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The Climate Technology Progress Report 2026

Navigating Ocean-based Technologies

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Navigating Ocean-based Technologies

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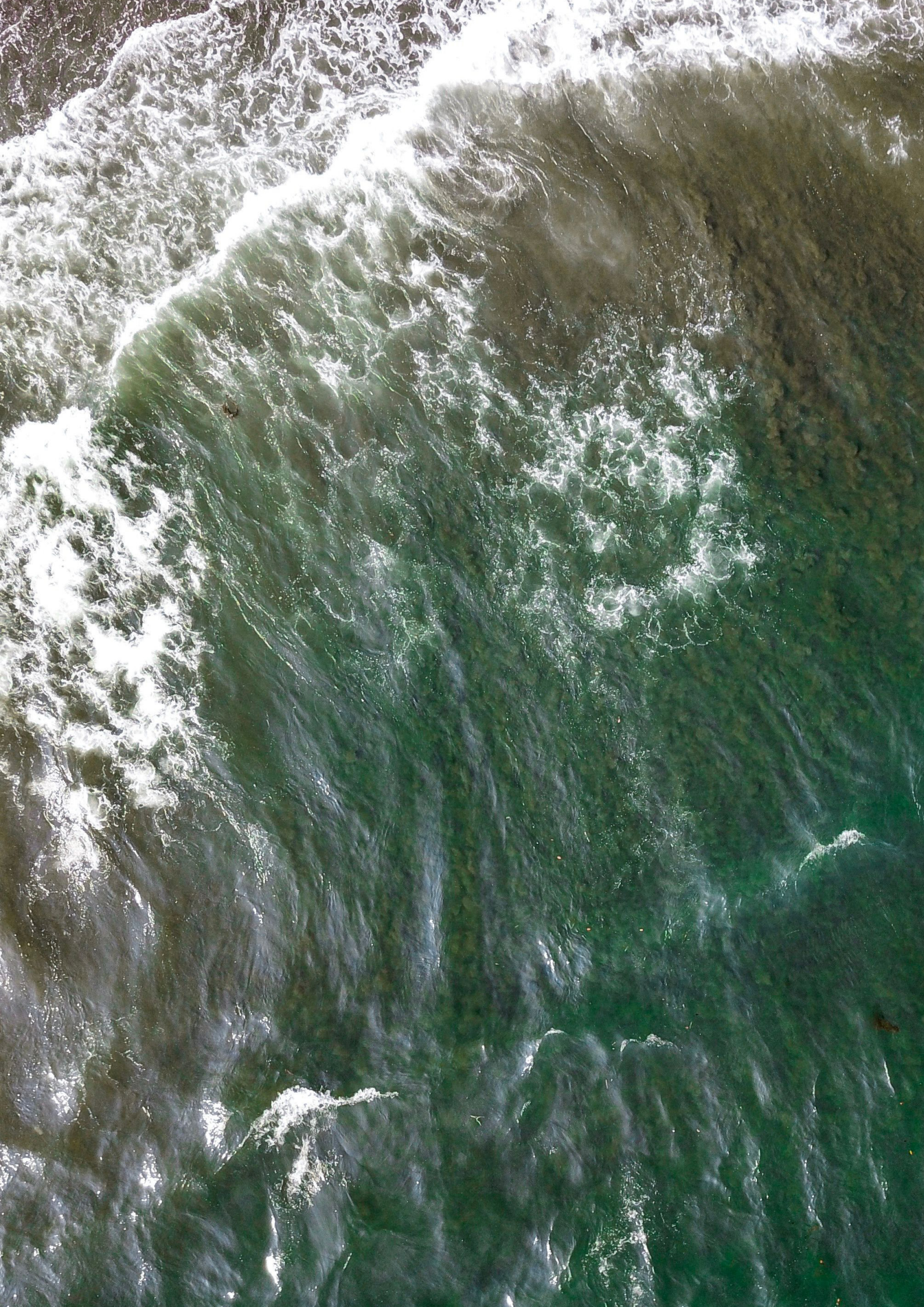
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GLOSSARY

Blue carbon ecosystems (BCEs)	Carbon stored in coastal and marine ecosystems, particularly vegetated coastal ecosystems such as mangroves, salt marshes and seagrass beds, which can store substantial amounts of carbon in biomass and sediments (IPCC 2019; Cooley et al. 2022; Lovelock and Duarte 2019). These ecosystems also provide important benefits for coastal resilience, biodiversity and livelihoods, making their protection and restoration relevant to both climate mitigation and adaptation.
Carbon dioxide removal (CDR)	Approaches that remove CO_2 from the atmosphere and store it durably, providing an essential long-term strategy to complement point-source carbon capture (IPCC 2022a). Marine carbon dioxide removal (mCDR) is a subset of CDR that seeks to enhance the ocean's capacity to remove and store atmospheric CO_2 (Oschlies et al. 2025).
Climate technology	Those technologies that help reduce greenhouse gas emissions and/or reduce climate risk and/or enhance the resilience of a natural or human system to the impacts of climate change (see definition of technology below).
Enabling environment	The set of resources and conditions within which the technology and the target beneficiaries operate. The resources and conditions that are generated by structures and institutions that are beyond the immediate control of the beneficiaries should support and improve the quality and efficacy of the transfer and diffusion of technologies (Nygaard and Hansen 2015).
Governance	The process of managing public and private interactions through collaboration, negotiation and coordination between different actors, including the state, civil society, national and international organizations and the private sector. Governance is broader than government and does not rely solely on top-down authority. Instead, it emphasizes participation, decentralization, cooperation and the use of wider collective strategies for implementation (Dubash et al. 2022, IPCC 2018).
Innovation	Both the processes of research and development and the commercialization of the technology, including its social acceptance and adoption (IPCC 2000).
Innovation system	All important economic, social, political, organizational and other factors that influence the development, diffusion and use of innovations (IPCC 2000).
Ocean-based climate technologies	Climate technologies that use, operate in, interact with or support ocean and coastal environments to reduce greenhouse gas emissions, remove carbon dioxide from the atmosphere, enhance climate resilience or generate the information and infrastructure needed to understand, monitor and respond to climate change.
Ocean Carbon Intelligence (OCI)	A holistic, data-driven capability that integrates ocean observations, digital infrastructure, analytical models and ocean-based climate technologies to quantify, predict and manage ocean carbon dynamics in support of climate mitigation and adaptation.
Regulation	A rule or order issued by governmental executive authorities or regulatory agencies and having the force of law. Regulations implement policies and are mostly specific to groups of people, legal entities or targeted activities. Regulation is also the act of designing and imposing rules or orders. Informational, transactional, administrative and political constraints may limit the regulator's capability to implement preferred policies (IPCC 2022a; b).
Responsible innovation	The process of designing and implementing innovations in a way that anticipates and evaluates potential impacts on society and the environment (Owen and Stilgoe 2013). It requires inclusive, transparent decision-making involving a broad range of stakeholders. The goal is to ensure that innovation aligns with societal needs and ethical standards, promoting sustainability and positive social outcomes while minimizing harm. This approach emphasizes responsibility throughout the innovation lifecycle.

Risk management	Plans, actions, strategies or policies to reduce the likelihood and/or magnitude of adverse potential consequences, based on assessed or perceived risks (IPCC 2022a; b). Risk management initiatives should seek to align diverse groups, ensuring that the negative socioeconomic and environmental impacts of digital innovations are adequately addressed.
Technology	Technology is "a piece of equipment, technique, practical knowledge or skills for performing a particular activity" (IPCC 2000). It is common practice to distinguish between three different components of technology (Müller 2003): • Hardware: the tangible component, such as equipment and products • Software: the processes associated with the production and use of the hardware • Orgware: the institutional framework, or organization, involved in the adoption and diffusion process of a technology. These three components are all part of a specific technology, but the relative importance of each component may vary from one technology to another.
Technology transfer	The exchange of knowledge, hardware and associated software, money and goods among stakeholders, which leads to the spread of technology for adaptation or mitigation. The term encompasses both the diffusion of technologies and technological cooperation across and within countries (IPCC 2022a).



CONTENTS

Acknowledgements 04
Glossary 05
Foreword 10
Foreword 11
Executive Summary 12

1. Introduction 17
1.1 Context 18
1.2 Ocean Agenda in International Climate Policy 19
1.3 Climate Technology and the Ocean 20
1.4 The 2026 CTPR 20
1.5 Structure of the Report 24

2. State of the Ocean Carbon Sink: Trends, Variability, Mechanisms and Future Change 26
2.1 Introduction 28
2.2 The Ocean in the Global Carbon Budget 28
2.3 Mechanisms of Carbon Uptake and Storage 30
2.4 Ocean Observations and Modelling 33
2.5 Marine Carbon Uptake During Future Climate Change 35

3. Technologies for Monitoring, Managing and Enhancing the Ocean Carbon Sink 40
3.1 Introduction 42
3.2 Monitoring the Ocean Carbon Sink: Observational Technologies and Digital Capabilities 42
3.3 Managing the Ocean Carbon Sink: Blue Carbon Ecosystems 46
3.4 Enhancing the Ocean Carbon Sink: Marine Carbon Dioxide Removal 50
3.5 Conclusion 55

4. Governance and Policy Implications of Ocean-based Climate Technologies 56
4.1 Introduction 58
4.2 International Governance Frameworks and Institutions 58
4.3 Social Equity, Inclusion and Governance Implications 62
4.4 Monitoring, Standards, and Certification 66
4.5 Knowledge and Capacity Gaps 67
4.6 Finance, Investment and Enabling Market Mechanisms 68
4.7 International Cooperation 71

5. Ocean-based Climate Technologies in SIDS 72
5.1 Introduction 74
5.2 Climate-related Risks in SIDS 74
5.3 Climate-Ocean Impacts: Ecological and Socioeconomic Implications 75
5.4 Opportunities and Progress in SIDS 79
5.5 Barriers to Financing Ocean-based Technologies in SIDS 83
5.6 Enabling Conditions for Technology Transfer 86
5.7 International Cooperation 87
5.8 Conclusion 88

References 90
Acronyms 115

FOREWORD

The ocean has never divided us; it has always connected us.

For generations, the ocean has carried our stories, sustained our livelihoods and shaped our cultures. It feeds our families, supports our economies and connects our islands to one another and to the wider world. Although we come from many nations, we are united by the ocean we share.

Today, that ocean is sending us a clear message. Rising seas, warming waters, coral bleaching and changing fisheries are affecting lives and livelihoods. These are not distant projections confined to scientific reports. They are realities already unfolding in our communities, reminding us that the future of our people and the future of the ocean are inseparable.

The 2026 Climate Technology Progress Report comes at a defining moment. As the world prepares for COP31, it highlights a simple but powerful truth: the ocean is not only essential to regulating the Earth's climate, it is also one of our greatest allies in building resilience to a changing world. Protecting it is fundamental to our shared future.

The report explores technologies that can help meet this challenge, from restoring blue carbon ecosystems and strengthening ocean observation systems to advancing responsible marine innovation. While technological advances are essential, their impact depends on the broader enabling conditions in which they are developed, deployed and used. Technology's greatest value lies in empowering people, informing better decisions and strengthening the resilience of communities on the front lines of climate change.

For Small Island Developing States (SIDS), this conversation is deeply personal. Although they contribute the least to global emissions, SIDS continue to experience some of the greatest consequences. Yet they continue to demonstrate that leadership is measured not by size, but by vision, partnership and the courage to act.

As Pacific COP31 Envoy for the Ocean, I believe we have both an opportunity and a responsibility to place the ocean where it belongs: at the heart of global climate action. This will require bold leadership, stronger partnerships and sustained investment, while recognizing that science, innovation and Indigenous knowledge together offer our best pathway towards a more resilient future.

In Fiji, we often say *Noda waitui, noda bula* – our ocean, our life. Those words express a truth understood across the Blue Pacific: when the ocean thrives, our people thrive. As we look towards COP31 and beyond, may this report inspire governments, researchers, innovators, investors and communities to work together with greater ambition and shared purpose. The science is clear. The solutions are within our reach. The opportunity before us is one we cannot afford to miss.

The ocean has connected us for generations. Let it now unite us in protecting the future we all share.



Honourable Inia B. Seruiratu
Pacific COP31 Envoy for the Ocean
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FOREWORD

The ocean is fundamental to climate stability and resilience. For decades, it has absorbed a significant share of human-generated carbon dioxide emissions and excess heat, helping to slow global warming, moderate climate impacts, and support the resilience of ecosystems and coastal communities. Yet this vital climate-regulating function is under growing pressure. Ocean warming, acidification, deoxygenation and ecosystem degradation are altering the processes that govern carbon uptake and storage, raising concerns about the long-term resilience of the ocean carbon sink and the resilience of the communities that depend on healthy marine ecosystems.

The 2026 Climate Technology Progress Report responds to this challenge by examining the role of ocean-based technologies in supporting climate action. It examines three interrelated areas: ocean observation and digital capabilities, the protection and restoration of blue carbon ecosystems, and emerging marine carbon dioxide removal technologies. While these technologies offer important opportunities to strengthen climate mitigation, adaptation and resilience, they differ significantly in their levels of maturity, associated challenges and risks.

Ocean observation and digital capabilities, as well as blue carbon ecosystem approaches, are increasingly established, whereas marine carbon dioxide removal technologies require further assessment to address scientific uncertainties, environmental and social impacts, and governance issues before implementation.

A central finding of this report is that ocean-based climate technologies are not a substitute for rapid and sustained greenhouse gas emissions reductions. Rather, they can contribute to broader efforts to protect and restore ecosystems, strengthen climate resilience, support vulnerable coastal communities and advance the goals of the Paris Agreement.

We hope this report serves as a valuable resource for policymakers, researchers, investors, practitioners and communities working to advance responsible and equitable ocean-based climate action. By investing in technology, strengthening the scientific evidence base and fostering effective governance and international cooperation, we can help safeguard the ocean's critical role in climate stability while enhancing adaptation, resilience and sustainable development in a changing climate.



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EXECUTIVE SUMMARY

The ocean is fundamental to climate stability, livelihoods and sustainable development. It currently absorbs approximately 30 per cent of human-induced carbon dioxide emissions and about 90 per cent of the additional heat generated by climate change. In doing so, it has substantially moderated the pace and scale of global warming. This climate-regulating function, however, cannot be assumed to continue indefinitely. Ocean warming, acidification, deoxygenation, shifting circulation and nutrient patterns, pollution and ecosystem degradation are altering the physical, chemical and biological processes that govern carbon uptake and storage.

Understanding and responding to these changes requires stronger capabilities to observe, analyse and appropriately manage ocean carbon dynamics. Ocean-based climate technologies, including ocean carbon monitoring systems, blue carbon ecosystems (BCEs) and marine carbon dioxide removal (mCDR) approaches, may contribute not only to climate mitigation but also to adaptation, resilience and sustainable ocean management. Reflecting this, the 2026 Climate Technology Progress Report highlights Ocean Carbon Intelligence (OCI) as a framework through which marine science and technology can be connected to help facilitate climate action. By strengthening scientific understanding through the integration of ocean observations, digital infrastructure and analytical models, together with Indigenous and local knowledge systems where appropriate, OCI enables complex marine data to be transformed into actionable, decision-ready insights, supporting the informed assessment and implementation of ocean-based climate technologies capable of protecting, restoring or enhancing ocean carbon sinks.

The report identifies six interrelated priorities for action aimed at sustaining the ocean's climate-regulating functions and supporting the responsible, equitable development and deployment of ocean-based climate technologies.

1. Deep and sustained greenhouse gas emissions reductions, alongside the complementary and appropriately governed use of ocean-based climate technologies, are indispensable for limiting further weakening of the ocean carbon sink and reducing pressure on marine ecosystems.
Ocean-based climate technologies cannot substitute for deep emissions reductions or comprehensive action to protect marine ecosystems. They can, however, support efforts to help preserve natural carbon sinks, strengthen climate resilience, improve the evidence base for decision-making and, where scientifically supported and appropriately governed, contribute to carbon dioxide removal.

Evidence assessed in this report indicates that human-induced climate change has already reduced the ocean's carbon sink capacity by an estimated 6 per cent compared with a world without human-derived climate change. Carbon uptake is also highly variable across regions, seasons and years, reflecting natural climate variability and complex interactions among ocean processes. A weakening or increasingly uncertain ocean carbon sink would leave a greater proportion of human-induced carbon dioxide in the atmosphere, further constraining the remaining global carbon budget and increasing the risks, costs and uncertainties associated with delayed climate action.

Rapid and sustained reductions in greenhouse gas emissions therefore remain the primary and indispensable climate response.

2. Securing long-term investment in ocean observation, data infrastructure and modelling, with particular attention to under-observed regions and the development of accessible, interoperable and locally relevant information, strengthens understanding of ocean carbon dynamics and supports evidence-based decision-making.
The effectiveness of OCI as an enabling framework depends on sustained, accessible and interoperable ocean observations. Significant geographic and thematic gaps remain, particularly in the Southern Ocean, the Arctic, the Indian Ocean and in many coastal regions. These gaps constrain our understanding of changes in the ocean carbon sink and limit the ability to identify sensitive regions, assess emerging risks and distinguish the effects of technological interventions from high levels of natural variability. Despite growing recognition of their importance, global capacities for observing the ocean carbon cycle have declined in recent years. Strengthening these capacities requires long-term international cooperation, dedicated financial and institutional support, improved data coordination and wider access to locally relevant information. The contributions of ocean observing systems to essential climate infrastructure should also be reflected through a more stable and sustainable footing, comparable to internationally mandated terrestrial and meteorological observing systems.

3. Key enablers for the evidence-based implementation of ocean-based climate technologies, including the integration of scientific evidence, monitoring systems, policy and finance, can be strengthened by embedding OCI in climate and ocean decision-making processes.
OCI is a holistic, data-driven capability that unites marine observations, knowledge and technologies to provide a more comprehensive understanding of ocean carbon sinks and sources and enable informed decision-making

across climate mitigation, adaptation and sustainable ocean management practices. It can help governments, communities, industry and investors assess ocean carbon dynamics, evaluate ocean-based climate technologies, strengthen monitoring, reporting and verification (MRV) systems, and inform marine spatial planning and climate policy. OCI also supports the assessment of the effectiveness, risks and scalability of ocean-based climate technologies while helping to ensure that their development and deployment are measurable, transparent, environmentally sound and responsive to local and regional needs.

4. Advancing ocean-based climate technologies through differentiated, evidence-based and precautionary pathways reflects the substantial differences in maturity, evidence base, scalability, potential climate benefits and environmental and social risks across technology areas.
The report considers three interrelated areas of ocean-based climate technology development: ocean carbon monitoring and digital infrastructure, management of BCEs, and implementation of mCDR technologies. These technology areas differ substantially in their maturity, evidence base, scalability, potential climate benefits and environmental and social risks, requiring differentiated pathways for research, development, deployment and governance.

Advancements in platforms, sensors and data handling technologies have significantly improved our ocean surface and interior monitoring capabilities. However, current observational configurations are not optimised for the assessment of evolving climate technologies that require more nuanced, targeted observations, including higher-resolution locally relevant data products and marine models. The development and implementation of these fit-for-purpose MRV approaches requires alignment with existing data standardisation and accessibility practices that support trust-building through wider participation and transparency.

Technologies supporting the restoration of BCEs, such as mangroves, seagrass meadows and saltmarshes, are relatively more mature than many other ocean-based climate technologies and deployable at scale. While their potential to enhance atmospheric carbon sequestration is relatively limited compared with overall carbon dioxide removal requirements under climate mitigation pathways, such techniques can support biodiversity, coastal protection, fisheries and community resilience. Realizing these benefits requires moving beyond short-term, project-based restoration towards adaptive, ecosystem-scale management integrated with coastal planning and climate adaptation. Standardized and affordable monitoring frameworks are also needed to distinguish among the protection of existing carbon stocks, additional atmospheric carbon dioxide uptake, and the avoidance or suppression of greenhouse gas emissions. mCDR technologies have greater potential for facilitating large-scale atmospheric carbon removal than BCEs but remain at lower technology readiness levels and are associated with significant scientific, environmental, social and governance uncertainties. Properly evaluating their potential contribution to climate mitigation efforts requires a carefully governed transition from predominantly theoretical research towards appropriately designed and funded field trials. The credibility and effectiveness of such trials depend, in part, on clearly defined scientific protocols, environmental safeguards, transparency and data-sharing requirements, as well as robust approaches to MRV. Scientific and technical research on mCDR needs to advance alongside social, economic, political and governance research.

Early engagement and co-design with potentially affected communities and stakeholders can help identify risks, clarify societal expectations, and inform decisions on whether, where, and under what conditions particular approaches may be appropriate. Such decisions should also take account of the multiple uses of the ocean, the rights and interests of affected communities, and broader considerations of equity, justice and environmental sustainability. Within this broader context, carbon removal approaches are best considered as potential complements to, rather than substitutes for, rapid emissions reductions and ecosystem protection.

5. Strengthening coherent and equitable governance at all levels, including robust environmental and social safeguards, protection of rights and livelihoods, transparent monitoring and meaningful participation by affected communities, provides the foundation for well-governed ocean-based climate technology development and deployment.
The shared and interconnected nature of the ocean, together with the potential for long-term and transboundary impacts associated with ocean-based climate technologies, makes robust governance particularly important. Existing international governance arrangements relevant to these technologies are fragmented across multiple institutions and legal regimes. This fragmentation creates gaps, overlaps and areas of uncertainty that may impede well-governed research and technology development while potentially weakening environmental and social safeguards. The fragmentation of existing arrangements highlights the importance of greater coordination across international regimes, supported by appropriate structural and institutional reforms. International action is complemented by coherent regional, national and subnational frameworks that provide clarity for researchers, communities, technology developers, regulators and investors. Adaptive governance, including mechanisms to revise monitoring

requirements, environmental safeguards and operational practices as new evidence emerges, are well suited to responding to new evidence, changing environmental conditions and evolving technologies. Monitoring mechanisms should also extend beyond carbon accounting to encompass ecosystem impacts, social outcomes and distributional effects. They should also be capable of addressing transboundary impacts and supporting adaptive decision-making under conditions of uncertainty.

Equity and justice are important considerations in the governance of ocean-based climate technologies. The development and deployment of these technologies may have implications for the distribution of benefits, risks and decision-making authority across different groups and regions. Governance frameworks that protect existing resource rights and ocean-dependent livelihoods, recognize Indigenous Peoples' and local communities' knowledge and governance systems, and support meaningful participation and equitable benefit-sharing may help address these challenges.

6. Improving access to finance, technology and capacity development, particularly for coastal developing countries and Small Island Developing States (SIDS), through sustained partnerships, technology cooperation and financing arrangements aligned with national circumstances and vulnerability, can support the wider implementation of ocean-based climate technologies and associated mitigation, adaptation and resilience benefits.

Financing for ocean-based climate technologies remains fragmented and appears insufficient relative to identified needs. Scaling sustainable investment will depend on shared enabling infrastructure, including standardized taxonomies, robust MRV systems, accessible data, stronger technology-transfer arrangements and policies that reduce risk without compromising environmental or social safeguards.

SIDS face some of the world's most severe and immediate ocean-climate risks despite contributing less than 1 per cent of global greenhouse gas emissions. Sea-level rise, ocean warming, acidification, extreme events and ecosystem degradation threaten livelihoods, infrastructure, freshwater security, food systems, cultural heritage and, in some cases, long-term habitability. Nature-based and hybrid coastal protection measures can offer important adaptation, mitigation, biodiversity and resilience benefits when designed for local ecological and social conditions. For example, mangrove restoration combined with coastal monitoring systems can help reduce storm impacts while supporting carbon sequestration and fisheries productivity. Emerging technologies, including artificial intelligence-enabled risk modelling and mCDR, may offer additional opportunities to strengthen resilience and support evidence-based decision-making. However, their application in SIDS requires rigorous safeguards, sustained operational capacity and meaningful community engagement.

Effective technology transfer extends beyond the delivery of equipment or short-term pilot projects. It depends on long-term human and institutional capacity, regional cooperation, peer learning, data access, interoperability and co-design with communities. Aligning technology development and deployment with traditional knowledge, Indigenous governance systems and national priorities is also essential to ensure effectiveness and local ownership.

Structural barriers continue to constrain access to climate and ocean finance in SIDS. These include limited fiscal space, high debt burdens, administrative constraints, fragmented financing arrangements and eligibility criteria based primarily on national income rather than climate vulnerability. More accessible, predictable and grant-based adaptation and loss and damage finance is needed, alongside appropriately designed instruments such as blue bonds and debt-for-nature swaps. When aligned with national priorities and robust governance arrangements, these instruments can help mobilize resources for ocean observation systems, blue carbon ecosystem restoration, coastal resilience measures and other ocean-based climate technologies, while reducing financing constraints and supporting long-term stewardship of marine resources. Financing mechanisms that reduce transaction costs, strengthen national ownership, build long-term institutional capacity, and avoid creating additional debt vulnerabilities can help support more effective and sustainable outcomes.

Collectively, these actions can help sustain the ocean's role as a carbon sink and provide a foundation for effective climate resilience. Delivering on this potential requires sustained international cooperation and a clear recognition that ocean-based climate technologies need to proceed alongside emissions reductions, ecosystem protection, social inclusion and strengthened governance mechanisms. If appropriately supported and implemented, OCI may serve as a framework for integrating advances in ocean science, data systems and technology into climate-related decision-making, in ways that support the objectives of the Paris Agreement and the United Nations Framework Convention on Climate Change.



1.
Introduction

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1.1 CONTEXT

As countries prepare for COP31 in 2026, the ocean is gaining prominence on the global climate agenda. Healthy and resilient oceans are fundamental to life on Earth, sustaining biodiversity, supporting food security and livelihoods, underpinning cultural values and human well-being, and contributing to economic development for communities around the world. At the same time, the ocean plays a critical role in regulating the Earth's climate system, currently absorbing roughly 30 per cent of global carbon dioxide (CO_2) emissions and taking up more than 90 per cent of the additional heat trapped by climate change (Friedlingstein et al. 2026; Von Schuckmann et al. 2023; Robinson, Sabine and Isensee 2024). These ecological, social and climate functions are deeply interconnected.

Although the ocean continues to absorb substantial amounts of anthropogenic carbon, the current rate of uptake is altering ocean chemistry and may reduce the efficiency of future carbon sequestration and long-term storage (Intergovernmental Panel on Climate Change [IPCC] 2021 and 2023). Warmer ocean waters hold less CO_2, and changes in ocean circulation, chemistry and biological processes, including acidification, deoxygenation and shifting nutrient patterns, are affecting the mechanisms through which carbon is absorbed, transported and stored in marine systems (Heinze et al. 2015; IPCC 2021; Müller et al. 2023). These changes not only influence the ocean's role as a carbon sink but also reduce the resilience of marine and coastal systems, placing growing pressure on ecosystems, coastal communities and ocean-dependent livelihoods. These pressures are particularly evident in Eastern Boundary Upwelling Systems, including the Humboldt Current System, which face compounded impacts from warming, ocean acidification and expanding Oxygen Minimum Zones, highlighting their importance as natural laboratories for understanding the vulnerability of ocean carbon sinks to environmental change.

Reflecting the growing urgency of these challenges, the 2026 Climate Technology Progress Report (CTPR) focuses specifically on ocean-based climate technologies that can help protect or enhance ocean carbon uptake and long-term storage, with particular attention paid to the size and stability of the ocean carbon sink as the climate changes. The report underscores the ocean's dual role as both a vital carbon reservoir and a foundation of climate resilience, where protecting ecosystems and strengthening adaptive capacity are widely recognized as important for sustaining long-term climate stability, coastal protection and ocean-based livelihoods. By framing ocean-climate action around the stability of the marine carbon sink and the technologies that can directly influence it, the report seeks to move beyond broad narratives towards a focused policy question:

How may the ocean's climate function be maintained while managing emerging risks and uncertainties?

The dynamic nature of ocean carbon fluxes also has important implications for climate mitigation. A weakening sink means that a greater share of anthropogenic CO_2 remains in the atmosphere, further constraining the remaining global carbon budget. Moreover, current national commitments remain insufficient to keep warming within the Paris Agreement's 1.5°C goal, increasing the likelihood of a temporary overshoot and subsequent reliance on accelerated emissions reductions and carbon dioxide removal (CDR) (IPCC 2023; WMO 2023; United Nations Environment Programme [UNEP] 2025; UNEP 2026a). The UNEP Emissions Gap Report 2026 finds that limiting warming to 1.5°C with no or limited overshoot is no longer feasible, shifting the priority to minimizing the magnitude and duration of overshoot and returning to 1.5°C by the end of the century (UNEP 2026b). Limiting this overshoot to approximately 0.3°C would require global greenhouse gas emissions to decline by around 26 per cent by 2030 and 46 per cent by 2035 relative to 2019 levels (UNEP 2025). However, these reductions may not be sufficient to return temperatures to around 1.5°C by the end of the century under some assessed pathways, which may also incorporate CDR, including through emerging ocean-based technologies (UNEP 2024; 2025). The Limiting Overshoot report (UNEP 2026a) further shows that, in scenarios where warming temporarily exceeds 1.5°C before subsequently returning to it, CDR would need to increase substantially beyond the level required at net zero, reaching around 15–24 gigatonnes of CO_2 per year by 2100. This highlights the risks, costs and uncertainties associated with delayed action and increasing reliance on future CDR.

In addition to these projected mitigation requirements, changes in the ocean's physical, chemical and biological systems are already increasing climate adaptation needs. The warming and disruption of marine ecosystems is placing additional pressure on fisheries, coastal protection, critical habitats and ecosystem practices. Strengthening resilience to these changes requires implementation measures such as climate-sustainable fisheries management, the protection and restoration of mangroves, coral reefs, seagrasses and other critical marine habitats, and investment in resilient coastal infrastructure. Indigenous Peoples and local communities can also make important contributions through locally grounded observation, customary management practices, nature-based approaches, and community-based monitoring and governance systems that support early warning, sustainable resource use, and the protection and restoration of blue carbon ecosystems (BCEs).

Technology deployment cannot, however, be assessed in isolation from its environmental and social impacts. Ocean-based interventions should be assessed in relation to their implications for ecological integrity, affected communities and livelihoods, while accounting for compounding risks such as marine heatwaves[1] and harmful algal blooms that can threaten marine ecosystems and coastal economies.

1.2 OCEAN AGENDA IN INTERNATIONAL CLIMATE POLICY

The growing focus on ocean-based climate action reflects a broader evolution in international climate policy. For decades, the ocean-climate nexus received limited attention in global climate negotiations. Although article 4(1)(d) of the 1992 United Nations Framework Convention on Climate Change (UNFCCC) recognized oceans as carbon sinks, early discussions focused primarily on sea level rise, with the term "ocean" notably absent from the 1997 Kyoto Protocol. A significant shift occurred with the 2015 Paris Agreement, which explicitly referenced the ocean in its preamble, encouraging coastal and island nations to incorporate ocean-related targets into their nationally determined contributions (NDCs). This momentum catalysed the formation of key coalitions and initiatives, including the Because the Ocean Initiative, the Ocean and Climate Platform, the Roadmap to Oceans and Climate Action (ROCA), and the Ocean and Climate Initiatives Alliance (OCIA). In 2017, UN-Oceans further strengthened coordination by inviting the UNFCCC Secretariat to enhance integration across relevant mandates. This growing momentum materialized at COP25 in 2019, the "Blue COP", which established a foundation for more structured ocean discussions under the UNFCCC. More recently, the ocean agenda has continued to gain political and institutional prominence. Early ratification of the 2023 Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction (the BBNJ Agreement) has established an important precedent for the cooperative governance of transboundary marine ecosystems. At COP30, Parties further reinforced ocean action through initiatives such as the Blue Package and the Blue Mutirão, which elevated the role of ocean-based solutions within broader climate and sustainable development agendas.

In 2023, global ocean trade in goods and services reached US$2.2 trillion, accounting for approximately 7 per cent of global trade (UNCTAD 2025). Leading international initiatives are increasingly translating the ocean-climate agenda into growing political momentum with concrete policy, financing and technology actions. The Food and Agriculture Organization (FAO) emphasizes sustainable fisheries and aquaculture as pathways to reducing ecological pressures and strengthening food-system resilience (FAO 2024). The Organisation for Economic Co-operation and Development (OECD) integrates marine biotechnology and circular economy approaches into strategies for a sustainable and low-carbon ocean economy (OECD 2025), while the World Bank's PROBLUE initiative supports financing for climate-smart fisheries, marine conservation and coastal resilience (World Bank 2025). More recently, UNEP provides governments with a systems-based approach to advancing regenerative and equitable blue economies, emphasizing ecosystem protection and restoration, climate resilience, inclusion and alignment of public and private finance with sustainable development objectives (UNEP 2026c).

The World Economic Forum's Ocean Action Agenda promotes the scaling of climate-aligned technologies across shipping, offshore renewable energy and coastal management (World Economic Forum 2023). Across these efforts, increasing attention is being directed towards interventions that can stabilize or enhance ocean carbon sequestration while simultaneously strengthening ecosystem resilience and community adaptive capacity.

