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

FACT SHEET

Biological methods

Artificial upwelling: More power for the ocean's biological carbon pump

Algae, zooplankton and fish are among the key players in the biological carbon pump, with the help of which the ocean naturally removes carbon dioxide from the atmosphere and stores the carbon it contains at great water depths. However, for this mechanism to function optimally, nutrients are needed, which are lacking in many places, at least in the light-flooded surface water. By pumping up nutrient-rich deep water, humans could remedy this nutrient deficiency. However, it is still uncertain whether such artificial upwelling would actually have an effect on the climate, what risks it would entail and whether it could be implemented technically and legally on a large scale. The research mission CDRmare provides answers.

The big climate goal: a net zero of carbon dioxide emissions

There is a consensus in scientific climate research that humanity will only mitigate climate change and its growing impacts and risks, if it reduces the amount of its annual carbon dioxide emissions into the atmosphere to net zero.

Human-induced carbon dioxide emissions result from the burning of fossil fuels such as oil, natural gas and coal, as well as from changes in land use. So far, no one knows how humankind will be able to avoid 100 per cent of these emissions in the future in an ecologically and socially acceptable way. On the contrary, experts assume that humanity will still be emitting residual amounts of carbon dioxide by the middle of the 21st century. These are expected to amount to 10 to 20 per cent of current emissions.

In order to compensate for these residual emissions, humankind will either have to capture the carbon dioxide directly at its source or remove it from the atmosphere to the same extent. The latter can also be achieved with the help of the sea. For this to happen, however, humanity would have to find ways to increase the sea's natural carbon dioxide uptake.

A Spanish research vessel deploys the wave pump of the research mission CDRmare for testing purposes in November 2022 Photo: D. Gutierrez

