

# Integrated Ocean Carbon Research

A vision  
primed for  
implementation



**unesco**

Intergovernmental  
Oceanographic  
Commission

Published in 2026 by the United Nations Educational,  
Scientific and Cultural Organization,  
7, place de Fontenoy, 75352 Paris 07 SP, France



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This document should be cited as follows: IOC of UNESCO.  
2026. *Integrated Ocean Carbon Research: a vision primed for  
implementation*. Paris, UNESCO. (IOC Technical Series, 214.)  
<https://doi.org/10.71245/FULK2623>

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Cover photo: Kogia - Karim Iliya

Design: UNESCO

Design and typesetting: UNESCO

Printed by UNESCO

Printed in France

(IOC/2026/TS/214)

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# Acknowledgments

The Intergovernmental Oceanographic Commission of UNESCO, the IOC-R co-chairs and authors would like to acknowledge the following support to the report:

Section 3.d was supported by the European Union under grant agreement no. 101083922 (OceanICU) and UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee [grant number 10054454, 10063673, 10064020, 10059241, 10079684, 10059012, 10048179]. This work also received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101136480 (SEA-Quester). The views, opinions, and practices used to produce this work are, however, those of the author(s) only and do not necessarily reflect those of the European Union or European Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. The work was also supported by UK Grant NE/Z503770/1 ("Impacts of bottom trawling on seabed carbon storage"), by the U.S. National Science Foundation (NSF) Directorate for Geosciences Division of Ocean Sciences Chemical Oceanography Program (NSF OCE 2446501) and Division of Earth Sciences Climate Impact on Human Health, Geobiology & Low-Temp Geochemistry, and Geomorphology & Land-use Dynamics Programs (NSF EAR 2219334).

The authors thank Ulf Riebesell for his valuable contributions to an earlier draft of section 3.e.

Maciej Telszewski acknowledges funding from the United States National Science Foundation (grant no. OCE-2513154) to the Scientific Committee on Oceanic Research (SCOR, United States) for the International Ocean Carbon Coordination Project (IOCCP).

Jamie Shutler acknowledges funding support from the European Space Agency (grant no. 3-18399/24/I-NB).

Linbin Zhou acknowledges support from the National Key R&D Program of China (2024YFF0507000) and the Ocean Negative Carbon Emission (ONCE) Program.

Judith Hauck acknowledges funding from the ERC-2022-STG OceanPeak (Grant 101077209).

The authors acknowledge the project ESM2025 (<https://www.esm2025.eu>) for the contribution to figure 6.

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# List of Acronyms

<b>BBNJ</b>	Marine Biological Diversity of Areas beyond National Jurisdiction
<b>BCI</b>	Blue Carbon Initiative
<b>BCG Argo</b>	Biogeochemical Argo
<b>C<sub>anth</sub></b>	Excess carbon in the atmosphere and ocean due to human activity
<b>CARE</b>	Principles for Indigenous Data Governance (Collective Benefit, Authority to Control, Responsibility Ethics)
<b>CBD</b>	Convention on Biological Diversity
<b>CDR</b>	Carbon dioxide removal
<b>CEOS</b>	Committee on Earth Observation Satellites
<b>CFCs</b>	Chlorofluorocarbons
<b>CLIVAR</b>	Climate and Ocean - Variability, Predictability, and Change Research Programme
<b>CMIP7</b>	7th Coupled Model Intercomparison Project
<b>CO<sub>2</sub></b>	Carbon Dioxide
<b>COBS</b>	Changing Ocean Biological Systems
<b>COP</b>	Conference of the Parties
<b>DIC</b>	Dissolved Inorganic Carbon
<b>DOC</b>	Dissolved Organic Carbon
<b>DOM</b>	Dissolved Organic Matter
<b>EOV</b>	Essential Ocean Variable
<b>ESMs</b>	Earth System Models
<b>FAIR</b>	Findable, Accessible, Interoperable and Reusable
<b>FDOM</b>	Fluorescent Dissolved Organic Matter
<b>G3W</b>	Global Greenhouse Gas Watch Programme
<b>GBF</b>	Kunming-Montreal Global Biodiversity Framework
<b>GCOS</b>	Global Climate Observation System
<b>GCP</b>	Global Carbon Project
<b>GESAMP</b>	Group of Experts on the Scientific Aspects of Marine Environmental Protection
<b>GLODAP</b>	Global Ocean Data Analysis Project
<b>GOA-ON</b>	Global Ocean Acidification Observing Network
<b>GOBMs</b>	Global Ocean Biogeochemical Models
<b>GOOS</b>	Global Ocean Observing System
<b>GO-BC</b>	Global Ocean Decade Programme for Blue Carbon
<b>GO-SHIP</b>	Global Ocean Ship-Based Hydrographic Investigations Program

<b>IAEA OA-ICC</b>	IAEA's Ocean Acidification International Coordination Centre
<b>ICES</b>	International Council for the Exploration of the Sea
<b>ICOS</b>	Integrated Carbon Observation System
<b>IMBeR</b>	Integrated Marine Biosphere Research
<b>IOC</b>	Intergovernmental Oceanographic Commission of UNESCO
<b>IOCCP</b>	International Ocean Carbon Coordination Project
<b>IOC-R</b>	Integrated Ocean Carbon Research
<b>IPBC</b>	International Partnership for Blue Carbon
<b>IPCC</b>	Intergovernmental Panel on Climate Change
<b>ITLOS</b>	International Tribunal for the Law of the Sea
<b>LOAC</b>	Land-Ocean-Aquatic Continuum
<b>mCDR</b>	Marine Carbon Dioxide Removal
<b>MRV</b>	Regulatory framework of Monitoring, Reporting and Verification
<b>NEP</b>	Net Ecosystem Productivity
<b>OAE</b>	Ocean Alkalinity Enhancement
<b>OARS</b>	Ocean Acidification Research for Sustainability Ocean Decade programme
<b>OCB</b>	Ocean Carbon & Biogeochemistry Program
<b>pCO<sub>2</sub></b>	Partial Pressure of Carbon Dioxide
<b>PIC</b>	Particulate Inorganic Carbon
<b>POC</b>	Particulate Organic Carbon
<b>POGO</b>	Partnership for Observation of the Global Ocean
<b>RECCAP</b>	Regional Carbon Cycle Assessment and Processes
<b>SDG</b>	Sustainable Development Goals
<b>SCOR</b>	Scientific Committee on Oceanic Research
<b>SOCAT</b>	Surface Ocean CO <sub>2</sub> Atlas
<b>SOCOM</b>	Surface Ocean pCO <sub>2</sub> Mapping Intercomparison
<b>SOCONET</b>	Surface Ocean CO <sub>2</sub> Observing Network
<b>SOLAS</b>	Surface Ocean - Lower Atmosphere Study
<b>SRM</b>	Solar Radiation Management
<b>SSPs</b>	Shared Socioeconomic Pathways
<b>TA</b>	Total Alkalinity
<b>UNFCCC</b>	United Nations Framework Convention on Climate Change
<b>WCRP</b>	World Climate Research Programme
<b>WMO</b>	World Meteorological Organization

# Executive Summary

The mission of the 'Integrated Ocean Carbon Research' (IOC-R) programme is to enhance our understanding of the ocean as a changing sink for human-produced CO<sub>2</sub> and its climate change mitigation capacity, as well as the vulnerability of ocean ecosystems to increasing CO<sub>2</sub> levels. The IOC-R programme aims to provide an actionable foundation for addressing the challenges of ocean carbon research. In doing so, it is contributing to the objectives of the United Nations (UN) Decade of Ocean Science for Sustainable Development by integrating the latest scientific findings and observational data for ocean carbon.

Supported by interdisciplinary research, the understanding of the ocean carbon cycle has advanced significantly since the last release of a report from the IOC-R community (IOC of UNESCO, 2021; Sabine et al., 2024). However, major knowledge and observational gaps remain, leading to considerable uncertainties in model projections. These hamper the development of climate change adaptation and mitigation strategies, including those involving ocean based solutions.

The IOC-R programme itself is co-sponsored by five international research and coordination programmes which have a strong involvement and focus on ocean carbon (Global Carbon Project<sup>1</sup>, SOLAS<sup>2</sup>, IMBeR<sup>3</sup>, CLIVAR<sup>4</sup> and IOCCP<sup>5</sup>) and the Intergovernmental Oceanographic Commission of UNESCO (IOC)<sup>6</sup>.

This IOC-R report is a global community effort with 72 authors and 13 reviewers from 23 countries. The report aims to guide the scientific focus of these programmes, as well as GOOS<sup>7</sup>, and to highlight new global cross-cutting priorities of ocean carbon research that help national and international ocean science funding entities determine future areas of investment. It will accomplish this by identifying knowledge gaps and coordinated research approaches to increase understanding about the ocean carbon cycle in a changing world.

1 See Global Carbon Project <https://www.globalcarbonproject.org>

2 See SOLAS <https://www.solas-int.org/>

3 See IMBeR <https://imber.info/>

4 See CLIVAR <https://www.clivar.org/>

5 See IOCCP <https://www.ioccp.org/>

6 See IOC <https://www.ioc.unesco.org/>

7 See GOOS <https://goosocean.org/>

The IOC-R community has defined five focus areas for ocean carbon research (**Figure ES1**), which will be further developed and explained in the report (**Section 3**):

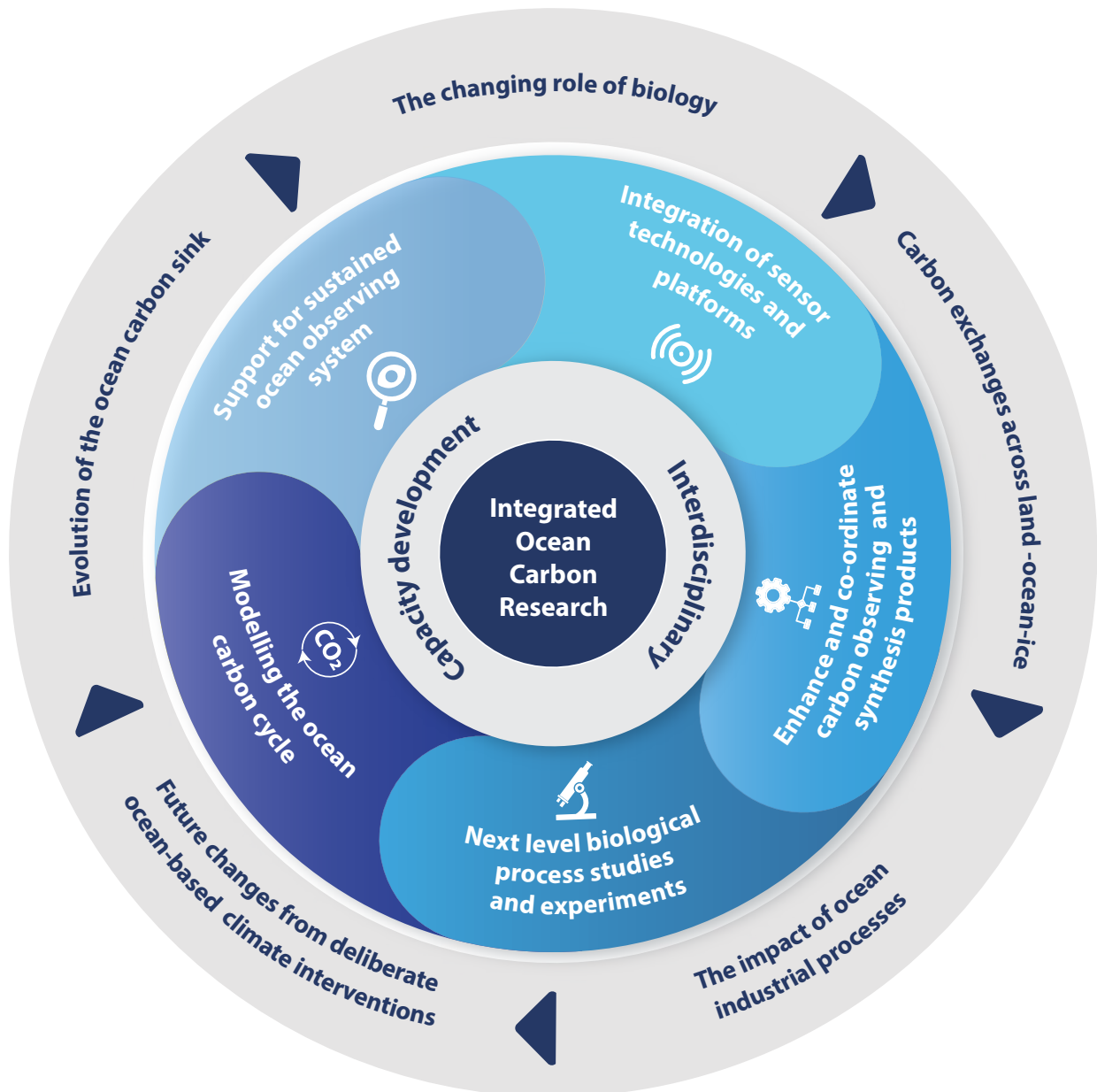
1. **Evolution of the ocean carbon sink under a changing climate,**
2. **The changing role of biology in the ocean carbon cycle,**
3. **Carbon exchanges across the land-ocean-ice continuum,**
4. **The impact of ocean industrial processes on the ocean biological carbon cycle,**
5. **Future changes in the carbon cycle from deliberate ocean-based climate interventions.**

In order to close the knowledge gaps identified within each focus area, a series of internationally co-ordinated approaches are required. These prioritised approaches (**Section 4**) are :

- Support for sustained ocean carbon observing systems,
- Integration of sensor technologies and platforms,
- Enhancement and co-ordination of carbon observing and synthesis products,
- Next level biological process studies and experiments, and
- Improved ocean carbon cycle models.

Developing these approaches should sit within a framework (Section 5) of transdisciplinarity involving non-academic participants such as policy makers, managers, science communicators and indigenous knowledge holders and a strong commitment to human and technological capacity development including improving access and participation from under-represented groups.

## Framework and approach



**Figure ES1.** Overview of the five identified focus areas for integrated ocean carbon research, prioritised approaches and a framework of interdisciplinarity and capacity development.

The report synthesises these approaches and aspects of the framework into overarching actions to support the development and continuous enhancement of robust and fundamental scientific work for humankind to understand and predict accelerating climate change and

the possibility of unexpected environmental responses (Section 6 and Figure ES2). Also identified are a series of specific actions presented as key recommendations and priorities for globally integrated carbon research within each focus area.



**Figure ES2.** Overview of overarching and specific actions to be taken forward in the field of ocean carbon research. Overarching actions (inner ring) are identified to support the development and continuous enhancement of robust and fundamental scientific work for humankind to understand and predict accelerating climate change and the possibility of unexpected environmental responses. Specific actions (middle ring) are identified to address specific research gaps detailed under the five focus areas (outer ring) for integrated ocean carbon research.

**Overarching actions:**

1. Sustain and further expand an integrated ocean observing system covering the surface to deep ocean and the land to ocean interface, involving *in situ* and remotely sensed multi-variable observations (physical, chemical and biological parameters), including further development of sensors and autonomous platforms.
2. Enhance ocean model process representations, addressing biases in the simulation of circulation and mixing, and forge improved collaborations between modellers and field-going and laboratory-based scientists to help resolve biogeochemical exchanges of matter through the ocean-atmosphere, ocean-land and ocean-ice interfaces.
3. Strengthen cooperation in human and technological capacity development activities, including improving access and participation from under-represented groups and cross-disciplinary knowledge exchange.
4. Foster the establishment of a transdisciplinary framework in ocean carbon research involving non-academic participants such as policy makers, managers, research communicators and indigenous knowledge holders, creating time and space to understand the contributions of the social sciences, the humanities and creative arts to the field of ocean carbon research.
5. Develop and further improve multinational cooperation and collaboration including the application of community based best practices including data quality control, access to reference materials and intercalibration of measurements and data archiving in accordance with FAIR<sup>8</sup> and CARE<sup>9</sup> principles.

**Specific actions related to the five focus areas:****Evolution of the ocean carbon sink during changing climate and emissions**

- Operationalize ocean carbon observations and related data products to be able to project and predict changes in the pools and fluxes of the ocean carbon cycle.
- Improve air-sea CO<sub>2</sub> flux parameterizations to reduce uncertainties in ocean CO<sub>2</sub> uptake estimates, refine the seawater carbonate equilibrium constants to increase the internal consistency of the marine carbonate system, and monitor changes in physical processes and how they affect ocean CO<sub>2</sub> uptake (e.g. changes in turbulence, warming and freshening).
- Provide access to ocean carbon certified reference materials via a network of international laboratories that produce and deliver climate relevant calibration materials in both seawater and gas mixtures

**The changing role of biology in the ocean carbon cycle**

- Couple observations of parameters and metabolic rates contributing to the biological carbon pump with a mechanistic understanding of the factors driving their variability and change over time.
- Undertake adaptation studies to assess and connect cellular, physiological, and behavioural mechanisms, incorporating microevolution and epigenetics, to yield a more comprehensive understanding of how organisms are responding and evolving in a changing environment.
- Develop multiple-driver mesocosm/macrocsm manipulation studies to advance the understanding of climate change effects on interactions between biogeochemistry, ecology and physiology.

<sup>8</sup> FAIR: data are findable, accessible, interoperable and reusable

<sup>9</sup> CARE: collective benefit, authority to control, responsibility, ethics in the context of the United Nations Declaration on the Rights of Indigenous Peoples and Indigenous data sovereignty

### Carbon exchanges across the land-ocean-ice continuum

- Improve linkages to community and indigenous knowledge holders, and between ocean and inland water research communities to further advance understanding about the polar, coastal and open ocean carbon cycle.
- Assemble data products at adequate spatial and temporal resolutions that reflect the high heterogeneity of coastal and polar carbon cycling, in order to use flexible scenarios including variable and evolving climate forcings and anthropogenic disturbances for future predictions.
- Launch a «land-induced global ocean CO<sub>2</sub> outgassing Model Intercomparison Project» to promote ensemble-mean assessments of the anthropogenic perturbation in the land-ocean carbon cycle.

### The impact of ocean industrial processes on the biological ocean carbon cycle

- Generate information on the key processes within the biological pump (such as grazing, remineralization, particle sinking and plankton mortality) that are likely to be impacted by industrial extraction and addition and degradation of plastics, and improve knowledge on the resilience of carbon sequestration to reorganisations of food webs by fisheries.
- Undertake coherent and targeted research programmes to quantify the consequences and impacts of fishing, trawling, mining, dredging, drilling, CO<sub>2</sub> injection and burial, and plastic pollution on processes affecting carbon export, transformation, remineralization and storage.
- Develop regionally focussed shared socio-economic pathways (SSPs) which explore how marine ecosystems may evolve under varying climate, socio-economic and industrial process conditions to drive numerical models, informed by representative stakeholder consultations encompassing both the groups that regulate human activities in the ocean and those that seek to undertake these actions for profit.

### Future changes in the carbon cycle from deliberate ocean-based climate interventions

- Improve models to be able to undertake relevant simulation experiments of the impacts of mCDR approaches.
- Undertake a systematic policy relevant review of the effectiveness and feasibility of mCDR methods (including biologically based approaches such as coastal blue carbon and chemically based approaches such as ocean alkalinity enhancement), which also includes the environmental effects on biodiversity, ecosystem functioning and ecosystem services.
- Undertake quantitative research on the ocean carbon cycle and related ecological processes in order to establish a wider consensus on whether mCDR can contribute to a credible, scalable, and politically-acceptable climate mitigation strategy.

While these integrated ocean carbon research actions will be critical to achieve global goals in mitigating and adapting to climate change and the sustainable use of marine resources, reducing atmospheric CO<sub>2</sub> concentrations is the only real long-term and viable action that will save the ocean and our climate for future generations to enjoy.

# 1. Introduction

*Christopher Sabine and Carol Robinson*

## IOC-R Update - Advancing Ocean Carbon Research Since 2021

This report updates the work of the Integrated Ocean Carbon Research (IOC-R) programme, building upon the foundational work established in our 2021 publication, «Integrated Ocean Carbon Research, and Vision of Coordinated Ocean Carbon Research and Observations» (IOC of UNESCO, 2021a). As an expert working group of the Intergovernmental Oceanographic Commission of UNESCO (IOC), IOC-R continues to contribute to the science elements of the United Nations (UN) Decade of Ocean Science for Sustainable Development (2021-2030), the Ocean Decade.

**The mission of IOC-R is to enhance our understanding of the ocean as a changing sink for human-produced carbon dioxide (CO<sub>2</sub>) and its climate change mitigation capacity, as well as the vulnerability of ocean ecosystems to increasing CO<sub>2</sub> levels.** By integrating the latest observational data and scientific findings, the report provides a robust and actionable foundation for addressing the challenges of ocean carbon research and contributing to the Ocean Decade's objectives. The IOC-R programme itself is co-sponsored by six international research and coordination programmes (CLIVAR, Global Carbon Project, IMBeR, IOCCP, SOLAS and IOC), which all have a strong involvement and focus on ocean carbon. IOC-R aims to guide the scientific focus of ocean carbon research within these programmes, as well as the Global Ocean Observing System (GOOS) at large, by identifying knowledge gaps and coordinated research approaches to increase understanding about the ocean carbon cycle in a changing world, as well as highlighting new global cross-cutting priorities of ocean carbon research, crucial for national and international ocean science funding mechanisms to determine future areas of investment.

The Ocean Decade is structured around 10 Challenges providing a framework to achieve the vision 'The science we need for the ocean we want'. Launched during the third year of implementation of the Ocean Decade, the Vision 2030 process aimed to establish a quantifiable measure of success by exploring the question 'What does success look like for each Challenge at the end of the Decade?'. This involved consideration not only of the science and knowledge, but also the associated capacity, resources, and infrastructure that would be required to meet the Ocean Decade Challenges. The mission of IOC-R aligns well with that of the Decade's Vision 2030 striving to enhance understanding of the ocean-climate nexus and generating solutions to mitigate and adapt to climate change, particularly through improved predictions and forecasts in order to fulfill the Ocean Decade Challenge 5 "Unlock ocean-based solutions to climate change" (Sabine et al., 2024; Robinson et al., 2025).

Originally the IOC-R addressed critical issues in ocean carbon research through a combined strategy of research and observational goals. The work was guided by four key questions formulated at the inaugural Expert Workshop in 2019 (IOC of UNESCO, 2021a):

1. Will the ocean uptake of anthropogenic CO<sub>2</sub> continue as primarily an abiotic process?
2. What is the role of biology in the ocean carbon cycle, and how is it changing?
3. What are the exchanges of carbon between the land-ocean-ice continuum and how are they evolving over time?
4. How are humans altering the ocean carbon cycle and resulting feedbacks, including possible purposeful carbon dioxide removal (CDR) from the atmosphere?

Since the release of the initial report in 2021, a number of research programmes within the six sponsor organizations and programmes, along with several Decade projects and programmes, have been established. Given these developments and advancement in the field of ocean carbon science since the 2019 meeting, IOC-R decided that a revised vision document, including references to possible implementation strategies, was needed, considering Ocean Decade activities and coordination mechanisms. In an effort to get a broader community input to the new document, an online meeting was held in December 2022. That workshop provided valuable information for an in-person meeting held on 3-5 May 2023 in Brussels, Belgium. Thirty-three experts attended in-person and 26 connected online from countries across the world.

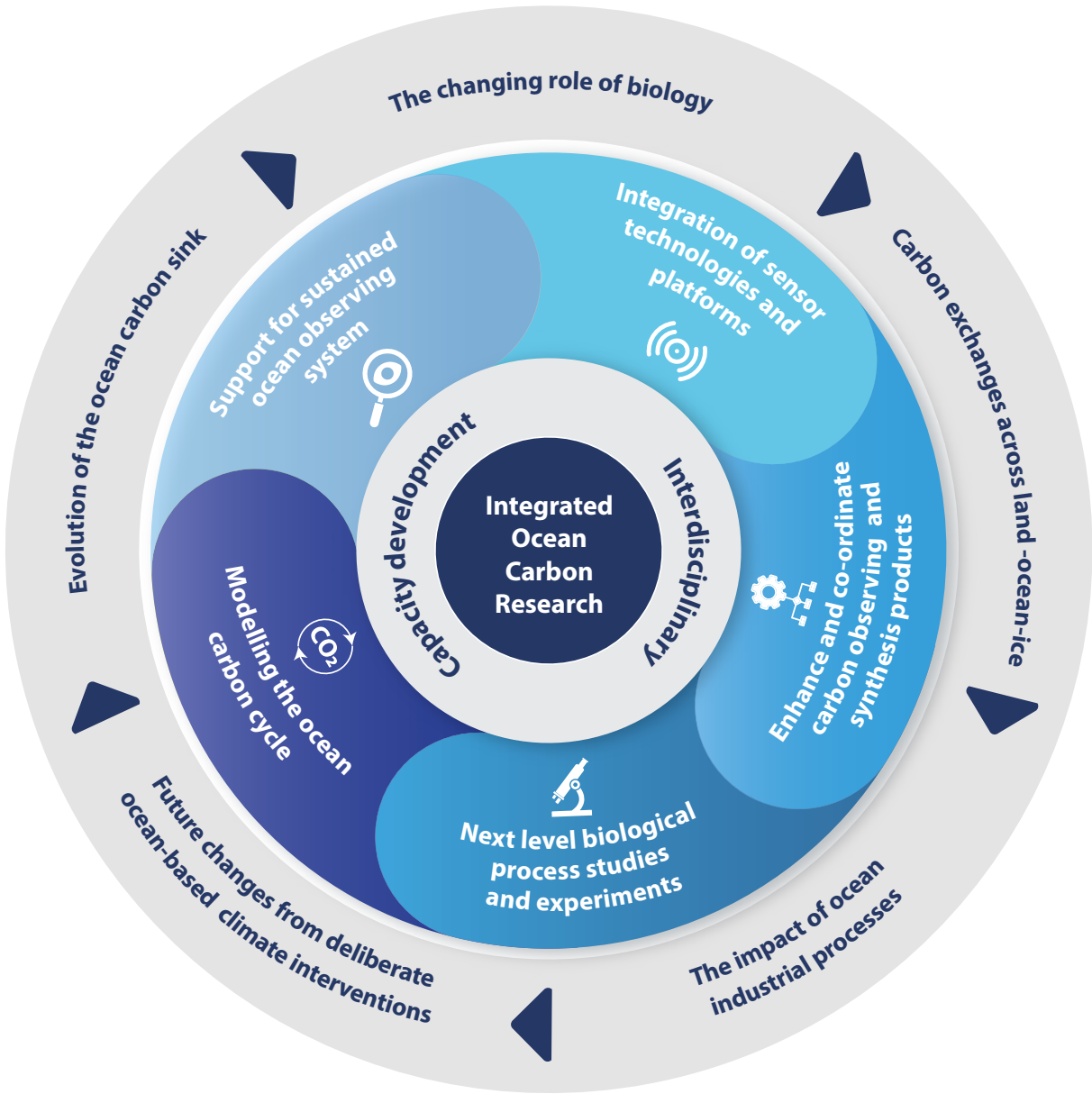
This updated report reflects the outcomes from those meetings, including the division of the fourth question of the previous report into two sections separating the human-driven alterations of the ocean and its processes into industrial processes and deliberate interventions in the marine environment referred to in this document as marine carbon dioxide removal (mCDR). The report therefore addresses these focus areas and knowledge gaps:

- 1. Evolution of the ocean carbon sink during changing climate and emissions.** This section explores the long-term capacity of the ocean to absorb CO<sub>2</sub> through physical and chemical processes, considering factors such as ocean circulation and stratification.
- 2. The changing role of biology in the ocean carbon cycle.** This assesses the influence of marine organisms on carbon uptake and sequestration, including the impacts of climate change on biological processes and ecosystem dynamics.
- 3. Carbon exchanges across the land-ocean-ice continuum.** This examines the carbon fluxes between different earth system components, focusing on the changing dynamics of coastal ecosystems and the impacts of melting ice.
- 4. The impact of ocean industrial processes on the ocean biological carbon cycle.** This section discusses the impacts of direct anthropogenic pressures by industry on the ocean biological carbon cycle across scales, e.g. disturbances of the seafloor and coast, fisheries and mariculture, and plastic pollution.
- 5. Future changes in the carbon cycle from deliberate ocean-based climate interventions.** This addresses the efficacy of mCDR as well as the potential and risks of various mCDR strategies.

Merely identifying the science gaps is not sufficient to advance integrated ocean carbon research. Therefore, current and emerging science approaches supporting knowledge generation are addressed extensively in **Section 4**, pointing to the importance of co-designed and co-implemented interdisciplinary research (**Section 5.a**) and capacity development (**Section 5.b**).

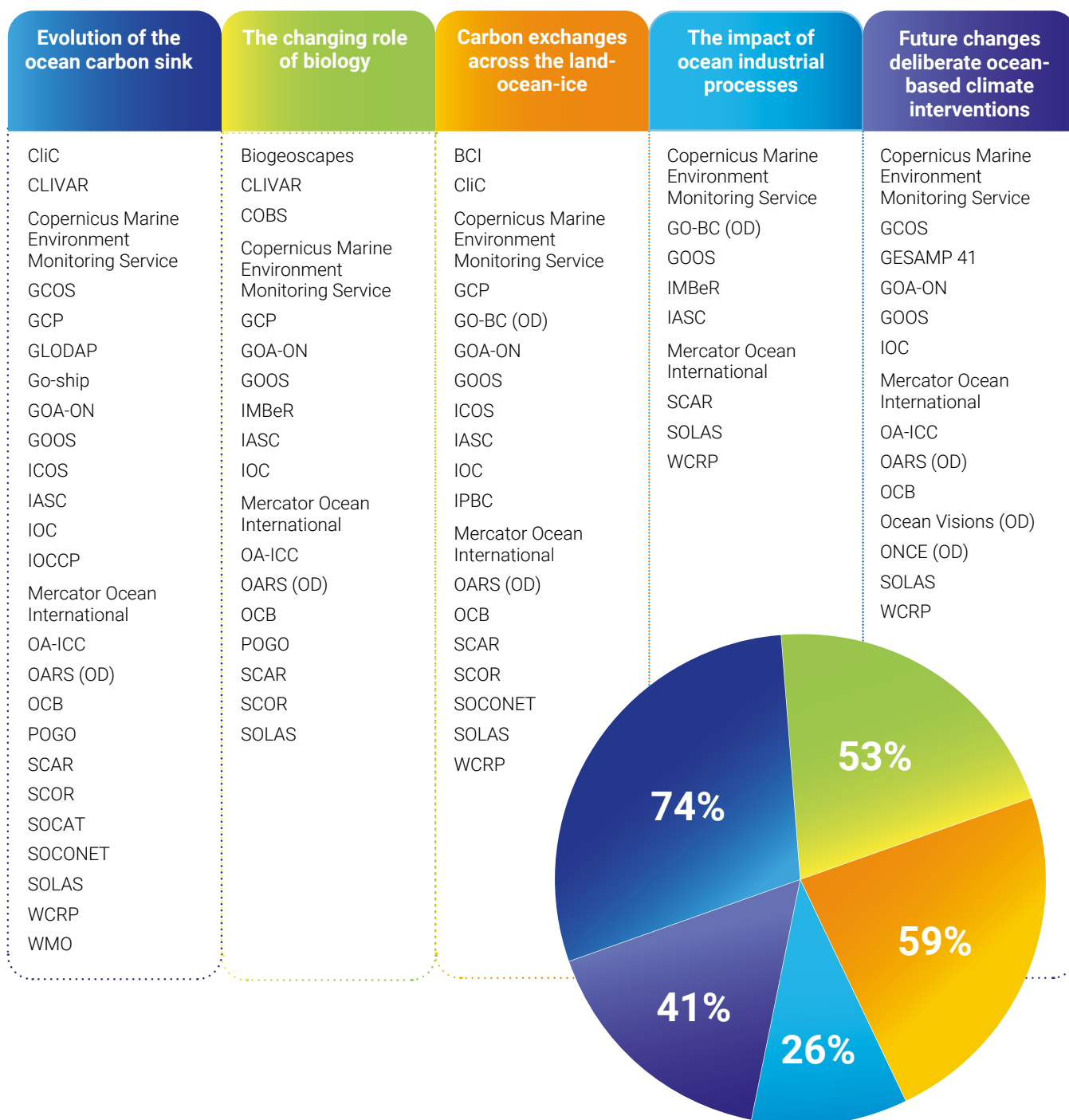
Given that more than 30 global initiatives are tackling parts of integrated ocean carbon research (**Figure 2**), the ambition is that this document will assist in optimizing future science investment and encourage global collaboration.

## Framework and approach



**Figure 1.** Overview of the five identified focus areas for integrated ocean carbon research, prioritised approaches and the central framework of interdisciplinarity and capacity development.

## Organizations, programmes, projects and partnerships focusing on different aspects in the ocean carbon cycle



**Figure 2.** International organizations, programmes and partnerships addressing the five IOC-R focus areas. Ocean Decade initiatives are marked with an OD. The table also shows the percentage of the 33 international organizations, programmes and partnerships addressing in one or more of the IOC-R focus areas. The list of organisations and programmes is not exhaustive.

# 2. The Case for Integrated Ocean Carbon Research

## 2.a The role of ocean carbon in the global carbon cycle

*Carol Robinson, Christopher Sabine, Signe Lemcke, Kirsten Isensee, Richard Sanders*

Our best understanding of the ocean carbon cycle, as shown in **Figure 3**, suggests that in the pre-industrial era (before ca. 1750), the ocean was a small net source of carbon to the atmosphere, which was offset by a net sink of atmospheric carbon in the terrestrial biosphere. The system was balanced by rivers that transported carbon from the terrestrial biosphere back to the ocean (**Figure 3**).

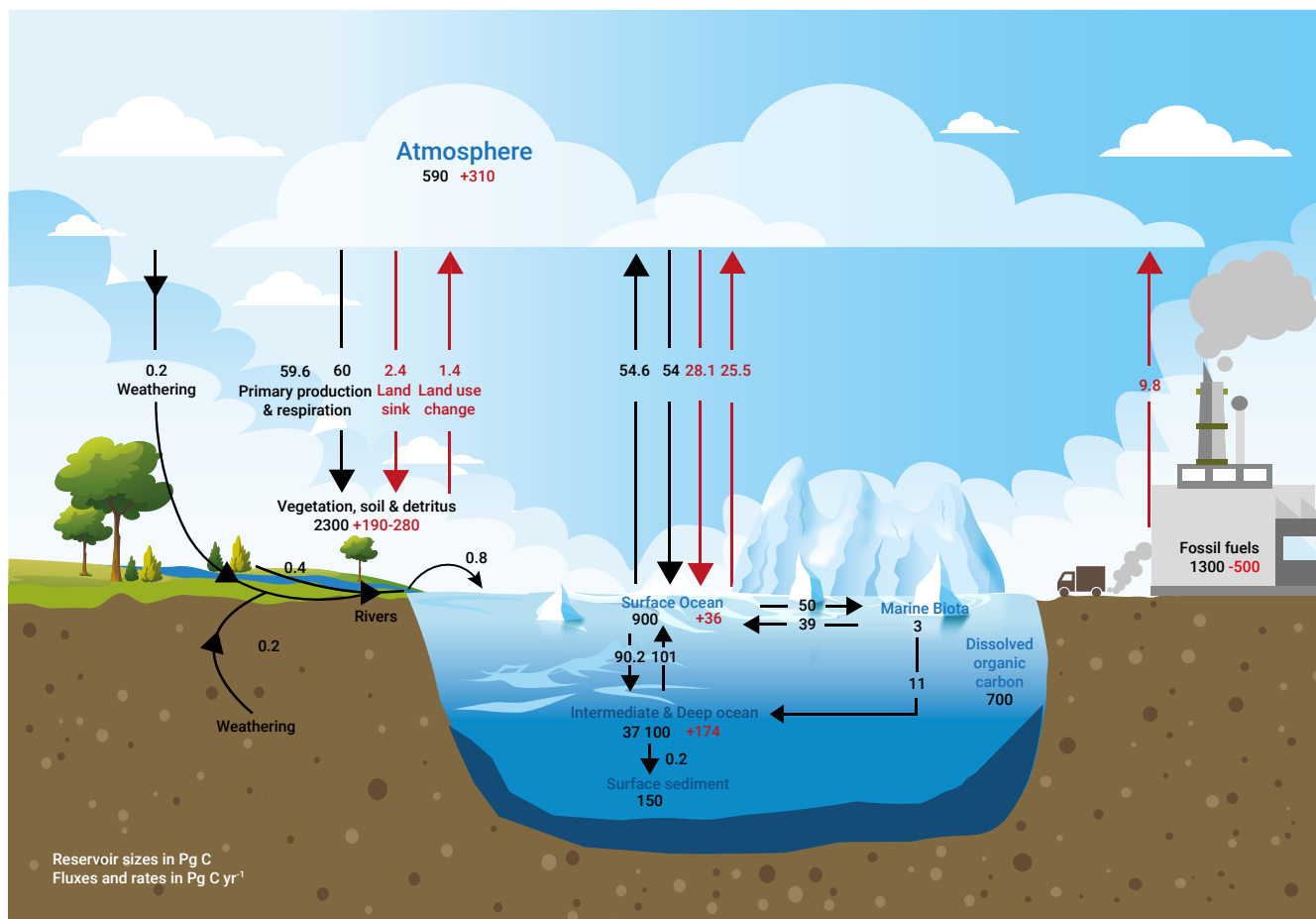
Today the situation has reversed, as CO<sub>2</sub> accumulates in the atmosphere from anthropogenic fossil fuel use, cement manufacture and land-use change, the higher partial pressure of atmospheric CO<sub>2</sub> exceeds the preindustrial ocean outgassing resulting in a net diffusion of CO<sub>2</sub> into the ocean. The ocean thus plays a pivotal role in the global carbon cycle and in regulating the Earth's climate: its immense capacity to remove and store carbon away from the atmosphere has been crucial in mitigating the greenhouse effects at the earth's surface.

The present day ocean carbon cycle involves a complex interplay of physical, chemical, and biological processes (**Figure 3**). Understanding the processes, interactions and feedbacks governing ocean carbon uptake, cycling and storage is essential for predicting future climate scenarios and developing effective mitigation strategies. The solubility pump continues to be the primary driver of ocean carbon absorption (**Section 3.a**), and this increased ocean carbon absorption is resulting in ocean acidification. Biological processes, driven by marine organisms, continue to play a significant role in ocean carbon cycling and storage (**Section 3.b**). Phytoplankton utilizes dissolved CO<sub>2</sub> for photosynthesis, converting it into organic carbon.

This organic carbon can then be transferred through the food web, eventually sinking to the deep ocean where it can be stored for centuries or even millennia.

The exchanges of carbon between the ocean and other earth system components, such as land, rivers and ice, are also critical to ocean carbon cycling and storage. Coastal ecosystems, including mangroves, salt marshes, and seagrass meadows, are particularly efficient at storing carbon, known as «blue carbon». Changing sea-ice distributions and circulation in the polar oceans is impacting carbon drawdown in those regions, including the fate of terrestrial carbon released by melting permafrost (**Section 3.c**).

Human activities through marine industries such as fishing, dredging, port construction and aquaculture are significantly altering the ocean carbon cycle through restructuring ecosystems, resuspending sediments and enhancing production in the coastal zone. Likewise, plastics are now an emergent component of the carbon cycle and may be altering critical earth system functions, including the strength of the biological carbon pump (**Section 3.d**). Furthermore, purposeful mCDR techniques, such as restoration of mangrove, saltmarsh and seagrass ecosystems, ocean fertilization or enhanced weathering, are being explored as potential mitigation strategies, but their long-term impacts on the ocean carbon cycle are still uncertain (**Section 3.e**).



**Figure 3** Inventories of major carbon reservoirs and transport between the reservoirs of the global carbon cycle, estimated for the period of 2015-2024. Black arrows and numbers indicate the natural carbon cycle fluxes and reservoirs, while red arrows and numbers indicate anthropogenic perturbations. The figure is adapted from Sarmiento and Gruber (2002), with the permission of the American Institute of Physics, updated to the period of 2014-2024 using values from Friedlingstein et al. (2025). Uncertainties in values range from 10-50%.

## 2.b Framework for Integrated Ocean Carbon Research

*Kirsten Isensee, Erik van Doorn, Maciej Telszewski, Joanna Post, Jeremy Sterling*

An integrated understanding of the ocean carbon cycle, accounting for the different and changing forms of ocean carbon and including carbon reservoirs, fluxes and transports, is crucial to determine current and future anthropogenic changes in the ocean and ultimately provide the best available scientific information for protecting the ocean and maintaining its services.

A number of multilateral agreements rely on the information provided by the ocean carbon scientific community, including the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC)<sup>10</sup>, the 2030 Agenda for Sustainable Development<sup>11</sup>, the London Protocol,<sup>12</sup> the Kunming-Montreal Global Biodiversity Framework (GBF) of the Convention on Biological Diversity (CBD)<sup>13</sup> and the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement).<sup>14</sup>

10 See [https://unfccc.int/sites/default/files/resource/parisagreement\\_publication.pdf](https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf)

11 See <https://undocs.org/en/A/RES/70/1>

12 See [https://www.wcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/LCLPDocuments/LP.4\(8\).pdf](https://www.wcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/LCLPDocuments/LP.4(8).pdf)

13 See <https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf>

14 See <https://www.un.org/bbnjagreement/en>

As these frameworks traditionally do not take into account different ecosystems but rather legal boundaries of different maritime zones, integrated ocean carbon research that produces co-developed and co-evolved scientific knowledge is essential for informing national, regional and international policy and decision making.

The UNFCCC and the Paris Agreement encourage its Parties to consider, as appropriate, ocean-based action in their national climate goals and in the implementation of these goals, including but not limited to nationally determined contributions, long-term strategies and adaptation communications (Decision 1/CP.27 and Decision 1/CMA.4). COP 28 (28th Conference of the Parties) invited all countries to preserve and restore the ocean and coastal ecosystems and scale up, as appropriate, ocean-based mitigation action<sup>15</sup>. The latest science and advances in integrated ocean carbon research will be indispensable to inform these efforts (**Sections 3.b** and **3.e**).

The Agenda 2030 for Sustainable Development Goal 14 (SDG 14) is to conserve and sustainably use the ocean and marine resources<sup>16</sup>. IOC is the custodian of SDG 14 target 14.3, which focuses on one part of the ocean carbon cycle, ocean acidification, aiming to ‘Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels.’ This target is supported by the associated SDG Indicator 14.3.1 recording ‘Average marine acidity (pH) measured at an agreed set of representative sampling stations’. IOC supports countries and their scientists in developing the ocean carbon and ocean acidification technical capacity to measure indicator 14.3.1 and analyze the respective data, and to use the information obtained to ensure sustainable development in the coastal and open ocean.

The Kunming-Montreal Global Biodiversity Framework (GBF)<sup>17</sup> target 8 provides a further concrete area of engagement for the IOC-R community to ‘Minimize the impact of climate change and ocean acidification on biodiversity and increase its resilience through mitigation, adaptation, and disaster risk reduction actions, including through nature-based solutions and/or ecosystem-based approaches, while minimizing

negative and fostering positive impacts of climate action on biodiversity’, as impacts can only be minimized if a) monitored (**Section 4**) and b) the underlying mechanisms are understood (**Section 3.a** and **3.b**).

The 2013 amendments to the London Protocol<sup>18</sup> addressing marine geoengineering have not yet entered into force but some states have already incorporated these rules in their national legislation. Increasing understanding of mCDR approaches, including the risks and opportunities, will be critical for further climate action (**Section 3.e**).

