Global Environmental Change 85 (2024) 102820

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

The rise, fall and rebirth of ocean carbon sequestration as a climate 'solution'

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ARTICLE INFO

Keywords:
Climate governance
Ocean governance
Geoengineering
Carbon dioxide removal
Hype cycles
Sociotechnical expectations

ABSTRACT

While the ocean has long been portrayed as a victim of climate change, threatened by ocean warming and acidification, it is now increasingly framed as a key solution to the climate crisis. In particular, the promising carbon sequestration potential of the ocean is being emphasised. In this paper, we seek to historicise the practices, discourses and actors that have constructed the ocean as a climate change solution space. We conceptualise the debate about the mitigation potential of the ocean as a contested site of governance, where varying actors form alliances and different sociotechnical narratives about climate action play out. Using an innovative quali-quantitative methodology which combines scientometrics with document analysis, observational fieldwork, and interviews, we outline three historical phases in the history of ocean carbon sequestration that follow recurring cycles of hype, controversy and disappointment. We argue that the most recent hype around ocean carbon sequestration was not triggered by a technological breakthrough or a reduction in scientific uncertainty, but by new socio-technical configurations and coalitions. We conclude by showing that how climate change solutions are put on the agenda and become legitimised is both a scientific and political process, linked to how science frames the climate crisis, and ultimately, its governance.

1. Introduction

In recent years, the role of the ocean in the fight against climate change has moved up the international agenda. While the ocean has long been portrayed as a victim, threatened by global warming and acidification, it is now increasingly framed as a key 'solution' to the climate crisis. For instance, at the launch of the United Nations (UN) Decade for Ocean Science for Sustainable Development, hosted in June 2021 by the German Ministry of Education and Research, its (then) Minister, Anja Karliczek, underlined the need for ocean-based carbon dioxide removal (OCDR), or negative emission technologies (NETs),[1] stating that the "oceans play a huge role in this […] because they act as a place of carbon storage" (fieldnotes, 2021). OCDR is also increasingly being discussed at the United Nations Framework Convention on Climate Change (UNFCCC). At the opening of the 2023 Ocean and Climate Change Dialogue, the Special Envoy for the Ocean Peter Thomson noted that "[…] the global conversation is now moving toward OCDR. The risks and costs of OCDR are glaring and we remain very deficient in our global knowledge and decisions on this subject. So, for better or worse, CDR will alter planetary conditions […]" (fieldnotes, 2023). Thomson emphasised that he saw CDR as warranting attention by the UN General Assembly, and he called for the establishment of a High Commission on the matter. Finally, carbon capture and storage (CCS) below the seabed also reached a milestone when Denmark inaugurated its first sub-seabed geological CO2 storage in the North Sea in March 2023 (Anonymous, 2023). The ocean is increasingly seen as the 'blue frontier' of carbon sequestration (Boettcher et al., 2021, Boettcher et al., 2023).

These examples illustrate the rising political attention paid to the role of the ocean in mitigating climate change. Research projects and assessments have been flourishing and policymakers have started including OCDR, and in particular carbon sequestration in coastal and marine ecosystems, so-called blue carbon approaches, in their Nationally Determined Contributions (NDCs) (Thoni et al., 2020) and long-term climate strategies (Jacobs, Gupta and Möller, 2023).

In documents and communication materials, OCDR technologies feature nicely as a portfolio of options (see e.g. Fig. 1), portraying a sense

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[1] Ocean-based NETs or CDR are synonyms. When not otherwise stated, we use CDR.

https://doi.org/10.1016/j.gloenvcha.2024.102820
Received 9 August 2023; Received in revised form 10 February 2024; Accepted 20 February 2024
Available online 2 March 2024

of neatness – as if they did not evolve in complex sociotechnical contexts – and of uniformity – as if they were on the same level of development, bore the same carbon sequestration potential and had the same level of public legitimacy. Furthermore, these technologies are often presented as ahistorical.

In reality, however, OCDR techniques do not all have the same potentials and trade-offs, and the same level of social acceptance. They also have not always been high on the agenda, and some of them have been the subject of debate and opposition (Factor, 2015; Fuentes-George, 2017; Barbesgaard, 2016; Friess et al., 2020). Overall, OCDR faces significant technical, (geo)political and socioeconomic challenges and scholars in the field have warned against the hype that surrounds debates about these approaches (Cox et al., 2021; Boettcher et al., 2021).

In this paper, we seek to historicise the practices, discourses and actors that have constructed the ocean as a means for climate change mitigation – that is, that have linked the ocean with strategies to sequester or remove CO2 from the atmosphere or from industrial sources. We build on research in Global Governance (Aykut and Maertens, 2021; Gupta and Möller, 2019) and in Science and Technology Studies (STS) (Borup et al., 2006; Joly, 2010). These approaches help conceptualise the debate about the mitigation potential of the ocean as a contested site of governance, where different actors form alliances and where different sociotechnical narratives of climate action are tested. In this perspective, scientific research on ocean-based climate change mitigation cannot be dissociated from the debate about global climate (and ocean) governance. Of particular interest to us are the cycles of hype, controversy and disappointment (van Lente, Spitters and Peine, 2013) that have characterised scientific and political discussions about OCDR, and that have been highlighted by actors themselves (Strong et al., 2009). Our analysis shows that the debate about OCDR (and climate solutions more broadly) shares similarities with those about many high-potential technologies such as biotechnology, stem cell manipulation or nanotechnology (Audétat, 2015).

More broadly, this paper contributes to shifting the focus of analysis from the social construction of climate change as a global environmental problem to the construction of the solutions to tackle it. It argues against the common view that differentiates between an 'alert' phase and a 'solution' phase (the so-called 'solution turn') in the governance of climate change (De Pryck and Wanneau, 2017). By taking a 'long durée' picture (van Beek et al., 2020; Carton et al., 2020; McLaren and Markusson, 2020; Schubert, 2022), it shows how these processes coevolve and how the (un)availability of climate solutions is the result of scientific and political dynamics, including shifting coalitions and conflicts about their contribution to climate mitigation. Such an approach is important to inform the ongoing debate, which tends to present ocean carbon sequestration as novel and indisputably desirable. Like Carton et al., (2020, p. 2), we believe that "the lessons from earlier experiences with carbon removal directly speak to the present possibilities, limitations, barriers, and conditions for [CDR] and should inform current research and policy promises if we are to avoid repeating past mistakes.".

After a brief presentation of our methods (2), this paper proceeds to its two main parts. The first part (3) is a sociohistorical analysis of ocean carbon sequestration. It distinguishes three phases: a first phase of problematisation and emerging promise of sequestering CO2 in the ocean; a second phase of experimentation but also concerns about marine 'geoengineering'; and a third phase of normalisation where ocean carbon sequestration becomes increasingly mainstreamed in climate policy. These phases describe an overall cycle of 'rise', 'fall' and 'rebirth' of ocean carbon sequestration, but specific cycles of hype and disappointment can also be observed for individual methods. The second part (4) is an analysis and discussion of the shifting coalitions of actors and narratives that have recently put ocean carbon sequestration in a new light.

2. Methodology

This paper relies on an original combination of quantitative and qualitative methods following an iterative process (Venturini, 2024).