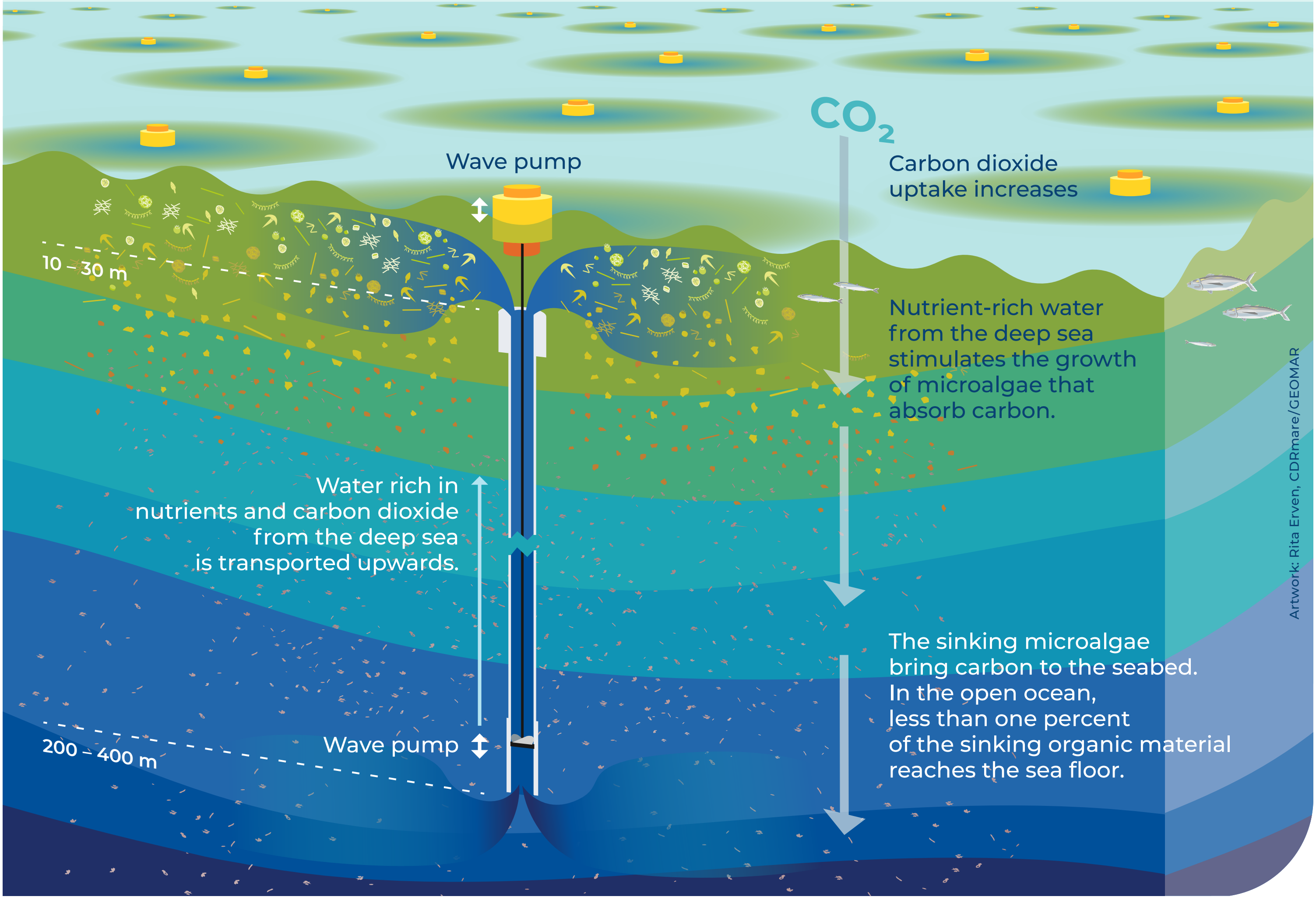
Artificial upwelling

Costs:
So far not quantifiable. Initial calculations take place within CDRmare.

Duration of storage:
for decades to centuries.

Scalability:
Carbon dioxide storage on a larger scale is theoretically possible; upwelling pumps could be used both **in the marginal seas and on the open ocean**.

Technical state of development:
in the early stages



Artwork: Rita Erven, CDRmare/GEOMAR

Solution approach: Copying a successful World Ocean concept

One conceivable solution is to boost the ocean's natural organic-biological carbon pump. Theoretically, such a step would be possible by pumping nutrient-rich water from 200 to 1000 metres water depth to the sea surface in nutrient-poor ocean regions. According to the idea, the deep water would act like fertiliser in the light-flooded surface layer: Algae would grow more, carry out more photosynthesis and in the course of this absorb more carbon dioxide from the water and incorporate the carbon it contains into their biomass. Increased algal growth, in turn, would mean more food for krill, copepods, jellyfish, winged snails and other free-drifting organisms (zooplankton) and fish, and would lead to increased transport of carbon-containing material such as particles, faecal pellets and carcasses to greater water depths. The carbon contained in the sinking material would thus be locked away in the depths of the ocean for decades, sometimes even centuries. This means that it could no longer escape into the atmosphere in the form of carbon dioxide for the time being.

Artificial upwelling is the name of this approach. It copies the functional principle of the large natural upwelling areas off the west coasts of Peru, Namibia, California and Mauritania (subtropical Africa and America). Driven by the wind, cold, nutrient-rich deep water rises to the sea surface there, allowing life to flourish in the surface water and is ultimately the reason why the upwelling areas are among the most productive and fish-rich marine regions in the world. However, artificial upwelling in hitherto less productive marine regions would require tens of thousands of pumps with a total pumping volume of one million cubic metres of water per second if their effect is to match that of natural upwelling areas.