Meanwhile, the 2023 BBNJ Agreement<sup>19</sup> is one of the first legally binding international agreements to explicitly link climate change, ocean acidification and the carbon cycle to ecosystem integrity and resilience (Art. 7(h)). Moreover, mCDR might be a fitting test case for the rules in the BBNJ Agreement on environmental impact assessment.

The United Nations Decade of Ocean Science for Sustainable Development (2021-2030) took note of these and other relevant frameworks and conventions and identified a suite of ten challenges for ocean science and sustainable development (IOC of UNESCO, 2021b). While ocean carbon research is a prerequisite to most of them, it is indispensable for Challenge 2, aiming to ‘Understand the effects of multiple stressors on ocean ecosystems, and develop solutions to monitor, protect, manage and restore ecosystems and their biodiversity under changing environmental, social and climate conditions’ (White paper for Challenge 2, Muller-Karger et al. 2024) and for Challenge 5 to ‘Enhance understanding of the ocean-climate nexus and generate knowledge and solutions to mitigate, adapt and build resilience to the effects of climate change across all geographies and at all scales, and to improve services including predictions for the ocean, climate and weather’ (White paper for Challenge 5, Sabine et al., 2024). The white paper for challenge 5 states the need for ocean observations, including ocean carbon, and the requirement to further investigate mCDR and its impacts.

15 See [https://unfccc.int/sites/default/files/resource/cma2023\\_L17\\_adv.pdf](https://unfccc.int/sites/default/files/resource/cma2023_L17_adv.pdf)

16 See <https://undocs.org/en/A/RES/70/1>

17 See <https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf>

18 See [https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/LCLPDocuments/LP.4\(8\).pdf](https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/LCLPDocuments/LP.4(8).pdf)

19 See <https://docs.un.org/en/A/RES/78/272>

In response to UNFCCC and to aid its Member States with implementation of the Paris Agreement, the World Meteorological Organization (WMO) has initiated the Global Greenhouse Gas Watch (G3W) Flagship Program (Carmichael et al., 2024). The G3W will provide 'a comprehensive framework of monitoring greenhouse gases', including the provision of flux estimates with a 1° latitude by 1° longitude resolution with a maximum delay of one month. Task Teams for observations, modelling and data flows are planning the comprehensive framework for the first phase of the G3W (2024-2027). The initial focus of G3W was on anthropogenic fluxes but the task teams have included natural fluxes, and monthly net air-sea CO<sub>2</sub> flux estimates as deliverables.

While the global scientific community recognizes the need for integrated and sustained ocean carbon observations and research, hurdles remain, including unequally distributed technical and human capacity in the northern and southern hemisphere, heavy

reliance on short-term funding to provide critical long-term observations, and restricted access to data, information, and areas under national jurisdiction, both for sampling and recovering ocean carbon instrumentation (IOCCP, 2024). Applying and improving uptake and implementation of internationally agreed codes of conduct, including FAIR (Wilkinson et al., 2016) and CARE<sup>20</sup> principles for data management, as well as national long-term commitments to invest in ocean science and observation, will be important stepping stones to improve future ocean science in general, and integrated ocean carbon research in particular. New areas of research, such as mCDR techniques, are also challenged by national and international legislation. Only community agreed best practices and standard operating procedures embedded in the current landscape of ocean carbon research can assist in obtaining the knowledge required to evaluate the feasibility of ocean-based climate change mitigation approaches (**Section 3.e**).

20 See Care principles <https://www.gida-global.org/care>

# 3. Fundamental and Emerging Research Questions

## 3.a Evolution of the ocean carbon sink under a changing climate

*Ute Schuster, Philip W. Boyd, Judith Hauck, Matthew P. Humphreys, Rik Wanninkhof, Galen A. McKinley, Jamie Shutler, Parvatha Suntharalingam*

«Anthropogenic carbon ( $C_{\text{anth}}$ )» is defined as the excess carbon in the atmosphere due to human activity, and hence oceanic «anthropogenic  $\text{CO}_2$  uptake» as the process that is driven by rising atmospheric  $\text{CO}_2$  as well as carbon-climate feedback associated changes in climate and ocean circulation. This would include (a) changes in  $\text{CO}_2$  fluxes between the surface ocean and atmosphere due to changes in atmospheric  $\text{CO}_2$  alone, and (b) changes in ocean carbon uptake and storage due to carbon-climate feedback induced changes in ocean circulation. It's important to note that the anthropogenic perturbation is small relative to the solubility, transport and storage of carbon due to the natural carbon cycle (i.e., that not derived from human activity); quantifying the resulting small anthropogenic signal within the large natural variability requires very high quality carbonate system observations.

Since the industrial revolution, this anthropogenic carbon sink in the ocean has so far been an almost entirely abiotic process, i.e. driven by physical and chemical principles. It is therefore considered here separately from processes associated with the biological carbon pump which are covered in **Section 3b**.

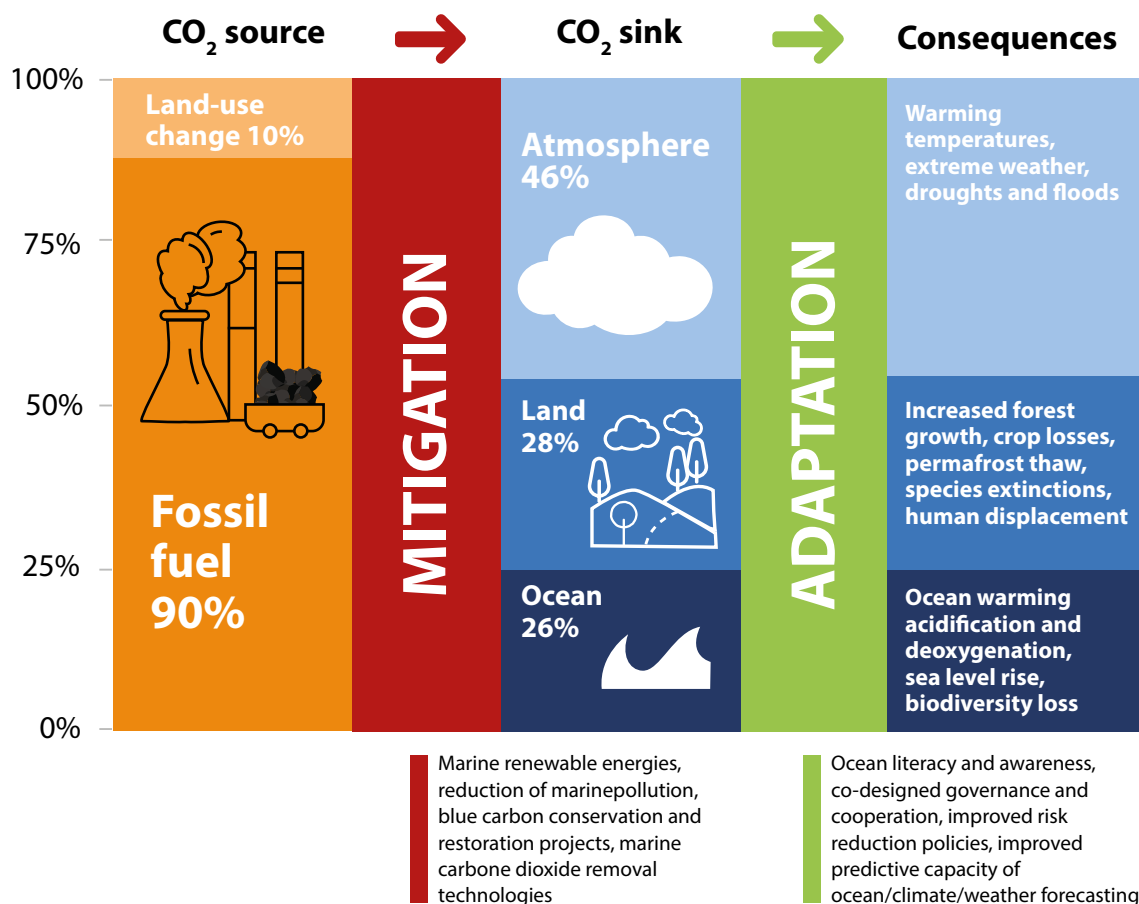
Oceanic  $\text{CO}_2$  uptake has significant impacts on the global carbon cycle, not only by reducing the  $\text{CO}_2$  content in the atmosphere, hence acting as a brake on climate change, but also altering seawater carbonate chemistry. The latter impact includes decreasing seawater pH and carbonate ion availability, a long-term effect known as ocean acidification, impacting marine ecosystems and ultimately reducing the ocean's capacity to further take up carbon due to a reduction in seawater buffer capacity.

Earth System Models (ESMs) project changes in the mechanisms involved in the global ocean carbon sink, through 2100 to be: warming, buffering, wind and circulation changes, including the reemergence of waters already laden with anthropogenic carbon to the surface ocean (a significant effect by 2100 under low emission scenarios) (Ridge and McKinley, 2021; McKinley et al., 2023; Terhaar et al., 2022). Global Ocean Biogeochemical Models (GOBMs) appear to underestimate the mean ocean carbon sink by 10 to 20%, relative to observations, as shown by a number of different approaches. These include comparison with interior ocean  $C_{\text{anth}}$  estimates (e.g. Gruber et al., 2019; Müller et al., 2023), surface ocean  $p\text{CO}_2$  (partial pressure of  $\text{CO}_2$ ) observation-based products (DeVries et al., 2023; Friedlingstein et al., 2025), atmospheric inversions (though they are not completely independent from  $p\text{CO}_2$ -products; Friedlingstein et al., 2025), atmospheric  $\text{O}_2$  to  $\text{N}_2$  ratios (Tohjima et al., 2019), and process-based model evaluation (Friedlingstein et al., 2025; Terhaar et al., 2022; RECCAP2 chapters<sup>21</sup>). Observation-based products, in turn, may overestimate decadal variability and trends of ocean carbon uptake, and recent investigations have focussed on assessing the impact of data scarcity and methodological deficiencies in the mapping methods (Gloege et al., 2021; Hauck et al., 2023b; Dong et al., 2024)).

Whilst confidence in estimates of the oceanic uptake of  $\text{CO}_2$  has significantly increased over recent decades, knowledge gaps remain, especially about the increasing discrepancy between model and surface ocean observation-based ocean sink estimates (Hauck et al., 2020; Friedlingstein et al., 2025).

In view of the discrepancies between observations and model estimates, the question whether - and how - the ocean will continue to act as a significant sink for anthropogenic  $\text{CO}_2$  is of fundamental, and increasing, importance (**Figure 4**).

21 See <https://www.globalcarbonproject.org/reccap/index.htm>



**Figure 4.** Global anthropogenic CO<sub>2</sub> (average 2013–2022) budgets (based on Friedlingstein et al. (2025)), as well as the consequences of CO<sub>2</sub> uptake in the ocean, on land, and in the atmosphere. The listed consequences are only a subset of current and predicted impacts in the ocean, on land, and in the atmosphere (IPCC 2021). The examples given of mitigation and adaptation activities taking place in the ocean and coastal zones are expected to affect the sources, sinks, and consequences in the future. Note that 100% for CO<sub>2</sub> source equals 10.8 pg and for CO<sub>2</sub> sink 11.3 pg, resulting in an imbalance in the global carbon budget. Figure adapted from Robinson et al. 2024.

### Major knowledge gaps

The major knowledge gaps in understanding the physical and chemical processes involved in oceanic CO<sub>2</sub> uptake can be summarised as: **What are the processes that lead to the discrepancies between observation- and model-based oceanic CO<sub>2</sub> uptake estimates and how will they affect future ocean carbon uptake?** Several questions contribute to the discrepancy, including:

#### 1. Temporal variability on interannual and decadal scales:

Do observation-based products overestimate decadal variability or do model-based products underestimate decadal variability, influencing trends in ocean CO<sub>2</sub> uptake? How does sparse and heterogeneous sampling of surface ocean pCO<sub>2</sub>

impact estimated variability and trends (Gloege et al. 2021; Hauck et al., 2023b; Heimdal et al., 2024; Heimdal and McKinley, 2024; Dong et al., 2024)?

#### 2. Significance of riverine inputs:

High uncertainties remain, regarding the magnitude and spatial distribution of riverine carbon outgassing (Hauck et al., 2023) and the “river offset” (correction of CO<sub>2</sub> uptake estimates) and its variability is poorly constrained (Regnier et al., 2022). This is mainly due to a lack of information on global terrestrial carbon and nutrient fluxes in the «land-to-ocean aquatic continuum», and a scarcity of observations (**Section 3.c**). If the “river offset” were at the smaller end of the estimates (e.g. ~0.2 Pg C yr<sup>-1</sup>; Lacroix et al. 2020) and observation-based products had too small an ocean CO<sub>2</sub> sink around 2000 (Heimdal et al., 2024), then it

might appear that the observation-based products and the models are closer in recent years.

### 3. Capturing of vertical temperature gradients (i.e., warm layers and the opposing skin effect) and errors in temperature assignment (e.g., warm bias within *in situ* data):

Accounting for these factors might reduce uncertainties and bias within observation-based and model-based ocean carbon sink assessments (Woolf et al., 2016; 2019; Shutler et al., 2020; Watson et al., 2020; Dong et al., 2022; Belanger et al., 2022; Ford et al., 2024; Park et al., 2024)

### 4. Impacts of different cryosphere processes in high latitude regions:

In the Arctic, climate change has appeared to increase ocean CO<sub>2</sub> uptake over the recent past, largely due to sea-ice retreat and greater surface area for air-sea CO<sub>2</sub> exchange (Yasunaka et al., 2023). Processes in the Southern Ocean are different, where altered wind patterns and resulting stronger upwelling seem to be reducing ocean CO<sub>2</sub> uptake (Hauck et al., 2023).

### 5. Impacts of changes in the ocean buffer factor:

These interact with the highly seasonal physical and biological processes in the ocean, and the impact on the annual mean net air-sea CO<sub>2</sub> flux is not well constrained (Fassbender et al., 2022; Hauck and Völker, 2015; Rodgers et al., 2008; Mongwe et al., 2024).

### 6. Extreme events:

An additional layer of complexity relates to the roles and impacts of extreme events and abrupt changes, including high wind speeds or precipitation, heatwaves (terrestrial and oceanic), acidification, deoxygenation and their compound effects. The frequency and intensity of extreme events are increasing under climate change and initial analyses of the effect of recent marine heatwaves on the ocean carbon sink are emerging (Mignot et al., 2022; Li et al., 2024). Knowledge of how these will impact long-term ocean CO<sub>2</sub> uptake and storage is currently missing.

## Actions to be taken

Three main interlinked actions are essential to significantly tackle knowledge gaps: increase sustained observations (**Section 4a**), enhance ocean model process representations (**Section 4e**) and intensify collaborations between modelers and observationalists. All are crucial to increase confidence in estimates of ocean CO<sub>2</sub> uptake and storage, especially when unexpected or extreme events occur, such as heat waves. These activities should address the key components of the ocean CO<sub>2</sub> uptake, including:

- I. **Quantification of variabilities** (e.g. across latitudes, from interannual through interdecadal time scales);
- II. **Refinement and extension of air-sea CO<sub>2</sub> flux parameterisations**, to reduce uncertainties in CO<sub>2</sub> uptake estimates via bulk methods;
- III. **Determination of seawater carbonate equilibrium constants**, to increase the internal consistency of calculation of the marine carbonate system; and
- IV. **Monitoring of changes in physical processes** and how they affect anthropogenic carbon uptake, e.g., warming and freshening, ocean circulation, stratification, and mixing.

These actions will be best achieved through:

- Ensuring integrated and coordinated, long-term, sustainable, multi-variable and multi-platform based observations from coasts to open ocean, including further targeted development of sensor technologies, expanding observations to under-observed regions;
- Maintaining a network of international laboratories that produce and deliver climate-relevant calibration materials (in seawater, as well as in gas mixtures);
- Achieving and agreeing on a robust understanding of the effect of near-surface ocean temperature and salinity gradients;
- Ensuring dedicated long-term, sustainable operating support for critical data synthesis products: the Surface Ocean CO<sub>2</sub> Atlas (SOCAT<sup>22</sup>) and the GLocal Ocean Data Analysis Project (GLODAP<sup>23</sup>);

22 See [www.socat.info](http://www.socat.info)

23 See [www.glodap.info](http://www.glodap.info)

- Enabling enhanced model development and calibration/validation via the identification and elimination of model biases (e.g. due to mixing schemes), and the incorporation of important missing processes and variables (e.g. organic alkalinity, near-surface temperature gradients and mesoscale dynamics);
- Employing other independent lines of evidence to constrain the ocean carbon sink, such as oceanic observations of CFCs and oxygen;
- Comprehensively and routinely identifying and characterising biases and uncertainty in the suite of observation-based air-sea CO<sub>2</sub> products (for example as achieved by Ford et al., (2024) for one product and begun by the SOCOMv2 community effort);
- Training and sharing of best practices and global capacity expansion.

### 3.b The changing role of biology in the ocean carbon cycle

*Sandy Thomalla, Nina Bednaršek, Philip W. Boyd, Emma Cavan, Feng Chen, Richard A. Feely, Helen S. Findlay, Stephanie Henson, Nianzhi Jiao, Marja Koski, Adrian Martin, Carol Robinson, Richard Sanders, Jamie Shutler, Xilin Xiao*

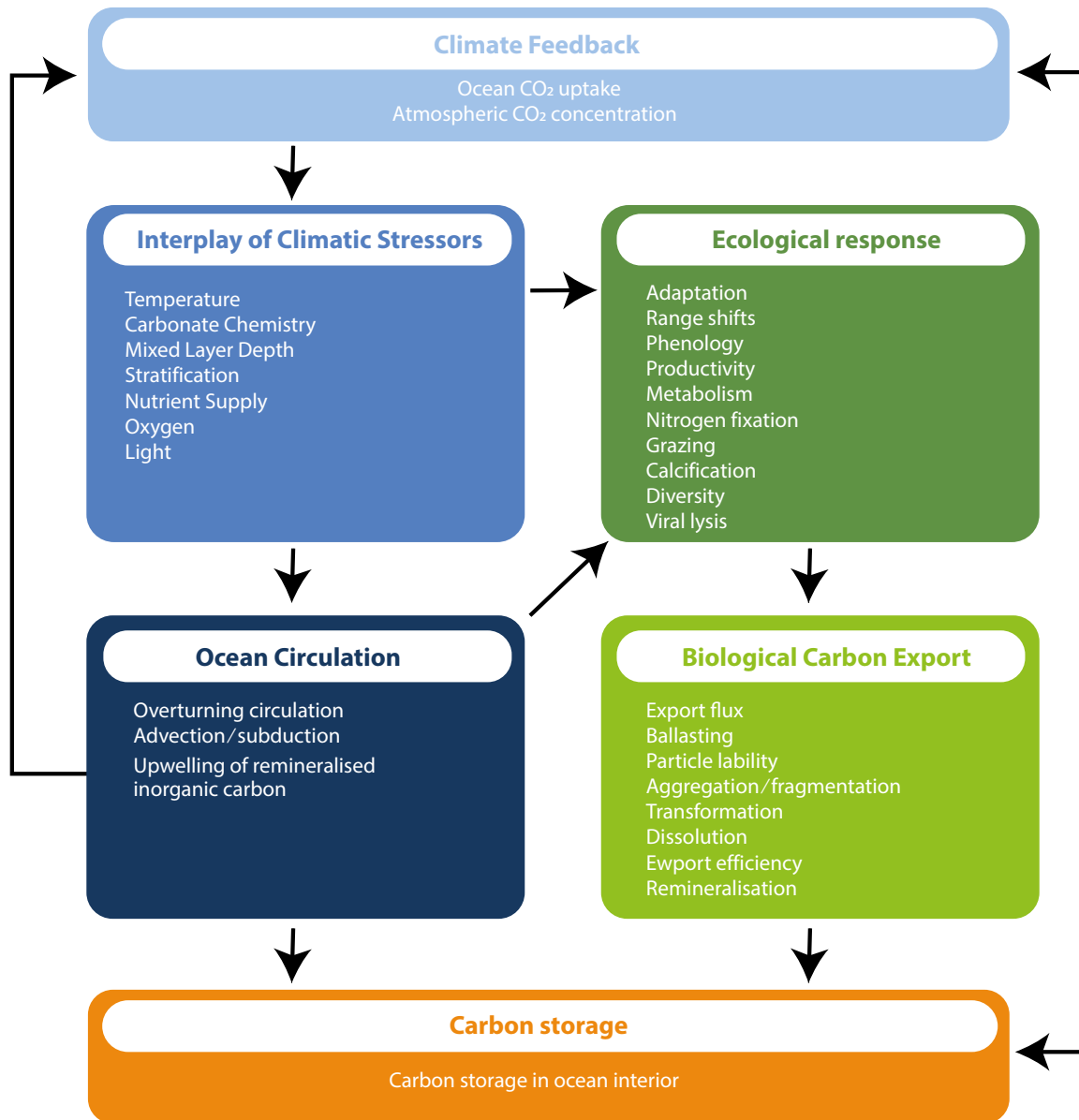
Biological processes in the ocean influence the uptake, storage and release of carbon on climatically relevant timescales. Without these processes, atmospheric CO<sub>2</sub> concentrations in the pre-industrial era would have been approximately 200-300 ppm higher (Maier-Reimer et al., 1996; Kwon et al., 2009; Carter et al., 2021). The strength and efficiency with which these biological processes impact the carbon cycle are unlikely to remain constant over time, as they are themselves affected by climate change, leading to feedbacks within the climate system (Crichton et al., 2023; Wilson et al., 2022; Henson et al., 2022, Frenger et al., 2024). Indeed, if the supply of nutrients to the ocean's euphotic zone, or the planktonic community's ability to utilise nutrients, changes, then atmospheric CO<sub>2</sub> concentrations can be impacted (Frenger et al., 2024). For example, during the last glacial maximum, iron fertilisation from dust and a subsequent increase in export flux and carbon burial, resulted in a reduction in atmospheric CO<sub>2</sub> of ~20 ppm (Lambert et al., 2015).

Anthropogenic forcing (driving changes such as warming, acidification, deoxygenation, stratification, and altered light and nutrient supply) affects ecosystem function and the transfer of carbon, energy, and nutrients through pelagic and benthic food webs. These changes create complex feedback mechanisms on ocean biogeochemistry, remineralisation, carbon storage, and climate (Barnes, 2018; Henley et al., 2020; Lee and Feely, 2021; Sulpis et al., 2021). Estimates of how climate change is impacting biological carbon flux are, however, poorly constrained due to a lack of understanding of the complexity of processes that interact to drive carbon production, remineralization, and export (Henson et al., 2022; 2024a; 2024b) (**Figure 5**). Factors that regulate phytoplankton growth (e.g. temperature, light, nutrients), particle formation and rates of sinking (e.g. aggregation, fragmentation, ballasting, senescence, grazing, viral lysis), physical processes (e.g. mixing, advection, subduction) and remineralization (microbial metabolism, chemical dissolution, zooplankton consumption) all modify the fate of carbon (Henson et al., 2022). This multitude of interacting factors affects the depth at which particulate organic and inorganic carbon fixed in surface waters is transformed to dissolved carbon, which ultimately determines its storage time in the ocean's interior. It is also important to recognise that carbon flux is not purely gravitational or vertical, but is influenced by additional 'particle injection pumps' by both biological (e.g. animal-migration) and physical (e.g., mixed layer dynamics, subduction) processes. These processes, which are often intensified at features such as eddies and fronts, transport suspended and sinking particles to depth (Boyd et al., 2019; Sulpis et al., 2021). In addition horizontal dispersal can advect organic material over large distances as it decomposes.

As primary producers, phytoplankton are responsible for determining the amount of organic carbon fixed in surface sunlit waters that is available for export and subsequent transfer to depth via a series of biological and physical mechanisms (the biological carbon pump). Particle feeders (e.g. zooplankton, metazoans) modulate carbon transfer by consuming, disaggregating and transforming sinking particles via remineralization, dissolution, and defecation processes. Marine microbes readily utilise most of the exported organic carbon, producing CO<sub>2</sub> through remineralisation (the microbial loop), but also produce refractory dissolved organic matter (DOM) that resists degradation enhancing storage (the microbial carbon pump) (Jiao et al., 2010). Linking

microbial community complexity with the chemical diversity of DOM has advanced our understanding of the role of microbes in ocean carbon cycling (Jiao et al. 2024). Major uncertainties still exist regarding the processes that govern the different biological pumps and how they interact, which makes it challenging to detect and determine changes in organic carbon flux in

response to climate stressors. This highlights the need for baseline knowledge of the magnitude of the biological carbon pump and the natural variability around it, so that changes in the biologically-mediated component of the ocean carbon cycle can be detected and attributed to climate forcing.



**Figure 5.** Conceptual schematic illustrating the complex interplay between key climate stressors, ocean circulation, ecosystem responses, and carbon cycling processes that feedback on climate. Climate feedbacks arising from changes in atmospheric CO<sub>2</sub> concentrations and ocean CO<sub>2</sub> uptake drive evolving climate stressors, the interplay of which in turn influences ocean circulation and ecological responses across key groups (e.g. phytoplankton, metazoans, microbes, viruses). These responses affect the efficiency of biological carbon export and long-term storage of carbon in the ocean interior, further modifying climate feedbacks and reinforcing a dynamic and interconnected system.

## Major Knowledge Gaps

Key knowledge gaps concerning the impact of biology on carbon uptake and storage and how it is changing, now or in the future, have been broadly divided into two categories below.

### *External forces shaping the biological community*

Knowledge gaps concerning climate-related drivers and their interplay (synergisms and antagonisms), impact on the role of community structure and function in driving carbon production and its fate:

- 1. Impacts of ocean acidification on rates of calcification, respiration, and dissolution processes** that influence the spatial patterns of organic and inorganic carbon ratios and the downward flux of carbon;
- 2. Effects of altered biomineralization** (calcification, dissolution) on subsurface total alkalinity and how will this feedback to CO<sub>2</sub> uptake from the atmosphere and transport within the ocean interior;
- 3. Impact of competitive responses in phytoplankton community structure (e.g. dominant cell size) on the efficiency of carbon export and sequestration,** and the transfer of carbon to higher trophic levels;
- 4. Changes in the epipelagic and mesopelagic communities,** and associated adjustments in substrate feeding preferences, vertical migration patterns, life cycles, and egested faeces density, affecting vertical transport and particle transformations through fragmentation, aggregation, degradation, and altering particle characteristics, and thus **impact long-term carbon sequestration;**
- 5. Impact of environmental change on the biogeochemical roles of viruses and viral lysis** through selective pressure on host populations, viral replication rates, host susceptibility, viral community composition, and their lytic/lysogenic patterns;

- 6. Synergistic effects of the biological carbon pump, microbial carbon pump, carbonate pump, and viral shunt/shuttle/sweep** on carbon storage and its response to climate change;
- 7. Variation of magnitude, efficiency, and relative contributions of these carbon pumps with depth, region, and time under changing climate conditions.**

### *Internal biological responses to environmental change*

Unlike the first knowledge gap, which is about external forces shaping the biological community, the second refers to internal biological responses to environmental change.

Knowledge gaps concerning how key organisms respond (evolve, adapt, and acclimate) to environmental change and in doing so impact carbon production, transport and storage:

- 1. Potential of plankton to adapt or acclimate** (e.g. by adapting their physiology and morphology) quickly enough to maintain growth, ecological roles, and competitiveness under changing conditions, and to what extent does functional redundancy among key groups buffer carbon cycling and ecosystem function against regional niche losses and ecological shifts;
- 2. Alteration of climate-related drivers on the physiological rates and traits of metazoan species** i.e., clearance, ingestion, metabolic, and egestion rates, predator-prey dynamics and their diet preference;
- 3. Influence of climate-driven changes in gene expression within microbial communities influence particle type,** the transformation of **bulk DOM** and the formation of **refractory DOM**, and to what extent will microevolution and functional redundancy provide a buffer against these changes;
- 4. Impact of altered viral lysis on the evolution of resistance mechanisms** that contribute to biodiversity and the resilience of marine ecosystems.

## Actions to be taken

The knowledge gaps are broad, with priority areas that span the full spectrum of functional types that influence carbon production and its fate. Albeit a daunting challenge, several targeted recommendations can be implemented to address key aspects of these knowledge gaps - advancing our understanding of this complex and important planetary carbon flux, and improving confidence in our ability to detect and predict change. These recommendations can be broadly organised into four strategic themes:

### I. Coordinated observations and model integration

Multinational coordination is essential to integrate emerging and synergistic observation approaches—particularly those involving technical advances that reduce the cost of observing and modelling biologically driven carbon fluxes across large spatial and temporal scales (e.g. ocean robotics, imaging, and satellite remote sensing). While progress has been made by the remote sensing community (e.g. Brewin et al., 2023; Shutler et al., 2024), broader engagement from across the ocean carbon community is needed to strengthen model validation, improve understanding of environmental controls, and better detect climate-driven change.

This integration should include state-of-the-art physical modelling (e.g. particle tracking) coupled with biogeochemical modelling and diverse observations (e.g. ship based, moorings, buoys, floats, autonomous platforms and satellites) to better resolve the three-dimensional trajectories and fate of carbon injected into the ocean via the biological carbon pump.

### II. Mechanistic understanding to inform models

Observing the biological carbon pump must be closely coupled with a mechanistic understanding of the factors driving its variability. This requires coordinated efforts that integrate sustained and targeted observations, experimental research across trophic levels, and model–data synthesis—focusing on how different functional types contribute to carbon production, export, remineralisation, and long-term storage. These targeted process studies should aim to determine the interplay across all functional groups and their integrated impact on carbon production, transport, and sequestration.

Mechanistic understanding gained from these observations should directly inform model parameterizations to improve predictive capabilities for assessing ocean carbon cycle changes.

### III. Experimental studies

Laboratory, *in situ* and mesocosm/macrocosm experiments are essential for improving model parameterisation, model evaluation and predictive capabilities in a changing ocean. Controlled single-species laboratory studies provide critical mechanistic insights, while multiple-driver mesocosm/macrocosm manipulation studies or marine ecosystem chamber experiments (that closely mimic *in situ* conditions) are needed to simulate a changing climate and tease apart the effects of environmental change on biogeochemical outcomes that transpire from complex functional group interactions and organismal physiology.

Studying physiological rates in the context of group-specific reaction norms under multiple stressors (e.g. thermal and dissolved oxygen performance curves and CO<sub>2</sub> affinity curves) can shed light on which organism groups will likely benefit or be disadvantaged in future oceanic conditions. Such group-specific reaction norms are needed to develop or improve model parameterizations.

### IV. Omics and adaptive capacity

Collecting *in situ* and *in vitro* omic data - including metagenomics, metatranscriptomics, metaproteomics, and metabolomics - for both prokaryote and eukaryotes communities that can provide crucial information on metabolic pathways including carbon fixation and degradation, diet composition, energy acquisition strategies, physiological stress responses, and rates of evolutionary adaptation.

Adaptation studies should connect cellular, physiological and behavioural mechanisms, incorporating microevolution and epigenetics in order to yield a more comprehensive understanding of how organisms will respond and evolve in changing environments.

### 3.c Carbon exchanges across the land-ocean-ice continuum

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The land-ocean-ice continuum involves the exchanges of carbon from land to ocean and between ocean and ice, including the complex transport and transformation of carbon components. Traditionally the Land-Ocean-Aquatic Continuum (LOAC; **Figure 6**), includes ecosystems such as river systems, estuaries, inshore waters, coastal regions, continental margins and the open ocean. This assessment broadens the term to also consider ocean carbon transport in the cryosphere.

Estuaries and coastal vegetated ecosystems collectively act as a net sink of CO<sub>2</sub> (~ -0.50 Pg CO<sub>2</sub> yr<sup>-1</sup> or -0.13 Pg C yr<sup>-1</sup>), but recent research has shown that anthropogenic activities resulted in a decrease of the sink capacity by about 25% between 1975 and 2020 (Laruelle et al., 2025; Rosentreter et al., 2023; Regnier et al., 2022). Mangrove forests, tidal marshes and seagrass meadows, often referred to as “coastal blue carbon ecosystems”, have been lost and remain under threat, yet these ecosystems capture a significant amount of *in situ* carbon, as well as transferring carbon from land to sea (e.g. Bianchi et al., 2020; Fourqurean et al., 2012; Hatje et al., 2021). Hence they effectively store both marine and terrestrial organic carbon in their soils and sediments, while also exporting a significant amount of fixed carbon (i.e. organic) to the coastal and open oceans (Cai, 2011; Regnier et al., 2022). Blue carbon ecosystems also contribute to lateral export of dissolved inorganic carbon (DIC) and total alkalinity (TA). For example, Alongi (2022) estimates a lateral export to the ocean of ~366 TgC yr<sup>-1</sup> (DIC) and ~17 TgC yr<sup>-1</sup> (TA) from the world’s mangroves. It is also worth highlighting that blue carbon ecosystems remain the only formally recognized mechanism within the current guidelines of the IPCC wetland supplement<sup>24</sup> and frameworks of the UNFCCC by which ocean climate change mitigation can be delivered.

Extending from the coast, the global continental margins (including shelf seas) were likely a near neutral or small pre-industrial source of atmospheric CO<sub>2</sub> (Cai, 2011; Dai et al., 2022; Regnier et al., 2013, 2022). Recent analyses suggest a globally integrated coastal ocean CO<sub>2</sub> uptake of 0.25 ± 0.05 Pg C yr<sup>-1</sup> over the last two decades, with polar and subpolar regions accounting for most of the CO<sub>2</sub> removal (>90%) (Dai et al., 2022; Roobaert et al., 2019). While biological production is a major driver for carbon sequestration in these areas, the continental margin CO<sub>2</sub> uptake may be strongly driven by regionally specific physical characteristics (e.g. Northwestern European shelf, Kitidis et al., 2019).

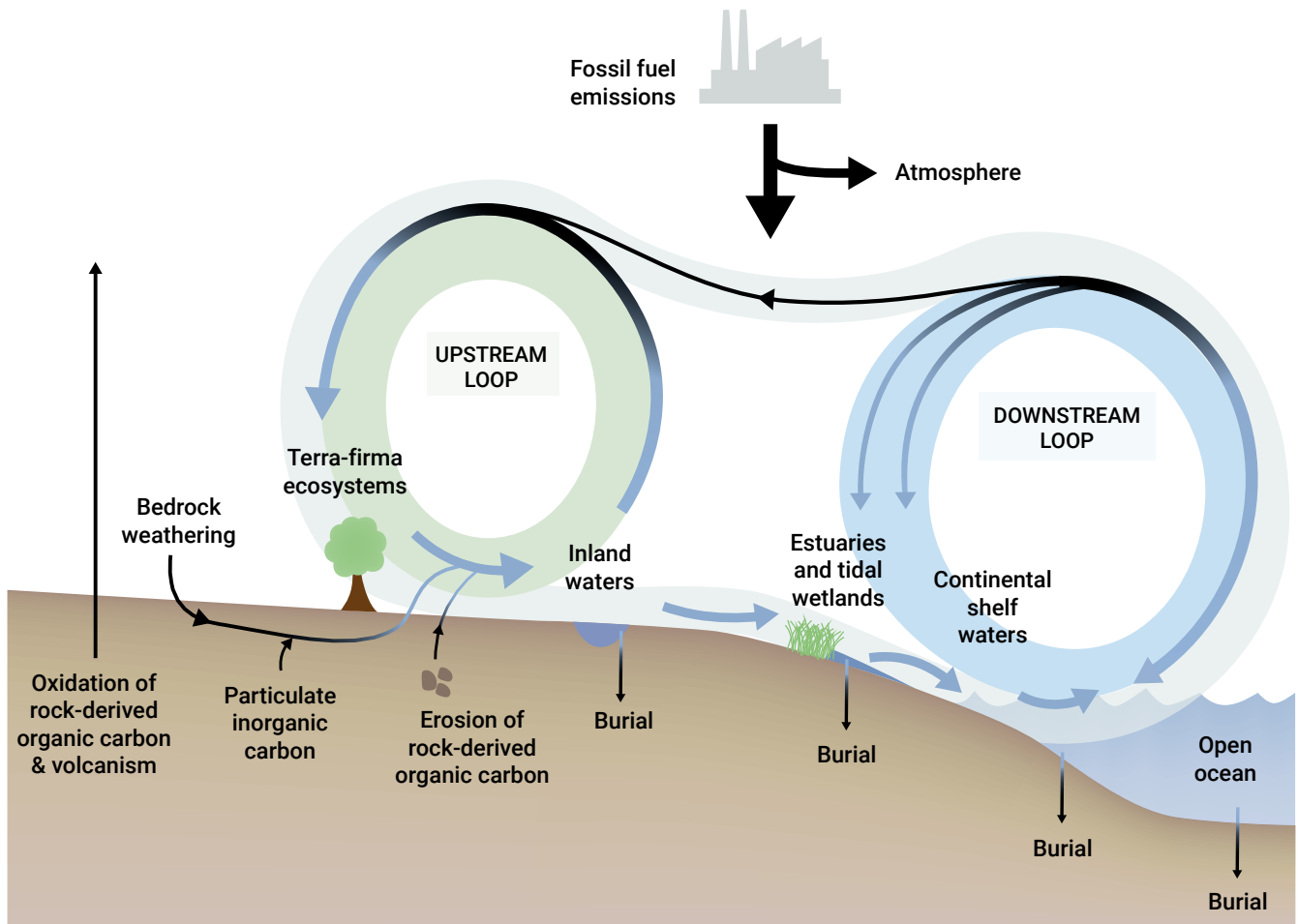
Anthropogenic activities have directly accelerated the carbon turnover between terrestrial ecosystems and inland waters (by up to 25%), with some evidence that this may be regionally (Dai et al., 2022) and temporally (Smeaton et al., 2021) important, but with limited evidence for its overall impact on global carbon export to the ocean (Regnier et al., 2022; Tian et al., 2023). However, the anthropogenic perturbations of land nutrient cycles extend beyond the terrestrial domain and there is evidence that these changes are causing significantly enhanced carbon uptake in the global coastal ocean (Jiao et al., 2011; Lacroix et al., 2021a; Mathis et al., 2024; Fernandes et al. 2025; Lacroix et al., 2021b; Resplandy et al., 2024; Roobaert et al., 2024), and thus reinforcing the effect of increasing atmospheric CO<sub>2</sub> on ocean uptake. For shelf seas it is suggested that the lateral export of both dissolved and particulate organic carbon to the open ocean, despite being difficult to measure and constrain in models (Huthnance et al., 2022; Fennel et al. 2019) largely offsets the input from advection and riverine sources, producing a net carbon deficit in coastal waters (Mathis et al. 2024). The difficulties in observing and modeling these land-ocean processes result in large uncertainties in quantifying and identifying the magnitude and drivers of increased shelf sea carbon uptake, especially in tropical regions (Resplandy et al., 2024)

<sup>24</sup> See 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands <https://www.ipcc-nggip.iges.or.jp/public/wetlands/>

Significant differences in air–sea  $\text{CO}_2$  fluxes occur between coastal regions and the adjacent open-ocean waters, particularly for upwelling or western boundary systems (e.g., Humboldt and California upwelling systems, or the Kuroshio current) and those dominated by large river plumes (e.g., Amazon, Changjiang, Mississippi rivers, with an estimated sink of  $0.07 \text{ Pg C yr}^{-1}$ ; Bourgeois et al., 2016; Dai et al., 2022). Other coastal regions and seas, for example the Mid-Atlantic Bight, South China Sea, and Baltic Sea, show different long-term patterns in air–sea  $\text{CO}_2$  fluxes, as various physical and biogeochemical processes can dominate carbon flux evolution in those areas (e.g. Dai et al., 2022; Siedlecki et al. 2021b).

Climate change is also altering carbon drawdown in high latitude ocean basins. In the Arctic, sea-ice loss, an increasing river flow to the ocean, permafrost melt, and coastal erosion are changing  $\text{CO}_2$  dynamics in ways that vary temporally and regionally (e.g. Clark et al., 2022; Lannuzel et al., 2020; Terhaar et al., 2019; Oziel et al., 2025). Equally, quantification of the coastal ocean  $\text{CO}_2$  sink in the Southern Ocean remains highly uncertain (Henley et al., 2020; Legge et al., 2015; 2017; Lencina-Avila et al., 2018; Monteiro et al., 2020a; 2020b; Droste et al., 2022; 2025).

**Section 3.e** addresses the potential of additional carbon sequestration in coastal ecosystems via intentional mCDR and nature based solutions.



**Figure 6.** Present day land-ocean-aquatic-continuum carbon fluxes. One long-range carbon loop (grey) connecting land ecosystems to the open ocean, and two short-range carbon loops respectively connecting land ecosystems to inland waters in the upstream portion of the LOAC (green), and tidal wetlands and shelf waters to the open ocean in the downstream portion of the LOAC (blue). Adapted from Regnier et al. 2022.

## Major knowledge gaps

The priorities for future research relate to seven key knowledge gaps:

### 1. Spatio-temporal patterns in land-derived carbon (and nutrient) inputs to the ocean and changes over time:

Observationally constrained assessments of land-ocean carbon (organic and inorganic) and nutrient and alkalinity fluxes, including contributions from groundwater, coastal erosion, and permafrost, remain critically needed at the global scale. Most importantly, the temporal variability and evolution of these fluxes needs to be better resolved across temporal scales (seasonal to decadal). Other research questions that need to be urgently tackled concern the DIC/TA ratio of land-derived inputs, the role of organic alkalinity, and the contribution of urban ecosystems (particularly coastal cities) to the inputs of anthropogenic organic carbon and nutrients.

### 2. Fate of land-derived carbon inputs in the ocean:

The source, composition, and lifetime of terrestrial and coastal marine organic matter remains highly uncertain, with major implications for the recycling of land-derived carbon in the ocean and associated air-sea CO<sub>2</sub> fluxes. Better constraints on the fate of (natural and anthropogenic) land-derived carbon and its evolution in time, together with the lateral exports of DIC and alkalinity, are required to improve the assessment of the anthropogenic coastal CO<sub>2</sub> sink. Melting permafrost and coastal erosion are a particularly large source of organic carbon to Arctic coastal waters, with an uncertain future trajectory (knowledge gap **item 6**, below). Future research also needs to better constrain the recycling efficiency of nutrients across continental shelves as a key controlling factor on the productivity of the global coastal ocean.

### 3. Changes in coastal ocean carbon cycling and lateral exchanges with the open ocean:

The evolution of the Net Ecosystem Productivity (NEP) and C<sub>anth</sub> sink of the global coastal ocean remain poorly quantified. The attribution of temporal trends to atmospheric composition change, changes in the ocean's physical climate, changes in land-derived carbon and nutrient inputs, and the role of

surface sediment carbon and alkalinity dynamics are also uncertain. These knowledge gaps reflect the insufficient observational coverage in both space and time of *in situ* approaches to quantify coastal carbon fluxes (partly due to limited dedicated data products and observing systems specifically designed for the highly heterogeneous coastal ocean) and the need to further improve the capabilities of numerical models to better represent physical and biogeochemical coastal processes at high spatial resolution.

### 4. Coastal carbon storage and contribution of blue carbon ecosystems in a changing world:

Present day and potential future changes in carbon storage in key reservoirs of the land-ocean aquatic continuum (LOAC; Regnier et al., 2022), including the specific contribution of blue carbon ecosystems, remain a challenge to fully quantify. Specifically, carbon fixation, burial, and lateral export fluxes from coastal vegetated ecosystems are based on relatively limited observations that are insufficient to deliver robust global estimates. Carbon fluxes to and from these ecosystems in response to anthropogenic perturbations, including accelerating sea-level rise, remain another priority for further research effort. Due to their disproportionate contribution to the total area of blue carbon systems globally and their wider significance for biodiversity and livelihoods, tropical ocean margins constitute hotspot regions for further research.