Within the climate regime, the UNFCCC Ocean and Climate Change Dialogue and the High-Level Panel for a Sustainable Ocean Economy are also advancing the integration of ocean-based solutions into global climate commitments. Since 2020, the UNFCCC has institutionalized the annual Ocean and Climate Change Dialogue to strengthen the integration of ocean-related issues within climate mitigation and adaptation efforts (UNFCCC 2024). The High-Level Panel for a Sustainable Ocean Economy (Ocean Panel), convened by 19 world leaders, has produced a series of evidence-based reports calling for coordinated policy action to enhance the ocean's contribution to climate resilience and sustainable development (High-Level Panel for a Sustainable Ocean Economy 2020), including the Blue Carbon Handbook (2023) and work on responsible governance of marine carbon dioxide removal (mCDR) (Doney et al. 2025). The Dialogue has highlighted NDCs as a key opportunity for Parties to strengthen climate ambition through ocean-based mitigation and adaptation measures. This is increasingly reflected in decisions under the UNFCCC process. For example, the Sharm el-Sheikh Implementation Plan,

1 Marine heatwaves are prolonged periods of unusually high ocean temperatures relative to the average seasonal temperature of a particular marine region. They can persist from several days to months and extend across areas spanning thousands of kilometres. Marine heatwaves are becoming more frequent and extreme as a result of human-induced warming, posing increasing risks to marine organisms and ecosystems and potentially pushing them beyond their capacity to adapt and recover (Frölicher et al. 2018).

adopted at COP27, encourages Parties to consider "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," recognizing the important role of the ocean in addressing climate change (UNFCCC 2022). Reflecting this evolution, the UNFCCC Technology Executive Committee (TEC) decided to undertake work on innovative ocean-climate solutions as part of its rolling workplan for 2023 to 2027 (UNFCCC Technology Mechanism 2022). This work contributes to the TEC's broader efforts to promote innovative technology solutions related to nature and ecosystems, recognizing the critical role of marine and coastal systems in climate mitigation, adaptation, resilience-building and sustainable development.

1.3 CLIMATE TECHNOLOGY AND THE OCEAN

Sustaining the ocean's role as a global carbon sink, while maintaining healthy and resilient marine ecosystems, requires understanding how the ocean carbon cycle and ecosystems are changing and how these changes affect carbon uptake and storage. Sustained and expanded marine observation networks, combined with improved integration of observations and models, are therefore fundamental to tracking changes in the ocean carbon sink and ecosystem condition (Gruber et al. 2023)

Such knowledge is particularly important for protecting carbon fluxes in BCEs, where degradation caused by changes in land and coastal management processes can reduce their capacity to sequester and store carbon and, in some cases, may result in the release of previously stored carbon. Where carbon stores and ecosystem functions have already been degraded, restoration and improved management techniques can help recover carbon storage and ecological function while strengthening resilience to climate impacts. Healthy BCEs can therefore contribute simultaneously to climate mitigation, coastal protection and other ecosystem benefits (Macreadie et al. 2021; Lovelock and Duarte 2019).

Alongside protecting and restoring existing ocean carbon sinks, a range of proposed ocean-based climate technologies aim to enhance carbon uptake into seawater or facilitate long-term storage in oceanic settings. These mCDR techniques include ocean alkalinity enhancement (OAE), direct ocean carbon capture and storage (DOCCS), macroalgal cultivation and sinking, and phytoplankton fertilization. However, such approaches remain subject to important questions regarding their effectiveness, permanence, ecological implications and governance, and require careful assessment before their potential contribution to climate action can be established (Doney et al. 2025; Oschlies et al. 2025). In all cases, the proposed application of these ocean-based climate technologies to increase carbon sequestration within the ocean does not negate the need for rapid and deep reductions in greenhouse gas emissions (UNEP 2026), thus they need to be considered as a part of a wider portfolio of climate mitigation actions.

Technologies may contribute to efforts to monitor and protect at-risk ecosystems, support restoration activities, and assess emerging approaches for enhancing marine carbon fluxes where appropriate. Ultimately the contribution of these ocean-based climate technologies to climate adaptation and mitigation efforts depends on the quality of the underlying evidence, the scale at which they are implemented, and the governance and implementation conditions under which they are deployed. This is particularly important where impacts are uncertain, difficult to measure or may emerge over long timescales. In this context, changes in the ocean carbon sink demonstrate that natural carbon sequestration cannot be treated as a fixed or guaranteed component of future carbon budgets. Sustaining the ocean's contribution to climate action is likely to depend on strengthened observation and knowledge, protection and restoration of marine ecosystems, careful assessment of emerging interventions, and continued reductions in greenhouse gas emissions (UNFCCC 2023; 2025; Eluri et al. 2025; GOOS 2025).

1.4 THE 2026 CTPR

1.4.1 Scope and relevance of the report

The CTPR series (Box 1.1) provides systematic annual assessments of the current state of technology adoption in selected areas, including enabling conditions for technology development and uptake. The 2026 CTPR explores the role of ocean-based climate technologies in strengthening climate mitigation, adaptation and resilience. The report analyses current trends in technology development and transfer, identifies barriers and enabling conditions, and highlights opportunities for accelerating the deployment of technologies that support climate mitigation, adaptation and resilience. The integration of climate technologies into ocean-climate strategies offers a powerful pathway for strengthening natural carbon sinks, improving climate information and decision-making, enhancing adaptive capacity and supporting sustainable development.

Box 1.1: The Climate Technology Progress Reports

Understanding the aspects of technology development and transfer significantly influences how we enhance and accelerate implementation of climate technologies. Climate Technology Progress Reports (CTPRs) provide systematic, annual assessments of the current state of technology adoption in selected areas, and the feasibility and requisite enabling conditions for technology development and transfer at the sectoral, regional and global levels. The reports ask the following questions, all within the context of enhancing technology development and transfer:

1) What progress is being made?
2) What has enabled it?
3) Where are the gaps?
4) Building on this understanding, how do we better enhance climate technology development and transfer?

While these guiding questions shape the overall direction of the report, they are adapted each year to reflect emerging issues in the global climate landscape.

The CTPR series forms part of the Technology Executive Committee's (TEC) rolling workplan for 2023–2027 and contributes to the first Joint Work Programme of the UNFCCC Technology Mechanism (UNFCCC Technology Mechanism 2022). Through its focus on emerging climate technologies, the series provides evidence and analysis to inform international discussions on technology development and transfer and their role in advancing climate action. The reports examine technological developments, opportunities and challenges across specific areas of climate action, with the aim of strengthening understanding of where technology can support mitigation and adaptation and where further innovation, enabling conditions and international cooperation may be needed. In this way, the CTPR contributes to the Technology Mechanism's broader efforts to support countries in implementing their climate goals and national climate plans.

A focus on climate technologies that support ocean system stability is relevant not only for coastal countries but also for landlocked nations. While coastal states depend directly on healthy marine ecosystems for livelihoods, food systems and climate resilience, landlocked countries are influenced by ocean-driven climate processes that affect precipitation patterns, droughts, floods and water security. Moreover, virtually all countries participate in global trade systems that depend heavily on maritime transport and associated infrastructure. By driving innovation, strengthening climate and ocean governance, and supporting shared mitigation and adaptation goals, ocean-based climate technologies may therefore contribute to climate resilience and sustainable development across diverse national contexts. They are particularly relevant to Small Island Developing States (SIDS), where ocean and coastal systems are closely linked to economic prosperity, environmental sustainability and long-term resilience. Reflecting this importance, the 2026 CTPR includes a dedicated regional chapter on SIDS, examining the opportunities, barriers and enabling conditions associated with climate technology development and transfer in these uniquely ocean-dependent contexts.

Box 1.2: Technology as defined in this report

Technology, as defined in this report, encompasses not only physical equipment and products (hardware), but also the processes and knowledge needed to produce and use them (software) and the institutional arrangements that enable their adoption and diffusion (orgware) (IPCC 2000; Müller 2003). The relative importance of these three components varies across technologies, but all are integral to their development and use. See glossary for further details.

The 2026 CTPR is guided by two overarching questions:

- How are climate technologies advancing across key ocean-related domains, and what progress has been achieved to date?

- What factors enable or constrain the development, deployment and accessibility of these technologies, and what actions can accelerate implementation across different national and regional contexts?

These questions guide the report's assessment of the intersection between ocean systems, technology development and climate action, including the conditions needed for technologies to contribute effectively to mitigation, adaptation and resilient ocean systems.

1.4.2 Ocean-based technologies for climate action

The 2026 CTPR focuses on three interrelated categories of ocean-based climate technologies: ocean observation and digital capabilities, BCE management and mCDR technologies. Together, these approaches have the potential to strengthen ocean carbon uptake, maintain long-term carbon storage, improve climate resilience and enhance adaptive capacity. They can support both mitigation and adaptation objectives while contributing to healthier oceans and more resilient coastal communities.

- **Ocean observation and digital capabilities:** Technologies and systems used to observe, measure, analyse, and communicate information on marine carbon system dynamics. These systems support climate mitigation by enabling monitoring, reporting, and verification, while also strengthening adaptation by improving climate-risk assessment, forecasting, and decision-making.

- **Blue carbon ecosystems (BCEs):** Technologies that support the sustainable management, protection and restoration of mangroves, seagrass meadows, and salt marshes. By preserving and enhancing natural carbon sinks, these technologies contribute to both climate mitigation and adaptation while providing additional benefits such as coastal protection and ecosystem resilience.

- **Marine carbon dioxide removal (mCDR):** Technologies and approaches that enhance the ocean's capacity to remove carbon dioxide from the atmosphere and store it over long timescales. These emerging approaches are being explored as potential complements to emissions reduction efforts and require careful consideration of their environmental, governance, and monitoring challenges.

The emphasis on these three technology categories are motivated by several key developments shaping the ocean-climate agenda. First, the growing demand for reliable data, observations and evidence-based climate decision-making has elevated the importance of advanced ocean monitoring, observation and data systems. Second, increasing recognition of the role of BCEs in climate regulation has generated growing interest in technologies and approaches that protect and restore coastal carbon sinks. Third, concerns about the scale of future carbon removal requirements and the rate of development of 'novel' CDR mechanisms (Edwards et al. 2026), have contributed to increasing interest in mCDR technologies. Collectively, these developments reflect a broader shift towards more integrated ocean-climate strategies that combine improved climate information, ecosystem-based approaches and technological innovation.

The technologies within each category span different levels of maturity, from relatively established to emerging technologies that remain under development, testing and validation. The report examines these differences in technological maturity alongside broader enabling conditions, including policy and governance, that shape their potential for deployment, scaling and contribution to climate action. The three categories are also highly interconnected. For example, effective BCE conservation and restoration, depend on robust monitoring and data systems to assess ecosystem health, carbon dynamics and climate impacts, while mCDR requires credible monitoring, reporting and verification (MRV) capabilities to evaluate effectiveness, permanence and environmental risks. Considering these technologies together consequently provides a more holistic understanding of progress in ocean-climate innovation, including the linkages between technological development, enabling conditions and technology transfer (Figure 1.1).

While not exhaustive, the three technology categories selected for this report represent some of the most policy-relevant and strategically significant pathways through which technology development and transfer can support climate action based on ocean systems. Other emerging areas also hold considerable potential, but the focus of the 2026 CTPR is on those technologies that are currently most central to strengthening ocean carbon management, climate resilience and adaptive capacity at global and regional scales.

1.4.3 Ocean Carbon Intelligence as an enabling foundation for marine climate action

The 2026 CTPR introduces the concept of Ocean Carbon Intelligence (OCI; Box 1.3) as the foundation for enabling informed climate action and the more effective management of, and reliance on, marine environments for climate change adaptation and mitigation purposes. Recognizing that the ocean's role in climate regulation, adaptation and mitigation pathways continues to evolve means there is a growing need to connect ocean observations, data, modelling, scientific knowledge and digital technologies in ways that can facilitate effective decision-making. This includes linking open-ocean observations with nearshore monitoring systems and terrestrial river-basin datasets to help address data sparsity in highly dynamic environments, such as upwelling systems and fjords, and to improve the attribution of carbon fluxes and compounding climate risks. OCI provides a framework for bringing these elements together to strengthen our understanding of marine carbon dynamics and inform the protection and enhancement of ocean carbon sinks, as well as to enable the responsible development and deployment of emerging ocean-based climate mitigation approaches (Figure 1.1).

Informed decision-making in these areas requires not only stronger data and knowledge systems, but also robust, science-based policy frameworks. By bridging the gap between ocean science, climate technologies and real-world implementation, OCI serves as a critical enabler of evidence-based decision-making and the effective design and delivery of ocean-climate solutions.

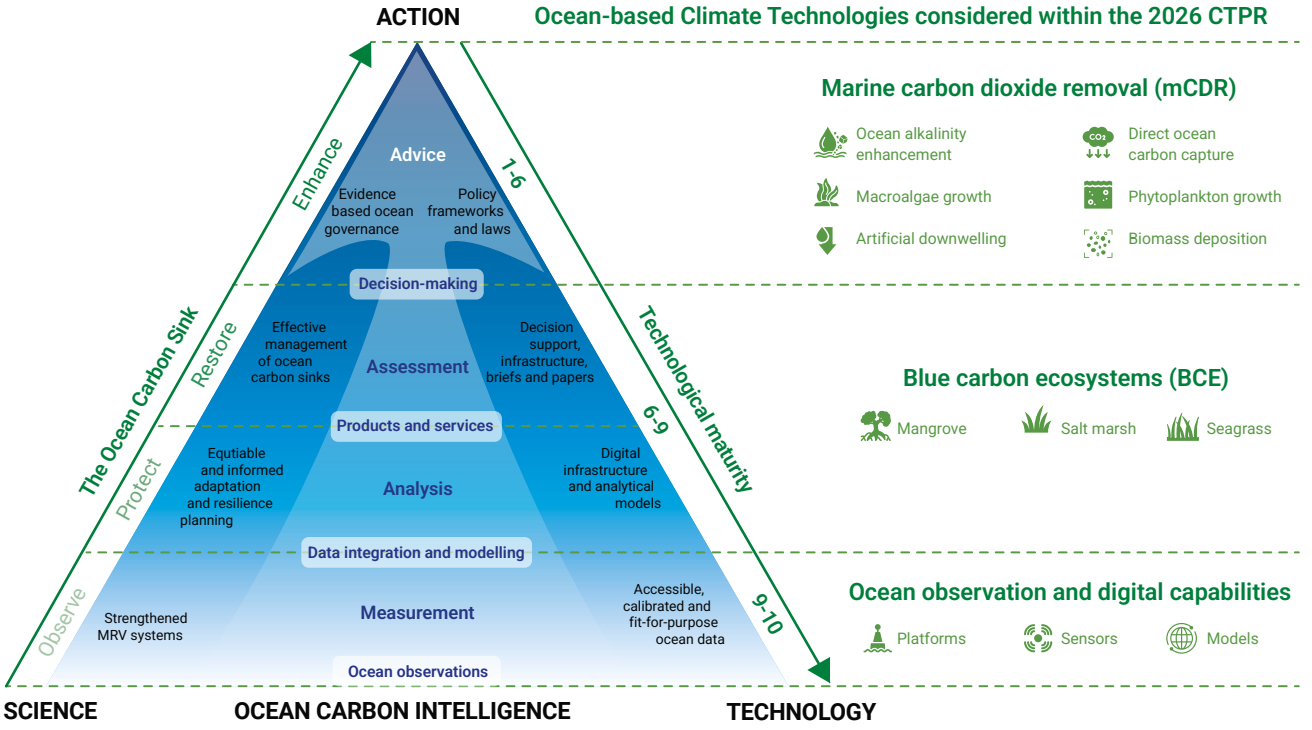


Figure 1.1: The OCI value chain, illustrating how ocean observations and digital infrastructure provide the foundation for transforming data into knowledge, intelligence and informed decision-making for managing and utilizing ocean carbon sinks. The OCI framework aligns with the Ocean Data Value Chain concept proposed by Heymans et al. (2021) (Box 1.3).

Box 1.3: Conceptualization of Ocean Carbon Intelligence

Definition
Ocean Carbon Intelligence (OCI) is a holistic, data-driven framework that integrates ocean observations, digital infrastructure, analytical models and ocean-based climate technologies to help quantify, predict and manage ocean carbon sinks and related processes in support of climate mitigation and adaptation.

Conceptual framing
OCI is aligned with the Ocean Data Value Chain concept (Heymans et al. 2021), with the underpinning rationale being to transform complex ocean data into actionable, decision-ready insights, enabling governments, industry and investors to assess and implement effective marine climate solutions. It provides the critical measurement, monitoring and decision-support infrastructure needed to:

- Assess and manage ocean carbon sinks and sources
- Support the evaluation of ocean-based climate technologies and, where appropriate, their deployment (e.g. blue carbon solutions, mCDR)
- Strengthen monitoring, reporting and verification (MRV) systems
- Inform evidence-based policy and marine spatial planning

At its core, OCI acts as the interface between science, technology and action, supporting the assessment of marine climate interventions with respect to transparency, measurability, scalability and potential environmental and social impacts.

Enabling role for marine climate action
By embedding marine climate technologies within an integrated intelligence framework, OCI ensures that ocean-based solutions are:

- Based on sound scientific principles with an evidence base of high-quality observations and models
- Environmentally responsible (minimizing unintended ecological impacts)
- Just and equitable (supporting inclusive access and fair benefit-sharing)
- Cost-effective, resource-efficient and scalable (reducing uncertainty and investment risk)

Value proposition
OCI is presented as a framework for supporting evidence-informed marine climate action. By transforming ocean data into actionable intelligence and integrating climate technologies into decision-making systems, OCI enables:

- Effective carbon management and climate mitigation
- Informed adaptation and resilience planning
- Trusted voluntary and compliance carbon markets and associated investment flows
- Sustainable and adaptive ocean governance

1.5 STRUCTURE OF THE REPORT

To provide both a comprehensive overview and targeted insights, the 2026 CTPR adopts a hybrid global and regional format. Chapters 2 to 4 take a global perspective on progress in the development and transfer of ocean-based climate technologies, while Chapter 5 provides a dedicated regional assessment focused on SIDS. As some of the countries most exposed to climate change impacts, SIDS depend disproportionately on healthy ocean ecosystems for livelihoods, food security, economic development and climate resilience. This structure enables an assessment of overall progress in technology development and transfer, while also providing deeper insights into the unique opportunities, challenges and enabling conditions shaping climate technology innovation in SIDS contexts. By combining global and regional analyses, the report generates evidence for tailored interventions that consider distinct governance, financing, institutional and environmental conditions, while also recognizing broader global patterns and interdependencies.



2.

State of the Ocean Carbon Sink: Trends, Variability, Mechanisms and Future Change

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CHAPTER HIGHLIGHTS

- The ocean is a critical yet dynamic climate regulator. It has mitigated human-caused climate change by absorbing nearly 30 per cent of anthropogenic CO_2 emissions in recent decades, and 90 per cent of the extra heat. However, the ocean carbon sink is subject to complex physical, chemical and biological mechanisms.
- Carbon uptake also varies significantly across time and space. The Southern Ocean plays a particularly important role in global ocean carbon uptake, while some regions can act as net sources of CO_2. Ocean warming generally reduces the capacity of the ocean to absorb CO_2 and can contribute to shifts from net uptake towards net emissions in some regions, reinforcing the importance of continued mitigation.
- Climate change is already degrading the ocean's sink capacity. Shifting wind fields and ocean warming are actively reducing the ocean's capacity to absorb carbon by about 6 per cent compared to a world without anthropogenic climate change. Rapid and substantial emission reductions would reduce the risk of further climate-driven weakening of the ocean carbon sink.
- Multiple climate-driven changes are altering the ocean carbon sink. Increasing stratification, ocean acidification and more frequent and intense marine heatwaves could further disrupt carbon uptake, increase regional variability and challenge the reliability of historical relationships used to assess the ocean carbon sink.
- Surface ocean CO_2 observations remain sparse and unevenly distributed, particularly in the Arctic Ocean and in the Southern Ocean, with the latter being disproportionately important to the global ocean carbon sink. Other regions, including coastal and Indian Ocean areas, may have observations but face challenges related to data access and coordination.
- Additional observations across the carbon cycle would improve understanding of the ocean carbon sink and support the development and validation of regional and global models, from physical processes to biological dynamics.
- Sustained international cooperation and dedicated resources play an important role in maintaining reliable ocean carbon observing networks. Uneven observational coverage and high variability in ocean carbon uptake currently limit the ability to assess changes in the sink, identify sensitive regions and emerging risks, and inform priorities for protection and management.

2.1 INTRODUCTION

Over recent decades, the ocean has absorbed approximately 30 per cent of anthropogenic CO_2 emissions, which it stores for decades to millenniums. This chapter assesses this ocean carbon sink: how large it is, which processes regulate and sustain it, how reliably it can be quantified, and how it is expected to change. The ocean carbon sink is not a fixed background condition. It responds to natural variability, rising atmospheric CO_2 and climate change. The following sections describe the size of the sink and its regional and temporal variations (section 2.2), the mechanisms of carbon uptake, export and storage (section 2.3), what information observations and models can and cannot resolve (section 2.4) and how the sink may respond under different future emission pathways (section 2.5). This chapter provides the scientific basis for Chapter 3, which examines approaches intended to protect, restore or enhance ocean carbon storage and assesses mCDR approaches, while also considering their potential role in supporting climate resilience.

2.2 THE OCEAN IN THE GLOBAL CARBON BUDGET

The ocean holds about 40 times more carbon than the atmosphere and about 10–20 times more than the land biosphere. It is therefore by far the largest of the three active carbon reservoirs that interact with each other to redistribute carbon in the Earth system (Canadell et al. 2021). The large ocean carbon reservoir results mainly from the chemistry of seawater. Atmospheric CO_2 dissolves in seawater and reacts with it until a balance between ocean and atmosphere is reached. These same chemical processes explain why the ocean is such an important sink of anthropogenic (i.e. human-caused) CO_2 emissions. In recent decades, only about 50 per cent of anthropogenic emissions remained in the atmosphere. About 20 per cent are taken up by the land biosphere and almost 30 per cent are taken up by the ocean, the latter corresponding to about 3.2 gigatonnes of carbon (GtC) per year on average over 2015–2024 (Friedlingstein et al. 2026a; see Figure 2.1). The ocean also stores approximately 90 per cent of the extra heat caused by climate change (von Schuckmann et al. 2023). Together, these two functions make the ocean a central regulator of the Earth's climate.

Box 2.1: Carbon budget, reservoir, uptake, sink and storage, sequestration – explained

The **global carbon budget** tracks where anthropogenic CO_2 emissions go. Some CO_2 remains in the atmosphere. Some is taken up by the land biosphere and some is taken up by the ocean. This annual balance determines how fast CO_2 accumulates in the atmosphere.

Ocean **carbon uptake** is the movement of CO_2 from the atmosphere into the ocean. Ocean **carbon release** is the movement in the opposite direction. The ocean acts as a global carbon sink when, on average, uptake is larger than release. Today, the ocean is a net sink for anthropogenic CO_2.

The ocean is a large **carbon reservoir**, it holds far more carbon than the atmosphere. **Carbon storage** is the sum of accumulation and retention of carbon in reservoirs. Depending on the reservoir, the carbon remains out of touch with the atmosphere (and therefore does not cause global warming) for different timescales. Carbon transported into the ocean interior can remain there for decades to centuries. Carbon buried in sediments can stay there for much longer. But the reservoir size does not necessarily determine the amount of carbon uptake.

Marine **carbon sequestration** describes the uptake of CO_2 from the atmosphere and deposition in the ocean carbon reservoir, where it is stored with a high durability. The volatile nature of the ocean continuum allows for spatial and temporal disconnect of carbon uptake and final sequestration.

The key point is that the ocean sink is dynamic. It depends on circulation, chemistry and biology, all of which are likely to be impacted by climate change. A large ocean reservoir does not guarantee a stable future ocean CO_2 sink.

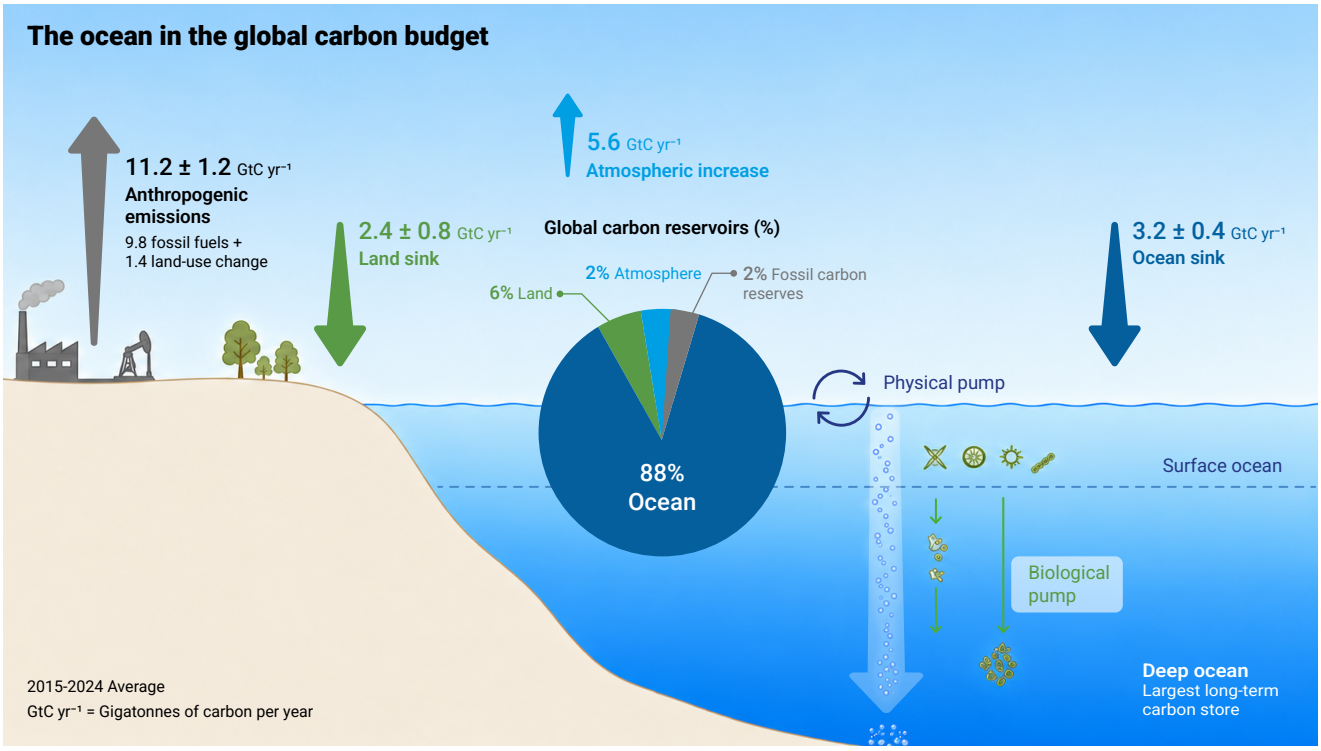


Figure 2.1: The ocean in the global carbon budget. The pie chart in the centre indicates the relative sizes of the marine, terrestrial, atmospheric and fossil carbon reservoirs, illustrating that the ocean holds by far the most carbon in the system: about 88 per cent of the total (around 39,500 GtC), compared with 8 per cent on land (about 3,500 GtC), 2 per cent in the atmosphere (885 GtC) and 2 per cent in fossil carbon reserves (about 900 GtC). The arrows indicate the role of the ocean and land in mitigating anthropogenic CO_2 emissions. About half of the emissions remain in the atmosphere, but 20 per cent are taken up by land and 30 per cent by the ocean. Data source: Global Carbon Project (GCP) (2026).

2.2.1 Regional imprints of marine carbon uptake

The ocean does not take up CO_2 uniformly. Some regions take up carbon from the atmosphere, while others release it (Takahashi et al. 2009; DeVries et al. 2023). In some regions, the direction of the net carbon flux changes with the seasons. In general, the ocean takes up CO_2 in cold and windy regions where ocean circulation transports recently absorbed carbon from the surface into the ocean interior (Takahashi et al. 2009). This allows the surface ocean to take up more CO_2 from the atmosphere. These conditions occur across many mid-latitude regions, in the high-latitude North Atlantic and in the Southern Ocean. The ocean tends to release CO_2 in warm regions, in areas where upwelling brings carbon-rich deep water back to the surface. Important source regions include the equatorial Atlantic, the Arabian Sea, coastal upwelling systems and, to a lesser extent, the North Pacific and parts of the polar Southern Ocean.

The **Southern Ocean** is a key player when it comes to the uptake of anthropogenic carbon emissions, currently accounting for 35 per cent of the anthropogenic ocean sink (Hauck et al. 2023b). Its importance stems largely from its unique circulation, which connects the deep ocean with the surface ocean. This connection causes deep waters to rise to the surface and exchange carbon with the atmosphere. They are then transported back into the ocean interior. Most of the anthropogenic CO_2 uptake occurs near formation regions of so-called intermediate and mode water masses that sink to water depths of around 1,000 metres and carry the anthropogenic carbon with it. This means that the recently absorbed carbon is out of contact with the atmosphere and stored in the marine carbon reservoir for centuries.

The **North Atlantic** subpolar gyre has the highest carbon flux into the ocean per area (Pérez et al. 2024). Similar to the Southern Ocean, this high flux is due to the rapid transfer of carbon from the surface to the interior ocean as cold, dense surface water sinks.

While the **Arctic Ocean** plays a relatively small role in the global ocean carbon sink, it currently appears to be the only region where climate change increases carbon uptake, as the retreat of sea ice creates more surface area for gas exchange (Yasunaka et al. 2023).

The air-sea carbon fluxes in the **tropical Pacific** are affected by the El Niño Southern Oscillation (ENSO) phenomenon.

In the tropical upwelling system, carbon-rich deep water is brought to the surface and CO_2 is lost to the atmosphere. Under El Niño conditions, however, warm surface water suppresses upwelling and reduces this carbon loss to the atmosphere (Ishii et al. 2025). ENSO in the tropical Pacific strongly affects year-to-year changes in air-sea CO_2 exchange, with more uptake in an El Niño phase and less uptake in years following El Niño and during periods with the reversed pattern ("La Niña"). The El Niño and La Niña dynamics in the tropical Pacific are so dominant that they also help explain why the global ocean carbon sink has not grown since 2016 (Friedlingstein et al. 2026a).

The **Indian Ocean** is an example of an ocean basin that is characterized by both uptake (South Indian Ocean) and release (North Indian Ocean). Due to its proximity to land masses, it is strongly affected by the monsoon-driven circulation and large riverine carbon inputs (Chakraborty et al. 2021; Sarma et al. 2023).

Coastal oceans are more complex than the largely circulation-driven open ocean. They interact with wetlands, estuaries, sediments and other systems at the land–ocean interface. Despite this complexity, mid- to high-latitude coastal regions typically act as carbon sinks, while low-latitude coastal waters typically act as carbon sources to the atmosphere (Resplandy et al. 2024).

2.2.2 Dynamics of marine carbon uptake in recent decades

The central role of the ocean in regulating the climate should not be regarded as a fixed background condition. The ocean carbon sink responds to rising atmospheric CO_2, long-term climate change and natural variability, including recurring changes in winds, ocean circulation and climate patterns such as El Niño and La Niña. This means that the ocean sink is not simply a passive buffer, it is a dynamic and turbulent part of the climate system whose future behaviour affects the planetary carbon budget.

The marine carbon sink shows substantial decadal variability. During the 1990s, the sink stagnated. This was likely linked to a combination of slower atmospheric CO_2 growth, the response to the volcanic eruption of Mount Pinatubo in 1991 and variability in ocean circulation. The sink strengthened again afterwards (Gruber et al. 2023; Landschützer et al. 2015). Over the past decade, the ocean sink has shown signs of renewed weakening due to natural climate variability. This is consistent with the repeated occurrence of La Niña conditions (Müller et al. 2025; Friedlingstein et al. 2026b). Such variability matters because it can temporarily amplify or dampen the rate at which CO_2 accumulates in the atmosphere.

As a response to human-induced rising atmospheric CO_2 concentrations, the long-term trend of the ocean sink is a continued increase. However, climate change is already lowering the sink's capacity by about 6 per cent, on average, compared with a world where atmospheric CO_2 is rising but without anthropogenic climate change (Friedlingstein et al. 2026a,b). The largest climate-related driver in recent decades has been changing wind fields. Winds influence the ocean carbon sink through two distinct pathways. The first, and by far the more important, is indirect: winds drive ocean circulation and mixing, redistributing the large ocean carbon reservoir and bringing carbon-rich waters towards the surface, where carbon can be lost back to the atmosphere. The second is direct, through the effect of wind speed on air-sea gas-exchange velocity, but this contribution is comparatively small (Bunsen, Nissen and Hauck 2024). Wind fields therefore dominate not because they accelerate exchange across the sea surface, but because they govern how much carbon is delivered to it. Ocean warming is the second major driver of climate impacts on the ocean carbon sink (Bunsen, Nissen and Hauck 2024). Recent work also suggests that marine heatwaves, which are periods of unusually high ocean temperatures lasting weeks to months, are beginning to leave a detectable signal in the global ocean carbon sink, for example by reducing CO_2 uptake in affected regions because CO_2 is less soluble in warmer water (Müller et al. 2025; Chau, Chevallier and Gehlen 2024b).