The desired transformation of the ecosystem

Artificial upwelling would have the greatest potential impact in nutrient-poor and consequently less productive ocean regions such as the subtropical gyres. These extend over 50 per cent of the Earth's surface. The biotic communities in their surface waters have so far been perfectly adapted to the nutrient poverty. For example, instead of many large diatoms, smaller algae species grow here, which sink less quickly after they die and also carry away less biomass (bound carbon) into the depths. The zooplankton is also comparatively small: For one thing, it does not need large mouthparts to crack hard diatoms. On the other hand, smaller organisms need less food and energy to survive. After all, both are in short supply in the nutrient-poor surface waters of the subtropical eddies.

If the amount of available nutrients was to change permanently due to artificial upwelling, the biocoenosis of the surface water would adapt to this. First, more diatoms would grow, and in a second step, larger zooplankton would settle, which would be able to break down the hard silicon shells of the diatoms. Large, nutritious zooplankton would in turn attract fish, which is why artificial upwelling would lead to an increase in fish stocks in the respective marine region in the long term. The benefits of artificial upwelling for food web production are not doubted in the scientific community. However, how well the hoped-for adaptation processes would work in practice has not yet been clearly clarified.

Marine plankton under the microscope: This image shows different organisms, including cyanobacteria, diatoms and copepods. What they all have in common is that their swimming direction is determined by the water current.

Foto: David Liittschwager, Wiki Commons

Interaction of the biological and physical carbon pump

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

The physical carbon pump is driven by the sinking of cold watermasses in the polar regions. Since cold water has a high gas solubility – that is, it can absorb a lot of gas – the water masses sinking in the high latitudes contain a corresponding amount of carbon dioxide. If cold, carbon dioxide-rich deep water is pumped to the sea surface, it warms up. At the same time, its gas solubility decreases and the stored carbon dioxide can escape back into the atmosphere. For increased carbon dioxide removal from the atmosphere through artificial upwelling, more carbon dioxide would have to be sustainably bound than reaches the surface with the deep water pumped up.

Recent, partly unpublished results of the research mission CDRmare on artificial upwelling now show that a net carbon dioxide removal by artificial upwelling is possible through an interaction of biological and physico-chemical processes. Accordingly, four arguments speak for a climate-significant mode of action of artificial upwelling:

- Firstly, the time when the rising deep water was last in contact with the atmosphere is, in many areas, before the start of the industrial revolution. For this reason, this water does not yet contain any additional carbon dioxide which is attributable to man-made emissions. Consequently, the water masses would still have the potential to absorb further carbon dioxide from the atmosphere at the sea surface.
- Secondly, the acid binding capacity of seawater (alkalinity) increases with depth in some regions. This deep water could therefore absorb more carbon dioxide than today's surface water. However, it would have to be transported from a depth of several hundred metres to the sea surface.
- Thirdly, the rise of cold deep water leads to an immediate cooling of the sea surface and the air masses above it. However, this cooling effect on the climate is bought about by a displacement of the warm surface water into deeper layers. As a result of this displacement, the ocean interior heats up and it is still unclear what ecological and physical effects this warming will have.
- Fourthly, mesocosm studies off Gran Canaria showed that the carbon dioxide removal balance of artificial upwelling processes can be quite positive, because the nutrients upwelling ended up organically sequestering more carbon than theoretically assumed. However, how positive this removal balance turns out depends on how efficiently the carbon-rich material is transported into the depths.

Another argument in favour of using artificial upwelling is that progressive climate change is increasing the stratification of water masses in the ocean. As a result, the surface water and the underlying intermediate water mix to a lesser extent, which is why the natural nutrient supply from the depths of the ocean is decreasing. Artificially generated upwelling could counteract this development to some extent. However, research into the feasibility of artificial upwelling methods and their consequences and risks is still in its infancy.

The first practical test: Do theory and technology deliver what they promise?

The research mission CDRmare aims to close fundamental gaps in our knowledge about the use and benefits of artificial upwelling. To this end, scientists have developed an interdisciplinary research approach with which they investigate the feasibility of artificial upwelling from a technical, ecological, biogeochemical, economic and legal perspective. They also test a wave-driven upwelling pump off the coast of Gran Canaria and document the functionality of the pump, the dispersion of the upwelled water and its effects on the ecosystem. The experts hope that the results will provide answers to many questions.