The quantitative part of our research focuses on mapping the scientific literature about ocean carbon sequestration. It is based on the analysis of a corpus of 11,363 bibliographic records collected from Scopus (Elsevier's abstract and citation database) using a query addressing carbon sequestration, CCS, CDR, NETs and other activities

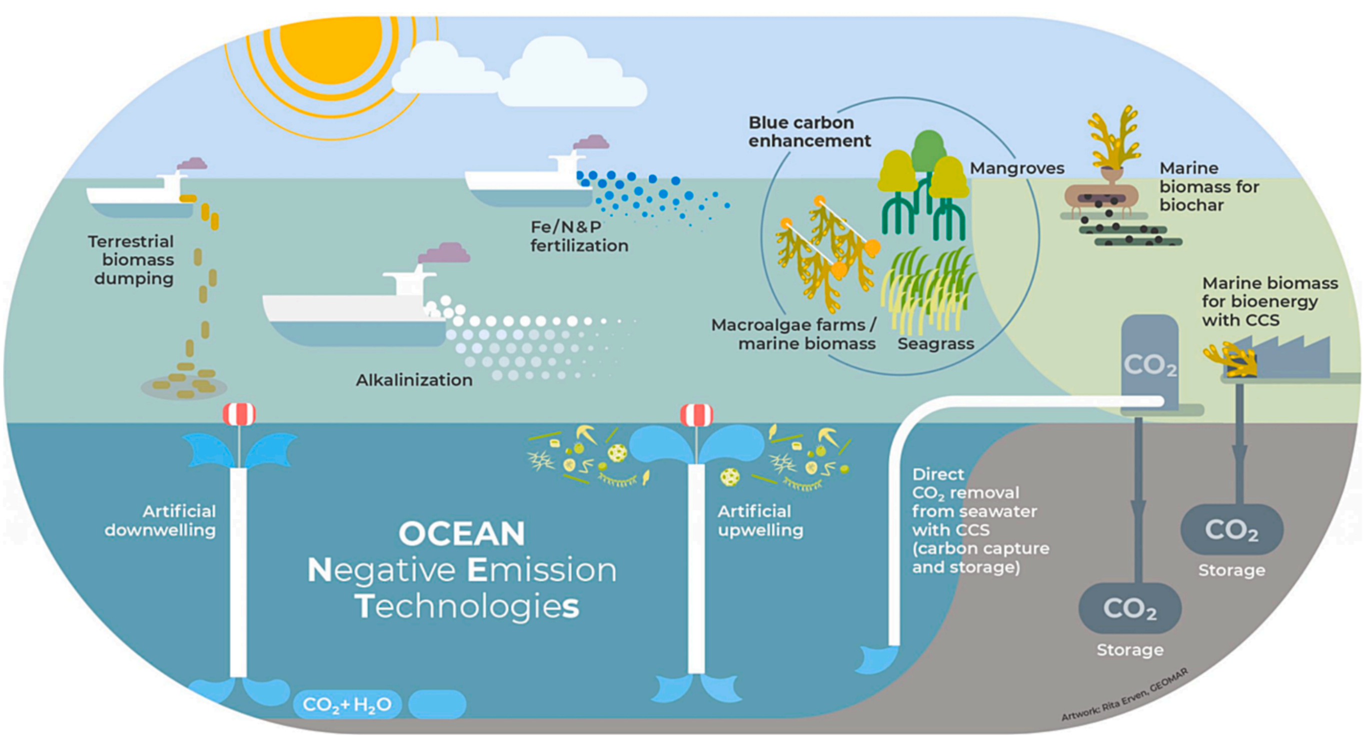

Fig. 1. Ocean-based NETs, also OCDR. Source: OceanNETs project.

aimed at using the ocean (including the coastal zone) to remove and sequester CO2 (see supplementary material). We used this data to map the scientometrics landscapes (Venturini and De Pryck, 2021) of the second and third phases of the history of ocean carbon sequestration (Figs. 2 and 3). Unfortunately, not enough records were available to generate a meaningful map of the first phase.

To produce the maps, we first built a network of the most important references appearing in our corpus, connecting them if they were cited together by the same paper (according to the co-citation approach, cf. Small, 1973). We spatialised this network using a force-directed algorithm so that (directly or indirectly) connected nodes were pulled closer together, while unconnected ones were pushed apart. This type of algorithm creates clusters of nodes that correspond to the relational communities present in the graph (Venturini et al., 2021). On this 'base' network made of references, we then projected the different *meta*-data found in the records (authors, keywords, funders, countries, etc.) using the same spatialisation algorithm. Finally, relying on the same bibliographic corpus, we also traced the temporal evolution of the publications addressing specific techniques (CCS, OAE, blue carbon, up/down welling and OIF) and generic terms (CDR, NETs, geoengineering) (Fig. 4).

Scientometrics is often employed as a stand-alone method to examine quantitative patterns and trends in scientific research. Such a method has for instance been used to study geoengineering research (Belter and Seidel, 2013; Oldham et al., 2014) and NETs (Minx et al., 2017). While useful to map the scope of a research field, bibliometric analysis often lacks qualitative insights to explain its evolution and the wider sociopolitical context in which it evolves. In this paper, we therefore combined it with qualitative techniques of document analysis (previous studies, scientific papers and comments, meeting reports, etc.), fieldwork (observation of scientific and political events related to ocean carbon sequestration) and 18 semi-structured interviews (see supplementary material).

3. Socio-historical analysis

This section introduces three phases in the history of ocean carbon sequestration. From the 1960s to the end of the 1990s, we observe a first phase (3.1) of problematization (in the sense of Callon, 1984) and hype, where advances in understanding the role of the ocean in absorbing atmospheric CO2 triggered an early interest in ocean-based mitigation, but also calls for caution. From the 2000s to the early 2010s (3.2), we describe a second phase of experimentation and renewed attention and expectations. Controversies about commercial tests in that period led to attempts at governing ocean carbon sequestration and to a general fall in their popularity. From 2014, (3.3), we observe a new phase of hype around ocean carbon sequestration, which has not yet led to major disappointment or controversy. The beginning and end of each period is not clear cut, and transition occurs over a few years.

3.1. Rise: Problematizing the role of the ocean in climate change mitigation and first hype (1960—–2000)

This section describes the first phase in the development of ocean carbon sequestration and contains two main parts. The first (3.1.1) historicises scientific developments since the 1960s about global climate change and the role of the ocean in absorbing atmospheric CO2. The second (3.1.2) focuses on the late 1980s and 1990s and debates in oceanography and paleoclimatology about the role of iron in impacting ocean productivity and ocean CO2 uptake. This second period is characterized by a first cycle of interest about OIF, followed by disappointment when scientists, concerned by increasing commercial interests, agreed not to deploy OIF for climate change mitigation, and to closely regulate OIF research. The debate remained restricted to a small community of oceanographers, and a few entrepreneurs.

3.1.1. Ocean carbon and the CO2 problem

The idea of using the ocean as a field of CO2 removal is indissociable from research interests about the role of the ocean in the climate system that developed in the second half of the 20th century. When the Intergovernmental Oceanographic Commission (IOC) was established in 1960, the need for a better understanding of the ocean carbon cycle was high on the agenda (Sabine et al., 2010). Roger Revelle, one of the key figures of oceanography at the time, was particularly concerned by the increase of atmospheric CO2 from fossil fuel combustion and the role of the ocean in absorbing it (Revelle and Suess, 1957).

International programs were launched, and expeditions set out to estimate and measure the concentration of CO2 in the ocean. Revelle and other influential scientists received government funding by capitalizing on a sustained interest in geophysical research triggered by the Cold War (Doel, 2003; Howe, 2014; Oreskes, 2021). From 1979, efforts to study ocean carbon were coordinated by the Committee on Climate Change and the Ocean (established by the IOC and the Scientific Committee on Oceanic Research, SCOR) and from 1998, by the Advisory Panel on Ocean CO2.

The improved understanding of the role of the ocean in the global carbon cycle led to suggestions to artificially accelerate it to solve climate change. For instance, the first issue of *Climatic Change* in 1977 featured a paper by Cesare Marchetti, an Italian physicist working at the International Institute for Applied System Analysis (IIASA). The paper entitled *On Geoengineering and the CO2 problem* discussed the technique of CCS in ocean currents (Marchetti, 1977). Marchetti (1977, p. 61) claimed that directly injecting CO2 into the deep ocean would "shortcut the atmospheric-ocean surface link".

