Test-ArtUp

Test-ArtUp –
Road testing Ocean Artificial Upwelling

CDRmare INSIGHTS

The six most important findings on artificial upwelling methods

Over the past three years, experts in the CDRmare research consortium on ocean artificial upwelling have been investigating whether pumping nutrient-rich deep water to the surface in selected ocean regions could enhance microalgae growth and consequently amplify the ocean's biological carbon pump to a climate-relevant extent. Below, we present the six most important findings of the consortium on the feasibility of the methods, potential risks and framework conditions that have not yet been met.

1 Methods for the artificial upwelling of nutrient-rich deep water could have a positive climate impact, not just because of the increased algal growth in the surface water. The colder deep water would also cool the surface water, amplifying the ocean's natural CO_2 uptake through physical and chemical processes.

2 As the nutrient iron is lacking in many parts of the ocean, deploying pumps globally to upwell nutrient-rich deep water would not suffice to lastingly enhance the ocean's CO_2 uptake via the biological carbon pump.

3 Studies conducted on the plankton community in »mesocosms« confirm that microalgae and zooplankton respond very differently to the upwelling of nutrient-rich deep water. However, this behaviour is not yet reflected in computer models.

4 To achieve maximum CO_2 uptake, artificial upwelling methods would have to be combined with the cultivation of macroalgae on the open ocean.

5 To gain deeper insights, the experts would need to test artificial upwelling methods in the ocean. The Test-ArtUp team's wave pump test run on the open ocean was not successful because the pump malfunctioned. However, newly developed flow models show how the targeted upwelling of deep water could successfully be implemented.

6 Depending on whether and where artificial upwelling methods are to be applied, a suite of legal and governance-related questions need to be answered in advance.

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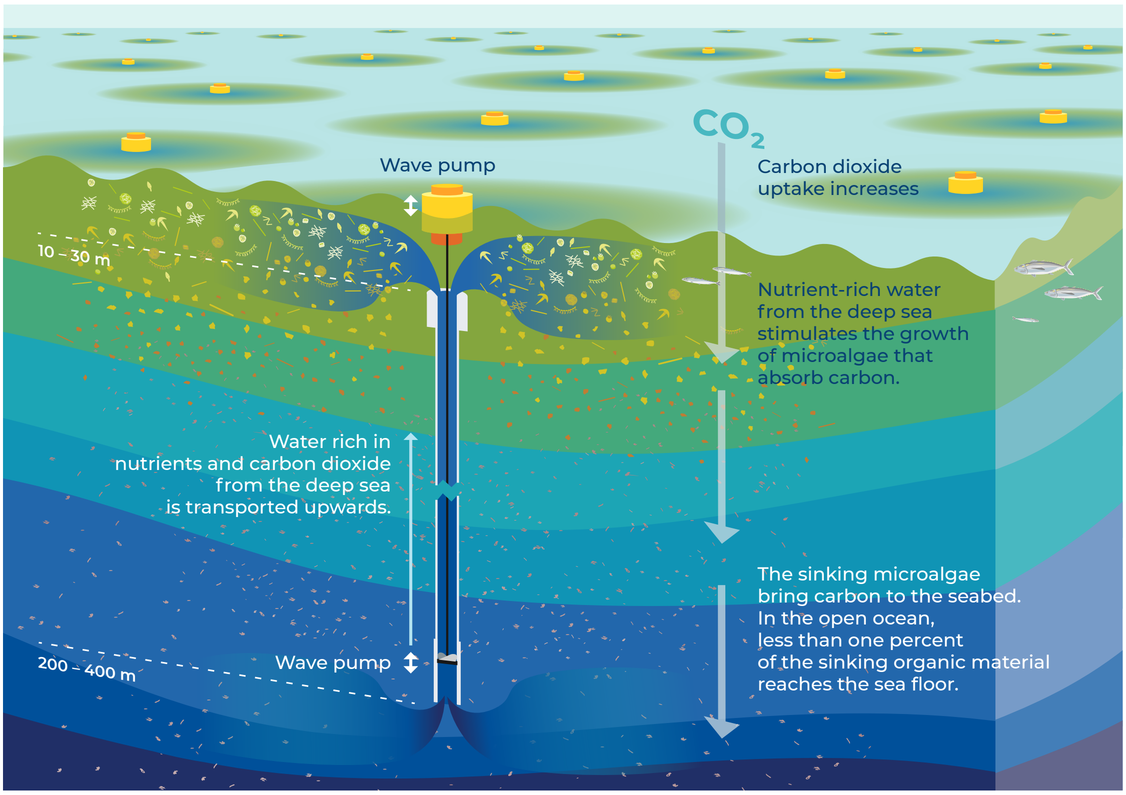
Key Message 1

Methods for the artificial upwelling of nutrient-rich deep water could have a positive climate impact, not just because of the increased algal growth in the surface water. The colder deep water would also cool the surface water, amplifying the ocean's natural CO_2 uptake through physical and chemical processes.