Which pumping technique could be used to generate artificial upwelling most efficiently?

The methods for artificial upwelling discussed so far differ on the one hand in the pumping technology, and on the other hand in the duration of upwelling. A key question is where the pumps get the energy they would need to transport large masses of water to the sea surface. Scientists involved in CDRmare have already gained experience with a wave pump developed in Kiel. Pumps of this type have a float that rises and falls in rhythm with the waves. Its movement is transferred to a water lifter in the upwelling tube, which then lifts the deep water upwards with the force of the waves.

The wave pump with a pipe length of 30 metres and a diameter of 0.4 m was successfully used off the coast of Gran Canaria and produced 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 output, millions of cubic metres of deep water per second would have to be pumped to the surface.

Higher pumping rates can be achieved with electrically driven propeller pumps. In Norway, such pumps are already used in salmon aquaculture farming to pump oxygen-rich and, above all, warmer deep water into the cages in winter. The salmon grow faster this way. However, propeller pumps have not yet been tested for artificial upwelling projects on the high seas. The electrically powered pumps would also only come into question if they could be operated on site with surplus wind or solar power.

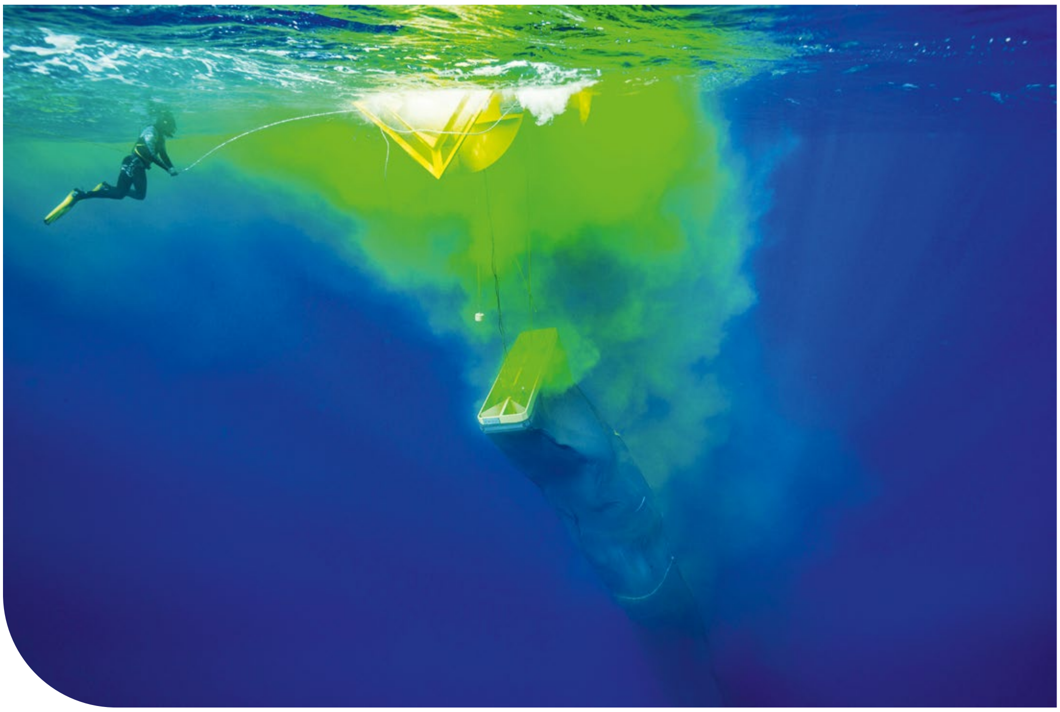
A second important parameter is the duration of upwelling. Here, experts distinguish between a one-time and a continuous supply of deep water, which, according to initial test runs, has different effects on the marine ecosystem and the production of rapidly sinking algae. In the first method (pulsed upwelling), the pump would be anchored in a stationary position. The surface water would flow steadily past it and each individual volume of water would be inoculated with deep water only once. In the second method, on the other hand, the pump would drift along with the current and could thus continuously supply one and the same body of water with deep water.