3.1.2. The iron hypothesis and the potential of fertilising the ocean

In the late 1980s, John H. Martin, from Moss Landing Marine Laboratories in California, made important developments on a key question in oceanography and paleoclimatology. Seeking to explain why phytoplankton populations were so low in certain parts of the ocean (in so-called high-nutrient, low-chlorophyll regions, or HNLC), Martin suggested that it was due to a lack of iron, which prevented them from blooming (Martin and Fitzwater, 1988). This became known as the Iron Hypothesis. Martin (1990) also suggested that during glacials, large amounts of dust blowing into the ocean produced phytoplankton blooms that, as they sank, locked huge volumes of CO2 away in the deep ocean. These findings contributed to informing scientific understandings of the modern carbon cycle but also considerations for 'purposeful mitigation' (Sigman and Boyle, 2000). As an interviewee (#10) noted: "[…] by extension, if you're looking at what controls climate in the past, then you're also then getting some idea about how it could be manipulated in the future".

Martin and his co-authors not only emphasised the relevance of their findings for fundamental research, but also for responding to global warming. "If the need arises", they argued, fertilising the ocean with iron "may turn out to be the most feasible method of stimulating the active removal of greenhouse gas CO2 from the atmosphere" (Martin, Gordon and Fitzwater, 1990, p. 156). Such statements were controversial. Some scientists, Martin included, claimed that OIF could be used to increase carbon storage in the deep ocean and alleviate global warming. Martin famously claimed at a conference in 1988 "give me a half tanker of iron, and I will give you an ice age". Others found it alarming. Meetings were held behind closed doors to "hear both sides of the iron debate" (Dopyera, 1996, p. 30). In 1991, the American Limnology and Oceanography Society (ASLO, 1991, p. 6) urged in a consensus statement "all governments to regard the role of iron in marine productivity as an area for further research and not to consider OIF as a policy option that significantly changes the need to reduce emissions of carbon dioxide". As an interviewee (#2) noted, "the consensus resolution [was] very clear. Research yes, geoengineering no".

Martin's hypothesis needed to be tested in the open ocean. He, however, died in 1993, before the first experiment was carried out in the

Equatorial Pacific, showing that iron causes algae blooms. While Martin's co-authors (Martin et al., 1994, p. 123) noted that "such experiments are not intended as preliminary steps to climate manipulation", the idea of exploring how OIF could contribute to removing CO2 from the atmosphere raised expectations. According to an interviewee (#1), "it did, in part, probably help get additional funding for the area to actually test out whether or not these ideas were [from] crazy scientists or whether they actually did have some truth behind them". OIF as a policy option was also picked up in Nordhaus' influential integrated climate economy modelling exercise, who noted that "the advantage of geoengineering over other policies is enormous […]", because it provided seemingly costless mitigation (Nordhaus, 1992, 1319). Commercial interest was increasing in the context of the negotiation of the Kyoto Protocol, and firms in the United States started lobbying governments to permit the sale of carbon credits, without success (Fuentes-George, 2017).

Other methods were also under discussion in the 1990s. In 1995, Haroon Kheshgi (ExxonMobil), wrote one of the first papers on ocean alkalinity enhancement (OAE) as a geoengineering option (Kheshgi, 1995; see also Rau and Caldeira, 1999). Interest in carbon storage in geological formations under the seabed was also growing and was examined by the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, or London Convention and its Protocol (LC/LP) and the International Energy Agency (IEA) Greenhouse Gas R&D Programme (GESAMP, 1997). The ocean was increasingly seen as a key space to dispose of CO2 (Brewer, 2000; Seibel and Walsh, 2001).

3.2. *Fall: Experimenting, facing critique and regulating ocean carbon sequestration (2000——2013)*

This second phase saw the conduct of several OIF experiments and increasing interest in carbon storage in sub-seabed geological formations. Commercial and entrepreneurial interests were also becoming more prominent in the context of the implementation of the Kyoto Protocol and the emerging carbon market. This phase is thus characterised by major disagreements over the use of ocean carbon sequestration as a mitigation strategy and by resistance from civil society organisations (3.2.1), culminating with several attempts at regulation by key international institutions (3.2.2). With OIF under scrutiny, attention shifted to purportedly less interventionist approaches that come with co-benefits, such as blue carbon enhancement.

3.2.1. *Experimenting with ocean carbon sequestration in the context of mounting concerns over geoengineering*

Fig. 2 represents the scientometrics landscape of research on ocean carbon sequestration between 2000 and 2013. It shows several distinct clusters of research, each characterized by a different set of authors, journals, articles, keywords and institutions. It reveals the prominence of research on OIF (left clusters and keywords such as iron fertilisation, algae, HNLC), which co-evolved with understandings of the role of the ocean in the global carbon cycle (cf. keywords such as biological pump, biogeochemistry, carbon cycle, air-sea interaction). The landscape also includes two smaller clusters of research on blue carbon (top right) and CCS (middle right). The latter includes notably the 2005 IPCC Special Report on Carbon Capture and Storage (SRCCS), which contained a chapter on ocean carbon storage.

Several OIF experiments were carried out in the 2000s to increase the understanding of the role of iron in ocean productivity, biogeochemical cycles and the Earth climate system (Yoon et al., 2018). At that time, the scientific community did not need permission to carry research out in the open ocean (interview #4). While the experiments were not primarily intended to study OIF as a mitigation strategy, commercial interest kept rising, and so did scientists' concerns. A workshop organized in Washington in 2001 brought together scientists, policy experts and industry representatives to develop a shared understanding of OIF, but participants could not unanimously agree on its final statement (interview #10). The community of oceanographers was divided. On the one hand, several scientists (among them many biological oceanographers) questioned the viability of OIF and raised concerns about the environmental consequences of dumping iron into the ocean (Chrisholm, Falkowski and Cullen, 2001). Others (among them many chemical oceanographers) argued that more research was needed to assess its potential (Johnson and Karl, 2002; Buesseler and Boyd, 2003).

Questions were also raised over propositions to sequester CO2 in the sub-seabed and the deep ocean and the IOC asked SCOR to organise a conference - the 2004 symposium on the *Ocean in a High CO2 World*, hosted by the United Nations Educational, Scientific and Cultural Organisation (UNESCO) in Paris. The LC/LP was also seeking to position itself on the governance of ocean carbon sequestration, and in particular CCS in the sub-seabed. In attempting to interpret the LC in light of the role of CCS as a way to mitigate climate change, Parties wrote in 2004: "With the London Convention responsible for protecting the marine environment in relation to deposits in the sea, it has a key role to play in the legal and scientific assessment of the option of CO2 sequestration there" (LC, 2004) and reiterated that "the LC/LP are well positioned to play an important role in ensuring that any development of CO2 sequestration in the marine environment is within a clear legal framework that permits climate change mitigation." (LC, 2004).

Several controversies, however, changed public attitudes toward ocean carbon sequestration, and in particular OIF. In 2007, a California-based firm named Planktos planned to dump 100 tonnes of iron particles into the Pacific Ocean off the Galapagos, seeking to sell carbon offsets from the experiment. The project was opposed by civil society organisations, including Greenpeace, the International Union for Conservation of Nature (IUCN) and the ETC Group, and aborted. Two years later, in 2009, it was a German-Indian scientific expedition (LOHAFEX) that was opposed by environmental organisations and the German Federal Ministry for the Environment (BMU), who saw the experiment as a violation of international agreements on the protection of the ocean, primarily the Convention for Biological Diversity (CBD) (Harnisch et al., 2015, Uther, 2014). Finally, in 2012, the ETC Group also raised concerns about an experiment run near Haida Gwaii (Canada) by the Haida Salmon Restoration Corporation and involving former Planktos CEO and philanthropist, Russ George (Buck, 2018; Gannon and Hulme, 2018). Civil society groups raised questions about the effectiveness of OIF in sequestering carbon, the scale of the intervention (framed as geoengineering), and the potential negative impacts on the marine environment (Fuentes-George, 2017).