The key question, therefore, is not only how much carbon the ocean holds today, but how the processes behind this uptake operate and how stable they are under changing climate conditions. The ocean carbon sink is maintained by physical, chemical and biological mechanisms that operate across very different timescales. Understanding these mechanisms is essential for assessing where the ocean can continue to take up carbon, how long this carbon will remain stored and where the limits of this natural climate service may lie.

2.3 MECHANISMS OF CARBON UPTAKE AND STORAGE

This section explains why the surface ocean can take up CO_2, how carbon is moved away from the surface and what determines how long it remains stored. Three sets of processes are central: air-sea gas exchange, the physical and chemical processes often referred to as the solubility pump, and biological processes that move carbon through marine food webs (Figure 2.2). These mechanisms work together. CO_2 first crosses the air-sea interface. Marine chemistry then determines how much

of this CO_2 can remain dissolved in seawater. Ocean circulation acts to transport dissolved carbon from the surface to the ocean interior. Marine organisms transform CO_2 into organic matter, some of which sinks or is injected below the surface. Only a small part of the carbon taken up at the surface is stored for decades to centuries or longer. Coastal vegetated ecosystems, such as mangroves, seagrasses and salt marshes, store carbon mainly through the sequestration of biomass and organic material in sediments, where it can remain for extended periods, in some cases centuries to millenniums (Macreadie et al. 2021). The protection and restoration of these BCEs (see Box 3.1) is considered further in Chapter 3.

2.3.1 Air-sea gas exchange

CO_2 moves continuously between the atmosphere and the surface ocean. The direction and strength of this exchange depend mainly on the difference between CO_2 in the air and CO_2 dissolved in surface seawater. If surface seawater contains less CO_2 than the air above it, CO_2 is taken up by the ocean. In contrast, if surface seawater contains more CO_2, the ocean will release CO_2 back to the atmosphere. The exchange of CO_2 across the air-sea interface is estimated from two components: the air-sea CO_2 concentration difference and the rate at which CO_2 can pass across the sea surface. This rate, called the gas transfer velocity, depends upon wind speed, waves, bubbles and surfactants (Wanninkhof et al. 2009; Blomquist et al 2017; Brumer et al. 2017; Mustaffa et al. 2020; Dong et al. 2025). Air-sea gas exchange at the ocean surface is a fast process that acts on a timescale of hours to days.

2.3.2 Solubility pump

The solubility pump describes the physical and chemical processes that allow the ocean to take up CO_2 and move dissolved carbon into the ocean interior. The solubility of CO_2 in seawater depends on temperature and salinity. CO_2 is more soluble in cooler, low-salinity waters. Once CO_2 dissolves, it reacts rapidly with seawater. Most of the dissolved CO_2 is converted into bicarbonate ions (~90 per cent) and carbonate ions (~10 per cent). Only a small fraction remains as dissolved CO_2 or carbonic acid (<1 per cent). Together, these forms make up dissolved inorganic carbon (DIC) (Zeebe and Wolf-Gladrow 2001). This chemical conversion matters because only dissolved CO_2 can easily re-exchange with the atmosphere. When almost 100 per cent of the dissolved CO_2 is converted into bicarbonate and carbonate, the concentration of freely dissolved CO_2 in surface water falls. This allows the ocean to take up large quantities of CO_2 resulting in a high background concentration of DIC.

Once dissolved, ocean circulation determines whether the dissolved carbon remains in contact with the atmosphere or is transported into the ocean interior, where it would be considered stored away. In high-latitude regions, cold, dense surface waters can sink and carry DIC into the ocean interior. Once there, the carbon can remain separated from the atmosphere for centuries to millenniums, depending on where it is transported and how quickly those waters return to the surface.

Box 2.2: Alkalinity – explained

The ocean's ability to absorb CO_2 also depends on alkalinity. Alkalinity refers to the ability of seawater to neutralize acid. It is mainly controlled by dissolved ions such as bicarbonate and carbonate ions, many of which ultimately come from the slow weathering of rocks on land and are transported to the ocean by rivers. The high proportions of bicarbonate and carbonate ions in seawater mean that an addition of acid is quickly neutralized with little change in pH. This is the acid-base buffer capacity, and it is responsible for the relatively constant pH of seawater. Continued uptake of anthropogenic CO_2 is reducing this buffer capacity, causing an increase in ocean acidity and a reduction in the availability of carbonate ions, a process known as **ocean acidification**. As the acidity of the ocean increases, its capacity to absorb CO_2 from the atmosphere decreases, impeding the ocean's role in moderating climate change (IPCC 2019). The reduction in carbonate ions also hinders the production of chalky calcium carbonate shells and skeletons by organisms such as plankton, shellfish and corals.

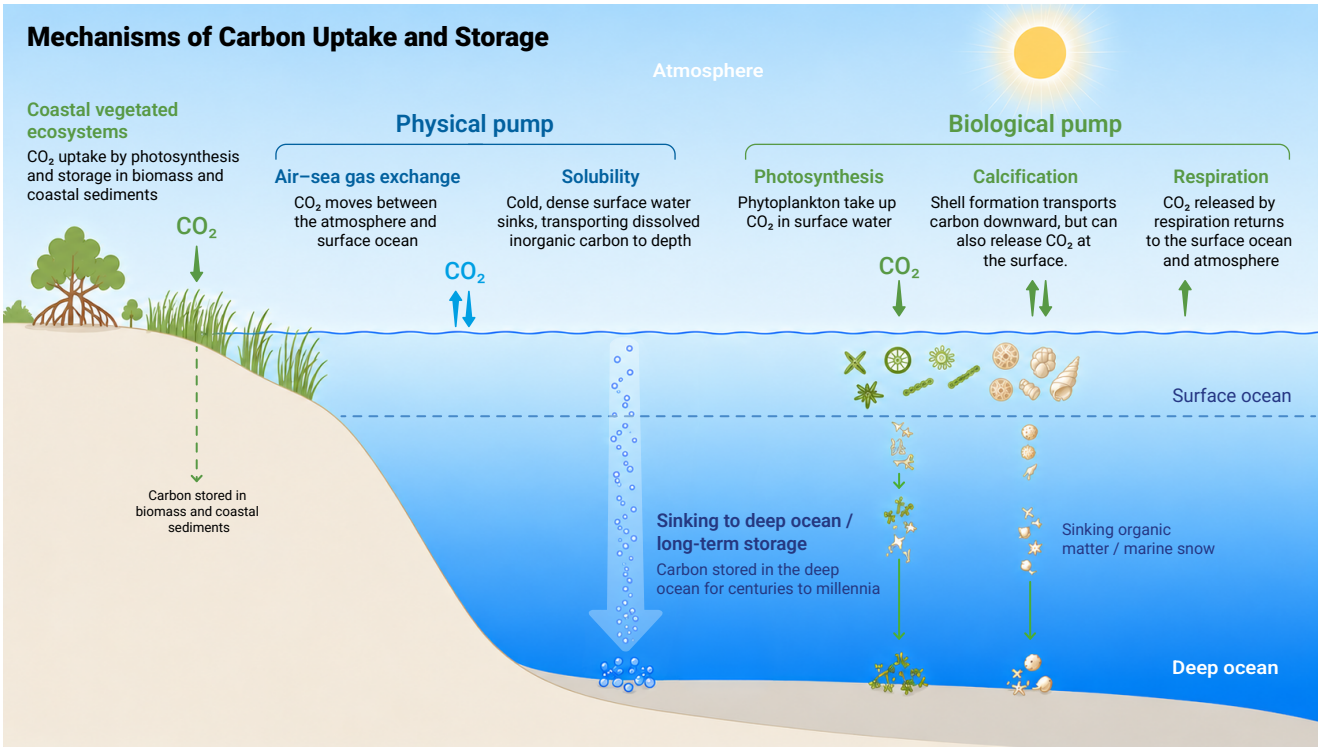


Figure 2.2: Mechanisms of carbon uptake and storage in the oceans. Illustration of key natural marine processes that contribute to carbon uptake from the atmosphere and storage in the ocean. This figure does not include the effect of increasing anthropogenically derived atmospheric CO_2, nor climate change.

2.3.3 Biological carbon pump

While the solubility pump is driven mainly by seawater chemistry, the biological carbon pump (BCP) depends on the activity of marine organisms. It refers to a collection of biological processes by which CO_2 is converted into organic and/or inorganic carbon and moved or "exported" from the surface ocean to depth. Phytoplankton need CO_2 and other nutrients during photosynthesis to produce new cells (particulate organic carbon [POC] and dissolved organic carbon [DOC]). Some plankton also produce particulate inorganic carbon (PIC) in the form of calcium carbonate shells or skeletons, in a process known as calcification. Phytoplankton form the basis of the marine food web and provide energy to higher trophic levels, such as zooplankton, fish and some marine mammals. Dead phytoplankton and zooplankton cells that are not eaten, together with faecal pellets from zooplankton and fish, sink to lower ocean layers because of gravity. As they sink, they are gradually degraded by zooplankton and bacteria, which respire organic carbon and transform it back into CO_2. Together with this gravitational sinking of particles, the vertical migration of zooplankton and the physical downward mixing of DOC create a "pump": surface waters have lower CO_2 concentrations, while deeper waters contain more carbon (Omand et al. 2015; Boyd et al. 2019; Keutgen de Greef, Resplandy and Poupon 2026). Bacteria and zooplankton respire the most reactive portion of DOC first, gradually creating a residual non-reactive pool of DOC which resists degradation on timescales of thousands of years (Jiao et al. 2010; 2014; 2024; Legendre 2024).

Photosynthesis, and therefore the type and size of particles that sink into the deep ocean, is influenced by the availability of fertilizing nutrients and trace metals such as iron, provided through ocean circulation or atmospheric deposition (Falkowski, Barber and Smetacek 1998; Siegel et al. 2023; Malsang et al. 2024; Joshi et al. 2025). The combination of particle type and prevalent plankton community governs the depth to which the particles sink before they are remineralized to CO_2; the deeper that this remineralization occurs, the longer the carbon is sequestered away from contact with the atmosphere. This "sequestration" is the best measure of BCP efficiency in storing carbon in the ocean. The biological cycle is finely balanced. Phytoplankton take up CO_2 during photosynthesis, while bacteria and zooplankton produce CO_2 during respiration. Only around 10 per cent of the carbon used in photosynthesis at the surface is exported to a depth of 1 kilometre (Doney et al. 2024) and therefore stored for centuries, and an even smaller fraction eventually accumulates in sediments. BCP efficiency also depends on how quickly circulation brings the remineralized carbon back to the surface (Wilson et al. 2022; Frenger et al. 2024). Unfortunately, it is difficult to measure BCP efficiency directly, and many models lack the process complexity to simulate it well (Henson et al. 2022; 2024).

2.4 OCEAN OBSERVATIONS AND MODELLING

2.4.1 Marine carbon sink observations

While accurate measurements of CO_2 concentration in the atmosphere have been made since the middle of the last century (Keeling 1960), systematic observations of the ocean carbon cycle, including surface partial pressure of CO_2 (pCO_2), DIC and alkalinity, started several decades later. An exploratory programme (the Geochemical Ocean Sections Study [GEOSECS]) in the late 1970s and early 1980s produced the first estimates of the ocean carbon inventory (Bradshaw et al. 1981). Subsequent programmes (the World Ocean Circulation Experiment [WOCE], Joint Global Ocean Flux Study [JGOFS] and Global Ocean Ship-based Hydrographic Investigations Program [GO-SHIP]) have focused on decadal trends, including the accumulation of anthropogenic CO_2, ocean heat content and changes to interior ocean oxygen and nutrient concentrations (Takahashi et al. 2002; Key et al. 2004; Schmidtko, Stramma and Visbeck 2017; Lauvset et al. 2022; Keppler et al. 2023). Observations collected at the ocean surface from research vessels, ships of opportunity and moorings are nowadays complemented by uncrewed surface vehicles (USVs) and sailboats (Sabine et al. 2020; Sutton, Williams and Tilbrook 2021; Patterson et al. 2025; Behncke et al. 2026). To obtain observational measurements beyond the ocean surface, the network of robotic profiling floats is increasingly equipped with biogeochemical (BGC) sensors (BGC-ARGO[2]; Williams et al. 2017; Bittig et al. 2018; Bushinsky et al. 2019).

The synthesis of surface ocean carbonate measurements led to the first observation-based climatological estimates of air-sea CO_2 fluxes at regional and global scales (Takahashi et al. 2002; 2009). Currently, surface ocean CO_2 observations are combined with atmospheric CO_2 concentrations to estimate the air-sea CO_2 flux, using various methods to interpolate the observations over the globe (Landschützer et al. 2014; Rödenbeck et al. 2015; Gregor and Gruber 2021; Fay et al. 2021). These observation-based assessments of the ocean carbon sink are checked against independent estimates based on atmospheric CO_2 measurements and knowledge about how this carbon is transported in the atmosphere to identify where carbon is lost from or added to the atmosphere. The assessments are updated annually to close the global carbon budget and track anthropogenic CO_2 emissions (Peters et al. 2005; Jacobson et al. 2007; Long et al. 2021; Friedlingstein et al. 2026a).

Through dedicated and long-standing international partnerships and networks, systematic measurements of CO_2 in the ocean surface have been sustained over the last several decades (Bakker et al. 2016), and several syntheses have produced data sets that compile surface and interior ocean carbon measurements (Jiang et al. 2026; the Ocean CO_2 Products unified interface[3]). Observational programmes have matured to include measurements of so-called Essential Ocean, Climate, Biological and Ecosystem Variables, which are used to help deliver ocean forecasts and early warnings, climate projections and assessments, and to protect ocean health and its benefits[4].

Despite the ongoing commitment to observational programmes, and international recognition of their importance, the number of ship-based observations has declined over recent years (Dong, Bakker and Landschützer 2024; Friedlingstein et al. 2025). This has implications for assessments of global and regional ocean carbon uptake, as observation-based estimates are sensitive to the inclusion, or sparsity, of data in poorly sampled regions (Fay et al. 2025). Additionally, a baseline understanding of both the magnitude of the ocean carbon sink, and the processes that drive natural variability is required to track anthropogenic change. These baselines require observations collected over appropriate spatial scales and sustained over decades (for example, Global Greenhouse Gas Watch, G3W).

2.4.2 Data sparsity as a structural problem

Existing surface ocean networks (the Surface Ocean CO_2 Atlas [SOCAT] and Surface Ocean CO2 Observing Network [SOCONET]) yield routine observations of only 2 per cent of the global ocean surface, and many of these observations (notably in the vast Southern Ocean) are seasonally biased towards summer (Figure 2.3), due to limited winter sampling and dependence on shipping routes (Djeutchouang et al. 2022; Heimdal et al. 2024; Zhong et al. 2024). Observing System Simulation Experiments (OSSEs) suggest that increasing that coverage to 5 per cent, with the consideration of site distribution, would not simply increase the number of observations, but would also significantly reduce the uncertainty in observation-based estimates of the ocean carbon sink (see, for example, Denvil-Sommer, Gehlen and Vrac 2021; Hauck et al. 2023a). Some regions, like the coastal ocean, the region north of 20°S in the Indian Ocean and high-latitude regions, both the Arctic and Southern Oceans, remain underrepresented, limiting resolution of seasonal, inter-annual and decadal variability in estimates of ocean carbon uptake (Bushinsky et al. 2019; Hauck et al. 2023a; Rodgers et al. 2023; DeVries et al. 2023, Mayot et al. 2023; Yasunaka et al. 2023; Resplandy et al. 2024; Dutch et al. 2025).

2 https://biogeochemical-argo.org

3 https://goosocean.org/what-we-do/framework/essential-ocean-variables/

4 https://wmo.int/all-activities/exchange-data/global-greenhouse-gas-watch-g3w

Additionally, as a result of the data sparsity, interpolated pCO_2 products do not resolve mesoscale variability (ocean fluctuations occurring at spatial scales of ~10–500 kilometres and temporal scales of ~10–100 days), which is increasingly recognized as important for understanding air-sea CO_2 exchange in dynamic ocean regions, including zones where different water masses meet and along boundary currents (Smith et al. 2023; Guo and Timmermans 2024). There are, however, ongoing efforts to reconstruct the ocean carbonate variables at higher spatial resolution to address observational data sparsity and better resolve mesoscale variability (Chau, Chevallier and Gehlen 2024; Gregor, Shutler and Gruber 2024; Joshi et al. 2024; 2025; Ghoshal, Joshi and Chakraborty 2025). Strengthening international coordination and reinforcing FAIR[5] data practices (Tanhua et al. 2021), particularly in data-sparse coastal and remote regions, and in developing countries and SIDS, can help build more comprehensive and accessible global data sets. Capacity constraints in many SIDS, including limited access to observing infrastructure, technical expertise and sustained financial resources, continue to contribute to gaps in ocean observation (United Nations 2022; Bax et al. 2018).

Beyond spatial gaps, observational sparsity is reinforced by institutional and technical constraints. Short-term, project-based funding interrupts long-term time series, and the lack of standardized sensor calibration across institutions limits how well data sets can be combined. Sustained observation requires stable national networks, shared calibration standards for biogeochemical sensors and closer integration of open-ocean and coastal monitoring.

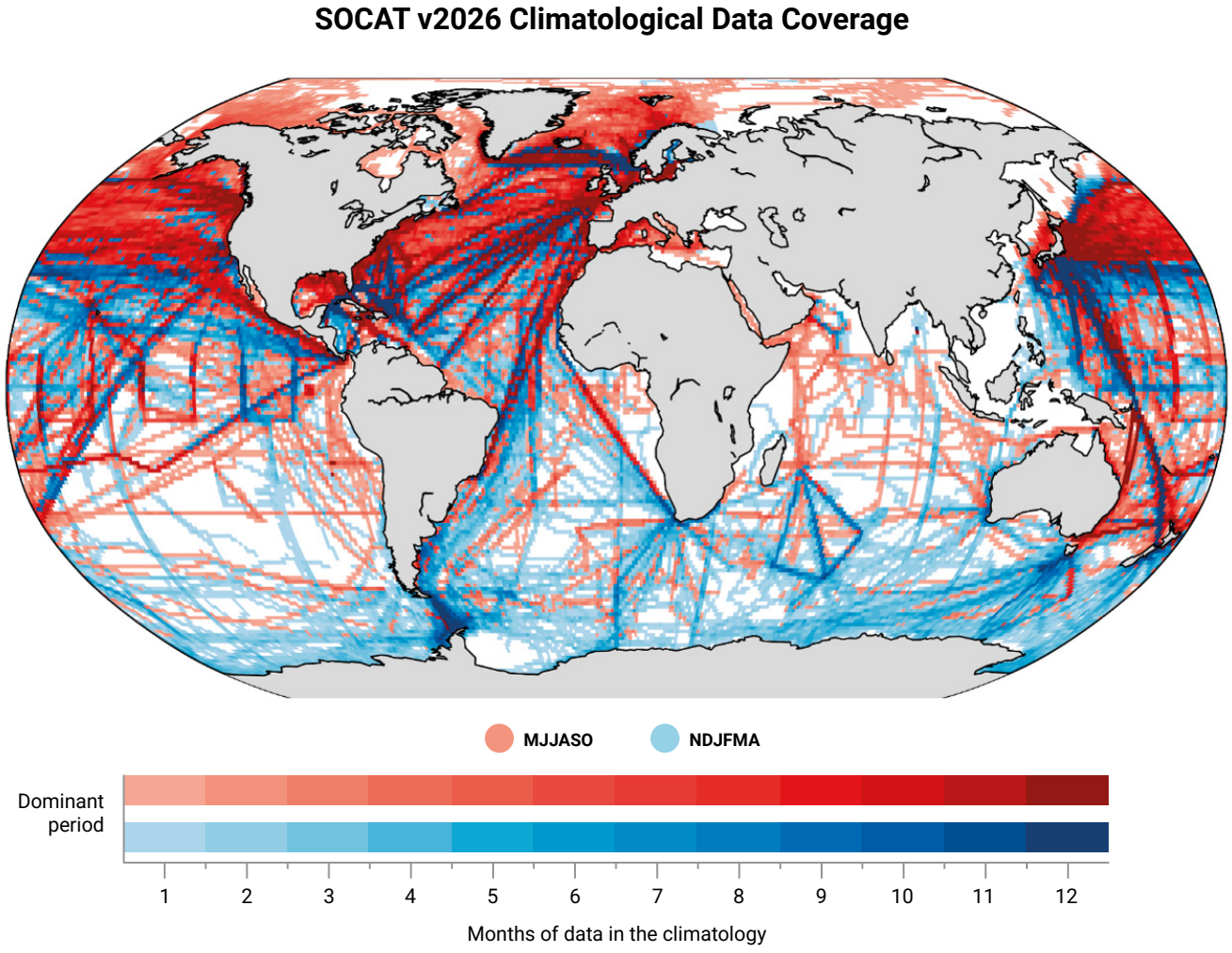


Figure 2.3: Spatial distribution of the SOCAT v2026 (Bakker et al. 2026) monthly gridded product shown as a monthly climatology, highlighting the seasonal sampling coverage independent of the observation year. Red-shaded grid cells represent regions where most observations were made during May to October, whereas blue-shaded grid cells indicate regions where most observations were made during November to April.

5 Findable, accessible, interoperable and reusable.

2.4.3 Modelling the marine carbon sink

The ocean carbon cycle, along with other physical and biogeochemical processes, is represented in a range of global ocean physical and biogeochemical models (GOBMs). These models simulate ocean uptake of atmospheric CO_2 by representing the physical transport and storage of anthropogenic CO_2 and the biogeochemical processes that influence the cycling of carbon in the ocean across a range of temporal and spatial scales. Despite much improvement over recent decades, discrepancies between GOBMs and observation-based estimates of the ocean carbon sink persist (Gloege et al. 2021; Hauck et al. 2023b; Heimdal et al. 2024; Arroyo, Fassbender and Rodgers 2026). The Southern Ocean remains particularly challenging, despite its outsized importance to the global ocean carbon sink, partly due to a scarcity of observations (Friedlingstein et al. 2025; Hauck et al. 2023a). However, significant discrepancies also remain in the North Atlantic, which has historically been well-observed, and the Indian Ocean, highlighting the need for progress at regional as well as global scale (Rodgers et al. 2023; Sarma et al. 2023; Pérez et al. 2024; Ghoshal, Joshi and Chakraborty 2025).

One limitation in the GOBMs is the difficulty of simulating the delicate balance between physical and biological drivers that regulate BCP efficiency, particularly during the biologically productive season, during which biological processes may dominate carbon uptake variability over relatively small spatio-temporal scales, with implications for regional annual estimates (Fassbender et al. 2022; Rodgers et al. 2023; Hauck et al. 2023b). While these processes are not the main controlling factor with regard to the global ocean carbon sink or the fate of anthropogenic emissions, a robust understanding of their magnitude and variability is important for projections of ecosystem change and ocean health (see, for example, Resplandy, Lévy and Bopp 2026).

Estimates of the amount of biologically produced carbon that is transferred from the surface ocean to depth vary substantially across ocean regions. The underlying complex processes are not yet fully understood and are therefore not sufficiently represented in models. Global observational campaigns remain limited, with only a few initiatives available to characterize these complex processes (for example, EXPORTS – see Siegel et al. 2016; and GEOTRACES – see Anderson et al. 2015). Additional observations are needed to improve understanding and support the development of parameterization schemes for regional and global models (Burd 2024).

A structural gap in current carbon budgeting is the poorly understood fate of carbon that is transported into the ocean through rivers. Observation-based estimates of air-sea CO_2 exchange include this carbon signal, but many models treat it differently or do not represent it explicitly (DeVries et al. 2023). Riverine carbon transport is also thought to be increasing (Regnier et al. 2022). This adds uncertainty to global ocean carbon budgets and creates even larger challenges for regional accounting because it remains unclear where river-derived carbon resurfaces in the ocean and is released back to the atmosphere (Lacroix, Ilyina and Hartmann 2020; Pérez et al. 2024).

Hybrid approaches that integrate numerical model outputs with observational constraints using advanced machine-learning techniques offer an effective pathway to reduce uncertainties in ocean carbon sink estimates (Bennington, Gloege and McKinley 2022; Mayot et al. 2024; Ghoshal, Joshi and Chakraborty 2025). However, because most model evaluations compare annual air-sea CO_2 fluxes, but not necessarily interior ocean observations of inorganic carbon, reconciling discrepancies between observation-based data products and simulations of the ocean carbon sink can be challenging (Hauck et al. 2023b).

Together, the sparse observational coverage and the differences between models limit what can currently be resolved about the ocean carbon sink. These factors shape how confidently changes in the sink can be detected, sensitive regions identified and priorities for protection and management set.

2.5 MARINE CARBON UPTAKE DURING FUTURE CLIMATE CHANGE

Anthropogenic emissions are the primary driver of rising atmospheric CO_2 concentrations, while natural carbon sinks in the oceans and on land act as a buffering system by absorbing a substantial share of these emissions. The rate at which atmospheric CO_2 accumulates therefore depends not only on the amount of CO_2 emitted but also on changes in marine (and terrestrial) carbon sinks from year to year. In 2024, atmospheric CO_2 increased by a record 3.73 parts per million (ppm) (7.9 GtC), linked to especially weak ocean and land carbon sinks in this year (Friedlingstein et al. 2026a).

While many of the processes that shape future marine carbon uptake are well understood in principle, considerable uncertainty remains regarding the magnitude and timing of future changes in carbon sinks because models represent these processes very differently (Gooya, Swart and Hamme 2023). On a global scale, model uncertainty is the dominant source of uncertainty in projections up

until the mid-twenty-first century. Thereafter, however, the amount of anthropogenic emissions causes the most uncertainty surrounding the development of the marine carbon sink (Gooya, Swart and Hamme 2023). Future emissions are deeply uncertain because they depend on complex changes in society, technology, policy and energy systems. As a result, model simulations are run with a range of possible future pathways or "emission scenarios". This section considers two contrasting futures: continued high emissions until the end of the century, and ambitious mitigation towards net-zero and, potentially, net-negative CO_2 emissions. These scenarios help to illustrate how the ocean carbon sink may respond under very different atmospheric CO_2 conditions.

2.5.1 Carbon sink dynamics under continued climate change

With continued high emissions until 2100, the ocean will initially continue to take up anthropogenic carbon (see Figure 2.4b). This process is driven by an increasing CO_2 difference between the atmosphere and the surface ocean (Ridge and McKinley 2021; Gooya, Swart and Hamme 2023), and by a CO_2 fertilization effect, where higher CO_2 levels cause a higher carbon uptake efficiency in coastal vegetated ecosystems (Riebesell, Körtzinger and Oschlies 2009). It has been shown that projected future air-sea CO_2 fluxes are strongly linked to simulated historical air-sea CO_2 fluxes, both in the magnitude of the sink and in its spatial pattern (Wang et al. 2016). This continued carbon uptake will further increase ocean acidification. However, there are several processes that counter this first-order response (Figure 2.4a and 2.4b).

Continued global warming, with accelerated ocean warming during recent decades (von Schuckmann et al. 2024), which spreads from the surface ocean towards deeper ocean layers, reduces marine CO_2 uptake by weakening the solubility pump (Bunsen, Nissen and Hauck 2024; Müller et al. 2025). As the ocean warms, regional marine heatwaves are expected to become more frequent and stronger (Frölicher, Fischer and Gruber 2018). During these periods of unusually high ocean temperatures that last for weeks to months, marine ecosystems, ocean circulation and CO_2 exchange between the ocean and the atmosphere are affected. Recent events in the North Atlantic (2023, 2024) and North Pacific (2023) reduced ocean carbon uptake in these regions. So far, marine heatwaves have not been large enough to dominate the global ocean carbon sink (Mignot et al. 2022; Friedlingstein et al. 2026a). More frequent and intense marine heatwaves could, however, increase variability in regional carbon uptake and make it difficult to rely on past relationships used to interpret the ocean sink.

Global warming increases the ocean's stratification, which means that warmer, lighter surface waters sit more stably above cooler, denser waters below. As the ocean warms from above, this layering becomes stronger. An increase in ocean stratification reduces the ocean's ability to form new deep water, that is the water that is transported away from the surface, keeping the carbon separated from the atmosphere (Nissen et al. 2022).

Global-warming-induced changes in wind patterns can further weaken ocean carbon uptake by altering ocean circulation and mixing. In particular, stronger winds can enhance the upwelling of carbon-rich deep waters, which are then in contact with the atmosphere and can release CO_2. Wind changes currently are the dominant driver of this climate-induced weakening of the ocean carbon sink, accounting for roughly half the globally averaged climate trend in marine carbon uptake, which is dominated by the subpolar Southern Ocean (Bunsen, Nissen and Hauck 2024). Increased stratification also reduces the upward supply of nutrients to the surface ocean, which can reduce biological primary production and carbon export.

A further, and in fact larger, effect is that the ocean becomes increasingly acidic, and with that it becomes progressively less efficient at absorbing additional CO_2 from the atmosphere, causing the ocean carbon sink to eventually level off, despite continously increasing atmospheric CO_2 concentrations (Figure 2.4b). Acidification causes shifts in the carbonate system and a reduced buffer capacity (Figure 2.4b). Furthermore, calcifying plankton communities that produce PIC in the form of calcium carbonate shells or skeletons are particularly impacted by further ocean acidification (Hofmann et al. 2010). Since acidification hinders the formation of the carbonate shells and skeletons, their weight and thereby sinking speeds are impacted, reducing the amount of exported biological carbon (Krumhardt et al. 2019; Henson et al. 2022).

The combined effects of warming, acidification and reduced nutrient availability are causing further ecosystem degradation, introducing another layer of vulnerability to biological ocean carbon storage (Heinze et al. 2015; Santana-Falcón et al. 2023).

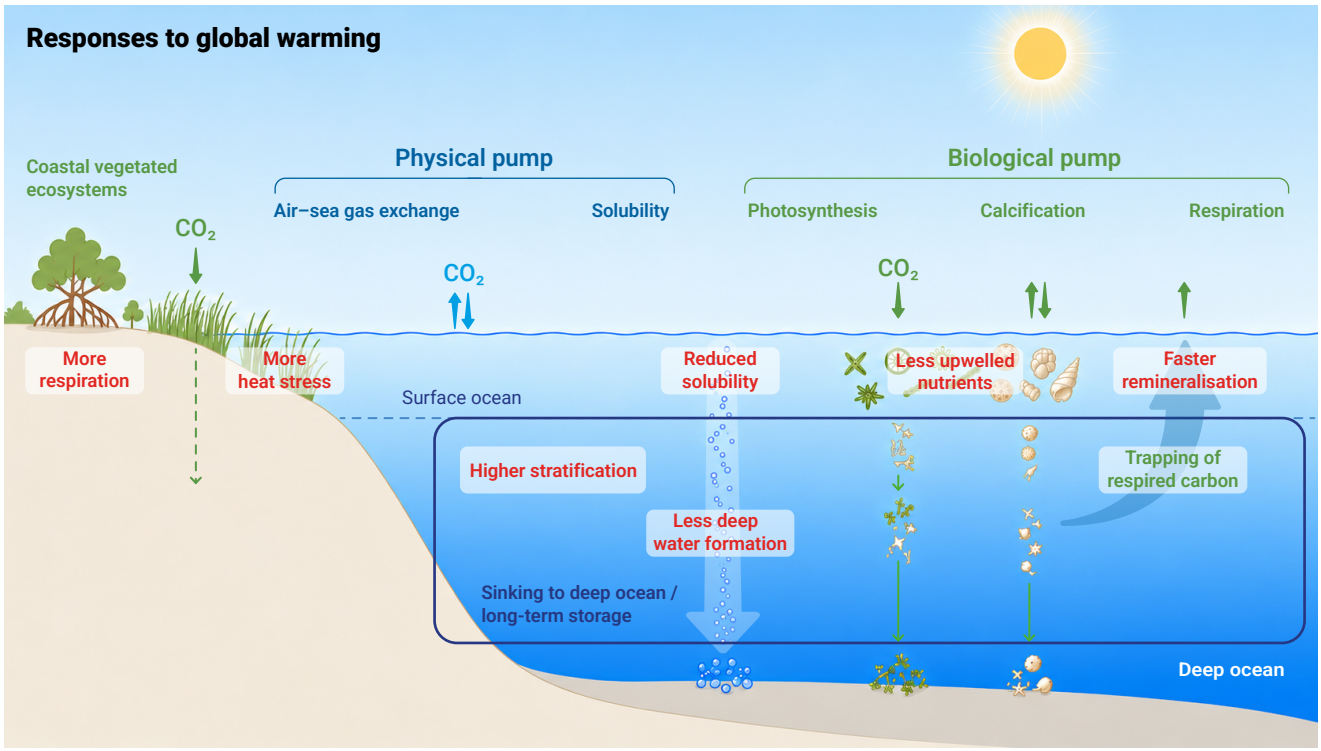


Figure 2.4a: Anticipated impact of global warming on marine carbon uptake and storage mechanisms (based on Henson et al. 2022). The text in green indicates increasing marine carbon uptake, and the red text indicates reduced carbon uptake.