The carbon dioxide content of the deep water (possible outgassing due to water heating) and its nutrient content are also decisive for the efficiency of artificial upwelling. The latter can vary greatly depending on the sea area in which the pump is used and the depth from which the water is brought up. Which nutrient constellation most efficiently enhances the carbon dioxide uptake of the ocean still needs to be investigated. This is another reason why an assessment of the carbon dioxide removal potential of artificial upwelling is not yet possible at this stage.

In the research mission CDRmare, researchers design, build and test a seaworthy wave-driven upwelling pump that is suitable for long-term offshore use in water depths of more than 200 metres. In parallel, they improve a flow model (simulation system) with which both the water mass transport to the sea surface and the subsequent distribution of nutrients, salt and energy can be simulated realistically and in high resolution for selected ocean regions.

With the flow model, the researchers also conduct comparative studies between continuous artificial upwelling and pulsed processes. Their goal is to optimise the fluid mechanical processes of artificial upwelling. To do this, the scientists change both the length of the pulse period and the amount of upwelled deep water in their model simulations. They also investigate the extent to which the ocean chemistry changes in the immediate vicinity of the pump and further away.

The simulation optimisations carried out in CDRmare make it possible to perform the world's first simulation of the nutrient upwelling potential of an upwelling pump. The results of this are directly incorporated into the development of the upwelling pump (optimal size, best possible design and mode of operation) as well as into the planning of its first offshore deployment for research purposes.



A green dye is used in the test of the wave pump. It is intended to show how the deep water is distributed on the sea surface.
Photo: Michael Sswat, GEOMAR

What are the consequences of artificial upwelling for marine ecosystems?

Artificial upwelling changes the nutrient availability in the surface water and thus one of the pillars of marine life. Researchers have investigated how profound this change can be and what differences may occur through comparative experiments in the Humboldt Current (natural upwelling area off the coast of Peru) and in a nutrient-poor marine region off the coast of Gran Canaria. They focused on three parameters: the mixing ratio between nutrient-rich deep water and nutrient-poor surface water (low to high), the upwelling duration (continuous or one-time supply of deep water) and the silicate content of the deep water, which is crucial for the growth of diatoms.

As expected by the researchers, all three parameters changed the growth and species composition of the algae. The strongest algal blooms occurred when a lot of deep water was brought up, it contained a lot of silicate and the surface water was fertilised with it once. Under these conditions, the algal blooms even stored a particularly large amount of carbon in their biomass. Experts call this phenomenon carbon overconsumption. The scientists concluded from this that in the future use of artificial upwelling, all three parameters investigated must be taken into account in the project planning.

To the surprise of the research team, however, the additionally formed algal biomass and its beneficial properties did not automatically lead to an increase in the desired ecosystem services in the experiments off Gran Canaria. The additionally formed algal biomass was hardly eaten by zooplankton and other marine organisms. This means that, unlike in the Humboldt Current, both, the hoped-for transfer of fixed carbon into the food web as well as the accelerating effect of zooplankton feeding on deep transport failed to materialise. Copepods and other zooplankton species form fast-sinking faecal pellets in which carbon is transported to the depths within a short time. Without their help, however, the carbon-rich material formed in the surface water only sank slowly and was degraded bacterially before it could reach great depths.

