atlantic Ocean south of Gran Canaria. The dark upwelling tube is initially wrapped around the yellow buoy and only unrolls when the bottom weight drops down into the ocean depths.

this type consist of a long upwelling tube and have a surface buoy at the upper end that rises and falls following the wave motion. This motion transfers to a pump in the upwelling tube which then lifts the deep ocean water to the surface using the force of the waves. A bottom weight keeps the tube upright in the water column.

When scientists in Germany used such a wave pump with a tube 30 metres in length and 0.4 metres in diameter off the coast of Gran Canaria, it generated an upward flow of about 35 cubic metres of water per hour. With wave frequencies and wave heights typical of oceanic regions in low to mid-latitudes, maximum flow rates of one to two cubic metres of water per second can be generated with larger dimensioned pumps of this type. However, to achieve a substantial climate-impacting throughput, at least one million cubic metres of deep ocean water per second would have to be pumped to the surface.

Higher pumping rates could be achieved using electrically driven propeller pumps. In Norway, such pumps are already in use in salmon aquaculture to pump oxygen-rich and warmer deep ocean water into the cages in winter. The salmon grow faster this way. However, propeller pumps have not yet been tested for artificial upwelling projects in the open ocean. Electrically powered pumps would only be an option if wind or solar power for their operation could be generated on-site.

Moreover, if artificial upwelling were to be used on a large scale, the maintenance effort would be considerable, because the pumps held vertically in the water column would be exposed to tremendous stresses around the clock. For example, one of the issues would be the varying current strengths depending on water depth. They would tug at the pump to varying degrees and put the material under constant stress, especially in ocean regions with strong currents, such as the subtropical gyres. Researchers from Germany experienced these impacts during the first test run of a newly developed wave-powered upwelling pump in November 2022. Three hours after the 200-metre-long pump was deployed, its bottom weight detached from its mount and sank. The wave pump then failed to operate.



6.6 > Researchers simulate the rise of deep water and its subsequent behaviour in the ocean's surface layer with the help of various flow models. This model illustration shows how the cold, nutrient-rich water (yellow) rises from the pump, then immediately sinks to medium depths and disperses.

Is it better to fertilize once or on an ongoing basis?

Apart from the pumping technique, a second important parameter is the upwelling mode. In this respect, experts distinguish between a one-time supply and a continuous supply of deep ocean water, which, according to initial test runs, has different effects on the marine ecosystem and the production of rapidly sinking biomass. For the first method (singular upwelling) the pump would be moored at sea, i.e. it would be stationary. The surface water would flow steadily past it and each individual unit of water would be enriched only once with upwelled nutrients. In contrast, with the second method (recurring upwelling) the pump would drift freely along with the current and could thus continuously supply one and the same body of water with nutrient-rich deep ocean water.

Initial results from experiments conducted as part of the EU research project *Ocean artUp* indicate that the

6.7 > In Norwegian salmon farms, electrically powered propeller pumps are used to create artificial upwelling. The aim is to supply the salmon with oxygen-rich and, during winter, warmer deep ocean water so that they grow more quickly.

biological carbon pump becomes more efficient when a body of water is continuously supplied with nutrients. This, in turn, would mean that the pumps would have to be deployed in a targeted manner and then allowed to drift freely along with the water masses – an approach that would entail many risks for humans and the environment and, on top of that, pose logistical and legal problems.

Simulations of artificial upwelling in flow models also suggest that the upwelled nutrient-rich deep ocean water does not disperse evenly at the ocean surface. Instead, due to its cooler temperature and resulting higher density, it probably sinks to medium depths, where low light levels limit photosynthesis by phytoplankton.

The success of artificial upwelling also depends on the nutrient concentration in the deep water. This can vary greatly depending on the area of the ocean where the pump is deployed and the depth from which the water is brought up. Which constellation of nutrients increases the carbon dioxide uptake of the sea most efficiently has not yet been sufficiently researched.

