Potential of marine carbon dioxide removal (mCDR) to increase the ocean carbon sink

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Introduction

The ocean contains 40 times more carbon compared to the atmosphere (37,100 Pg C as dissolved inorganic carbon vs 900 Pg C – IOC-R, 2021) and hence is a key driver of the global carbon cycle. The ocean component of the global carbon cycle is being perturbed in many ways by climate change. For example, through complex physical processes, the ocean absorbs around 2.7 Pg C yr^{-1} (Gruber et al. 2023; **Figure 21**) and stores ~1.9 Pg C yr^{-1} (IOC-R, 2021), as well as the majority of additional heat released to the atmosphere (IPCC, 2022). Thus, the ocean plays a key role in regulating the global climate. The absorption and transport of heat and carbon dioxide by the ocean is causing a wide range of changes on ocean physics (stratification), chemistry (hypoxia, acidification) with consequent effects on ocean biota (productivity and biogeochemistry) along with a range of carbon cycle feedbacks (altered ability to absorb carbon dioxide) (IPCC, 2022).

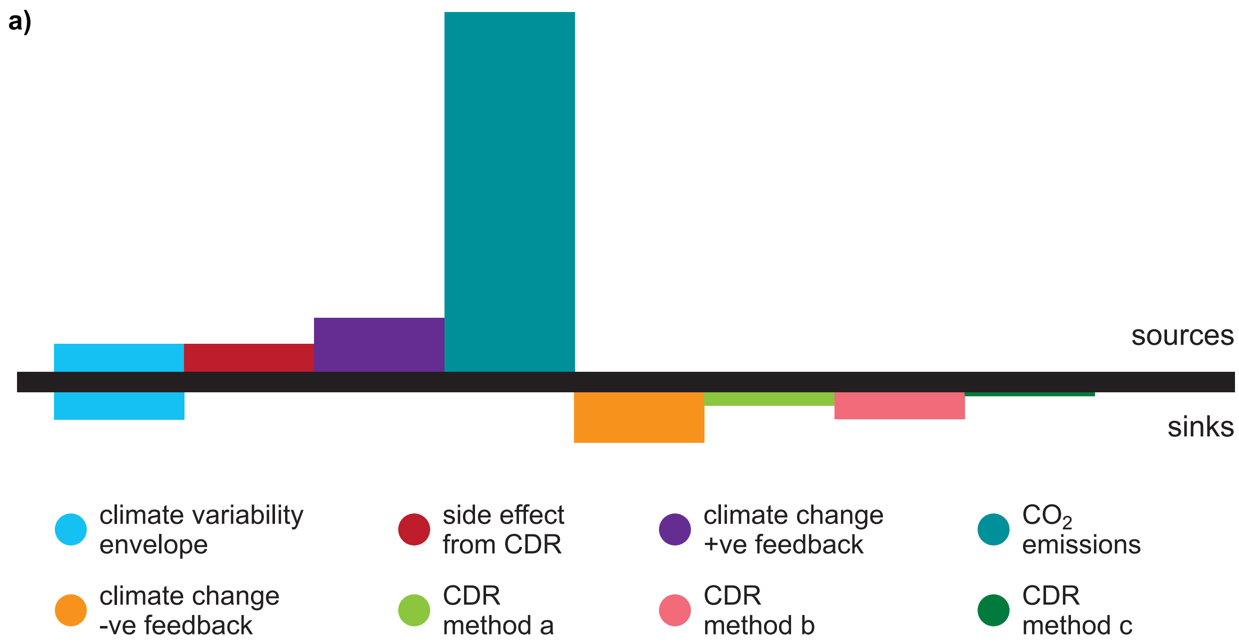
Since net zero greenhouse gas emissions targets have become a keystone of climate policy, there has been increasing debate about the need to actively remove carbon dioxide from the atmosphere (termed 'carbon dioxide removal', CDR) in addition to reducing emissions (IPCC, 2022). Since 2020, there has been a surge of interest in marine CDR (mCDR) techniques to store carbon in ocean reservoirs using wide-ranging methods (Table 4). Most interest is currently focused on ocean alkalinity enhancement (which includes electrochemical techniques), sinking biomass (e.g. crop wastes and seaweeds) into the deep ocean and ocean iron fertilization (OIF), which pose many technical, environmental, political, legal and regulatory challenges, among others. This increased interest is reflected in the large continuing increase in the number of scientific papers on mCDR, the growing number of start-ups developing mCDR techniques, the significant funding for mCDR research announced by the US and the EU in 2023[10] and the current consideration of potential regulation of several mCDR techniques by the London Protocol Parties.[11]

Description of findings, trends, status

As the technical and political challenges of the land-based CDR approaches are becoming more apparent, the oceans seem to be becoming the new 'blue' frontier for enhanced carbon drawdown strategies. This has led to significant number of field trials[12] covering artificial upwelling, biomass sinking, direct ocean capture and ocean alkalinity enhancement.