One explanation for these observations could be the short duration of the experiments. It 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 were therefore not able to utilise the sudden food surplus and consume the well-armoured diatoms and other large algae species. The study result would thus be due to the experimental research approach and, on top of that, also to be expected for stationary pumps, where the surface water flows past, thereby only experiencing one single nutrient pulse. Whether this assumption is correct, however, still needs to be tested.

In addition, answers are still lacking to the questions of what risks to marine life are associated with artificial upwelling and how long it would take, for example, for the local ecosystem to fully adapt and be able to sequester the maximum amount of carbon and export it to the deep ocean after one or more pumps are put into operation. It is also necessary to investigate what effects the export of carbon-rich biomass could have on deep ocean ecosystems and how deep ocean communities react to possible changes in temperature and water mass stratification.

In the research mission CDRmare, scientists conduct complex experiments in the nutrient-poor waters off the coast of Gran Canaria. They want to check the results of previous studies on artificial upwelling and test for possible further influencing factors. To do this, they will, among other things, manipulate the upwelling mode, the mixing ratio between surface water and nutrient-rich deep water, as well as the nutrient ratios in the deep water of the mesocosms (tube-like »giant test tubes« floating in the sea, each with a capacity of 55,000 litres). Their goal is to find out at which basic constellation the algae and zooplankton community produces the highest possible carbon export. The data sets obtained will also be examined to see what risks and side effects might arise for the water column ecosystem.

In laboratory experiments, the researchers address the question which mechanisms enable certain plankton species to bind a particularly large amount of carbon per available nutrient quantity. In addition, the scientists conduct growth and feeding experiments with selected plankton species and investigate the composition of their cell contents depending on the culture conditions.

The combination of all the collected biological, physical and chemical research data will then provide information on how a natural ecosystem reacts to artificial upwelling. With the help of data synthesis, the scientists also want to identify the natural laws between upwelling mode and intensity as well as nutrient ratios and concentrations in the upwelling water. This knowledge is needed to parameterise the biogeochemical effects of artificial upwelling and to integrate them into Earth system models.

In order to test the reaction of the phyto- and zooplankton to the nutrient-rich deep water pumped up under realistic conditions, the scientists use so-called mesocosms. Mesocosms are hose-like tubes floating in the ocean that are filled with seawater but do not exchange water with their surroundings.

Photo: Ulf Riebesell, GEOMAR

Can artificial upwelling effectively enhance the ocean's carbon uptake even in a warming world?

As climate change increases, the world's oceans will become warmer, more acidic and less oxygenated – changes that will have a lasting impact on marine life. From a global perspective, for example, the biomass production of the oceans will decrease, so the question arises as to whether artificial upwelling methods can also increase the ocean's carbon uptake in the long term in an even warmer world.

First computer simulations provide surprising findings. According to these, the carbon dioxide removal potential through artificial upwelling increases with each degree of additional warming, quite irrespective of the decreasing biomass production as a result of ocean warming, acidification and oxygen losses. The physical carbon pump described above is responsible for this – i.e. the dissolution of carbon dioxide in the surface water of cold ocean regions.

According to model calculations, in a warmer world it would benefit in three ways from large-scale deployments of artificial upwelling: First, the upwelling of cold deep water would lead to a cooling of the air layers near the surface and simultaneously reduce the temperature of the surface water. Secondly, the deep water of the oceans so far only stores carbon from natural carbon dioxide sources. It therefore still has sufficient buffer capacity to absorb additional carbon dioxide and help compensate for carbon dioxide emissions from humans that are difficult to avoid. Thirdly, the alkalinity of the deep water is higher than that of the surface water in some ocean regions. Artificial upwelling would lead to an increase in alkalinity in the surface water there, which would allow increased carbon dioxide uptake but counteract the corresponding acidification.

However, it is not yet clearly understood, which of the two carbon pumps is the most important in terms of artificial upwelling, and how their carbon dioxide removal potential changes in the course of climate change.