### 5. Impact of human activities and global change factors individually and in combination on global coastal ocean carbon:

The interactions between direct human activities (fishing, sea-bed disturbance, aquaculture, energy generation, conservation/protection and rewilding) and global change factors (physical climate, sea-level rise, acidification, eutrophication/hypoxia) as regulators of the delivery and fate of carbon in the ocean needs to be better studied. Anthropogenic activities along watersheds such as river damming, and land-use change, as well as permafrost thawing, also impact the land-ocean carbon fluxes (Best, 2019; Clark et al. 2022; Vargas and Gelcich, 2024). In particular, the role of sea-level rise and its impact on carbon exchanges across the LOAC remains poorly understood. As well as a focus on these longer-term trends, further research should also investigate the

impact of extreme and slow onset events (droughts, altered riverine flows and sediment delivery through damming, marine heat waves, storms, and tsunamis), because they are likely to influence regional and global carbon budgets, as well as local and regional economies.

## 6. Polar shelf carbon cycling.

Polar shelves are currently experiencing changes at a faster pace than anywhere else on Earth. However, the delivery of freshwater, carbon, and nutrients to the coastal ocean in response to a changing cryosphere (losses of glacier ice, ice sheets, sea ice and permafrost) remains highly uncertain, as is the response of the polar ocean carbon cycle (e.g. NEP, CO<sub>2</sub> uptake, acidification). Nissen et al. (2024) suggest that by 2100 seawater pH may decline by up to 0.36 (total scale) in the upper 200 m within Antarctic coastal regions and in the Barents Sea in the Arctic decreases of up to 0.51 pH are predicted by 2100 (Årthun et al., 2025). Changes in sea ice and meltwater appear to be changing carbon uptake in varied and unpredictable ways. Both data and most models currently lack sufficient temporal and spatial resolution, as well as fundamental process understanding, to capture these changes. The lack of winter observations, as well as geographically sparse sampling, is a particularly severe limitation to regional flux estimates in polar regions.

## 7. Integration of the land-ocean aquatic continuum into global carbon cycle assessments and Earth System Models (ESMs).

As stated in the IPCC AR6 Report (WG I, chapters 2, 5, and 12 in IPCC, 2021), integrating the LOAC or at least the coastal ocean into global carbon cycle assessments and ESMs is urgently needed but remains a significant challenge. This is because it will require the online coupling of the C-(N-P) cycles of the river-estuary-blue carbon-shelf continuum with land surface and ocean schemes of ESMs. This goal is crucial in assessing how LOAC carbon fluxes impact the carbon cycles of the global ocean.

## Actions to be taken

Filling these research gaps requires strengthening multilateral cooperation, promoting scientific innovation and developing human and technical capacity, to overcome the north south bias in ocean observation, to improve the knowledge base in high latitudes and priority coastal areas, supporting the delivery of fit-for-purpose local, regional and global models. The specific actions required include:

### I. Establish a fit-for-purpose land-ocean global observation system.

Large networks are needed to support sustained monitoring and compile existing data (IOC of UNESCO, 2024). Research efforts in coastal and open ocean areas should also be better linked through international collaborations among researchers and governments. Collaboration between ocean and inland water research communities (including those studying groundwater fluxes and coastal erosion) is key to co-develop global datasets of river carbon and nutrients (Liu et al., 2024; Virro et al., 2021). Co-location of the water column observing network with benthic observations at the sediment/water interface is also critical. Machine-learning methods and geographical information systems (GIS) should be developed to fill spatial and temporal gaps and tackle regional differences (e.g. Dai et al., 2022; Krishnamoorthy et al., 2025; Laruelle et al., 2025; Roobaert et al., 2024).

### II. Develop and share best practices.

Best practices should be developed for i) closing geographical gaps through, ideally, high quality and affordable observations; ii) the characterization of riverine, blue carbon ecosystems and coastal sources of alkalinity, carbon (including terrestrial DOC) and nutrients (e.g. Dickson et al., 2007; Mantovani et al., 2024). Best practices also need to be developed for estimating carbon fluxes and accounting for the carbon stocks in coastal and blue carbon ecosystems, with the application of advanced mapping, including groundwater (Tomer et al., 2025), seafloor and submerged sediments, as in **action item 1** above. Estimates should also account for changes in carbon storage due to climate change, sea-level rise, and eutrophication, as well as direct

human perturbations (e.g., fisheries and aquaculture, see **action item 5** below). Best practices also include building capacity for ocean observations, data quality control, access to reference materials, reporting, and data archiving in accordance with FAIR and CARE principles (Tanhua et al., 2021).

### III. Develop ocean biogeochemistry models.

Features of the land-ocean and ocean-ice continuum need to be nested into global and regional ocean biogeochemistry models under different scenarios, by using variable grid sizes and improving data assimilation systems for LOAC carbon and nutrient observations from multiple platforms (ships of opportunity, buoys, uncrewed surface vehicles, satellites (Myers-Pigg et al., 2025)). Assembling data products at adequate spatial and temporal resolutions that reflect the high heterogeneity of the LOAC is needed, but assimilation into numerical models is a particular challenge. Flexible scenarios should be used to include variable and evolving climate forcings and local as well as global anthropogenic disturbances (e.g., effluents, pollutants, erosion, high-risk events). These modelling efforts also depend on the strength of the networks cited in **action items 1 and 2**, above, in collaboration with the ocean biogeochemistry modelling community.

### IV. New approaches to study the land-ocean carbon cycle.

A multi-stressor (climate, natural and anthropogenic forcing) approach to studying the changing land-ocean carbon cycle may help inform local economies, develop adaptation and mitigation policies, and design regional sustainability initiatives for marine spatial planning. Socio-economic dimensions should also be integrated into coastal ocean carbon research. Dedicated essential variables for the coastal ocean (current GOOS EOVs are limited in this respect<sup>25</sup>) should be defined, using the tailored strategies in **action items 1 to 3**, above.

### V. Multidisciplinary and multinational research effort.

Substantial multidisciplinary research effort is required to improve our understanding of air–sea CO<sub>2</sub> fluxes and land-derived carbon and nutrient inputs (amount, composition, reactivity) in polar

regions and how the polar oceans are changing with climate (Willis et al., 2023). Particular priorities include: i) focussed air–sea CO<sub>2</sub> flux measurements and biogeochemical observations under varied conditions, through more and multiple sensors deployed on uncrewed platforms designed to operate in sea ice conditions; ii) expanded process studies of the relationships between climate conditions, the annual sea-ice cycle, and carbon drawdown; iii) better quantification of sea-ice carbonate chemistry and the biogeochemical lability and fate of permafrost carbon, within both terrestrial and marine aquatic systems; and iv) biogeochemical responses to increasing temperatures (Gou et al., 2025; Vonk et al. 2025). The more generalized needs detailed in **action items 1 to 4** above, also apply in the polar regions.

### VI. Model intercomparison project.

A “land-induced global ocean CO<sub>2</sub> outgassing Model Intercomparison Project” should be launched with the upcoming 7th Coupled Model Intercomparison Project (CMIP7), to promote ensemble-mean assessments of “the anthropogenic perturbation in the land-ocean carbon cycle” within its initiatives (“MIPs”). Recent land-to-ocean model developments<sup>26</sup>, should be leveraged to achieve fully coupled and interactive carbon and associated nutrient cycles in Global Ocean Biogeochemical Models (GOBMs). This action depends on **action items 1 to 5** cited above.

### VII. Integrate satellite and *in situ* observations.

Arguably the only viable way to observe synoptic scale variations in river to ocean flows and its constituents is from space. Some synoptic scale assessments using satellite and *in situ* observations show promise and could help constrain land to ocean fluxes (which may include sediment loads, river plume extension, primary production, particulate organic carbon and salinity) and their variability, particularly for larger river systems (e.g. as demonstrated within Shutler et al., 2024), but these sorts of synergistic approaches, where the benefits of multiple observation data types are exploited, need more widespread development.

25 See <https://goosoocean.org/what-we-do/framework/essential-ocean-variables/>

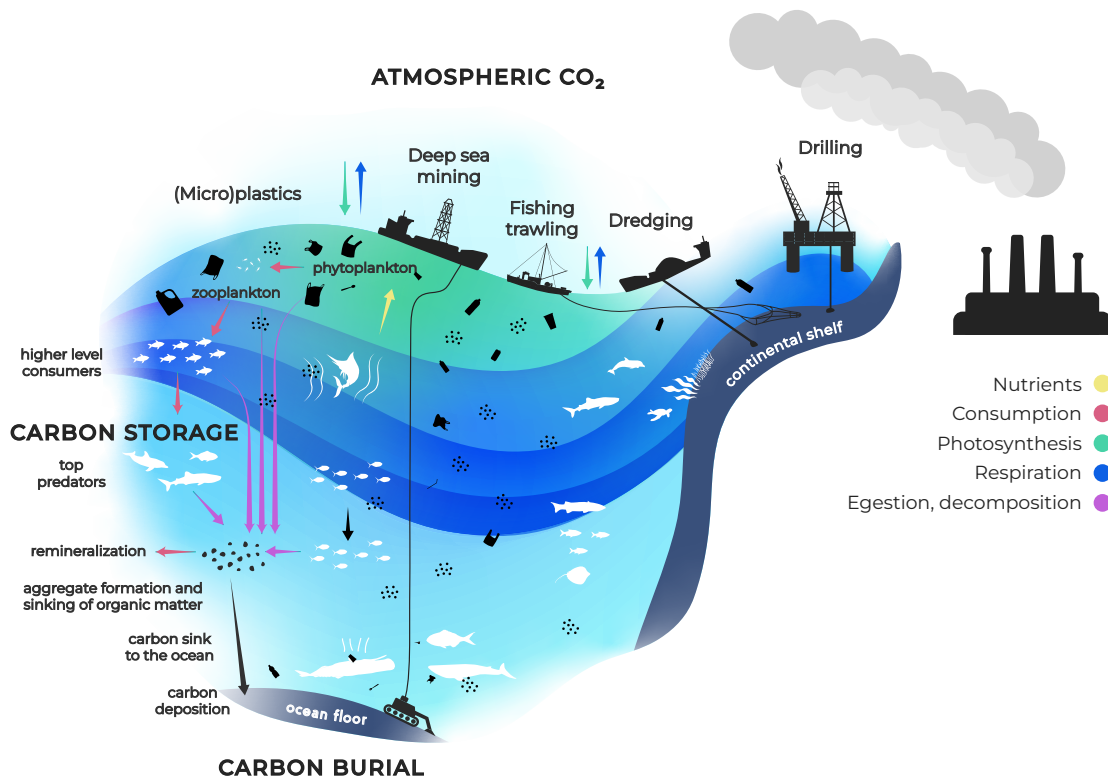
26 See <https://www.globalcarbonproject.org/reccap/publications.htm>

### 3.d The impact of ocean industrial processes on the ocean biological carbon cycle

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In most evaluations, the natural ocean carbon cycle is considered to be unchanged, with the perturbation to the ocean carbon cycle suggested to be limited to an enhanced air to sea flux (see e.g. the graphical overview presented in **Figure 3**). However, climate change, resource extraction and pollution are likely at a scale where this assumption may well be unfounded. The effects

of resource extraction on the biological component of the marine carbon cycle can be conceptually separated into those that disturb and resuspend large amounts of sediment (e.g. mining, trawling, dredging, port construction and drilling), those that restructure ecosystems via biomass removal (e.g. fishing and whaling) and those that enhance biomass production in the coastal zone such as aquaculture. With respect to pollution, plastics are now an emergent component of the carbon cycle and may be altering critical earth system functions, including the strength of the biological carbon pump. See **Figure 7** for a conceptual overview of key processes.



**Figure 7.** Conceptual overview of how industrial processes can alter the functioning of the biological carbon pump. The figure shows simplified ocean biological pump processes that industrial activities have the capacity to distort. The black elements illustrate the various industrial processes considered ranging from i) deep sea mining, which can adjust sediment carbon burial and water column storage via the suspension of sediments, ii) trawling on the shelf, which can affect ecosystems and sedimentary storage, and iii) fishing, which can restructure ecosystems. The figure also shows widespread plastic pollution. *Source:* Seascope Belgium for the OceanICU Horizon Europe project, adapted from Lutz and Martin (2014), a conceptual diagram of marine vertebrate carbon services | Version 2.7 - CC BY-NC-ND 4.0 DEED.

Seafloor removal during mining operations has long-lasting (many thousands of years) effects on sediment biogeochemical processes and fluxes (Jones et al., 2025). Reduced bioturbation activity and microbial organic carbon remineralization rates leading to

enhanced carbon burial, reduced nutrient release from the seafloor, reduced benthic oxygen uptake, and enhanced oxygen diffusion into the sediment, have all been documented (Haffert et al., 2020; Volz et al., 2020; Vonnahme et al., 2020).

These impacts result from the mode of operation of the mining process. The proposed collection of polymetallic nodules from the seafloor leads to suspended sediment plumes that remain relatively close to the seafloor but disperse several kilometers away from the mining area (Weaver et al., 2022). Ship-based processing of the nodules results in streams of waste water being injected into the water column at various depths (Weaver et al., 2022). The anticipated impacts of these sediment and wastewater plumes include scavenging of suspended organic and inorganic carbon by aggregates and a possible enhancement to the downward flux of material via the so-called 'ballast effect'. In addition, particles release absorbed nutrients (e.g. Cheize et al., 2019) and some modelling studies suggest that mineral particles may interfere with zooplankton grazing (e.g. Fakhraee et al., 2023).

Additionally, processes that disturb seabed sediments (mining, trawling, dredging, drilling) can liberate carbon stored in the sediment, leading to a reduction in long-term sedimentary carbon stores, with the scale of this being highly contentious, depending on the refractory nature of the carbon and the oxidation to CO<sub>2</sub> of pyrite contained in the sediments (Sala et al., 2021; Hiddink et al., 2023; Zhang et al., 2024; Kalapurakkal et al., 2025). Sediment resuspension can also affect light fields and thus potentially alter photosynthesis (Lotsberg and Stamnes, 2010), leading to a reduction in the biological component of the continental shelf pump.

The impact(s) of ecosystem restructuring via biomass removal depend on the role that commercially exploited species play in ocean carbon cycling. Fish play important roles in the biological pump through deadfall to the seabed and defecation, contributing up to 16-18% to total carbon export (Saba et al., 2021; McMonagle et al., 2024). There have been suggestions that whales play an important role in the biological pump via the so-called 'whale pump' (e.g. Pearson et al., 2023) and also that krill may be important (Cavan et al., 2019) potentially storing 20 MtC each year through their faecal pellets alone (Cavan et al., 2024).

Fishing is clearly a highly mature industry; it has been estimated that fish biomass and recycling rates produced roughly 10% of carbon export and oxygen consumption in the preindustrial era, but this has now halved (Bianchi et al., 2021). Future projections are that the fraction of human protein demands supplied via fisheries will increase (Costello et al., 2020), implying

that the role of fish and the fishing industry in biological carbon sequestration and storage may change also.

The future trajectories of other industrial processes are less well characterised. Wind farms, which can effectively operate as 'no take zones', as can oil rigs, are increasing in number and spatial scale: Xu et al. (2020) suggest an average annual growth rate of over 20% over the period 2008-2018 in the North Sea, (Chirosca et al., 2022). Whilst multiple studies have considered frameworks for evaluating the impact of wind farms on ecosystem processes and the tradeoffs involved (e.g. Punt et al., 2009) there appear to be few systematic studies of the overall impact on ocean carbon cycling. However, since biodiversity in such regions is enhanced (Knoorn et al., 2024), carbon storage is also likely to be enhanced.

Deep sea mining is in its startup phase, and whilst frameworks for evaluating the impacts of these activities exist (e.g. Amon et al., 2022) the future demand is highly uncertain and dependent on multiple external factors (**Section 3.c**). A useful framework for considering the future evolution of ocean resource extraction processes is the concept of ocean system pathways (OSPs; Maury et al., 2017; 2025). These are an extension of the shared socioeconomic pathways (SSPs) which use considerations of the different trajectories along which human society may evolve, to create emission scenarios (Riahi et al., 2017). OSPs can be used to evaluate likely future trajectories for fisheries under diverse human society evolution pathways (Maury et al., 2017; 2025) and an extension into considering the likely future evolution of other industrial processes is plausible.

Plastic levels in the 2010's were identified as a potential planetary boundary threat, including to the functioning of critical earth system functions (Arp et al., 2021). Instead of taking action to reduce plastic pollution, plastic production and accumulation in the environment continue to increase exponentially (OECD, 2022). To compare plastics to other carbon cycle terms, plastic masses are converted to carbon mass assuming plastics are approximately 83% carbon by mass (Stubbins et al., 2021). Conversion of the most recent estimates of plastic mass data (OECD, 2022) to carbon indicates global production increased to 0.38 Pg C yr<sup>-1</sup> in 2019, is likely to reach 0.43 Pg C yr<sup>-1</sup> in 2025 and will breach almost 1 Pg-C yr<sup>-1</sup> by 2060. Approximately 95% of primary plastic production accumulates on earth (Stubbins et al., 2021), suggesting that in 2025 0.41 Pg plastic-carbon was

added to the earth system, which is more than double the global rates of biogenic organic carbon accumulation in inland waters (approximately 0.2 Pg C yr<sup>-1</sup>), deep ocean sediments (around 0.2 Pg C yr<sup>-1</sup>) and as blue carbon in coastal systems (approximately 0.1 Pg C yr<sup>-1</sup>), all of which are of significance to the global carbon cycle (Ciais et al., 2013; Canadell et al., 2022). Although plastics are accumulating at the sea floor and throughout the water column (Zhao et al., 2025), most data have been collected in surface waters of the subtropical gyres. For instance, in the North Pacific subtropical gyre, areal concentrations of microplastics in the surface 15 cm range from 0.03 to 34 kg km<sup>-2</sup> (Lebreton et al., 2018), which equates to 0.1 to 21.9 g C L<sup>-1</sup> (average 4.7 g C L<sup>-1</sup>). Particulate organic carbon (POC) concentrations in the upper 5 m of the North Pacific at Station ALOHA average 26 ± 7 g C L<sup>-1</sup><sup>27</sup>. Thus, microplastic-carbon may constitute 0.1 to 57% (average 15%) of the total POC in the North Pacific subtropical gyre surface waters. When microplastics are incorporated into particles, the resulting marine plastic snow can have slower sinking rates than plastic-free marine snow (Ziervogel et al., 2024). Plastics also represent an addition of reduced organic carbon to the ocean and therefore a potential energy source for heterotrophs. Sunlight can photodegrade and dissolve these plastics at the ocean surface to form plastic-derived dissolved organic carbon (pDOC) (Zhu et al., 2020; Romera-Castillo et al., 2018; Tuttle et al., 2024). This pDOC is among the most biolabile forms of DOC and may be altering microbial ecology and the stoichiometric balance of the surface ocean. Plastics are increasing in the oceans year on year (Eriksen et al., 2023; Lebreton et al., 2018). Understanding how plastics are altering the carbon cycle and ecology of the oceans is critical to informing policy to reduce plastic production and proliferation.

### Major knowledge gaps

Key uncertainties and knowledge gaps include:

- 1. The impact that adding sediment to pelagic systems** has on multiple processes in the ocean carbon cycle (e.g. ballasting, inhibition of grazing, protection of adsorbed organic matter, release of nutrients, shading).
- 2. The lability and bioavailability of organic and inorganic matter released from the seabed** during activities that disturb the seafloor. There appears to be no information on the impact of sediment resuspension on inorganic carbon remineralization and this is likely a key knowledge gap to close.
- 3. The precise role commercially exploitable and exploited fish species** play in ocean carbon cycling. Selective fishing can alter the structure of food webs, often by so-called predator release (or trophic cascade effect), i.e. if we fish the predators, their prey will increase. There are multiple studies on how fishing affects food webs, (e.g. Sun et al., 2024), but extending this to how carbon fluxes will respond is largely unexplored. In particular, the extent to which the flux from the surface ocean to depth is resilient to a reorganisation of higher trophic levels within a particular region (i.e. will the export mediated via fish in a perturbed system simply happen via a different pathway if they are removed or will export not occur?).
- 4. The role of on-shelf fisheries.** Most research on the contribution of fish to the biological carbon pump has concentrated in the deep (>1 km) off-shelf part of the ocean, where carbon can be sequestered in abyssal sediments over geological timescales. However, most fishing activity takes place on the shallow (<0.2 km) tidally-swept continental shelves, and the mechanisms of carbon export relative to remineralization under these conditions are not well understood (ICES, 2024).
- 5. Future trajectories of resource extraction, expanding marine protected areas, and wind farms** with their associated exclusion zones. Mining will release sediment into the water, with significant spatial and temporal footprints and the removal of the biologically active seafloor layer. Trawling, dredging, and drilling will have similar effects.
- 6. The impact of future changes in regulatory and legislative regimes on activity levels.** The recently adopted Kunming-Montreal Global Biodiversity Framework of the Convention on Biological Diversity calls nations to protect 30% of the ocean by 2030 (CBD, 2022). The rate at which nations progress this target will have a bearing on the role that biological systems play in ocean carbon storage. In addition, the regulatory regime around deep sea mining is complex and rapidly evolving. The precise details of how this unfolds will be an important factor (Pickens et al., 2024)

<sup>27</sup> See <https://hahana.soest.hawaii.edu/hot/dataaccess.html>

7. **Future trajectories of plastics production**, waste generation and the proportion that accumulates in the surface ocean, throughout the water column, and at the seafloor.
8. **The current and future impacts of plastics** upon critical ocean functions including carbon cycling, particle sinking rates, microbial ecology and fisheries productivity.

### Actions to be taken

- I. **Generate information on the key processes within the biological pump** (such as grazing, particle sinking, remineralization and plankton mortality), that are likely to be impacted by industrial extraction and the addition and degradation of plastics. Multiple approaches to address this can be envisaged ranging from *in vitro* incubations (Geisen et al., 2022), mesocosm studies (e.g. Lagaria et al., 2017) and *in situ* studies potentially around mine tailing discharge (e.g. Ramirez-Llodra et al., 2022) as an analogue for deep sea mining discharges.
- II. **Quantify the lability and bioavailability of material released from the seabed during industrial activities and that produced through photodegradation of plastics.** Studies to address this should take place at a range of scales, from bottle incubations, through to *in situ* studies along trophic gradients (e.g. Pusceddu et al., 2005) and large scale meta analyses / modelling (e.g. Zhang et al., 2024).
- III. **Improve knowledge on the resilience of carbon sequestration** to distortions / reorganisations of food webs by fisheries.
- IV. **Undertake coherent and targeted research on the effects of fishing, industrial processes (including wind farms) and plastic pollution** on plankton ecology and biogeochemistry in a range of settings, including the continental shelves.
- V. **Improve numerical models to receive, use and generate new information:** many of the models that we currently use to predict the future evolution of climate contain simplified representations of the ecosystem that do not consider or parameterise explicitly the key processes (such as photochemistry and competition between bacteria and phytoplankton for nutrients), taxa and functional groups that will be impacted by human activity in the ocean.

VI. **Adapt fishery ecosystem models to provide explicit knowledge about the consequences of removing large numbers of fish**, e.g. reduced deadfall and defecation flux. This problem is much more difficult for the shelf than for the off-shelf seas, and effort should be focussed there.

VII. **Develop regionally focussed ocean system pathways to drive numerical models**, informed by representative stakeholder consultations encompassing both the groups that regulate human activities in the ocean and those that seek to undertake these actions for profit.

### 3.e Future changes in the carbon cycle from deliberate ocean-based climate interventions

*Phillip Williamson, Nina Bednaršek, Jean-Pierre Gattuso, Nianzhi Jiao, Robert C. Steenkamp, Erik van Doorn, Philip W. Boyd*

There are two main groups of ocean-based climate interventions: those aiming to reduce atmospheric CO<sub>2</sub> (mCDR; **Figure 8**); and those intended to reflect sunlight (solar radiation management, SRM). Whilst ocean-based SRM methods (e.g. marine cloud brightening and sea-surface foams) are likely to impact ocean ecosystems, and therefore the carbon cycle, such effects would be indirect, through changes in light availability, temperature, and ocean mixing. SRM approaches are therefore not considered further here.

Climatically-meaningful mCDR (i.e. at Gt scale) would necessarily change the carbon cycle: that is its purpose. However, many marine processes can be used for initially capturing carbon, with many different pathways for the subsequent fate of captured carbon. As a result, there is high method-specificity for carbon-related consequences, and for other environmental impacts, scalability, and storage durability. These factors affect acceptability and cost, hence the likelihood of implementation.

*Biologically-based mCDR approaches include:*

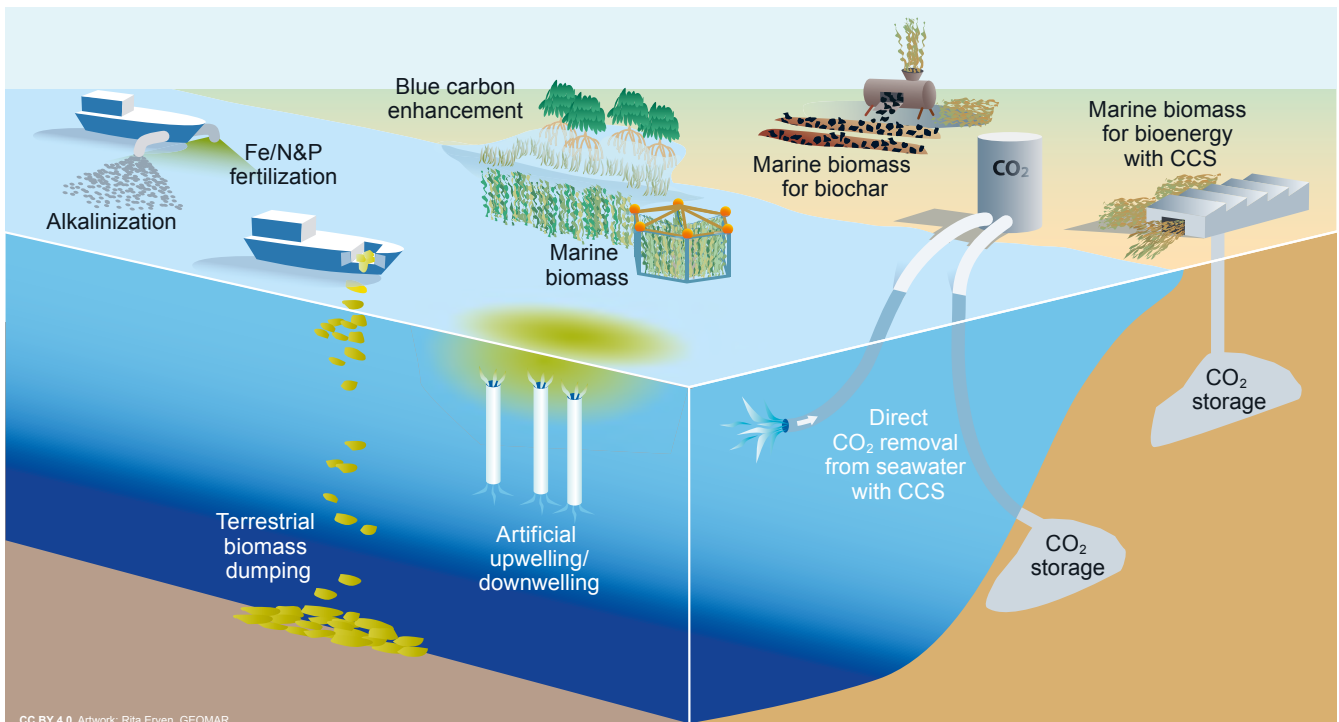
- **Coastal blue carbon:** the restoration of mangrove, saltmarsh and seagrass ecosystems that accumulate organic carbon in their sediments.
- **Large-scale seaweed cultivation** (also known as ocean afforestation), with either deep-sea sinking of macro-

algal biomass (with impacts on benthic ecosystems and seafloor pH and  $O_2$ ) or its removal to land for processing into biofuel (with carbon capture and storage) or biochar.

- *Ocean fertilization* to increase phytoplankton productivity and subsequent deep-water carbon sequestration through the biological pump. Fertilization can be achieved by directly adding limiting micronutrients (ocean iron fertilization) or macronutrients (nitrogen or phosphorus), or by physical manipulation, increasing nutrient supply through enhanced upwelling. The latter has the counterproductive effect of bringing  $CO_2$ -rich water to the surface.

Chemically-based mCDR involves the manipulation of carbonate chemistry, for example:

- *Adding alkaline minerals*, to convert dissolved  $CO_2$  to carbonate and bicarbonate ions, thereby increasing the ocean capacity to take up anthropogenic  $CO_2$  from the atmosphere, and potentially mitigating ocean acidification at the local level. This is referred to as ocean alkalinity enhancement (OAE).
- *Electrochemical  $CO_2$  removal* from seawater, with its subsequent collection and geological storage (direct ocean removal, DOR). After further processing, climate benefits are obtained when  $CO_2$ -depleted seawater is released and re-equilibrates with the atmosphere.



**Figure 8.** Overview of carbon dioxide removal approaches using ocean processes and ocean-land linkages.

Source: "Carbon dioxide removal: overview of options II" by Rita Erven, GEOMAR, licensed under CC BY 4.0, [www.cdrmare.de/en/spp-1689-materialien/](http://www.cdrmare.de/en/spp-1689-materialien/)

In addition, a range of land-ocean hybrid methods would involve ocean storage for carbon initially captured on land (e.g. Raven et al., 2024; Zhu et al., 2024).

For further details of specific methods, and discussion of their effectiveness, risks, costs and governance, see Gattuso et al. (2018, 2021), GESAMP (2019), Hoegh-Guldberg et al. (2023), Cai and Jiao (2022), NASEM (2022), Williamson et al. (2022), Zhang et al. (2022),

Cross et al. (2023), Jiao et al. (2023), Doney et al. (2024), Roberts et al. (2024), and Oschlies et al. (2025).

Unlike land-based CDR, mCDR has yet to be included in IPCC mitigation scenarios. That is due to scientific uncertainties regarding effectiveness and potential environmental risks, in addition to legal constraints. In particular, open-ocean mCDR methods are currently strongly discouraged as geoengineering under the UN Convention on Biological Diversity (CBD), and the

deployment of ocean fertilisation is restricted under the London Protocol (IMO, 2023). Furthermore, the International Tribunal for the Law of the Sea (ITLOS) has recently designated anthropogenic CO<sub>2</sub> as a marine pollutant, with hazards that should not be transferred from one area to another (ITLOS, 2024; Klerk, 2025).

In contrast, coastal blue carbon has relatively high public and political acceptability. This 'nature-based' mCDR approach was identified as a climate mitigation policy in 23 initial Nationally Determined Contributions to the Paris Agreement (Gallo et al., 2017) and was considered a no-regrets action by Gattuso et al. (2021) on account of its important co-benefits. However, IPCC assessed the mitigation potential of coastal blue carbon as 'very modest' or 'small', at 0.05 – 0.3 Gt CO<sub>2</sub> per year (Bindoff et al., 2019; Canadell et al., 2021), and there are concerns that such removal rates may be over-estimated (Williamson and Gattuso, 2022).

## Major knowledge gaps

### 1. Demonstrating safety and long-term effectiveness.

The potential climatic benefits of other mCDR methods (with much greater theoretical CO<sub>2</sub> removals) could arguably be achieved if their main knowledge gaps could be resolved, demonstrating their safety and long-term effectiveness. NASEM (2022) recommended a ~\$1.5 billion mCDR research program to address such issues, in the context of increasing need for CDR to meet the internationally-agreed goal of net zero (IPCC, 2023), together with realisation of the limitations of land-based CDR approaches (Boysen et al., 2017; Deprez et al. 2024). There are also market opportunities for UNFCCC-approved carbon trading under Article 6.4 of the Paris Agreement.

### 2. Demonstrating additionality.

To qualify for emission credits, mCDR methods need to demonstrate additionality: i.e. that their climate benefits are unequivocal and can be reliably measured relative to a well-established baseline (Michaelowa et al., 2019). Uncertainties relating to additionality are crucial for mCDR research and development (Boyd and Bressac, 2016; Bach 2024; Bach et al., 2024), requiring information on the energy used (as

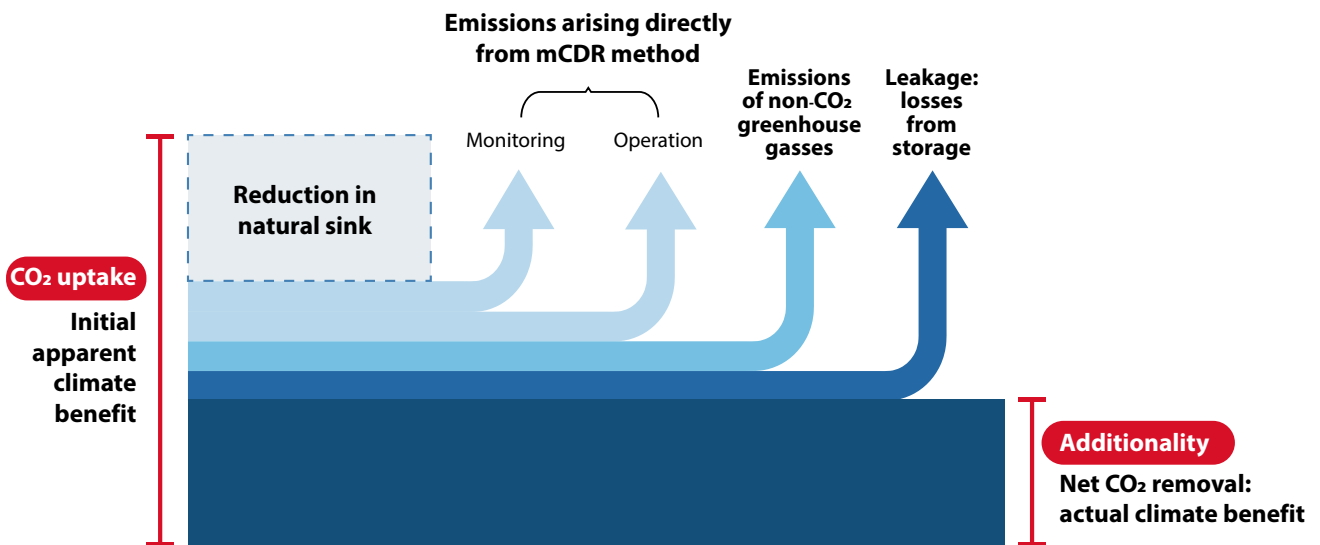
CO<sub>2e</sub>) to carry out the mCDR action as well as an assessment of all its climate-related biogeochemical consequences; i.e. a fully comprehensive life cycle analysis (Terlouw et al., 2021; Delval et al., 2025), relative to a counterfactual baseline.

Many of those consequences (shown conceptually in **Figure 9**) will likely occur over large spatial and temporal scales, influenced by ocean conditions over thousands of km<sup>2</sup> and decadal-to-century time periods. Their robust quantification is extremely challenging, with future conditions depending on emission scenarios.

Although models can greatly assist in determining mCDR additionality for open-ocean mCDR (Zhou et al., 2024), direct measurements will still be needed, not only of carbon-related parameters (Doney et al., 2024) at much greater accuracy than currently possible (McKinley et al., 2024) but also of other environmental impacts (that may be adverse or beneficial) within a regulatory framework of Monitoring, Reporting and Verification (MRV; Smith et al., 2024). Such monitoring is itself likely to involve significant CO<sub>2e</sub> emissions, affecting the cost-effectiveness of the intervention.

The relative importance of factors determining mCDR additionality is technique-specific. However, for most mCDR actions, the following are relevant (in addition to CO<sub>2e</sub> costs for implementation and MRV):

**2.1 Reduction in natural carbon sinks**, shown as a dashed rectangle in **Figure 9**. Increasing local productivity through ocean fertilization can decrease productivity 'downstream' through nutrient depletion (Gnanadesikan et al., 2003; Aumont and Bopp, 2006; Tagliabue et al., 2023), with similar effects occurring for large-scale seaweed cultivation (Berger et al., 2023). Abiotically-induced regional changes in the ocean carbon sink may also affect terrestrial sink efficiency (Keller et al., 2018; Boyd et al., 2025), as also likely for ocean storage of land-derived biomass. These feedback effects need to be taken into account when comparing mCDR effectiveness with any other CDR approaches (Yamamoto et al., 2024; Jeltch-Thömmes et al., 2024; Oschlies et al., 2025).



**Figure 9.** Conceptual representation of additionality (excluding albedo effects) for a generic mCDR action, adapted from Bach et al. (2024). See text for details.

## 2.2 Emission of non-CO<sub>2</sub> greenhouse gases.

Anaerobic conditions in coastal sediments and mid-water oxygen minimum zones favour methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) production, with the potential to significantly offset the CO<sub>2</sub> removal benefits of coastal blue carbon (Rosentreter et al., 2021, 2023) and ocean fertilization (Law and Ling, 2001). Measurement of the efflux of these gases therefore needs to be included in MRV protocols. For seaweed cultivation, the production of dimethyl sulphide (DMS) and halomethanes (e.g. bromoform, CHBr<sub>3</sub>) may also have climatic impacts (Carpenter et al., 2009).

**2.3 Leakage.** The non-permanence of carbon storage for most biotic mCDR approaches is a cause for concern, since the durability of CO<sub>2</sub> removal is critical for effective climate mitigation (Brunner et al., 2024). For ocean fertilization, leakage results in declining effectiveness over time for global-scale deployment (Aumont and Bopp, 2006; Oschlies et al., 2025); similar effects are likely for seaweed cultivation with deep-sea biomass sinking. For coastal blue carbon, rising sea level, warmer temperatures, and human disturbance all threaten the long-term integrity of carbon stores (Williamson and Gattuso, 2022).

## Actions to be taken

### I. Model improvement

Roberts et al. (2024) reviewed the inclusion of CDR-relevant parameters in marine ecosystem models and ESMs. They identified 14 deficiencies with medium/high relevance to specific mCDR methods: most related to seaweed cultivation, including the effects of changes to surface ocean ecosystems, benthic smothering, and the attraction of seafloor biomass to deep sea fauna.

Modelling priorities identified by Buesseler et al. (2024) for ocean iron fertilization included observing system simulation experiments, storage durability, and the biological carbon pump. Despite the research attention given to the biological carbon pump, many aspects remain poorly understood (Henson et al., 2022; Baker et al., 2022; **Sections 3.a, 3.b, 3.d** and **4.a**).

### II. Field experiments and operational deployment

Buesseler et al. (2024) also proposed a new generation of iron fertilization field experiments, of larger size and longer duration than previously,

to improve understanding of carbon fluxes and environmental impacts. MRV protocols should also be developed and tested, using autonomous platforms and novel biogeochemical sensors (including for total alkalinity and dissolved inorganic carbon). Relatively few field experiments have been carried out on ocean alkalinity enhancement (Cyronak et al., 2023). Although controversial (Cornwall, 2024), these are needed to demonstrate safety (or otherwise) and should be closely linked to experimental studies of potential biological impacts (Bednaršek et al., 2025; Ferderer et al., 2022), as well as high-resolution modelling of physico-chemical processes and exposure risk (Laurent et al., 2025; Wang et al., 2025).

The only mCDR method currently in operational deployment is coastal blue carbon, regulated through the voluntary carbon market. It is unclear whether the MRV protocols developed to date (e.g. VERRA, 2023) meet UNFCCC certification requirements, since major methodological uncertainties remain (Kristensen et al., 2025; Dahl et al., 2025; Williamson et al., 2025).

### **III. Updated comprehensive assessment of proposed marine-based climate interventions**

An updated version of the GESAMP (2019) report is needed to provide a systematic, policy-relevant review of the effectiveness and feasibility of mCDR methods. In addition to potential for climate mitigation, assessments of wider implications should include environmental effects on biodiversity, ecosystem functioning, and ecosystem services – issues not always well-covered in other reviews. The new Scientific Summary for Policymakers released in 2025 provides a first overview in this respect (GESAMP, 2025).

### **IV. Improving mCDR credibility**

The scientific literature shows that a wide range of interventions to increase the ocean uptake of CO<sub>2</sub> are theoretically possible. Further research on the ocean carbon cycle and related ecological processes should help resolve key knowledge gaps; such research will also be necessary to establish a wider consensus on whether or not mCDR can contribute to a credible and scalable climate mitigation strategy, that is also both societally and politically acceptable.

# 4. Approaches to achieve Integrated Ocean Carbon Research

## 4.a Support for sustained ocean carbon observing systems

*Rik Wanninkhof, Richard A. Feely, Dorothee C. E. Bakker, Nianzhi Jiao, Richard Sanders, Ute Schuster, Jamie Shutler, Andrew Watson*

Sustained ocean carbon and environmental observations are critical to monitor changes in the surface and deep ocean to inform policies for emissions reductions. This will aid timely implementation of adaptation and mitigation efforts necessary to address rising atmospheric CO<sub>2</sub> levels. Furthermore, these observations are needed to monitor and guide ocean health issues caused by rapidly increasing greenhouse gas concentrations and other changes in the upper ocean. The trends and variability of the sea-air CO<sub>2</sub> fluxes can also be used in tandem with emissions and atmospheric CO<sub>2</sub> levels to constrain the land carbon fluxes and any resulting policy guidance (Shutler et al., 2020). Systematic observations of ocean carbon and related biogeochemical variables provide unprecedented opportunities to quantify and understand biogeochemical processes in a changing ocean.

The IOC-R effort identifies the need for sustained *in situ* and satellite observations through enhancing existing and establishing new observing networks capable of making ocean carbon and relevant biogeochemical observations. These networks with associated data management and service capacities, along with improved mechanistic understanding, modeling, and machine learning approaches, are critical elements of an ocean carbon observing system. Such an ocean carbon observing system must be sustained on decadal scales and measure specific essential ocean carbon variables for defined goals. They should also meet appropriate requirements for spatial (e.g. 1°x1° at basin-scale or

global) and temporal (e.g. seasonal, monthly, or annual) resolution, as well as data and product delivery times (e.g. real-time, monthly, or within 1 year). Requirements will be application- and science-question-specific. For example, high-frequency daily to weekly 0.25 km x 0.25 km assessments are needed for extreme events such as marine heatwaves, but monthly data at 1°x1° are adequate for global and annual net ocean CO<sub>2</sub> sink or acidification assessments.

Complementary ocean observing networks covering the surface to deep ocean are necessary for a comprehensive ocean carbon observing system. Established efforts such as the decadal global ocean surveys under the aegis of GO-SHIP<sup>28</sup>, a GOOS<sup>29</sup>-endorsed network, are essential in providing reference-quality observations to discern the changes in the interior ocean, including storage of anthropogenic carbon. The reference quality measurements serve to check observations and add information to other networks, such as the BGC-Argo (Biogeochemical Argo) float array. This array provides measurements from the surface to 2000 m depth at 10-day intervals of oxygen, nitrate, pH, chlorophyll-a, suspended particles, and downwelling irradiance, in addition to the standard Argo float measurements of temperature, salinity, and pressure. The BGC-Argo network<sup>30</sup> is of particular importance for elucidating the biological carbon pump. Quantifying decadal changes in the ocean carbon cycle is aided by the decadal reoccupation of ocean transects in all major basins under the aegis of the GO-SHIP network that also serves as an example of successful international partnerships and engagement.