Impacts on marine ecosystems

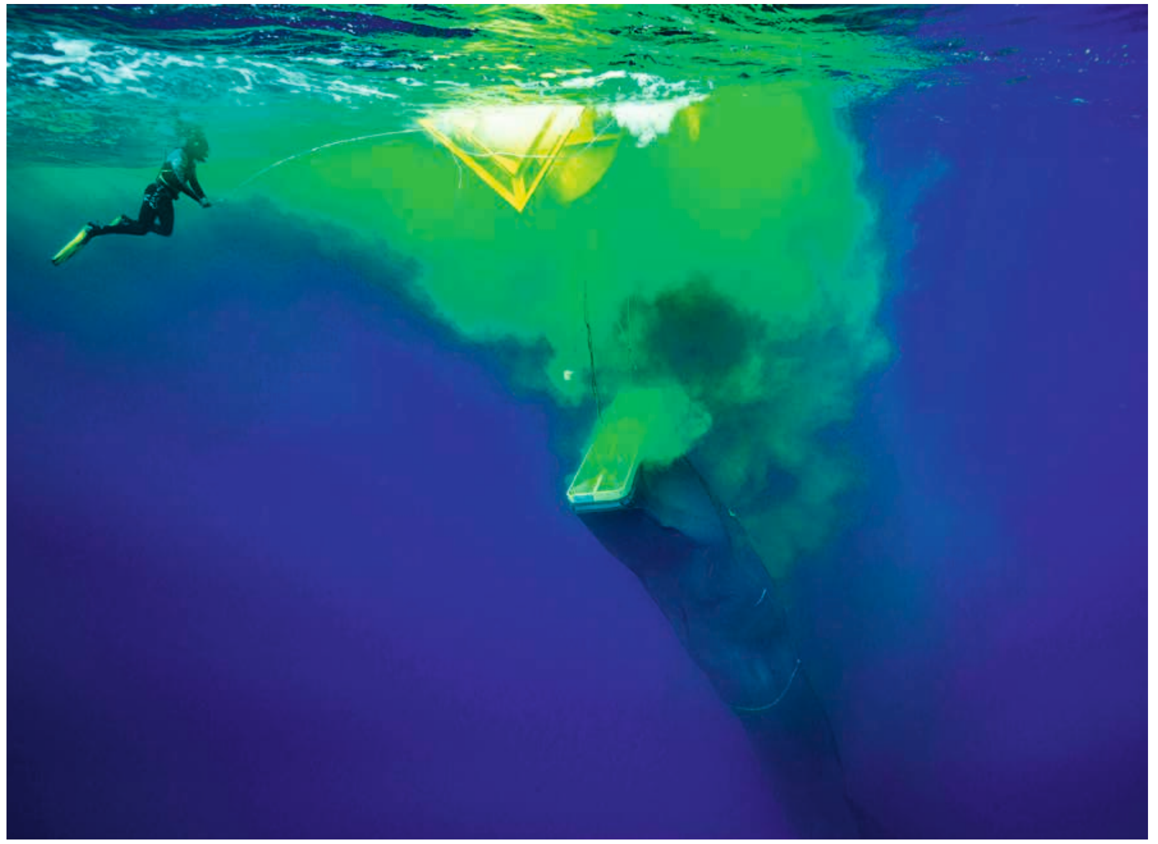
Artificial upwelling alters nutrient availability in surface waters and thus one of the pillars of marine life. Scientists have investigated how profound this change can be and what differences occur, using comparative experiments in the Humboldt Current (a natural upwelling area off the coast of Peru) and in a nutrient-poor marine region off the coast of Gran Canaria respectively. They focused on three parameters: the mixing ratio of nutrient-rich deep to nutrient-impoverished surface waters (low to high), the upwelling mode (recurrent or singular supply of deep ocean water) and the deep water's silicate content, which in turn is crucial for the growth of diatoms.

As expected by the researchers, all three parameters changed the algal growth and species community composition. The strongest algal blooms occurred when a lot of deep ocean water was brought up, this contained a lot of silicate and the surface water was fertilized just once. Under these conditions, the algal blooms even stored a particularly large amount of carbon in their biomass. Experts call this phenomenon carbon overconsumption.

However, to the research team's surprise, in the experiments off Gran Canaria the additionally formed algal biomass and its beneficial properties did not automatically lead to an increase in carbon transport to the ocean depths. Zooplankton and other marine organisms hardly capitalized on the additionally formed algal biomass. In other words, unlike in the Humboldt Current, whose biotic communities are accustomed to nutrient abundance, off Gran Canaria both the hoped-for transfer of fixed carbon in the food web and the accelerating effect on the downward transport of zooplankton feeding on phytoplankton failed to occur. Instead, the carbon-rich biomass formed in the surface water sank only slowly and was degraded by microorganisms before it could reach great depths.

One explanation for these observations could be the experiments' short duration. This gave the biotic community off the coast of Gran Canaria, which is accustomed to a lack of nutrients, insufficient time to adapt to the sudden increase in food supply. The marine organisms, the researchers reckon, were therefore unable to utilize the sudden food surplus and consume the well-armoured diatoms and other large algae species. This is an important finding, because the scientists expect similar results in the future for the use of moored upwelling pumps in nutrient-poor marine regions. The surface water would flow past these permanently installed pumps and only receive a one-time nutrient pulse, which will presumably present the plankton communities with the same problems as in the experiments off Gran Canaria.