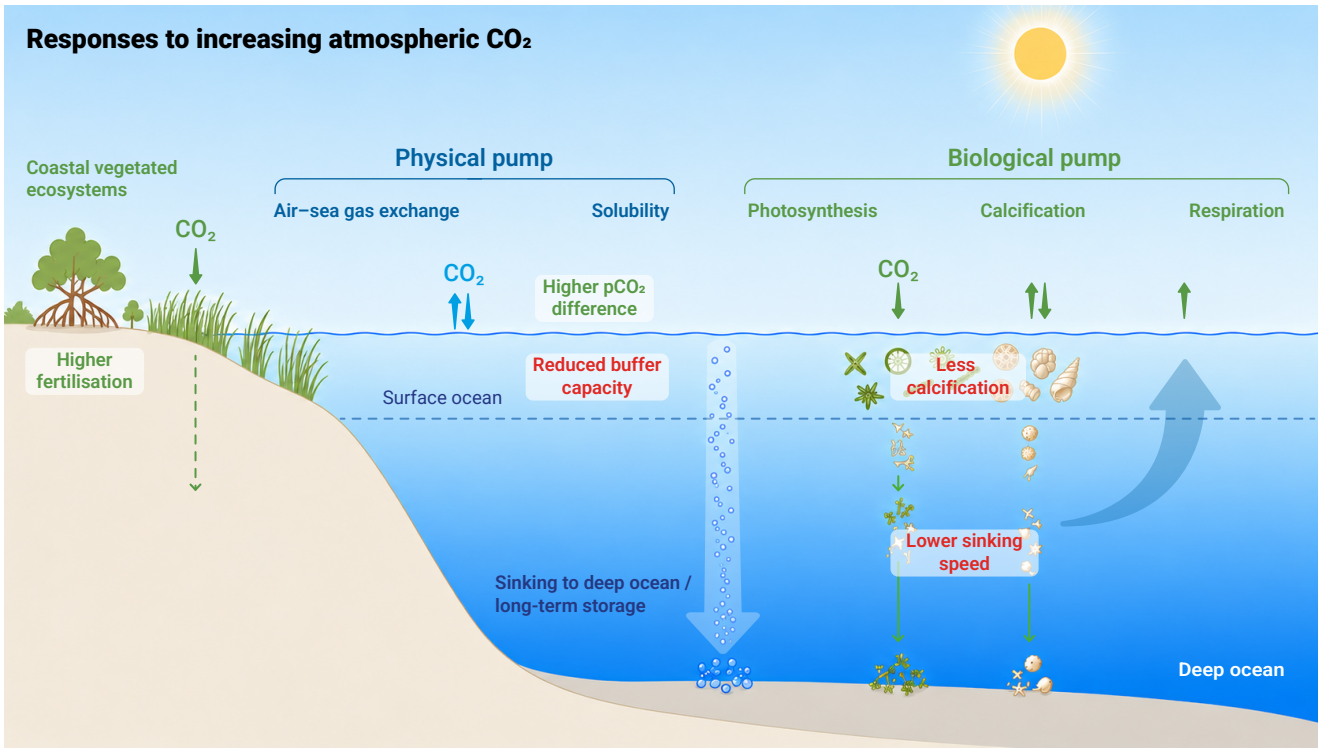


Figure 2.4b: Anticipated impact of increasing atmospheric CO_2 on marine carbon uptake and storage mechanisms (based on Henson et al. 2022). The text in green indicates increasing marine carbon uptake, and the red text indicates reduced carbon uptake.

2.5.2 The ocean carbon sink in ambitious mitigation scenarios

Ambitious mitigation scenarios in line with the Paris Agreement's 1.5-2 °C temperature limits require a strong decrease in anthropogenic greenhouse gas emissions to net-zero by mid-century (Rogelj et al. 2019; Tagomori et al. 2026). One consequence of emission reductions has received limited attention: as atmospheric CO_2 concentrations level off or decrease, the efficiency and intensity of ocean carbon uptake also changes (Melnikova et al. 2021). Idealized experiments in which CO_2 emissions were abruptly reduced to zero have shown that the ocean's heat and carbon uptake strongly decline as a consequence, but models differ in terms of how much carbon uptake remains by up to a factor of three (MacDougall et al. 2020). In a simulated 1.5 °C scenario (corresponding to the SSP126, green line in Figure 2.5), it was found that the ocean absorbs less anthropogenic carbon than under high-emission scenarios (corresponding to the SSP585, red line in Figure 2.5) (Ridge and McKinley 2021). This is because the carbon difference between the surface ocean and the atmosphere becomes smaller or can eventually reverse, causing the ocean to release CO_2 rather than absorb it, while the carbon difference between surface and deeper waters also becomes smaller, weakening the transport of carbon to depth. As atmospheric CO_2 levels off, ocean carbon uptake declines, especially in major ocean currents in the mid-latitudes, such as the Gulf Stream and the subpolar North Atlantic (Gooya, Swart and Hamme 2023). Importantly, reduced ocean carbon uptake under low-emissions scenarios reflects declining atmospheric CO_2 concentrations and a reduced atmospheric-ocean CO_2 gradient, rather than a failure of climate mitigation efforts.

If emissions become net-negative (in other words, the active removal of CO_2 from the atmosphere outweighs remaining emissions), as anticipated in so-called overshoot-reversal pathways, large areas of the ocean are projected to show much reduced carbon uptake (Melnikova et al. 2021; Gooya, Swart and Hamme 2023). Physical-chemical uptake through the solubility pump (see section 2.2) is especially sensitive to atmospheric CO_2 conditions in such pathways, and may even reverse, causing the ocean to release CO_2 overall rather than absorb it (Koeve et al. 2024). This is because the solubility pump depends directly on the CO_2 difference between the atmosphere and the surface ocean. In contrast, the BCP appears less sensitive to declines in atmospheric CO_2 concentrations, as it depends more on ecosystem structure, nutrient availability and ocean circulation. It is therefore less directly affected by declining atmospheric CO_2 concentrations. On multi-centennial timescales, the BCP may therefore become the larger component of the anthropogenic marine CO_2 storage (Koeve et al. 2024).

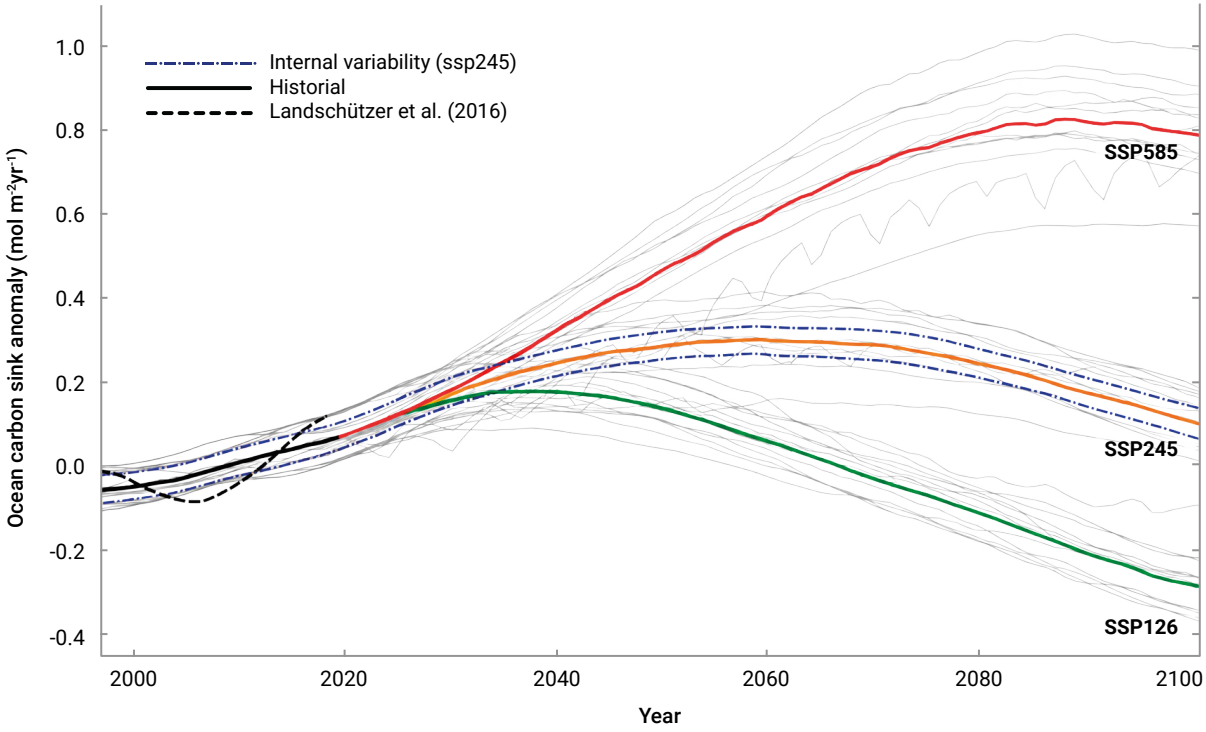


Figure 2.5: Future marine carbon uptake under different emissions pathways. The thick lines show the average across models, expressed as the change in global ocean carbon uptake relative to the 1995–2015 average. The colours indicate the level of mitigation ambition: from business as usual (SSP585, red), middle of the road (SSP245, yellow), and Paris Agreement conformity (SSP126, green). The grey lines show the individual models. The black dashed line shows an observation-based estimate for comparison (Landschützer, Gruber and Bakker 2016). All time series are smoothed with a 10-year running mean. The blue dashed lines show internal variability.

Together, changes in these processes indicate that the ocean carbon sink is not a passive or steadily increasing buffer, but a dynamic system whose present strength and future evolution are jointly shaped by atmospheric CO_2 levels, climate-driven physical changes and ecosystem responses, with anthropogenic emissions ultimately acting as the dominant external force that constrains all three by influencing atmospheric composition, ocean physics and marine ecosystems. Rapid and sustained CO_2 emission reductions would reduce future risks of ocean warming, acidification and circulation change, all of which affect the ocean's capacity to take up and store carbon and ecosystems.

At the same time, reducing additional human pressures on marine ecosystems and sediments (see Box 2.3 for an overview) can help safeguard natural carbon stores and strengthen the resilience of carbon storage in the face of climatic changes. This cannot, however, offset the effects of continued climate change or replace emission reductions.

Box 2.3: Anthropogenic pressures on marine carbon uptake and storage

Marine carbon uptake and storage are affected not only by climate change, but also by direct human pressures on the ocean and coastal vegetated ecosystems. These pressures can disturb sediments, damage ecosystems, alter food webs and reduce the resilience of natural carbon-storing systems.

Relevant pressures include:

- Resource extraction, including mining, dredging, drilling, trawling, fishing
- Construction and infrastructure, including offshore wind energy, seabed cables and pipelines
- Pollution of the marine environment, including plastics and nutrient inputs such as nitrate and phosphate

Because the ocean carbon sink is dynamic, regionally uneven and affected by multiple interacting processes and pressures, better knowledge of ocean circulation, including large-scale circulation features, is critical for quantifying the future ocean carbon sink. This requires expanded marine carbon observations, improved representation of relevant processes in models, including higher-resolution features, and more comprehensive studies of biogeochemical responses to ambitious mitigation scenarios (Ridge and McKinley 2021; MacDougall et al. 2022).

Robust MRV systems are also needed to track changes in marine carbon uptake and storage. These can help identify where natural marine carbon sinks are vulnerable, where they can be better protected and where management action may reduce avoidable losses. MRV is also essential for assessing benchmarks against which ocean-based climate action, including mCDR, can be assessed (Mengis, Paul and Fernández-Mendez 2023). Ocean-based climate action can take two complementary forms: protecting and restoring natural carbon-storing ecosystems, and actively enhancing ocean carbon uptake through ocean-based climate technologies. Both of these approaches are explored in detail in Chapter 3.

3.

Technologies for Monitoring, Managing and Enhancing the Ocean Carbon Sink

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CHAPTER HIGHLIGHTS

- Ocean-based climate technologies can support climate adaptation and mitigation actions by strengthening our capacity to observe and assess marine carbon fluxes, informing equitable management practices to protect and restore ocean carbon sinks, and evaluating and enabling techniques that enhance carbon removal in marine settings.
- Ocean Carbon Intelligence facilitates the development and optimization of ocean-based climate technologies through implementation of the Ocean Data Value Chain, providing the foundational knowledge, mechanisms and pathways required for transforming complex marine data into actionable, decision-ready insights.
- Sustained long-term investment in innovation, observing infrastructure and marine data systems is needed to enable responsible technology development and informed decision-making. Operationalizing the Ocean Data Value Chain by making ocean monitoring part of internationally mandated and legislated observing and data infrastructure (on a par with terrestrial meteorological efforts) would help to safeguard ocean observing systems against short-term disruptions and support long-term assessments of ocean-based climate technologies.
- Current ocean observing configurations are not optimized to assess evolving climate technologies that require more nuanced, targeted observations, including higher-resolution locally relevant data products and marine models capable of resolving low-level perturbations on top of high-level natural variability. The development and implementation of fit-for-purpose MRV approaches must be aligned with existing data standardization, assimilation and accessibility practices that invite trust through wider participation and transparency.
- Effective utilization of BCEs as an ocean-based climate technology for protecting or restoring ocean carbon sinks necessitates a shift from project-based restoration to adaptive, ecosystem-scale management integrated with local ecological knowledge and aligned to both local and regional priorities.
- Low-cost monitoring frameworks capable of distinguishing BCE contributions to climate mitigation, such as protection of carbon stocks, uptake of atmospheric CO_2 and impacts on greenhouse gas emissions, need to be developed through participatory and co-designed approaches to ensure that emerging market and policy incentives are scientifically credible and socially acceptable. Implementation of these MRV pathways in SIDS and other coastal developing states should also be supported through provision of technical expertise, laboratory facilities, long-term monitoring programmes and access to remote sensing products where required.
- mCDR technologies are emerging techniques for enhancing ocean carbon uptake, with significant uncertainties and challenges that need to be addressed before implementation. Further evaluation of their potential as climate mitigation pathways will require carefully designed field trials, conducted where appropriate under robust scientific, social and environmental safeguards.
- The capacity to accurately attribute carbon removal and any environmental or ecological impacts to specific mCDR interventions currently remains limited. Robust crediting and attribution mechanisms will ultimately require customized biogeochemical models built on an observationally constrained systemic understanding and trained on appropriate marine data. Advances in the scientific understanding of mCDR techniques facilitated through these MRV systems must be aligned with social, political and governance requirements to ensure that technologies only develop and scale in accordance with societal needs.

3.1 INTRODUCTION

Interest in the potential for using marine environments and processes to help achieve the Paris Agreement targets has increased significantly in recent years, driven by the need to rapidly diversify and upscale climate mitigation pathways (Edwards et al. 2026) and recognition of the ocean's role as a central regulator of global climate (Friedlingstein et al. 2026a). If implemented alongside robust emissions reduction policies, ocean-based climate technologies could support climate adaptation and mitigation efforts by improving our understanding of marine carbon fluxes, and consequently our ability to effectively manage them.

Ocean monitoring, observation and digital systems support both mitigation and adaptation by generating the information needed to understand marine carbon dynamics, assess climate risks and inform evidence-based decision-making and action. As highlighted in Chapter 2, ocean observation technologies and models underpin this knowledge base, providing the data and analysis required to develop OCI (Box 1.3). Similarly, BCEs can deliver adaptation benefits by enhancing ecosystem resilience, supporting biodiversity and strengthening coastal protection. Improved management and conservation of these carbon-rich natural environments can increase their resilience to future perturbations while providing important protective benefits for coastal communities. Several emerging techniques have been proposed to increase carbon sequestration in oceanic settings (i.e. mCDR), though significant challenges remain to be addressed before these techniques can be implemented at scale (Brun et al. 2026; Oschlies et al. 2025).

This chapter discusses how these established and nascent ocean-based climate technologies might support climate action via their ability to help monitor, manage and enhance the ocean carbon sink. Recent advances within each sector are considered alongside the enablers of that progress, while remaining knowledge gaps and pathways for responsibly accelerating their development and implementation potential are also identified. The chapter builds on the scientific concepts and processes introduced in Chapter 2, and highlights some of the societal and governance requirements that will also determine the feasibility of these technologies. These are discussed further in Chapter 4. The steps identified for realizing the potential of each technology support the role of OCI as the enabling foundation of ocean-based climate action (Chapter 1), with integration of the fit-for-purpose ocean observations, data analysis and assessment mechanisms that are essential for transforming essential for transforming complex marine processes and information into actionable, decision-ready insights.

3.2 MONITORING THE OCEAN CARBON SINK: OBSERVATIONAL TECHNOLOGIES AND DIGITAL CAPABILITIES

3.2.1 Recent advances

Surface and interior ocean observation capabilities have undergone significant transformation over the last three decades, facilitated by advancements in platform and sensor technology as well as the development and widespread adoption of new data handling methods. Sensor-equipped shipborne underway systems, gliders, floats, and autonomous surface and underwater vehicles now traverse the global ocean to reveal the finer details of ocean machinery and biogeochemical cycling (Sutton et al. 2021), while satellite-based remote sensing complements *in situ* measurements to provide a more synoptic view (Shutler et al. 2024). Importantly, shipborne hydrological surveys and fixed-point time series remain at the core of the Global Ocean Observing System (GOOS), ensuring that data quality, consistency and interoperability are maintained between platforms (Sloyan et al. 2019). Collectively, these observations enable the chemical, biological and physical processes that impact the ocean carbon system to be monitored across local and global scales, covering time frames of minutes to decades (Figure 3.1; Intergovernmental Oceanographic Commission [IOC] of UNESCO 2026; Chai et al. 2020).

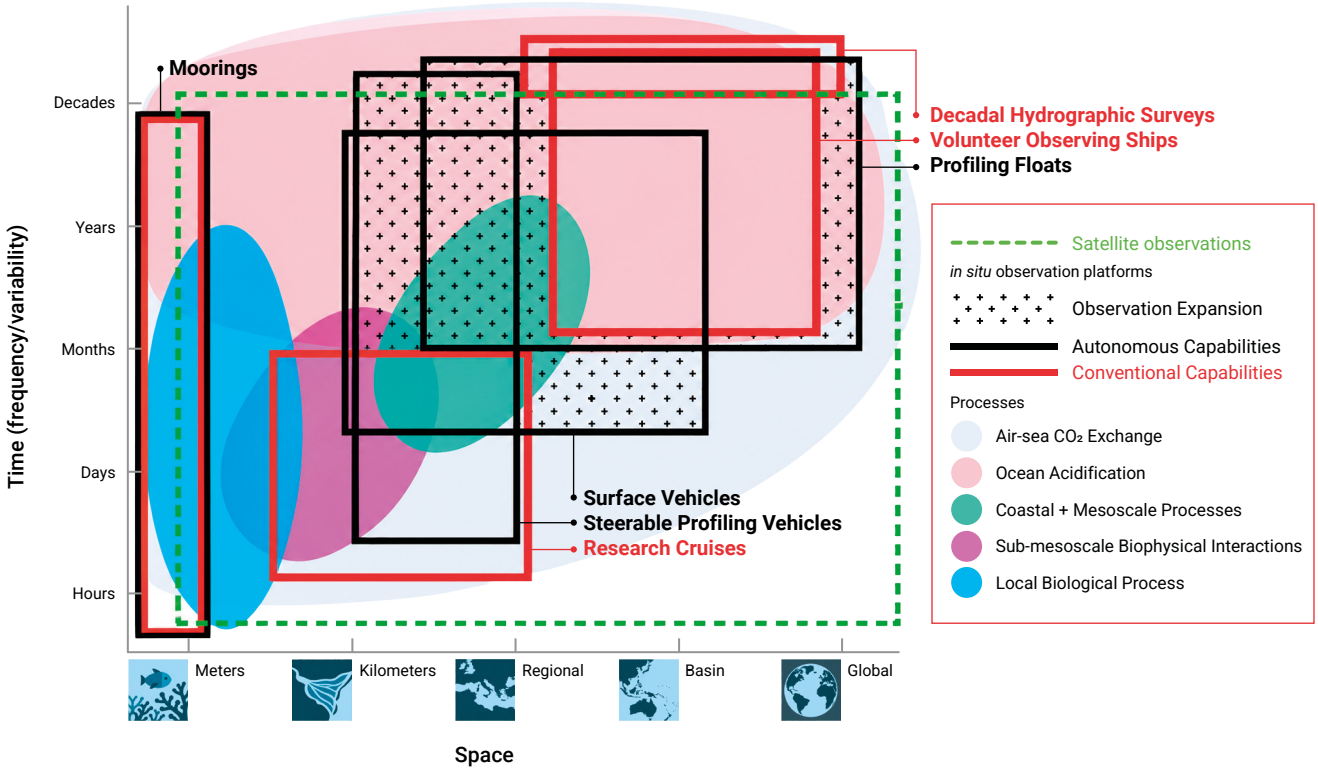


Figure 3.1: *In situ* and satellite-based observation capabilities of marine carbon cycle processes as a function of time and space (IOC of UNESCO 2026).

Machine-learning techniques provide increasingly powerful mechanisms for linking remote sensing, surface and interior data, thus helping to improve marine carbon budgets by compensating for each method's inherent limitations (Heimdal et al. 2024; Zhang et al. 2026; Landschützer et al. 2020). Together with direct observations, these data products provide the foundation for advancing global ocean biogeochemistry models (GOBMs) (section 2.3), supporting risk assessment, mitigation planning and the projection of environmental responses to perturbations in ocean carbon uptake (Friedlingstein et al. 2026a).

The potential for current ocean observing systems and data interpretation mechanisms to deliver the information required to facilitate robust MRV of ocean-based climate technologies remains under evaluation, and is a recognized research priority for both BCE and mCDR approaches (sections 3.3 and 3.4 respectively). Notably, although bespoke MRV tools grounded in high-resolution, locally relevant data will likely be required for individual climate adaptation or mitigation actions. Such locally tuned MRV systems will eventually need to link up with wider regional and global observations, likely through the proliferation and expansion of GOOS observing components.

3.2.2 Enabling mechanisms

The availability of autonomously powered sensor data from a wide range of platforms has been critical in advancing understanding of the ocean carbon sink. Reliable, field-tested sensor technology has become a routine tool for collecting carbon-relevant data such as surface partial pressure of CO_2 (pCO_2), with measurements performed on buoys (Sutton et al. 2014), Saildrones (Nickford et al. 2022), wave gliders (Morgan et al. 2025; Nicholson et al. 2022) and ship-based underway systems (Pierrot et al. 2009). BGC-Argo has routinely measured another critical carbon-related parameter – pH – globally for years (Riser, Swift and Drucker 2018), and glider-based pH measurements are also well-established (Saba et al. 2019; Takeshita et al. 2021). Sensor capabilities for other carbonate system parameters, such as total alkalinity and total dissolved carbon, have also started to emerge (Spaulding et al. 2014; Briggs et al. 2017; Qiu et al. 2023; Ringham et al. 2024; Schaap et al. 2025) and have the potential to provide transformative knowledge concerning ocean carbon fluxes and biogeochemical responses.

Effective utilization of the information provided by these marine sensors and platforms is facilitated through the Ocean Data Value Chain, through which raw data are

progressively transformed into information, knowledge and action, with societal value increasing at each stage (Figure 3.2; Heymans et al. 2021). For example, progress towards fully open-access data sets compliant with FAIR principles has supported ocean monitoring mechanisms by facilitating equitable access to marine data sets while recognizing data sovereignty and ownership of marine information. These are considerations that are of particular importance for SIDS and other developing coastal states (Chapter 5). This improved ability to access different data sets has been aided by international inter-comparison exercises and projects that mitigate issues associated with inter-sensor comparability, something that is especially valuable when assessing new and emerging technology against well-established methods (Steinhoff et al. 2025; Bockmon and Dickson, 2016), and is enabling the full potential of globally collected data sets to be realized in combination with each other (for example interior Argo and surface CO_2 data; Delaigue et al. 2026). OCI reflects the implementation of this Ocean Data Value Chain for enabling effective management of ocean carbon sinks and processes in support of climate adaptation and mitigation efforts, thus further emphasizes the importance of ocean observations in facilitating sound decision-making, planning and management.

Historically, the state of ocean observing infrastructure and associated data synthesis products has been the result of national and coordinated international efforts, primarily fuelled by pressing research questions and supported through piecemeal funding. Multiple examples prove that such collaboration can deliver fruitfully if members participate equitably (for example Argo, SOCAT; see Chapter 2) but, similarly, it can become vulnerable if member commitments are not met (see, for example, Zhu et al. 2026).

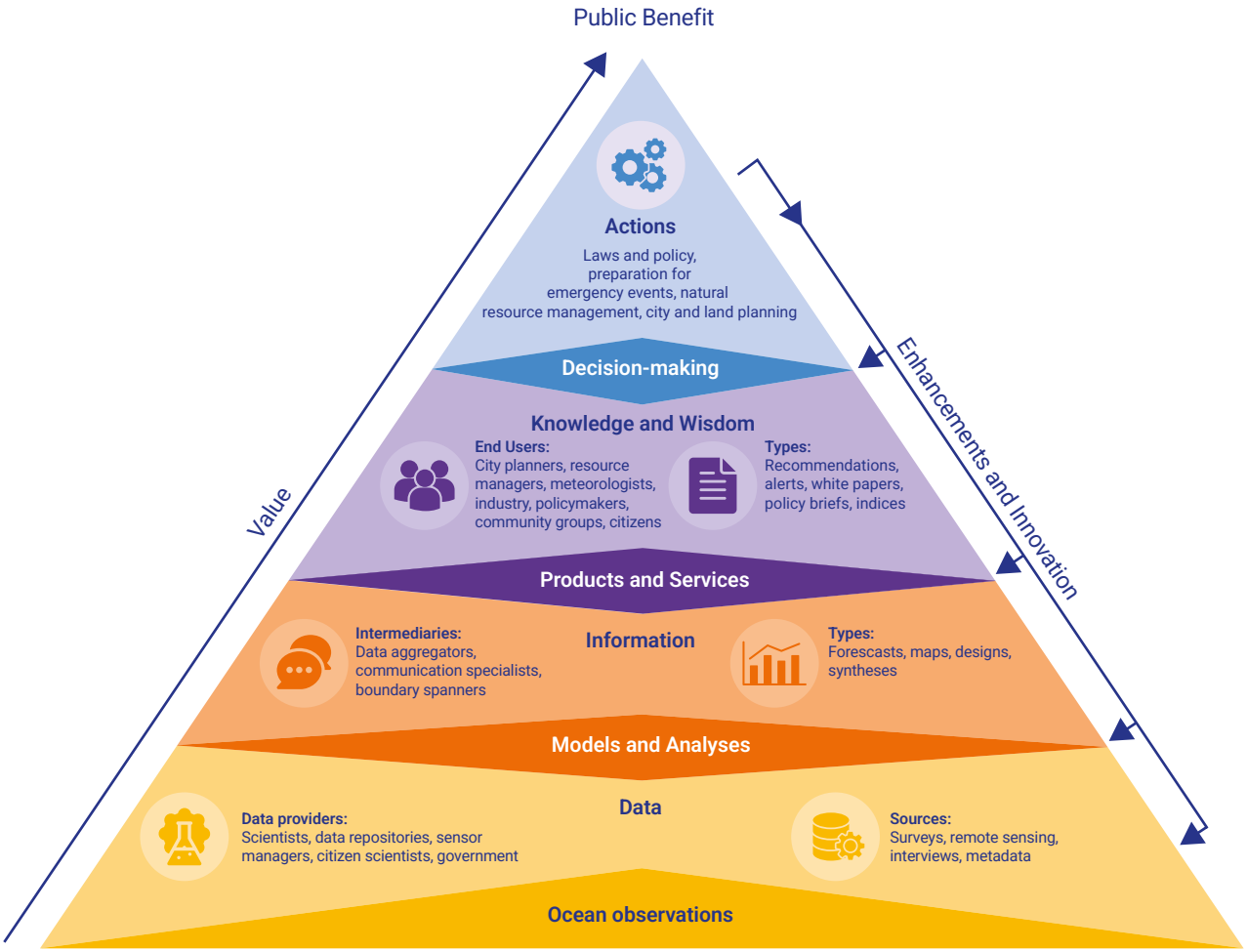


Figure 3.2: The Ocean Data Value Chain (Heymans et al. 2021), highlighting how ocean observations and digital infrastructure provide the basis for effective decision-making. OCI reflects the implementation of this value chain for enabling the effective management of ocean carbon sinks in support of climate adaptation and mitigation (see also Figure 1.1).

3.2.3 Remaining knowledge gaps

Despite the advances in platform and sensor capabilities, current global observing configurations are not optimized to assess marine climate technologies. GOOS networks were primarily established to detect long-term, slow state changes in the global open ocean, thus the variability of coastal and basin-scale carbon fluxes remains poorly captured and unresolved in both global models and data. In addition, observations in the Southern Ocean remain sparse, despite the region playing a disproportionally significant role in modulating carbon uptake (section 2.3; Gruber et al. 2019). Robust characterization of localized carbon management interventions will require much more nuanced, targeted observing, providing higher-resolution data products and models capable of resolving perturbations against high natural variability.

Whether for climate adaptation or mitigation purposes, new marine carbon observational technologies will need to be implemented in a manner compliant with existing global data sets and methods. Data calibration and standardization have long been recognized as barriers to achieving the full interoperability of data sets collected from different platforms (Macovei et al. 2021), sensors (Arruda et al. 2020; Macovei et al. 2025) and research cruises (Dickson et al. 2016, Pérez et al. 2026). For example, although data assimilation and processing algorithms have been widely adopted and implemented for surface CO_2 measurements (Bakker et al. 2016) and the BGC-Argo float programme (Bittig et al. 2019), the recommended mechanisms and pathways for handling data from other individual sensors and platforms are often missing or incomplete. The development and maintenance of such practices by data providers is consequently a priority to ensure that the collected data can be fully utilized (Palevsky et al. 2023).

Once collected, the most straightforward way of leveraging marine data is by integrating new data streams and processing routines into established data pipelines. However, these assimilation mechanisms are poorly developed (IOC of UNESCO 2026), with one notable issue being that the applicability and use of ocean data sets depend on their quality. Data provided by new sensors may not meet the most accurate "climate" standard required for detecting long-term trends, especially at the onset of implementation. On the other hand, coastal areas typically have less stringent requirements for data accuracy (so-called "weather" quality data that aims to resolve large short-term changes). The deployment of new technologies with low-quality data is therefore often welcomed. Regardless of whether data are generated of climate or weather standard, data quality should be traceable to a common certified standard to ensure consistency across data sets. The recurring issue of access to seawater standards also remains largely unresolved and requires urgent resolution, both for maintaining the global observing network and for responding to the need for quality traceable data to support climate mitigation efforts (García-Ibáñez and Easley-Vidal 2025).

Finally, fast-moving developments in the understanding of ocean-based climate technologies such as ocean alkalinity enhancement (OAE, one of the more advanced mCDR approaches; see section 3.4) increasingly highlight gaps in cost-effective integrated observing. Traditional academic research funding cannot mobilize sustainable technology development, so specialized programmes are needed to support field-appropriate innovation. Similarly, the amount of funding that currently goes into collecting, managing and assessing marine data lags behind the socioeconomic value that it produces for enabling informed decision-making through the Ocean Data Value Chain. An equivalent funding gap is expected when considering the collection of data for managing marine carbon fluxes. This needs to be recognized and acted upon when implementing OCI.

3.2.4 Pathways to accelerate development and implementation

While often underappreciated or recognized, the global ocean observing network is at the core of climate-relevant decision-making by the UNFCCC and national actors, and it has benefited from hand-in-hand advancements in monitoring technologies and data intelligence. Nevertheless, parts of the network remain fragmented when considering its purpose, measurement standardization, governance, funding mechanisms and global coverage.

Operationalizing the Ocean Data Value Chain would help to preserve and expand the ocean observing network, as it would take ocean monitoring out of the realm of research projects and into that of internationally mandated and legislated observing and data infrastructure, on a par with terrestrial meteorological efforts (Révelard et al. 2022). This would help to safeguard observational infrastructure, at least in part, against short-term regional disruptions. Regional observing systems offer practical examples of how data infrastructure can be operationalized in this manner. For example, the CHONOS platform in Patagonia utilizes a network of 15 oceanographic buoys to provide open-access, real-time data and forecasts for environmental monitoring in fjord ecosystems, while the Chilean Integrated Ocean Observing System (Sistema Integrado de Observación del Océano Chileno, SIOOC), despite insufficient implementation and the challenges it faces, illustrates efforts to integrate dispersed nearshore and open-ocean data streams under unified standards.