28 See GO-SHIP: [www.go-ship.org/](http://www.go-ship.org/)

29 See GOOS <https://www.goosocean.org/>

30 See BGC-Argo: <https://biogeochemical-argo.org>

An emerging network in GOOS that is of high relevance for IOC-R is the Surface Ocean Carbon Observing Network, SOCONET<sup>31</sup> (Wanninkhof et al., 2019; 2025). This network will help to further integrate ocean carbon observations into the information delivery mechanisms for critical management and policymaking bodies, such as UNFCCC assessments, WMO's State of the Climate Report, and the WMO's Global Greenhouse Gas Watch (G3W), a WMO Flagship Program (Carmichael et al., 2024). The G3W has the objective to deliver monthly CO<sub>2</sub> fluxes and emissions at 1°x 1° resolution, with a one month delay. The ongoing SOCONET, SOCAT<sup>32</sup> and SOCOM<sup>33</sup> efforts are critical in this endeavor, and the support from the Committee on Earth Observation Satellites (CEOS) will be key to ensuring the satellite observations that the G3W deliverables critically rely upon. These efforts, collectively referred to as the air-sea CO<sub>2</sub> flux observing system, are highlighted in the Declaration on Operationalizing the Surface Ocean Carbon Value Chain (**Figure 10**; IOCCP, 2024).

Ocean carbon observing systems provide an efficient framework for the specified deliverables but also yield information on gaps and can serve as incubators of new ideas and new and improved approaches. They are now beginning to be used to guide conservation and mitigation strategies (e.g. Shutler et al., 2024). Several ocean observing systems operate under the umbrella of GOOS, and, as such, GOOS serves as a means to coordinate and develop synergies and efficiencies between these elements. The provision and support for agency and industry satellite observation sensors and platforms can be guided and coordinated by CEOS. Networks can serve multiple stakeholders, and they often serve multiple objectives, which can facilitate the integration and collaboration required.

### IOC-R priorities

1. **Establishing and maintaining the disparate observing systems requires operational approaches** (e.g. sustained funding and dedicated human resources and technical infrastructure) that are not fully embraced by government funding agencies nor by relevant operational agencies.
2. A systematic approach and resources are needed to execute each step of the value change process. A proper **emphasis on data curation, including quality control**, is necessary.
3. There is a **lack of authoritative requirements** (e.g. a definitive statement of the minimum quantity and quality) **for ocean carbon observing networks**.
4. **Regular intercomparisons of instrumentation** (including new technology) and access to reference materials for core variables are crucial to ensure the delivery of globally comparable data.

### Actions to be taken

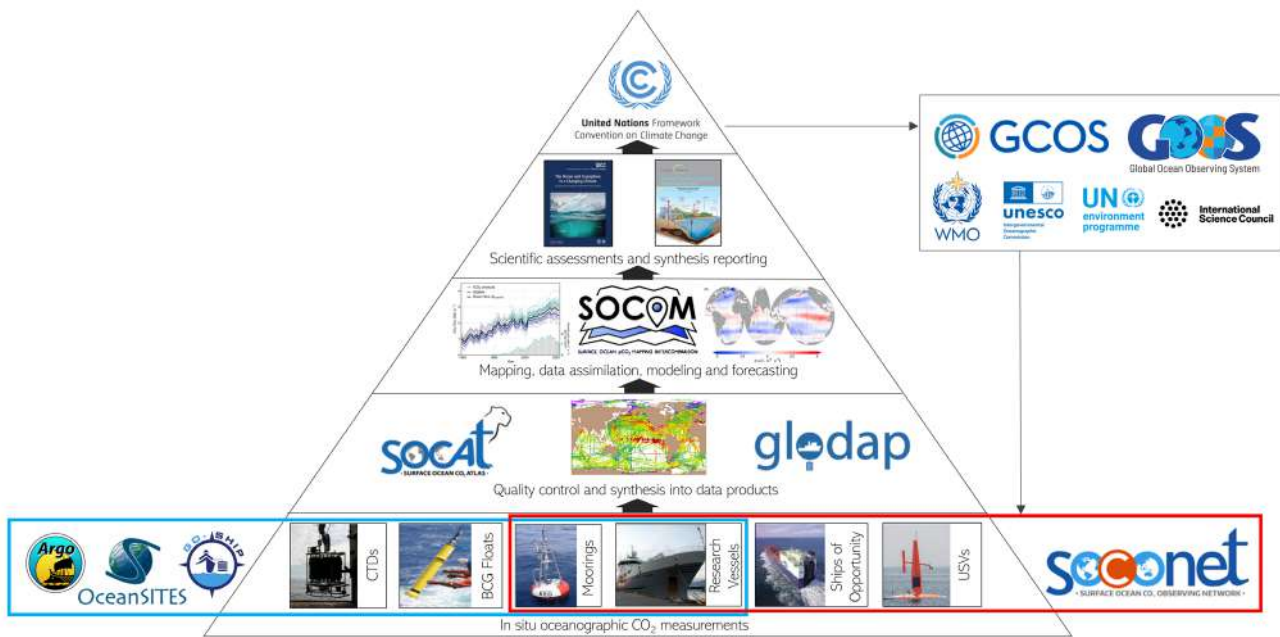
Efforts to sustain long-term observations and encapsulate them into an observing system concept are critical and include:

- I. **Engaging with the operational communities**, such as marine meteorological services, on operational practices and procedures;
- II. **Developing sustained funding mechanisms** beyond the traditional research funding agencies such as governmental and private sector operational services;
- III. **Establishing working groups on requirement setting for operational ocean carbon networks** in coordination with GOOS.

31 See SOCONET: [www.aoml.noaa.gov/ocd/gcc/SOCONET/](http://www.aoml.noaa.gov/ocd/gcc/SOCONET/),

32 See SOCAT: [www.socat.info](http://www.socat.info)

33 See SOCOM: <https://www.bgc-jena.mpg.de/SOCOM/>



**Figure 10.** The value chain of inorganic ocean carbon measurements. The base of the value chain is the in situ measurement of ocean carbon and other biogeochemical and physical variables from a variety of programs and platforms, e.g. moorings, research vessels, and uncrewed surface vehicles. Observations are coordinated through observing networks such as Soconet for the surface ocean, utilizing one set of observing platforms (examples such as moorings and research vessels in red box) and through observing networks such as Go-Ship, OceanSITES and Argo for the interior ocean utilizing a different set of observing platforms (examples such as CTDs and BGC-Argo in blue box). The data are then stored at data centers and quality controlled for consistency and synthesis in programmes such as SOCAT. At the next level, the observational products are used for mapping and modeling purposes, such as within the Surface Ocean CO<sub>2</sub> Mapping and Intercomparison Project, SOCOM. These outputs are, in turn, used in scientific assessments where they provide guidance for policy, such as within the United Nations Framework Convention on Climate Change (UNFCCC) processes. The needs and guidance from intergovernmental organizations are relayed back to the observational, synthesis, and modeling community in a feedback loop through the Global Climate Observing System (GCOS) and the Global Ocean Observing System (GOOS). Figure amended from Figure 2.2 in Guidi et al., 2020.

#### 4.b Integration of sensor technologies and platforms critical for ocean carbon observation

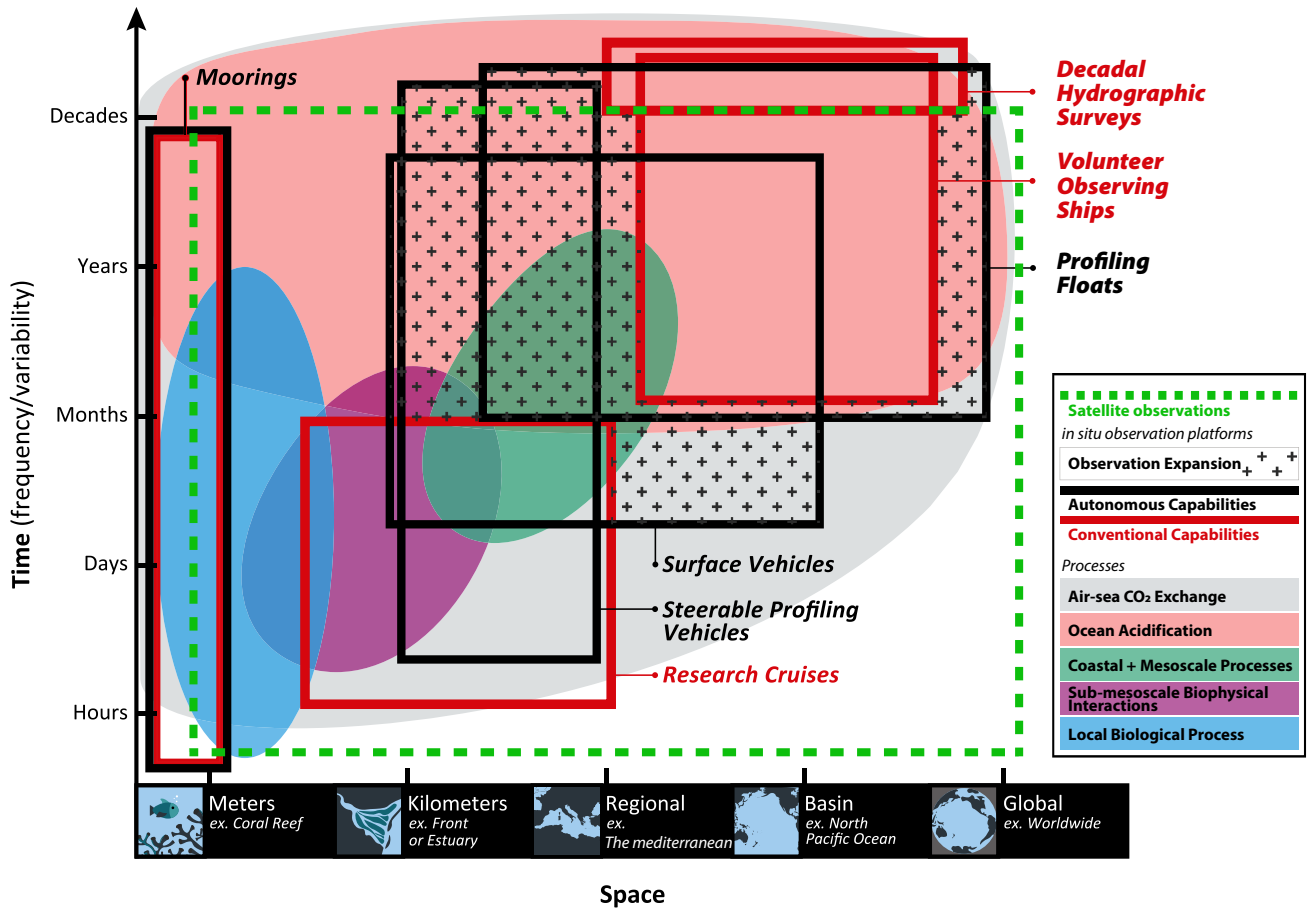
*Kenneth S. Johnson, Jamie Shutler, Socratis Loucaides, Ute Schuster*

Resolving the driving processes for the upper ocean carbon cycle, such as the role of biology, in controlling ocean carbon storage or the air-sea CO<sub>2</sub> flux, will require comprehensive, biogeochemical observations with seasonal resolution and an appropriate spatial scale across the global ocean. The rationale for such observations is presented in **Section 4a**. Making these sustained observations requires a system of robust and distributed autonomous *in situ* observing platforms and sensors, as well as orbiting satellites. These sustained observations must be routinely supported by reference

instruments and systems installed on moorings, uncrewed vehicles, and crewed ocean-going ships. These sensors and reference systems must scale to large networks that observe the global ocean for key parameters and, in many cases, must extend from the surface through the water column. The data products provided by observing systems should be capable of resolving decadal scale change. The use of AI methods to gap-fill the real-time data returned by autonomous sensor systems might enable the production of biogeochemical products with little to no time lag (e.g. Sharp et al., 2023). These products will enable novel applications in fisheries and carbon cycle studies.

Oceanographic observations from ocean-going ships provide an essential baseline, often with higher accuracy, for long-term observations and function as reference measurements for all other observation platforms. Ships also provide the necessary platforms for targeted process or experimental studies, and several biological processes, which contribute to the efficiency or otherwise of ocean carbon storage cannot be measured

with uncrewed systems. However, individual ships or uncrewed platforms cannot sample or view the global ocean, so satellite observations from space are needed to gain a synoptic view. The combination of all of these observation and analysis technologies will result in a truly global system with seasonal resolution, often in real-time, whilst being logistically, economically, and scientifically efficient (**Figure 11**).



**Figure 11.** *In situ* and satellite observational capabilities and carbonate system processes as a function of time and space. Ocean processes that affect the carbonate system (solid color shapes - labeled in the legend) are depicted as a function of the temporal and spatial scales over which they must be observed to capture important variability and/or long-term change. Figure adapted from Bushinsky et al. 2019.

*In situ observations and capabilities*

A variety of different sensors and uncrewed platforms have been, and are being, developed, which enable an essential set of biogeochemical observations (Chai et al., 2020).

Platforms include surface drifters, moorings, uncrewed surface vehicles, buoyancy-driven gliders, propeller driven uncrewed profiling vehicles, and profiling floats (**Figure 12**). The ability to operate large arrays of uncrewed platforms at the global and decadal scales,

and successfully integrate the data from hundreds of independent sensors, has been demonstrated by the successful surface drifter program (Laurindo et al., 2017) and the profiling floats of the Argo program (Riser et al., 2016; Claustre et al., 2020; Roemmich et al., 2019).

A challenge now is to operate networks of these platforms with different spatial and temporal reach in regions including the harshest conditions such as the Southern Ocean.

A set of chemical and biological sensors that are capable of long-term operation on these platform arrays now enable a variety of biogeochemical processes to be observed over large regions (Claustre et al., 2020; Sarmiento et al., 2023). Surface ocean carbon dioxide partial pressure ( $p\text{CO}_2$ ) is critical to quantify the uptake of atmospheric  $\text{CO}_2$  by the ocean. Infrared sensors with gas calibration standards provide data to allow surface ocean  $p\text{CO}_2$  to be tracked over full annual cycles on surface moorings (Sutton et al., 2014; 2019) and over great distances on uncrewed surface vehicles (Sutton et al., 2021). Primary productivity (Johnson and Bif, 2021), net community production (Emerson and Yang, 2022) and respiration (Hennon et al., 2016), which drive the biological carbon pump, can be tracked across ocean basins with data from oxygen sensors on large arrays of profiling floats. Ultraviolet (UV) optical nitrate sensors also provide data to track net community production (Arteaga et al., 2019) and investigate the linkage to dissolved inorganic carbon (DIC; Johnson et al., 2022) at the scale of ocean basins. Sensors for pH provide data to track acidification (Mazloff et al., 2023), seasonal variations in upper ocean  $p\text{CO}_2$  (Bushinsky et al., 2019), and the coupling of deep physical processes to regional variations in air-sea  $\text{CO}_2$  flux (Prend et al., 2022). Bio-optical sensor data can be used to track production (Stoer and Fennel, 2023), export (Dall’Olmo et al., 2016; Lacour et al., 2023) and loss of particulate organic carbon (Kheireddine et al., 2020). The challenge now is to extend the set of chemical and biological sensors to allow for greater resolution of carbon cycling and quantifying the driving processes at the global scale.

#### *Satellite-based observations and capabilities*

Satellite observations allow synoptic scale processes to be mapped with high spatial resolution across the ocean and over decadal time scales. These remote sensing observations are now a fundamental component for all global scale observation-based carbon assessments (**Section 4.c**; Shutler et al., 2020; Brewin et al., 2023; Shutler et al. 2024). Satellite ocean color and sea surface temperature observations are extensively used to estimate surface biological state and production enabling, for example, estimates of chlorophyll-a, net primary productivity, net community production, and the distribution of particulate inorganic and organic carbon (Brewin et al., 2023). Hyperspectral data are now beginning to be used for the identification of phytoplankton functional groups and other relevant ocean carbon parameters<sup>34</sup>.

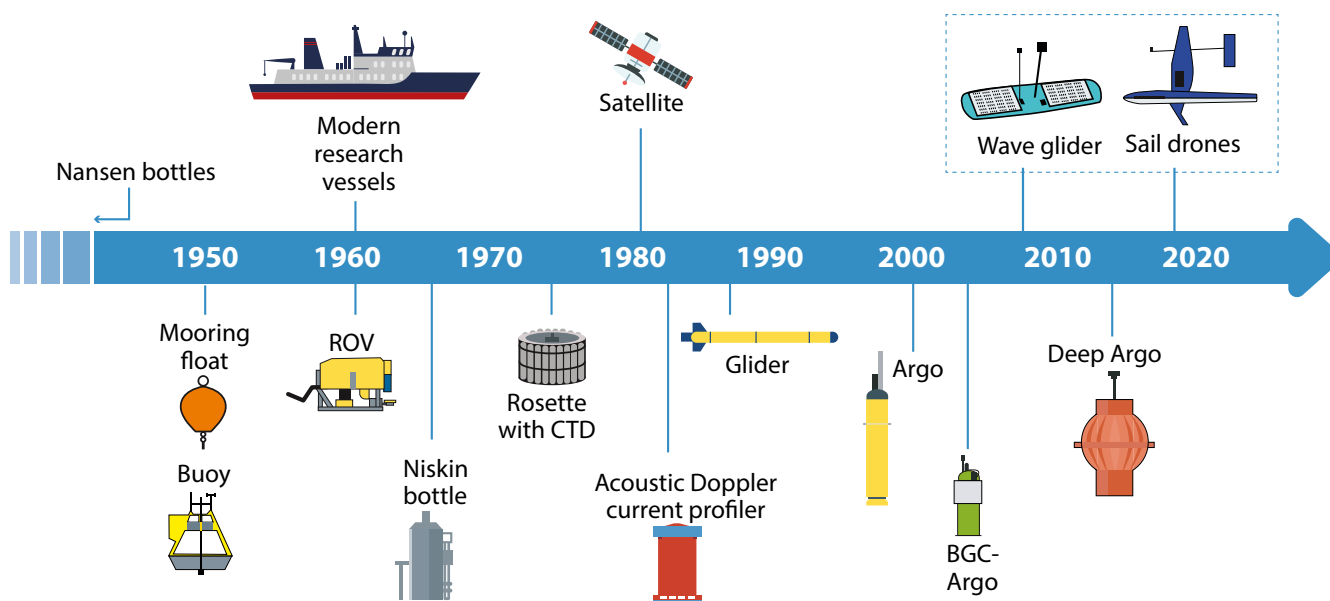
Machine learning and artificial intelligence methods used to intelligently gap-fill the sparse *in situ* surface ocean  $\text{CO}_2$  data use satellite data to drive the algorithms (e.g. Landschützer et al., 2016; Watson et al., 2020; Gregor and Gruber, 2021). The resultant data are then used, in conjunction with more satellite observations and reanalysis data, to estimate global and regional air-sea  $\text{CO}_2$  exchange and the ocean  $\text{CO}_2$  sink (e.g. all observation-based ocean sink methods in Friedlingstein et al., 2025). Beyond this, satellite observations in combination with *in situ* data are increasingly being used to quantify all surface water carbonate chemistry variables (e.g. Gregor and Gruber, 2021; Land et al., 2019). Consequently, both satellite observations and *in situ* data are fundamental to any global ocean carbon monitoring approach (Shutler et al., 2024). Merging satellite observations with bio-optical data from BGC-Argo profiling floats enables depth-resolved observations to be extended from the surface into the ocean interior (Fox et al., 2024; Stoer and Fennel, 2024). Such combined products demonstrate the synergism that results from operating multiple types of sensor arrays.

### IOC-R priorities

#### 1. Sensors for ocean carbon observations

Only a small set of chemical and biological sensors have capability for large-scale, sustained observing. In addition, these systems do not encompass all of the desired chemical species. *In situ* and remotely sensed DIC and alkalinity concentrations (TA) are essential to understanding the evolving ocean stocks of these species and will be essential if mCDR by altering ocean alkalinity becomes widespread. Dissolved inorganic carbon (Fassbender et al., 2015; Wang et al., 2015) and alkalinity sensors (Briggs et al., 2020) are in the early stages of development. While capable  $p\text{CO}_2$  sensors are available for surface measurements, and synergistic satellite and *in situ* approaches enable synoptic scale observations, systems or approaches with comparable performance for subsurface observations are still emerging. Commercial sensors that are capable of submerged  $p\text{CO}_2$  and pH measurements do exist, but various limitations in stability, precision, reliability, or power requirements have prevented widespread adoption for the required long-term deployments of large network arrays.

<sup>34</sup> See Pace project: <https://pace.oceansciences.org/>



**Figure 12.** Timeline of oceanographic observation platforms that support biogeochemical understanding and capabilities. Sensor and platform development has developed towards autonomous systems including surface drifters, moorings, uncrewed surface vehicles (USV), buoyancy-driven gliders, propeller driven autonomous profiling vehicles, and profiling floats. Oceanographic observations from ocean-going ships provide an essential baseline to verify and calibrate all of these platforms and systems. Figure adapted from Chai et al. 2020.

A variety of additional *in situ* sensors would be useful to fully characterize the ocean carbon cycle. Particulate inorganic carbon (PIC) sensors would shed light on the effects of ocean acidification on calcium carbonate production. Prototype PIC sensors have been developed (e.g. Bishop et al, 2022), but they have not yet been demonstrated during extended deployments on autonomous platforms. Sensors for dissolved organic carbon (DOC) would be highly desirable. Sensors for fluorescent dissolved organic matter (FDOM) have been used to track particle dynamics (Organelli and Claustre, 2019). However, there is no quantitative correlation between the FDOM signal and DOC concentrations. Optical backscatter sensors operating at one or two wavelengths can provide a sense of particulate organic carbon concentration, but limited information on particle size distributions (Briggs et al., 2020). More capable imaging systems, which resolve particle size and are capable of deployment on autonomous platforms, are now available (Picheral et al., 2022), and are being

deployed on some BGC-Argo floats but are not yet routinely part of the sensor package.

## 2. Sensors for concurrent biogeochemical measurements

In addition to carbon system specific sensors, observations of additional biogeochemical parameters that influence the ocean carbon cycle would be of use. This includes the ability to observe nutrient supply and specific chemical compounds, such as dissolved orthosilicic acid or various compounds of iron that regulate the uptake of inorganic carbon through photosynthesis. Some *in situ* sensors for these are now available (Mowlem et al., 2021), but further work is needed to increase autonomy (deployment duration) and improve analytical performance. Many of the biological processes involved in the biological carbon pump e.g. respiration rates, egestion rates, carbon content of particles etc. cannot be observed with the sensor suite currently in development.

## Actions to be taken

### I. Sustained observation network

Sustained and integrated actions can strengthen our autonomous observing capability, greatly enhancing our understanding of the ocean carbon cycle. Existing *in situ* observing networks and satellite capabilities routinely rely upon short-term and small-scale funding. Actions for improved global carbon budget assessments must be sustained and expanded to ensure the establishment of a resilient, long-lasting, and high-quality network (**Section 4.a**). Most autonomous biogeochemical observing systems are operated as research projects without long-term support, and many satellite datasets used and relied upon are likely non-optimal as they were originally designed for other uses and not for climate carbon assessments (Shutler et al., 2024). As these systems mature and their capabilities are proven, there needs to be a pathway to move them into a sustained, operational status with the production of climate quality data records. Such records will enable the production of decadal scale, observation-based assessments that are needed to observe climate impacts and feedbacks. The intelligent combination of all sensor types and platforms (**Figure 12**) to achieve internally consistent and depth-resolved carbon budgets has yet to be attempted and could offer a way forward.

### II. Improved suite of sensors

Broadening the suite of sensors and continuing to improve performance of existing sensors is essential to answer key questions, such as the role of biology in modulating the ocean carbon sink and how this may change in the future. The technical challenges to achieve this are significant. Progress will require sustained support for the analytical chemistry, engineering, and technical groups that develop sensors and transition those sensors to commercialization. Further, the often high cost of *in situ* sensors is a major impediment to widespread adoption. For example, there are several manufacturers of high quality oxygen sensors and costs for these systems are relatively affordable, hence they are widely used on autonomous platforms. However, there is only one, widely used and high pressure capable nitrate sensor. The costs for these systems are reported to be 5 to 8 times that of an

oxygen sensor, and so they are used in much lower numbers on autonomous platforms. A challenge here is to reduce cost whilst not compromising data quality to an extent that makes the advancement of human understanding impossible, keeping in mind that the quality is relevant to the desired application.

## 4.c Enhance and co-ordinate carbon observing and synthesis products

*Siv K. Lauvset, Amanda R. Fay, Stephanie A. Henson, Matthew P. Humphreys, Peter Landschützer*

Ocean carbon observation and assessment approaches require extensive coordination and synthesis products due to the complexity and diversity of the global datasets on which these assessments critically rely. For example, co-located high-quality measurements of physical and biogeochemical variables that allow for the separation of natural variability from anthropogenic changes are a key component to monitoring, understanding, and underpinning advice on how to mitigate the impacts of anthropogenic climate change (Tanhua et al., 2021). Presently two major, carbonate chemistry focused community-driven synthesis products - SOCAT (Bakker et al., 2016) and GLODAP (**Figure 13a**; Lauvset et al., 2024) - deliver such quality controlled datasets, but the available observations within these two datasets are biased toward the Northern Hemisphere (**Figure 13**) and specifically to the boreal summer months. The BGC-Argo network<sup>35</sup> provides a comprehensive dataset on ocean biogeochemistry, and while the network is growing, these data still primarily cover the Southern Ocean. Several other data products exist as detailed in Jiang et al. (2025), but, combining the information in these data products is non-trivial due to the lack of interoperability, common metadata vocabularies, and quality control procedures (e.g. Jiang et al., 2022). It is highly likely that sparse *in situ* sampling in some regions or seasons is limiting our ability to provide reliable and robust ocean carbon assessments (e.g. Gloege et al., 2021; Hauck et al., 2023). It is also possible that the future reduction in observations in critical locations could have large detrimental effects on any resulting assessments and policy advice. Similarly, satellite climate quality data records require long-term international efforts in order to cross-calibrate and merge data from multiple satellites (Shutler et al., 2024). These international efforts are often invisible or

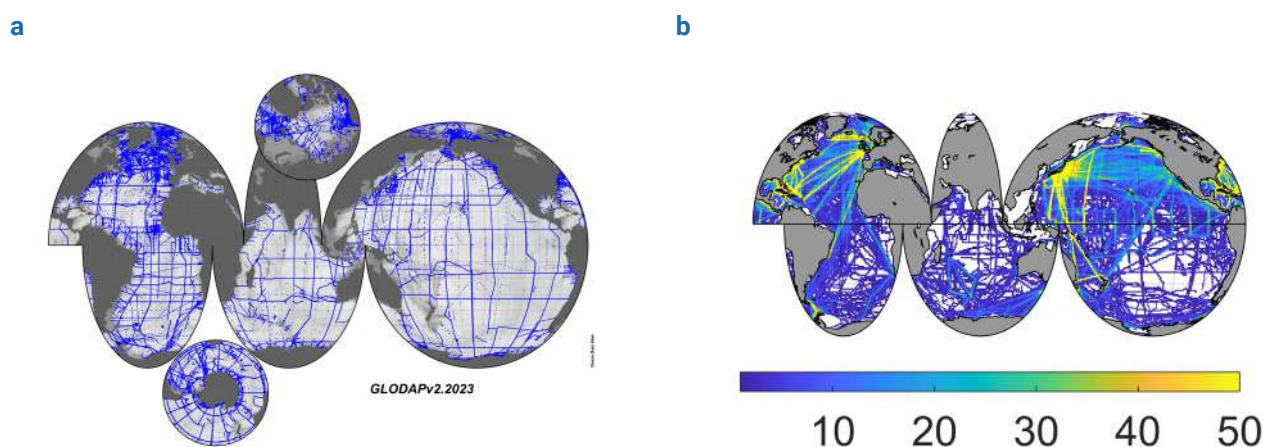
<sup>35</sup> See Biogeochemical Argo: <https://biogeochemical-argo.org>

overlooked, by both scientists and policy makers, but they require continued and ongoing support as without them global-scale carbon assessments would be impossible (Shutler et al., 2024).

The spatial and temporal distribution of surface ocean carbon observations is highly variable, and there are large gaps in both space and time where no data exist (**Figure 13b**). Thus, observations are combined with data from remote sensing, reanalysis information and models of varying complexity (from statistical analysis to artificial intelligence) to create gap-filled fields on a regular spatial grid and with uniform temporal frequency (see Jiang et al., 2025 for a comprehensive list). These elaborated products are then used to assess the global ocean carbon sink strength and its variations in time (Friedlingstein et al., 2025). The Surface Ocean  $p\text{CO}_2$  Mapping Intercomparison (SOCOM) provides a framework and community for comparison and evaluation of gap-filled surface ocean  $p\text{CO}_2$  and air-sea  $\text{CO}_2$  flux products (e.g. Rödenbeck et al., 2015, Roobaert et al., 2024), and is helping to guide community best practice and address questions about data sparsity and drivers of uncertainties. Use of these products range from inclusion in the annually updated Global Carbon Budget<sup>36</sup> (Friedlingstein et al., 2025) and other synthesis efforts, such as RECCAP

and IPCC reports, to hypothesis-driven research, such as extreme event analysis and ocean acidification projections (IPCC, 2021; DeVries et al., 2023; Burger et al., 2022; Jiang et al., 2019).

To answer key knowledge gaps, such as changes in ocean heat, oxygen, and carbon content, observation-based data products covering the entire water column are needed (Tanhua et al., 2021), but the spatial and temporal distribution of interior ocean carbon data is even more sparse than for the surface (e.g. Lauvset et al., 2024). There has been little in terms of coordinated work on gap-filled and elaborated products for the interior ocean. This was one of the motivations for the creation of the SCOR Working Group 168 (4D-BGC<sup>37</sup>), which is coordinating scientific communities involved in developing and validating gridded four dimensional data products from observational datasets - especially the BGC-Argo network. Efforts at mapping biological carbon storage have focused on mesopelagic POC content and fluxes by merging the BGC-Argo network dataset with satellite observations using machine learning approaches (e.g. Sauzède et al., 2024; GLOBESINK project<sup>38</sup>). As for the surface ocean products, an overall aim is to guide community best practice and address questions about sensor quality and data sparsity and drivers of uncertainties.



**Figure 13. a)** Location of stations in GLODAPv2.2023. Source: GLODAP, Lauvset et al., 2016 and Key et al., 2015.

**b)** SOCAT version 2024: The number of individual months with  $1^\circ \times 1^\circ$  gridded surface ocean  $f\text{CO}_2$  between 1970 and 2023. Source: Bakker et al., 2024.

36 See Global Carbon Project: <https://www.globalcarbonproject.org/>

37 See SCOR WG 168 website: <https://4d-bgc.github.io/>

38 See GLOBESINK project: [https://bio-carbon.ac.uk/bio-carbon/sites/bio-carbon/files/documents/Globesink\\_Nathan\\_Briggs\\_Mar23.pdf](https://bio-carbon.ac.uk/bio-carbon/sites/bio-carbon/files/documents/Globesink_Nathan_Briggs_Mar23.pdf)

The observation-based gap-filled products, both for the surface and interior ocean, are also important and useful for model validation and biogeochemical sensor evaluation, and as initial conditions for regional and global ocean models (e.g., Beadling et al., 2023; Lovato et al., 2023; Fu et al., 2022).

### IOC-R priorities

Several areas are identified where there is a need for improved coordination in order to better enhance carbon observing and synthesis products:

- 1. Coordination of observing campaigns:** Despite the great efforts of the observing network GO-SHIP and the emerging observing network SOCONET there is currently limited coordination of observing campaigns. There is also an overall lack of sustained funding for observations and their synthesis, which is critical since biogeochemical data collection is limited by the lack of sensor technology and the time and cost requirements for wet chemical analyses (**Section 4a**).
- 2. Data integration:** There are challenges related to integrating data from various platforms and measurement technologies. Sensors on moorings, floats or uncrewed platforms are often less accurate than 'traditional' ship-based observations, and/or only measure proxies for the desired variables rather than make direct measurements. The sensors also usually measure at much higher temporal resolution, which makes it challenging to combine these two data types (sensors and ship-based observations) into a single data product. Combining data made with different technologies also challenges the quantification of uncertainties in the final product (**Section 4b**).
- 3. Sustained funding to data products:** The creation of elaborated gap-filled data products lacks international coordination and funding. Insufficient financial support does not allow to develop a standardized approach to assess the uncertainties, or to benchmark the reliability of the methods used (only available for SOCOM).
- 4. Integration of marginal seas, coastal areas and riverine fluxes:** Our current observational syntheses and elaborated gap-filled data products are largely open-ocean products and we lack methods that efficiently integrate marginal seas, coastal regions,

and riverine fluxes into a total estimate of the ocean carbon sink (**Section 3.c**).

### Actions to be taken

Regarding carbon observing and synthesis products the recommendations for actions that should be taken involve both high-level and short term actions.

High-level actions:

- I. Improved international cooperation and collaboration** for all steps in the carbon data value chain (observations -> synthesis products -> gap-filled observation-based products, **Figure 10**) is needed. This includes collaborative efforts on data management, data archival, and data quality control. This should comprise clear pathways between the levels of the value chain with clear responsibilities at each layer, culminating in an international strategy for the long-term funding of ocean observations.
- II. The impact of removing data streams** (i.e. simulating the impact of withdrawing a funding stream which supports data collection) as well as the impact of increasing sampling coverage (i.e. the impact of funding specific new *in situ* sampling efforts) needs to be assessed to provide the necessary evidence base to enable continued support of all synthesis products. Such assessments can be achieved via observing system simulation experiments (e.g. Shutler et al., 2024).
- III. International collaboration securing long-term funding** for existing key observational programs such as GO-SHIP and OneArgo<sup>39</sup>, as well as emerging networks such as SOCONET and the BGC-Argo mission of OneArgo is needed.

Specific, short-term, actions include:

- I. Funding to support data synthesis efforts such as SOCAT and GLODAP.** The ocean is very sparsely covered by data so useful gap-filled products begin with properly collated and quality controlled synthesis products.
- II. Funding for efforts such as SOCOM and 4D-BGC** such that the information contained in the data synthesis products can be fully utilized to fill knowledge gaps.

<sup>39</sup> See OneArgo <https://argo.ucsd.edu/oneargo/>

**V. Establishment of federated data systems<sup>40</sup>** to ease interoperability of the various sources of data and metadata, and to make it easier to combine many data streams into one product.

**VI. Increase the utilization of full water column data products** to quantify the ocean carbon sink.

**VII. Establish annual meetings for the communities generating SOCAT, GLODAP, and other observational data products**, with those who develop elaborated gap-filled data products in order to secure enhanced cooperation in the short and long-term.

#### 4.d Next level biological process studies and experiments

*Nina Bednaršek, Philip W. Boyd, Richard A. Feely, Helen S. Findlay, Nianzhi Jiao, Maria Koski, Linbin Zhou*

Effective decision-making and conservation management require a comprehensive understanding of complex ocean carbon dynamics and their interactions. However, our current knowledge is incomplete, especially concerning the integration of physical, chemical, and biological processes across various temporal and spatial scales (Lindenmayer and Likens, 2009). This includes quantifying direct and indirect ecological responses to environmental change and providing ecological data to develop informed ecological syntheses and prognostic ecological models. Current gaps in our understanding of carbon dynamics and their feedbacks are related to modes of action and underlying mechanisms. Some of these gaps can be targeted through integrated studies that simultaneously address the impacts of multiple climate change stressors, the occurrence of extreme events, and their interactions, as well as anthropogenic pressures (fishing, pollution, mining, dredging, and dumping) on the carbon cycle. Differentiating the drivers of biogeochemical and ecological consequences (e.g. enhanced coastal and ocean acidification, hypoxia, eutrophication, and marine heat waves) is especially important in the coastal areas where these drivers overlap. The requirement is to identify the impacts with the greatest magnitude vs. those with the fastest rates of change, the areas of 'extreme' risks vs. resilience, and the impact of mitigation and adaptation strategies (e.g.

marine protected areas, and mCDR), both currently and in the context of future climate change. This research requires new process studies and novel experiments that can close existing knowledge gaps (Frenger et al., 2024).

Investigating the different climatic stressors and anthropogenic pressures on the marine carbon cycle requires common approaches that provide for the integration of laboratory, field, and modelling studies, with mutual cross-validation. This includes studying scenarios related to habitat variability, not only in terms of shifts in average conditions but also regarding the frequency and intensity of extreme events or regime changes. Crucially, the development of scenario-based and mechanistic investigations that provide a conceptual understanding of the interacting mechanisms at play is required to move beyond (empirical) extrapolations that are not based on process-level understanding. Integration between efforts and disciplines also requires solving scalability issues. This includes upscaling understanding from experiments conducted in a laboratory or within mesocosms into field observations and modelling exercises that address non-linearities and identify tipping points in the process (Boyd et al., 2019). Co-located chemical and biological observations need to be integrated into observational networks in a coordinated way using high-resolution modelling and advanced sensor technologies for *in situ* observations (McClure et al., 2023). This can promote the development of indicators and best practices to identify the causality of changes to ocean systems.

Understanding how ecosystems are responding to global climate change requires the development of state-of-the-art synthetic approaches and ultra-high-resolution molecular level techniques for understanding and monitoring biogeochemical processes. For example, high throughput functional gene arrays, single-cell genomics and metatranscriptomics, *in situ* and *in vitro* -omics and eDNA techniques supported through the use of improved isotopic analyses, are needed to provide data on distribution, diet/energy preferences and evolution rates. Such approaches need to be closely integrated with advanced modelling approaches capable of handling non-linearities and complex interactions. Downscaling necessitates linking community-level responses to individual organismal processes, and

<sup>40</sup> A federated data system is a type of meta-database management system, which transparently maps multiple autonomous database systems into a single federated database. It requires standardisation and automation of metadata provision.

identifying potential bottlenecks or vulnerabilities within the ecosystem (Harfoot et al., 2014). Artificial Intelligence (AI) and Machine Learning (ML) approaches offer powerful tools for analyzing large, complex datasets from various sources, automating data processing and analysis, and identifying patterns and correlations needed for developing predictive models (Dong et al., 2022).

The studies that address carbon export, sequestration, and transformation, and their responses to multiple and co-occurring environmental stressors include 1) experimental studies (single species and community); 2) ship-based studies on organismal behavior, ecophysiology, environmental tolerance, and ecosystem processes; and 3) current short-term and long-term *in situ* observations that characterize the biodiversity (genetic, taxonomic or functional traits) and their relation to environmental variables. These approaches aim at determining the mechanisms of interaction with environmental forcing, while also contributing information required for effectively mitigating or managing changes resulting from the anthropogenic pressures. To be able to validate results across scales and contexts, different approaches need to be integrated. This validation, in turn, is essential for the development, calibration, and validation of predictive biogeochemical models, forecasting future changes and proactive management interventions. The outputs from such a combined approach will effectively address ecosystem functioning and resilience and implement specific conservation and management approaches, while also representing a baseline to assess the efficacy and potential impacts of mCDR technologies, including long-term effects and risk assessment.

### IOC-R priorities

The integration of physical, chemical, and biological processes across various temporal and spatial scales will require:

1. Development of **scenario based and mechanistic investigations related to habitat variability**, not only in terms of shifts in average conditions but also regarding the frequency and intensity of extreme events or regime changes.
2. **Application of synthetic approaches and ultra-high-resolution molecular level techniques** for understanding and monitoring biogeochemical processes.

3. **Integration of co-located chemical and biological observations** into observational networks in a coordinated way using high-resolution modelling and advanced sensor technologies for *in situ* observations.

4. More **studies combining experimental and long-term observations** in order to validate results across scales and contexts.

### Actions to be taken

#### I. Conduct large scale manipulation experiments with multiple stressors

Extend manipulative experimental studies that focus on the impact of multiple stressors on individual species, community structure and ecosystem functions. Historically, these experiments have typically manipulated one or more environmental stressors, and have included both coastal e.g., macroalgae (Pessarodona et al., 2023) and pelagic studies, including microbial and plankton communities (Spisla et al., 2021; Riebesell et al., 2017) and ecosystems (Nagelkerken et al., 2020). The stressors typically manipulated in such studies include temperature, pH, dissolved oxygen, nutrients, and light, with a recent focus on mCDR methods including manipulating alkalinity (e.g. Riebesell et al., 2023) and non-essential elements, such as aluminium (Zhou et al., 2018; 2021; 2023). The experiments have produced several recommendations for best practices so that similar studies can be undertaken (Boyd et al., 2018). The essential next step is for such manipulative experimental studies to be conducted on larger scales to more accurately address the implications for carbon export and storage and their environmental effects. Such studies need to include the identification of biological and ecological essential ocean variables (Miloslavich et al., 2018) and early-warning indicators and thresholds (Bednaršek et al., 2017) which directly respond to environmental stressors. *In situ* experimental ecophysiological studies should use a space-for-time approach that investigates multiple co-linear stressors in the field (Bednaršek et al., 2022).

As part of this endeavour, there is an urgent need to strengthen our observational and monitoring capacities of environmental variability in coastal zones, where patterns of variability can change over spatial scales ranging from a few to several hundred kilometres (Vargas et al., 2017; Vargas et al., 2022). Integrating the characterization of environmental variability regimes is essential not only to design more realistic experiments, but also to ensure that future manipulation experiments do not inadvertently expose populations to stressor levels already encompassed within their current environmental variability.

## II. Extend ship-board process studies

Although studies to date have increased our understanding of the processes that result in the production and degradation of sinking particles, gaps remain in matching the carbon budgets in different depth layers (Henson et al., 2022). Budgeting needs to be improved with targeted field and simulated experimental studies (e.g., Jiao et al., 2018), including the use of natural analogues, coupled with digital-twin ocean models (Jiao et al., 2024), that allow for consideration of scaling issues and potential nonlinear effects. Particular attention needs to be given to the processes that account for the impact of viral infection and mesopelagic daily fish migrations.

Hence, it is necessary to extend ship-board process studies that estimate carbon production and abundance, vertical flux, and its fate, integrating across physical, bio-optical, sedimentary, acoustical, metagenomic, and proteomic methodologies. These studies usually centre around the deployments of short-term sediment traps along with autonomous and remote sensing observations to measure the quantity and quality of vertical flux to relate them to water-column processes such as primary production, particle production, particle modification and sinking, consumption through zooplankton activities and bacterial remineralization (e.g. Thomalla et al., 2023), and transformation of organic carbon from labile to refractory states (Jiao et al., 2010; 2014).

## III. Support sustained biological observatories and global biodiversity sampling campaigns

Support sustained distributed biological observatories and global sampling campaigns targeting biodiversity at different levels with the use of advanced technology (e.g. Picheral et al., 2022). Examples of sampling campaigns include BioGO-SHIP (Boss et al., 2022; Clayton et al., 2022), Tara Oceans and the MOSAIC expedition (e.g. Snoeijis-Leijonmalm et al., 2022) that have provided the most complete record of genetic diversity of marine microorganisms to date (e.g. Sunagawa et al., 2020), and have sampled previously inaccessible areas, such as the Arctic Ocean.

Long-term ocean observatories such as PAPA<sup>41</sup> and Hausgarten<sup>42</sup> as well as initiatives like BioGOSHIP<sup>43</sup>, and the Distributed Biological Observatories<sup>44</sup>, a network of stations of advanced sensor technologies on moored equipment (e.g. autonomous platforms, underwater robotics) and transect lines, serve as vital detection arrays for monitoring coupled physical-biological responses (e.g. Swoboda et al., 2024; Kohlman et al., 2024) and should be continued.