Moreover, there are other unanswered questions, such as potential risks to marine life that may be associated with artificial upwelling, or the length of time it would take for the local ecosystem to fully adapt and be able to sequester the maximum amount of carbon and export it to the ocean depths after one or more pumps are put into operation. Experts suggest that increasing algal blooms could result in nutrient scarcity and reduced light penetration in the surface water, as well as increasing oxygen deficiency at mid-depths – where microorganisms would decompose the sinking biomass.



6.8 > In a wave pump test off Gran Canaria, the scientists poured a non-toxic bright green liquid made of seawater and the harmless fluorescent dye uranine into the upwelling tube in order to be able to observe how the deep water is distributed at the sea surface. Technical problems ultimately caused the experiment to fail.

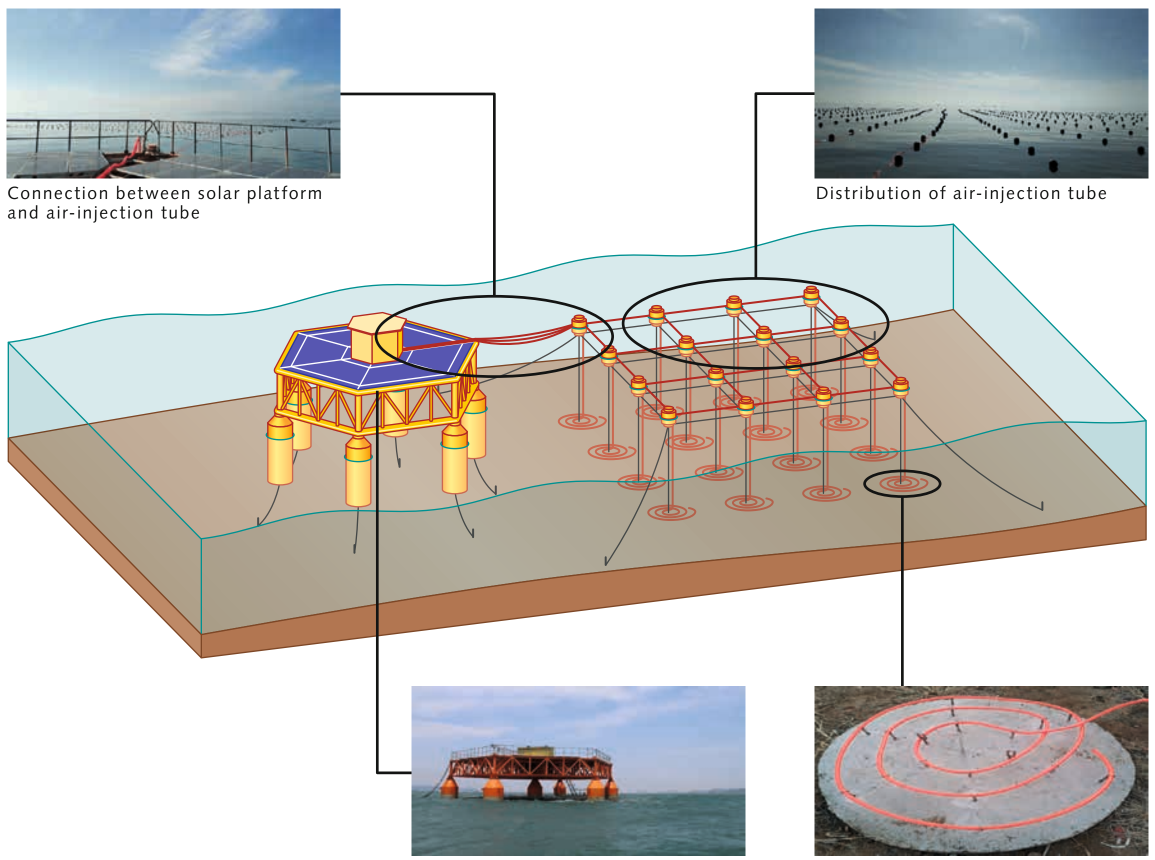
It is also necessary to investigate the effects an increased transport of carbon-rich biomass might have on ecosystems in the deep ocean and how deep-sea communities react to possible changes in temperature and water mass stratification. Scientists involved in the German research mission *CDRmare* are conducting corresponding experiments, lab-based studies and computer simulations, the results of which will however only become available in the course of 2024.

An unclear legal framework

The legal framework for the use of artificial upwelling has not yet been clearly defined at all. For example, the question arises as to whether the deployment of large numbers of upwelling pumps would violate currently applicable law or whether their deployment would even require a permit. Should permits be needed, then who would be allowed to issue these and under what conditions? Consideration must also be given to the fact that artificial upwelling constitutes an activity at sea that legally falls within the regulatory framework of international maritime law, but in substance aims to increase the ocean's potential to sequester CO_2 and thus pursues an objective of climate law. The international law of the sea does not yet take such new marine use plans into account.