The challenges associated with relating the implementation of ocean-based climate technologies to their regional or global impact will require the development of locally relevant, fit-for-purpose MRV systems and processes. The effective utilization of those tools through OCI will facilitate informed decision-making on climate adaptation and mitigation activities, and help to leverage the local socioeconomic environment to enable effective governance and community benefits. It is therefore imperative that as more data begins to flow in from ocean-based climate technologies, FAIR data principles are enforced to encourage wider participation and invite trust through transparency. Initiating those monitoring practices before implementation is also considered essential for establishing robust, data-driven environmental baselines against which mitigation efforts can be assessed.

Finally, the technological revolution that has enabled the advancements in ocean monitoring mechanisms and digital infrastructure to date needs to continue. The adoption of, and improvements in, ocean observational technologies must reflect their outsized role in underpinning the Ocean Data Value Chain. More funding and capacity-sharing is needed, with examples including programmes such as Future Marine Research Infrastructure (FMRI), Accelerating Adoption of Sensor Innovation (AASI) and the European OceanEye Initiative, which commits both to supporting 35 per cent of global ocean observing by 2035 and to making sustainable investments in observing infrastructure.

3.3 MANAGING THE OCEAN CARBON SINK: BLUE CARBON ECOSYSTEMS

3.3.1 Recent advances

BCEs (Box 3.1) epitomize the potential to protect and restore marine carbon sinks through improved management and conservation practices. As some of the most efficient natural carbon sinks on Earth (Macreadie et al. 2021), BCEs play a critical role in regulating carbon cycling in coastal environments, while also delivering an array of ecosystem-related services, including high biodiversity levels, nursery habitats and coastal protection (Chapter 5; IPCC 2022). However, their sensitivity to human and climate-change induced pressures has resulted in a significant loss of habitat, impacting their ecological benefits and increasing greenhouse gas emissions through ecosystem degradation (Schindler et al. 2023). Established management techniques such as sediment regrading, hydrological reconnection and assisted revegetation are becoming more effective, scalable and context-specific, and are able to support long-term sediment carbon sequestration within BCEs while providing other climate adaptation, mitigation and societal benefits (Macreadie et al. 2026).

Box 3.1: Blue carbon ecosystem terminology and use

Blue carbon ecosystems (BCEs) are classically defined as vegetated coastal ecosystems, including mangroves, coastal wetlands and seagrasses, that occur globally (Figure 3.3), are characterized by high organic carbon accumulation rates and large, persistent soil carbon stocks, and are amenable to management (Lovelock and Duarte 2019; Macreadie et al. 2026). Recently, the potential to manage organic carbon sequestration in other coastal and non-coastal ecosystems has broadened use of the term "blue carbon", with "emerging" BCEs, including rooted or floating macroalgae (Krause-Jensen and Duarte 2016; Filbee-Dexter and Wernberg 2020); tidal forested wetlands (Adame et al. 2024), tidal flats and benthic microalgal biofilms (Underwood et al. 2026). While acknowledging the intrinsic value of these emerging BCEs and their potential to support climate adaptation and mitigation efforts (for example the potential use of macroalgae cultivation and sinking as an mCDR approach; see section 3.4), this report focuses on managing classical coastal BCEs as a marine climate technology (IPCC 2022).

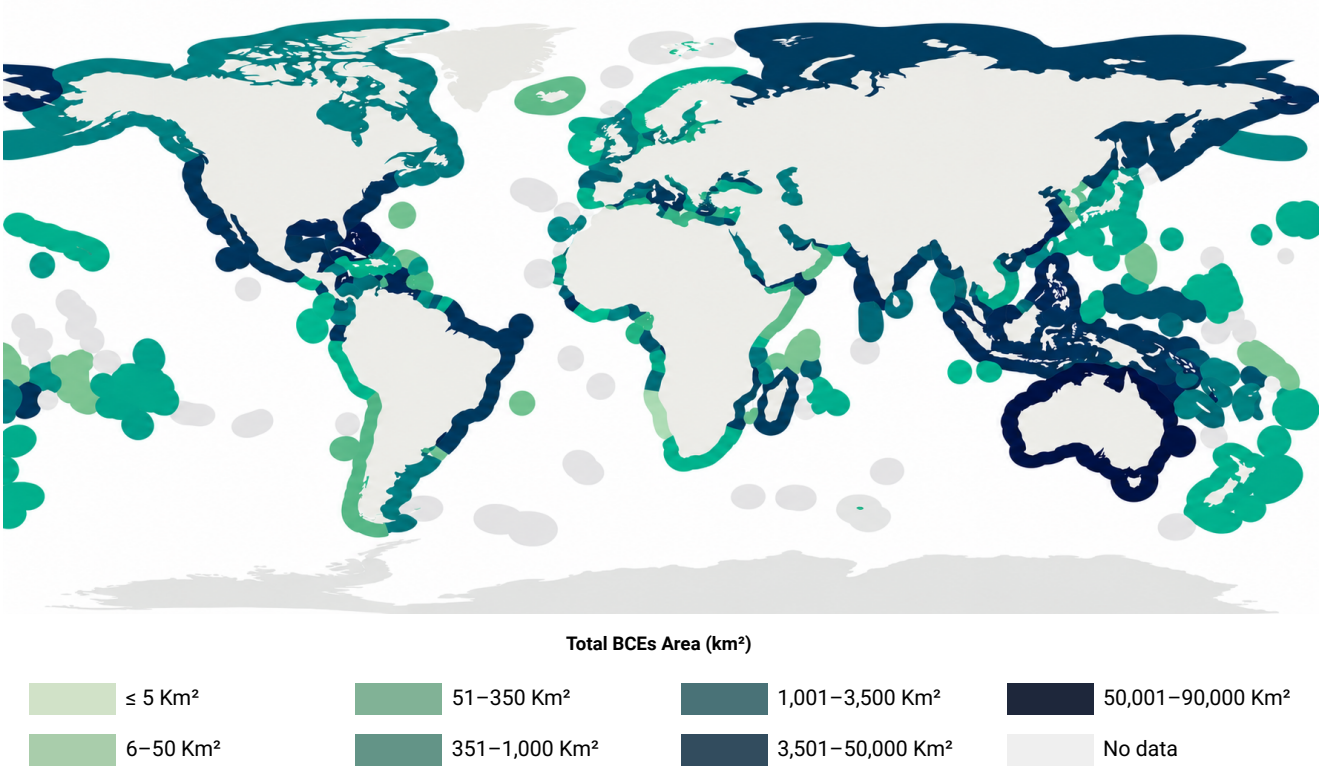


Figure 3.3: Distribution of BCE areas (Hilmi et al. 2026).

At present BCEs sequester approximately 111 Mt C yr^{-1}corresponding to an economic value of US$ 228.6 billion per year when applying the Global Social Cost of Carbon (Hilmi et al. 2026). However, coverage and carbon accumulation rates vary substantially across environmental settings: coastal wetlands accumulate approximately 202 g C m^{-2} yr^{-1} (Yan et al. 2025); mangrove ecosystem productivity is estimated at 109 Mt C yr^{-1}(67 Mt C yr^{-1} after accounting for lateral carbon losses, demonstrating that mangroves retain substantial quantities of carbon despite losses through respiration and tidal exchange; Adame et al. 2024); and seagrass meadows have a global net primary production of 83–137 Mt C yr^{-1} (Gomis et al. 2025). Globally, restored coastal wetlands exhibit a mean net greenhouse gas benefit of approximately 18 t C ha^{-1} yr^{-1}, with large-scale restoration estimated to sequester 4–56 Mt C yr-1 depending on the extent restored (Mason et al. 2023).

Similarly, the management of seagrass meadows, including reductions in land-based pollution and protection of adjacent coastal habitats, has been shown to increase sediment carbon accumulation by 24–30 per cent, highlighting the importance of integrated land-sea management for maintaining and enhancing coastal carbon sinks (Dahl et al. 2022).

The scale of these carbon fluxes, and the effectiveness of restoration and conservation activities, mean that BCEs are increasingly being incorporated into national and international climate frameworks. Several countries have included blue carbon actions in their NDCs under the Paris Agreement and are incorporating coastal carbon stocks into national greenhouse gas inventories (Chapter 4; IPCC 2023). Notable investments in BCE restoration and conservation include large-scale projects in Indonesia, Australia, Kenya, the United Arab Emirates and the United States. The emergence of blue carbon methodologies under voluntary carbon market standards has also created new opportunities for financing conservation and restoration efforts, with mechanisms such as Verra's Verified Carbon Standard enabling projects to monetize BCE carbon sequestration benefits, attracting investment from governments, development agencies, philanthropic organizations and the private sector (Verra 2021; Vanderklift et al. 2022; Perera et al. 2025).

3.3.2 Enabling mechanisms

Understanding of BCE contributions to net carbon removal has been aided by an increasingly holistic view of carbon cycle processes. Studies considering a full suite of greenhouse gas fluxes (Rosentreter et al. 2023; Roth et al. 2023) and lateral inorganic carbon fluxes (Reithmaier et al. 2023) have demonstrated that such processes can exceed the rates of organic carbon accumulation and may push the ecosystem towards net CO_2 equivalent emissions. Advances in monitoring technologies (remote sensing, *in situ* measurements, coupled ecological-carbon models) have also provided scalable

and cost-effective alternatives for mapping blue carbon inventories and fluxes (Araya-López et al. 2023, Pham et al. 2023, Macreadie et al. 2026).

The effectiveness and sustainability of BCE restoration efforts has been improved by increasing the role of local communities and Indigenous People in managing coastal ecosystems. Successful restoration projects that benefit local communities require structured engagement and participatory decision-making (Costa et al. 2026), as well as the integration of local or traditional ecological knowledge (Chapter 4; 5; Grimm et al. 2024). Community-led projects that include gender-sensitive engagement and adaptive participation strategies have supported successful natural hydrology and mangrove propagule planting restoration projects (Ravaoarinorotsihoarana et al. 2023), while increasing recognition of the co-benefits that BCE restoration brings, such as coastal protection, biodiversity provision, food-system resilience and livelihoods, have also helped strengthen community buy-in (Macreadie et al. 2026).



Finally, many countries have strengthened their policy and governance frameworks related to coastal zone management, ecosystem restoration and climate action, with the Paris Agreement, IPCC assessments and the Kunming-Montreal Global Biodiversity Framework all highlighting the importance of conserving and restoring natural ecosystems as part of climate mitigation and adaptation efforts (Chapter 4; IPCC 2023). The ensuing development of national blue carbon strategies, marine protected areas and ecosystem restoration targets have provided enabling environments for BCE project implementation and investment, with opportunities for capacity-building, knowledge-sharing and the development of best practices between scientists, governments, NGOs and local communities currently being supported by The Blue Carbon Initiative, the Global Mangrove Alliance, the United Nations Decade of Ocean Science for Sustainable Development and the High-Level Panel for a Sustainable Ocean Economy.

3.3.3 Remaining knowledge gaps

Despite recent scientific advances, BCE research and long-term monitoring must be strengthened to improve understanding of coastal carbon dynamics, including carbon stocks, sequestration rates, greenhouse gas fluxes and carbon permanence (Macreadie et al. 2021; Vanderklift et al. 2022). Expanding baseline data sets and regional inventories remains a priority, particularly for data-poor regions such as Africa (Hatje et al. 2023; Adams et al. 2026). Establishing shared data repositories, adopting standardized monitoring protocols and developing accessible national and regional carbon databases will also bolster greenhouse gas inventories and support consistent reporting across jurisdictions (Howard et al. 2014; Crooks et al. 2018; Howard et al. 2023; Dahl et al. 2025).

Shifting baselines caused by climate change mean that adaptive management is essential for enabling effective restoration (Macreadie et al. 2021; Kirwan et al. 2023). BCE carbon accumulation rate models therefore need to be expanded to improve the prediction of net greenhouse gas balances. Carbon fluxes remain highly site-specific with uncertainties in long-term permanence under climate stressors (warming, sea level rise, storms). Incorporating CH_4 and N_2O fluxes, as well as lateral exchanges of dissolved greenhouse gases and carbon across habitats, into numerical models will help to improve understanding of how BCE carbon dynamics may respond to future pressures (Macreadie et al. 2026). Restoration success has often been evaluated using short-term or structural indicators, such as area restored, vegetation cover or survival rates, while long-term ecosystem function, resilience and carbon integrity have received comparatively less attention (Bayraktarov et al. 2015; Gatt et al. 2024). Although there are several described studies on seagrass restoration (Unsworth et al. 2025), few of these have documented recovery of carbon stocks and improvement in carbon accumulation. This is partly due to the fact that natural seagrass sediment dynamics, such as resuspension and mixing, make it difficult to estimate sediment and carbon accumulation using radionuclide techniques (Lafratta et al. 2020). In all BCEs, successful restoration must address the drivers of decline, rather than relying solely on active transplantation efforts (Duarte et al. 2025).

As highlighted above, the participation of BCE restoration projects in carbon markets remains subject to debate (see, for example, Williamson and Gattuso 2022), with barriers to participation including high monitoring and verification costs, complex certification requirements, uncertainty around carbon credit pricing and limited access for community-led projects. Reliable MRV systems are therefore essential for improving carbon accounting, increasing transparency and facilitating access to climate finance, yet these systems remain expensive and technically demanding (Crooks et al. 2018; Lovelock et al. 2023; Macreadie et al. 2022). Many developing countries also lack the technical expertise, laboratory facilities, long-term monitoring programmes and access to remote sensing products required to facilitate robust MRV (Macreadie et al. 2022; Omollo et al. 2026).

Despite the progress made by many countries, BCE governance remains underdeveloped, with limited national strategies and inventories, unclear carbon rights, and evolving legal and policy frameworks for carbon trading (Chapter 4; Omollo et al. 2026; Lovelock and Duarte 2025). In particular, more attention needs to be paid to BCE projects that promote livelihoods, gender equity, cultural values, benefit-sharing and the use of Indigenous and local knowledge to improve social and environmental outcomes (Figure 3.4; Vierros 2017; Macreadie et al. 2026; Lovelock and Duarte 2025; Perera et al. 2025).

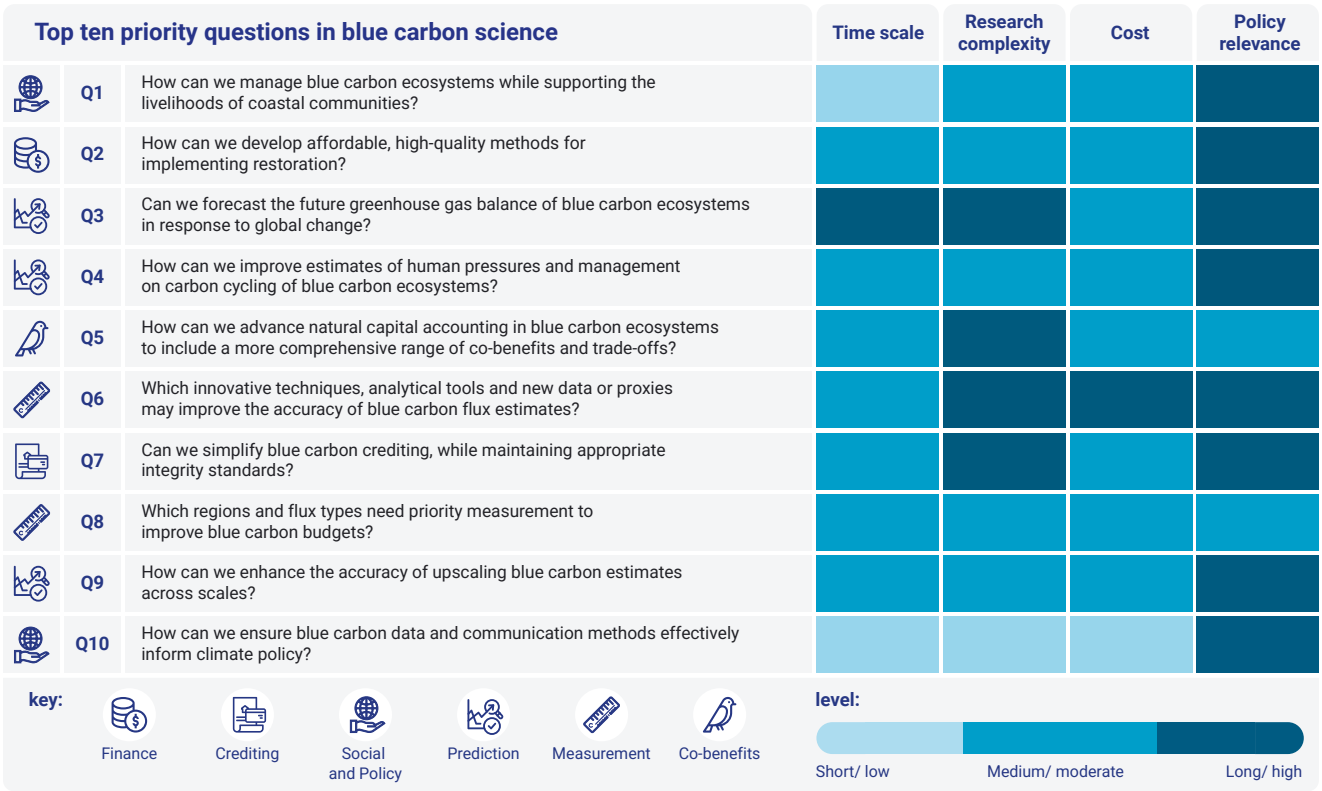


Figure 3.4. Top 10 priority questions for blue carbon science (Macreadie et al. 2026)

3.3.4 Pathways to accelerate development and implementation

Enabling the effective management of BCEs and other carbon-rich marine environments, including protecting and restoring their ocean carbon sinks as an ocean-based climate technology, necessitates a shift from project-based restoration to adaptive, ecosystem-scale management integrated with climate adaptation planning. Standardized, low-cost BCE MRV systems developed through participatory and co-designed approaches are needed to ensure that monitoring frameworks are scientifically credible, socially acceptable and aligned with both local and regional priorities (Vanderklift et al. 2022; Macreadie et al. 2025). This includes "catchment to coast", "ridge to reef" or coastal corridor monitoring strategies that ensure connectivity across ecosystems and beyond man-made boundaries (Macreadie et al. 2026).

Monitoring frameworks also need to be able to distinguish between the different climatic benefits (i.e. protection of carbon stocks, uptake of atmospheric CO_2 or suppression of greenhouse gas emissions) that any intervention or restoration effort may be expected to deliver. These may include the synergistic benefits of conserving land-to-sea ecosystems, as the health of each ecosystem supports the functioning of adjacent habitats (Carlson et al. 2021) and the drivers of degradation frequently occur outside the boundaries of interest (Chmura 2025).

Participatory approaches that build local capacity and ensure inclusive decision-making are essential for effective BCE management. Incorporating traditional or local ecological knowledge improves restoration and conservation outcomes, as this knowledge is rooted in generations of ecosystem interaction (Vierros 2017). Focusing on the co-benefits of BCE management may also aid implementation by enabling the blue carbon market to "deliver results for people, nature and climate" (Beeston et al. 2024). The provision of substantial social, economic and ecological benefits alongside climate mitigation efforts will aid inclusion in economic and policy frameworks (Hilmi et al. 2026). Finally, while BCEs have expanded from a niche concept to a more established component of carbon markets and policy frameworks, the current levels of investment remain insufficient, and governance systems must evolve to ensure equitable and scalable outcomes (Lovelock and Duarte 2025). Targeted reforms within existing legislative systems may help remove barriers to ecological restoration and enable implementation at scale (Chapter 4; Bell-James et al. 2025), while investment in training, infrastructure and institutional capacity may strengthen local expertise and support effective blue carbon management in developing countries (Chapter 5).

3.4 ENHANCING THE OCEAN CARBON SINK: MARINE CARBON DIOXIDE REMOVAL

3.4.1 Recent advances

Interest in the potential for using marine-based climate technologies to actively enhance ocean carbon uptake has increased in recent years as the scale of CDR needed to help limit the impacts of global climate change has become clearer (see, for example, Edwards et al. 2026). mCDR techniques are among the most prominent of these ocean-based climate mitigation technologies. While still considered nascent and subject to significant challenges (see Brun et al. 2026; Oschlies et al. 2025), their potential to scale to climatically significant levels remains uncertain and requires further assessment (National Academies of Sciences, Engineering and Medicine [NASEM] 2022; Doney et al. 2025). An array of mCDR approaches have been proposed. They differ substantially in their functional principles, expected permanence and potential environmental trade-offs (Table 3.1; Box 3.2). At the highest level, however, all mCDR technologies can be classified according to the mechanism through which they aim to facilitate an increase in the amount of atmospheric CO_2 being absorbed and stored in seawater:

- **Biological mCDR approaches** operate by stimulating additional photosynthetic CO_2 uptake and conversion to organic matter, or by limiting the amount of organic matter being respired (degraded) back to CO_2. They encompass a range of interventions, including macroalgae (seaweed) cultivation and sinking, phytoplankton fertilization using iron or macronutrients, and BCE restoration.

- **Chemical mCDR approaches** increase ocean CO_2 uptake by abiotically reducing the concentration of CO_2 at the sea surface, encouraging transfer from the atmosphere into seawater (see Chapter 2). This can be achieved by adding alkaline materials such as crushed silicate, lime or carbonate rocks to enhance ocean alkalinity (OAE), or by actively extracting CO_2 from seawater through electrochemically generated pH shifts and storing it durably elsewhere (direct ocean carbon capture and storage [DOCCS]).[6]

6 Chemical mCDR can also be integrated with existing coastal infrastructure. Electrochemical OAE, for exampe, generates alkalinity from saline solutions such as seawater or desalination brine. Electrochemical OAE and CO_2 extraction systems can therefore be co-located with desalination plants and share their intakes and outfalls (Benjamin et al. 2026; Refaie et al. 2026). Wastewater treatment plants can similarly add alkalinity to effluents before discharge; an approach tested in a recent field trial (Savoie et al. 2025). However, energy requirements, by-product management and MRV remain key challenges.

- **Physical mCDR approaches,** such as artificial downwelling, aim to use currents and/or pumping mechanisms to subduct carbon-rich surface waters into the deep ocean interior.

"Blended" mCDR solutions are also starting to appear. These solutions integrate chemical mCDR approaches like coastal enhanced weathering into coastal management efforts, with the increased carbon removal being considered a co-benefit relative to the primary ecosystem or climate adaptation function of the intervention (see, for example, Kitch, Khan and Woollen 2026).

Box 3.2: Marine carbon dioxide removal terminology and use

Marine carbon dioxide removal (mCDR) – also termed ocean-based carbon dioxide removal (oCDR) or ocean negative carbon emissions (ONCE) – refers to processes that aim to reduce atmospheric CO_2 levels by increasing the amount of carbon being absorbed and stored in seawater (Ho and Bopp 2024). The enhanced uptake of CO_2 into the ocean can be stimulated by removing dissolved carbon in surface waters through biological, chemical or physical mechanisms (Figure 3.5), which differ substantially in their functional principles, expected permanence and potential environmental trade-offs (Table 3.1; NASEM 2022; Oschlies et al. 2025). A number of marine carbon storage techniques that seek to use marine environments as reservoirs for carbon captured on land have also been proposed, including the deposition of terrestrially derived biomass in deep marine or anoxic settings (Raven et al. 2026) and mineralization of the oceanic crust using carbon-rich fluids (Yao et al. 2026). Such approaches are often considered alongside mCDR technologies as they share similar MRV requirements and potential ecological impacts (see, for example, Blackford et al. 2026). In the interest of clarity, however, this report only discusses mCDR approaches sensu stricto (i.e. those that increase atmospheric CO_2 absorption into seawater; Figure 3.5).

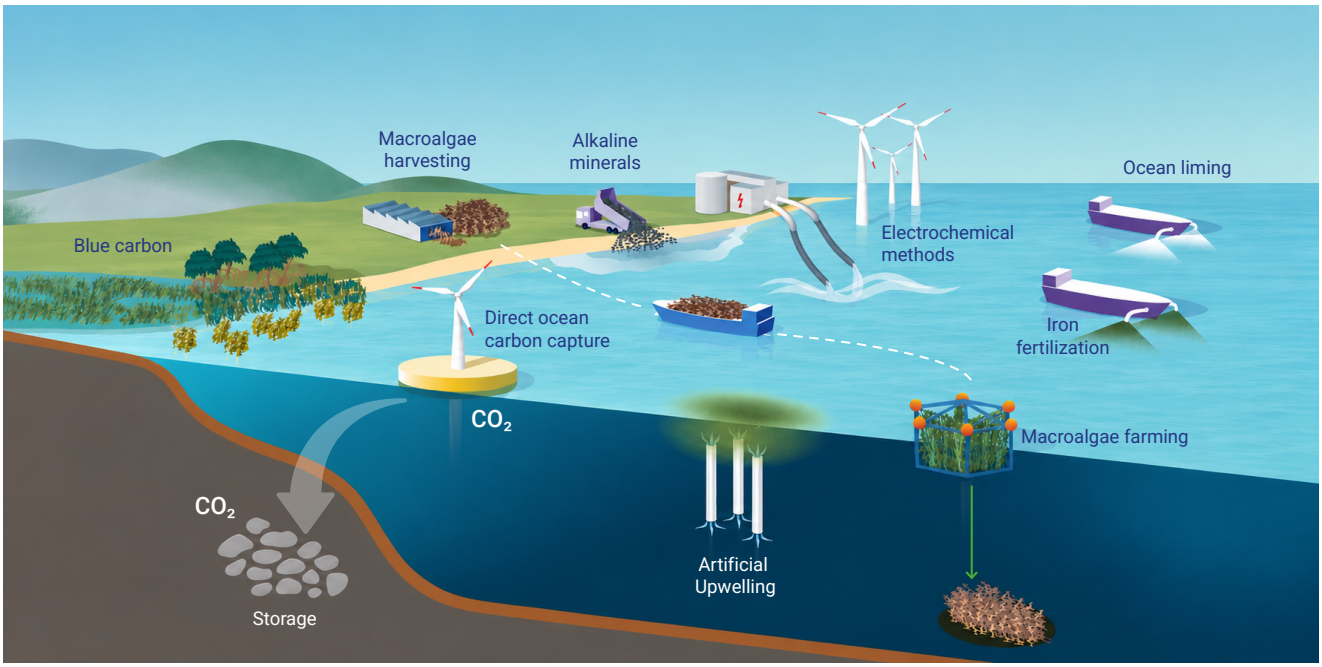
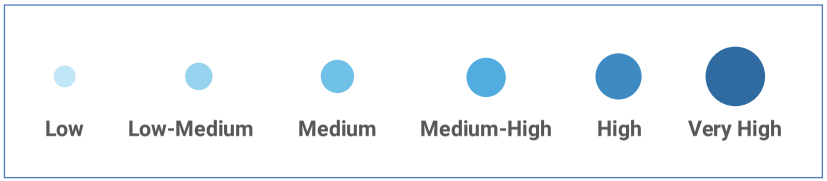


Figure 3.5. Schematic overview of biological, chemical and physical mCDR approaches (redrawn from GESAMP 2025).

Table 3.1. Summary of the climate mitigation potential and technological readiness of chemical, biological and physical mCDR techniques (see supplementary table for full details in Annex A). Adapted from Doney et al. (2025).

Approach	Technology *Example Methods*	Stock	Efficacy	Durability	Sequestration Potential	Cost	TRL	Technology & Infrastructure Capacity | Requirements	Scientific Principles Understanding | Gaps	Environmmental Implications Co-benefits | Impacts	MRV Readliness (Carbon Crediting Mechanisms)
Biological mCDR	**Macroalgae Growth** *Farming and deep-sea depositoin* *Sargassum sinking*						4				
	Phytoplankton Growth *Iron Fertilisation* *Nutrient Fertilisation*						5				
	Blue Carbon Ecosystems *Mangroves* *Seagrass Meadows* *Saltmarshes*						6				
Chemical mCDR	**Ocean Alkalinity Enhancement** *Coastal Enhanced Weathering* *Mineral dissolution* *Ocean liming*						5				
	Direct Ocean Carbon Capture *Electrolysis* *Electrodialysis*	N/A					4				
Physical mCDR	**Artificial Downwelling** *Pumps, Pipes & Turbines*	N/A					1-2				



Stock: Amount of carbon currently stored globally in that ocean reservoir. Low (<1 GtC); Medium (1-100 GtC); Large (100-1000 GtC); Very Large (>1000 GtC)
Efficacy: Level of confidence that the technology will remove atmospheric CO_2 and increase ocean carbon storage. Low; Medium; High
Durability: Likely duration over which CO_2 is expected to be removed from the atmosphere and stored away from the surface ocean. Short (years-decades); Medium (decades-centuries); Long (centuries-millennia); Permanent (>10,000 yrs)
Sequestration potential: Anticipated maximum extent of net annual CO_2 removal that could be achieved by the technology if conducted globally at appropriate locations in the future. Small (<0.1 Gt CO_2/yr); Medium (0.1-1 Gt CO_2/yr); Large (1-5 Gt CO_2/yr); Very Large (>5 GtCO_2/yr)
Estimated cost at scale: Approximate cost (dollars per metric ton CO_2) for deployment at scale in the future, excluding the cost of MRV and associated development. Low (<50 \$t/CO_2); Medium (50-100 \$t/CO_2); High (100-500 \$t/CO_2); Very High (>500 \$t/CO_2)
TRL: Technology Readiness Level, based on IPCC AR6 WGIII scheme (defined above)

TRL Levels	
Basic Research	1: Initial idea
Applied Research	2: Application formulated (technology concept and application of solution formulated)
	3: Concept needs validation (solutions need to be prototyped and applied)
	4: Early prototype (prototype proven in test conditions)
	5: Full prototype at scale (components proven in conditions to be deployed)
Demonstration	6: Full prototype at scale (prototype proven at scale in conditions to be deployed)
	7: Pre-commercial demonstration (solutions working in expected conditions)
	8: First-of-a-kind commercial (commercial demonstration, full scale deployment in final form)
Deployment	9: Commercial operation in early environment (solution is commercial available, needs evolutionary improvement to stay competitive)
	10:Integration needed at scale (solution is commercial and competitive but needs further integration efforts)
	11: Proof of stability reached (Predictable growth)

Note: The current state of progress/understanding regarding the Technology & Infrastructure, Scientific Principles, and Environmental Implications of each mCDR approach have been indicatively ranked out of 3 (Low; Medium; High) for both positive (green) and negative (red) considerations. The relative current state of MRV readiness is represented using a single scale out of 6 (Low; Low-Medium; Medium; Medium-High; High; Very High). Further information regarding these indicative rankings is provided in Annex A.

Scientific understanding of the carbon uptake mechanisms for these mCDR techniques, as well as their associated biogeochemical and ecological interactions and impacts, have been meaningfully progressed through laboratory experiments, early small-scale field trials and advances in modelling capabilities (Doney et al. 2025). These research activities have particularly emphasized the characterization of OAE approaches, due to their relatively high theoretical sequestration potential and the expected durability of carbon storage on millennial timescales (Renforth and Henderson 2017; Doney et al. 2024; Oschlies et al. 2025). The resulting advances in understanding coincided with the first reported purchase of 115,000 tonnes of OAE carbon credits in 2025; however, further research is needed to assess durability, storage permanence, additionality and verification approaches associated with carbon removal achieved through OAE (Bach et al. 2024; Hartmann et al. 2023), as well as to develop quantitative tools that link alkalinity addition to inorganic carbon drawdown (Tyka 2025).

Understanding of biological (Gim et al. 2018; Guo et al. 2022; Gately et al. 2023; Hutchins et al. 2023; Li et al. 2024; Zhang et al. 2024) and ecosystem (Ferderer et al. 2022; Subhas, Lehmann and Rickaby 2022; Gately et al. 2026) responses to mCDR implementation have also been improved through laboratory and mesocosm experiments. Although such assessments remain a priority for future mCDR research, initial findings provide the basis for developing mCDR environmental impact assessment (EIA) frameworks (see, for example, Weighman, Jankowska and Andrews 2026; Fawcett et al. 2026; and the ongoing Ocean Visions EIA framework) intended to help guide future *in situ* trials. Modelling studies have also begun to map regional and seasonal variations in mCDR efficiency, providing a first-order basis for evaluating where and when interventions might be most effective (Zhou et al. 2024; He and Tyka 2023; Wang et al. 2023; Mu, Palter and Wang 2023).

In parallel with these scientific and technological advances in the understanding of mCDR, there has been increasing recognition of the need for such technologies to be co-designed with the communities involved to ensure that (where appropriate) they can be adopted and scaled at the rate necessary to address climate change (see, for example, Brun et al. 2026). At present, however, the governance and policy frameworks required to facilitate the equitable and just implementation of mCDR techniques remain fragmented (Chapter 4).