## 4.e Modelling the ocean carbon cycle

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Models of the carbon cycle and other key biogeochemical processes have been developed since the 1990s (Fennel et al., 2022). Early models were based on the work of two distinct communities. One community was interested in plankton dynamics, whereas the second community was motivated by understanding the role of the ocean in anthropogenic carbon uptake (Fennel et al., 2022). These two threads were combined in the seminal work by Ernst Maier-Reimer (Maier-Reimer, 1993) and several such models now exist and are incorporated into ocean circulation models and ESMs.

The range of biogeochemical and ecosystem model applications is broad, including re-analyses for the assessment of past and current physical and biogeochemical ocean states, short-term to seasonal and multi-annual forecasts, what-if scenario

41 See <https://www.pmel.noaa.gov/ocs/Papa>

42 See [www.awi.de/en/science/biosciences/deep-sea-ecology-and-technology/observatories/lter-observatory-hausgarten.html](http://www.awi.de/en/science/biosciences/deep-sea-ecology-and-technology/observatories/lter-observatory-hausgarten.html)

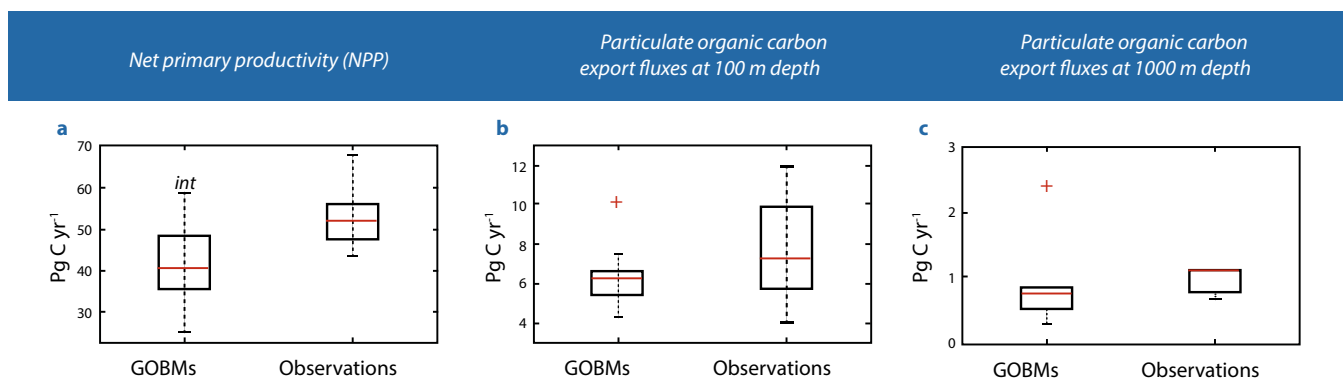
43 See <https://biogoship.org/>

44 See <https://www.pmel.noaa.gov/dbo/>

simulations, and climate change projections making use of comprehensive ESMs (e.g. Bunsen et al., 2024; Le Quéré et al., 2010; Li et al., 2019; Terhaar et al., 2022). A strength of modelling approaches is their ability to attribute simulated changes to drivers, e.g. to separate natural and anthropogenic components. Ocean biogeochemistry models are today run in global (Hauck et al., 2020) and regional configurations (e.g. Oziel et al., 2020; Xiu and Chai, 2014). High-resolution simulations are becoming more common, although they are still computationally costly and often allow for only a shorter simulation period. Notably, data-assimilation systems in both ocean-only and ESM configurations are starting to appear (Caroll et al., 2020; Bunsen et al., 2025; Moseley et al., 2025), though they may not have reached full maturity yet. In the meantime, insufficient observations pose a bottleneck for ocean biogeochemical model development that ultimately limits progress to reduce uncertainties and deliver robust forecasts (e.g. model evaluation against SOCAT CO<sub>2</sub> observations in Friedlingstein et al., 2025; IOC of UNESCO, 2024).

On global and decadal scales, coupled physical-biogeochemical ocean models can be used to estimate the air-sea CO<sub>2</sub> flux and long-term trends of the ocean's

uptake of anthropogenic CO<sub>2</sub>. Long-term globally-integrated anthropogenic carbon sink estimates vary between models, but uptake estimates diverge much more on regional and interannual scales (Hauck et al., 2020; Fay and McKinley, 2021). These model differences remain large due to coarse resolutions, the parameterizations required to represent critical smaller-scale physical processes (Sane et al., 2023), and partially inadequate or incomplete biogeochemical parameterizations (Hauck et al., 2023). Because model results fall within poorly-constrained observational ranges, a lack of process-understanding from experiments and field observations hinders further model development (e.g. Gloege et al., 2017; Planchat et al., 2023; Hinrichs et al., 2023). Therefore, improving observational coverage and process-understanding are critical steps to guide model development and improvement. With regard to biological processes, model uncertainty is much larger than for physically and chemically driven processes such as ocean anthropogenic carbon uptake (Frölicher et al., 2016), and observational constraints are even weaker (Henson et al., 2022). Different types of modeling approaches and observations must be integrated to cover the necessary spatial and temporal scales.



**Figure 14.** Box-whisker plots showing median values, interquartile ranges, and outliers (red plus symbol when present) of biological pump parameters from the RECCAP2 global ocean biogeochemical model (GOBM) ensemble (left) and observational estimates (right). Global integrated, annual **a)** net primary productivity NPP, **b)** particulate organic carbon export fluxes at 100 m F100, and **c)** 1,000 m depth F1000, all in Pg C yr<sup>-1</sup> (note that the median line for F1000 is also the upper interquartile because two of the three observational estimates match). Global and annual average surface export efficiency ratio (adapted from Doney et al. 2024).

### IOC-R priorities:

#### 1. Uncertainty in ocean CO<sub>2</sub> uptake and mixing

With regard to the ocean uptake of anthropogenic CO<sub>2</sub>, biases in the simulation of circulation and mixing are the primary source of uncertainty. The transport of

carbon out of the surface mixed layer (“ventilation”) is thought to be a key bottleneck of ocean anthropogenic carbon uptake (e.g. Goris et al., 2018; Iudicone et al., 2016). Evidence is accumulating that inadequate representation of ocean ventilation leads to the underestimation of the simulated ocean carbon

sink in recent decades by 10-20% (Friedlingstein et al., 2022; Terhaar et al., 2022). While no remedies to these model deficiencies are available yet, improved turbulence understanding may be a way forward (Qiao et al., 2016). The fact that ocean biogeochemistry and ESMs continue to typically have too coarse resolution to simulate mesoscale dynamics in transporting carbon and other key biogeochemical elements may also be a critical issue (e.g. mesoscale eddies that are prevalent throughout the oceans, Ford et al., 2023). Other sources of uncertainty are related to the conceptual difference between modeled anthropogenic and observational-based air-sea CO<sub>2</sub> fluxes (Friedlingstein et al., 2025). A comparison requires an adjustment for the preindustrial ocean outgassing related to rivers, which in turn requires assumptions to be made (**Section 3c**). For air-sea CO<sub>2</sub> fluxes, gap-filled observation-based estimates are likely to constrain mean and seasonality, but are unlikely to capture different frequencies of variability well (Gloege et al., 2021; Hauck et al., 2023b; Heimdal et al., 2024). In all cases, effort is needed to ensure that the use of these observation-based data are appropriate to the question or model process being evaluated.

## 2. Need for robust future projections

While biogeochemical model tuning and calibration against observations may be sufficient for attaining a reasonable model state for the present day, underlying processes must be described mechanistically to obtain robust future projections (e.g. Frölicher et al., 2016; Henson et al., 2022). While model development is possible even with the current understanding, this is limited by deficiencies in available data (Siegel et al., 2023).

Biogeochemical models initially had rather simple plankton dynamics, and have evolved to include a large variety of complex representations of biological processes (e.g. Wright et al., 2021; Stock et al., 2020). Nevertheless, many parameterizations are empirical, rather than based on mechanistic understanding (**Section 3.b**). For the global-mean biological pump of carbon from the surface to the deep ocean, model results tend to fall within “observational constraints” (Doney et al., 2024), but the reported observational range is so large (e.g. export production of organic matter estimates 4-12 PgC yr<sup>-1</sup>; **Figure 14**) that different model realizations cannot be

sufficiently constrained. In addition, biogeochemical observational data sets are usually too sparse for a comprehensive evaluation or optimization of biogeochemical models and this becomes more severe at regional scales (Gloege et al., 2017). Major knowledge gaps in biological carbon storage are summarized by Henson et al. (2022; 2024). The increasing amount of satellite-observed organic and inorganic surface ocean carbon datasets, and their ongoing advancement, offers potential for addressing many of these observation and knowledge gaps (Brewin et al., 2021; 2023; Shutler et al., 2024), at least for the ocean surface.

## 3. Poor estimates of the land-ocean carbon continuum in the global models

In addition to physics and biology in the open ocean, the coastal areas and the land-ocean interface represent a major knowledge gap (Dai et al., 2022; Resplandy et al., 2024). Global models, even those with higher spatial resolution, poorly represent the land-ocean carbon continuum because they do not incorporate all pertinent processes in this realm (e.g., coastal vegetation, water-sediment interactions). Land-ocean coupling through rivers and erosion is not well understood and represented (**Section 3c**). Current estimates of river carbon, nutrient, and alkalinity input to the ocean, the processing of these materials in the coastal ocean, and their redistribution in the open ocean are too few and partly contradict each other (Regnier et al., 2022). A dearth of observations across coastal systems that are heterogeneous and rapidly varying is a major barrier to progress. The lack of local to global understanding of how carbon moves off the land, across the coastal zones, and to the open ocean is a first-order uncertainty in comparisons of modelled (not including these riverine effects) and observation-based estimates (including riverine effects) of ocean carbon uptake (Hauck et al., 2020; Friedlingstein et al., 2025). Modelling of carbon cycling processes in the polar oceans is additionally hampered by poor understanding of sea-ice and bottom associated processes and their role in water mass transformations. Process gaps in ocean carbon cycling models are also a major challenge for the development of mCDR efforts, their future monitoring and the assessment of potential side effects (Hinrichs et al., 2023; Fennel et al., 2023).

## Actions to be taken

Models will always be simplifications of the real world; however, continuous model development is needed to ensure that the models are fit-for-purpose. Recommended actions to be taken to support and develop models:

- I. **Increase funding in support of continual efforts in model development** that should focus on processes either to be represented with refined mechanistic process understanding (e.g., for biological processes; **Sections 3.b** and **4.d**) or where confidence that observational estimates are robust exist (e.g., mean CO<sub>2</sub> flux, seasonality).
- II. Observations are fundamental to constrain and improve models. As such, **enhanced physical, biological, and chemical observations from the open ocean**, across the **coastal zone and upstream into rivers**, as well as **laboratory and *in situ* experiments** to investigate underlying processes, are critical. To maximize the use of available observations, it is important to develop targeted process-based evaluation metrics for the model application of interest in contrast to (only) harvesting easily accessible data.
- III. **Major model development is needed to resolve coastal and polar areas**, which requires not only higher resolution, but also implementation of processes relevant to the resolved scales and to the biogeochemical exchange of matter through the land-ocean and ice-ocean interface. This will also pave the way for the use of high-resolution models for MRV of mCDR (Ho et al., 2023).
- IV. **Improved mechanistic understanding is required**, not only of physical processes (ventilation and deep water formation) that can likely be tackled via higher resolution and improved mixing schemes (Babanin, 2023), but also of chemical and biological processes. These improvements call for a strong collaboration of modelers with field-going and laboratory-based scientists.
- V. **The use of machine learning methods as a post-simulation correction for models** (Gloege et al., 2022; Bennington et al., 2022; Liu et al., 2023), as well as for development of model parameterizations (Zanna et al., 2020; Sane et al. 2023) should be evaluated and may contribute to a reduction of model computational costs. Equation discovery tools could also contribute to this endeavor (Ross et al., 2023), building upon laboratory-based experiments.
- VI. In a parallel endeavor, **data-assimilation systems are needed to ultimately merge observations and models**. For this to be successful, both the data assimilation systems and the observational coverage in the ocean need major improvement, and training in data assimilation methods has to be provided to the community.
- VII. **Detailed technical implementation of all model development must occur in individual working groups and modeling centers**. Coupling this detailed work to robust support for international coordination, collaboration and model intercomparison is essential to accelerate model development in support of understanding and quantification of the ocean carbon cycle.

# 5. Engaging new communities in integrated ocean carbon research

## 5.a Adoption of an interdisciplinary approach in ocean carbon research

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To maintain, restore, and increase our understanding of ocean carbon cycling there is an urgent need for a common transdisciplinary framework in ocean carbon research. Oceans are interconnected social-ecological systems that are complex and adaptive (Preiser et al., 2018), characterised by uncertainty and unpredictability (Partelow, 2018), and challenged by a myriad of complex problems. Solutions require integrated research to understand the dynamic ecosystem that is shaped by its physical, biogeochemical, and biological components, and how these affect our social, economic, and governance systems (Partelow, 2018; Kelly et al., 2019; Bammer et al., 2020). International effort in ocean carbon research to date has largely focused on understanding carbon uptake and storage by the ocean—drawing extensively on expertise in the physical, chemical and biological sciences—with little evidence of inter- and transdisciplinary approaches being undertaken. Recognising diverse perspectives and leveraging multi-, inter-, and transdisciplinary approaches in ocean carbon research (**Figure 15**) will help to advance innovation.

Interdisciplinary research approaches can facilitate combining previously disconnected ideas, concepts, methods, and resources - and in doing so, can expand disciplinary expectations to produce novel scientific societal advances and outputs with high impact (Fortunato et al., 2018). Researchers should work together to gain these collective and interdisciplinary insights and include for example, the social acceptability of the technology and the required legal and governance implications. At present, interdisciplinary approaches to ocean carbon research,

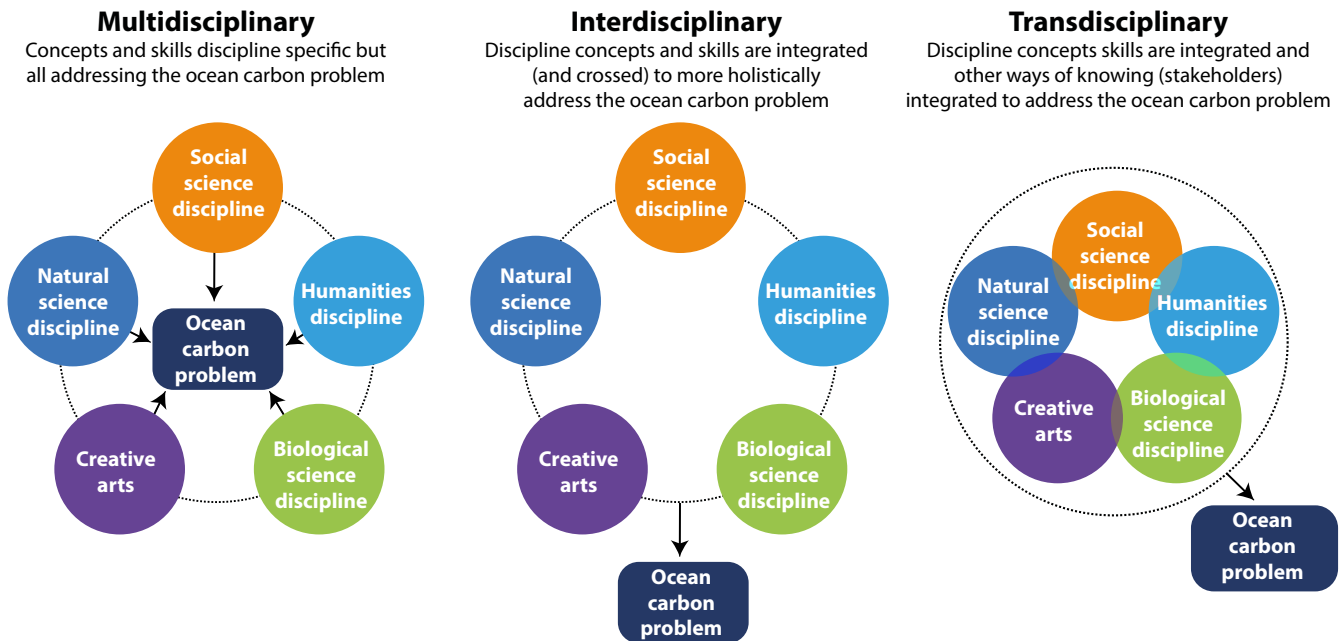
development, and implementation that include a social dimension are mostly lacking (Loomis et al., 2022).

Implementing interdisciplinary research in practice is complex and requires significant resourcing and time to engage diverse disciplinary collaborators, build collaborations and (co-)develop and apply novel approaches (**Figure 15**; reviewed by Karcher et al., 2022). Researcher capability is needed, and researchers must transcend their own disciplines to inform others' work and create new intellectual spaces. One approach for initiating such efforts is for an expert group to offer advice or co-creation time (at no cost) to other disciplines or research efforts (one example being the international expert group on satellite observations proposed by Shutler et al. (2024)). Interdisciplinarity requires an understanding of and respect for other disciplines. Unfortunately, there has been a lack of awareness and understanding of marine social science, which is often attributed only to a service role in the wider system of research and practice (Shellock et al., 2023; McKinley et al., 2022). By co-designing projects around ocean carbon, scientists from both natural and social disciplines can present theories, knowledge, and perspectives that may be integrated to help understand and address the complexity of global ocean carbon cycling, for example, by helping to understand how carbon sequestration efforts may affect society, or how behavioural and policy changes may best be managed, implemented or guided (Shellock et al., 2023).

Moving from a multi- to an interdisciplinary approach is the first step but a transdisciplinary approach will ultimately be necessary for ocean carbon research. This will require effective incorporation of other ways of knowing, and collaboration with for example indigenous knowledge. Research is most successful when it includes diverse perspectives, values, skills and networks (Christie et al., 2011), for example also including the humanities and the creative arts (as a way of knowing).

Stepping into another discipline can be overwhelming as “disciplinary understanding is required to reach interdisciplinary understanding” (You et al., 2018), and many disciplinary uncertainties around ocean carbon remain. Therefore, efforts to implement interdisciplinary approaches in ocean carbon research must seek to

train and engage all researchers including early career researchers and scientists from under-represented, marginalised and overburdened groups (Johri et al., 2021; Bennett et al., 2021; Shellock et al., 2022; Shellock et al., 2023, Strand et al., 2022).



**Figure 15.** Difference between multi-, inter-, and trans-disciplinary research to address research priorities in ocean carbon. Adapted from McPhee et al. (2018). In multi-disciplinary research each discipline provides a perspective, in interdisciplinary research the contributions are integrated, and in transdisciplinary research the boundaries of the disciplines are transcended to address ocean carbon problems.

There are some promising signs for regional and global interdisciplinary approaches for the physical, biogeochemical and biological components such as in IMBeR<sup>45</sup>, COBS<sup>46</sup>, various SCOR working groups<sup>47</sup> and through national and regional research grants for more small scale working groups, and individual limited term projects. However, these efforts are still mainly multi-disciplinary, and it is apparent that the field would benefit from leveraging diverse disciplinary expertise in more integrated and holistic ways and moving from multi- to interdisciplinarity.

### Examples of benefits of and recommendations for incorporating interdisciplinarity in ocean carbon research

**Ocean Governance:** Governance of ocean activities is both complicated and incomplete (Haas et al., 2021). Any ocean scale carbon sequestration technologies (e.g., marine cloud brightening, Diamond et al., 2022) that are developed over the coming decades will be situated in this incomplete governance landscape. Researchers working in technology development will benefit from interdisciplinarity by extending the sphere to legal and (international) political sciences to ensure appropriate governance arrangements.

45 See <https://imber.info/>

46 See <https://scor-int.org/project/changing-ocean-biological-systems-cobs/>

47 SCOR Ocean Carbon Working Groups – Scientific Committee on Oceanic Research (SCOR) (<https://scor-int.org/>).

**Human Behaviour:** Dealing with different carbon-capture technologies and incentives to implement them, will need inter- and transdisciplinary research to determine how and if incentives around marine carbon sequestration will be taken up or indeed change human behaviour. Collaboration with social scientists (e.g., on public perception and ocean literacy research) and behavioural scientists (economists, sociologists, psychologists, and cultural anthropologists) is key. These same behavioural sciences can provide insight into the impacts of different technologies and the trade-offs associated with different societal choices and management actions. It is important to also consider cultural perspectives on the governance of ocean carbon technologies, as cross-cultural differences can have unexpected impacts on the outcomes. Inter and cross-cultural psychology have a large role to play in the acceptability and implementation of various management options.

**Compliance:** For the effectiveness of mCDR technologies to be assessed it will be necessary to establish monitoring technologies, assessment methods, and standard systems (Smith et al, 2024; GESAMP, 2025). To develop such assessment and monitoring systems, social sciences can provide insight into best practices and how compliance can be facilitated. This is especially the case when it concerns market-based trading schemes, as recent evidence of inaccurate reporting and lack of compliance in the carbon trading system (Chubb et al., 2022) demonstrates that policing and monitoring will be key.

**Economics:** Interdisciplinary approaches will also be required to establish the social, ecological, and economic implications of climate-driven changes to the biological carbon pump. Interdisciplinary approaches can highlight differences in research infrastructure, resources and projected impacts of climate change (ecological, economic and social) among regions. Collaboration between disciplines and stakeholders can help find innovative and inclusive solutions for these complex problems (Nyboer et al., 2023) at relevant scales and contexts. While ocean carbon research is globally important, regional differences in the capacity to respond and adapt to climate change must be addressed to achieve equitable partnerships, collaborations and research outcomes. For impacted human communities, restorative economics is one discipline that may be informative in the recovery of marine carbon systems (e.g. blue carbon ecosystems).

**Different ways of knowing and inclusion:** Creating time and space to understand the potential contributions of the social sciences, the humanities and creative arts (as a way of knowing) to the field of ocean carbon sequestration is key. At a fundamental level, early career researchers and diverse and minority voices need to be engaged as they are the scientists and knowledge holders of today and tomorrow. Therefore, efforts to implement interdisciplinary approaches in ocean carbon research must be inclusive.

**Ocean literacy:** Most importantly, interdisciplinary approaches are essential to understand and boost the levels of ocean literacy and understanding within the general population (McKinley et al., 2022). This understanding can help identify where ocean carbon research is relevant, what gaps exist, and what knowledge is held by stakeholders that can help to inform ocean carbon research to ensure research is relevant and can be applied in service to society. It is essential to leverage this capability to push the population's demand for the urgent government level policy changes that are needed to drastically reduce emissions. Ultimately, this is the only real long-term and viable action that will save the oceans and our climate for future generations to enjoy.

## 5.b Capacity development

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Capacity development for ocean carbon research builds on decades of existing efforts, conducted by a wide range of scientists, networks and organizations. Depending on the overall objectives and mandates of many organizations (**Figure 2**), their capacity development activities focus on specific topics of the ocean carbon cycle and they are carried out by applying different approaches, such as online training, in person workshops and summer schools or mentorship programmes. The ocean carbon community is thereby contributing actively to the seven main outputs of capacity development as defined by the IOC Capacity Development Strategy (IOC of UNESCO, 2024) and amended in the Ocean Decade Vision 2030 process (Arbic et al. 2024): 1. Human resources developed at individual and institutional levels; 2. Access to technology, physical infrastructure, data and information established or improved; 3. Global, regional and sub-regional mechanisms strengthened; 4. Development of ocean research policies in support

of sustainable development objectives promoted; 5. Visibility, awareness and understanding on the roles and values of the ocean and ocean research in relation to human wellbeing and sustainable development increased; 6. Sustained resource mobilization reinforced; 7. Diverse representation in decision-making spaces, redressing of imbalance through inclusive codesign, listening to all relevant voices.

Among the organizations supporting integrated ocean carbon research, nine programmes and organizations, including science networks and programmes, Ocean Decade activities and UN organizations were identified as having a specific mandate in capacity development (**Table 1**). Many of these focus on human and technical capacity development, as well as awareness raising. However, only a few organizations put emphasis on research policies.

In addition to the international programmes and activities identified in Table 1, NGOs and philanthropic organizations are pivotal partners in building capacities and capabilities in ocean carbon science. The Global Ocean Science Report 2020 (IOC of UNESCO, 2020), stresses their importance in conducting and financing ocean science and particularly in capacity development. Examples are The Ocean Foundation and Conservation International, which champion closing the capacity gaps in ocean carbon science, with dedicated programmes focusing on multiple parts of the global ocean carbon cycle, such as advancing capabilities to study ocean acidification and blue carbon science.

### Major capacity gaps and recommendations for future capacity development activities:

- 1. National research strategies and policies:** The development of research policies, identification of research priorities and financial stability for ocean carbon research and observation are key enablers to maintain and further develop capacities. Research strategies securing long-term commitments to ocean carbon observation and research at the national level are required to ensure that relevant instrumentation is used and to avoid loss of human capacity locally due to migration to another country or that experts take on new roles in other fields.
- 2. Establishment of baselines and measures of success:** Based on capacity needs assessments of existing capabilities, definitions of baselines and measures of success of ocean carbon capacity development (Abric et al., 2024; Newton et al., 2024) will allow the optimization of impact and use of financial and human resources.
- 3. Co-design of capacity development activities:** Capacity development activities ought to be adapted to local contexts (Dupont et al., 2024) through early, frequent, and open discussion with engaged researchers as well as pre-evaluations of existing ocean carbon capacity and capacity needs. There is not one type of capacity development which fits all, and fostering trust and respect requires power-sharing among all participants.
- 4. Partnerships:** Organizations have different mandates and focus areas (**Table 1** and **Figure 2**). Strengthening collaborative capacity development will ensure that a wider audience can benefit from and participate in training and knowledge transfer. Ocean carbon research, like ocean science development in general, needs to seek new avenues for financial support. Engagement with the private sector, decision and policymakers will allow for greater impact.
- 5. Sharing of data and knowledge:** While human and technical development is the foundation for the delivery of the science required to fill the knowledge gaps explained in **Section 3**, providing easy access to ocean carbon data and knowledge at no cost as well as the ability to define ocean carbon data uncertainties to the research community worldwide will support researchers in less developed regions to compare local data and benefit from knowledge generated in other regions without any delay.
- 6. Equity and diversity:** Guiding principles for all ocean carbon research capacity development must include generational, geographical and gender balance.

**Table 1.** Mapping of capacity development activities and outputs in the field of ocean carbon. The table shows categories of capacity development outputs adapted from the UNESCO-IOC Capacity Development Strategy by Abric et al. (2024) and a selection of organisations and programmes conducting capacity development in the field of ocean carbon research, observation and policy. The organisations are Climate and Ocean: Variability, Predictability and Change project,<sup>48</sup> (CLIVAR), the Ocean Acidification Research for Sustainability programme of the Global Ocean Acidification Observing Network<sup>49</sup> (GOA-ON OARS), the Ocean Acidification International Coordination Centre of the IAEA<sup>50</sup> (IAEA OA-ICC), the Integrated Marine Biosphere Research programme<sup>51</sup> (IMBeR), the Intergovernmental Oceanographic Commission of UNESCO<sup>52</sup> (UNESCO-IOC), the International Ocean Carbon Coordination Project<sup>53</sup> (IOCCP), Ocean Carbon & Biogeochemistry<sup>54</sup> (OCB), the Partnership for Observation of the Global Ocean<sup>55</sup> (POGO), Surface Ocean Lower Atmosphere Study<sup>56</sup> (SOLAS). X represents a capacity development effort carried out by the relevant organisation or programme.

Category	CLIVAR	GOA-ON OARS	IAEA OA-ICC	IMBeR	IOC	IOCCP	OCB	POGO	SOLAS
1. Human resources developed at individual and institutional levels	X	X	X	X	X	X	X	X	X
2. Access to technology, physical infrastructure, data and information established or improved	X	X	X	X	X	X	X	X	X
3. Global, regional and sub-regional mechanisms strengthened	X	X	X	X	X	X		X	X
4. Development of ocean research policies in support of sustainable development objectives promoted		X			X				X
5. Visibility, awareness and understanding of the roles and values of the ocean and ocean research in relation to human wellbeing and sustainable development increased	X	X	X	X	X				X
6. Sustained resource mobilization reinforced		X	X	X	X	X		X	X
7. Diverse representation in decision-making spaces, redressing of imbalance through inclusive codesign, listening to all relevant voices		X	X	X	X			X	X

48 See [www.clivar.org/](http://www.clivar.org/)

49 See [www.goa-on.org/oars/overview.php](http://www.goa-on.org/oars/overview.php)

50 See [www.iaea.org/services/oa-icc](http://www.iaea.org/services/oa-icc)

51 See [imber.info/](http://imber.info/)

52 See [www.ioc.unesco.org/](http://www.ioc.unesco.org/)

53 See [www.ioccp.org/](http://www.ioccp.org/)

54 See [www.us-ocb.org/](http://www.us-ocb.org/)

55 See [pogo-ocean.org/](http://pogo-ocean.org/)

56 See [www.solas-int.org/](http://www.solas-int.org/)

# 6. Integrated Ocean Carbon Research - Global Priorities

Overarching actions to fill the research gaps and address the emerging questions identified in this report include creating an integrated and sustained ocean observing system covering the surface to deep ocean and the land to ocean interface, involving *in situ* and remotely sensed multi-variable observations (physical, chemical and biological), and including targeted development of sensors and autonomous platforms. Broadening the suite of sensors and continuing to improve the performance of existing sensors is essential to answer key questions, such as the role of biology in modulating the ocean carbon sink.

Enhancing ocean model process representations, addressing biases in the simulation of circulation and mixing, forging improved collaborations between modellers and field-going and laboratory-based scientists and resolving biogeochemical exchange of matter through the land-ocean and ice-ocean interfaces are also required. Continuous model development efforts are needed to ensure that the models are fit-for-purpose focusing on processes that can be represented with refined mechanistic process understanding or where observational estimates are robust.

It is vital to build global human and technological capacity to fully implement ocean carbon research. This involves continued and increased training opportunities for early career ocean professionals, access and participation from under-represented groups and personnel based in less developed countries, and a focus on the priority technologies (e.g. sensors, observing platforms, machine learning, coding), disciplines (e.g. physical, ecological, social, inter- and transdisciplinary research approaches) and geographies (e.g. coastal, polar, mesopelagic). Future activities aiming at democratizing access to ocean carbon data will be critical to increase the capabilities of projecting ocean change at locally relevant scales.

There is an urgent need for an interdisciplinary framework in ocean carbon research. Creating time and space to understand the contributions of the social sciences, the humanities and creative arts to the field of ocean carbon research is crucial. Interdisciplinary approaches will be vital in enabling equitable ocean governance, development of best practices and compliance with mCDR monitoring and evaluation, incorporation of local community knowledge in management and conservation, identification of economic and social as well as ecological impacts of climate change and understanding and increasing the levels of ocean literacy in the general population. Transdisciplinarity (involving non-academic participants such as policy makers, managers, research communicators and indigenous knowledge holders) can ensure ocean carbon research is relevant and can be applied in service to society.

Improved international cooperation and collaboration are needed for all steps in the carbon data value chain, from observations to synthesis products to elaborated observation-based products. Multinational coordination of studies that address carbon export, sequestration, and transformation, and their responses to multiple and co-occurring environmental stressors are required. International knowledge exchange and sharing of best practice including data quality control, access to reference materials and intercalibration of measurements, reporting, and data archiving in accordance with FAIR (Wilkinson et al., 2016) and CARE (for indigenous knowledge) principles are needed (**Figure 16**).



**Figure 16.** Overview of overarching and specific actions to be taken forward in the field of ocean carbon research. Overarching actions (inner ring) are identified to support the development and continuous enhancement of robust and fundamental scientific work for humankind to understand and predict accelerating climate change and the possibility of unexpected environmental responses. Specific actions (middle ring) are identified to address specific research gaps detailed under the five focus areas (outer ring) for integrated ocean carbon research.

### Evolution of the ocean carbon sink under a changing climate and emissions

In addition to the overarching actions above, actions within this focus area should address the key components of CO<sub>2</sub> uptake by the ocean: air-sea CO<sub>2</sub> flux parameterizations to reduce uncertainties in CO<sub>2</sub> uptake estimates, refinement of seawater carbonate equilibrium

constants to increase the internal consistency of the marine carbonate system, and monitoring of changes in physical processes and how they affect CO<sub>2</sub> uptake e.g. warming, freshening and changes in turbulence. Establishment and maintenance of an international network of facilities that produce climate-relevant calibration materials for both seawater and gas mixtures are also required. Sustained global-scale observations

over time are essential for documenting the changes in ocean carbon, and these observations and related data products should be operationalised. Enhanced model development and calibration/validation should be enabled through the identification and elimination of model biases, such as those arising from mixing schemes, and the incorporation of missing processes and variables such as organic alkalinity, near-surface temperature gradients and submesoscale mixing. Comprehensive identification of biases and uncertainties in various «gap-filling» techniques is also essential.

### The changing role of biology in the ocean carbon cycle

Multinational efforts are required to enable the coordination and synthesis of biological carbon pump data across large spatial and temporal scales, both of which are crucial for understanding environmental controls on processes, climate change trends, and for developing and validating models. These multinational efforts should fully utilize new approaches and instrumentation, such as ocean robotics, optical imaging, and hyperspectral satellites. Observations of parameters and metabolic rates contributing to the biological carbon pump must be closely coupled with a mechanistic understanding of the factors driving the variability and change over time of these parameters and rates. This understanding needs to be incorporated into model parameterizations for developing effective predictive capabilities to address change in the ocean's carbon cycle. The collection of *in situ* and *in vitro* omic data, encompassing both prokaryotes and eukaryotes, can provide crucial metabolic pathway information on diet, energy preferences, and evolution rates of key organisms. The study of rates in the context of reaction norms under multiple stressors, such as thermal and dissolved oxygen performance curves and CO<sub>2</sub> affinity curves, can shed light on which organism groups will likely be impacted the most from changes to oceanic conditions. Adaptation studies should connect cellular, physiological, and behavioural mechanisms, incorporating microevolution and epigenetics to yield a more comprehensive understanding of how organisms will respond and evolve in changing environments. Targeted process studies should aim to determine the interplay across all functional groups and their integrated impact on carbon production, transport, transformation, remineralization and sequestration. Multiple-driver mesocosm/macrocsm manipulation studies or the use

of marine ecosystem chamber systems which mimic *in situ* marine environments as closely as possible, are needed to simulate a changing climate, thereby enabling the disentanglement of environmental change effects on biogeochemical outcomes resulting from complex functional group interactions and organismal physiology. Physical modelling, such as particle tracking, should be incorporated with biogeochemical modelling and observations for improved understanding of the three-dimensional trajectories followed by carbon injected into the ocean via the biological carbon pump.

### Carbon exchanges across the land-ocean-ice continuum

The ideal is to establish a fit-for-purpose land-ocean global observation system to support sustained monitoring and compilation of existing data. Research efforts in coastal and open ocean areas should be better linked through community and indigenous collaborations, and it is key to liaise with inland water research communities to co-develop global datasets of riverine carbon species and nutrients, as well as with the marine sediment geochemistry community. The application of machine-learning methods and geographical information systems should be used to fill spatial and temporal gaps and tackle regional differences. Best practices should be developed for enhanced, good quality, and affordable observations and characterization of riverine, permafrost, blue carbon ecosystem, and coastal sources of alkalinity, carbon and nutrients, including the biogeochemical lability and fate of terrestrial dissolved organic carbon in the ocean.

The features of the land-ocean-aquatic continuum (LOAC) need to be nested into global and regional ocean biogeochemistry models under different scenarios, using variable grid sizes. Assembling data products at adequate spatial and temporal resolutions that reflect the high heterogeneity of the LOAC is needed, and flexible scenarios should be used to include variable and evolving climate forcings and anthropogenic disturbances. Best practices also need to be developed for estimating carbon fluxes and accounting for the carbon stocks in coastal and blue carbon ecosystems, with the application of advanced mapping, including groundwater, seafloor, and submerged sediments. Estimates should also account for changes in carbon storage due to climate, sea-level rise, and eutrophication, as well as direct human perturbations. A multi-stressor approach to studying the

changing coastal ocean carbon cycle will help inform local economies, develop adaptation and mitigation policies, and design regional sustainability initiatives for Marine Spatial Planning. Socio-economic dimensions should be integrated into coastal carbon research, and dedicated coastal ocean essential variables be defined. Substantial multidisciplinary research effort is required to improve our understanding of air–sea CO<sub>2</sub> fluxes and land-derived carbon and nutrient inputs in polar regions and how the polar oceans are changing with climate, including development of platforms designed to operate in sea-ice and quantification of sea-ice carbonate chemistry. A «land-induced global ocean CO<sub>2</sub> outgassing Model Intercomparison Project» should be launched with the upcoming CMIP7, to promote ensemble-mean assessments of «the anthropogenic perturbation in the land-ocean carbon cycle».

### **The impact of ocean industrial processes on the ocean biological carbon cycle**

Priority actions include generating better information on the key processes within the biological pump (such as grazing, remineralization, particle sinking and plankton mortality) that are likely to be impacted by industrial processes (such as dredging, drilling, aquaculture, fishing) and the addition and degradation of plastics, and improving knowledge on the resilience of carbon sequestration to reorganisation of foodwebs by fisheries. Numerical models should be developed to specifically parameterise the key taxa and functional groups that are and will be impacted by human activity in the ocean. Fishery ecosystem models should be adapted to provide explicit knowledge, particularly on the shelf, of what happens when millions of tonnes of fish are harvested, such as reduced deadfall and defecation flux.

Quantification of the consequences of sediment release, from trawling, dredging and drilling, into different water depths on processes affecting carbon export, transformation and storage is required. The anticipated impacts include scavenging of organic and inorganic carbon by particle aggregates leading to

enhanced export fluxes to the seafloor and effects on diel plankton migration. Likewise, current and future impacts of plastics need to be quantified, including on particle sinking rates, microbial growth and fisheries productivity. Integrated observational and modelling process studies are required at a range of time and space scales to understand the effect of sediment plumes on fish stocks and fishing activities. Models should also continue to be developed using the framework of ocean system pathways to evaluate likely future trajectories for fisheries and other industrial processes, including the impact of future changes in regulatory and legislative regimes and changes in priorities for marine spatial planning.

### **Future changes in the carbon cycle from deliberate ocean-based climate interventions**

Actions include model improvement to address deficiencies in mCDR-relevant parameters in marine ecosystem models and ESMs, particularly regarding seaweed cultivation, such as changes to surface ocean ecosystems, benthic smothering, and deep-sea faunal attraction to enhanced seafloor biomass. Modelling priorities also include observing system simulation experiments, storage durability, and poorly understood aspects of the biological carbon pump. Field experiments and operational deployments are crucial, requiring larger, longer-duration iron fertilization field experiments, field experiments on ocean alkalinity enhancement linked to impact studies, and evaluation of monitoring, reporting and verification protocols, including coastal blue carbon projects. An updated assessment (modelled on GESAMP, 2019) is needed to provide a systematic, policy-relevant review of the effectiveness and feasibility of mCDR methods, including environmental effects on biodiversity, ecosystem functioning, and ecosystem services. Quantitative research on the ocean carbon cycle and related ecological processes is necessary to establish a wider consensus on whether or not mCDR can contribute to a credible, scalable, and politically-acceptable climate mitigation strategy.