That's the conclusion reached by experts in the CDRmare research consortium for artificial upwelling (Test-ArtUp) after simulating the global deployment of wave- or propeller-type deep water pumps in a global Earth system model. As such, their findings reject the common assumption that artificial upwelling methods could only produce a positive climate impact because the nutrients found in deep water would set off a biological chain reaction on the ocean's surface (see figure below).

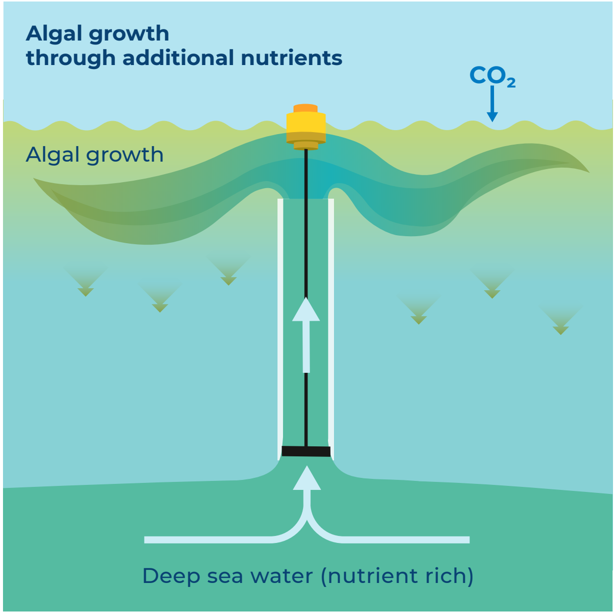
However, their simulations also indicate that the artificial upwelling of deep water – in the model, from a depth of 1,000 meters – would change three further observational parameters that influence the ocean's natural CO_2 uptake: the acid-binding capacity (alkalinity), temperature, and the percentage of carbon dioxide fixed in the surface water.

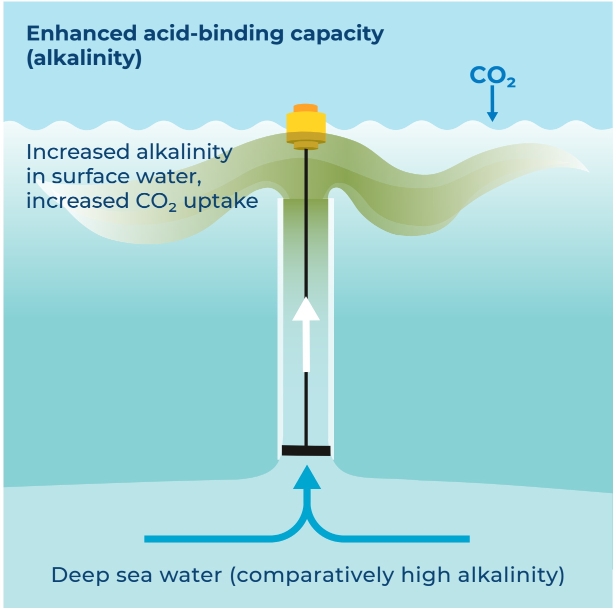
When deep water and surface water mix, it increases the latter's alkalinity and with it, the ocean's capacity to chemically fix dissolved CO_2 in the surface water. As a result, the ocean can absorb more CO_2 from the atmosphere. By way of explanation: Deep water has a high alkalinity because the remains of bivalves, snails and other calcium carbonate-forming organisms break down from a certain water depth. In the process, dissolved mineral by-products are released, increasing the water's alkalinity.