These commercial expeditions raised questions about the regulation of OIF. A transnational coalition of concerned parties, including Greenpeace, the ETC Group, the IUCN and marine scientists presented research highlighting the environmental risks of OIF to the LC/LP and the CBD. In 2007, the scientific group of the LC/LP (IMO, 2007, p. 1) issued a statement of concern, noting that "knowledge about the effectiveness and potential environmental impacts of ocean iron fertilization currently was insufficient to justify large-scale operations". Given their respective mandates to protect the marine environment and global biodiversity, faced with this information about potential risks, the LC/LP and the CBD were then required to engage with the issue (Boettcher and Kim, 2022, Fuentes-George, 2017).

3.2.2. *Governing ocean carbon sequestration*

Regulating OIF became a key issue, principally within the LC/LP and the CBD.[2] The LC/LP Parties passed five resolutions between 2006 and 2013.[3] Its 2013 amendment noted that "all ocean fertilization activities other than those referred to in paragraph 3 shall not be permitted" (LP,

[2] The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) also prohibited in 2007 the storage of carbon dioxide streams in the water column or on the seabed.

[3] See LP (2006); LC/LP (2008); LP (2009); LP (2013).

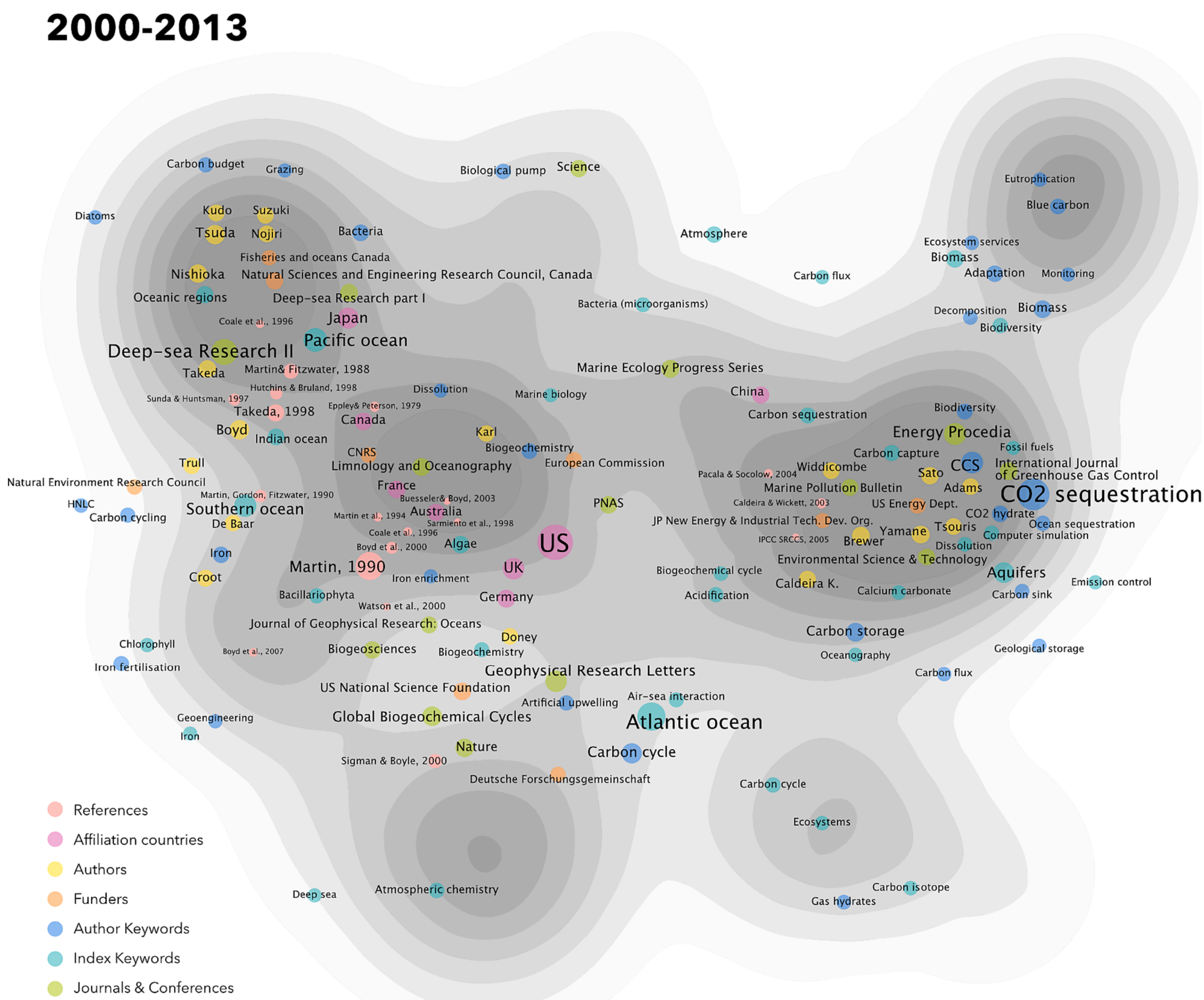

Fig. 2. Bibliometric maps of the field of ocean carbon sequestration (2000–2013). The headmaps in the background display the density of reference nodes in the base maps.

2013, p. 3). In addition to restricting activities *in general*, the LC/LP thus also put in place a framework for permitting *some* activities - those which involve sub-seabed CO2 sequestration, and those which classify as "legitimate scientific research" (LP, 2013, p. 4). The reasoning behind this approach was on balancing the risks to the ocean with the need to assess the potential role the ocean may play in mitigating the effects of climate change.

After first discussing geoengineering in the context of OIF at its ninth meeting in 2008, the CBD issued two main decisions. In 2010 it was decided that, "[i]n the absence of science based, global, transparent and effective control and regulatory mechanisms for geoengineering […] no climate-related geoengineering activities that may affect biodiversity take place, […] with the exception of small-scale scientific research studies that would be conducted in a controlled setting" (CBD, 2010). The CBD thus focused on prevention of harm to biodiversity and precaution in relation to climate intervention activities, while at the same time acknowledging the need for more research in this area to explore *both* risks and co-benefits for biodiversity in the face of continued climate change.

As noted by Boettcher and Kim (2022), the LC/LP and the CBD supported different types of governance outcomes. The former took a more permissive approach to marine geoengineering, while the latter supported precautionary governance. This is in part due to structural and organisational differences between the two institutions. As an interviewee (#1) noted, "the CBD wanted an end to geoengineering research, because they thought it was sort of a dead end. And because the government representatives at CBD meetings are the representatives from environmental bodies, protection bodies, and their priority naturally is protecting biodiversity". LP/LC members, on the contrary, are familiar with regulating all sorts of material disposal at sea and defining guidance documents to evaluate these practices (interview #8). Coming up with the LP/LC Assessment Framework for Scientific Research Involving Ocean Fertilisation was thus in line with common practice.