# References

- Årthun, M., Dinh, K. V., Dörr, J., Dupont, N., Fransner, F., Nilsen, I., Renaud, P. E., Skogen, M. D., Assmy, P., Chierici, M. and Duarte, P. 2025. The future Barents Sea - A synthesis of physical, biogeochemical, and ecological changes toward 2050 and 2100. *Elementa: Science of the Anthropocene*, vol. 13(1). <https://doi.org/10.1525/elementa.2024.00046>
- Alongi, D. M. 2022. Lateral Export and Sources of Subsurface Dissolved Carbon and Alkalinity in Mangroves: Revising the Blue Carbon Budget. *Journal of Marine Science and Engineering*, vol. 10. <https://doi.org/10.3390/JMSE10121916>
- Amon, D. J., Gollner, S., Morato, T., Smith, C. R., Chen, C., Christiansen, S., Currie, B., Drazen, J. C., Fukushima, T., Gianni, M., et al. 2022. Assessment of scientific gaps related to the effective environmental management of deep-seabed mining. *Marine Policy*, vol. 138, p. 105006. <https://doi.org/10.1016/j.marpol.2022.105006>
- Arp, H. P. H., Kühnel, D., Rummel, C., MacLeod, M., Potthoff, A., Reichelt, S., Rojo-Nieto, E., Schmitt-Jansen, M., Sonnenberg, J., Toorman, E. and Jahnke, A. 2021. Weathering plastics as a planetary boundary threat: exposure, fate, and hazards. *Environmental Science & Technology*, vol. 55(11), pp. 7246-7255. <https://doi.org/10.1021/acs.est.1c01512>
- Arteaga, L. A., Pahlow, M., Bushinsky, S. M. and Sarmiento, J. L. 2019. Nutrient controls on export production in the Southern Ocean. *Global Biogeochemical Cycles*, vol. 33(8), pp. 942-956. <https://doi.org/10.1029/2019GB006236>
- Aumont, O. and Bopp, L. 2006. Globalizing results from ocean *in situ* iron fertilization studies. *Global Biogeochemical Cycles*, vol. 20. <https://doi.org/10.1029/2005GB002591>
- Babanin, A. V. 2023. Ocean waves in large-scale air-sea weather and climate systems. *Journal of Geophysical Research: Oceans*, vol. 128. <https://doi.org/10.1029/2023JC019633>
- Bach, L. T. 2024. The additionality problem of ocean alkalinity enhancement. *Biogeosciences*, vol. 21, pp. 261-277. <https://doi.org/10.5194/bg-21-261-2024>
- Bach, L. T., Tamsitt, V., Gower, J., Hurd, C. L., et al. 2021. Testing the climate intervention potential of ocean afforestation using the great Atlantic Sargassum belt. *Nature Communications*, vol. 12. <https://doi.org/10.1038/s41467-021-22837-2>
- Bach, L. T., Vaughan, N. E., Law, C. S. and Williamson, P. 2024. Implementation of marine CO<sub>2</sub> removal for climate mitigation: the challenges of additionality, predictability, and governability. *Elementa: Science of the Anthropocene*, vol. 12. <https://doi.org/10.1525/elementa.2023.00034>
- Baker, C. A., Martin, A. P., Yool, A. and Popova, E. 2022. Biological carbon pump sequestration efficiency in the North Atlantic: A leaky or a long-term sink? *Global Biogeochemical Cycles*, vol. 36. <https://doi.org/10.1029/2021GB007286>
- Bakker, D. C. E., Pfeil, B., Landa, C. S., Metzl, N., O'Brien, K. M., Olsen, A., Smith, K., Cosca, C., Harasawa, S., Jones, S. D., et al. 2016. A multi-decade record of high-quality fCO<sub>2</sub> data in version 3 of the Surface Ocean CO<sub>2</sub> Atlas (SOCAT). *Earth Syst. Sci. Data*, vol. 8(2), pp. 383-413. <https://doi.org/10.5194/essd-8-383-2016>
- Bakker, D. C. E., Alin, S. R., Bates, N., Becker, M., Gkritzalis, T., Jones, S. D., Kozyr, A., Lauvset, S. K., Metzl, N., Nakaoka, S.-i. et al. 2024. Surface Ocean CO<sub>2</sub> Atlas Database Version 2024 (SOCATv2024) (NCEI Accession 0293257). NOAA National Centers for Environmental Information. Dataset. <https://doi.org/10.25921/9wpm-th28>. [Accessed 22/10/2024].
- Bammer, G., O'Rourke, M., O'Connell, D., Neuhauser, L., Midgley, G., Klein, J. T., Grigg, N. J., Gadlin, H., Elsum, I. R., Bursztyn, M., et al. 2020. Expertise in research integration and implementation for tackling complex problems: When is it needed, where can it be found and how can it be strengthened? *Palgrave Communications*, vol. 6(1), pp. 1-16. <https://doi.org/10.1057/s41599-019-0380-0>
- Barnes, D. K. A., Fleming, A., Sands, C. J., Quartino, M. L. and Dereqibus, D. 2018. Icebergs, Sea ice, blue carbon and Antarctic climate feedbacks. *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* vol. 376. <http://dx.doi.org/10.1098/rsta.2017.0176>
- Bednaršek, N., Carter, B. R., McCabe, R. M., Feely, R. A., Howard, E., Chavez, F. P., Elliott, M., Fisher, J. L., Jahncke, J. and Siegrist, Z. 2022. Pelagic calcifiers face increased mortality and habitat loss with warming and ocean acidification. *Ecological Applications*, vol. 32(7). <https://doi.org/10.1002/eap.2674>
- Bednaršek, N., Klinger, T., Harvey, C. J., Weisberg, S., McCabe, R. M., Feely, R. A., Newton, J. and Tolimieri, N. 2017. New ocean, new needs: Application of pteropod shell dissolution as a biological indicator for marine resource management. *Ecological Indicators*, vol. 76, pp. 240-244. <https://doi.org/10.1016/j.ecolind.2017.01.025>
- Bednaršek, N., van de Mortel, H., Pelletier, G., García-Reyes, M., Feely, R. A. et al. 2025. Assessment framework to predict sensitivity of marine calcifiers to ocean alkalinity enhancement—identification of biological thresholds and importance of precautionary principle. *Biogeosciences*, vol. 22, pp. 473-498. <https://doi.org/10.5194/bg-22-473-2025>
- Bellenger, H., Bopp, L., Ethé, C., Ho, D. T., Duvel, J. P., Flavoni, S., Guez, L., Kataoka, T., Perrot, X., Parc, L., and Watanabe, M. 2023. Sensitivity of the Global Ocean Carbon Sink to the Ocean Skin in a Climate Model. *Journal of Geophysical Research: Oceans*, vol. 128(7). <https://doi.org/10.1029/2022JC019479>
- Bennett, N. J., Katz, L., Yadao-Evans, W., Ahmadi, G. N., Atkinson, S., Ban, N. C., Dawson, N. M., de Vos, A., Fitzpatrick, J., Gill, D. and Imirizaldu, M. 2021. Advancing social equity in and through marine conservation. *Frontiers in Marine Science*, vol. 8. <https://doi.org/10.3389/fmars.2021.711538>

- Bennington, V., Gloege, L. and McKinley, G. A. 2022. Variability in the global ocean carbon sink from 1959 to 2020 by correcting models with observations. *Geophysical Research Letters*, vol. 49. <https://doi.org/10.1029/2022GL098632>
- Berger, M., Kwiatkowski, L., Ho, D. T. and Bopp, L. 2023. Ocean dynamics and biological feedbacks limit the potential of macroalgae carbon dioxide removal. *Environmental Research Letters*, vol. 18, 024039. <https://doi.org/10.1088/1748-9326/acb06e>
- Best, J. 2019. Anthropogenic stresses on the world's big rivers. *Nature Geoscience*, 12(1), pp. 7–21. <https://doi.org/10.1038/s41561-018-0262-x>
- Bianchi, T. S., Arndt, S., Austin, W. E. N., Benn, D. I., Bertrand, S., Cui, X., Faust, J. C., Kozirowska-Makuch, K., Moy, C. M., Savage, C., Smeaton, C., Smith, R. W. and Syvitski, J. 2020. Fjords as Aquatic Critical Zones (ACZs). *Earth Science Reviews*, vol. 203, 103145. <https://doi.org/10.1016/j.earscirev.2020.103145>
- Bianchi, D., Carozza, D. A., Galbraith, E. D., Guiet, J. and DeVries, T. 2021. Estimating global biomass and biogeochemical cycling of marine fish with and without fishing. *Science Advances*, vol. 7(41). <https://doi.org/10.1126/sciadv.abd7554>
- Bindoff, N. L., Cheung, W. W. L., Kairo, J. G., Arístegui, J., et al. 2019. Chapter 5: Changing ocean, marine ecosystems and dependent communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (Eds: H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría et al.). Cambridge University Press, pp. 447-587. <https://doi.org/10.1017/9781009157964>
- Bishop, J. K., Amaral, V. J., Lam, P. J., Wood, T. J., Lee, J. M., Laubach, A., Barnard, A., Derr, A. and Orrico, C. 2022. Transmitted cross-polarized light detection of particulate inorganic carbon concentrations and fluxes in the ocean water column: Ships to ARGO floats. *Frontiers in Remote Sensing*, vol. 3, pp. 837938. <https://doi.org/10.3389/frsen.2022.837938>
- Blain, C. O., Hansen, S. C. and Shears, N. T. 2021. Coastal darkening substantially limits the contribution of kelp to coastal carbon cycles. *Global Change Biology* 27(21), pp. 5547-5563. <https://doi.org/10.1111/gcb.15837>
- Boettcher, M., Brent, K., Buck, H. J., Low, S., McLaren, D. and Mengis, N. 2021. Navigating potential hype and opportunity in governing marine carbon removal. *Frontiers in Climate*, vol. 3. <https://doi.org/10.3389/fclim.2021.664456>
- Boss, E., Waite, A. M., Karstensen, J., Trull T., Muller-Karger, F., Sosik, H. M., Uitz, J., Acinas, S. G., Fennel, K., Berman-Frank, I., et al. 2022. Recommendations for plankton measurements on OceanSITES moorings with relevance to other observing sites. *Frontiers in Marine Science*, vol. 9. <https://doi.org/10.3389/fmars.2022.929436>
- Bourgeois, T., Orr, J. C., Resplandy, L., Terhaar, J., Ethé, C., Gehlen, M. and Bopp, L. 2016. Coastal-ocean uptake of anthropogenic carbon. *Biogeosciences*, vol. 13, pp. 4167–4185. <https://doi.org/10.5194/bg-13-4167-2016>
- Boyd, P. W. and Bressac, M. 2016. Developing a test-bed for robust research governance of geoengineering: the contribution of ocean iron biogeochemistry. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 374. <https://doi.org/10.1098/rsta.2015.0299>
- Boyd, P. W., Claustre, H., Legendre, L., Gattuso, J.-P. and Le Traon, P.-Y. 2023. Operational monitoring of open-ocean carbon dioxide removal deployments: Detection, attribution, and determination of side effects. In: *Frontiers in Ocean Observing: Emerging Technologies for Understanding and Managing a Changing Ocean*. Kappel, E. S., Cullen, V., Costello, M. J., Galgani, L., Gordó-Vilaseca, C., Govindarajan, A., Kouhi, S., Lavin, C., Cartin, L., Müller, J. D., Pirenne, B., Tanhua, T., Zhao, Q., and Zhao, S., eds. *Oceanography*, vol. 36, pp. 2-10. <https://doi.org/10.5670/oceanog.2023.s1.2>
- Boyd, P. W., Claustre, H., Levy, M., Siegel, D. A., and Weber, T. 2019. Multi-faceted particle pumps drive carbon sequestration in the ocean. *Nature*, vol. 568, pp. 327-335. <https://doi.org/10.1038/s41586-019-1098-2>
- Boyd, P. W., Collins, S., Dupont, S., Fabricius, K., Gattuso, J. P., Havenhand, J., Hutchins, D. A., Riebesell, U., Rintoul, M. S., Vichi, M. and Biswas, H. 2018. Experimental strategies to assess the biological ramifications of multiple drivers of global ocean change – a review. *Global Change Biology*, vol. 24. <https://doi.org/10.1111/gcb.14102>
- Boyd, P. W., Gattuso, J. P., Legendre, L., Moustakis, Y. and Pongratz, J. 2025. Effective carbon dioxide removal requires a One-Earth approach. *Environmental Research Letters*, vol. 20, 111004. <https://doi.org/10.1088/1748-9326/ae15a8>
- Boysen, L. R., Lucht, W., Gerten, D., Heck, V., et al. 2017. The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future*, vol. 5, pp. 463-474. <https://doi.org/10.1002/2016EF000469>
- Brewin, R. J., Sathyendranath, S., Kulk, G., Rio, M. H., Concha, J. A., Bell, T. G., Bracher, A., Fichot, C., Frölicher, T. L., Galí, M. and Hansell, D. A. 2023. Ocean carbon from space: Current status and priorities for the next decade. *Earth-science reviews*, vol. 240. <https://doi.org/10.1016/j.earscirev.2023.104386>
- Brewin, R. J., Sathyendranath, S., Platt, T., Bouman, H., Ciavatta, S., Dall'Olmo, G., Dingle, J., Groom, S., Jönsson, B., Kostadinov, T. S. and Kulk, G. 2021. Sensing the ocean biological carbon pump from space: A review of capabilities, concepts, research gaps and future developments. *Earth-Science Reviews*, vol. 217. <https://doi.org/10.1016/j.earscirev.2021.103604>
- Briggs, E. M., De Carlo, E. H., Sabine, C. L., Howins, N. M. and Martz, T. R. 2020. Autonomous ion-sensitive field effect transistor-based total alkalinity and pH measurements on a barrier reef of Kaneohe Bay. *ACS Earth and Space Chemistry*, vol. 4. <https://doi.org/10.1021/acsearthspacechem.9b00274>
- Briggs, N., Dall'Olmo, G. and Claustre, H. 2020. Major role of particle fragmentation in regulating biological sequestration of CO<sub>2</sub> by the oceans. *Science*, vol. 367, pp. 791-793. <https://doi.org/10.1126/science.aay1790>

- Brodie, S., Addey, C. I., Cvitanovic, C., Dias, B. S., Frainer, A., García-Morales, S., Jiang, S., Kaikkonen, L., Lopez, J., Mathesius, S., et al. 2022. Solving complex ocean challenges through interdisciplinary research: advances from early career marine scientists. *Frontiers in Marine Science*, vol. 9.  
<https://doi.org/10.3389/fmars.2022.913459>
- Brunner, C., Hausfather, Z. and Knutti, R. 2024. Durability of carbon dioxide removal is critical for Paris climate goals. *Communications Earth & Environment*, vol. 5.  
<https://doi.org/10.1038/s43247-024-01808-7>
- Buesseler, K. O., Bianchi, D., Chai, F., Cullen, J. T., Estapa, M., Hawco, N., John, S., McGillicuddy, D.J., Morris, P.J., Nawaz, S., et al. 2024. Next steps for assessing ocean iron fertilization for marine carbon dioxide removal. *Frontiers in Climate*, vol. 6.  
<https://doi.org/10.3389/fclim.2024.1430957>
- Bunsen, F., Nissen, C. and Hauck, J. 2024. The Impact of Recent Climate Change on the Global Ocean Carbon Sink. *Geophysical Research Letters*, vol. 51.  
<https://doi.org/10.1029/2023GL107030>
- Bunsen, F., Hauck, J., Torres-Valdés, S. and Nerger, L. 2025. Ocean carbon sink assessment via temperature and salinity data assimilation into a global ocean biogeochemistry model. *Ocean Science*, vol. 21, pp. 437-471.  
<https://doi.org/10.5194/os-21-437-2025>
- Bunsen, F., Nissen, C. and Hauck, J. 2024. The Impact of Recent Climate Change on the Global Ocean Carbon Sink. *Geophysical Research Letters*, vol. 51.  
<https://doi.org/10.1029/2023GL107030>
- Burger, F. A., Terhaar, J. and Frölicher, T. L. 2022. Compound marine heatwaves and ocean acidity extremes. *Nature Communications*, vol. 13.  
<https://doi.org/10.1038/s41467-022-32120-7>
- Bushinsky, S. M., Landschützer, P., Rödenbeck, C., Gray, A. R., Baker, D., Mazloff, M. R., Resplandy, L., Johnson, K. S. and Sarmiento, J. L. 2019. Reassessing Southern Ocean air-sea CO<sub>2</sub> flux estimates with the addition of biogeochemical float observations. *Global Biogeochemical Cycles*, vol. 33, pp. 1370-1388.  
<https://doi.org/10.1029/2019GB006176>
- Bushinsky, S. M., Takeshita, Y. and Williams, N. L. 2019. Observing Changes in Ocean Carbonate Chemistry: Our Autonomous Future. *Current Climate Change Reports*, vol. 5, pp. 207–220.  
<https://doi.org/10.1007/s40641-019-00129-8>
- Cai, W.-J. 2011. Estuarine and coastal ocean carbon paradox: CO<sub>2</sub> sinks or sites of terrestrial carbon incineration? *Annual Review Marine Science*, vol. 3, pp. 123-45.  
<https://doi.org/10.1146/annurev-marine-120709-142723>
- Cai, W.-J. and Jiao N. 2022. Wastewater alkalinity addition as a novel approach for ocean negative carbon emissions. *The Innovation*, vol. 3.  
<https://doi.org/10.1016/j.xinn.2022.100272>
- Canadell, J. G., Monteiro, P. M., Costa, M. H., Da Cunha, L. C., Cox, P. M., Eliseev, A. V., Henson, S., Ishii, M., Jaccard, S., Koven, C., et al. 2021. Global Carbon and other Biogeochemical Cycles and Feedbacks. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [eds: Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, et al.]. *Cambridge University Press*, pp. 673–816.  
<https://doi.org/10.1017/9781009157896.007>
- Carpenter, L. J., Jones, C. E., Dunk, R. M., Hornsby, K. E. and Woeltjen J. 2009. Air-sea fluxes of biogenic bromine from the tropical and North Atlantic Ocean. *Atmospheric Chemistry and Physics*, vol. 9, pp. 1805-1816.  
<https://doi.org/10.5194/acp-9-1805-2009>
- Carmichael, G., Peuch, V.-H., Chevallier, F., Combley, S., Grubišić, V., Kralidis, T., Manning, A., Meijer, Y., Ott, L., Sawa, Y., et al. 2024. Global Greenhouse Gas Watch (G3W) – The Implementation Plan. *World Meteorological Organization*.  
<https://wmo.int/media/update/global-greenhouse-gas-watch-implementation-plan-be-presented-executive-council-ec-78>. INFCOM-3-INF07-2-IMPLEMENTATION-PLAN-FOR-G3W-en-approved.pdf. [Last access 17/10/2024].
- Carroll, D., Menemenlis, D., Adkins, J. F., Bowman, K. W., Brix, H., Dutkiewicz, S., Fenty, I., Gierach, M. M., Hill, C., Jahn, O., et al. 2020. The ECCO-Darwin Data-assimilative Global Ocean Biogeochemistry Model: Estimates of Seasonal to Multi-decadal Surface Ocean pCO<sub>2</sub> and Air-sea CO<sub>2</sub> Flux. *Journal of Advances in Modeling Earth Systems*, vol. 12.  
<https://doi.org/10.1029/2019ms001888>
- Carter, B. R., Bittig, H. C., Fassbender, A. J., Sharp, J. D., Takeshita, Y., Xu, Y. Y., Álvarez, M., Wanninkhof, R., Feely, R. A. and Barbero, L. 2021. New and updated global empirical seawater property estimation routines. *Limnology and Oceanography Methods*, vol. 19, pp. 785-809.  
<https://doi.org/10.1002/lom3.10461>
- Cavan, E. L., Mackay, N., Hill, S. L., Atkinson, A., Belcher, A. and Visser, A. 2024. Antarctic krill sequester similar amounts of carbon to key coastal blue carbon habitats. *Nature Communications*, vol. 15.  
<https://doi.org/10.1038/s41467-024-52135-6>
- Cavan, E. L., Belcher, A., Atkinson, A., Hill, S. L., Kawaguchi, S., McCormack, S., Meyer, B., Nicol, S., Ratnarajah, L., Schmidt, K., et al. 2019. The importance of Antarctic krill in biogeochemical cycles. *Nature Communications*, vol. 10.  
<https://doi.org/10.1038/s41467-019-12668-7>
- CBD. 2022. Decision adopted by the conference of the parties to the Convention on Biological Diversity 15/4 (Kunming-Montreal Global Biodiversity Framework).  
<https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf>
- Chai, F., Johnson, K. S., Claustre, H., Xing, X., Wang, Y., Boss, E., Riser, S., Fennel, K., Schofield, O. and Sutton, A. 2020. Monitoring ocean biogeochemistry with autonomous platforms. *Nature Reviews Earth & Environment*, vol. 1, pp. 315–326.  
<https://doi.org/10.1038/s43017-020-0053-y>

- Chavez, F. P., Pennington, J. T., Michisaki, R. P., Blum, M., Chavez, G. M., Friederich, J., Jones, B., Herliem, R., Kieft, B., Hobson, B., et al. 2017. Climate variability and change: Response of a coastal ocean ecosystem. *Oceanography*, vol. 30(4), pp. 128-145.  
<https://doi.org/10.5670/oceanog.2017.429>
- Chavez, F. P., Sevadjian, J., Wahl, C., Friederich, J. and Friederich, G. E. 2018. Measurements of pCO<sub>2</sub> and pH from an autonomous surface vehicle in a coastal upwelling system. *Deep Sea Research Part II: Topical Studies in Oceanography*, vol. 151, pp. 137-146.  
<https://doi.org/10.1016/j.dsr2.2017.01.001>
- Cheize, M., Planquette, H. F., Fitzsimmons, J. N., Pelleter, E., Sherrell, R. M., Lambert, C., Bucciarelli, E., Sarthou, G., Le Goff, M., Liorzou, C., et al. 2019. Contribution of resuspended sedimentary particles to dissolved iron and manganese in the ocean: An experimental study. *Chemical Geology*, vol. 511, pp. 389-415.  
<https://doi.org/10.1016/j.chemgeo.2018.10.003>
- Chirosca, A. M., Rusu, L. and Bleoju, A. 2022. Study on wind farms in the North Sea area. *Energy Reports*, vol. 8 (16), pp. 162-168.  
<https://doi.org/10.1016/j.egyr.2022.10.244>
- Christie, P. 2011. Creating space for interdisciplinary marine and coastal research: five dilemmas and suggested resolutions. *Environmental Conservation*, vol. pp. 38, 172-186.  
<https://doi.org/10.1017/s0376892911000129>
- Chubb, I., Bennett, A., Gorrington, A., and Hatfield-Dodds, S. 2022. Independent Review of ACCUs. *Department of Climate Change, Energy, the Environment and Water*, Canberra, December. CC BY 4.0.  
<https://www.dceew.gov.au/sites/default/files/documents/independent-review-accu-final-report.pdf>
- Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., et al. 2013. Carbon and other biogeochemical cycles. In: *Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.  
[https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5\\_Chapter06\\_FINAL.pdf](https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter06_FINAL.pdf)
- Clark, J. B., Mannino, A., Tzortziou, M., Spencer, R. G. M. and Hernes, P. 2022. The Transformation and Export of Organic Carbon Across an Arctic River-Delta-Ocean Continuum. *Journal of Geophysical Research: Biogeosciences*, vol. 127, e2022JG007139.  
<https://doi.org/https://doi.org/10.1029/2022JG007139>
- Claustre, H., Legendre, L., Boyd, P. W., Levy, M. 2021. The Oceans' biological carbon pumps: Framework for a research observational community approach. *Frontiers in Marine Science*, vol, 8, Article 780052.  
<https://doi.org/10.3389/fmars.2021.780052>
- Claustre, H., Johnson, K. S. and Takeshita, Y. 2020. Observing the global ocean with biogeochemical-Argo. *Annual review of marine science*, vol. 12, pp. 23-48.  
<https://doi.org/10.1146/annurev-marine-010419-010956>
- Clayton, S., Alexander, H., Graff, J. R., Poulton, N. J., Thompson, L. R., Benway, H., Boss, E. and Martiny, A. 2022. Bio-GO-SHIP: the time is right to establish global repeat sections of ocean biology. *Frontiers in Marine Science*, vol. 8, pp. 767443.  
<https://doi.org/10.3389/fmars.2021.767443>
- Cooley, S., Schoeman, D., Bopp, L., Boyd, P. W., Donner, S., Ito, S.-i., Kiessling, W., Martinetto, P., Ojea, E., Racault, M. F., et al. 2023. Oceans and Coastal Ecosystems and Their Services, in: *IPCC Climate Change 2022 – Impacts, Adaptation and Vulnerability. Cambridge University Press*, pp. 379-550.  
<https://doi.org/10.1017/9781009325844.005>
- Cornwall, W. 2024. Will regulators OK controversial effort to supercharge ocean's ability to absorb carbon? *Science* (online).  
<https://doi.org/10.1126/science.z6zf50v>
- Costello, C., Cao, L., Gelcich, S., Cisneros, M. A., Free, C. M., Froehlich, H. E., Golden, C. D., Ishimura, G., Maier, J., Macadam-Somer, I., et al. 2023. The future of food from the sea. In *The Blue Compendium: From Knowledge to Action for a Sustainable Ocean Economy* (pp. 1-14). Cham: Springer International Publishing.
- Costello, C., Cao, L., Gelcich, S. et al. 2020. The future of food from the sea. *Nature*, vol. 588, pp. 95-100.  
<https://doi.org/10.1038/s41586-020-2616-y>
- Crichton, K. A., Wilson, J. D., Ridgwell, A., Boscolo-Galazzo, F., John, E. H., Wade, B. S. and Pearson, P. N. 2023. What the geological past can tell us about the future of the ocean's twilight zone. *Nature Communications*, vol. 14, 2376.  
<https://doi.org/10.1038/s41467-023-37781-6>
- Cross, J. N., Sweeney, C., Jewett, E. B., Feely, R. A., McElhany, P., Carter, B., Stein, T., Kitch, G. D. and Gledhill, D. K. 2023. Strategy for NOAA Carbon Dioxide Removal Research: A white paper documenting a potential NOAA CDR Science Strategy as an element of NOAA's Climate Interventions Portfolio. *NOAA Special Report*. NOAA, Washington DC.  
<https://doi.org/10.25923/gzke-8730>
- Cvitanovic, C., Blythe, J., van Putten, I., Maddison, L., Bopp, L., Brodie, S., Fulton, B., Lopes, P., Pecl, G., Penca, J., et al. 2024. Building Successful International Summer Schools to Enhance the Capacity of Marine Early Career Researchers. *Ocean and Society*, vol. 1.  
<https://doi.org/10.17645/oas.9328>
- Currie, K., Sabine, C., Lowder, K., Hassoun, A. E. R., Meléndez, M., Chu, S., Easley, R., García-Ibáñez, M. I., K. Schoo, Isensee, K., et al. 2024. Practical Best Practices for Ocean Acidification Monitoring (1.1). *The Ocean Foundation*.  
<https://doi.org/10.5281/zenodo.13876198>
- Cyronak, T., Albright, R. and Bach, L. T. 2023. Chapter 7: Field experiments in ocean alkalinity enhancement research, in: *Guide to Best Practices in Ocean Alkalinity Enhancement Research*. [Edited by: Oschlies, A., Stevenson, A., Bach, L. T., Fennel, K., Rickaby, R. E. M., Satterfield, T., Webb, R., and Gattuso, J.-P.]. *Copernicus Publications, State Planet*.  
<https://doi.org/10.5194/sp-2-oae2023-7-2023>

- Dahl, M., Lavery, P. S., Mazarrasa, I., Samper-Villarreal, J., Adame, M. F., Crooks, S., Duarte, C. M., Friess, D. A., Krause-Jensen, D., Leiva-Duenas, C., et al. 2025. Recommendations for strengthening blue carbon science. *One Earth*, vol. 8, 101175. <https://doi.org/10.1016/j.oneear.2025.101175>.
- Dai, M., Su, J., Zhao, Y., Hofmann, E. E., Cao, Z., Cai, W.J., Gan, J., Lacroix, F., Laruelle, G. G., Meng, F., et al. 2022. Carbon Fluxes in the Coastal Ocean: Synthesis, Boundary Processes and Future Trends. *Annual Review of Earth and Planetary Sciences*, vol. 50, pp. 593–626. <https://doi.org/10.1146/annurev-earth-032320-090746>
- Dall’Olmo, G., Dingle, J., Polimene, L., Brewin, R. J. and Claustre, H. 2016. Substantial energy input to the mesopelagic ecosystem from the seasonal mixed-layer pump. *Nature Geoscience*, vol. 9, pp. 820-823. <https://doi.org/10.1038/ngeo2818>
- Delval, M. H., Thonemann, N., Henriksson, P. J. G., Tanzer, S. E. and Behrens, P. 2025. Life cycle assessment of ocean-based carbon dioxide removal approaches: A systematic literature review. *Renewable and Sustainable Energy Reviews*, vol. 224. <https://doi.org/10.1016/j.rser.2025.116091>
- Deprez, A., Leadley, P., Dooley, K., Williamson, P., Cramer, W., Gattuso, J.-P., Rankovic, A., Carlson, E. L. and Creutzig, F. 2024. Sustainability limits needed for CO<sub>2</sub> removal. *Science*, vol. 383, pp. 484-486. <https://doi.org/10.1126/science.adj6171>.
- DeVries, T., Yamamoto, K., Wanninkhof, R., Gruber, N., Hauck, J., Müller, J. D., Bopp, L., Carroll, D., Carter, B., Chau, T. T. T., et al. 2023. Magnitude, trends, and variability of the global ocean carbon sink from 1985 to 2018. *Global Biogeochemical Cycles*, vol. 37. <https://doi.org/10.1029/2023GB007780>
- Diamond, M. S., Gettelman, A., Lebsock, M. D., McComiskey, A., Russell, L. M., Wood, R. and Feingold, G. 2022. To assess marine cloud brightening’s technical feasibility, we need to know what to study - and when to stop. *Proceedings of the National Academy of Sciences*, vol. 119. <https://doi.org/10.1073/pnas.2118379119>
- Dickson, A. G., Sabine, C. L. and Christian, J. R. (eds). 2007. Guide to best practices for ocean CO<sub>2</sub> measurement. , *North Pacific Marine Science Organization*, PICES Special Publication 3; IOCCP Report 8. <https://doi.org/10.25607/OBP-1342>
- Doney, S. C., Mitchell, K. A., Henson, S. A., Cavan, E., DeVries, T., Gruber, N., Hauck, J., Mouw, C. B., Müller, J. D. and Primeau, F. W. 2024. Observational and Numerical Modeling Constraints on the Global Ocean Biological Carbon Pump. *Global Biogeochemical Cycles*, vol. 38. <https://doi.org/10.1029/2024GB008156>
- Doney, S. C., Wolfe, W. H., McKee, D. C. and Fuhrman, J. G. 2025. The science, engineering, and validation of marine carbon dioxide removal and storage. *Annual Review of Marine Science*, vol.17, pp. 55-81. <https://doi.org/10.1146/annurev-marine-040523-014702>
- Dong, Y., Bakker, D. C. E., and Landschützer, P. 2024. Accuracy of ocean CO<sub>2</sub> uptake estimates at a risk by a reduction in the data collection. *Geophysical Research Letters*, vol. 51, e2024GL108502. <https://doi.org/10.1029/2024GL108502>
- Dong, C., Xu, G., Han, G., Bethel, B.J., Xie, W. and Zhou, S. 2022. Recent developments in artificial intelligence in oceanography. *Ocean-Land-Atmosphere Research*, vol. 2022. <https://doi.org/10.34133/2022/9870950>
- Dong, Y., Bakker, D. C. E., Bell, T. G., Huang, B., Landschützer, Liss, P. S. and Yang, M. 2022. Update on the temperature corrections of global air-sea CO<sub>2</sub> flux estimates. *Global Biogeochemical Cycles*, vol. 36, pp. 1-13. <https://doi.org/10.1029/2022GB007360>
- Droste, E. S., Bakker, D. C. E., Venables, H. J. V., Jones, E. M., Meredith, M. P., Dall’Olmo, G., Hoppema, M., Legge, O. J., Lee, G. A. and Queste, B. 2025. Sea ice controls net ocean uptake of carbon dioxide by regulating wintertime stratification. *Communications Earth and Environment*, vol. 6, 457. <https://doi.org/10.1038/s43247-025-02395-x>
- Droste, E. S., Hoppema, M., González-Dávila, M., Santana-Casiano, J. M., Queste, B. Y., Dall’Olmo, G., Venables, H. J., Rohardt, G., Ossebaar, S., Schuller, D., et al. 2022. The influence of tides on the marine carbonate chemistry of a coastal polynya in the south-eastern Weddell Sea. *Ocean Science*, vol. 18 (5), pp. 1293-1320. <https://doi.org/10.5194/os-18-1293-2022>
- Dupont, S., Edworthy, C., Sanchez-Noguera, C., Metian, M., Fredrich, J., Flickinger, S., Bantelman, A., Galdino, C., Graba, F., Anghelici, O., et al. 2025. The IAEA Ocean Acidification International Coordination Centre Capacity Building Program: Empowering member states to address and minimize the impacts of ocean acidification. *Oceanography*, vol. 38 (1), pp. 111–113. <https://doi.org/10.5670/oceanog.2025.102>.
- Emerson, S. and Yang, B. 2022. The Ocean’s Biological Pump: *In Situ* Oxygen Measurements in the Subtropical Oceans. *Geophysical research letters*, vol. 49. <https://doi.org/10.1029/2022GL099834>
- Eriksen, M., Cowger, W., Erdle, L. M., Coffin, S., Villarrubia-Gómez, P., Moore, C. J., Carpenter, E. J., Day, R. H., Thiel, M. and Wilcox, C. 2023. A growing plastic smog, now estimated to be over 170 trillion plastic particles afloat in the world’s oceans - Urgent solutions required. *Plos one*, vol. 18. <https://doi.org/10.1371/journal.pone.0281596>
- Fakhraee, M., Li, Z., Planavsky, N. J. and Reinhard, C. T. 2023. A biogeochemical model of mineral-based ocean alkalinity enhancement: impacts on the biological pump and ocean carbon uptake *Environmental Research Letters*, vol. 18. <https://doi.org/10.1088/1748-9326/acc9d4>
- Fassbender, A. J., Schlunegger, S., Rodgers, K. B. and Dunne, J. P. 2022. Quantifying the role of seasonality in the marine carbon cycle feedback: an ESM2M case study. *Global Biogeochemical Cycles*, vol. 36. <https://doi.org/10.1029/2021GB007018>
- Fassbender, A. J., Sabine, C. L., Lawrence-Slavas, N., De Carlo, E. H., Meinig, C. and Maenner Jones, S. 2015. Robust sensor for extended autonomous measurements of surface ocean dissolved inorganic carbon. *Environmental science & technology*, vol. 49 (6), pp. 3628-3635. <https://doi.org/10.1021/es5047183>

- Fay, A. R., and McKinley, G. A. 2021. Observed Regional Fluxes to Constrain Modeled Estimates of the Ocean Carbon Sink. *Geophysical Research Letters*, vol. 48 (20). <https://doi.org/10.1029/2021gl095325>
- Fennel, K., Alin, S., Barbero, L., Evans, W., Bourgeois, T., Cooley, S., Dunne, J., Feely, R. A., Martin Hernandez-Ayon, J., Hu, X., et al. 2019. Carbon cycling in the North American coastal ocean: A synthesis. *Biogeosciences*, vol. 16 (6), pp. 1281–1304. <https://doi.org/10.5194/BG-16-1281-2019>
- Fennel, K., Mattern, J. P., Doney, S. C., Bopp, L., Moore, A. M., Wang, B. and Yu, L. 2022. Ocean Biogeochemical Modelling. *Nature Reviews Methods Primers*, vol. 2. <https://doi.org/10.1038/s43586-022-00154-2>
- Ferderer, A., Chase, Z., Kennedy, F., Schulz, K. G. et al. 2022. Assessing the influence of ocean alkalinity enhancement on a coastal phytoplankton community, *Biogeosciences*, vol. 19, pp. 5375–5399. <https://doi.org/10.5194/bg-19-5375-2022>
- Fernandes, T. da F., Peixoto, R. B., Queiroz Pinho, L., da Cunha, L. C., Veloso Franklin, T., Pollery, R. C., Peruzzi de Oliveira, V., Amora-Nogueira, L. and Marotta, H. 2025. Eutrophication triggers diel and seasonal shifts of carbon dioxide and oxygen in tropical urban coastal waters. *Limnology and Oceanography Letters*, vol. 10. <https://doi.org/10.1002/lol2.70006>
- Ford, D. J., Shutler, J. D., Blanco-Sacristán, J., Corrigan, S., Bell, T. G., Yang, M., Kitidis, V., Nightingale, P. D., Brown, I., Wimmer, W., et al. 2024. Enhanced ocean CO<sub>2</sub> uptake due to near-surface temperature gradients. *Nature Geoscience*, vol. 17 (11), pp. 1135–1140. <https://doi.org/10.1038/s41561-024-01570-7>
- Ford, D. J., Tilstone, G. H., Shutler, J. D., Kitidis, V., Sheen, K. L., Dall’Olmo, G. and Orselli, I. B. 2023. Mesoscale eddies enhance the air-sea CO<sub>2</sub> sink in the South Atlantic Ocean. *Geophysical Research Letters*, vol. 50(9), p.e2022GL102137. <https://doi.org/10.1029/2022GL102137>
- Fortunato, S., Bergstrom, C. T., Börner, K., Evans, J. A., Helbing, D., Milojević, S., Petersen, A. M., Radicchi, F., Sinatra, R., Uzzi, B., et al. 2018. Science of science. *Science*, vol. 349. <https://doi.org/10.1126/science.aao0185>
- Fourqurean, J. W., Duarte, C. M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M. A., Apostolaki, E. T., Kendrick, G. A., Krause-Jensen, D., McGlathery, K. J., et al. 2012. Seagrass ecosystems as a globally significant carbon stock. *Nature Geoscience*, vol. 5. <https://doi.org/10.1038/ngeo1477>
- Fox, J., Behrenfeld, M. J., Halsey, K. H. and Graff, J. R. 2024. Global Estimates of Particulate Organic Carbon Concentration From the Surface Ocean to the Base of the Mesopelagic. *Global Biogeochemical Cycles*. vol. 38. <https://doi.org/10.1029/2024GB008149>
- Frenger, I., Landolfi, A., Kvale, K., Somes, C. J., Oschlies, A., Yao, W. and Koeve, W. 2024. Misconceptions of the marine biological carbon pump in a changing climate: Thinking outside the “export” box. *Global Change Biology*, vol. 30 (1), e17124. <https://doi.org/10.1111/gcb.17124>
- Friedlingstein, P., O’sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Landschützer, P., Le Quéré, C., Li, H., Luijckx, I. T., Olsen, A., et al. 2025. Global carbon budget 2024. *Earth System Science Data*, 17, 965–1039. <https://doi.org/10.5194/essd-17-965-2025>
- Frölicher, T. L., Rodgers, K. B., Stock, C. A. and Cheung, W. W. L. 2016. Sources of Uncertainties in 21st Century Projections of Potential Ocean Ecosystem Stressors: Uncertainties in Stressor Projections. *Global Biogeochemical Cycles*, vol. 30 (8), pp. 1224–1243. <https://doi.org/10.1002/2015GB005338>
- Fu, W., Moore, J. K., Primeau, F., Collier, N., Ogunro, O. O., Hoffman, F. M. and Randerson, J. T. 2022. Evaluation of ocean biogeochemistry and carbon cycling in CMIP earth system models with the International Ocean Model Benchmarking (IOMB) software system. *Journal of Geophysical Research: Oceans*, vol. 127, e2022JC018965. <https://doi.org/10.1029/2022JC018965>
- Galbraith, E. D. and Skinner, L. C. 2020. The biological pump during the Last Glacial Maximum. *Annual Reviews of Marine Science*, vol. 12, pp. 559–586. <https://doi.org/10.1146/annurev-marine-010419-010906>
- Gallo, N. D., Victor, D. G. and Levin, L. A., 2017. Ocean commitments under the Paris Agreement. *Nature Climate Change*, vol. 7, pp. 833–838. <https://doi.org/10.1038/nclimate3422>
- Gattuso, J.-P., Magnan, A. K., Bopp, L., Cheung, W. W., Duarte, C. M., Hinkel, J., Mcleod, E., Micheli, F., Oschlies, A., Williamson, P., et al. 2018. Ocean solutions to address climate change and its effects on marine ecosystems. *Frontiers in Marine Science*, vol. 5, 337. <https://doi.org/10.3389/fmars.2018.00337>
- Gattuso, J.-P., Williamson, P., Duarte, C. M. and Magnan, A. K., 2021. The potential for ocean-based climate action: negative emissions technologies and beyond. *Frontiers in Climate*, vol. 2. <https://doi.org/10.3389/fclim.2020.575716>
- Geisen, C., Ridame, C., Journet, E., Delmelle, P., Marie, D., Lo Monaco, C., Cardinal, D. et al. 2022. Phytoplanktonic response to simulated volcanic and desert dust deposition events in the South Indian and Southern Oceans. *Limnology and Oceanography*. vol. 67, pp.1537–1553. <https://doi.org/10.1002/lno.12100>
- GESAMP. 2019. High level review of a wide range of proposed marine geoengineering techniques, GESAMP Working Group 41 (eds: P.W. Boyd and C.M.G. Vivian). *GESAMP Reports and Studies*, no. 98, 144 pp. <http://www.gesamp.org/site/assets/files/1723/rs98e.pdf>
- GESAMP. 2025. The State of the Science for Marine Carbon Dioxide Removal (mCDR) – A Scientific Summary for Policy-Makers. Paris, UNESCO-IOC, (IOC Technical Series, 209). <https://doi.org/10.5281/zenodo.15490407>
- Gloege, L., McKinley, G. A., Landschützer, P., Fay, A. R., Frölicher, T. L., Fyfe, J. C., Ilyina, T., Jones, S., Lovenduski, N. S., Rodgers, K. B., et al. 2021. Quantifying errors in observationally based estimates of ocean carbon sink variability. *Global Biogeochemical Cycles*, vol. 35, e2020GB006788. <https://doi.org/10.1029/2020GB006788>

- Gloege, L., McKinley, G. A., Mouw, C. B. and Ciochetto, A. B. 2017. Global evaluation of particulate organic carbon flux parameterizations and implications for atmospheric pCO<sub>2</sub>. *Global Biogeochemical Cycles*, vol. 31 (7), pp. 1192–1215. <https://doi.org/10.1002/2016gb005535>
- Gloege, L., Yan, M., Zheng, T. and McKinley, G. A. 2022. Improved Quantification of Ocean Carbon Uptake by Using Machine Learning to Merge Global Models and pCO<sub>2</sub> Data. *Journal of Advances in Modeling Earth Systems*, vol. 14 (2). <https://doi.org/10.1029/2021ms002620>
- Gnanadesikan, A., Sarmiento, J. L. and Slater, R. D. 2003. Effects of patchy ocean fertilization on atmospheric carbon dioxide and biological production. *Global Biogeochemical Cycles*, vol. 17. <https://doi.org/10.1029/2002GB001940>
- Goris, N., Tjiputra, J. F., Olsen, A., Schwinger, J., Lauvset, S. K. and Jeansson, E. 2018. Constraining Projection-Based Estimates of the Future North Atlantic Carbon Uptake. *Journal of Climate*, vol. 31, pp. 3959–3978. <https://doi.org/10.1175/JCLI-D-17-0564.1>
- Gou, R., Wolf, K. K. E., Hoppe, C. J. M., Wu, L. and Lohmann, G. 2025. The changing nature of future Arctic marine heatwaves and its potential impacts on the ecosystem, *Nature Climate Change*, vol. 15. <https://doi.org/10.1038/s41558-024-02224-7>
- Gregor, L. and Gruber, N. 2021. OceanSODA-ETHZ: a global gridded data set of the surface ocean carbonate system for seasonal to decadal studies of ocean acidification. *Earth System Science Data*, vol. 13 (2), pp. 777–808. <https://doi.org/10.5194/essd-13-777-2021>
- Gruber, N., Clement, D., Carter, B. R., Feely, R. A., Van Heuven, S., Hoppema, M., Ishii, M., Key, R. M., Kozyr, A., Lauvset, S. K., et al. 2019. The oceanic sink for anthropogenic CO<sub>2</sub> from 1994 to 2007. *Science*, vol. 363, pp. 1193–1199. <https://doi.org/10.1126/science.aau5153>
- Guidi, L., Fernandez Guerra, A., Canchaya, C., Curry, E., Foglini, F., Irisson, J.-O., Malde, K., Marshall, C. T., Obst, M., Ribeiro, et al. [Eds.] *Future Science Brief 6 of the European Marine Board*, Ostend, Belgium. ISSN: 2593-5232. ISBN: 9789492043931. <https://doi.org/10.5281/zenodo.3755793>
- Haas, B., Mackay, M., Novaglio, C., Fullbrook, L., Murunga, M., Sbrocchi, C., McDonald, J., McCormack, P. C., Alexander, K., Fudge, M., et al. 2022. The future of ocean governance. *Reviews in Fish Biology and Fisheries*, vol. 32, pp. 253–270. <https://doi.org/10.1007/s11160-020-09631-x>
- Haffert, L., Haeckel, M., Stigter, H. de and Janssen, F. 2020. Assessing the temporal scale of deep-sea mining impacts on sediment biogeochemistry. *Biogeosciences*, vol. 17 (10). <https://doi.org/10.5194/bg-17-2767-2020>
- Harfoot, M., Tittensor, D. P., Newbold, T., McInerney, G., Smith, M. J. and Scharlemann, J. P. W. 2014. Integrated assessment models for ecologists: The present and the future. *Global Ecology and Biogeography*, vol. 23, pp. 124–143. <https://doi.org/10.1111/geb.12100>
- Hatje, V., Masqué, P., Patire, V. F., Dórea, A. and Barros, F. 2021. Blue carbon stocks, accumulation rates, and associated spatial variability in Brazilian mangroves, *Limnology and Oceanography*, vol. 66, pp. 321–334. <https://doi.org/10.1002/lno.11607>
- Hauck, J., Gregor, L., Nissen, C., Patara, L., Hague, M., Mongwe, P., Bushinsky, S., Doney, S. C., Gruber, N., Le Quéré, C., et al. 2023. The Southern Ocean carbon cycle 1985–2018: Mean, seasonal cycle, trends, and storage. *Global Biogeochemical Cycles*, vol. 37. <https://doi.org/10.1029/2023GB007848>
- Hauck, J., Nissen, C., Landschützer, P., Rodenbeck, C., Bushinsky, S. and Olsen, A. 2023b. Sparse observations induce large biases in estimates of the global ocean CO<sub>2</sub> sink: an ocean model subsampling experiment. *Philosophical Transactions of the Royal Society A*, vol. 381. <https://doi.org/10.1098/rsta.2022.0063>
- Hauck, J. and Völker, C. 2015. Rising atmospheric CO<sub>2</sub> leads to large impact of biology on Southern Ocean CO<sub>2</sub> uptake via changes of the Revelle factor. *Geophysical Research Letters*, vol. 42, pp. 1459–1464. <https://doi.org/10.1002/2015GL063070>
- Hauck, J., Zeising, M., Le Quéré, C., Gruber, N., Bakker, D. C. E., Bopp, L., Chau, T. T. T., Gürses, Ö., Ilyina, T., Landschützer, P., et al. 2020. Consistency and Challenges in the Ocean Carbon Sink Estimate for the Global Carbon Budget. *Frontiers in Marine Science*, vol. 7. <https://doi.org/10.3389/fmars.2020.571720>
- He, J. and Tyka, M. D. 2023. Limits and CO<sub>2</sub> equilibration of near-coast alkalinity enhancement, *Biogeosciences*, vol. 20, pp. 27–43. <https://doi.org/10.5194/bg-20-27-2023>
- Heimdal, T. H., and McKinley, G. A. 2024. The importance of adding unbiased Argo observations to the ocean carbon observing system. *Scientific Reports*, vol. 14 (1). <https://doi.org/10.1038/s41598-024-70617-x>
- Heimdal, T. H., McKinley, G. A., Sutton, A. J., Fay, A. R. and Gloege, L. 2024. Assessing improvements in global ocean pCO<sub>2</sub> machine learning reconstructions with Southern Ocean autonomous sampling. *Biogeosciences*, vol. 21, pp. 2159–2176. <https://doi.org/10.5194/bg-21-2159-2024>
- Henley, S. F., Cavan, E. L., Fawcett, S. E., Kerr, R., Monteiro, T., Sherrell, R. M., Bowie, A. R., Boyd, P. W., Barnes, D. K. A., Schloss, I. R., et al. 2020. Changing Biogeochemistry of the Southern Ocean and Its Ecosystem Implications. *Frontiers in Marine Science*, vol. 7. <https://doi.org/10.3389/fmars.2020.00581>
- Hennon, T. D., Riser, S. C. and Mecking, S. 2016. Profiling float-based observations of net respiration beneath the mixed layer. *Global Biogeochemical Cycles*, vol. 30, pp. 920–932. <https://doi.org/10.1002/2016GB005380>
- Henson, S. A., Laufkötter, C., Leung, S., Giering, S. L. C., Palevsky, H. I. and Cavan, E. L. 2022. Uncertain Response of Ocean Biological Carbon Export in a Changing World. *Nature Geoscience*, vol. 15, pp. 248–254. <https://doi.org/10.1038/s41561-022-00927-0>