For all the proposed wide range of mCDR techniques, their potential to enhance the ocean carbon sink is largely unknown and based on model simulations (Table 4). Major unknowns include how they will interact with the ocean carbon cycle and whether these interactions will lead to feedbacks (**Figure 21**). These unknowns are superimposed upon uncertainties on constraining the magnitude of the present day ocean carbon sink that is influenced by internal forcing such as El Niño (**Figure 21**). These findings demonstrate that without improved understanding of how the ocean sequesters carbon, it will be difficult to establish a baseline, or at the very least a benchmark (Boyd et al., 2023), with which to assess the efficacy of a range of mCDR methods. A range of confounding factors can propagate additional uncertainties. These include the concurrent deployment of different mCDR approaches, each with potentially unknow side-effects (i.e. sign and magnitude) (**Figure 21a**) overlaid on emissions reductions, carbon cycle feedbacks (such as ocean buffering capacity), the influence of terrestrial CDR (Keller et al., 2018) and the interplay of external forcing (climate change) on internal forcing. The cumulative effect of these carbon cycle unknowns means that robust monitoring, reporting and verification (MRV) is essential to quantify any enhancement of the ocean C sink by mCDR approaches.

[10] See https://time.com/6328555/energy-department-funding-ocean-carbon-capture-research/, https://oceanacidification.noaa.gov/fy23-nopp-mcdr-awards/ and http://arpa-e.energy.gov.
[11] See https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/LC-45-LP-18.aspx.
[12] See https://oceanvisions.org/mcdr-field-trials/.