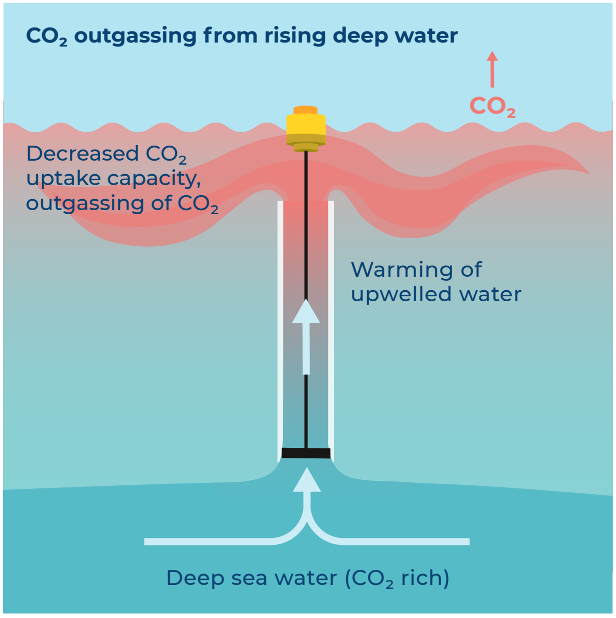


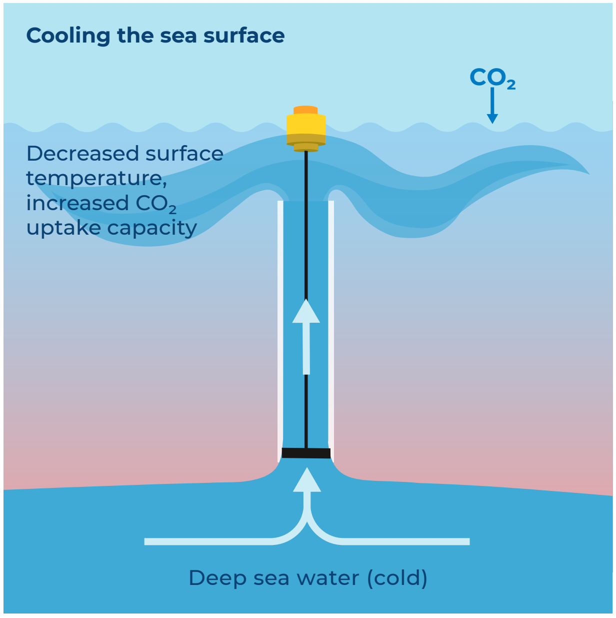
Graphic: Rita Erven, CDRmare

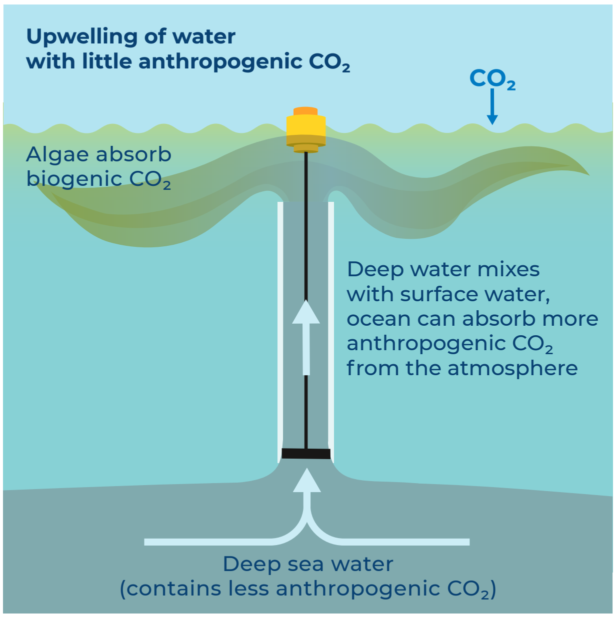
Artificial upwelling methods are intended to increase algal growth in ocean regions with nutrient-poor surface water. When more algae grow, more CO_2 is captured in biomass through photosynthesis. When the algae sink, the carbon contained in their biomass is transported to moderate or great depths. Only a tiny percentage of the initial biomass reaches the seafloor; microorganisms break down the particles as they sink.











The artificial upwelling of nutrient-rich deep water can produce a range of climate-relevant effects, depending on local conditions. These five graphics describe the potential effects.

Graphics: Rita Erven, CDRmare

When the deep water rises, it mixes with the surface water, increasing the latter's alkalinity. At the same time, this cools the surface layer, producing two climate-relevant changes. First of all, air masses over the ocean become cooler. Secondly, more oxygen and CO_2 dissolve in colder than in warmer waters. As such, the cooler surface layer can now absorb more CO_2 from the atmosphere.

To understand how the deep water changes the percentage of CO_2 dissolved in the surface water, it is important to know that today, deep water generally contains more dissolved CO_2 in a chemically fixed form than does surface water. This is due to microorganisms, which break down all animal and plant matter that sinks to the deep. In the process, these organisms consume oxygen and produce CO_2 and nutrients. When this CO_2-rich deep water mixes with surface water through artificial upwelling, the microalgae in the sunlit water layer can re-absorb the dissolved, biogenic CO_2 and store it as biomass.

If the algae absorb sufficient CO_2, the upwelled deep water would theoretically contain less dissolved human-made (anthropogenic) CO_2 than the surface water. Why? Because the last time the deep water was at the sea surface, hundreds or thousands of years ago, the atmosphere contained far less anthropogenic CO_2 than it does today. Consequently, if we assume the microalgae fix all biogenic CO_2, deep water could be used to enhance CO_2 uptake at the sea surface.

However, the large-scale artificial upwelling of deep water would also entail two risks: If the deep water contained too much CO_2, part of it could be outgassed at the sea surface, releasing it into the atmosphere. This assumption has also been confirmed in the model-based simulations. Secondly, the upwelling of cold deep water would mean that elsewhere, warm surface water would sink to the deep to replenish the deep-sea water reservoir. If the process continued for an extended period, the ocean's depths would gradually grow warmer and their capacity to chemically store carbon would steadily decline.