- Henson, S., Baker, C. A., Halloran, P., McQuatters-Gollop, A., Painter, S., Planchat, A. and Tagliabue, A. 2024. Knowledge gaps in quantifying the climate change response of biological storage of carbon in the ocean. *Earth's Future*, vol. 12. <https://doi.org/10.1029/2023EF004375>
- Henson, S., Bisson, K., Hammond, M. L., Martin, A., Mouw, C. and Yool, A. 2024b. Effect of sampling bias on global estimates of ocean carbon export, *Environmental Research Letters*, vol. 19. <https://doi.org/10.1088/1748-9326/ad1e7f>
- Hiddink, J. G., van de Velde, S. J., McConnaughey, R. A., De Borger, E., Tian, J., Kaiser, M. J., Sweetman, A. K. and Sciberras, M. 2023. Quantifying the carbon benefits of ending bottom trawling. *Nature*, vol. 617, E1–E2. <https://doi.org/10.1038/s41586-023-06014-7>
- Hinrichs, C., Köhler, P., Völker, C. and Hauck, J. 2023. Alkalinity Biases in CMIP6 Earth System Models and Implications for Simulated CO<sub>2</sub> Drawdown via Artificial Alkalinity Enhancement. *Biogeosciences*, vol. 20 (18), pp. 3717–3735. <https://doi.org/10.5194/bg-20-3717-2023>
- Ho, D. 2023. Carbon dioxide removal is not a current climate solution – we need to change the narrative. 2023. *Nature*, vol. 616. <https://doi.org/10.1038/d41586-023-00953-x>
- Ho, D. T., Bopp, L., Palter, J. B., Long, M. C., Boyd, P. W., Neukermans, G. and Bach, L. T. 2023. Monitoring, reporting, and verification for ocean alkalinity enhancement, in: Guide to Best Practices in Ocean Alkalinity Enhancement Research, edited by: Oschlies, A., Stevenson, A., Bach, L. T., Fennel, K., Rickaby, R. E. M., Satterfield, T., Webb, R. and Gattuso, J.-P. *Copernicus Publications, State Planet, 2-oe2023*. <https://doi.org/10.5194/sp-2-oe2023-12-2023>
- Hoegh-Guldberg, O., Northrop, E., Ashford, O. S., Chopin, T., Cross, J., Quesada, C. M. D., Gaines, S., Geirs, T., Gössling, S., Haugan, P., et al. 2023. The ocean as a solution to climate change: Updated opportunities for action. Special Report. Washington, *World Resources Institute*. <https://doi.org/10.69902/98e3de92>
- Houston, A., Kennedy, H. and Austin, W. E. N. 2024. Additionality in Blue Carbon Ecosystems: Recommendations for a Universally Applicable Accounting Methodology, *Global Change Biology*, vol. 30. <https://doi.org/10.1111/GCB.17559>
- Howard, J., Sutton-Grier, A. E., Smart, L. S., Lopes, C. C., Hamilton, J., Kleypas, J., Simpson, S., McGowan, J., Pessarrodona, A., Alleway, H. K., et al. 2023. Blue carbon pathways for climate mitigation: Known, emerging and unlikely. *Marine Policy*, vol. 156. <https://doi.org/10.1016/J.MARPOL.2023.105788>
- Huthnance, J., Hopkins, J., Berx, B., Dale, A., Holt, J., Hosegood, P., Inall, M., Jones, S., Loveday, B. R., Miller, P. I., et al. 2022. Ocean shelf exchange, NW European shelf seas: Measurements, estimates and comparisons. *Progress in Oceanography*, vol. 202. <https://doi.org/10.1016/J.POCEAN.2022.102760>
- ICES. 2024. Workshop on Assessing the Impact of Fishing on Oceanic Carbon (WKFISHCARBON; outputs from 2023 meeting). *ICES Scientific Reports*, vol 12. <https://doi.org/10.17895/ices.pub.24949122.v1>
- IMO. 2023. Statement on Marine Geoengineering, as adopted by the 45th Consultative Meeting of Contracting Parties to the London Convention and the 18th Meeting of Contracting Parties to the London Protocol (LC 45/LP 18). Available here: [https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/LC\\_LP/2023%20STATEMENT%20ON%20MARINE%20GEOENGINEERING.pdf](https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/LC_LP/2023%20STATEMENT%20ON%20MARINE%20GEOENGINEERING.pdf)
- IOCCP. 2024. Declaration on Operationalising the Surface Ocean Carbon Value Chain. [https://www.ioccp.org/images/Gnews/Declaration\\_on\\_Operationalising\\_the\\_Surface\\_Ocean\\_Carbon\\_Value\\_Chain.pdf](https://www.ioccp.org/images/Gnews/Declaration_on_Operationalising_the_Surface_Ocean_Carbon_Value_Chain.pdf). Published 0/01/2024. Last access 08/01/2024.
- IOC of UNESCO. 2020. Global Ocean Science Report 2020: Charting Capacity for Ocean Sustainability. K. Isensee (ed.), Paris, UNESCO Publishing. <https://unesdoc.unesco.org/ark:/48223/pf0000375148>
- IOC of UNESCO. 2021a. Integrated Ocean Carbon Research: A Summary of Ocean Carbon Research, and Vision of Coordinated Ocean Carbon Research and Observations for the Next Decade. R. Wanninkhof, C. Sabine and S. Aricò (eds.). UNESCO, Paris. 46 pp. (IOC Technical Series, 158Rev.) <https://unesdoc.unesco.org/ark:/48223/pf0000376708>
- IOC of UNESCO. 2021b. The United Nations Decade of Ocean Science for Sustainable Development (2021-2030) Implementation Plan. UNESCO, Paris (IOC Ocean Decade Series, 20). <https://unesdoc.unesco.org/ark:/48223/pf0000377082>
- IOC of UNESCO. 2024. State of the Ocean Report. Paris, IOC of UNESCO. (IOC Technical Series, 190) <https://doi.org/10.25607/4wbg-d349>
- IOC of UNESCO. 2024. IOC Capacity Development Strategy, 2023–2030. Paris, IOC Information document (IOC/INF1433). <https://unesdoc.unesco.org/ark:/48223/pf0000390082>
- IPCC. 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. <https://www.ipcc.ch/srocc/>
- IPCC. 2021. Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3–32. [https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC\\_AR6\\_WGI\\_SummaryVolume.pdf](https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SummaryVolume.pdf)
- IPCC. 2023. Summary for Policymakers. In: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [eds: Core Writing Team, H. Lee and J.H. Romero]. IPCC, Geneva, Switzerland, pp. 1-34. [https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC\\_AR6\\_SYR\\_SPM.pdf](https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf)

- ITLOS. 2024. Advisory Opinion on a request for an advisory opinion submitted by the commission of small island states on climate change and international law. [https://www.itlos.org/fileadmin/itlos/documents/cases/31/Advisory\\_Opinion/C31\\_Adv\\_Op\\_21.05.2024\\_orig.pdf](https://www.itlos.org/fileadmin/itlos/documents/cases/31/Advisory_Opinion/C31_Adv_Op_21.05.2024_orig.pdf)
- Iudicone, D., Rodgers, K. B., Plancherel, Y., Aumont, O., Ito, T., Key, R. M., Madec, G. and Ishii, M. 2016. The formation of the ocean's anthropogenic carbon reservoir. *Scientific Reports*, vol. 6, pp. 1–16. <https://doi.org/10.1038/srep35473>
- Jeltsch-Thömmes, A., Tran, G., Lienert, S., Keller, D.P., Oschlies, A. and Joos, F. 2024. Earth system responses to carbon dioxide removal as exemplified by ocean alkalinity enhancement: Tradeoffs and lags. *Environmental Research Letters*, vol. 19. <https://doi.org/10.1088/1748-9326/ad4401>
- Jiang, L.-Q., Carter, B. R., Feely, R. A., Lauvset, S. K. and Olsen, A. 2019. Surface ocean pH and buffer capacity: past, present and future. *Scientific Reports*, vol. 9. <https://doi.org/10.1038/s41598-019-55039-4>
- Jiang, L.-Q., Fay, A., Müller, J. D., Keppler, L., Carroll, D., Lauvset, S. K., DeVries, T., Hauck, J., Rödenbeck, C., Gregor, L., et al. 2025. Synthesis of data products for ocean carbonate chemistry. *Earth Syst. Sci. Data Discuss* [preprint]. <https://doi.org/10.5194/essd-2025-255>, in review
- Jiang, L. Q., Pierrot, D., Wanninkhof, R., Feely, R. A., Tilbrook, B., Alin, S., Barbero, L., Byrne, R. H., Carter, B. R., Dickson, A.G., et al. 2022. Best Practice Data Standards for Discrete Chemical Oceanographic Observations. *Frontiers in Marine Science*, vol. 8. <https://doi.org/10.3389/fmars.2021.705638>
- Jiao, N., Cai, R., Zheng, Q., Tang, K., Liu, J., Jiao, F., Wallace, D., Chen, F., Li, C., Amann, R., et al. 2018. Unveiling the enigma of refractory carbon in the ocean. *National Science Review*, vol. 5, pp. 459-463. <https://doi.org/10.1093/nsr/nwy020>
- Jiao, N., Herndl, G. J., Hansell, D. A., Benner, R., Kattner, G., Wilhelm, S. W., Kirchman, D. L., Weinbauer, M. G., Luo, T., Chen, F., et al. 2010. Microbial production of recalcitrant dissolved organic matter: long-term carbon storage in the global ocean. *Nature Reviews Microbiology*, vol. 8, pp. 593-599. <https://www.nature.com/articles/nrmicro2386>
- Jiao, N., Luo, T., Chen, Q., Zhao, Z., Xiao, X., Liu, J., Jian, Z., Xie, S., Thomas, H., Herndl, G.J., et al. 2024. The microbial carbon pump and climate change. *Nature Reviews Microbiology*, vol. 22, pp. 408–419. <https://www.nature.com/articles/s41579-024-01018-0>
- Jiao, N., Robinson, C., Azam, F., Thomas, H., Baltar, F., Dang, H., Hardman-Mountford, N. J., Johnson, M., Kirchman, D. L., Koch, B. P., et al. 2014. Mechanisms of microbial carbon sequestration in the ocean future research directions. *Biogeosciences*, vol. 11, pp. 5565-5565. <https://doi.org/10.5194/bg-11-5285-2014>
- Jiao, N., Tang, K., Cai, H.Y. and Mao, Y. J. 2011. Increasing the microbial carbon sink in the sea by reducing chemical fertilization on the land. *Nature Reviews Microbiology*, vol. 9. 75 <https://www.nature.com/articles/nrmicro2386-c2>
- Jiao, N., Zhu, C., Liu, J., Luo, T., Bai, M., Yu, Z., Chen, Q., Rinkevich, B., Weinbauer, M., Thomas, H., et al. 2023. A roadmap for Ocean Negative Carbon Emission eco-engineering in sea-farming fields. *The Innovation Geoscience*, vol. 1. <https://doi.org/10.59717/j.xinn-geo.2023.100029>
- Jin, D., Hoagland, P. and Buesseler, K. O. 2020. The value of scientific research on the ocean's biological carbon pump. *Science of The Total Environment*, vol. 749. <https://doi.org/10.1016/j.scitotenv.2020.141357>
- Johnson, K. S. and J. A. Needoba. 2008. Mapping the spatial variability of plankton metabolism using nitrate and oxygen sensors on an autonomous underwater vehicle. *Limnology and Oceanography*, vol. 53, pp. 2237-2250. [https://doi.org/10.4319/lo.2008.53.5\\_part\\_2.2237](https://doi.org/10.4319/lo.2008.53.5_part_2.2237)
- Johnson, K. S. and Bif, M. B. 2021. Constraint on net primary productivity of the global ocean by Argo oxygen measurements. *Nature Geoscience*, vol. 14, pp. 769-774. <https://doi.org/10.1038/s41561-021-00807-z>
- Johnson, K. S., Mazloff, M. R., Bif, M. B., Takeshita, Y., Jannasch, H. W., Maurer, T. L., Plant, J. N., Verdy, A., Walz, P. M., Riser, S.C., et al. 2022. Carbon to nitrogen uptake ratios observed across the Southern Ocean by the SOCCOM profiling float array. *Journal of Geophysical Research: Oceans*, vol. 127. <https://doi.org/10.1029/2022JC018859>
- Johri, S., Carnevale, M., Porter, L., Zivian, A., Kourantidou, M., Meyer, E. L., Seevers, J. and Skubel, R. A. 2021. Pathways to justice, equity, diversity, and inclusion in marine science and conservation. *Frontiers in Marine Science*, vol. 8. <https://doi.org/10.3389/fmars.2021.696180>
- Jones, D. O., Arias, M. B., Van Audenhaege, L., Blackbird, S., Boolukos, C., Bribiesca-Contreras, G., Copley, J. T., Dale, A., Evans, S., Fleming, B. F., et al. 2025. Long-term impact and biological recovery in a deep-sea mining track. *Nature*, vol. 642, pp. 112-118. <https://doi.org/10.1038/s41586-025-08921-3>
- Kalapurakkal, H. T., Dale, A. W., Schmidt, M., Taubner, H., Scholz, F., Spiegel, T., Fuhr, M. and Wallmann, K., 2025. Sediment resuspension in muddy sediments enhances pyrite oxidation and carbon dioxide emissions in Kiel Bight. *Communications Earth and Environment*, vol. 6. <https://doi.org/10.1038/s43247-025-02132-4>
- Karcher, D. B., Cvitanovic, C., Shellock, R., Hobday, A. J., Stephenson, R. L., Dickey-Collas, M. and van Putten, I. E. 2022. More than money - the costs of knowledge exchange at the interface of science and policy. *Ocean & Coastal Management*, vol. 225. <https://doi.org/10.1016/j.ocecoaman.2022.106194>
- Keller, D. P., Lenton, A., Littleton, E. W., Oschlies, A., Scott, V. and Vaughan, N. E. 2018. The effects of carbon dioxide removal on the carbon cycle. *Current Climate Change Reports*, vol. 4, pp. 250-265. <https://doi.org/10.1007/s40641-018-0104-3>

- Kelly, R., Mackay, M., Nash, K.L. et al. 2019. Ten tips for developing interdisciplinary socio-ecological researchers. *Socio-Ecological Practice Research*, vol. 1, pp. 149–161.  
<https://doi.org/10.1007/s42532-019-00018-2>
- Key, R. M., Olsen, A., van Heuven, S., Lauvset, S. K., Velo, A., Lin, X., Schirnack, C., Kozyr, A., Tanhua, T., Hoppema, M., et al. 2015. Global Ocean Data Analysis Project, Version 2 (GLODAPv2), ORNL/CDIAC-162, NDP-093. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge.  
[https://glodap.info/wp-content/uploads/2017/08/NDP\\_093.pdf](https://glodap.info/wp-content/uploads/2017/08/NDP_093.pdf)
- Kheireddine, M., Dall'Olmo, G., Ouhssain, M., Krokos, G., Claustre, H., Schmechtig, C., Poteau, A., Zhan, P., Hoteit, I. and Jones, B. H. 2020. Organic carbon export and loss rates in the Red Sea. *Global Biogeochemical Cycles*, vol. 34.  
<https://doi.org/10.1029/2020GB006650>
- Kitidis, V., Shutler, J. D., Ashton, I., Warren, M., Brown, I., Findlay, H., Hartman, S. E., Sanders, R., Humphreys, M., Kivimäe, C. and Greenwood, N. 2019. Winter weather controls net influx of atmospheric CO<sub>2</sub> on the north-west European shelf. *Scientific Reports*, vol. 9.  
<https://doi.org/10.1038/s41598-019-56363-5>
- Klerk, B.E. 2025. The ITLOS advisory opinion on climate change: Revisiting the relationship between the United Nations Convention on Law of the Sea and the Paris Agreement. *Review of European, Comparative & International Environmental Law*, pp. 1-13.  
<https://doi.org/10.1111/reel.12588>
- Knorrn, A. H., Teder, T., Kaasik, A. and Kreitsberg, R. 2024. Beneath the blades: Marine wind farms support parts of local biodiversity - a systematic review. *Science of The Total Environment*, vol. 935.  
<https://doi.org/10.1016/j.scitotenv.2024.173241>
- Kohlman, C., Cronin, M. F., Dziak, R., Mellinger, D. K., Sutton, A., Galbraith, M., Robert, M., Thomson, J., Zhang, D. and Thompson, L. 2024. The 2019 marine heatwave at Ocean Station Papa: A multi-disciplinary assessment of ocean conditions and impacts on marine ecosystems. *Journal of Geophysical Research: Oceans*, vol. 129.  
<https://doi.org/10.1029/2023JC020167>
- Köhler, P., Hartmann, J. and Wolf-Gladrow, D. A. 2010. Geoengineering potential of artificially enhanced silicate weathering of olivine. *Proceedings of the National Academy of Sciences*, vol. 107, pp. 20228–20233.  
<https://doi.org/10.1073/pnas.1000545107>
- Krishnamoorthy, R., Tanaka, K., and Begum, M. A. 2025. Integrating GIS-Remote Sensing: A Comprehensive Approach to Predict Oceanographic Health and Coastal Dynamics. *Remote Sensing in Earth Systems Sciences*, vol. 8, pp. 200-212.  
<https://doi.org/10.1007/s41976-024-00185-1>
- Kristensen, E., Flindt, M. R. and Quintana, C. O. 2025. Predicting climate mitigation through carbon burial in blue carbon ecosystems - challenges and pitfalls. *Global Change Biology*, vol. 31.  
<https://doi.org/10.1111/gcb.70022>
- Kwon, E., Primeau, F. and Sarmiento, J. 2009. The impact of remineralization depth on the air–sea carbon balance. *Nature Geoscience*, vol. 2, pp. 630–635.  
<https://doi.org/10.1038/ngeo612>
- Lacour, L., Llorc, J., Briggs, N., Strutton, P. G. and Boyd, P. W. 2023. Seasonality of downward carbon export in the Pacific Southern Ocean revealed by multi-year robotic observations. *Nature Communications*, vol. 14.  
<https://doi.org/10.1038/s41467-023-36954-7>
- Lacroix, F., Ilyina, T., and Hartmann, J. 2020. Oceanic CO<sub>2</sub> outgassing and biological production hotspots induced by pre-industrial river loads of nutrients and carbon in a global modeling approach. *Biogeosciences*, vol. 17, pp. 55–88.  
<https://doi.org/10.5194/bg-17-55-2020>
- Lacroix, F., Ilyina, T., Laruelle, G. G., and Regnier, P. 2021b. Reconstructing the Preindustrial Coastal Carbon Cycle Through a Global Ocean Circulation Model: Was the Global Continental Shelf Already Both Autotrophic and a CO<sub>2</sub> Sink? *Global Biogeochemical Cycles*, vol. 35.  
<https://doi.org/10.1029/2020GB006603>
- Lacroix, F., Ilyina, T., Mathis, M., Laruelle, G. G. and Regnier, P. 2021a. Historical increases in land-derived nutrient inputs may alleviate effects of a changing physical climate on the oceanic carbon cycle. *Global Change Biology*, vol. 27, pp. 5491–5513.  
<https://doi.org/10.1111/GCB.15822>
- Lagaria, A., Mandalakis, M., Mara, P., Papageorgiou, N., Pitta, P., Tsiola, A., Kagiorgi, M. and Psarra, S. 2017. Phytoplankton Response to Saharan Dust Depositions in the Eastern Mediterranean Sea: A Mesocosm Study. *Frontiers in Marine Science, Sec. Marine Ecosystem Ecology*, vol. 3.  
<https://doi.org/10.3389/fmars.2016.00287>
- Lambert, F., Tagliabue, A., Shaffer, G., Lamy, F., Winckler, G., Farias, L., Gallardo, L. and De Pol-Holz, R. 2015. Dust fluxes and iron fertilization in Holocene and Last Glacial Maximum climates. *Geophysical Research Letters*, vol. 42, pp. 6014–6023.  
<https://doi.org/10.1002/2015GL064250>
- Land, P. E., Findlay, H. S., Shutler, J. D., Ashton, I. G., Holding, T., Grouazel, A., Girard-Ardhuin, F., Reul, N., Piolle, J.F., Chapron, B. and Quilfen, Y. 2019. Optimum satellite remote sensing of the marine carbonate system using empirical algorithms in the global ocean, the Greater Caribbean, the Amazon Plume and the Bay of Bengal. *Remote Sensing of Environment*, vol. 235.  
<https://doi.org/10.1016/j.rse.2019.111469>
- Landschützer, P., Gruber, N. and Bakker, D. C. E. 2016. Decadal variations and trends of the global ocean carbon sink. *Global Biogeochemical Cycles*, 30 (10), pp. 1396-1417.  
<https://doi.org/10.1002/2015GB005359>
- Lannuzel, D., Tedesco, L., Van Leeuwe, M., Campbell, K., Flores, H., Delille, B., Miller, L., Stefels, J., Assmy, P., Bowman, et al. 2020. The future of Arctic sea-ice biogeochemistry and ice-associated ecosystems, *Nature Climate Change*, vol. 10, pp. 983–992.  
<https://doi.org/10.1038/s41558-020-00940-4>

- Laruelle, G. G., Rosentreter, J. A. and Regnier, P. 2025. Extrapolation-Based Regionalized Re-evaluation of the Global Estuarine Surface Area. *Estuaries and Coasts*, vol. 48. <https://doi.org/10.1007/s12237-024-01463-3>
- Laurent, A., Wang, B., Atamanchuk, D., Rakshit, S., Azetsu-Scott, K., Algar, C. and Fennel, K. 2025. A high-resolution nested model to study the effects of alkalinity additions in Halifax Harbour, a mid-latitude coastal fjord. *EGUsphere* (preprint). <https://doi.org/10.5194/egusphere-2025-3361>
- Laurindo, L. C., Mariano, A. J. and Lumpkin, R. 2017. An improved near-surface velocity climatology for the global ocean from drifter observations. *Deep Sea Research Part I: Oceanographic Research Papers*, vol. 124, pp.73-92. <https://doi.org/10.1016/j.dsr.2017.04.009>
- Lauvset, S. K., Key, R. M., Olsen, A., van Heuven, S., Velo, A., Lin, X., Schirnack, C., Kozyr, A., Tanhua, T., Hoppema, M., et al. 2016. A new global interior ocean mapped climatology: the 1°x1° GLODAP version 2. *Earth System Science Data*, vol. 8, pp. 325–340. <https://doi.org/10.5194/essd-8-325-2016>
- Lauvset, S. K., Lange, N., Tanhua, T., Bittig, H. C., Olsen, A., Kozyr, A., Álvarez, M., Azetsu-Scott, K., Brown, P. J., Carter, B. R., et al. 2024. The annual update GLODAPv2.2023: the global interior ocean biogeochemical data product. *Earth System Science Data*, vol. 16, pp. 2047–2072. <https://doi.org/10.5194/essd-16-2047-2024>
- Law, C. S. and Ling, R. D. 2001. Nitrous oxide flux and response to increased iron availability in the Antarctic Circumpolar Current. *Deep Sea Research Part II: Topical Studies in Oceanography*, Vol. 48, pp. 2509-2527. [https://doi.org/10.1016/S0967-0645\(01\)00006-6](https://doi.org/10.1016/S0967-0645(01)00006-6).
- Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., Hajbane, S., Cunsolo, S., Schwarz, A., Levivier, A., et al. 2018. Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. *Scientific Reports*, vol. 8. <https://www.nature.com/articles/s41598-018-22939-w>
- Lee, K. and Feely, R.A. 2021. Dissolution resolution. *Nature Geoscience*, vol. 14, pp. 356–357. <https://doi.org/10.1038/s41561-021-00765-6>
- Legge, O. J., Bakker, D. C. E., Johnson, M. T., Meredith, M. P., Venables, H. J., Brown, P. J. and Lee, G. A. 2015. The seasonal cycle of ocean-atmosphere CO<sub>2</sub> Flux in Ryder Bay, West Antarctic Peninsula. *Geophysical Research Letters*, vol. 42, pp. 2934-2942. <https://doi.org/10.1002/2015GL063796>
- Legge, O. J., Bakker, D. C. E., Meredith, M. P., Venables, H. J., Brown, P. J., Jones, E. M. and Johnson, M. T. 2017. The seasonal cycle of carbonate system processes in Ryder Bay, West Antarctic Peninsula. *Deep Sea Research Part II: Topical Studies in Oceanography*, vol. 139, pp. 167-180. <https://doi.org/10.1016/j.dsr2.2016.11.006>
- Lencina-Avila, J. M., Goyet, C., Kerr, R., Orselli, I. B. M., Mata, M. M., and Touratier, F. 2018. Past and future evolution of the marine carbonate system in a coastal zone of the Northern Antarctic Peninsula. *Deep Sea Research Part II: Topical Studies in Oceanography*, vol. 149, pp. 193–205. <https://doi.org/10.1016/j.dsr2.2017.10.018>
- Le Quéré, C., Takahashi, T., Buitenhuis, E. T., Rödenbeck, C. and Sutherland, S. C. 2010. Impact of climate change and variability on the global oceanic sink of CO<sub>2</sub>. *Global Biogeochemical Cycles*, vol. 24. <https://doi.org/10.1029/2009GB003599>
- Li, C., Burger, F. A., Raible, C. C. and Frölicher, T. L. 2024. Observed Regional Impacts of Marine Heatwaves on Sea-Air CO<sub>2</sub> Exchange. *Geophysical Research Letters*, vol. 51. <https://doi.org/10.1029/2024GL110379>
- Li, H., Ilyina, T., Müller, W. A. and Landschützer, P. 2019. Predicting the variable ocean carbon sink. *Science Advances*, vol. 5. <https://doi.org/10.1126/sciadv.aav6471>
- Lindenmayer D. B. and Likens G. E. 2009. Adaptive monitoring: a new paradigm for long-term research and monitoring. *Trends in Ecology and Evolution*, vol. 24, pp. 482–486. <https://doi.org/10.1016/j.tree.2009.03.005>
- Liu, G., Bracco, A. and Brajard, J. 2023. Systematic bias correction in ocean mesoscale forecasting using machine learning. *Journal of Advances in Modeling Earth Systems (JAMES)*, vol. 15. <https://doi.org/10.1029/2022MS003426>
- Liu, M., Raymond, P. A., Lauerwald, R., Zhang, Q., Trapp-Müller, G., Davis, K. L., Moosdorf, N., Xiao, C., Middelburg, J. J., Bouwman, A.F., et al. 2024. Global riverine land-to-ocean carbon export constrained by observations and multi-model assessment. *Nature Geoscience*, vol. 17, pp. 896–904. <https://doi.org/10.1038/s41561-024-01524-z>
- Loomis, R., Cooley, S. R., Collins, J. R., Engler, S. and Suatoni, L. 2022. A Code of Conduct Is Imperative for Ocean Carbon Dioxide Removal Research. *Frontiers in Marine Science*, vol. 9. <https://doi.org/10.3389/fmars.2022.872800>
- Lotsberg, J K. and Stamnes J. J. 2010. Impact of particulate oceanic composition on the radiance and polarization of underwater and backscattered light. *Optics Express*, vol. 18, pp. 10432-10445. <https://doi.org/10.1364/OE.18.010432>
- Lovato, T., Peano, D., Butenschön, M., Materia, S., Iovino, D., Scoccimarro, E., Fogli, P. G., Cherchi, A., Bellucci, A., Gualdi, S., et al. 2022. CMIP6 simulations with theCMCC Earth System Model (CMCC-ESM2). *Journal of Advances in Modeling Earth Systems*, vol. 14. <https://doi.org/10.1029/2021MS002814>
- Ma, W., Schott, D. and van Rhee, C. 2019. Numerical calculations of environmental impacts for deep sea mining activities. *Science of The Total Environment*, vol. 652, pp. 996-1012. <https://doi.org/10.1016/j.scitotenv.2018.10.267>

- Magnan, A. K., Colombier, M., Billé, R., Joos, F., Hoegh-Guldberg, O., Pörtner, H.-O., Waisman, H., Spencer, T. and Gattuso, J.P. 2016. Implications of the Paris agreement for the ocean. *Nature Climate Change*, vol. 6, pp. 732–735.  
<https://doi.org/10.1038/nclimate3038>
- Maier-Reimer, E. 1993. Geochemical Cycles in an Ocean General Circulation Model. Preindustrial Tracer Distributions. *Global Biogeochemical Cycles*, vol. 7, pp. 645–677.  
<https://doi.org/10.1029/93GB01355>
- Maier-Reimer, E., Mikolajewicz, U. and Winguth, A. 1996. Future ocean uptake of CO<sub>2</sub>: Interaction between ocean circulation and biology. *Climate Dynamics*, vol. 12, pp. 711–722.  
<https://doi.org/10.1007/s003820050138>
- Mantovani, C., Pearlman, J., Rubio, A., Przeslawski, R., Bushnell, M., Simpson, P., Corgnati, L., Alvarez, E., Cosoli, S. and Roarty, H. 2024. An ocean practices maturity model: from good to best practices. *Frontiers in Marine Science*, vol. 11.  
<https://doi.org/10.3389/fmars.2024.1415374>
- Mathis, M., Lacroix, F., Hagemann, S., Nielsen, D. M., Ilyina, T. and Schrum, C. 2024. Enhanced CO<sub>2</sub> uptake of the coastal ocean is dominated by biological carbon fixation. *Nature Climate Change*, vol. 14, pp. 373–379.  
<https://doi.org/10.1038/s41558-024-01956-w>
- Maury, O., Campling, L., Arrizabalaga, H., Aumont, O., Bopp, L., Merino, G., Squires, D., Cheung, W., Goujon, M., Guivarch, C., et al. 2017. From shared socio-economic pathways (SSPs) to oceanic system pathways (OSPs): Building policy-relevant scenarios for global oceanic ecosystems and fisheries. *Global Environmental Change*, vol. 45, pp. 203–216.  
<https://doi.org/10.1016/j.gloenvcha.2017.06.007>
- Maury, O., Tittensor, D., Eddy, T., Allison, E., Bari, T., Barrier, N., Campling, L., Cheung, W., Frieler, K., Fulton, B., et al. 2024. The Ocean System Pathways (OSPs): A New Scenario and Simulation Framework to Investigate the Future of the World Fisheries. *Earth's Future*, vol. 13.  
<https://doi.org/10.1029/2024EF004851>
- Mazloff, M. R., Verdy, A., Gille, S. T., Johnson, K. S., Cornuelle, B. D. and Sarmiento, J. 2023. Southern Ocean Acidification Revealed by Biogeochemical-Argo Floats. *Journal of Geophysical Research: Oceans*, vol. 128.  
<https://doi.org/10.1029/2022JC019530>
- McClure, M., Sabine, C., Feely, R., Hammond, S., Meinig, C., McPhaden, M., Stabeno, P. and Bernard, E. 2023. The history and evolution of PMEL: Purposeful research that impacts environmental policy. *Oceanography*, vol. 36, pp. 10–25.  
<https://doi.org/10.5670/oceanog.2023.235>
- McKinley, G. A., Bennington, V., Meinshausen, M. and Nicholls, Z. 2023. Modern air-sea flux distributions reduce uncertainty in the future ocean carbon sink. *Environmental Research Letters*, vol. 18.  
<https://iopscience.iop.org/article/10.1088/1748-9326/acc195/pdf>
- McKinley, G. A., Fay, A. R., Hatlen Heimdal, T., Moseley, L., Shaum, C. and Acquaviva, V. 2024. Ocean carbon sink uncertainties at the scale of mCDR, GC21A-06, AGU Fall Meeting 2024.
- McKinley, E., Kelly, R., Mackay, M., Shellock, R., Cvitanovic, C. and van Putten, I. 2022. Development and expansion in the marine social sciences: Insights from the global community. *iScience*, vol. 25.  
<https://doi.org/10.1016/j.isci.2022.104735>
- McMonagle, H., Llopiz, J. K., Maas, A. E., Steinberg, D. K., Govindarajan, A. F. and Essington, T. E. 2024. Quantifying uncertainty in the contribution of mesopelagic fishes to the biological carbon pump in the Northeast Atlantic Ocean. *ICES Journal of Marine Science*, vol. 81, pp. 2037–2051.  
<https://doi.org/10.1093/icesjms/fsae149>
- McPhee, C., Bliemel, M. and van der Bijl-Brouwer, M. 2018. Editorial: Transdisciplinary Innovation (August 2018). *Technology Innovation Management Review*, vol. 8, pp. 3–6.  
<http://doi.org/10.22215/timreview/1173>
- Michaelowa, A., Hermwille, L., Obergassel, W. and Butzengeiger, S. 2019. Additionality revisited: guarding the integrity of market mechanisms under the Paris Agreement. *Climate Policy*, vol. 19, pp. 1211–1224.  
<https://doi.org/10.1080/14693062.2019.1628695>
- Middelburg, J. J., Soetaert, K., and Hagens, M. 2020. Ocean Alkalinity, Buffering and Biogeochemical Processes. *Reviews of Geophysics*, vol. 58.  
<https://doi.org/10.1029/2019RG000681>
- Mignot, A., von Schuckmann, K., Landschützer, P., Gasparin, F., van Gennip, S., Perruche, C., Lamouroux, J., and Amm, T. 2022. Decrease in air-sea CO<sub>2</sub> fluxes caused by persistent marine heatwaves. *Nature Communications*, vol. 13.  
<https://doi.org/10.1038/s41467-022-31983-0>
- Miloslavich, P., Bax, N. J., Simmons, S. E., Klein, E., Appeltans, W., Aburto-Oropeza, O., Andersen Garcia, M., Batten, S.D., Benedetti-Cecchi, L., Checkley Jr, D. M., et al. 2018. Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. *Global Change Biology*, vol. 24, pp.2416–2433.  
<https://doi.org/10.1111/gcb.14108>
- Monteiro, T., Kerr, R. and Machado, E. da C. 2020a. Seasonal variability of net sea-air CO<sub>2</sub> fluxes in a coastal region of the northern Antarctic Peninsula, *Scientific Reports*, vol. 10.  
<https://doi.org/10.1038/s41598-020-71814-0>
- Monteiro, T., Kerr, R., Orselli, I. B. M. and Lencina-Avila, J. M. 2020b. Towards an intensified summer CO<sub>2</sub> sink behaviour in the Southern Ocean coastal regions, *Progress in Oceanography*, vol. 183.  
<https://doi.org/10.1016/j.pocean.2020.102267>
- Moseley, L. A., McKinley, G. A., Carroll, D., Menemenlis, D., Dussin, R. and Nguyen, A. T. 2025. The ASTE-BGC Data-Assimilative Regional Ocean Biogeochemistry Model, JAMES, in review.  
doi: 10.22541/essoar.173870817.79303064/v1

- Mowlem, M., Beaton, A., Pascal, R., Schaap, A., Loucaides, S., Monk, S., Morris, A., Cardwell, C. L., Fowell, S. E., Patey, M.D, et al. 2021. Industry partnership: lab on chip chemical sensor technology for ocean observing. *Frontiers in Marine Science*, vol. 8. <https://doi.org/10.3389/fmars.2021.697611>
- Müller, J. D., Gruber, N., Carter, B., Feely, R., Ishii, M., Lange, N., Lauvset, S. K., Murata, A., Olsen, A., Pérez, F. F., et al. 2023. Decadal trends in the oceanic storage of anthropogenic carbon from 1994 to 2014. *AGU Advances*, vol. 4. <https://doi.org/10.1029/2023AV000875>
- Muller-Karger, F. E., Tan, A. S. H., Allcock, L., Appeltans, W., Barón Aguilar, C., Blanco, A., Bograd, S. J., Buttigieg, P., Costello, M. J., Darnaude, et al. 2024. Ocean Decade Vision 2030 White Papers – Challenge 2: Protect and Restore Ecosystems and Biodiversity. Paris, *UNESCO-IOC (The Ocean Decade Series, 51.2)*. <https://doi.org/10.25607/y60m-4329>
- Myers-Pigg, A. N., Moanga, D., Bond-Lamberty, B., Ward, N. D., Megonigal, J. P., White, E., Bailey, V. L., and Kirwan, M. L. 2025. Advancing the understanding of coastal disturbances with a network-of-networks approach. *Ecosphere*, vol. 16. <https://doi.org/10.1002/ECS2.70156>
- Nagelkerken, I., Goldenberg, S.U., Ferreira, C.M., Ullah, H. and Connell, S.D. 2020. Trophic pyramids reorganize when food web architecture fails to adjust to ocean change. *Science*, vol. 369, pp. 829-832. <https://doi.org/10.1126/science.aax0621>
- NASEM (National Academies of Sciences Engineering and Medicine). 2022. A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. Washington, D.C.: The National Academies Press, 307 pp. <https://doi.org/10.17226/26278>
- Newton, J., Widdicombe, S., Isensee, K., Dupont, S., Flickinger, S., Grabb, K., Keister, E., Schoo, K., Kenworthy, A. and Valauri-Orton, A. 2025. Ocean acidification capacity is needed at all levels to develop a multistakeholder ocean acidification action platform. *Oceanography*, vol. 38, pp. 99–100. <https://doi.org/10.5670/oceanog.2025.101>
- Nissen, C., Lovenduski, N. S., Brooks, C. M., Hoppema, M., Timmermann, R. and Hauck, J. 2024. Severe 21st-century ocean acidification in Antarctic Marine Protected Areas. *Nature Communications*, vol. 15, pp. 1–15. <https://doi.org/10.1038/s41467-023-44438-x>
- Nyboer, E. A., Reid, A. J., Jeanson, A. L., Kelly, R., Mackay, M., House, J., Arnold, S. M., Simonin, P. W., Sedanza, M. G. C., Rice, E. D., et al. 2023. Goals, challenges, and next steps in transdisciplinary fisheries research: Perspectives and experiences from early-career researchers. *Reviews in Fish Biology and Fisheries*, vol. 33, pp. 349–374. <https://doi.org/10.1007/s11160-022-09719-6>
- Organelli, E. and Claustre, H. 2019. Small phytoplankton shapes colored dissolved organic matter dynamics in the North Atlantic subtropical gyre. *Geophysical Research Letters*, vol. 46, pp.12183-12191. <https://doi.org/10.1029/2019GL084699>
- Oschlies A., Bach L., Fennel K., Gattuso J.-P. and Mengis N. 2025. Perspectives and challenges of marine carbon dioxide removal. *Frontiers in Climate*, vol 6. <https://doi.org/10.3389/fclim.2024.1506181>
- Oziel, L., Gürses, Ö., Torres-Valdés, S., Hoppe, C. J. M., Rost, B., Karakuş, O., Danek, C., Koch, B. P., Nissen, C., Koldunov, N., et al. 2025. Climate change and terrigenous inputs decrease the efficiency of the future Arctic Ocean's biological carbon pump. *Nature Climate Change*, vol. 15. <https://doi.org/10.1038/s41558-024-02233-6>
- Oziel, L., Schourup-Kristensen, V., Wekerle, C. and Hauck, J. 2022. The Pan-Arctic Continental Slope as an Intensifying Conveyor Belt for Nutrients in the Central Arctic Ocean (1985–2015). *Global Biogeochemical Cycles*, vol. 36. <https://doi.org/10.1029/2021GB007268>
- Parc, L., Bellenger, H., Bopp, L., Perrot, X. and Ho, D. T. 2024. Global ocean carbon uptake enhanced by rainfall. *Nature Geoscience*, vol. 17, pp. 851-857. <https://doi.org/10.1038/s41561-024-01517-y>
- Parsons, E. C. M., Favaro, B., Aguirre, A. A., Bauer, A. L., Blight, L. K., Cigliano, J. A., Coleman, M. A., Cote, I. M., Draheim, M., Fletcher, S., et al. 2014. Seventy-one important questions for the conservation of marine biodiversity. *Conservation Biology*, vol. 28, pp. 1206–1214. <https://doi.org/10.1111/cobi.12303>
- Partelow, S. 2018. A review of the social-ecological systems framework: applications, methods, modifications, and challenges. *Ecology and Society*, vol. 23. <https://doi.org/10.5751/ES-10594-230436>
- Pearson, H. C., Savoca, M. S., Costa, D. P., Lomas, M. W., Molina, R., Pershing, A. J., Smith, C. R., Villaseñor-Derbez, J. C., Wing, S. R. and Roman, J. 2023. Whales in the carbon cycle: can recovery remove carbon dioxide? *Trends in Ecology & Evolution*, vol. 39. <https://doi.org/10.1016/j.tree.2022.10.012>
- Pessarrodona, A., Franco-Santos, R. M., Wright, L. S., Vanderklift, M. A., Howard, J., Pidgeon, E., Wernberg, T. and Filbee-Dexter, K. 2023. Carbon sequestration and climate change mitigation using macroalgae: a state of knowledge review. *Biological Reviews*, vol. 98. <https://doi.org/10.1111/brv.12990>
- Picheral, M., Catalano, C., Brousseau, D., Claustre, H., Coppola, L., Leymarie, E., Coindat, J., Dias, F., Fevre, S., Guidi, L., et al. 2022. The Underwater Vision Profiler 6: an imaging sensor of particle size spectra and plankton, for autonomous and cabled platforms. *Limnology and Oceanography: Methods*, vol. 20, pp.115-129. <https://doi.org/10.1002/lom3.10475>
- Pickens, C., Lily, H., Harrould-Kolieb, E., Blanchard, C. and Chakraborty, A. 2024. From what-if to what-now: Status of the deep-sea mining regulations and underlying drivers for outstanding issues. *Marine Policy*, vol. 169. <https://doi.org/10.1016/j.marpol.2023.105967>