The controversies around OIF, coupled by attempts at regulating it, led to a decline in research on the topic (see Fig. 3). While the legal status of the CBD decisions and the LC/LP amendment is weak – CBD decisions are 'soft-law' and the LP amendment has not yet entered into force (interview #13) – their introduction sent a strong signal that shaped the research landscape on ocean carbon sequestration. As several interviewees noted, OIF was considered too controversial and funding agencies were reluctant to support new research in the open ocean. As an American oceanographer remembered (interview #3), "our program

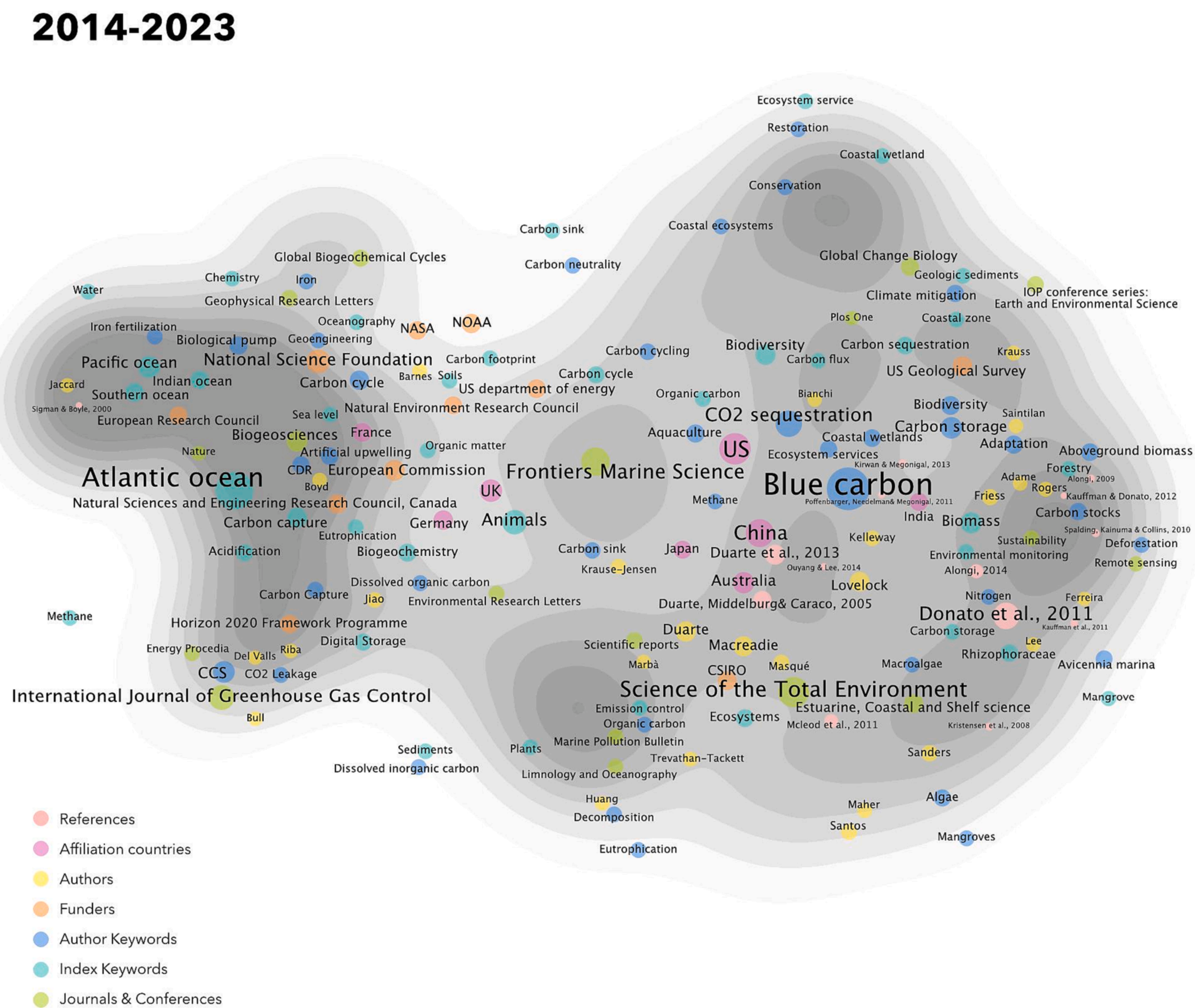

Fig. 3. Bibliometric maps of the field of ocean carbon sequestration (2014——2023). The headmaps in the background display the density of reference nodes in the base maps.

manager at the National Science Foundation (NSF) told me that […] he didn't want to manage another OIF experiment. It was controversial for NSF to be involved in that. And so, we had to look for other funding". A German oceanographer (interview #4) noted a similar attitude: "There was huge hesitation to get into this research, because they [German funding agencies] felt it was still too controversial, [that] society would not support research on this". The regulating mechanism introduced by the LC/LP also rendered funding applications more cumbersome. "That scared off a lot of academic funders and scientists from even trying to move ahead because of the complexity of the application process […]" (fieldnotes, 2021).

3.3. Rebirth: Constructing ocean based sequestration as a necessity (2014 -)

This third phase introduces a new cycle of hype. We observe a changing research landscape (3.3.1), with research on blue carbon significantly increasing. The involvement of new actors in the debate has also led to renewed attention to ocean carbon sequestration. On the one hand, a loose coalition of advocates (scientists, civil society, international organisation and governments) has pushed for greater linkages between climate change and the ocean, positioning the ocean as a key 'solution space' (3.3.2). On the other hand, the IPCC, by including CO2 removal in its emissions scenarios limiting global warming to 1.5 °C and 2 °C, contributed to legitimising carbon sequestration as a mitigation strategy (3.3.3).

3.3.1. A changing research landscape and the rise of OCDR as an umbrella term

Fig. 3 shows how, in the 2010s, OIF research has dramatically decreased (left cluster) and has been overtaken by research on blue carbon (right clusters, cf. keywords such as biomass, aquaculture, biodiversity, adaptation). Research on CCS (bottom left) remains stable and autonomous, and its activities remain largely permitted (Dixon et al., 2009).

Research on OIF did not stop, but scientists went on to conduct research that did not involve in situ experiments, such as natural analogs and modelling exercises of large-scale CDR deployment. While research interest in OIF declined, interest in blue carbon increased. The role of coastal ecosystems in buffering excess anthropogenic carbon in the atmosphere has been well-researched (Ver et al., 1999), but gained wider attention when a group of intergovernmental bodies (including the Food and Agriculture Organisation and the UN Environment Programme) published the report 'Blue carbon: The role of healthy oceans in binding carbon' in 2009. The report (Nellemann et al., 2009) highlighted the importance of improved management and protection of marine ecosystems to mitigate climate change. It was published in preparation for the 15th Conference of the Parties (COP15) to the UNFCCC to advocate for the carbon sequestration potential of blue carbon ecosystems to be valued equal to 'green' carbon sinks (such as terrestrial forests) within the REDD+ program (Reduced Emissions from Deforestation and forest Degradation) and underlying market mechanisms. Only mangrove forests had been included in the Clean Development Mechanism (CDM). In 2011, the uptake of blue carbon ecosystems was ultimately unsuccessful (Murray et al., 2012). Reasoning was reportedly remaining uncertainty about the underlying science behind blue carbon and concerns that market mechanisms would not adequately be able to conserve nature. Challenges in mainstreaming blue carbon in the UNFCCC, however, did not prevent research from significantly increasing (de Paula et al., 2022).

While research on OIF, blue carbon and ocean CCS involve different authors, journals and institutions, as well as distinct imaginaries of climate intervention (top-down versus bottom-up, 'technological 'or 'natural' processes, etc.), these methods are now increasingly lumped in together under the umbrella terms of OCDR, or ocean-based NETs (as shown in Fig. 1). The last years have seen a proliferation of conferences, workshops, expert reports and policy briefs on ocean carbon sequestration. For instance, the Ocean Solutions Initiative set out in 2016 to assess ocean-based NETs (Gattuso et al., 2018; 2021). The authors concluded that they "are uncertain but potentially highly effective" (Gattuso et al., 2021, p. 1). In 2019, GESAMP (2019) also published a High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques. In 2021, the National Academies of Sciences, Engineering, and Medicine (NASEM) published a Research Strategy for Ocean Carbon Dioxide Removal and Sequestration. These publications, often written by experts working on different methods, contributed to legitimising ocean carbon sequestration as a climate mitigation strategy.