3.4.2 Enabling mechanisms

Scientific progress has primarily been enabled by growing public and private investment in mCDR, with dedicated research programmes and philanthropic organizations mobilizing substantial resources for *in situ* field trials and technology development. Recent research initiatives include the Locking away Ocean Carbon in the Northeast Shelf and Slope (LOC-NESS) OAE field trial led by the Woods Hole Oceanographic Institution on the US Northeast Shelf in 2025, and the ongoing Tufts Cove OAE field trial in Halifax, Canada, launched by Planetary Technologies in 2023 and supported by independent, monitoring and scientific assessment from Dalhousie University (Figure 3.6). Other significant mCDR research programmes include the Horizon-Europe funded Ocean-based Negative Emission Technologies (OceanNETs), Strategies for the Evaluation and Assessment of Ocean-based Carbon Dioxide Removal (SEAO2-CDR), Ocean Alkalinity Enhancement: Sustainability and Impacts across Scales (OAeSIS) and Measurement and Reporting for Responsible Marine CO_2 Removal (MAR-CO_2) projects, the German Government funded CDRmare mission, the Chinese-led Global ONCE project, the US-funded Sensing Exports of Anthropogenic Carbon through Ocean Observation (Sea-CO_2) project and a forthcoming Phytoplankton Carbon Solutions research programme coordinated by the Environmental Defense Fund.



Figure 3.6. Dye-tracer release at Tufts Cove, Halifax Harbour, a site for the OAE field trial led by Planetary Technologies in partnership with Dalhousie University. [© Ocean Alk-Align Project]

Strong international cooperation and private-academic collaboration facilitated through those research projects and field trials has supported the development of scientific consensus in mCDR evaluations, with other enabling mechanisms including the facilitation of expert panels (see, for example, NASEM 2022; Doney et al. 2025, Muri et al. 2025), the development of best practice guides (for example Oschlies et al. 2023) and the coordination of organizational networks such as the Surface Ocean - Lower Atmosphere Study (SOLAS; Hoffmann et al. 2026), the International Council for the Exploration of the Sea (ICES; Grabb, Wood and McElhany 2026) and the Global Ocean Acidification Observing Network (GOA-ON; Findlay et al. 2025). Initiatives aimed at synthesizing knowledge on mCDR and fisheries have also helped to consolidate scientific understanding, identify research priorities and develop standardized protocols. For example, associations such as the Fishery Friendly Climate Action Campaign have supported the integration of fishing communities into mCDR decision-making.

Collectively, these efforts have been important in creating shared conceptual frameworks and terminology, including for key concepts that underpin any mCDR assessment and verification process, such as additionality, durability and efficiency (Fennel 2026; Doney et al. 2025). Similarly, recognition that robust mCDR MRV frameworks will rely on a deliberate combination of observational and modelling tools (Ho et al. 2023) has sharpened focus on approaches which balance reliability and efficiency. While *in situ* data will play a critical role in regulatory compliance, the ultimate attribution of carbon removal will likely be made by models that are built on an observationally constrained systemic understanding and trained on appropriate marine data. Efforts to develop operational mCDR MRV frameworks based on this concept are currently underway.

3.4.3 Remaining knowledge gaps

While many specific knowledge gaps persist with regards to the viability and impacts of specific mCDR techniques, four interconnected challenges currently limit assessment of whether these techniques can be responsibly developed and deployed as effective climate mitigation technologies (Brun et al. 2026, Oschlies et al. 2025, Doney et al. 2025).

- The ability to accurately attribute carbon removal and any environmental or ecological impacts to specific interventions remains limited. For example, the total amount of atmospheric CO_2 removed is ultimately determined as the difference between a perturbed ocean carbon budget following the mCDR intervention, and a hypothetical "counterfactual" outcome in which there was no intervention. This requires skilfully validated biogeochemical models operating against a natural background of much larger carbon fluxes, creating a signal-to-noise challenge for MRV. Similarly, uncertainties in the long-term rebalancing of ocean carbon cycle perturbations, greenhouse gas emissions associated with implementation of the mCDR technique (including

cradle-to-grave emissions incurred during the whole lifecycle of the mCDR activity) and potential ecological impacts (for example oxygen depletion and habitat disruption) compound an already complex verification environment.

- Existing international governance frameworks are still evolving, and questions regarding research authorization, liability, environmental safeguards and benefit-sharing remain the subject of ongoing discussion (see Chapter 4). This regulatory vacuum is particularly consequential given the transboundary nature of ocean processes.

- Despite recent increases in investment, the mCDR funding landscape remains imbalanced. Private investment and associated activities primarily rely on the volatile voluntary carbon market, while public investment and support for the underpinning research remains insufficient and lags behind ambition. The scale of funding needed, coupled with the requirement for transparency in funding mechanisms and outputs, mean that public investment is essential to help address critical knowledge gaps.

- The societal goals and desirability of implementing mCDR remain poorly defined. Understanding the type and scale of mCDR deployment that should be considered, under what conditions, and the extent to which it should contribute to broader climate action, has yet to be meaningfully resolved through inclusive public deliberation.

3.4.4 Pathways to accelerate development and implementation

Improving understanding of mCDR technologies will require evidence from carefully designed field trials, undertaken in accordance with applicable governance frameworks, transparency requirements and environmental safeguards. These field trials should be governed by clearly defined scientific protocols, transparency requirements, and social and environmental safeguards, based on international agreement on minimum standards for trial design (which are presently lacking), monitoring scope and reporting. This is essential to ensure that results are comparable, defensible and usable for governance purposes, and can generate the empirical data needed to validate and constrain the biogeochemical models on which MRV ultimately depends. Collaboration between private mCDR operators and academic research institutions at these field sites offers the potential mutual benefits of knowledge exchange and transfer, but should be pursued with caution due to the possibility of conflicts of interest.

While such mCDR assessments are undoubtedly required, the resulting advances in scientific understanding will not facilitate equivalent progress in the potential for responsible utilization unless they are aligned with social, political and governance research that can ensure that the technology develops and scales in accordance with societal needs. A population explicitly engaged with, and involved in, mCDR decision-making from an early stage is more resilient to setbacks and uncertainty. This implies a need to shift away from societal acceptance towards engaged and intentional co-design. If mCDR can be tested in carefully structured field trials guided by the principles of co-design and engagement, this significantly increases the likelihood that mCDR interventions can meet societal expectations and ultimately deliver on their promises.

3.5 CONCLUSION

Marine-based climate technologies could play a critical role in supporting climate adaptation and mitigation by enabling ocean carbon uptake to be observed, protected, restored and enhanced. Advances in understanding of established BCE pathways have already enabled their inclusion in NDCs, while the rapidly developing mCDR sector includes a portfolio of approaches that are currently being investigated for their potential contribution to net-zero policies and climate mitigation efforts. Facilitating the responsible development and deployment of these technologies requires improved scientific understanding, monitoring capabilities and governance mechanisms that can transform complex data into decision-ready insights able to keep pace with demands and ambition. The potential for wider utilization of these technologies through added ecosystem services or the Ocean Data Value Chain further emphasizes the foundational role that they play within marine systems, and the additional benefits that they have within climate policy. Government-level investment is needed to develop the co-designed implementation mechanisms, facilitate independent field trials, and enhance the monitoring capabilities and data-access processes required to improve scientific understanding of these marine technologies. Failure to do so will create blind spots in the understanding of key climatic processes and limit the ability to align policy frameworks with the Paris Agreement and the UNFCCC.

4.

Governance and Policy Implications of Ocean-based Climate Technologies

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CHAPTER HIGHLIGHTS

- Robust governance frameworks are essential for enabling the responsible development, deployment and transfer of ocean-based climate technologies while safeguarding environmental integrity and promoting positive social outcomes. Achieving this will require coordinated and complementary action across international, regional, national and subnational governance levels.
- The international governance framework relevant to ocean-based climate technologies remains highly fragmented, comprising multiple international regimes that address different aspects of technology development, deployment and transfer. Limited coordination across these regimes has created regulatory gaps and areas of ambiguity that may constrain effective technology development and transfer, while potentially weakening environmental and social safeguards. Addressing these challenges will require targeted reforms within relevant international frameworks, alongside institutional mechanisms that enhance coordination, coherence and synergies across regimes.
- The UNFCCC recognizes the ocean as a critical component of the global carbon cycle and an important carbon sink. However, ocean carbon uptake is not fully reflected in greenhouse gas accounting under the Convention. Resource, technical and institutional capacity constraints, particularly in developing countries, limit the ability to quantify and account for ocean carbon uptake and, consequently, to fully realize the potential of ocean-based climate technologies.
- Just and equitable development and transfer of ocean-based climate technologies require governance frameworks and institutional arrangements that prevent the reinforcement of existing inequalities and avoid shifting additional social, economic or environmental burdens onto vulnerable populations.
- Robust environmental and social safeguards, together with effective protection of tenure and resource rights, are essential to ensure that ocean-based climate technologies do not undermine existing livelihoods, displace resource users or generate adverse social impacts, particularly for Indigenous Peoples and local communities whose livelihoods depend on affected areas. This highlights the need for inclusive governance.
- Long-term, transboundary monitoring systems are required to verify climate outcomes, assess broader environmental and socioeconomic co-benefits, and identify, evaluate and manage potential adverse impacts associated with ocean-based climate technologies.
- While a range of financing mechanisms exists to support ocean-based climate technology projects, access to capital remains fragmented and insufficient to meet investment needs. Scaling investment will require the development of enabling infrastructure, including standardized taxonomies, robust MRV systems and strengthened support for technology development, transfer and capacity-building.
- International cooperation is a key enabler of ocean-based climate technology development and transfer, and existing governance frameworks provide opportunities to enhance coordination while safeguarding environmental and social outcomes.

4.1 INTRODUCTION

The development, testing and deployment of ocean-based climate technologies are shaped by governance frameworks at local, national and international levels. Together, these policies, institutions and regulatory mechanisms influence where technologies can operate, how they are regulated and the conditions under which they can scale.

Governance refers broadly to the legal, policy and social context in which technologies are developed and deployed. Technology governance mechanisms may have both enabling and constraining features, on the one hand supporting or facilitating technology development, while on the other also guarding against potential adverse environmental and social impacts. Governance relies on formal institutions such as laws and treaties, but also on informal institutions at the local and community level.

In the ocean-based climate technology space, the shared nature of the ocean resource and the potential for transboundary impacts (Chapter 3) make international governance especially important. International rules and standards are needed to guide decisions about whether, when, where and how ocean-based climate technologies are developed and deployed. At the same time, however, decision-making processes should be inclusive of and equitable for coastal communities and other local groups who may be directly affected (either positively or negatively) by the technologies. This highlights the need for action to both support and regulate ocean-based climate technologies across multiple spheres of governance, from international to regional, national and local levels. Across all levels, robust governance and sustainable deployment can support responsible development of ocean-based climate technologies in a way that advances sustainable development goals. Since many ocean-based climate technologies are still nascent, there is a need for adaptive governance that is responsive to new information and enables consideration of a range of potential solutions and management approaches (Röschel and Neumann 2023).

This chapter reviews progress in the design and implementation of governance, policies and institutions for ocean-based climate technologies. Section 4.2 provides an overview of existing international governance frameworks that are potentially relevant for the development and deployment of ocean-based climate technologies. Section 4.3 addresses social equity and inclusion in ocean-based climate technology development, highlighting the impacts and issues to address in policies and governance. Section 4.4 explores strategies to manage social equity issues and, more generally, fill gaps in existing governance frameworks. It highlights the importance of robust safeguards, protecting ownership rights, and improved monitoring, standards and certification processes to advance safe and equitable technology development. This is followed, in section 4.5, by a discussion of the need for capacity-strengthening, particularly in developing coastal countries and SIDS, to enable them to play a more active role in ocean-based climate technology development. Section 4.6 provides a non-exhaustive overview of selected trends and developments in finance, investment and enabling market mechanisms relevant to ocean-based climate technologies. Section 4.7 concludes with a discussion of pathways forward, highlighting in particular the urgent need for greater international cooperation in governance and policymaking for ocean-based climate technologies.

4.2 INTERNATIONAL GOVERNANCE FRAMEWORKS AND INSTITUTIONS

The existing international governance framework for ocean-based climate technologies is highly fragmented, with many different international regimes addressing various aspects of technology development and use, but in a disjointed way. Historically, regimes for addressing climate change and protecting ocean environments developed separately, and work under each remains siloed. Greater alignment across international regimes is essential for effective governance of ocean-based climate technologies.

In considering the governance of ocean-based climate technologies, it is useful to start with the United Nations Convention on the Law of the Sea (UNCLOS), which defines the extent of States' jurisdiction over the ocean. Under UNCLOS, each State's sovereign territory extends to the outer edge of its territorial sea, up to 12 nautical miles from the baseline (normally the low waterline along the coast).[7] Extending beyond the territorial sea, 12 to 200 nautical miles from the baseline, is the State's exclusive economic zone.[8] Within its exclusive economic zone, the State has sovereign rights to exploit, manage and conserve natural resources and perform other activities for the economic exploitation of the zone, as well as jurisdiction over artificial islands and other structures, marine scientific research, and the protection and preservation of the marine environment. States' territorial seas and exclusive economic zones collectively cover approximately 40 per cent of the ocean's surface.[9] The remainder of the ocean comprises the so-called high seas, which fall outside the exclusive jurisdiction of any one

7 UNCLOS, articles 2 and 3

8 UNCLOS, articles 2 and 3.

9 https://www.noaa.gov/maritime-zones-and-boundaries

State, and are instead open to use by all in accordance with the principle of "freedom of the high seas" articulated in UNCLOS. This legal division of the ocean creates challenges in utilizing it to advance climate goals.

4.2.1 Treatment of ocean-based climate technologies in the global climate change regime

The UNFCCC recognizes the role of the "ocean" as a carbon "sink" (United Nations 1992). But carbon uptake by the ocean is not fully reflected in greenhouse gas accounting under the UNFCCC. Parties to the UNFCCC are required to develop national greenhouse gas inventories, which detail "emissions and removals taking place within [the party's] national territory and offshore areas over which [it] has jurisdiction," including its territorial sea and potentially also its exclusive economic zone (Boettcher et al. 2025). With limited exceptions (for international shipping, for example), high seas areas are excluded from national inventories. Moreover, even in areas covered by national inventories, accounting for ocean carbon fluxes is often technically challenging (Boettcher et al. 2025). This can create uncertainty around the mitigation benefits of ocean-based climate technologies and limit their integration into climate policy and reporting frameworks.

In the case of mCDR technologies, interventions occurring within one State's jurisdictional waters, such as OAE or direct ocean capture (DOC), could lead to emissions or removals in the waters of another State or the high seas. This may make it difficult for implementing countries to account for the resulting altered carbon fluxes in their national greenhouse gas inventories. Compounding the difficulties, there is currently no internationally standardized methodology for integrating these types of carbon fluxes into national inventories (Muri et al. 2025). The 2027 IPCC Methodology Report on Carbon Dioxide Removal Technologies, Carbon Capture, Utilization, and Storage for National Greenhouse Gas Inventories is expected to provide a first methodology for carbon dioxide "removal through direct capture of [carbon dioxide] from water already processed by inland and coastal facilities." However, it will not cover other mCDR technologies, such as offshore DOC or OAE (IPCC 2025).

Governments have also faced challenges in integrating blue carbon into their emissions accounting and climate targets. Within the global climate change regime, there have recently been calls for Parties to "scale up" ocean-based mitigation and adaptation action, which has led to greater focus on BCEs (Khan et al. 2025a; 2025b). Governments increasingly support BCE management as a climate adaptation strategy, but many still overlook its potential to also contribute to mitigation goals (Khan et al. 2025b). This is likely due, at least in part, to the fact that national inventories often do not fully account for carbon fluxes in BCE (Chapter 3; Reise, Wissner and Urrutia 2025).

Using internationally agreed methodologies to integrate blue carbon into national greenhouse gas inventories can support the achievement of climate mitigation targets (Chapter 3; Khan et al. 2025a; 2025b). The 2013 Wetlands Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories already provides methodologies for multiple BCE management approaches (IPCC 2014). The 2027 update to the IPCC methodologies is expected to cover coastal wetlands carbon dioxide removal types not included in previous IPCC Guidelines and to provide additional information on mangroves, tidal marshes and seagrass in coastal waters (IPCC 2025). Even so, some countries, particularly developing countries and SIDS, may continue to face challenges in quantifying carbon fluxes due to technical, institutional and financial constraints, as well as limitations in monitoring capacity and data availability (Schindler Murray et al. 2023; Boettcher et al. 2025). International and regional collaborations, such as the International Partnership for Blue Carbon and the Blue Carbon Initiative, are helping to build capacity, but additional financial resources, technical assistance and other support will be needed (see sections 4.5 and 4.6; see also Chapter 3). Using internationally agreed methodologies to integrate blue carbon into national greenhouse gas inventories can support the achievement of climate mitigation targets (Chapter 3; Khan et al. 2025a; 2025b).

4.2.2 Other international legal regimes pertinent to ocean-based climate technologies

Looking beyond the global climate regime, various other international regimes may also apply to the development and deployment of ocean-based climate technologies. For example, BCE management has been addressed under the Ramsar Convention on Wetlands of National Importance and the Convention on Biological Diversity (CBD), among others. Across regimes, there has been a growing recognition of the importance of BCEs for both climate change mitigation and adaptation, as well for addressing biodiversity loss.[10] However, differences in the regimes' coverage, objectives and requirements have resulted in an inconsistent governance landscape that risks undermining coordinated action (He and Cao 2026). Alignment across regimes will become especially important as more countries integrate blue carbon into their National Biodiversity

10 See, for example, Convention on Biological Diversity Decision 16/22: Biodiversity and Climate Change, CBD/COP/DEC/16/22 (1 November 2024).

Strategies and Action Plans (NBSAPs) under the CBD, and into their NDCs under the Paris Agreement. It will also be important to ensure that NBSAPs and NDCs accurately and consistently account for potential changes in BCEs (for example, reduced carbon storage, increased emissions) due to rising temperatures and other climate change impacts (see Chapter 3).

The development of mCDR technologies could also implicate various international agreements and rules of customary international law (see Table 4.1; Webb, Silverman-Roati and Gerrard 2023; Doney et al. 2025). The question of when and how different instruments will apply to different mCDR techniques is often highly uncertain and there is potential for conflicting outcomes. For example, some mCDR techniques that involve adding materials to ocean waters (as with OAE and ocean fertilization, for example) might qualify as both sources of marine pollution and methods of pollution remediation under international law (Webb 2024; Boettcher and Kim 2026). Moreover, differences in where and how the techniques are deployed could result in them being subject to vastly different legal requirements, even where they pose similar risks and benefits (Webb, Silverman-Roati and Gerrard 2023; Webb and Silverman-Roati 2026). As an illustration, a recent study of the mCDR technique of DOC concluded that different international laws may apply depending on whether a DOC system is deployed in coastal areas or the open ocean, the processes it uses to strip carbon dioxide out of ocean waters, and how the carbon dioxide is handled (including whether, where and how it is stored) (Webb and Silverman-Roati 2026).

Agreement	Parties/ Ratifications	Objective/Intent	Relevance to mCDR
UNFCCC	198	Prevent dangerous anthropogenic interference with the climate system	Parties are directed to conserve and enhance greenhouse gas "sinks." mCDR could be one means of doing this.
Paris Agreement	194	Strengthen the global response to climate change	Sets temperature targets which can only be achieved with use of CDR. Parties have called for scaling up ocean-based mitigation action, which could include mCDR specifically.
CBD	196	Promote the conservation of biological diversity and the sustainable use of its components	Parties have issued several non-binding statements addressing "ocean fertilization" and "geoengineering" (a broad term that could include various mCDR techniques). The statements allow for some research but seek to restrict deployment.
UNCLOS	172	Protect and preserve the marine environment	Some mCDR techniques could be viewed as sources of marine pollution under UNCLOS. Includes rules for marine scientific research that could apply to mCDR field trials.
BBNJ Agreement	93	Protect areas beyond national jurisdiction	Provides area-based management tools that could be used to regulate mCDR. Also includes EIA requirements that could ensure robust ex-ante review of mCDR projects.
London Convention	87	Prevent pollution of the sea by the dumping of waste or other matter	Parties have issued several non-binding decisions addressing "ocean fertilization" and "marine geoengineering." The decisions allow for some research but seek to restrict deployment.
London Protocol	56	Prevent, reduce and, where practicable, eliminate pollution caused by dumping	In 2013, Parties adopted an amendment to regulate "the placement of matter into the sea ... for [certain listed] marine geoengineering activities." The amendment allows for some research but seeks to restrict deployment. The amendment has not entered into force as it requires 37 Parties to ratify it. So far, nine have ratified it.

Table 4.1: Key international agreements potentially applicable to mCDR activities (adapted from Silverman-Roati and Webb 2026)

The early stage of mCDR technology development and the resulting uncertainty surrounding the efficacy and impacts of these technologies have led to calls for a precautionary approach (see section 4.3). In a 2008 decision addressing the mCDR technology of ocean fertilization, the Conference of the Parties to the CBD:

> "***requests*** Parties and ***urges*** other Governments, in accordance with the precautionary approach, to ensure that ocean fertilization activities do not take place until there is an adequate scientific basis on which to justify such activities, including assessing associated risks, and a global, transparent and effective control and regulatory mechanism is in place for these activities; with the exception of small-scale scientific research studies within coastal waters. Such studies should only be authorized if justified by the need to gather specific scientific data, and should also be subject to a thorough prior assessment of the potential impacts of the research studies on the marine environment, and be strictly controlled, and not be used for generating and selling carbon offsets or any other commercial purposes."[11]

A second decision, covering so-called "geoengineering activities", a broad category that could include some mCDR techniques (Webb Silverman-Roati and Gerrard 2023), was adopted in 2010. It similarly invited Parties to ensure "in accordance with the precautionary approach ... that no climate-related geoengineering activities that may affect biodiversity take place, until there is...an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks..., with the exception of small-scale scientific research studies."[12] As indicated, both decisions expressly allow some research activities, though there is uncertainty as to what qualifies (Webb, Silverman-Roati and Gerrard 2023). Moreover, the decisions are not legally binding and use soft language, for example requesting or inviting countries to consider certain things. This further undermines their utility as a governance tool.

There have been efforts to develop a binding framework under the 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter (London Protocol), but this has proved challenging. In 2013, the Parties to the London Protocol agreed to an amendment (not yet in force) to regulate "the placement of matter into the sea" for certain listed "marine geoengineering" activities. Only ocean fertilization is currently listed, but the Parties have been discussing listing additional mCDR technologies, namely OAE and biomass sinking (as well as certain marine solar radiation management approaches). This ability to list additional activities, which would then be governed by the amendment, highlights its "capacity to adapt to future scientific and technological developments" which is especially important in an evolving field like mCDR (Brent, Burns and McGee 2019). Even so, there have been challenges in trying to fit this new class of technologies into a long-standing agreement, designed for different activities.

The London Protocol has limited membership (56 countries) and not all mCDR technologies fall within its scope (see, for example, Webb and Silverman-Roati 2026). Moreover, because the Protocol focuses on protecting the marine environment from pollution, the 2013 amendment similarly aims "to protect the marine environment from [mCDR] technologies, not to govern research or development of … [the] technologies per se" (emphasis in original) (Brent et al. 2019). There are unresolved questions about how to distinguish mCDR research from deployment (Brun et al. 2026), how to evaluate the benefits and risks of mCDR technologies (VanderZwaag and Mahamah 2024), how to approach trade-offs (Röschel, 2025b), and how to deal with uncertainty (Cabus 2025). Even assuming that these issues can be resolved, it is notable that, after more than a decade, the 2013 amendment has still not entered into force and appears unlikely to do so in the near-term. Only nine Parties have ratified the 2013 amendment,[13] which is well below the two-thirds majority required for its entry into force.

As the foregoing discussion indicates, while many existing international legal frameworks could apply to mCDR, each has limitations and gaps. Moreover, the different regimes are progressing work on mCDR separately, with little consideration of interactions or overlaps between them (Webb 2024). Technologies with similar risk profiles are approached differently, and gaps and grey areas within and between international regimes may create uncertainty that may delay action and complicate the implementation of environmental and social safeguards. Greater alignment across global climate change, ocean protection and environmental governance regimes is needed to support the responsible development and deployment of ocean-based climate technologies. Achieving such alignment may require adjustments to existing institutional arrangements and enhanced coordination across international frameworks (He and Cao 2026).

Looking ahead, the new BBNJ Agreement includes various tools and structures that could be used to improve international coordination and management of mCDR activities. For example, the BBNJ Agreement's

11 Report of the Conference of the Parties to the Convention on Biological Diversity on the Work of its Ninth Meeting, Decision IX/16, art/ C(4) (2008).

12 Report of the Conference of the Parties to the Convention on Biological Diversity on the Work of its Tenth Meeting, Decision X/33, art. 8(w) (2010).

13 IMO Status Book, https://www.imo.org/en/about/conventions/pages/statusofconventions.aspx

area-based management tools (ABMTs) could provide a global framework for directing where and how mCDR activities take place (Webb 2024; Burns and Webb 2026). The BBNJ Agreement also establishes detailed EIA requirements, which could apply both to mCDR activities occurring in areas beyond national jurisdiction (ABNJ) and to those that have effects in ABNJ (even if they occur in a country's jurisdictional waters). Robust EIA should also ensure a more holistic assessment of the risks and benefits of mCDR (Webb 2024; Boettcher and Brent 2024; Craik and Scott 2026; Burns and Webb 2026). In addition, the BBNJ Agreement's Clearing House Mechanism is being designed to facilitate information sharing and capacity-strengthening on ocean-related topics, and could therefore support greater international transparency and the exchange of diverse knowledge relevant to mCDR assessment and governance (Boettcher and Brent 2024; see also section 4.5). However, scholars have noted that whether the BBNJ Agreement achieves these goals will depend on how it is implemented, and have emphasized the need for work under the agreement to be harmonized with work occurring in other international regimes (Boettcher and Brent 2025; Burns and Webb 2026; Craik and Scott 2026).[14]

4.2.3 Informal governance of ocean-based climate technologies

Beyond formal legal structures, other more informal governance frameworks can also be used to support the responsible development and deployment of ocean-based climate technologies. For example, multi-stakeholder initiatives like the Blue Carbon Initiative bring together governments, Indigenous Peoples, civil society and the private sector to build knowledge on ocean-based climate solutions and support their implementation. International and regional scientific bodies, environmental NGOs and other groups have developed codes of conduct, best practice guides, MRV protocols and other similar documents to help advance safe and responsible ocean-based climate technology development (for example American Geophysical Union 2024; Aspen Institute 2023; Doney et al. 2025; Weighman, Jankowska and Andrews 2026; Nawaz and Belotti 2025; Oschlies et al. 2023). Implementation of these guides and protocols is currently limited, but they may become increasingly important in the future (NASEM 2022; NASEM 2026).

4.3 SOCIAL EQUITY, INCLUSION AND GOVERNANCE IMPLICATIONS

While ocean-based climate technologies may pose social equity risks, they can also create opportunities to enhance livelihoods, strengthen local stewardship, support climate resilience and expand participation in sustainable ocean economies. Potential benefits include income diversification, improved ecosystem stewardship, greater recognition of Indigenous Peoples' and local knowledge systems, and enhanced climate resilience (IPCC 2023). The realization and distribution of these benefits, as well as associated risks, will depend on how ocean-based climate technologies are designed, governed and implemented. Where social and environmental considerations are inadequately addressed, interventions may result in adverse impacts for coastal and ocean-dependent communities, particularly those already experiencing multidimensional poverty. These trade-offs may influence community engagement with ocean-based climate technologies, as well as broader public acceptance. Social equity and inclusion therefore have important governance implications, both for directly affected communities and for wider society. This report, and this section in particular, focuses on coastal and ocean-dependent communities that may be directly affected by technology development and deployment, including those in SIDS (see also Chapter 5).

The importance of social equity considerations is heightened by the fact that ocean-based climate technologies are likely to be developed and deployed within marine and coastal contexts characterized by pre-existing systemic inequities. Coastal communities and ocean-dependent groups, such as small-scale fishers, particularly in SIDS, depend on and manage marine ecosystems for livelihoods, cultural identity and food security, yet often experience multiple and overlapping vulnerabilities (Chapter 5; Basurto et al. 2025). These vulnerabilities are frequently compounded by systemic marginalization and may be further exacerbated by climate change and responses to it.

At the same time, ocean-based climate technologies are emerging within a context of increasing and often competing demands on ocean space and resources, expanding commercial use and allocation of marine resources, and ongoing pressures on marine ecosystems. As noted by Blythe et al. (2026, p. 123):

> "Ocean inequity is growing rapidly as countries and corporations increasingly look to the ocean to meet human demand for resources. Benefits from

14 UNEP is currently supporting the implementation of the BBNJ Agreement through its Regional Seas Programme and related ocean and biodiversity work, providing countries with technical, policy and legal support, capacity building and expertise on ecosystem-based management and area-based conservation. See https://www.unep.org/topics/ocean-seas-and-coasts/regional-seas-programme/about-unep-regional-seas-programme

the world's oceans are accrued by a handful of powerful actors, whereas the burdens of the surging ocean economy, which range from exposure to pollution and toxic waste to the impacts of climate change and biodiversity loss, are borne by the most vulnerable. Many who constitute this group, including Indigenous Peoples, local communities, women and small-scale fishers, are not fully recognized, are excluded from ocean decision-making processes and do not gain a fair share of ocean benefits."

While the extent and distribution of these challenges vary across regions and sectors, the literature highlights the importance of addressing equity considerations in ocean governance.

Given this context, it is important that governance frameworks for ocean-based climate technologies incorporate equity and environmental justice principles. Box 4.1 provides a brief overview of these principles; further detail is available in the Ocean Equity Index framework (Blythe et al. 2026).

4.3.1 Ocean carbon monitoring and data systems

Investments in ocean carbon monitoring and data systems can contribute to more just and equitable outcomes by strengthening scientific knowledge, technical capacity and evidence-based decision-making, particularly in low-income countries and SIDS. Enhanced monitoring capacity can improve understanding of local ocean conditions, support the assessment of climate mitigation outcomes and co-benefits, and enable countries to participate more effectively in the development, governance and evaluation of ocean-based climate technologies. In this way, monitoring systems can help to address existing gaps in scientific infrastructure and to reduce disparities in the production and use of ocean-related data.

Monitoring and data systems can also support transparency, accountability and public trust by providing information on the effectiveness and potential impacts of ocean-based climate technologies. Accessible and reliable data can facilitate stakeholder engagement, support informed decision-making and strengthen the ability of coastal and ocean-dependent communities to participate in governance processes. However, realizing these benefits will require careful attention to issues of data ownership, access, transparency, interoperability and benefit-sharing, as well as sustained investment in technical infrastructure, training and institutional capacity. These challenges may be particularly significant for low-income coastal countries and SIDS, where financial, technical and human resource constraints can limit the ability to generate, manage, analyse and use ocean carbon data effectively (see section 4.5).

Box 4.1: Key equity and justice principles relevant to ocean governance

Recognitional justice relates to whether and how diverse actors, countries, communities and social groups are identified, valued and respected in governance, including their identities, knowledges and practices, as well as tenure and other rights. It is the foundation for other forms of justice.

Procedural justice relates to fairness, openness, inclusivity and quality of decision-making processes, rule-making and institutional governance itself, as well as access to justice (e.g. for restitution). Beyond participation, it requires addressing power asymmetries so that previously marginalized actors, countries, communities, and social groups can equitably shape decisions. At the interface with communities and externally led initiatives, a key operationalizing practice is that of "free, prior and informed consent".

Distributional justice relates to the fairness of outcomes (material and non-material), across groups, countries, space and time. This includes the allocation of resources, benefits and opportunities, as well as risks and burdens from initiatives such as mCDR or Blue Carbon projects.

Equity relates to the subjective concept of fairness in procedural, distributive or other dimensions of ocean governance. The concept of equity is often used in operationalizing justice principles. Achieving equity may require addressing pre-existing inequalities so that historically disadvantaged actors, countries, communities, and social groups receive fair treatment and outcomes.

Sources: Drawn from Bennett et al. (2019), Yadao-Evans et al. 2025; Österblom et al. (2020)

4.3.2 Blue carbon ecosystems

While BCE initiatives bring the promise of local benefits, such as income generation, livelihood diversification, ecosystem restoration and climate resilience, these are not guaranteed. Achieving them requires governance that is designed with equality and justice principles in mind and, among other things, ensures effective recognition of local tenure and inclusive and equitable decision-making, benefit-sharing and risk-sharing. Noting that interventions in ocean contexts have often not incorporated these principles, studies (including Atchison, Foster and Bell-James 2024; Yadao-Evans et al. 2025; Lawless et al. 2026a, b) have warned of significant social and gender risks from ocean-based climate technology development. The risks include:

- Ocean grabbing, a term used in the literature to describe the exclusionary appropriation of marine space and resources, has been identified as a potential risk where traditional and customary tenure rights are insufficiently recognized or protected. Some studies have cautioned that BCE projects could, under certain governance arrangements, contribute to processes described as dispossession of customary rights. For example, Lawless et al. (2026a, p. 761) warn that BCE projects risk "… being the latest wave of dispossession as projects are typically foreign-led and require permanence (usually 100 years for carbon storage), meaning rightsholders forgo their rights to use, access and manage resources (known as 'tenure'), losing power and agency to govern their territories and benefit from vital livelihood services" (Lawless et al. 2026a, p. 761).