The simulations were run with an Earth system model that combines the climate components ocean, atmosphere and sea ice and employs a simplified representation of the marine ecosystem and food web. The experts defined e.g. how much carbon the algal community could absorb and fix in relation to the amount of nutrients added. In reality, this carbon-to-nutrient ratio is subject to substantial environmental fluctuations.

In addition, when certain artificial upwelling methods are used, the deep water grows warmer on its way to the surface (see also Key Message 5). If these methods were implemented, the sea surface would not be cooled and the previously described climate-relevant effects would not be produced.

Key Message 2

As the nutrient iron is lacking in many parts of the ocean, deploying pumps globally to upwell nutrient-rich deep water would not suffice to lastingly enhance the ocean's CO_2 uptake via of the biological carbon pump.

This conclusion, too, is based on extensive model-based simulations. Their functional logic is based on the fact that, in order to amplify the biological carbon pump (through microalgae growth and sinking biomass), the requisite nutrients and carbon dissolved in the water have to be pumped to the sea surface – in sufficient quantities and at the right ratio. The relevant nutrients in this context are phosphorus, nitrogen in the form of nitrate, silicate, and (in lower concentrations) iron and other micro-nutrients.

The model-based experiments conducted in Test-ArtUp have revealed that neither the ocean-wide deployment of 500-metre-long upwelling pumps nor their limited deployment in selected regions would amplify the biological carbon pump – because in both cases, the surface water is lacking iron, an essential micro-nutrient. The deep water would chiefly transport phosphorus and nitrogen to the surface, but not enough of the iron needed for algal growth. Consequently, the model-based simulations did not yield the envisioned boost in algal growth and resulting enhanced ocean CO_2 uptake.

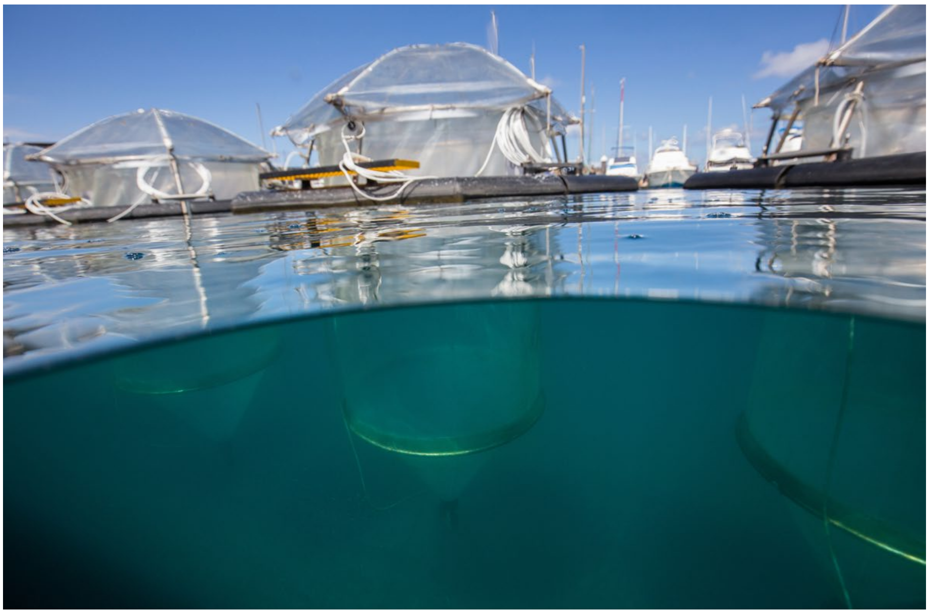
This natural limitation to algal growth could be overcome if, in addition to artificial upwelling, the surface water would be enriched with iron. Model-based experiments have shown that, using a combined approach consisting of deep water pumps and iron fertilization, the ocean would absorb more CO_2 from the atmosphere than if iron fertilization alone were used. However, in these model-based experiments the experts also assumed a fixed carbon-to-nutrient ratio – which doesn't always reflect the actual conditions in marine ecosystems, as various tests run with microalgae and zooplankton in what are known as mesocosms have shown (see also Key Message 3).

Key Message 3

Studies conducted on the plankton community in »mesocosms« confirm that microalgae and zooplankton respond very differently to the upwelling of nutrient-rich deep water. However, this behaviour is not yet reflected in computer models.

How the wide-scale deployment of artificial upwelling methods would affect marine biotic communities is an aspect that researchers from the CDRmare research consortium Test-ArtUp assessed on the coast of Gran Canaria in mesocosms – long, cylindrical bags made of transparent plastic foil that float upright on the sea and extend somewhat above the surface. Closed at the bottom, each mesocosm encloses ca. 6,000 litres of seawater, including all microorganisms living in the water. These included microalgae, a variety of small crustaceans, small jellyfish, and even fish larvae. The experts simulated the upwelling of nutrient-rich deep water by adding deep water enriched with additional nutrients.