3.3.2. Linking climate change and the ocean in the UNFCCC

Attempts by a loose coalition of scientists, civil society actors and policymakers to link climate change and the ocean and lobby the UNFCCC also contributed to raising the profile of OCDR (Chan, 2021). Strategies to bring the ocean into the negotiations were particularly visible in the run up to COP21. In 2014, NGOs and research institutes launched the *Ocean & Climate Platform* to support interactions between the ocean, climate and biodiversity. Under the *Oceans 2015 Initiative,* a group of scientists also called for an agreement that would take the ocean into account (Gattuso et al., 2018). At COP21, 23 countries (mainly European, Latin American and island states) launched the *Because the Ocean Initiative*, supporting the preparation of an IPCC Special Report on the ocean and the convening of a high-level UN ocean conference.

Advocacy continued at COP23 with the launch of the *Ocean Pathway Partnership* by the Fijian COP Presidency and of the multi-stakeholder *Ocean & Climate Initiatives Alliance* to support ocean action. It became crucial not only to draw attention to the impact of climate change on the ocean, but also to the solutions that the ocean can provide (interview #7 and Hoegh-Guldberg et al., 2019). In 2019, the IPCC published its Special Report on the Ocean and Cryosphere (SROCC), which provided an assessment of OCDR techniques, in particular blue carbon. At COP25 in 2019, the importance of the ocean was highlighted in the COP decision - it has been called the "Blue COP". According to Chan (2021, p. 8), the release of SROCC "provided a hook for the COP25 decision, marking the beginning of the 'integration' of the ocean into the climate negotiations […]". COP15 also called for the organisation of an Ocean Dialogue, which has been held annually since 2022 and aims at strengthening ocean-based adaptation and mitigation action. Blue carbon is often prominently featured in these discussions.

3.3.3. Locking in carbon removal as climate mitigation

Ocean carbon sequestration has also benefited from a renewed interest in carbon removals *in general*. On the one hand, the 2015 Paris Agreement put greater emphasis on carbon sinks, by inscribing the need "to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (Article 4.1). As an interviewee (#4) noted, "[…] the Paris Agreement made it very clear that along with drastic reductions in emissions, […] we need to consider net negative technologies to remove what we've already released. So I think there's been a big ground shift from 15 years ago, say, when we were finishing up these experiments and being told, no, this will cause irreparable harm". On the other hand, many interviewees also mentioned the IPCC Special Report on Global Warming of 1.5 °C (SR15) as a game changer. As noted by the biogeochemist Phillip Williamson (2018): "There will be at least one inescapable conclusion in the upcoming publication of [SR15]: unconventional interventions will be needed to avoid dangerous climate change.".

SR15 built on previous IPCC reports, and in particular on its Fifth Assessment Report (AR5), which locked in CDR in emission scenarios limiting global warming to 2 °C (Beck and Mahony, 2018). The IPCC has thus acted as a powerful anchor, legitimising CDR, and framing them as a "matter of necessity" (Otto et al., 2021, p. 5). The initial focus on land-based CDR has been criticised by several scientists. Commenting on the release of a report on NETs by the NASEM (2019), the biogeochemist Rau (2019) noted that "rather than being a CDR agenda that seeks to maximize global opportunities, it is one that excludes 70 % of the planet". An interviewee also wondered (#4) "Why ignore the ocean? Because compared to land, there is a lot more carbon storage in the ocean than on land, 40 times more in the deep ocean […]".

In the last few years, advocates of ocean carbon sequestration have benefited from increasing scepticism about land-based CDR (Boettcher et al., 2021). The deployment of afforestation/reforestation methods and bioenergy with carbon capture and storage (BECCS) has come under increasing criticism because of the risks of competing land use and land grabbing, and the potential negative impacts of such deployment on biodiversity. The potential of the ocean as the largest long-term sink for anthropogenic CO2 thus looms large. OCDR technologies are now increasingly included in the portfolio of climate solutions, offering complements to land-based CDR and other options.

Commercial interest has been rising too again. At COP27 in Egypt for instance, in discussions on carbon removal activities under the Article 6.4 mechanism of the Paris Agreement, several companies (Running Tide, Hayes Limnology Lab, Ocean-based Climate Solutions, Planetary Technology) submitted statements supporting the inclusion of ocean-based methods such as OAE, ocean biomass dumping and ocean microalgae removal (another term for OIF) - despite major uncertainty related to the monitoring, reporting and verification of these removals. In this context, questions of desirability and governability are being replaced by questions of design and marketisation (cf. 'normalisation' as defined by Gupta and Möller, 2019).

4. Drivers of historical change

In this section, we discuss what can be learned from our socio-historical analysis by linking it to relevant discussions in the STS and Global Governance literature and highlighting the configuration of actors and narratives that drive the debate around ocean carbon sequestration, especially in its latest phase. We dive deeper into the cycles of hype, controversy and disappointment that have characterised the debate over time (4.1), the processes of co-production (4.2) and climatisation underpinning it (4.3); and finally, the ongoing (re)framing and (re)labelling of ocean carbon sequestration aimed at pragmatically moving research and development forward (4.4).

4.1. Temporal patterns and expectations in the debate about ocean carbon sequestration

Research in STS helps situate the craze about ocean-based sequestration in broader reflections about the role of science and technology in society, showing that the evolution of the debate closely follows that of many technological innovations, by being characterised by cycles of hype and disappointment (Borup et al., 2006). Actors involved in the debate have themselves highlighted its cyclical nature. Taking stock of OIF, Aaron Strong, John Cullen and Sallie Chisholm (2009, 236) noted that “throughout these two decades [the 1990s and 2000s] there has been a repeated cycle: Scientific experiments are followed by media and commercial interest and this triggers calls for caution and the need for more experiments”. A panellist of a NASEM workshop also stated that the debate on OIF and artificial upwelling reminded him of the phoenix, ”that magical, mystical bird that dies and then rises from the ashes again. […]. The discussions have risen up and died, revived and died. We are probably already in the third wave.” (fieldnotes, 2021). This three-wave cycle also affected the debate about other technologies. Interest in OAE, for instance, was slow to develop: “the concern around [OIF] just sort of put a damper on other research in the ocean” (interviews #17 and 16). Blue carbon, on the contrary, might have benefited from opposition to OIF. The UNEP report (Nellemann et al., 2009, p. 65) for instance presented it as an option that, unlike OIF, does not raise serious ecological and political challenges, but brings multiple co-benefits for food security, health, etc.

Panels A and B in Fig. 4 show the evolution of research on these methods and reflect some of those trends, showing a strong decrease in research on OIF and an exponential increase of research on blue carbon in the 2010s, as well as a small hype about OAE in the 2020s.

Specific expectations and promises drive cycles of hype. OIF for instance fuelled much interest because it has frequently been framed as an effective and inexpensive solution that does not require major transformational change to the economy. According to Factor (2015, p. 316), OIF advocates “sought to bring about the conditions of possibility for the development of a research strategy that would help bypass the potential expense of overcoming the carbon economy”.

In the last decade, promises about ocean carbon sequestration have been significantly tempered. Disappointment with regard to the carbon sequestration potential of many techniques and the challenges to integrating them into carbon markets have led advocates to re-consider how to push forward research and deployment. If their potential for climate mitigation continues to be emphasised over risks, a more modest and ’pragmatic’ narrative has emerged. OCDR approaches are being more clearly framed as complementary to emission reduction strategies, and as contributions to the ’portfolio’ of climate response strategies. As an interviewee (#8) noted, “It is also worth saying that there’s almost certainly […] no silver bullet and no single technique that will be the answer. We are much more likely to find a portfolio of techniques that may be more effective in different locations, for different reasons”.

The cycles of hype and disappointment about ocean carbon sequestration are not only a matter of rhetoric. They involve practices of experimentation, instruments, investments, individuals and institutions that support them and build momentum (Low and Boettcher, 2020; Boettcher et al., 2021). The last decade has seen the emergence of new coalitions of actors that have pushed for enhanced ocean climate action, including scientific (the Ocean Visions network) and philanthropic institutions (ClimateWorks Foundation), NGOs (Ocean Conservancy), multistakeholder platforms (Ocean & Climate Platform), entrepreneurial and business actors (Microsoft, Elon Musk, the World Ocean Council), small start-ups (Project Vesta, Origen), and governments (members of the Ocean Panel, China, Germany and island states) (Boettcher et al., 2023). The role of the IPCC’s emission scenarios in designing futures where CDR is unavoidable has also been considerable.