In the research mission CDRmare, researchers combine a global biogeochemical ocean model with an ecosystem model so that they can simulate carbon fluxes and changes in ocean chemistry in the wake of artificial upwelling. This capability enables them to investigate three questions at once. Firstly, they use local observations of small-scale pulsed artificial upwelling to calculate what effects larger-scale deployments would have at the regional and global scales. Secondly, they conduct a series of numerical model experiments for selected carbon dioxide emission and climate scenarios to find out how progressive climate change will affect the performance of the biological and physical carbon pump. Thirdly, they analyse the individual physical, chemical and biological processes running in the background, in which artificial upwelling intervenes, in order to identify negative side effects on the ocean – such as changes in the oxygen content. All the knowledge gained is then incorporated into the economic evaluation of the processes.

Would the use of artificial upwelling processes be a sensible decision in terms of climate policy and economics?

Science explores approaches and ideas for combating climate change using integrated assessment models. These models are developed to understand how certain social or economic developments affect nature and the climate. For this reason, each of these models incorporates information on both the Earth system and society. This means that the models take into account natural laws as well as changes in human behaviour and also calculate undesirable side effects or intended benefits of certain measures and decisions. So far, however, there is no evaluation model that can depict artificial upwelling procedures and their advantages and disadvantages for humans and nature. This means that the benefits of artificial upwelling for achieving climate and development goals cannot yet be determined more precisely.

In the research mission CDRmare, researchers develop a global integrated assessment model that can represent the biological processes and the regionally varying carbon dioxide uptake as a result of artificial upwelling, thus enabling an economic and climate-political assessment of the method on a global scale. They also use an ecological-economic regional model to investigate the consequences and economic benefits of using artificial upwelling for fisheries off the coast of Gran Canaria.

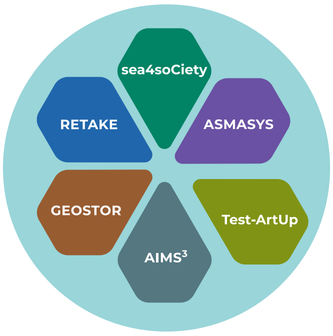
Based on these analyses, the experts then carry out an economic evaluation of various upwelling scenarios. They then summarise their findings on the benefits of artificial upwelling for the climate, nature and people and derive options for action for decision-makers in politics, business and civil society. This knowledge should enable all stakeholders to engage in a fact-based discussion about the benefits and risks of a possible use of artificial upwelling to increase the ocean's carbon dioxide uptake.

Would the use of upwelling pumps in the ocean be legally permissible at all, and if so, who would be allowed to issue the corresponding permit and under what conditions?

The legal framework for the use of artificial upwelling has not yet been clearly defined. For example, there is the question of whether the deployment of many upwelling pumps would violate current law and whether a deployment would even require a permit – and if so, who would be allowed to grant a permit and under what conditions. Complicating matters further is the fact that artificial upwelling is an activity in the sea that legally falls within the regulatory framework of international maritime law, but in substance aims to increase the carbon dioxide uptake potential of the ocean and thus pursues a climate change law objective.

As part of the research mission CDRmare, researchers want to create clarity and legal certainty in matters of artificial upwelling. Legal scholars examine the legal framework for large-scale pumping operations to increase the ocean's carbon dioxide uptake. Relevant conventions and principles are the London Protocol and the German Law on the Prohibition of the Dumping of Wastes and Other Substances and Objects into the High Seas.

In addition, the experts will analyse the extent to which artificial upwelling operations could be regulated under international law, what decision-making powers individual states have and how artificial upwelling measures can be integrated into international marine environmental and climate protection law without jeopardising other forms of marine use and environmental and species protection concerns. In doing so, the researchers want to find out what changes would have to be made to the legal conventions and principles in order to create an appropriate regulatory framework for the management of artificial upwelling.



All research activities described here are carried out within the CDRmare consortium »Test-ArtUp – Road testing ocean artificial upwelling«.

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.

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