In response, particularly diatom growth increased considerably. At the same time, the experts observed that the amount of carbon absorbed by the algae in relation to the amount of nutrients added varied depending on the nitrate and silicate concentrations in the deep water added. This led them to conclude that, in the context of artificial upwelling, nutrient concentrations in the deep water are what determine the (carbon-to-nutrient) ratio at which the microalgae absorb carbon and transform it into biomass.



6,000 litres of seawater were filled into each of the mesocosms that researchers from CDRmare and the partner project OceanNETs used for their experiments on Gran Canaria concerning targeted ocean CO_2 removal.

Photos: Michael Sswat, GEOMAR

The experts monitored changes in the plankton community in response to added nutrients (right) by taking samples at regular intervals (left). Photos: Michael Sswat, GEOMAR

According to the researchers' findings, more silicate in the deep water would promote a higher carbon-to-nutrient ratio, just as they had hoped. However, they were not able to rule out the possibility that the outcome was influenced by the experimental setup. From observations of natural upwelling areas it is known that, as nutrient upwelling increases, the algae's carbon uptake efficiency tends to decrease. This could be because the plankton community in the surface layer of nutrient-poor regions has adapted to the naturally low nutrient concentrations and initially doesn't know what to do with the additional nutrients.

Enhanced carbon uptake by diatoms would be advantageous in terms of achieving CO_2 sequestration through algal growth. However, it would also have certain drawbacks: Firstly, the researchers observed that, after dying, the remains of the more efficient carbon-absorbing algae sank to the deep more slowly than those of the algae that had lived in the water without additional nutrients. In turn, sinking more slowly means the microorganisms in the upper and middle water column have more time to break down the algae's biomass. Consequently, only a fraction of the additional carbon stored in the biomass would make its way to the sequestration-relevant depths of the ocean. In addition, the algae's increased carbon content would entail changes in the marine food web. Why? Because carbon-rich biomass has less nutritional value – so those organisms that feed on algae would have to eat more of it if they wanted to keep living and growing as they did in the past.

Accordingly, the plankton community's responses to the upwelling of nutrient-rich deep water are complex and depend on a range of parameters. So far, the computer models employed in Test-ArtUp have not been able to reflect these interdependencies and complexity. As such, on the basis of the models' outcomes alone, it cannot conclusively be said to what extent the biological carbon pump would enhance ocean CO_2 uptake if deep water pumps were deployed.

Key Message 4

To achieve maximum CO_2 uptake, artificial upwelling methods would have to be combined with the cultivation of macroalgae on the open ocean.

Macroalgae like seaweed are the masters of fixing CO_2. Few plants are more efficient when it comes to using nutrients for photosynthesis, absorbing CO_2 in the process, and storing the carbon in their biomass. Nevertheless, to date they have only successfully been farmed in coastal waters. In many parts of the open ocean, nutrient concentrations in the surface water are too low for macroalgae to thrive if they were cultivated e.g. on platforms in the upper water column.

This natural obstacle to ocean-wide macroalgae farming could be partly overcome through the targeted upwelling of nutrient-rich deep water. In simulations run with an Earth system model, researchers from the CDRmare partner project OceanNETs have already shown that the surface area of ocean where macroalgae could be grown would nearly double if 1,000-metre-long upwelling pumps were deployed in all regions with a depth of more than 3,000 metres and in which the temperature of the surface water did not exceed the specific limit for algae (20 degrees Celsius).

These modelling outcomes, together with the insights gained in the CDRmare research consortium Test-ArtUp, clearly show that artificial upwelling methods can enhance ocean CO_2 uptake. To tap the full potential of this approach, the upwelling of nutrient-rich deep water would have to be combined with the cultivation of macroalgae. Whether – and if so, how – this combination could be used to deliver optimal results has yet to be studied in depth. Further research is needed.