- Failure to recognize and value local stewardship and traditional knowledge systems, thus missing the opportunity to build on the strengths of community management and practices, and limiting legitimacy and effectiveness.

- Top-down interventions lacking meaningful community decision-making power and leadership, compounded by a lack of transparency (due, for example, to inaccessible project information).

- Compounding marginalization of women, especially women from low-income, Indigenous or other already marginalized groups. For example, women may be particularly affected by loss of access to food resources, reduced decision-making autonomy and increased unpaid care and resource-management responsibilities. In some contexts, such changes may exacerbate existing gender inequalities and vulnerabilities, including vulnerability to gender-based violence.

- Insufficient participation in decision-making processes. Conversely, meaningful and transparent engagement can strengthen local ownership, improve project outcomes and enhance the legitimacy of BCE initiatives.

- Inequitable distribution of benefits and costs, with economic revenues potentially flowing to external actors rather than local communities, even as those communities bear costs from reduced access to the resources on which they depend for subsistence, livelihoods and cultural values. Additionally, the commodification of resources can attract new, more powerful players who displace local community members from their traditional livelihoods.

To help mitigate these risks, governance frameworks can draw on the principles outlined in the Ocean Equity Index, including the protection of local tenure rights, the promotion of local leadership and agency, and transparent and equitable engagement processes.

4.3.3 Marine carbon dioxide removal

mCDR technology development remains at an early stage. However, if proven effective in contributing to climate change mitigation, mCDR approaches could help reduce climate-related risks to coastal communities, including those associated with sea level rise. Certain mCDR technologies may also generate environmental co-benefits, such as reductions in local ocean acidification, with potential benefits for fisheries and the communities that depend on them.

At the same time, mCDR projects may give rise to social equity, inclusion and governance challenges at both global and local scales. From a global perspective, the development and deployment of mCDR technologies may require substantial financial, technical and institutional resources. As a result, patents, expertise, decision-making influence and economic benefits could become concentrated in countries and regions with greater financial, technological and institutional capacity, potentially reinforcing existing disparities in access to climate technologies and their associated benefits. Addressing these risks may require governance arrangements that support equitable research partnerships,

technology transfer, capacity-building, knowledge-sharing and fair benefit-sharing mechanisms.

These global equity considerations also have important local dimensions. As Röschel (2025b, p. 4) notes, "mCDR may exacerbate global inequities if wealthy nations deploy these technologies in ways that displace environmental risks onto vulnerable communities". The social implications of mCDR deployment are likely to vary across technologies and contexts, but may include effects on access to marine resources, livelihoods, cultural practices, food security, human health and existing patterns of social and gender inequality. Key social and gender considerations associated with selected mCDR techniques are summarized in Table 4.2.

The distribution of benefits and burdens associated with mCDR will depend not only on the technologies employed and the scale of deployment, but also on the governance frameworks through which decisions are made and implemented. Inclusive and participatory governance processes, together with robust environmental and social impact assessment, can help to identify and address potential risks before deployment, and ensure that affected communities are meaningfully engaged in decision-making. Existing governance frameworks, including the BBNJ Agreement, provide mechanisms that may support these objectives, although further strengthening and implementation may be required (Burns and Webb 2026; Craik and Scott 2026).

The risks identified in Table 4.2 are potential and context-dependent. Their occurrence and magnitude will vary according to local environmental, social, governance and regulatory conditions.

mCDR type	Social risks include	Gender risks include
Direct ocean capture	Requires substantial maritime and coastal infrastructure, meaning the footprints can physically displace small-scale artisanal fishers and Indigenous maritime communities from traditional waters and ancestral sites. Current expert-led governance approaches may place greater emphasis on technical and scientific expertise, potentially limiting the incorporation of Indigenous and local knowledge systems unless deliberate measures are taken to ensure inclusion.	Ocean engineering, maritime shipping and chemical innovation sectors are heavily male-dominated. Similar to social risk, existing gender imbalances in technical and maritime sectors may contribute to the underrepresentation of women in decision-making processes and reduce recognition of women's knowledge and expertise unless inclusive governance approaches are adopted.
Ocean alkalinity enhancement	OAE may require scaling up terrestrial mining, crushing and transporting of alkaline minerals (e.g. olivine). These localized environmental burdens may disproportionately affect marginalized or rural communities, including some communities in developing countries.	When localized industrial pollution impacts a community, the burdens of managing family health typically fall unevenly on women (systemic gender divisions of unpaid labour). This increases women's time poverty, restricting their ability to pursue education or paid work.
Ocean fertilization and biomass sinking	Nutrient addition or biomass sinking may change marine food webs, oxygen dynamics and ecosystem functioning, with potential consequences for fisheries and coastal livelihoods. Changes may alter nutrient availability and marine food webs, potentially affecting fisheries productivity and food security beyond the immediate area of deployment. There is also a health and safety risk in terms of unintentional harmful algal blooms of opportunistic toxin-producing species.	If biotic mCDR alters local ecology or prompts toxic habitats in nearshore waters, women's important food and economic niches (such as tidal gleaning areas) are directly affected, undermining health and economic empowerment Existing social and household power dynamics may influence how food resources are distributed, potentially resulting in disproportionate nutritional impacts on women and girls. Wild fish stock disruptions may thus contribute to micronutrient deficiencies, malnourishment and anaemia among women and girls.

Table 4.2: Social and gender risks associated with biological and chemical mCDR options

Sources: Chapter 3; Boettcher et al. (2021); Oschlies et al. (2025); Brun et al. (2026).

4.4 MONITORING, STANDARDS, AND CERTIFICATION

Ocean-based climate technologies require governance arrangements that are proportionate to their different levels of maturity, spatial scale, reversibility, and environmental and social risks (see sections 4.2 and 4.3). Table 4.3 highlights some key considerations for governing the three ocean-based climate technology categories examined in this report.

For BCE management in coastal areas, it will be especially important to ensure that existing resource rights and uses are not displaced. Environmental safeguards and meaningful stakeholder participation are therefore important, as are clear arrangements for stewardship, access and benefit-sharing. For BCE management, monitoring should consider carbon sequestration alongside ecosystem condition and longer-term social outcomes (see also Chapter 3). These requirements are consistent with the need for long-term restoration programmes and environmental safeguards identified for mangroves and coastal wetlands (Lo 2026; UNEP FI and GIZ 2023).

For mCDR, governance needs to reflect the early stage of development of most proposed technologies. Robust interdisciplinary assessment is required before large-scale deployment, particularly in relation to carbon storage permanence, additionality, leakage, and wider ecological and social impacts (Muri et al. 2025; Baatz et al. 2025). Current MRV systems are not sufficiently mature to support credible large-scale implementation (Muri et al. 2025). International MRV standards are therefore increasingly important (Hoffman et al. 2026; Doney et al. 2025; Muri et al. 2025). Observational networks, modelling and environmental monitoring will also be necessary to strengthen both regulatory systems and the scientific basis for mCDR and natural marine carbon flux monitoring (Muri et al. 2025).

For ocean carbon monitoring and data systems, governance should address issues relating to data quality, interoperability, access, long-term operation and ownership of monitoring systems.

Technology	Safeguards	Ownership and tenure	Monitoring
Ocean carbon monitoring and data systems	Protect data integrity, transparency and equitable access to information.	Clarify ownership of infrastructure and data, including data sovereignty.	Maintain long-term observational networks, modelling and verification capacity.
Blue carbon ecosystems	Protect ecosystem integrity, livelihoods and meaningful stakeholder participation.	Recognize customary and statutory tenure, access, stewardship and benefit-sharing.	Monitor carbon, permanence, ecosystem condition and social outcomes.
Marine carbon dioxide removal	Assess ecological, fisheries, food security and wider social risks before scaling.	Clarify responsibility for deployment areas, infrastructure and cross-border effects.	Require robust MRV for permanence, additionality, leakage and ecological impacts.

Table 4.3: Key considerations for governing ocean-based climate technologies

Sources: United Nations (2024); OECD (2024a); OECD (2024b).

Standards and certification can provide supporting mechanisms for environmental assessment, verification, traceability and social safeguards. While existing schemes (see Table 4.4) provide useful governance precedents, none were developed specifically for carbon removal, ocean carbon accounting or the unique ecological uncertainties associated with mCDR technologies. As a result, significant adaptation or supplementary standards are likely to be required. Overall, these schemes provide useful foundations for developing more coherent and technology-specific standards for the responsible deployment and monitoring of ocean-based climate technologies.

Standard/ certification/ governance frameworks	Scope	Relevance to ocean-based climate technologies	Dimensions	Reference
Marine Stewardship Council (MSC) Fisheries Standard	Wild capture fisheries	Ecosystem and fisheries safeguards where technologies affect marine resources.	Environmental; Governance	MSC (2025)
MSC Chain of Custody Standard	Seafood supply chains	Precedent for traceability and integrity of verified sustainability claims.	Governance; Economic	MSC (2025)
Certified Seafood International (CSI)	Fisheries management	Independent verification precedent for responsible marine resource management.	Environmental; Governance	CSI (2025)
International Electrotechnical Commission (IEC) TC 114 Standards	Marine energy technologies	Technical precedent for design, performance and environmental assessment of marine technologies.	Environmental; Governance; Economic	IEC (2025)
European Marine Energy Centre (EMEC) Validation	Marine technology testing	Precedent for independent testing and performance verification.	Environmental; Economic; Governance	EMEC (2025)
Bureau Veritas NI 631	Marine energy systems	Certification precedent for safety, performance and environmental requirements for marine installations.	Environmental; Governance; Economic	Bureau Veritas (2025)
EU CATCH Digital Catch Certification System	Digital fisheries verification	Relevant precedent for digital traceability, regulatory compliance and verification systems.	Governance; Environmental; Economic	European Commission (2025)
Fairness, Integrity, Safety, Health (FISH) Standard for Crew	Marine labour conditions	Social safeguard precedent for recruitment, health, safety and worker welfare.	Social; Governance	FISH Standard (2025)
Climate Bonds Marine Renewable Energy Criteria	Climate finance	Precedent for linking marine technologies with eligibility requirements for climate finance.	Environmental; Economic; Governance	Climate Bonds Initiative (2025)
UNEP Sustainable Blue Economy Transition Framework*	Ocean governance	Cross-cutting framework for integrated environmental, social and economic governance.	Environmental; Social; Economic; Governance	UNEP (2026)
Best Aquaculture Practices (BAP)	Aquaculture	Additional precedent for environmental and social safeguards, traceability and auditable performance.	Environmental; Social; Governance	BAP (2026)
Green Marine Environmental Certification	Shipping, ports and maritime operations	Relevant model for verified environmental performance of marine operations and infrastructure.	Environmental; Governance	GM (2026)

Table 4.4: Standard and certification system examples

*Not a certification scheme, but is a cross-cutting governance framework.

4.5 KNOWLEDGE AND CAPACITY GAPS

Effective governance of ocean-based climate technologies depends on an evidence base that is not yet uniformly available. Policymakers face (among other things) uncertainties in carbon dynamics and environmental impacts, limitations in observational and modelling capability, and MRV systems, and marked geographic differences in the capacity to generate and interpret evidence. These gaps directly shape the information available to policymakers considering emerging ocean-based climate technologies, making it more difficult for them to assess risks, and design and implement safeguards that advance responsible technology development.

Capacity development requires sustained investment in people and institutions, as well as equipment and infrastructure. Developing countries need scientific and technical expertise to design research, operate observational systems, analyses and model data, assess emerging technologies and participate in the methodological processes through which evidence is translated into policy. Gaps in technical expertise, institutional infrastructure and trained personnel constrain effective technology

transfer and sustain the monitoring capacity gap in the Global South (Garcia-Soto 2026; Boettcher and Brent 2024). Institutions that lack the capacity to interpret, validate or challenge evidence produced elsewhere remain dependent on external methodologies, limiting their ability to shape the evidence base used in national and international decision-making.

This capacity will need to be developed across all three technology areas, including ocean carbon monitoring and data systems, BCEs and mCDR. Expanding locally led research programmes, strengthening universities and developing regional research networks can increase the ability of developing countries to generate evidence relevant to their own contexts. This is particularly important for mCDR, where the evidence base remains geographically limited and environmental responses may be context-specific: greater geographic diversity in research improves understanding of how interventions perform under different conditions while enabling research-hosting countries to help define the questions being asked (Doney et al. 2025).

Knowledge and capacity gaps will evolve as research progresses. How evidence is generated also shapes where financing flows: without a localized understanding of where research needs are greatest, there is a risk that investment will be concentrated where capacity already exists, rather than where it is most needed. This concentration is already visible in ocean innovation funding: Latin America and the Caribbean captured just 3.8 per cent of global ocean startup investment in 2024, against 43.5 per cent for North America and 30.1 per cent for Europe, even as the region invests only 0.6 per cent of GDP in research and development (CAF, WEF and WRI 2026), a distributional gap addressed further in the next section of this chapter.

4.6 FINANCE, INVESTMENT AND ENABLING MARKET MECHANISMS

Globally, only US$13 billion, representing less than 1 per cent of official development assistance and philanthropic funding, was directed towards ocean-climate sustainability over the last decade. This remains far below the estimated US$550 billion required annually to secure long-term ocean health (Thiele et al. 2025). Some key financing mechanisms available are outlined below, and Table 4.5 provides a summary along with some examples.

- **Thematic bonds:** Debt instruments that raise capital through fixed-income markets, with proceeds ring-fenced for eligible ocean projects. These instruments can support BCE conservation and restoration activities, fund mangrove and seagrass restoration, finance early-stage mCDR infrastructure and support large-scale ocean monitoring systems, including buoys and sensor networks.

- **Outcome-based finance:** Links disbursements or investor returns to independently verified environmental outcomes. Examples include certified blue carbon credits, sustainability-linked loans and bonds, payments for ecosystem services, and biodiversity or water-quality credits. For mCDR, sustainability-linked instruments could in future be tied to verified volumes of carbon dioxide removed as technologies and compliance markets mature.

- **Risk mitigation tools:** Parametric insurance and catastrophe bonds provide rapid payouts when predefined weather or environmental thresholds are exceeded. These instruments transfer climate-related risks to insurers or capital markets, thereby improving resilience. Ocean monitoring systems that provide real-time environmental data are often important enabling components of these mechanisms.

- **Fiscal and economic instruments:** Debt-for-nature swaps, taxes and fees can generate funding for ocean conservation and climate action. Savings generated through debt swaps are often directed towards ocean monitoring systems, data infrastructure and activities that support compliance and environmental management.

- **Dedicated funds and facilities:** Public finance remains the largest contributor to blue finance. Blended finance vehicles can help de-risk investments and mobilize private capital. Such facilities can support restoration pipelines for BCE projects, early-stage mCDR pilots and the deployment of ocean monitoring infrastructure and data systems.

Category	Subcategory	Description	Recent examples
Thematic bonds	Development bank and FI-issued blue bonds	Debt instruments issued by multilateral development banks or financial institutions to raise capital, to attract private investors at low cost	Market: $15.25 billion by mid-2025 (World Bank 2025b) and is projected to grow to $70 billion by 2030 (Pandey 2025). Banco del Estado de Chile's CHF 100 million Swiss blue bond (October 2025) to fund ocean conservation and sustainable fishing activities (Cleary Gottlieb Steen & Hamilton 2025).
Outcome-based finance	Biodiversity credits (including payments for ecosystem services)	Raises finance via biodiversity/water-quality and blue carbon credits tied to ecosystem outcomes	Blue carbon credit market valued $2.8 billion (2025) and estimated to grow to $8.9 billion (2034) (Dataintelo 2025).
	Program-for-results (PfoR)	Disburses funds to national governments in tranches tied to verified progress on policy reforms and sectoral milestones	Morocco – Blue Economy Program-for-Results Project to strengthen selected sectors for a climate-resilient blue economy (World Bank 2022).
	Article 6.2 / Internationally transferred mitigation outcome (ITMO) carbon transfers	Enables international transfer of verified carbon-removal credits under Paris Agreement article 6.2	Norway–Switzerland pilot ITMO transfer in June 2025 (ClimeFi 2025). CO2 stored 2,600m below North Sea seabed (Inherit Carbon Solutions, no date).
Risk mitigation tools	Parametric insurance	Automatic payouts triggered by predefined physical thresholds; lowers disaster recovery costs	Mesoamerican Reef Insurance Programme launched in 2021 by the Mesoamerican Reef Fund (MAR Fund) finances rapid emergency response and restoration for coral reefs in Mexico, Belize, Guatemala and Honduras following hurricane impacts (MAR Fund 2020).
	Catastrophe bonds	Risk-linked bonds financing coastal and blue infrastructure resilience	World Bank issued a catastrophe (cat) bond that provides the Government of Jamaica with $150 million in financial protection for four hurricane seasons (2024–27) (World Bank 2025a).
Fiscal and economic instruments	Sovereign debt swaps	Restructures sovereign debt into conservation funding	Galápagos swap in Ecuador: $1.6 billion in 2023 (IMF 2024). Bahamas Debt-for-Ocean-Conservation Swap: $120 million for mangroves/ marine protected areas (MPAs) in 2024 (Inter-American Development Bank 2024).
Dedicated funds and facilities	Multilateral and development bank funds	Combines public/concessional capital to attract private investment and close the financing gap; de-risks first-of-kind technology deployment and unlocks private investment	PROBLUE Multi-donor Trust Fund; Green Climate Fund committed $1.5 million (targeting $300 million+) to Blue Halo S, Indonesia (2022) for protection of BCEs and MPAs (Green Climate Fund 2022). One Ocean Finance Facility to mobilize diverse sources of capital and deploy them through blended finance instruments into investable pipeline of projects across ocean-dependent sectors (United Nations Environment Programme 2026).
	Public funding	Capital provided directly by governments or bilateral donors typically as grants, concessional loans or guarantees	$24 million for mCDR research funding in the United States (National Oceanic and Atmospheric Administration 2023). SEAO2-CDR project funded by EU/UK Research and Innovation (SEAO2-CDR, no date).
	Private investment funds	Commercially driven vehicles to deploy private equity and market-rate capital into ocean economy	Ocean 14 Capital Fund mobilized €200 million for investment in marine ecosystems and marine food security in 2024 (Ocean 14 Capital 2024).

Table 4.5: Summary description and recent examples of ocean-climate project financing



Despite the growing range of financing instruments available, significant barriers continue to constrain investment in ocean-based climate technologies. Mobilizing private finance requires well-defined blue financing taxonomies, standardized key performance indicators (KPIs) and measurement of ocean-related financial risks. Initiatives like the Ocean Investment Protocol, a framework for financial institutions, (re)insurers, industries, governments and development finance institutions, can help unlock private capital towards a Sustainable Ocean Economy (UNEP Finance Initiative and UN Global Compact 2025).

Attention must be paid to strengthening institutional capacity, technical support and coastal community inclusion (see sections 3 and 4). Dedicated ocean technology programmes within the CTCN and similar mechanisms can help close these gaps. For SIDS and least developed countries (LDCs), strengthening access to ocean-based climate technologies remains an important component of capacity-building and technology transfer efforts. Possible approaches discussed in the literature include preferential licensing arrangements, patent pools and targeted intellectual property flexibilities to facilitate technology diffusion while maintaining incentives for innovation (Schmidt 2025). Such approaches could help improve access to relevant technologies, knowledge and technical

expertise while supporting the development of local capabilities for technology adaptation, deployment and maintenance. Any such measures would need to be designed in a manner that is consistent with applicable international legal frameworks and that balances innovation incentives with broader sustainable development objectives.

Marine projects face environmental, operational, technological, regulatory and performance risks, as previously discussed. In the case of mCDR, voluntary carbon markets currently represent one of the principal commercialization pathways (Jennerjahn et al. 2026). However, these markets remain relatively small and have experienced limited growth in recent years. Government support is therefore likely to remain important for scaling mCDR deployment. Integrating mCDR into compliance markets, such as emissions trading systems, represents one possible policy pathway. Similarly, cooperative approaches under article 6.2 of the Paris Agreement could help stimulate demand and attract investment in BCE and mCDR projects.

A number of challenges continue to constrain investment. These include MRV complexity, uncertainty regarding permanence and reversal risks, and concerns regarding environmental and social safeguards (Doney et al. 2025). Projects will require credible additionality assessments, reversal-risk mechanisms, transparent financial management, independent oversight, equitable benefit-sharing arrangements, and robust environmental and social safeguards. Credible and independently verifiable MRV systems, including ocean observation and digital ocean platforms capable of supporting real-time monitoring and predictive modelling, will be important for scaling investment and improving accountability. Examples include the European Digital Ocean System, which provides a single entry point for high-quality ocean data, and the European Digital Twin Ocean, which is expected to be fully operational by 2030 (European Commission 2026). Similarly, scaling insurance products and lowering premiums will require standardized approaches to ecosystem valuation and risk-pooling, while over-reliance on volatile carbon revenue remains a concern. Overall, improved data, standardized methodologies and stronger MRV frameworks can help scale BCE projects (International Finance Corporation 2023).

4.7 PATHS FORWARD WITH INTERNATIONAL COOPERATION

Across all aspects of governance and policy, increased international cooperation will be important to support the responsible development, deployment and transfer of ocean-based climate technologies, while maintaining robust environmental and social safeguards. Several existing forums and mechanisms could be leveraged to strengthen such cooperation.

As discussed in section 4.2, action is needed at the global level to improve coordination across the various international agreements relevant to ocean-based climate technologies. The new BBNJ Agreement incorporates several institutional mechanisms that could support this objective, including a Clearing House Mechanism designed to facilitate information sharing, technical cooperation and capacity-building on ocean-related issues. This mechanism could help foster more coordinated international engagement on developing and deploying ocean-based climate technologies. While the BBNJ Agreement is particularly relevant to activities in ABNJ, it may also apply where activities undertaken within national waters have implications for ABNJ (Burns and Webb 2026; Boettcher and Brent 2026). Given this broad scope, the institutional frameworks established under the agreement could play an important role in advancing international cooperation.

At the regional level, regional seas conventions can support cooperation among neighbouring States to manage and protect shared marine environments. They can help translate global principles into regionally tailored approaches to environmental protection, monitoring, and coordinated ocean management, which may be particularly important where BCE activities, mCDR projects or ocean monitoring systems span multiple jurisdictions. Scientific cooperation can also be strengthened through initiatives associated with the United Nations Decade of Ocean Science for Sustainable Development (Ocean Decade), which support shared observation systems, data exchange, research capacity and science-policy collaboration.

For SIDS and other capacity-constrained countries, South-South and triangular cooperation remain important complements to formal governance mechanisms. Knowledge exchange, technical training and institutional partnerships can strengthen ocean monitoring, data management and technology maintenance capabilities, while also supporting data sovereignty and greater national ownership of marine information systems (United Nations 2024; OECD 2024a; 2024b).

Ultimately, international cooperation is likely to be most effective when it combines scientific collaboration, coordination with national programmes, financing support and locally led capacity development, enabling countries to participate not only as recipients of technology, but also as active contributors to its development, deployment and governance.

5.

Ocean-based Climate Technologies in SIDS

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CHAPTER HIGHLIGHTS

- SIDS are highly exposed to climate-related risks despite contributing less than 1 per cent of global greenhouse gas emissions, with sea level rise, warming, ocean acidification, extreme events and ecosystem degradation threatening livelihoods, infrastructure, freshwater security, cultural heritage and habitability.
- BCEs (including mangrove restoration, reef rehabilitation and integrated sea wall vegetation systems) offer important adaptation, mitigation, biodiversity and community resilience co-benefits when designed for local contexts.
- Emerging ocean-based climate technologies, including mCDR, ocean observing systems, satellite-based monitoring, artificial intelligence (AI)-enabled risk modelling, and citizen science initiatives present opportunities for SIDS, but require rigorous safeguards, MRV and long-term operational support.
- Data access, interoperability, bathymetry, ocean intelligence and localized climate information systems are foundational enabling conditions for selecting, adapting and sustaining appropriate OCI technologies across SIDS.
- Technology transfer in SIDS depends on sustained human and institutional capacity, regional cooperation, peer learning, co-design with communities, alignment with traditional knowledge and Indigenous governance systems, and long-term partnerships, rather than short-term pilot projects.
- Structural barriers – including constrained fiscal space, high debt burdens, limited administrative capacity, fragmented financing modalities and official development assistance (ODA) eligibility rules based on income rather than vulnerability – continue to restrict access to climate and ocean finance for SIDS.
- Scaling ocean-based climate technology solutions for SIDS requires more accessible, predictable and grant-based adaptation and loss and damage finance, alongside innovative instruments such as blue bonds and debt-for-nature swaps that are designed to reduce transaction costs and support nationally led priorities.

5.1 INTRODUCTION

SIDS are among the countries most exposed to climate change impacts, with significant implications for communities, livelihoods, economies and marine ecosystems. This chapter examines the opportunities and challenges associated with ocean-based climate technologies in SIDS contexts. It explores the climate and ocean-related risks facing SIDS, reviews progress in the development and application of relevant technologies, and assesses the structural, financial and capacity-related barriers that may constrain their uptake. The chapter also identifies technology needs, enabling conditions for effective technology transfer, and policy and financing priorities that could support the equitable and sustainable deployment of ocean-based climate technologies in SIDS.

5.2 CLIMATE-RELATED RISKS IN SIDS

SIDS are home to 70 million people, accounting for less than 1 per cent of the global population (Vousdoukas et al. 2023) (Figure 5.1). Despite contributing less than 1 per cent of global greenhouse gas emissions, these heterogeneous nations, comprising 39 United Nations Member States and 18 non-member States or Associate Members (United Nations Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States [UN-OHRLLS], no date), are among the regions most vulnerable to climate change impacts, facing immediate climate-related hazards as well as significant long-term risks associated with warming temperatures, sea level rise and ecosystem change (Gordon-Strachan et al. 2024).

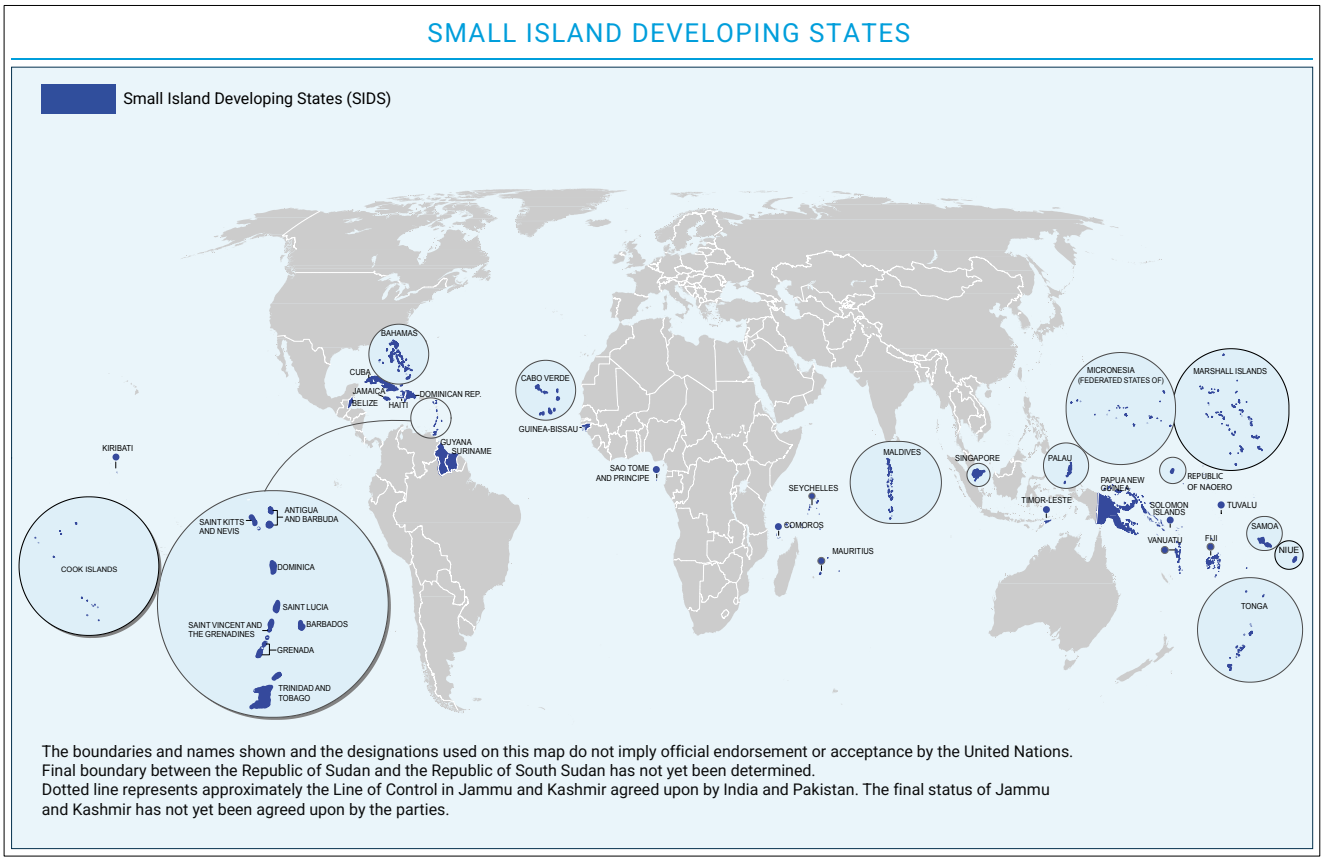


Figure 5.1: SIDS map including 4 atoll nations (Kiribati, Marshall Islands, Tuvalu and Maldives), 14 volcanic islands (Cabo Verde, Comoros, Sao Tome and Principe, Dominica, Grenada, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Fiji, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu) and 4 continental countries (Belize, Guinea-Bissau, Guyana, Suriname).

Climate change in SIDS is evidenced by a robust warming trend. In the Western Pacific and Caribbean regions, surface ocean temperatures have consistently increased over recent decades, with regional warming trends ranging from ~0.15°C to 0.25°C per decade (IPCC 2021). There is a clear projected trend indicating that SIDS across the Caribbean, East Atlantic and Pacific regions will experience continued surface air and ocean warming through to 2100 (IPCC 2021). Future trends in rainfall are currently difficult to project due to high inter-annual and decadal variability, driven by remote factors such as the ENSO or lack of sufficient data (Mycoo et al. 2022). Projections determine that the West/North Caribbean, Central Pacific and Southwest Indian Ocean will experience a drying trend, while the West Pacific and East Caribbean will be slightly wetter or will experience more extreme seasonality (Mycoo et al. 2022).

Furthermore, islands within SIDS are experiencing relative sea level rise that varies significantly by region, with observed rates between 1993 and 2014 ranging from 2.5 millimetres per year in the Western Caribbean up to 11 millimetres per year in the Western Tropical Pacific. By 2100, future levels are projected to rise between 0.28 and 0.82 metres under a low-warming scenario (1.5°C) and could reach up to 1.00 metre under high-emission scenarios (such as RCP8.5) (Mycoo et al. 2022). In addition, SIDS are experiencing sea level rise, which will be exacerbated by the increasing frequency and intensity of extreme events such as storm surges, wave-driven flooding and typhoons. Rapid ocean acidification and deoxygenation are also impacting SIDS (Asch et al. 2018; Mycoo et al. 2022), while the severity of tropical cyclones is intensifying, in both the North Atlantic (relevant for Cabo Verde) and South Pacific (Knutson et al. 2019; Kossin et al. 2020).

The vulnerability of SIDS is varied. While low-lying atolls face severe risks to habitability, freshwater security and critical infrastructure arising from sea level rise and coastal inundation, volcanic and mountainous islands are experiencing increased exposure to landslides, flooding and ecosystem shift. Despite this variation, the vulnerability of SIDS is deeply rooted in shared physical and geographical realities, such as limited land area and extreme isolation (Oppenheimer et al. 2019). Moreover, this vulnerability is further exacerbated by the fact that their primary economic activities, including agriculture, tourism and fisheries, are significantly sensitive to environmental conditions (IPCC 2019; Panwar et al. 2023; Havea et al. 2024). Remote geographies result in high import and export costs, as well as high dependence on international trade. Combined with small populations, this leaves these nations exposed to external economic shocks. Moreover, their fragile land and marine ecosystems are exceptionally susceptible to biodiversity loss (Mycoo et al. 2024). In many SIDS economies, biodiversity-dependent industries such as fisheries and tourism account for more than half of the national gross domestic product (GDP) (UNEP 2014; Thomas et al. 2020; Havea et al. 2024), while biodiversity holds profound aesthetic and spiritual value, serving as a fundamental pillar of their cultural identity (IPCC 2023).