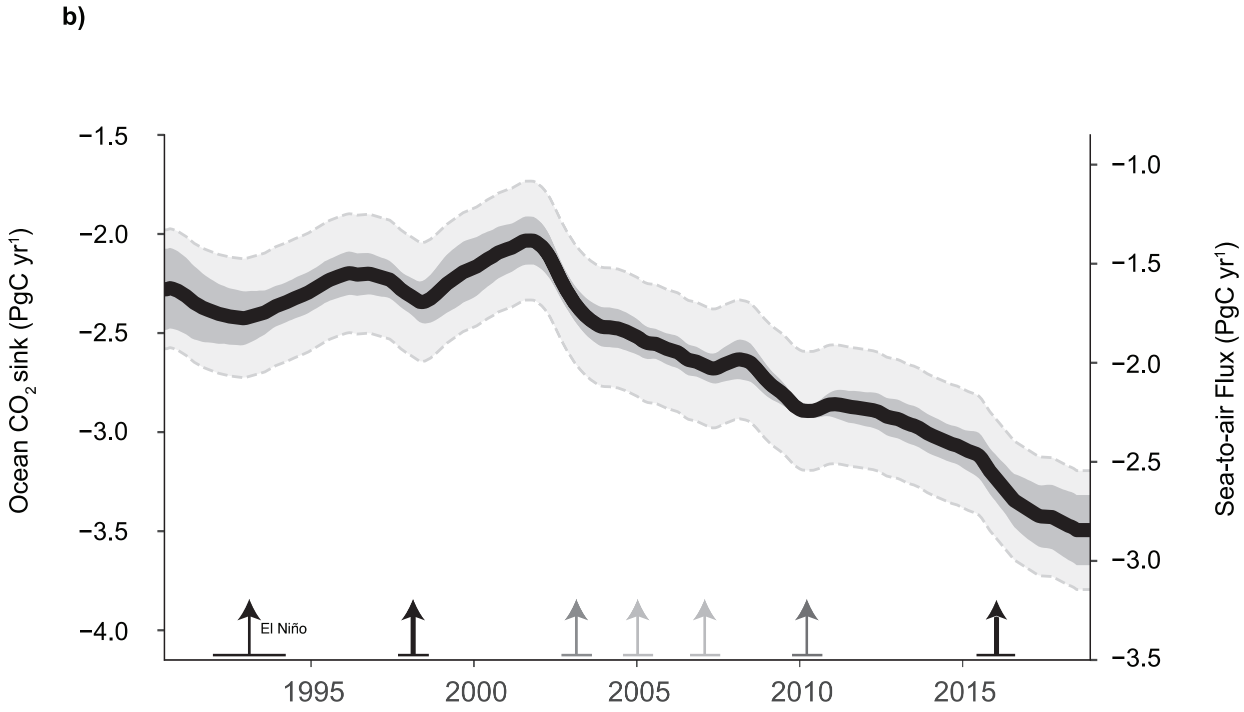


Figure 21. Confounding issues around detection and attribution of alteration of the ocean carbon sink by mCDR methods. *Sources*: **a)** – modified from Boyd and Bressac (2017); **b)** – modified from Figure 3 in Gruber et al. (2023). Notes: **a)** denotes a range of naturally occurring and/or climate-change driven changes to ocean carbon sinks or sources which will place important constraints and sets thresholds on the detection and attribution of multiple mCDR activities. Owing to many unknowns, it is problematic to provide scalebars for each panel, but note the Pg C year^{-1} scale in panel b. of reported changes along with the error estimates for the ocean carbon cycle. **b)** The black line is the mean estimate of the global ocean CO_2 sink estimates by six ocean partial pressure of CO_2 (pCO_2) observation-based products contained in Seaflux (Fay et al., 2021). The dark grey regions denote the standard error across the six products. Grey dashed lines are the uncertainty estimates for the ocean sink that incorporate that associated with the river outgassing flux. The timing of El Niño events in the Pacific are denoted by vertical arrows (darker arrows are stronger events).

Table 4. Examples of marine CDR approaches in five categories along with their modelled potential to act as oceanic C sinks.

Category	Prominent example	Sources of evidence-based knowledge (potential for C sink)	Nature of field studies	Knowledge gaps	Wider applicability of OF regulations
CDR – biology	Ocean iron fertilization (OIF)	Theory, natural analogues, modelling (~10% of current CO_2 emissions, Keller et al., 2014, but see Tagliabue et al., 2023), field studies	Unconstrained, transient, 100 km scale, not legal	Detection, attribution, upscaling issues, side effects	Regulated by the LC/LP
CDR – physical transport	Liquid CO_2 on the Seabed	Theory, natural analogues, field studies	Unconstrained, transient, m scale	Upscaling issues, side effects	Not applicable Banned by the LP but LC position uncertain,
Hybrid technologies for CDR/ food security	Ocean afforestation	Theory, natural analogues, modelling (<<10% of current CO_2 emissions, based on Wu et al., 2023 but constrained with Paine et al., 2023), field studies	Unconstrained, transient, < 5 km	Upscaling issues, side effects	Many differences from OIF, likely limited to coastal ocean (Iron limitation, Paine et al., 2023)
CDR – geochemical	Ocean alkalinization	Theory, natural analogues, modelling (~10% of current CO_2 emissions, Keller et al., 2014), lab tests, field studies	Unconstrained, transient, 10 km scale	Detection, attribution, upscaling issues, side-effects	Parallels, large-scale transboundary issues
CDR – physical transport and biogeochemistry	Artificial upwelling	Theory, natural analogues, modelling (<10% of current CO_2 emissions, Keller et al., 2014), field studies	Tests - from catastrophic failure (< 1 day) to 35 days	Detection, attribution, upscaling issues, side effects	Parallels, large-scale transboundary issues

Source: Modified from summary table in GESAMP (2019).

However, MRV of mCDR remains very technically and politically challenging, especially on the high seas (Boyd et al., 2023) – significant advances in sustained large-scale ocean monitoring would be needed to be able to detect and attribute the enhancement of long-term marine carbon storage (Frenger et al., 2024) by mCDR. Such detection and attribution for open ocean mCDR methods that rely upon enhancing carbon sequestration (Table 4) must also overcome additional challenges given that the ocean, and its ability to sequester carbon, is already changing (Wang et al., 2023).

In the coastal ocean, there is much interest in restoring/ expanding coastal blue carbon habitats (mangrove forests, seagrass meadows and tidal saltmarshes) to increase sequestration of carbon. However, concerns have been raised about the reliability of the data on CO_2 removal using coastal blue carbon restoration, as it has questionable effectiveness (Williamson and Gattuso, 2022). The restoration of coastal blue carbon ecosystems is nevertheless highly advantageous for climate adaptation, coastal protection, food provision and biodiversity conservation.

Conclusions and next steps

Recent syntheses have revealed that there is still much being learned about how the ocean sequesters carbon (Gruber et al., 2023). For example, the estimated magnitude of the C sink in the Southern Ocean and other ocean provinces has altered significantly over the last two decades (see **Figure 3** in Gruber et al., 2023). In the Southern Ocean, where there is interest to deploy some mCDR methods such as OIF at scale, major knowledge gaps include the role of the winter physics and summer biology in setting the magnitude of the carbon sink (Hauck et al., 2023).

The surge of interest in (mCDR) techniques poses many technical, environmental, political, legal and regulatory challenges. These techniques are all still at early stages of development with much still to be learned about them and their effects on the ocean carbon cycle before any decisions could be made about large-scale deployment.

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