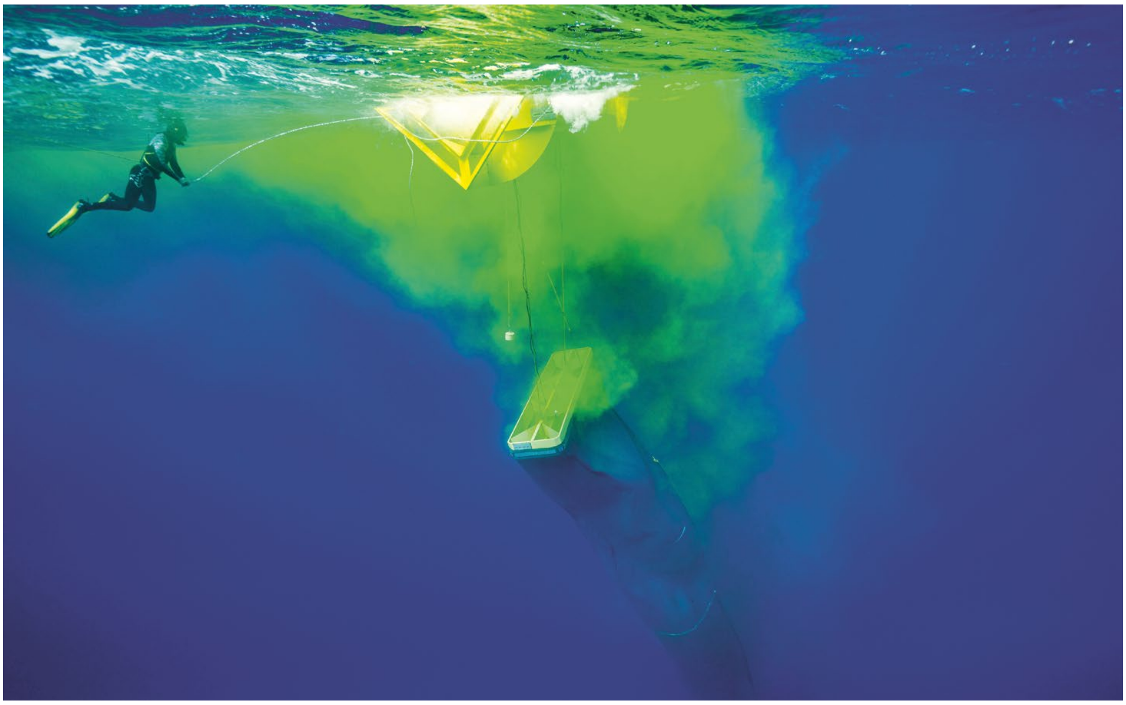
Key Message 5

To gain deeper insights, the experts would need to test artificial upwelling methods in the ocean. The Test-ArtUp team's wave pump test run on the open ocean was not successful because the pump malfunctioned. However, newly developed flow models show how the targeted upwelling of deep water could successfully be implemented.

As a rule, nutrient-rich deep water is colder than the surface layer. Consequently, it has a higher density and is heavier than the water at the sea surface. These properties lead to a well-known problem for the use of artificial upwelling methods: If deep water were pumped up to the sea surface, it (and all its nutrients) would simply sink below the warmer and lighter surface water – at least, that has been the common assumption to date.

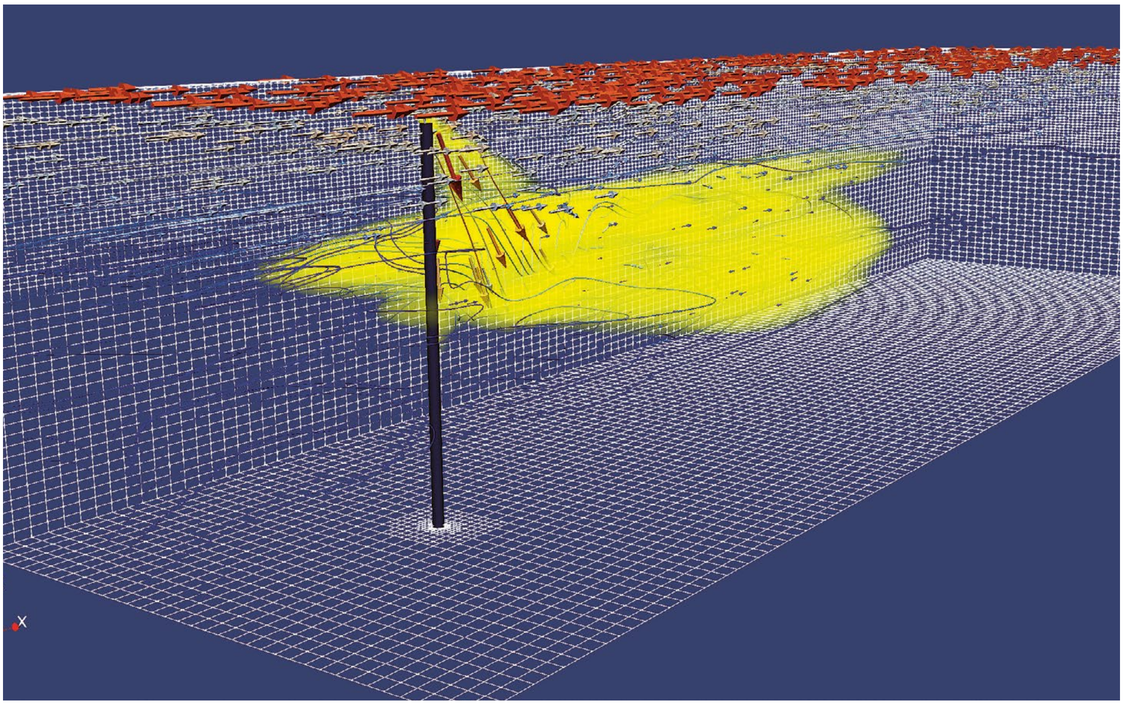
In the research consortium Test-ArtUp, experts have now used a new flow model to simulate the behaviour of deep water at a new level of detail. According to their findings, while the cold water transported upward by a propeller pump does indeed sink as expected, it does not sink far below the surface water. Rather, it settles in the lower part of the mixed layer. The water masses in this layer are mixed by the wind, waves and currents, which means that over time, the deep water is also dispersed throughout this layer. As such, the experts assume that a large percentage of the upwelled nutrients would remain in the ocean's cover layer, where they could promote algal growth.