- Planchat, A., Kwiatkowski, L., Bopp, L., Torres, O., Christian, J. R., Butenschön, M., Lovato, T., Séférian, R., Chamberlain, M. A., Aumont, O., et al. 2023. The Representation of Alkalinity and the Carbonate Pump from CMIP5 to CMIP6 Earth System Models and Implications for the Carbon Cycle. *Biogeosciences*, vol. 20, pp. 1195–1257. <https://doi.org/10.5194/bg-20-1195-2023>
- Preiser, R., Biggs, R., De Vos, A. and Folke, C. 2018. Social-ecological systems as complex adaptive systems: organizing principles for advancing research methods and approaches. *Ecology and Society*, vol. 23. <https://doi.org/10.5751/ES-10558-230446>
- Prend, C. J., Gray, A. R., Talley, L. D., Gille, S. T., Haumann, F. A., Johnson, K. S., Riser, S. C., Rosso, I., Sauvé, J. and Sarmiento, J. L. 2022. Indo-Pacific sector dominates Southern Ocean carbon outgassing. *Global Biogeochemical Cycles*, vol. 36. <https://doi.org/10.1029/2021GB007226>
- Punt, M. J., Groeneveld, R. A., Van Ierland, E. C. and Stel, J.H. 2009. Spatial planning of offshore wind farms: A windfall to marine environmental protection? *Ecological Economics*, vol. 69, pp. 93-103. <https://doi.org/10.1016/j.ecolecon.2009.07.013>
- Pusceddu, A., Fiordelmondo, C., Polymenakou, P., Polychronaki, T., Tselepidis, A. and Danovaro, R. 2005. Effects of bottom trawling on the quantity and biochemical composition of organic matter in coastal marine sediments (Thermaikos Gulf, northwestern Aegean Sea). *Continental Shelf Research*, vol. 25, pp. 2491-2505. <https://doi.org/10.1016/j.csr.2005.08.013>
- Qiao, F., Yuan, Y., Deng, J., Dai, D. and Song, Z. 2016. Wave-turbulence interaction-induced vertical mixing and its effects in ocean and climate models. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 374. <https://doi.org/10.1098/rsta.2015.0201>
- Ramirez-Llodra, E., Trannum, H. C., Andersen, G. S., Baeten, N. J., Brooks, S. J., Escudero-Oñate, C., Gundersen, H., Kleiv, R. A., Ibragimova, O., Lepland, A., et al. 2022. New insights into submarine tailing disposal for a reduced environmental footprint: Lessons learnt from Norwegian fjords. *Marine Pollution Bulletin*, vol. 174. <https://doi.org/10.1016/j.marpolbul.2021.113150>
- Ratnarajah, L., Abu-Alhija, R., Atkinson, A., Batten, S., Bax, N. J., Bernard, K. S., Canonico, G., Cornils, A., Everett, J. D., Grigoratou, M., et al. 2023. Monitoring and modelling marine zooplankton in a changing climate, *Nature Communications*, vol. 14. <https://doi.org/10.1038/s41467-023-36241-5>
- Raven, M. R., Crotteau, M. A., Evans, N., Girard, Z.C., Martinez, A. M., Young, I. and Valentine, D. L. 2024. Biomass storage in anoxic marine basins: Initial estimates of geochemical impacts and CO<sub>2</sub> sequestration capacity. *AGU Advances*, vol. 5. <https://doi.org/10.1029/2023AV000950>
- Regnier, P., Friedlingstein, P., Ciais, P., Mackenzie, F. T., Gruber, N., Janssens, I. A., Laruelle, G. G., Lauerwald, R., Luysaert, S., Andersson, A. J., et al. 2013. Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nature Geoscience*, vol. 6, pp. 597–607. <https://doi.org/10.1038/ngeo1830>
- Regnier, P., Resplandy, L., Najjar, R. G. and Ciais, P. 2022. The land-to-ocean loops of the global carbon cycle. *Nature*, vol. 603, pp. 401–410. <https://doi.org/10.1038/s41586-021-04339-9>
- Resplandy, L., Hogikyan, A., Müller, J. D., Najjar, R. G., Bange, H. W., Bianchi, D., Weber, T., Cai, W. J., Doney, S.C., Fennel, K., et al. 2024. A synthesis of global coastal ocean greenhouse gas fluxes. *Global Biogeochemical Cycles*, vol. 38. <https://doi.org/10.1029/2023GB007803>
- Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., et al. 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, vol. 42, pp. 153-168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>
- Ridge, S. M. and McKinley, G. A. 2021. Ocean carbon uptake under aggressive emission mitigation. *Biogeosciences*, vol. 18, pp. 2711-2021. <https://bg.copernicus.org/articles/18/2711/2021/bg-18-2711-2021.pdf>
- Riebesell, U., Bach, L. T., Bellerby, R. G., Monsalve, J. R. B., Boxhammer, T., Czerny, J., Larsen, A., Ludwig, A. and Schulz, K. G. 2017. Competitive fitness of a predominant pelagic calcifier impaired by ocean acidification. *Nature Geoscience*, vol. 10, pp.19-23. <https://doi.org/10.1038/ngeo2854>
- Riebesell, U., Basso, D., Geilert, S., Dale, A. W., and Kreuzburg, M. 2023. Mesocosm experiments in ocean alkalinity enhancement research, in: Guide to Best Practices in Ocean Alkalinity Enhancement Research, edited by: Oschlies, A., Stevenson, A., Bach, L. T., Fennel, K., Rickaby, R. E. M., Satterfield, T., Webb, R., and Gattuso, J.-P., Copernicus Publications, State Planet. <https://doi.org/10.5194/sp-2-oae2023-6-2023>
- Riser, S. C., Freeland, H. J., Roemmich, D., Wijffels, S., Troisi, A., Belbéoch, M., Gilbert, D., Xu, J., Pouliquen, S., Thresher, A., et al. 2016. Fifteen years of ocean observations with the global Argo array. *Nature Climate Change*, vol. 6, pp. 145–153. <https://doi.org/10.1038/nclimate2872>
- Rixen, T., Gaye, B., Emeis, K. C. and Ramaswamy, V. 2019. The ballast effect of lithogenic matter and its influences on the carbon fluxes in the Indian Ocean. *Biogeosciences*, vol. 16, pp. 485–503. <https://doi.org/10.5194/bg-16-485-2019>
- Roberts, K. E., Rohr, T., Raven, M. R., Diamond, M. S., Visoni, D., Kravitz, B., Heneghan, R., Petrik, C. M., Bianchi, D., Ortega-Cisneros, K., et al. 2025. Potential impacts of climate interventions on marine ecosystems. *ESS Open Archive* (preprint). <https://essopenarchive.org/users/713517/articles/1253635-potential-impacts-of-climate-interventions-on-marine-ecosystems?commit=db60c6bed8c49dd3f5557bc3e661388e6aac5cce>

- Robinson, C., Sabine, C. and Isensee, K. 2025. Providing solutions to mitigate, adapt and build resilience to the effects of climate change. *ICES Journal of Marine Science*, vol. 82. <https://doi.org/10.1093/icesjms/fsae170>
- Rödenbeck, C., Bakker, D. C. E., Gruber, N., Iida, Y., Jacobson, A.R., Jones, S., Landschützer, P., Metzl, N., Nakaoka, S., Olsen, A., et al. 2015. Data-based estimates of the ocean carbon sink variability – First results of the Surface Ocean pCO<sub>2</sub> Mapping intercomparison (SOCOM). *Biogeosciences*, vol. 12, pp. 7251-7278. <https://doi.org/10.5194/bg-12-7251-2015>
- Roemmich, D., Alford, M. H., Claustre, H., Johnson, K., King, B., Moum, J., Oke, P., Owens, W. B., Pouliquen, S., Purkey, S., et al. 2019. On the Future of Argo: A Global, Full-Depth, Multi-Disciplinary Array. *Frontiers in Marine Science*, vol. 6. <https://doi.org/10.3389/fmars.2019.00439>
- Romera-Castillo, C., Pinto, M., Langer, T. M., Álvarez-Salgado, X. A. and Herndl, G. J. 2018. Dissolved organic carbon leaching from plastics stimulates microbial activity in the ocean. *Nature Communications*, vol. 9. <https://doi.org/10.1038/s41467-018-03798-5>
- Roobaert, A., Laruelle, G. G., Landschützer, P., Gruber, N., Chou, L. and Regnier, P. 2019. The spatiotemporal dynamics of the sources and sinks of CO<sub>2</sub> in the global coastal ocean. *Global Biogeochemical Cycles*, vol. 33, pp. 1694-1714. <https://doi.org/10.1029/2019GB006239>
- Roobaert, A., Ford, D.J., Rödenbeck, C., Gruber, N., Hauck, J., Fay, A. R., Hatlen Heimdal, T., Behncke, J., Shaum, A., Luke, G., et al. 2024. SOCOMv2: On the strengths and limits of pCO<sub>2</sub> interpolation products to estimate the ocean carbon sink. OS51C-0705, AGU Fall Meeting.
- Roobaert, A., Regnier, P., Landschützer, P. and Laruelle, G. G. 2024. A novel sea surface pCO<sub>2</sub>-product for the global coastal ocean resolving trends over the 1982-2020 period. *Earth System Science Data*, vol. 16, pp. 421-441. <https://doi.org/10.5194/essd-16-421-2024>
- Rosentreter, J. A., Laruelle, G. G., Bange, H. W., Bianchi, T. S., Busecke, J. J., Cai, W. J., Eyre, B. D., Forbrich, I., Kwon, E. Y., Maavara, T., et al. 2023. Coastal vegetation and estuaries are collectively a greenhouse gas sink. *Nature Climate Change*, vol. 13, pp. 579-587. <https://doi.org/10.1038/s41558-023-01682-9>
- Rosentreter, J. A., Al-Haj, A. N., Fulweiler, R. W. and Williamson, P. 2021. Methane and nitrous oxide emissions complicate coastal blue carbon assessments. *Global Biogeochemical Cycles*, vol. 35. <https://doi.org/10.1029/2020GB006858>
- Ross, A., Li, Z., Perezhogin, P., Fernandez-Granda, C. and Zanna, L. 2023. Benchmarking of machine learning ocean subgrid parameterizations in an idealized model. *Journal of Advances in Modeling Earth Systems*, vol. 15. <https://doi.org/10.1029/2022MS003258>
- Ryan, J. P., Dierssen, H. M., Kudela, R. M., Scholin, C. A., Johnson, K. S., Sullivan, J. M., Fischer, A. M., Rienecker, E. V., McEnaney, P. R. and Chavez, F. P. 2005. Coastal ocean physics and red tides: An example from Monterey Bay, California. *Oceanography*, vol. 18, pp. 246-255. <https://doi.org/10.5670/oceanog.2005.58>
- Saba, G. K., Burd, A. B., Dunne, J. P., Hernández-León, S., Martin, A. H., Rose, K. A., Salisbury, J., Steinberg, D. K., Trueman, C. N., Wilson, R.W., et al. 2021. Toward a better understanding of fish-based contribution to ocean carbon flux. *Limnology and Oceanography*, vol. 66, pp. 1639-1664. <https://doi.org/10.1002/lno.11709>
- Sabine, C., Robinson, C., Isensee, K., Bastian, L., Batten, S., Bellerby, R., Blasiak, R., Laarissa, S., Lira Loarca, A., McGeachy, C. et al. 2024. Ocean Decade Vision 2030 White Papers – Challenge 5: Unlock Ocean-Based Solutions to Climate Change. *Paris, UNESCO-IOC (The Ocean Decade Series, 51.5)*. <https://doi.org/10.25607/kbtq-nm78>
- Sakamoto, C. M., Johnson, K. S., Coletti, L. J., Maurer, T. L., Massion, G., Pennington, J. T., Plant, J. N., Jannasch, H. W. and Chavez, F. P. 2017. Hourly *in situ* nitrate on a coastal mooring: A 15-year record and insights into new production. *Oceanography*, vol. 30, pp. 114-127. <https://doi.org/10.5670/oceanog.2017.428>
- Sala, E., Mayorga, J., Bradley, D., Cabral, R. B., Atwood, T. B., Auber, A., Cheung, W., Costello, C., Ferretti, F., Friedlander, A. M., et al. 2021. Protecting the global ocean for biodiversity, food and climate. *Nature*, vol. 592, pp. 397-402. <https://doi.org/10.1038/s41586-021-03371-z>
- Sane, A., Reichl, B. G., Adcroft, A. and Zanna, L. 2023. Parameterizing Vertical Mixing Coefficients in the Ocean Surface Boundary Layer Using Neural Networks. *Journal of Advances in Modeling Earth Systems*, vol. 15. <https://doi.org/10.1029/2023ms003890>
- Sarmiento, J. L., Johnson, K. S., Arteaga, L. A., Bushinsky, S. M., Cullen, H. M., Gray, A. R., Hotinski, R. M., Maurer, T. L., Mazloff, M. R., Riser, S. C., et al. 2023. The Southern Ocean carbon and climate observations and modeling (SOCCOM) project: A review. *Progress in Oceanography*, vol. 219. <https://doi.org/10.1016/j.pocean.2023.103130>
- Sauzede, R., Claustre, H., Uitz, J., Jamet, C., Dall'Olmo, G., D'Ortenzio, F., Gentili, B., Poteau, A. and Schmechtig, C. 2016. A neural network-based method for merging ocean color and Argo data to extend surface bio-optical properties to depth: Retrieval of the particulate backscattering coefficient. *Journal of Geophysical Research. Oceans*, vol. 121. <https://doi.org/10.48670/moi-00046>
- Sharp, J. D., Fassbender, A. J., Carter, B. R., Johnson, G. C., Schultz, C. and Dunne, J. P. 2023. GOBAI-O 2: temporally and spatially resolved fields of ocean interior dissolved oxygen over nearly two decades. *Earth System Science Data Discussions*, vol. 15, pp. 4481-4518. <https://doi.org/10.5194/essd-15-4481-2023>
- Shellock, R. J., Cvitanovic, C., Badullovich, N., Catto, D., DelBene, J. A., Duggan, J., Karcher, D. B., Ostwald, A. and Tuohy, P. 2023. Crossing disciplinary boundaries: motivations, challenges, and enablers for early career marine researchers moving from natural to

- social sciences. *ICES Journal of Marine Science*, vol. 80, pp.40-55.  
<https://doi.org/10.1093/icesjms/fsac218>
- Shellock, R. J., Cvitanovic, C., Mackay, M., McKinnon, M. C., Blythe, J., Kelly, R., Van Putten, I. E., Tuohy, P., Bailey, M., Begossi, A., et al. 2022. Breaking down barriers: the identification of actions to promote gender equality in interdisciplinary marine research institutions. *One Earth*, 5, pp.687-708.  
<https://doi.org/10.1016/j.oneear.2022.05.006>
- Shellock, R. J., Cvitanovic, C., McKinnon, M. C., Mackay, M., van Putten, I. E., Blythe, J., Kelly, R., Tuohy, P., Maltby, K. M., Mynott, S. and Simmonds, N. 2023. Building leaders for the UN Ocean Science Decade: a guide to supporting early career women researchers within academic marine research institutions. *ICES Journal of Marine Science*, vol. 80, pp.56-75.  
<https://doi.org/10.1093/icesjms/fsac214>
- Shutler, J. D., Wanninkhof, R., Nightingale, P. D., Woolf, D. K., Bakker, D. C., Watson, A., Ashton, I., Holding, T., Chapron, B., Quilfen, Y., et al. 2020. Satellites will address critical science priorities for quantifying ocean carbon. *Frontiers in Ecology and the Environment*, vol. 18, pp. 27–35.  
<https://doi.org/10.1002/fee.2129>
- Shutler, J. D., Gruber, N., Findlay, H. S., Land, P. E., Gregor, L., Holding, T., Sims, R. P., Green, H., Piolle, J. F., Chapron, B., et al. 2024. The increasing importance of satellite observations to assess the ocean carbon sink and ocean acidification. *Earth-Science Reviews*, vol. 250.  
<https://doi.org/10.1016/j.earscirev.2024.104682>
- Siedlecki, S. A., Pilcher, D., Howard, E. M., Deutsch, C., MacCready, P., Norton, E. L., Frenzel, H., Newton, J., Feely, R. A., Alin, S. R., et al. 2021a. Coastal processes modify projections of some climate-driven stressors in the California Current System. *Biogeosciences*, vol. 18, pp. 2871–2890.  
<https://doi.org/10.5194/BG-18-2871-2021>
- Siedlecki, S. A., Salisbury, J., Gledhill, D. K., Bastidas, C., Meseck, S., McGarry, K., Hunt, C. W., Alexander, M., Lavoie, D., Wang, Z. A., et al. 2021b. Projecting ocean acidification impacts for the Gulf of Maine to 2050: New tools and expectations. *Elementa: Science of the Anthropocene*, vol. 9.  
<https://doi.org/10.1525/ELEMENTA.2020.00062>
- Siegel, D., DeVries, T., Cetinic, I. and Bisson, K. 2023. Quantifying the Ocean's Biological Pump and Its Carbon Cycle Impacts on Global Scales. *Annual Reviews of Marine Science*, vol.15.  
<https://doi.org/10.1146/annurev-marine-040722-115226>
- Smeaton, C., Cui, X., Bianchi, T. S., Cage, A. G., Howe, J. A. and Austin, W. E. N. 2021. The evolution of a coastal carbon store over the last millennium. *Quaternary Science Reviews*, vol. 266.  
<https://doi.org/10.1016/j.quascirev.2021.107081>
- Smith, S. M., Geden, O., Gidden, M., Lamb, M. J., Nemet, G.F., Minx, J., Buck, H., Burke, J., Cox, E. and Edwards, M. 2024. Chapter 10: Monitoring, reporting and verification. In: *The State of Carbon Dioxide Removal*, 2nd Edition. pp. 182- 204.  
<https://doi.org/10.17605/OSF.IO/F85QJ>
- Snoeijs-Leijonmalm, P., Flores, H., Sakinan, S., Hildebrandt, N., Svenson, A., Castellani, G., Vane, K., Mark, F. C., Heuzé, C., Tippenhauer, S., et al. 2022. Unexpected fish and squid in the central Arctic deep scattering layer. *Science advances*, vol. 8.  
<https://doi.org/10.1126/sciadv.abj7536>
- Spisla, C., Taucher, J., Bach, L. T., Haunost, M., Boxhammer, T., King, A. L., Jenkins, B. D., Wallace, J. R., Ludwig, A., Meyer, J., et al. 2021. Extreme levels of ocean acidification restructure the plankton community and biogeochemistry of a temperate coastal ecosystem: a mesocosm study. *Frontiers in Marine Science*, vol. 7.  
<https://doi.org/10.3389/fmars.2020.611157>
- Stock, C. A., Dunne, J. P., Fan, S., Ginoux, P., John, J., Krasting, J. P., Laufkötter, C., Paulot, F. and Zadeh, N. 2020. Ocean Biogeochemistry in GFDL's Earth System Model 4.1 and Its Response to Increasing Atmospheric CO<sub>2</sub>. *Journal of Advances in Modeling Earth Systems*, vol. 12.  
<https://doi.org/10.1029/2019MS002043>
- Stoer, A. C. and Fennel, K. 2024. Carbon-centric dynamics of Earth's marine phytoplankton. *Proceedings of the National Academy of Sciences*, vol. 121.  
<https://doi.org/10.1073/pnas.2405354121>
- Stoer, A.C. and Fennel, K. 2023. Estimating ocean net primary productivity from daily cycles of carbon biomass measured by profiling floats. *Limnology and Oceanography Letters*, vol. 8, pp.368-375.  
<https://doi.org/10.1002/lol2.10295>
- Strand, M., Ortega-Cisneros, K., Niner, H. J., Wahome, M., Bell, J., Currie, J. C., Hamukuaya, H., La Bianca, G., Lancaster, A. M., Maseka, N., et al. 2022. Transdisciplinarity in transformative ocean governance research—reflections of early career researchers. *ICES Journal of Marine Science*, vol. 79, pp. 2163-2177.  
<https://doi.org/10.1093/icesjms/fsac165>
- Stubbins, A., Law, K. L., Muñoz, S. E., Bianchi, T. S. and Zhu, L., 2021. Plastics in the Earth system. *Science*, vol. 373, pp. 51-55.  
<https://doi.org/10.1126/science.abb0354>
- Sulpis, O., Jeansson, E., Dinauer, A., Lauvset, S. K., and Middelburg, J. J. 2021. Calcium carbonate dissolution patterns in the ocean. *Nature Geoscience*, vol. 14, pp. 423–428.  
<https://doi.org/10.1038/s41561-021-00743-y>
- Sun, R., Sun, P., Yu, H., Ju, P., Ma, S., Liang, Z., Heino, M., Shin, Y. J., Barrier, N. and Tian, Y. 2024. Exploring fishing impacts on the structure and functioning of the Yellow Sea ecosystem using an individual-based modeling approach. *Journal of Marine Systems*, vol. 242.  
<https://doi.org/10.1016/j.jmarsys.2023.103946>
- Sunagawa, S., Acinas, S. G., Bork, P., Bowler, C., Eveillard, D., Gorsky, G., Guidi, L., Iudicone, D., Karsenti, E. and Lombard, F. 2020. Tara Oceans: towards global ocean ecosystems biology. *Nature Reviews Microbiology*, vol. 18, pp. 428-445.  
<https://doi.org/10.1038/s41579-020-0364-5>

- Sutton, A. J., Sabine, C. L., Maenner-Jones, S., Lawrence-Slavas, N., Meinig, C., Feely, R. A., Mathis, J. T., Musielewicz, S., Bott, R., McLain, P. D., et al. 2014. A high-frequency atmospheric and seawater pCO<sub>2</sub> data set from 14 open-ocean sites using a moored autonomous system. *Earth System Science Data*, vol. 6, pp. 353–366. <https://doi.org/10.5194/essd-6-353-2014>
- Sutton, A. J., Feely, R. A., Maenner-Jones, S., Musielwicz, S., Osborne, J., Dietrich, C., Monacci, N., Cross, J., Bott, R., Kozyr, et al. 2019. Autonomous seawater pCO<sub>2</sub> and pH time series from 40 surface buoys and the emergence of anthropogenic trends. *Earth System Science Data*, vol. 11, pp. 421–439. <https://doi.org/10.5194/essd-11-421-2019>
- Sutton, A. J., Williams, N. L. and Tilbrook, B. 2021. Constraining Southern Ocean CO<sub>2</sub> flux uncertainty using uncrewed surface vehicle observations. *Geophysical Research Letters*, vol. 48. <https://doi.org/10.1029/2020GL091748>
- Swoboda, S., Krumpfen, T., Nöthig, E. M., Metfies, K., Ramondenc, S., Wollenburg, J., Fahl, K., Peeken, I. and Iversen, M. 2024. Release of ballast material during sea-ice melt enhances carbon export in the Arctic Ocean. *PNAS nexus*, vol. 3. <https://doi.org/10.1093/pnasnexus/pgae081>
- Tagliabue, A., Twining, B. S., Barrier, N., Maury, O., Berger, M. and Bopp, L., 2023. Ocean iron fertilization may amplify climate change pressures on marine animal biomass for limited climate benefit. *Global Change Biology*, vol. 29, pp. 5250–5260. <https://doi.org/10.1111/gcb.16854>
- Takeshita, Y., Jones, B. D., Johnson, K. S., Chavez, F. P., Rudnick, D. L., Blum, M., Conner, K., Jensen, S., Long, J. S., Maughan, T., et al. 2021. Accurate pH and O<sub>2</sub> measurements from spray underwater gliders. *Journal of Atmospheric and Oceanic Technology*, vol. 38, pp. 181–195. <https://doi.org/10.1175/JTECH-D-20-0095.1>
- Tanhua, T., Lauvset, S. K., Lange, N., Olsen, A., Álvarez, M., Diggs, S., Bittig, H. C., Brown, P. J., Carter, B. R., da Cunha, L. C., et al. 2021. A vision for FAIR ocean data products. *Communications Earth & Environ*, vol. 2. <https://doi.org/10.1038/s43247-021-00209-4>
- Terhaar, J., Fröhlicher, T. L. and Joos, F. 2022. Observation-constrained estimates of the global ocean carbon sink from Earth system models. *Biogeosciences*, vol. 19, pp. 4431–4457. <https://doi.org/10.5194/bg-19-4431-2022>
- Terhaar, J., Orr, J. C., Ethé, C., Regnier, P. and Bopp, L. 2019. Simulated Arctic Ocean response to doubling of riverine carbon and nutrient delivery. *Global Biogeochemical Cycles*, vol. 33, pp. 1048–1070. <https://doi.org/10.1029/2019GB006200>
- Terlou, T., Bauer, C., Rosa, L. and Mazzotti, M. 2021. Life cycle assessment of carbon dioxide removal technologies: A critical review. *Energy and Environmental Science*, vol. 14, pp. 1701–1721. <https://doi.org/10.1039/d0ee03757e>
- Thomalla, S. J., Du Plessis, M., Fauchereau, N., Giddy, I., Gregor, L., Henson, S., Joubert, W. R., Little, H., Monteiro, P. M., Mtshali, et al. 2023. Southern Ocean phytoplankton dynamics and carbon export: insights from a seasonal cycle approach. *Philosophical Transactions of the Royal Society A*, vol. 381. <https://doi.org/10.1098/rsta.2022.0068>
- Thorén, H. and Persson, J. 2013. The Philosophy of Interdisciplinarity: Sustainability Science and Problem-Feeding. *Journal for General Philosophy of Science*, vol. 44, pp. 337–355. <https://doi.org/10.1007/s10838-013-9233-5>
- Tian, H., Yao, Y., Li, Y., Shi, H., Pan, S., Najjar, R. G., Pan, N., Bian, Z., Ciais, P., Cai, W. et al. 2023. Increased terrestrial carbon export and CO<sub>2</sub> evasion from global inland waters since the Preindustrial Era. *Global Biogeochemical Cycles*, vol. 37. <https://doi.org/10.1029/2023GB007776>
- Tohjima, Y., Mukai, H., Machida, T., Hoshina, Y. and Nakaoka, S.-I. 2019. Global carbon budgets estimated from atmospheric O<sub>2</sub>/N<sub>2</sub> and CO<sub>2</sub> observations in the western Pacific region over a 15-year period. *Atmospheric Chemistry and Physics*, vol. 19, pp. 9269–9285. <https://doi.org/10.5194/acp-19-9269-2019>
- Tomer, A. S., Mckenzie, T., Majtényi-Hill, C., Cabral, A., Yau, Y. Y., Call, M., Chen, X., Correa, R. E., Davis, K., Jeffrey, L. et al. 2025. Groundwater releases CO<sub>2</sub> to diverse global coastal ecosystems. *Science Advances*, vol. 11. <https://doi.org/10.1126/sciadv.adr3240>
- Tremblay-Boyer, L., Gascuel, D., Watson, R., Christensen, V. and Pauly, D. 2011. Modelling the effects of fishing on the biomass of the world's oceans from 1950 to 2006. *Marine Ecology Progress Series*, vol. 442, pp. 169–185. <https://doi.org/10.3354/meps09375>
- Tuttle, E., Wiman, C., Muñoz, S., Law, K. L. and Stubbins, A. 2024. Sunlight-driven photochemical removal of polypropylene microplastics from surface waters follows linear kinetics and does not result in fragmentation. *Environmental Science & Technology*, vol. 58, pp. 5461–5471. <https://doi.org/10.1021/acs.est.3c07161>
- Valauri-Orton, A. V. O., Lowder, K., Currie, K., Sabine, C., Dickson, A., Chu, S., Acosta, A., Asuquo, F., Bermudez, R., Bilounga, U., et al. 2025. Perspectives from developers and users of the GOA-ON in a Box kit: A model for capacity sharing in ocean sciences. *Oceanography*, vol. 38, pp. 96–98, <https://doi.org/10.5670/oceanog.2025.135>
- Vargas, C. A., Cuevas, L. A., Broitman, B. R., San Martín, V. A., Lagos, N. A., Gaitán-Espitia, J. D. and Dupont, S. 2022. Upper environmental pCO<sub>2</sub> drives sensitivity to ocean acidification in marine invertebrates. *Nature Climate Change*, vol. 12, pp. 200–207. <https://doi.org/10.1038/s41558-021-01269-2>
- Vargas, C. A., and Gelcich, S. 2024. Integrated actions across multiple sustainable development goals (SDGs) can help address coastal ocean acidification. *Communications Earth & Environment*, vol. 5, pp. 1–7. <https://doi.org/10.1038/s43247-024-01485-6>
- Vargas, C. A., Lagos, N. A., Lardies, M. A., Duarte, C., Manríquez, P. H., Aguilera, V. M., Broitman, B., Widdicombe, S. and Dupont, S. 2017. Species-specific responses to ocean acidification should

- account for local adaptation and adaptive plasticity. *Nature Ecology & Evolution*, vol. 1.  
<https://doi.org/10.1038/s41559-017-0084>
- VERRA, 2023. VM0033 Methodology for Tidal Wetland and Seagrass Restoration, v2.1.  
<https://verra.org/methodologies/vm0033-methodology-for-tidal-wetland-and-seagrass-restoration-v2-1/>
- Virro, H., Amatulli, G., Kmoch, A., Shen, L. and Uuemaa, E. 2021. GRQA: Global River Water Quality Archive. *Earth System Science Data*, vol. 13, pp. 5483–5507.  
<https://doi.org/10.5194/essd-13-5483-2021>
- Volz, J. B., Haffert, L., Haeckel, M., Koschinsky, A. and Kasten, S. 2020. Impact of small-scale disturbances on geochemical conditions, biogeochemical processes and element fluxes in surface sediments of the eastern Clarion–Clipperton Zone, Pacific Ocean. *Biogeosciences*, vol. 17.  
<https://doi.org/10.5194/bg-17-1113-2020>
- Vonk, J. E., Fritz, M., Speetjens, N. J., Babin, M., Bartsch, A., Basso, L. S., Bröder, L., Göckede, M., Gustafsson, Ö., Hugelius, G., et al. 2025. The land–ocean Arctic carbon cycle. *Nature Reviews Earth and Environment*, vol. 6, pp. 86–105.  
<https://doi.org/10.1038/s43017-024-00627-w>
- Vonnahme, T. R., Molari, M., Janssen, F., Wenzhöfer, F., Haeckel, M., Titschack, J. and Boetius, A. 2020. Effects of a deep-sea mining experiment on seafloor microbial communities and functions after 26 years. *Science advances*, vol. 6.  
<https://doi.org/10.1126/sciadv.aaz5922>
- Waldbusser, G. G., Powell, E. N. and Mann, R. 2013. Ecosystem effects of shell aggregations and cycling in coastal waters: An example of Chesapeake Bay oyster reefs. *Ecology*, vol. 94, pp. 895–903.  
<https://doi.org/10.1890/12-1179.1>
- Wang, B., Laurent, A., Pei, Q., Sheng, J., Atamanchuk, D. and Fennel, K., 2025. Maximizing the detectability of ocean alkalinity enhancement (OAE) while minimizing its exposure risks: Insights from a numerical study. *Earth's Future*, vol. 13.  
<https://doi.org/10.1029/2024EF005463>
- Wang, Z. A., Sonnichsen, F. N., Bradley, A. M., Hoering, K. A., Lanagan, T. M., Chu, S. N., Hammar, T. R. and Camilli, R. 2015. *In situ* sensor technology for simultaneous spectrophotometric measurements of seawater total dissolved inorganic carbon and pH. *Environmental science & technology*, vol. 49 (7), pp. 4441–4449.  
<https://doi.org/10.1021/es504893n>
- Wanninkhof, R., Pickers, P. A., Omar, A. M., Sutton, A., Murata, A., Olsen, A., Stephens, B. B., Tilbrook, B., Munro, D., Pierrot, D., et al. 2019. A Surface Ocean CO<sub>2</sub> Reference Network, SOCONET and Associated Marine Boundary Layer CO<sub>2</sub> Measurements. *Frontiers in Marine Science*, vol. 6.  
<https://doi.org/10.3389/fmars.2019.00400>
- Wanninkhof, R., Triñanes, J. A., Landschützer, P., Jersild, A., Feely, R. A. and Carter, B. R. 2024. Global Ocean Carbon Cycle. *Global Oceans* [in “State of the Climate in 2023”]. G. C. Johnson and R. L. Lumpkin, editors. *American Meteorological Society*, vol. 105, pp. 198–201.  
<https://doi.org/10.1175/BAMS-D-24-0100.1>
- Wanninkhof, R., Tilbrook, B., Gkritzalis, T., O'Brien, K., Bates, N. R., Nakaoka, S.-I., Bakker, D., Steinhoff, T., Kramp, M., Tedesco, et al. 2025. First steps to implement SOCONET-Tier 1 measurements and data delivery. SOCONET program document, IOCCP, 27 pp.  
<https://doi.org/10.5281/zenodo.15681842>
- Watson, J. A., Schuster, U., Shutler, J. D., Holding, T., Ashton, I. G. C., Landschützer, P., Woold, D. K. and Goddign-Murphy, L. 2020. Revised estimates of ocean-atmosphere CO<sub>2</sub> flux are consistent with ocean carbon inventory. *Nature communications*, vol. 11.  
<https://doi.org/10.1038/s41467-020-18203-3>
- Weaver P. P. E., Aguzzi J., Billet D. S. M., Boschen-Rose R., Colaco A., de Stigter H., Gollner S., Haeckel M., Hauton C., Helmons, R., et al. 2022. Assessing plume impacts caused by polymetallic nodule mining vehicles. *Marine Policy*, vol. 139.  
<https://doi.org/10.1016/j.marpol.2022.105011>
- Werdell, P. J., Behrenfeld, M. J., Bontempi, P. S., Boss, E., Cairns, B., Davis, G. T., Franz, B. A., Gliese, U. B., Gorman, E. T., Hasekamp, et al. 2019. The Plankton, Aerosol, Cloud, Ocean Ecosystem mission: status, science, advances. *Bulletin of the American Meteorological Society*, vol. 100, pp.1775-1794.  
<https://doi.org/10.1175/BAMS-D-18-0056.1>
- Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J. W., da Silva Santos, L.B., Bourne, P. E., et al. 2016. The FAIR Guiding Principles for scientific data management and stewardship. *Scientific data*, vol. 3, pp. 1-9.  
<https://doi.org/10.1038/sdata.2016.18>
- Williamson P. and Gattuso J.-P. 2022. Carbon removal using coastal blue carbon ecosystems is uncertain and unreliable, with questionable climatic cost-effectiveness. *Frontiers in Climate*, vol. 4.  
<https://doi.org/10.3389/fclim.2022.853666>
- Williamson, P., Boyd, P. W., Harrison, D. P., Reynard, N. and Mashayek, A. 2022. Chapter 10: Feasibility of using biologically-based processes in the open ocean and coastal seas for atmospheric CO<sub>2</sub> removal. In: *Greenhouse Gas Removal Technologies* (eds: M. Bui and N. Mac Dowell). *The Royal Society of Chemistry*, London, pp. 291-350. <https://doi.org/10.1039/9781839165245-00291>
- Williamson, P., Gore, C., Johannessen, S., Kristensen, E., Michaelowa, A., Wang, F. and Zhang, J. 2025. Additionality revisited for blue carbon ecosystems: Ensuring real climate mitigation. *Global Change Biology*, vol. 31. <https://doi.org/10.1111/gcb.70181>
- Willis, M. D., Lannuzel, D., Else, B., Angot, H., Campbell, K., Crabeck, O., Delille, B., Hayashida, H., Lizotte, M., Loose, B., et al. 2023. Polar oceans and sea ice in a changing climate. *Elementa: Science of the Anthropocene*, vol. 11. <https://doi.org/10.1525/ELEMENTA.2023.00056>
- Wilson, J. D., Andrews, O., Katavouta, A., de Melo Virissimo, F., Death, R. M., Adloff, M., Baker, C. A., Blackledge, B., Goldsworth, F. W., Kennedy-Asser, A. T., et al. 2022. The biological carbon pump in

- CMIP6 models: 21st century trends and uncertainties. *Proceedings of the National Academy of Sciences*, vol. 119. <https://doi.org/10.1073/pnas.2204369119>
- Woolf, D. K., Land, P. E., Shutler, J. D., Goddijn-Murphy, L. M. and Donlon, C. J. 2016. On the calculation of air-sea fluxes of CO<sub>2</sub> in the presence of temperature and salinity gradients. *Journal of Geophysical Research: Oceans*, vol. 121, pp. 1229-1248. <https://doi.org/10.1002/2015JC011427>
- Woolf, D. K., Shutler, J. D., Goddijn-Murphy, L., Watson, A. J., Chapron, B., Nightingale, P. D., Donlon, C. J., Piskozub, J., Yelland, M. J., Ashton, I., et al. 2019. Key uncertainties in the recent air-sea flux of CO<sub>2</sub>. *Global Biogeochemical Cycles*, vol. 33, pp. 1548-1563. <https://doi.org/10.1029/2018GB006041>
- Wright, R. M., Le Quéré, C., Buitenhuis, E., Pitois, S. and Gibbons, M. J. 2021. Role of jellyfish in the plankton ecosystem revealed using a global ocean biogeochemical model. *Biogeosciences*, vol. 18, pp. 1291–1320. <https://doi.org/10.5194/bg-18-1291-2021>
- Xiu, P. and Chai, F. 2014. Variability of oceanic carbon cycle in the North Pacific from seasonal to decadal scales. *Journal of Geophysical Research: Oceans*, vol. 199. <https://doi.org/10.1002/2013JC009505>
- Xu, W., Liu, Y., Wu, W., Dong, Y., Lu, W., Liu, Y., Zhao, B., Li, H. and Yang, R. 2020. Proliferation of offshore wind farms in the North Sea and surrounding waters revealed by satellite image time series. *Renewable and Sustainable Energy Reviews*, vol. 133. <https://doi.org/10.1016/j.rser.2020.110167>
- Yamamoto, K., DeVries, T. and Siegel, D.A. 2024. Metrics for quantifying the efficiency of atmospheric CO<sub>2</sub> reduction by marine carbon dioxide removal (mCDR). *Environmental Research Letters*, vol. 19. <https://doi.org/10.1088/1748-9326/ad7477>
- Yasunaka, S., Manizza, M., Terhaar, J., Olsen, A., Yamaguchi, R., Landschützer, P., Watanabe, E., Carroll, D., Adiwira, H., Müller, J. D., et al. 2023. An assessment of CO<sub>2</sub> uptake in the Arctic Ocean from 1985 to 2018. *Global Biogeochemical Cycles*, vol. 37. <https://doi.org/10.1029/2023GB007806>
- You, H. S., Marshall, J. A. and Delgado, C. 2018. Assessing students' disciplinary and interdisciplinary understanding of global carbon cycling. *Journal of Research in Science Teaching*, vol. 55, pp. 377-398. <https://doi.org/10.1002/tea.21423>
- Zanna, L., and Bolton, T. 2020. Data-Driven Equation Discovery of Ocean Mesoscale Closures. *Geophysical Research Letters*, vol. 47. <https://doi.org/10.1029/2020gl088376>
- Zhang, C., Shi, T., Liu, J., He, Z., Thomas, H., Dong, H., Rinkevich, B., Wang, Y., Hyun, J.H., Weinbauer, M., et al. 2022. Eco-engineering approaches for ocean negative carbon emission. *Science Bulletin (Beijing)*, vol. 67, pp. 2564-2573. <https://doi.org/10.1016/j.scib.2022.11.016>
- Zhang, W., Porz, L., Yilmaz, R., Wallmann, K., Spiegel, T., Neumann, A., Holtappels, M., Kasten, S., Kuhlmann, J., Ziebarth, N., et al. 2024. Long-term carbon storage in shelf sea sediments reduced by intensive bottom trawling. *Nature Geoscience*, vol. 17, pp. 1268–1276. <https://doi.org/10.1038/s41561-024-01581-4>
- Zhao, S., Kvale, K. F., Zhu, L., Zettler, E. R., Egger, M., Mincer, T. J., Amaral-Zettler, L. A., Lebreton, L., Niemann, H., Nakajima, R., et al. 2025. The distribution of subsurface microplastics in the ocean. *Nature*, vol. 641, pp. 51-61. <https://doi.org/10.1038/s41586-025-08818-1>
- Zhou, L., Huang, L., and Tan, Y. 2023. Iron-aluminum hypothesis and the potential of ocean aluminum fertilization as a carbon dioxide removal strategy. *Journal of Tropical Oceanography*, vol. 42, pp. 1-18. <https://doi.org/10.1111/gcb.16990>
- Zhou, L., Liu, F., Liu, Q., Fortin, C., Tan, Y., Huang, L. and Campbell, P. G. C. 2021. Aluminum increases net carbon fixation by marine diatoms and decreases their decomposition: Evidence for the iron–aluminum hypothesis. *Limnology and Oceanography*, vol. 66. <https://doi.org/10.1002/lno.11784>
- Zhou, L., Tan, Y., Huang, L., Fortin, C. and Campbell, P. G. C. 2018. Aluminum effects on marine phytoplankton: implications for a revised Iron Hypothesis (Iron-Aluminum Hypothesis). *Biogeochemistry*, vol. 139, pp. 123-137. <https://doi.org/10.1007/s10533-018-0458-6>
- Zhou, M., Tyka, M. D., Ho, D. T., Yankovsky, E., Bachman, S., Nicholas, T., Karspeck, A. R. and Long, M.C. 2024. Mapping the global variation in the efficiency of ocean alkalinity enhancement for carbon dioxide removal. *Nature Climate Change*, vol. 15, pp. 59-65. <https://doi.org/10.1038/s41558-024-02179-9>
- Zhu, K., Jia, H., Sun, Y., Dai, Y., Zhang, C., Guo, X., Wang, T. and Zhu, L. 2020. Long-term phototransformation of microplastics under simulated sunlight irradiation in aquatic environments: Roles of reactive oxygen species. *Water Research*, vol. 173. <https://doi.org/10.1016/j.watres.2020.115564>
- Zhu, C., Hu, C., Liu, J., Chi, Z. and Jiao, N. 2024. Integrating bicarbonate-based microalgal production with alkaline sewage for ocean negative carbon emissions. *Trends in Biotechnology*, vol. 42, pp. 1592-1600. <https://doi.org/10.1016/j.tibtech.2024.06.015>
- Ziervogel, K., Kehoe, S., Jesus, A., Saidi-Mehrabad, A., Robertson, M., Patterson, A. and Stubbins, A. 2024. Microbial interactions with microplastics: Insights into the plastic carbon cycle in the ocean. *Marine Chemistry*, vol. 262. <https://doi.org/10.1016/j.marchem.2024.104395>

The ocean is critical to climate change prediction and mitigation, but major knowledge gaps remain.

The Integrated Ocean Carbon Research (IOC-R) Report identifies clear global priorities for integrated ocean carbon research, observation, and cooperation.

IOC-R has brought together the foremost international scientists in ocean carbon research to provide a consensus on the priority research needs required to close these fundamental knowledge gaps. These include operationalising ocean carbon observations, undertaking multiple driver manipulation and adaptation studies on marine plankton, creating a land-ocean observational programme which incorporates local and indigenous knowledge, and evaluating the impact of future ocean based industrial processes including fisheries. Improved quantification of the ocean carbon sink can then be used to assess whether ocean based climate interventions are feasible, safe and effective.

By setting the priority needs for integrated ocean carbon research, observation, and cooperation, the report allows the international community to identify those essential actions for moving ocean carbon research forward to which they can contribute. The report invites the global community of countries, policymakers, funding bodies, local communities, and researchers, to partake and address the interdisciplinary challenges in understanding, predicting and mitigating inevitable changes of the global carbon cycle.

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