Moving beyond what is perceived as an unproductive opposition between those in favour of or opposed to ocean carbon sequestration, these actors are increasingly working together to define a pragmatic way to develop and deploy these methods, e.g. through the definition of codes of conduct, and open letters calling for responsible OCDR research and development.

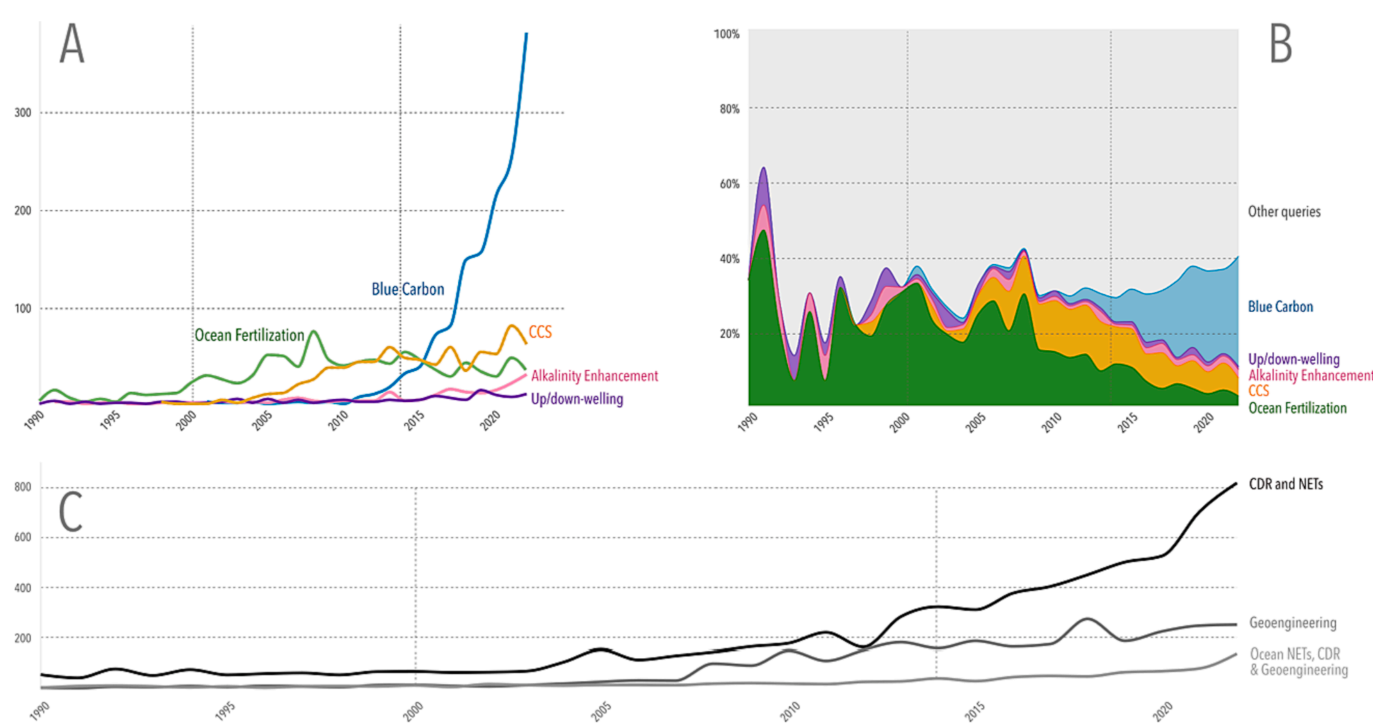

Fig. 4. Number of records related to key methods (ocean fertilisation, blue carbon, CCS, alkalinity enhancement, up/down-welling), per year (A panel) and in absolute (B panel), and to umbrella terms (CDR/NETs, geoengineering) (C panel). Because the scientific literature is scant before 1990, we start from 1990.

4.2. The definition of the climate problem is inseparable from the debate about solutions

A key tenet in social studies of science is that science and governance are co-produced. This means that scientific knowledge about climate change has shaped how solutions to the climate crisis have been imagined over time (Miller, 2007; Edwards, 2010). In our case, this means that thinking about ocean carbon sequestration as a form of climate change mitigation has closely co-evolved with modern comprehension of the Earth climate system, and in particular of the global carbon cycle - where carbon dioxide naturally flows between land, ocean and atmosphere and can remain stored in natural sinks over long periods of time.

As the excessive release of CO2 into the atmosphere creates an imbalance, scientists wondered early on whether such a problem could be solved by accelerating the global carbon cycle and enhancing sinks' storage capacity. Marchetti (1977, p. 61) for instance noted in his seminal paper on geoengineering: "The problem appears, at least for the next 100 or 200 years, to be essentially a problem of global kinetics: so kinetics is the place where the cure has to be applied. The obvious line of attack would be to avoid the whole chain of dilutions and interfaces and to put CO2 directly into the deep ocean". Scientific understanding of the role of the carbon cycle thus underpinned political imaginaries to tackle climate change through a globalized "CO2 management system" (Marchetti, 1977). The possibility of 'tricking', or at least taking advantage of the global carbon cycle has become a commonly held view in the field. Similar imaginaries have been used to characterize many OCDR techniques. A panellist presented OIF as a way to "put the biological pump on steroids" (fieldnotes, 2021). The carbon removal company Running Tide, specialized in marine biomass sinking and OAE, claims on its website to help "rebalanc[ing] the carbon cycle", by moving "carbon from the fast to the slow carbon cycle to restore ocean health". Blue carbon advocates also emphasise the contribution of marine vegetation to the global carbon cycle, e.g. to highlight the need to fight mangrove deforestation (Donato et al., 2011).

The fact that human beings are already changing the climate system by releasing CO2 into the atmosphere, hence disrupting the global carbon cycle, is often used to normalise carbon sequestration. An often-cited reference in the field is Revelle and Suess, 1957) statement that "human beings are now carrying out a large-scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future". Following such a statement, it can become logical to want to engineer the climate back to a preindustrial state. As an interviewee (#6) noted, "geoengineering […] had a bad name, in spite of the fact that we have been actively geoengineering the planet for probably the last 100 years or so".

4.3. The climatisation and carbonification of the ocean

Aykut and Maertens, 2021) define 'climatisation' as the "process through which an issue, actor or institution is framed as related to anthropogenic climate change and relevant to climate politics". For the authors, global climate governance is no longer restricted to the UNFCCC and extends to other areas, as climate change is increasingly becoming "the frame of reference through which other policy issues and forms of global activism are mediated and hierarchized" (Aykut and Maertens, 2021). Climatisation of the ocean mainly occurred outside the UNFCCC and has only recently become a central theme in the COPs.

What our analysis showed is that the ocean was 'climatised' early on. More precisely, it has been 'carbonified' (Stephan, 2012) in the sense that it was understood through the large amount of CO2 that it stores. In fact, carbon, and in particular CO2 have indeed always been a key theme in ocean sciences, because of the role of the ocean in the global carbon cycle (Sabine et al., 2010). Of particular interest was the fate of the atmospheric CO2 absorbed by the ocean (cf. 3.1.1). Carbonification was thus a first form of climatization of the ocean, reducing the ocean ecosystem to carbon stocks and sequestration potential in million/billion tons of CO2. By focusing on its carbon characteristics, such discourse supported narratives about 'silver bullet' proposals to manipulate the ocean to mitigate climate change (i.e., using OIF). It also underpinned a process of commodification, as some actors sought to gain carbon credits from ocean carbon sequestration projects.