Nevertheless, the researchers have also investigated the possibility of adjusting the deep water's temperature during the upwelling process, so as to avoid the nutrient-rich water masses subsequently sinking. This could be achieved if, instead of wave pumps or propeller pumps, Stommel pipes were used. In simplified terms, these pipes are driven by differences in the water masses' salinity and therefore in their density. However, this can only work if the surface water is warmer and has a higher salinity than the nutrient-rich deep water (see the figure on page 10).



In terms of testing the wave pump, a non-toxic, neon green dye was used to show the distribution of deep water at the sea surface. Because the pump malfunctioned, the researchers gained very little useful information from the size and shape of the dye cloud.

Photo: Michael Sswat

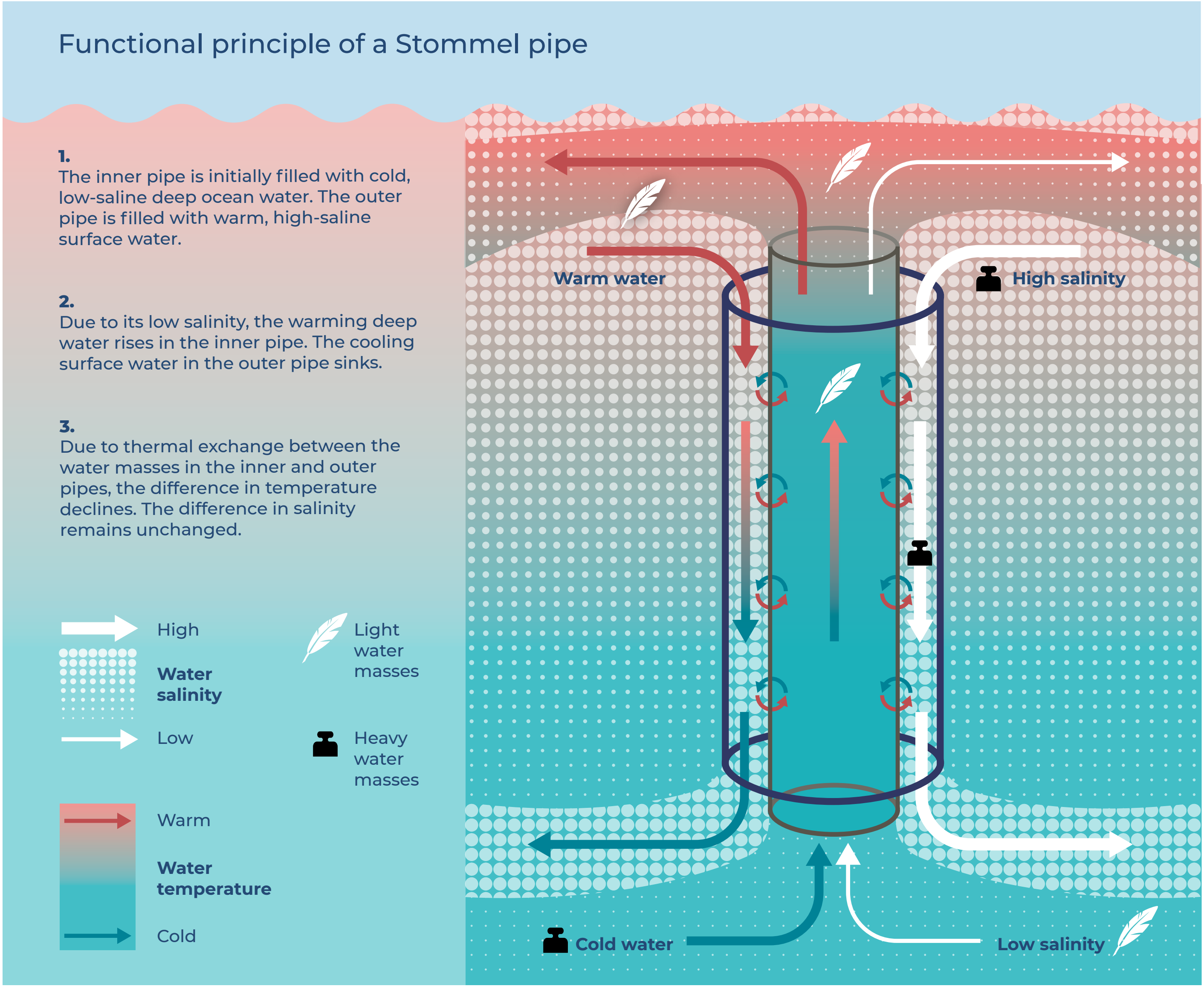


Simulations using a flow model, which show how the cold deep water initially sinks and then spreads along the lower end of the cover layer, were more conclusive.

Graphic: Jost Kemper, CAU

If, under these conditions, a long pumping hose were installed vertically in the water column and filled from below with cold, low-saline deep water, the rising ambient temperature toward the top would gradually warm the deep water in the hose. Further, because the deep water is low-saline, it would gradually move up the hose as it warmed. In turn, new deep water would automatically flow into the bottom end of the hose, where it, too, would be warmed and rise. In other words, from this point the Stommel pipe would run perpetually.

Using this pumping method would have three key advantages: Firstly, aside from filling the hose once, no external energy input would be needed to keep the pump operating. Secondly, this type of pump has very few components, making it less prone to breakdowns than wave or propeller



Graphic: Rita Erven, CDRmare based on a template from Jost Kemper, CAU

Functional principle of a Stommel pipe: Due to thermal exchange between the cold, low-saline deep water and the warm, high-saline surface water, the deep water – once given a brief initial impulse – essentially warms on its own and rises inside the inner pipe, while the surface water within the outer pipe cools and sinks. The advantage of this approach: The rising deep water is warm enough to mix with the surface water.

pumps. And thirdly, as the deep water would be warmed during its transport to the sea surface, it wouldn't sink once expelled from the upper end of the hose but rather mix with the surface water. Its nutrients would then be readily available and could drive algal growth.

However, there would also be certain disadvantages: For example, the deep water would no longer be able to cool the sea surface or the atmospheric layers above it – and the corresponding climate effects would not be produced. Moreover, as the deep water's temperature rises, so does the probability of CO_2 from the potentially CO_2-rich deep water being released into the atmosphere at the sea surface, which would negatively affect the CO_2 uptake efficiency for the upwelling project.