For this reason, legal scholars are currently reviewing the legal framework for large-scale upwelling operations to increase the ocean's carbon dioxide uptake. Relevant conventions and principles in this context include the international London Protocol and the German Sea Pollu-

Schematic diagram of an artificial upwelling system



6.9 > With this system, consisting of a solar-powered platform, air-injection tubes and numerous nozzles, Chinese scientists succeeded in transporting nutrient-rich deep water to the sea surface in an over-fertilized marine bay. As a result, not only did the farmed macroalgae grow better, but the issue of eutrophication also diminished.

tion Act (*Gesetz über das Verbot der Einbringung von Abfällen und anderen Stoffen und Gegenständen in die Hohe See* – Law on the prohibition of dumping wastes and other substances and objects into the high seas). In addition, the experts are analysing the extent to which artificial upwelling operations could be regulated under international law, what decision-making powers rest with individual nations, and how artificial upwelling measures could be integrated into international marine environmental protection and climate law without compromising other forms of marine use and environmental and species protection concerns. The legal scholars aim to determine what changes would need to be made to the legal conventions and principles in order to create an appropriate regulatory framework for the governance of artificial upwelling (for more on legal frameworks please refer to Chapter 9).

Growth-aid for macroalgae

In view of the comparatively low carbon dioxide removal potential, the many and large knowledge gaps and the enormous technical and logistical effort that would be required to implement artificial upwelling on an industrial scale, it is considered rather unlikely that these processes will actually be used on a large scale one day to strengthen the ocean's biological carbon pump. In contrast, the use of artificial upwelling appears much more useful when it comes to the question of supplying sufficient nutrients to kelp farms in coastal waters.

This assertion is based, among other things, on experiments conducted by Chinese researchers in the Yellow Sea in the period of 2018 to 2020, more precisely in Aoshan Bay in the Chinese province of Shandong, a centre of Chinese macroalgae production. So many macroalgae are now grown in that region that the amount of nutrients in the surface water is no longer sufficient and diseases and deficiencies are therefore spreading among the farmed algae populations. In contrast, the bottom water and porewater in the seabed are far too nutrient-rich because these coastal waters have been over-fertilized for a long time. For the farmed macroalgae at the sea surface, however, these surplus nutrients are out of reach.

This observation gave the scientists the idea of using artificial upwelling to transport the nutrient-rich deep ocean water to the surface. They used a moored floating solar platform to provide power to an air-injection system that forms a large-scale rising bubble plume for two hours each day. The results confirmed the scientists' working hypothesis: Macroalgae growing in the immediate vicinity of the upwelling site had produced more than four times as much biomass as macroalgae harvested at a greater distance. At the same time, the macroalgae had taken up lots of phosphorus and nitrate from the depths and improved the water quality of the over-fertilized marine bay.

Used in the right place, artificial upwelling techniques have the potential to increase algal growth and thus the oceanic uptake of carbon dioxide, and also contribute to improving the environmental status of over-fertilized coastal waters. However, it appears more than questionable at the present time that this method will ever actually be used to enhance phytoplankton growth and thus boost the ocean's biological carbon pump.

Conclusion

Artificial upwelling – the verdict: "of limited utility"

"Artificial upwelling" is the term used to describe processes that aim to transport nutrient-rich deep ocean water to the sea surface in order to boost the growth of microscopic algae and thus the ocean's biological carbon pump.

This would store a certain proportion of the now newly formed biomass in the depths of the ocean and lock away the carbon it contains for several decades to centuries.

However, to function as a negative emission technology the boosted food web must bind and sequester more carbon in the depths of the ocean than outgasses at the surface from the mostly carbon dioxide-rich deep ocean water upwelled to the surface – a requirement that can presumably only be met under very specific conditions, which is why the potential for additional carbon dioxide removal is rather low.

There is also a high degree of uncertainty as to the technical means by which artificial upwelling can be generated on a climate-relevant scale and what risks the processes entail for the marine environment – especially for the numerous biotic communities at mid-depths and in the deep ocean. Uncertainties also surround the regulatory framework that would be required for large-scale deployment, precisely because the use of many pumps would presumably severely restrict other forms of marine use. So far, the use of artificial upwelling would appear to only make sense and be economically worthwhile as an aid in kelp farming. The artificially generated nutrient input from the depths increases the growth of the macroalgae and helps them to absorb more carbon dioxide and bind more carbon in their biomass.