In the 2000s, concerns over potential environmental consequences of carbon sequestration in the deep ocean led the IOC to host, together with SCOR, a scientific meeting on ocean carbon sequestration science. The 2004 symposium brought about a second form of climatisation, as it contributed to raising awareness about the issue of ocean acidification - a consequence of the passive uptake of CO2 by the ocean. In the following years, research on ocean acidification significantly increased and has become "one of the fastest growing fields of research in marine sciences" (Riebesell and Gattuso, 2015). Attention to ocean acidification underpinned narratives about the ocean being a 'victim' of climate change and brought forward the need to protect the ocean, as well as communities living off the ocean. Such narratives feed into OCDR proposals that emphasise 'nature-based solutions', with a focus on protecting, sustainably managing, restoring, and expanding (blue carbon) ecosystems. In these narratives, the ocean is not only presented as a carbon sink, but also as a key provider of economic and non-economic (co)benefits to coastal communities.

In the last decade, ocean advocates have supported a more balanced storyline, highlighting both the risks and opportunities that climate change represents for the ocean. With interventionist approaches to the ocean coming under scrutiny, ocean carbon sequestration is increasingly framed as mimicking (sometimes only rhetorically) natural processes and bringing wider co-benefits to society. This reframing has allowed OCDR to gain renewed attention as climate mitigation strategies, and, possibly, social acceptance.

4.4. (Re)framing and (re)labelling ocean carbon sequestration

Narrative change is an important driver to understand the renewed interest in OCDR, in a context in which shaping the sustainability transition is becoming more important than raising alert (Hajer and Pelzer, 2018). In this section, we emphasise key reframing and relabelling strategies that have put ocean carbon sequestration in a new light.

Overall, the OCDR benefitted from a general reframing trend that sought to replace the negatively-connotated term 'geoengineering' with the more neutral concepts 'CDR' or 'NET' (Gupta and Möller, 2019). As an interviewee argued (#12) "a lot of people wouldn't touch CDR, because it was called climate engineering, or geoengineering. […] The field [then] sort of split. And now […] the SRM work is separate from the CDR work". Panel C in Fig. 4 shows the rising popularity of the CDR/NET framing in research, at the expense of the term 'geoengineering'. Such trend is also observed in recent assessments by GESAMP, NASEM and IPCC which use the OCDR/NET framing (Boettcher et al., 2021).

OCDR techniques have also been specifically promoted as 'nature-based solutions', bringing multiple co-benefits to society and posing fewer risks than inaction in the face of dangerous climate change. We can observe a change from framing research as being about 'engineering' ocean-based climate interventions to focusing on the need to develop 'nature-based solutions' that have multiple environmental and economic co-benefits. This reframing can be seen as an attempt to bring together marine conservation and climate change communities, and to counter opposition to research on OCDR (Low et al., 2022). Blue carbon enhancement for instance, which is posited to offer environmental, social and economic co-benefits for local communities, has become privileged over more 'engineered' interventions into the ocean. The UNEP (Nellemann et al., 2009, p. 65) report presented it as "one of the strongest win–win mitigation efforts known today". Framings that posit OCDR technologies as "mimick[ing] Mother Nature" (interviewee #4) and highlight co-benefits have thus become more frequent. For instance, OIF is increasingly being presented as a nature-based solution using terms such as 'ocean pasture', 'marine biomass regeneration', 'artificial whale poo' (ETC Group, 2023) or 'ocean restoration' (Tollefson, 2017). The co-benefits for fisheries enhancement are also highlighted (NASEM, 2021). A similar framing and labelling exercise has been observed with OAE. In an interview, the CEO of Project Vesta Corporations presented OAE as 'nature-based' because it is "accelerating a geological process", and as bringing "an extremely important co-benefit" (Bencsik, 2023) – OAE advocates in fact put forward that it has the potential to counter ocean acidification (Hartmann et al., 2013; Bach et al., 2019).

Finally, there is increased talk of 'risk–risk' balancing, between the risks of damage from climate change and the risks of damage from OCDR (Möller, 2020). Arguments about the potential risks to marine ecosystems are frequently countered with reference to the risks of unmitigated climate change to the ocean environment (ongoing ocean acidification, coral reef bleaching, etc.). The NASEM report (2021, p. 2) noted that "it is critical that ocean CDR approaches be assessed against the consequences of no action […]". This argument was also present in many interviews. As an interviewee (#4) noted: "I just don't think with the forest fires that we're seeing, with the people dying in heat waves, sea level rise, ice melt, that we can just say: 'hands off the ocean'". Another also (#5) stated: "When I think of ocean CDR, you could do nothing. But the ocean has already been impacted, the ocean temperature, ocean acidity, sea level rise, changes to ecosystems, deoxygenation, this idea that we are screwing up the oxygen cycle. So, doing nothing is a choice that's having really bad consequences". This reframing puts the responsibility back onto opponents to show that undertaking OCDR activities would be more harmful than doing nothing in the face of climate change.

5. Conclusion

In this article, we investigated how and why ocean carbon sequestration approaches have been recently put back on the agenda as credible and legitimate mitigation strategies, despite major disagreements regarding their efficacy and safety (cf. Boyd and Vivian, 2019). Using quali-quantitative methodology, we contributed to recent debates aimed at historicising climate 'solutions' and studying how they become normalised and institutionalised, or how they are opposed or sidelined. Our analysis showed that the debate about ocean carbon sequestration approaches as climate solutions is as old as climate change science, thus showing clear intertwinement in scientific knowledge production between the definition of the problem and that of the measures to tackle it. It also showed that the fate of a solution or technology has as much to do with social and political factors as with technical and scientific factors. OCDR approaches are increasingly being framed as viable solutions, although it remains unclear for many scientists whether they actually work, as major knowledge gaps remain.

We identified three main phases (1960—2000; 2000—2014; and 2014 -) in the history of ocean carbon sequestration, characterised by periods of hype, as research advanced and key climate outcomes (Kyoto in 1997; Paris in 2015) were negotiated, and of controversy and disappointment, as doubts were raised about the effectiveness of these approaches and the motives of those advocating for them. Our analysis also shows that the recent hype (2014 -) was not triggered by a technological breakthrough or a reduction of the scientific uncertainties about the risks and potentials of these methods, but by new socio-technical configurations, coalitions and narratives. On the one hand, a heightened sense of urgency around the climate crisis is being used as a justification not to disregard any solution. On the other hand, removal approaches are being normalised by authoritative institutions (the IPCC and the UNFCCC) and supported by a heterogenous group of actors. Finally, a narrative change, linking ocean carbon sequestration proposals (in particular OAE and blue carbon enhancement) to nature-based solutions and emphasising co-benefits, contributed to putting it in a new light.

These elements have offered a new, and potentially lasting window of opportunity for advocates of ocean carbon sequestration. Whether we will see a repeat of the previously observed cycles of hype, controversy and disappointment depends not only on the scientific feasibility of novel OCDR proposals, but on the stability of these new OCDR coalitions and narratives.

CRediT authorship contribution statement

Kari De Pryck: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Miranda Boettcher:** Writing – review & editing, Writing – original draft, Validation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The documents are available online; interviews are for the purpose of the OCEANNET project; the query for the scientometrics analysis is available as supplementary material

Acknowledgement

We thank all interviewees for their time, as well as the OCEANNETS and ASMASYS partners. We are grateful to Tommaso Venturini for helping with the scientometrics, to Lina Roeschel and Shinichiro Asayama for their comments on earlier drafts and to the two anonymous reviewers for their constructive comments. KDP acknowledges financial support from OCEANNETS, funded by the European Union's Horizon 2020 Research and Innovation Programme, grant number: 869357. MB acknowledges financial support from the ASMASYS project, funded by the German Federal Ministry of Education and Research (BMBF), grant number: 03F0898E

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2024.102820.

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Further reading

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