Key Message 6

Depending on whether and where artificial upwelling methods are to be applied, a suite of legal and governance-related questions need to be answered in advance.

This especially applies to the legal framework conditions. Artificial upwelling methods, like most CO_2 removal methods, are characterised by the fact that, while they can help mitigate climate change, they can also produce negative environmental effects – effects that can manifest across national borders. Consequently, marine CO_2 removal methods applied beyond a given country's coastal waters must comply with the law of the sea and international environmental law.

At the international level, two multilateral agreements are essential: the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) and the corresponding protocol from 1996 (London Protocol). In 2013, the latter was supplemented with regulations on marine geoengineering, an area that the majority of artificial upwelling methods belong to. However, these regulations have not yet entered into force because not enough countries have ratified them. In addition, artificial upwelling methods have not yet been added to Appendix IV of the updated regulations (from 2013) of the London Protocol, which would be a prerequisite for their approvability.

Nevertheless, the Federal Republic of Germany has already implemented the requirements under the new regulations of the London Protocol into national law and even (to a permissible extent) introduced more stringent ones. The High Seas Dumping Act (HSEG) and the Federal Water Act (WHG) were amended accordingly in 2018. In particular the HSEG in its current form prohibits marine negative-emissions technologies, which, it is widely agreed, also include artificial upwelling methods unless their use for research purposes is expressly permitted. In order to lift this ban, these CO_2 removal methods would have to be added to an Appendix of the HSEG, which hasn't yet happened.

Another amendment to the High Seas Dumping Act was prepared in 2024. The draft called for expanding the catalogue of permissible marine geoengineering measures in order to explore further options for sequestering atmospheric CO_2 and assess their environmental impacts; artificial upwelling methods were on the list. However, due to the collapse of the »traffic light« coalition in November 2024, the Bundestag did not have a chance to ratify the amendment before the new elections in February 2025. Accordingly, using artificial upwelling methods to amplify the ocean's biological carbon pump is still prohibited, even for research purposes (as of June 2025).

IMPRINT

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Test-ArtUp – Road testing ocean artificial upwelling is a research consortium within the CDRmare research mission. In the **CDRmare research mission** of the German Marine Research Alliance (DAM) various methods of marine CO_2 removal and storage (alkalinisation, blue carbon, artificial upwelling, CCS) are being investigated with regard to their potential, risks and trade-offs and brought together in a transdisciplinary assessment framework.