5.3 CLIMATE-OCEAN IMPACTS: ECOLOGICAL AND SOCIOECONOMIC IMPLICATIONS

Climate impacts on SIDS are differential, arising from multiple, interacting hazards that interact with varying levels of exposure and vulnerability across the islands. On average, to date, SIDS have been experiencing annual losses that reach 9 per cent of their GDP due to coastal disasters (Global Facility for Disaster Reduction and Recovery (GFDRR) no date). In July 2024, Hurricane Beryl swept past Jamaica as an unprecedented early-season Category 4 storm, causing extensive destruction to critical infrastructure and agriculture. Beryl devastated over 80 per cent of crop yields in the southern breadbasket parishes of Jamaica, resulting in damages and economic losses equivalent to nearly 2 per cent of the nation's GDP (Economic Commission for Latin America and the Caribbean [ECLAC] 2024).

Between 2000 and 2022, extreme weather events attributable to climate change caused thousands of deaths and billions of dollars in economic losses across SIDS (Panwar et al. 2023), while rising temperatures have led to increased heat-related mortality and vast losses in potential labour hours (for example, over 4.4 billion hours were lost in 2023), strongly impacting the agriculture and construction sectors (Gordon-Strachan et al. 2024). By 2100, climate change is projected to amplify direct economic damages from coastal flooding by more than 14 times under high-emission scenarios, potentially costing tens of billions of dollars annually (Vousdoukas et al. 2023).

Coastal flooding driven by sea level rise leads to saltwater intrusion into coastal aquifers. This is drastically reducing the availability of fresh groundwater, putting at risk water security in SIDS (IPCC 2019; 2022; Zamrsky, Oude Essink and Bierkins 2024). Biodiversity is also heavily threatened by ocean warming and acidification, declining dissolved oxygen concentrations and reduced net primary production, which could result in substantial declines in marine biodiversity and localized species losses in some regions (Asch et al. 2018). Severe coral bleaching and mass mortality events are becoming more frequent (McField 2017; Raoult et al. 2025; Doherty, Johnson and Goodbody-Gringley 2025). Degradation of reef, mangrove and seagrass systems is associated with reduced wave attenuation capacity, which correlates with increased coastal erosion and storm exposure in SIDS (IPCC 2019; 2022). As a result, the loss of healthy reefs, mangroves

and seagrasses eliminates crucial natural barriers that attenuate wave energy, leaving coasts in SIDS exposed to severe erosion and storm impacts (IPCC 2019; 2022).

In Fiji, for example, mangrove extent declined by 1,135 hectares between 2001 and 2018, with tropical cyclones accounting for 77 per cent of this loss (Cameron et al. 2021a). Mangrove areas were expected to be reduced by between 30 and 50 per cent due to coastal development, aquaculture expansion and overharvesting (Cameron et al. 2021b). In the Caribbean, field-based stock-change analyses in the Dominican Republic showed that converting mangrove forest to abandoned shrimp ponds reduced ecosystem carbon stocks from 706–1,131 megagrams of carbon per hectare (Mg C ha^{-1}) to approximately 95 Mg C ha^{-1}, generating potential emissions of 2,244–3,799 megagrams of carbon dioxide equivalent per hectare (Kauffman et al. 2014). The BCE loss has economic consequences. For Grenada, blue carbon habitat decline is projected to generate welfare losses of US$5.4–19.4 million over 50 years, under a business-as-usual scenario (McHarg et al. 2022).

Climate change impacts in SIDS extend far beyond quantifiable economic damages, deeply affecting the cultural and social fabric. Extreme events and coastal erosion destroy cultural heritage sites, ancestral lands and Indigenous knowledge (IPCC 2019; UNFCCC 2024). In addition, flooding and resource scarcity are reducing habitability and increasing the likelihood of migration, planned relocation and displacement in some contexts. This causes profound psychological distress, threatening social cohesion, loss of cultural identity and inequitable outcomes (Gussmann and Hinkel 2020; Kelman 2015; Cassin, Melindi-Ghidi and Prieur 2022).

Coastal economies face cascading socioeconomic crises due to compound risks, where marine heatwaves interact with deoxygenation and ocean acidification to trigger harmful algal blooms. Due to their smaller economies and high reliance on BCEs, isolated climate hazards in SIDS frequently multiply to impact small-scale fisheries, aquaculture and local food security. Droughts, heatwaves and extreme storms severely damage crops, while ocean warming and coral reef degradation are projected to cause declines in marine fisheries catch potential (≥ 50 per cent declines in maximum catch potential in Pacific Island countries and territories) (Asch et al. 2018), a vital source of protein and economic revenue for SIDS (Boyd, McNevin and Davis 2022). These impacts to blue ecosystems are exacerbated in SIDS by extreme weather events and the warming of sea surface temperatures, and due to the heavy reliance on marine resources in these States. Despite these significant impacts, SIDS possess globally important BCEs that present opportunities for both climate mitigation and adaptation.



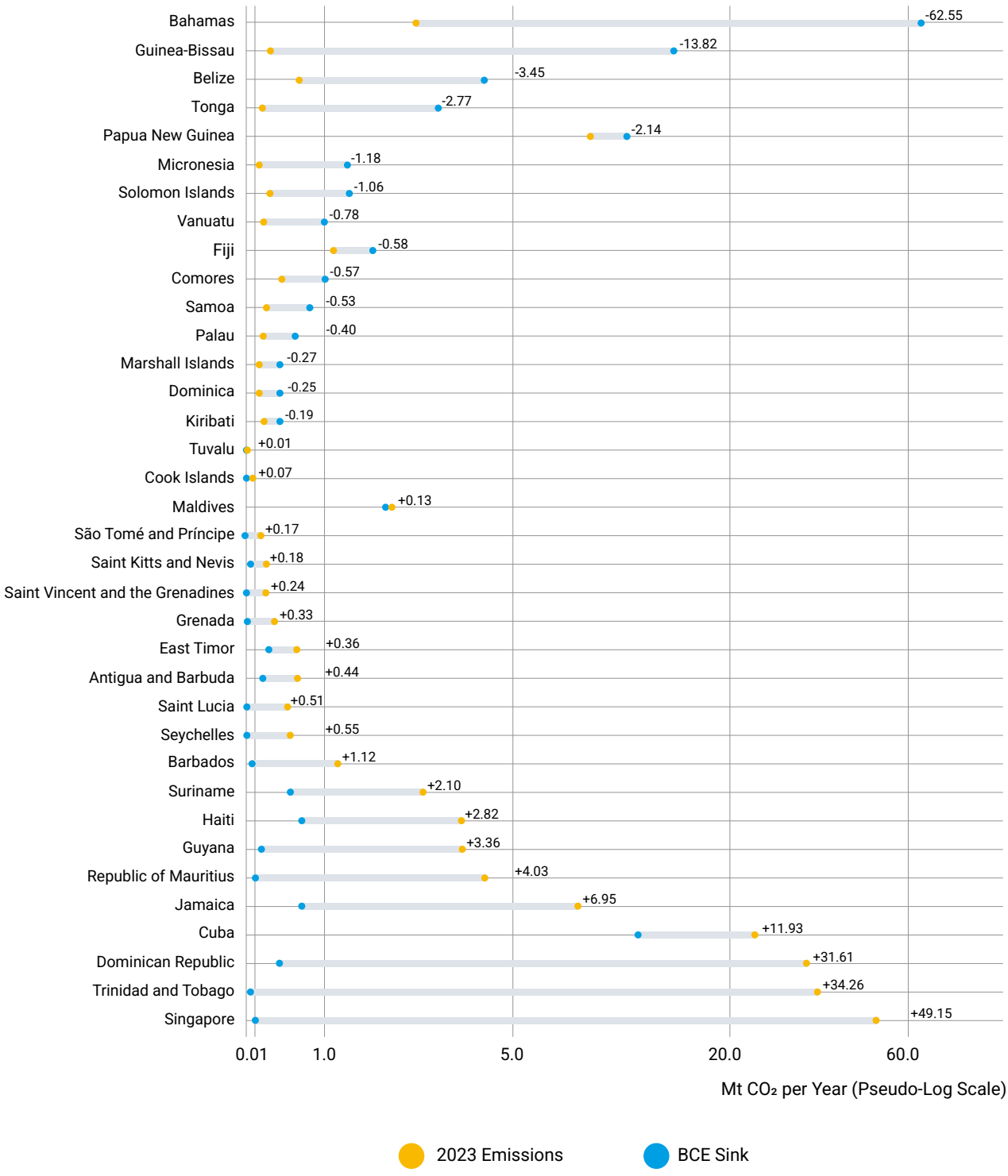


Figure 5.2: SIDS ranked by net carbon position based on 2023 greenhouse gas emissions and coastal BCEs. Source: Hilmi et al. 2026. Note: Emissions reflect 2023 inventory levels.

5.3.1 Inequity in ocean-climate impacts and carbon accounting

Globally, BCEs span 350,000 square kilometres (Macreadie et al. 2019). Exclusive economic zones (EEZs) collectively cover 41 per cent of the global ocean surface. For context, the EEZ of SIDS covers an estimated 30 per cent of all oceans (UN-OHRLLS, no date). However, these ecosystems are subjected to several pressures, both climate and anthropogenic, that reduce their coverage and sequestration capacity. As shown in Figure 5.3, SIDS in particular have the largest BCE areas after developing economies. As a result of these significant natural resources, mangrove sequestration in 16 SIDS offset more than 10 per cent of their total emissions from the agriculture, forestry, and other land uses sector in 2020 (Browne 2024).

Because ocean systems are transboundary, the carbon sequestration performed by BCEs is often considered a service to the global commons. However, when these systems are mapped against national emissions (Hilmi et al. 2026), several SIDS may be considered net carbon sinks when assessed using emerging approaches that account for the sequestration potential of coastal blue carbon ecosystems. Despite the important function of these ecosystems, national accounting systems are predominantly based on terrestrial sinks. While it is commonly recognized that SIDS are the smallest contributors to global emissions, when coastal BCEs are taken into account, their potential contribution as significant carbon sinks becomes more apparent. These findings raise important considerations regarding the treatment of marine carbon sinks in existing accounting methodologies and the implications for climate finance allocation to protect coastal ecosystems that continue to function as carbon sinks.

Globally, this inequity highlights the importance of re-evaluating the role of marine ecosystems in climate change mitigation, not only for SIDS, but also to ensure that the measures taken to reduce emissions draw on the latest science and data-driven assessments of the most effective technologies, interventions and existing ecosystems. Considering current emissions trajectories and projections, which indicate that achieving the 1.5°C temperature goal is becoming increasingly challenging without immediate, deep and sustained emissions reductions (UNEP 2026a), mitigation strategies should be informed by the best available science and incorporate a comprehensive understanding of carbon sinks, including opportunities to protect and enhance coastal and marine ecosystems. The ocean and coastal BCEs therefore represent potentially important components of future mitigation and adaptation strategies.

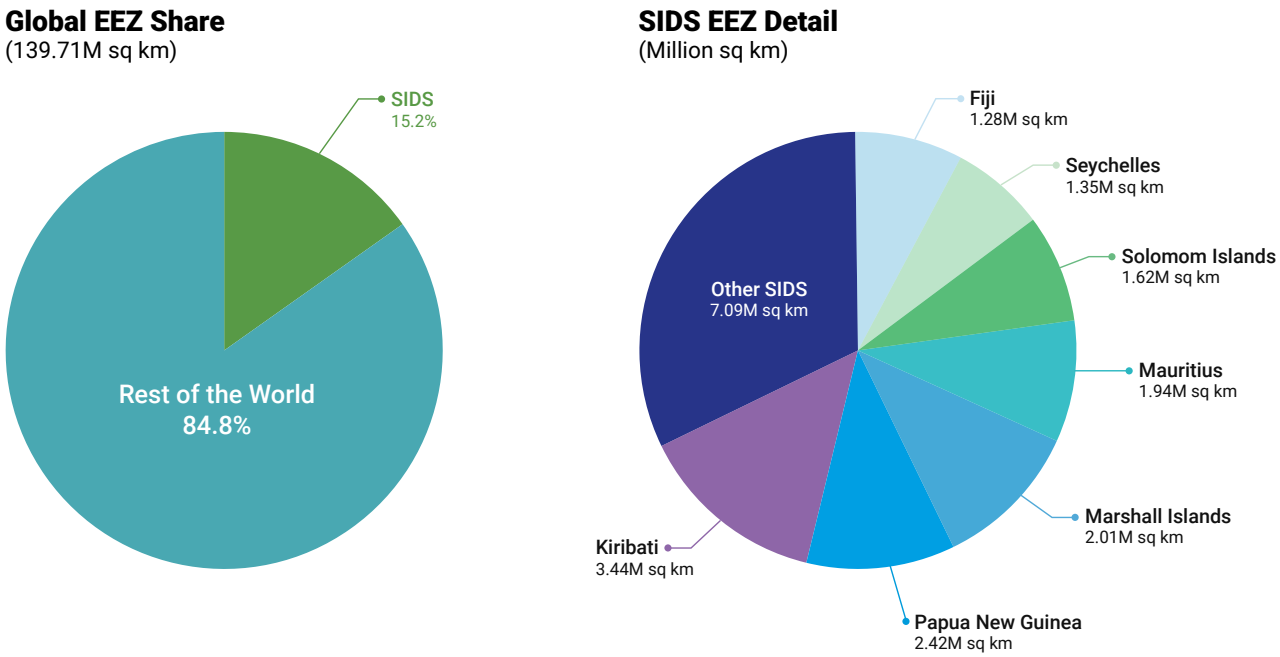


Figure 5.3: Global EEZ Distribution (SIDS v. non-SIDS). Note: The total global exclusive economic zone (EEZ) covers approximately 139.71 million sq km. Small Island Developing States (SIDS) stewardship encompasses 21.96 million sq km, representing 15.2% of the world's marine economic areas. SIDS manage a vast oceanic footprint — demonstrating their crucial role as Large Ocean States in global ocean governance.

Sources: Chaplin-Kramer et al. (2023).

5.4 OPPORTUNITIES AND PROGRESS IN SIDS

5.4.1 Ocean-based climate technologies in SIDS

For SIDS, ocean-based climate technologies offer opportunities not only to contribute to global climate action, but also to strengthen national resilience, support sustainable ocean economies and enhance local environmental stewardship. Ocean monitoring, observation and digital systems provide the foundational information required to understand marine carbon dynamics, assess climate-related risks and support evidence-based policy and management decisions. Improved ocean observations and analytical capabilities can strengthen OCI, enabling SIDS to better quantify and manage marine carbon resources, monitor ecosystem change and inform national climate reporting and planning processes.

BCEs, including mangroves, seagrasses and tidal wetlands, are particularly significant for many SIDS. These ecosystems support long-term carbon storage while delivering a wide range of co-benefits, including biodiversity conservation, fisheries support, coastal protection and enhanced resilience to climate impacts. Protecting, restoring and sustainably managing these ecosystems can therefore contribute simultaneously to mitigation, adaptation and broader sustainable development objectives. In many island settings, BCEs also represent some of the most accessible and immediately actionable nature-based climate solutions.

Alongside these established approaches, a range of emerging mCDR technologies are being explored for their potential to enhance ocean carbon sequestration. While these approaches may offer future opportunities to contribute to climate mitigation, substantial scientific, technical, environmental, governance and financial uncertainties remain. Their suitability for deployment in SIDS contexts will depend on robust evidence, effective monitoring systems, inclusive governance frameworks and careful consideration of local environmental and socioeconomic priorities.

This section examines the potential of these ocean-based climate technologies to support climate action in SIDS through their capacity to monitor, manage and enhance marine carbon sinks. It explores recent advances across ocean observation and digital systems, blue carbon ecosystems and emerging mCDR approaches, while highlighting the enabling conditions required for their successful development and implementation. Particular attention is given to the capacity-building, financing, governance and partnership needs that will shape the accessibility and effectiveness of these technologies within island contexts. Building on the scientific foundations established in earlier chapters, this chapter emphasizes the importance of OCI as an enabling framework that integrates observations, data systems and assessment capabilities to transform complex marine information into actionable knowledge, supporting informed decision-making and resilient, locally relevant ocean-based climate action in SIDS.

5.4.2 Ocean monitoring, observations and digital systems

Underpinning the introduction of new technologies is data access, sharing and interoperability. Investment in robust data architecture provides a vital foundation for climate information systems and multi-hazard early warning systems that provide actionable, granular and context-specific data. The availability of data and data-sharing structures also facilitates the ability to assess real-time risks and provide information to enable timely responses after disasters. In addition to timely, accurate and localized data, the use and application of predictive modelling using AI and machine learning can also enable the identification of site-specific technologies adapted to the local context.

AI and blockchain technologies may support ocean intelligence, marine science and governance in resource-constrained SIDS through applications such as predictive hazard modelling, environmental monitoring and decision-support systems, provided that appropriate safeguards, governance frameworks, technical capacity and data infrastructure are in place (Addison 2025). Next-generation early warning systems can also help to identify risks to coastal infrastructure (Benitez, Ababao and Sampedro 2025). Deploying advanced digital twins, as in the example of Tuvalu described in Box 5.1, or AI predictive models requires overcoming the disconnection between local community data and national research centres. Integrating qualitative local ecological knowledge (traditional ecological knowledge and Indigenous local knowledge [TEK/ILK]) with quantitative oceanographic monitoring can create localized, context-specific early warning systems capable of detecting rapid coastal changes.

Box 5.1: 'Future Now' digital twin initiative in Tuvalu

An example of ocean intelligence is the Digital Earth Pacific (DEP) analytical platform, designed as a decision-support tool capable of aggregating, enhancing and analysing ocean intelligence and information. The platform features dashboards to document and assess spatial and temporal changes in coastlines, mangrove coverage and canopy density, satellite-based bathymetry, intertidal zones and seagrass beds.

The platform enables decision makers to track coastal erosion and sea level rise to guide infrastructure planning. Mangrove monitoring through the dashboard also supports the identification of blue carbon sinks and changes in mangrove coverage following cyclones (Metherall et al. 2026). DEP uses AI-based algorithms to detect patterns in Landsat archives and Sentinel data. Machine learning is also used to remove cloud cover that can obscure changes in coastlines and to enable image compositing, combining multiple images in a single dashboard. Together, these capabilities facilitate the monitoring of blue carbon ecosystems and contribute to ocean carbon intelligence in Pacific SIDS.

The size of EEZs poses challenges for patrolling, monitoring and managing marine resources. SIDS also represent a diverse typology of countries, with each requiring a contextualization and assessment of suitable technology needs and opportunities for ocean monitoring. The EEZ for Kiribati, for example, is 3.5 million square kilometres, as shown in Figure 5.3. The costs associated with monitoring an EEZ of this size is a significant barrier to the introduction of the new technologies required for effective OCI.



Box 5.2: Sargassum tracking and monitoring in the Caribbean

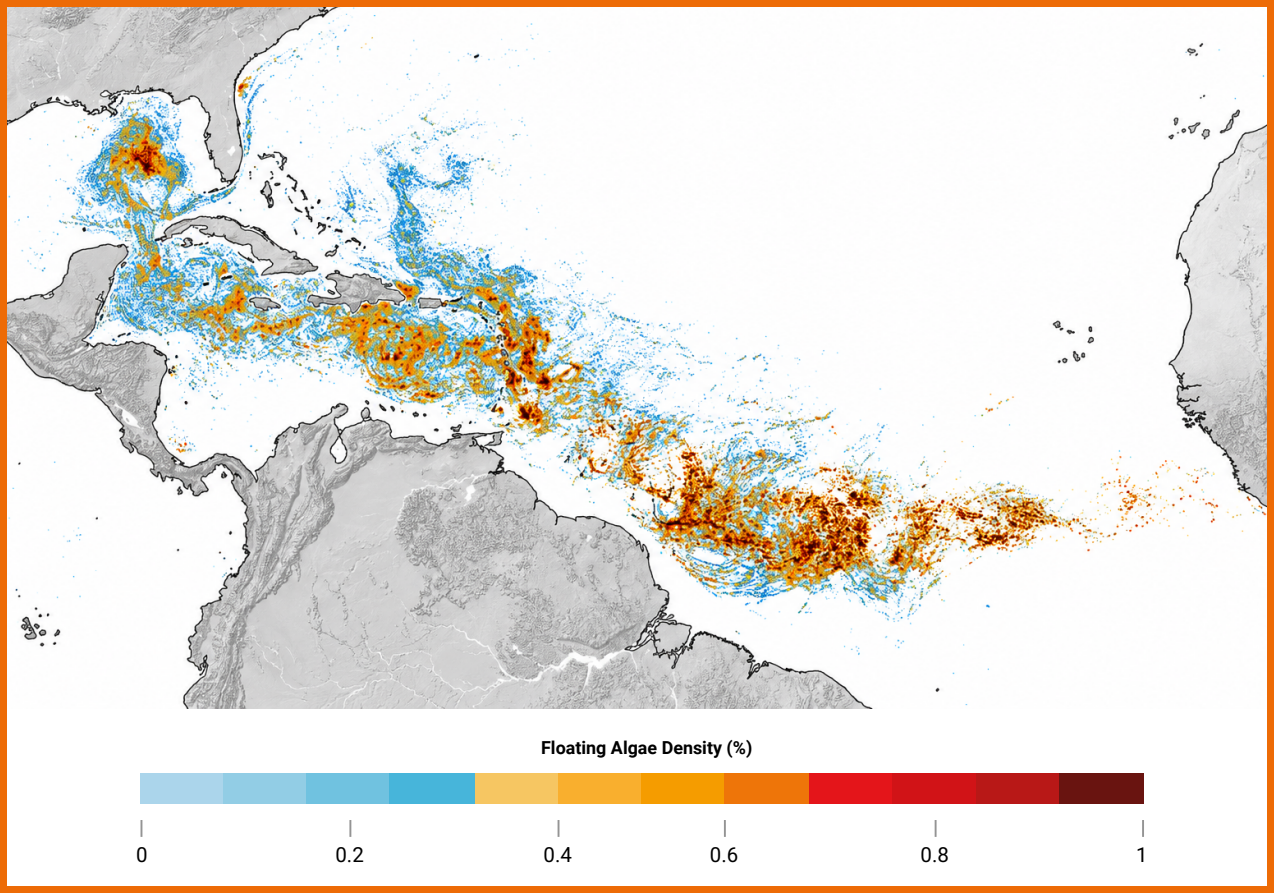


Figure 5.4: Sargassum density in the tropical Atlantic Ocean, June 2026, measured by the Ocean Color Instrument aboard NASA's PACE satellite.

Sargassum, the largest canopy-forming algae, poses significant coastline management challenges in tropical contexts, notably in the Caribbean region. Sargassum is an attractive potential solution for developing products (including biofertilizers, biodegradable packaging and construction materials), not only because of its climate-driven proliferation, but also due to its high carbon content (UN-OHRLLS 2020), which can be twice as much as mangroves and seagrasses per unit area (Gouvêa et al. 2020). While sargassum blooms pose ecological challenges for Caribbean coastal communities, floating macroalgae also play an important role in the oceanic carbon pump. Accurately modelling these carbon attributes of sargassum requires high-resolution spatial data on bloom distribution and density. Sargassum tracking and monitoring tools have therefore been developed. An example of ocean monitoring technology is the Caribbean Coastal Ocean Observing System (CARICOOS Sargassum Tracker), which uses satellite imagery to track and forecast sargassum concentrations. The CARICOOS system leverages satellite data, radar and data buoys to provide detailed, site-specific information on sargassum algae blooms in the Caribbean.

This satellite-enabled tracking of blooms is also strengthened by a citizen science initiative, Sargassum Watch (iNaturalist), which compiles observations of different species of sargassum and their locations. The potential co-benefit of addressing the challenge of managing sargassum (which has generated extensive ecological and socioeconomic challenges across many SIDS due to large-scale bloom events) (Mohan and Strobl 2024) lies in its potential as a source of marine-sourced products and technologies that could capitalize on its properties in SIDS.

While new technologies are emerging, there are opportunities for scaling existing solutions, while remaining aligned with national priorities for ocean-based climate action. Combined approaches involving geoengineering, nature-based solutions and ocean-based climate investments have the potential to leverage the resources most accessible to SIDS, if coupled with enablers such as marine-spatial planning, data accessibility, conductive policies and equitable access to finance.

To effectively deploy OCI solutions, the opportunities, risks, uncertainties, governance requirements and conditions associated with these solutions should be assessed for responsible application. Technology needs assessments, such as those conducted by the CTCN, funded by the Global Environment Fund (GEF) under the Global Technology Needs Assessment Project, are therefore employed to take into consideration the characteristics, potential co-benefits, externalities and negative impacts in terms of these solutions' overall suitability for the context in which they could potentially be deployed. Innovation pathways must also incorporate long-term considerations and externalities that could potentially materialize because of technological solutions.

5.4.3 Blue carbon ecosystems

The incorporation of nature-based solutions is recognized as the most effective way to combine the benefits of carbon storage and broader co-benefits such as environmental conservation (Hoegh-Guldberg et al. 2023). A systematic review of 53 nature-based solution interventions found that nearly three quarters of cases reported positive climate adaptation outcomes, illustrating the potential to reduce exposure to hazards while delivering "triple wins" for climate, biodiversity and people (Brown et al. 2026). Solutions that require large-scale engineering or capital-intensive interventions are not always appropriate for smaller geographies with dispersed islands across a wide area. Innovation pathways that target low-lying atolls must be tailored to their unique circumstances, which combine high climate vulnerability with a limited land area and unique ecosystems that have developed over time.

To achieve long-term resilience and sustainability, hybrid (or blended) solutions are increasingly being integrated, particularly for SIDS, in order to make use of locally available materials. This approach combines engineered shorelines with nature-based solutions to achieve climate change adaptation needs. An example of this is the "Strengthening the Adaptative Capacity of Coastal Communities of Fiji to Climate Change through Nature-Based Seawalls" project. The premise of this project is the use of local materials to construct a nature-based solution sea wall with four components (mangrove hedge, boulders, backfill, vetiver grass), with the combined effect of adaptation measures that make use of locally available materials.

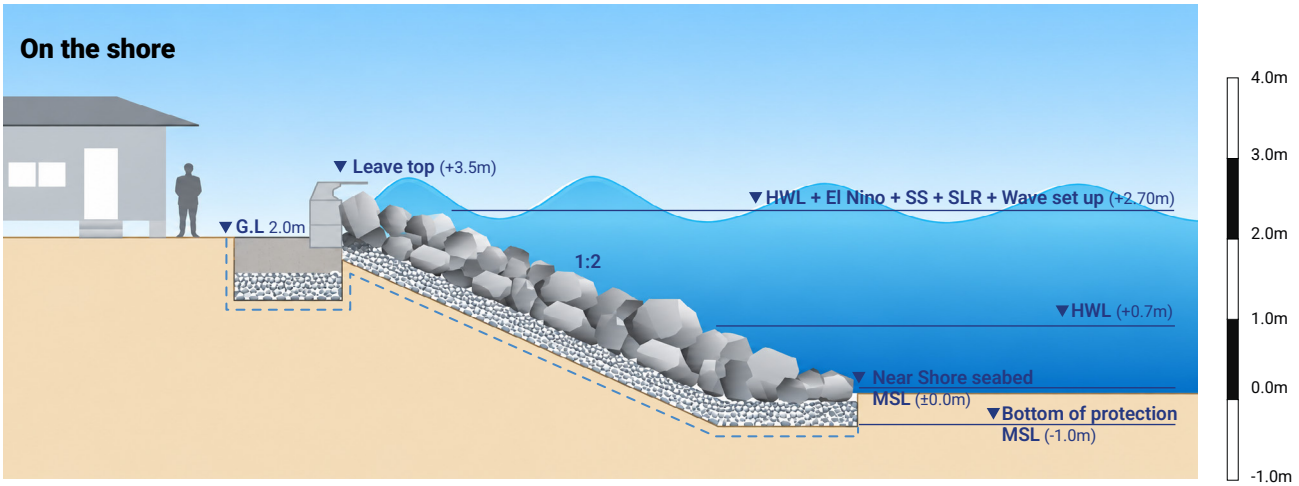


Figure 5.5a: Hybrid sea wall illustration (On the shore).

Source: redrawn from Nonaka et al. 2024.

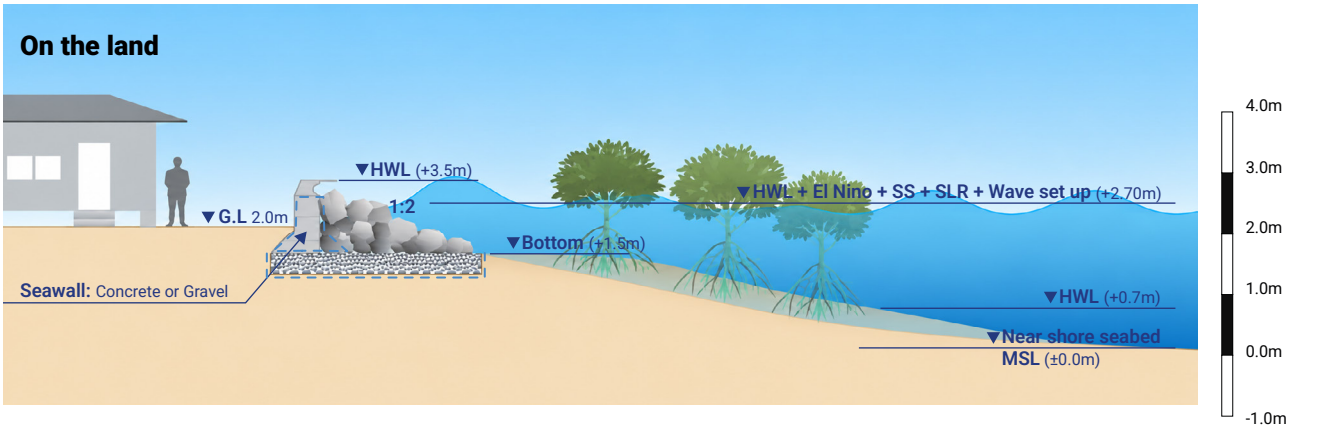


Figure 5.5b: Hybrid sea wall illustration (On the land).

Source: redrawn from Nonaka et al. 2024.

This combined approach includes the incorporation of sea walls with mangrove restoration, coral reef rehabilitation and other solutions that harness the co-benefits of coastal protection while fostering increased biodiversity. The combination of these approaches has resulted in indicative cost-effectiveness rather than relying on hard infrastructure alone (Reddy, Reddy and Singh 2024). Hybrid solutions have also shown an ability to lower long-term maintenance costs and improve wave attenuation properties due to the adaptive nature of reef structures and vegetative buffers (Amini et al. 2025; van Zelst et al. 2021). Given the current rate of global mean sea level rise (3.64 millimetres per year) (Copernicus Climate Change Service [C3S] 2026), hybrid solutions are increasingly being explored and proposed as an innovation, both to increase carbon storage and due to various co-benefits to coastal communities in SIDS.

5.4.4 Marine carbon dioxide removal

mCDR solutions would require robust localized governance, close collaboration and engagement with communities, and rigorous environmental monitoring to be tested for feasibility. Among nature-based approaches, pelagic sargassum, a dominant canopy-forming macroalgae, presents severe coastal management challenges across tropical regions, most notably in the Caribbean. However, it also represents an attractive candidate for mCDR and product valorization, including in the form of biofertilizers, biodegradable packaging and construction materials. This potential stems from its climate-driven proliferation across the Atlantic (UN-OHRLLS 2020) and its substantial biomass production capacity per unit area (Gouvêa et al. 2020). Transforming excess sargassum biomass from an environmental management challenge (Mohan and Strobl 2024) into a circular economy feedstock offers SIDS a dual benefit: mitigating coastal pollution while unlocking an underutilized resource for carbon sequestration and sustainable innovation.

For mCDR in SIDS, technologies remain at the research or pilot stage (see Chapter 3), with their effectiveness at scale under SIDS conditions yet to be demonstrated. Some mCDR technologies might provide environmental co-benefits such as reducing local ocean acidification, with flow-on benefits for fisheries and the communities that rely on them. At the same time, however, mCDR projects could also pose environmental and social risks both globally and locally, as discussed in Chapters 3 and 4 of this report.

5.5 BARRIERS TO FINANCING OCEAN-BASED TECHNOLOGIES IN SIDS

5.5.1 Systemic constraints

For SIDS, the costs of adaptation are significant, considering both high debt-to-GDP ratios and the increasing projected economic losses due to both rapid- and slow-onset events. Globally, sea level rise alone could result in an estimated US$400–520 billion in losses annually by 2100 (Depsky et al. 2022). Of the current climate finance flows for the latest year available (2023), an estimated US$1.8 trillion was committed to mitigation activities compared with US$66.59 billion for adaptation, representing a substantial difference in the allocation of climate finance and highlighting ongoing international discussions regarding the balance between mitigation and adaptation funding.

Due to the co-benefits and natural carbon storage potential, climate change adaptation funding is increasingly being allocated to coastal nature-based solutions such as the hybrid sea wall example in Fiji (Figure 5.5), mangroves, seagrasses and other interventions in SIDS. According to the 2025 Adaptation Gap Report, US$310 billion is required per year in adaptation finance for developing countries, which is approximately 14 times greater than the current financial flows (UNEP 2025). This is

despite the fact that adaptation has been integrated into national policies and strategy documents such as the National Adaptation Plans (NAPs) and NDCs.

Moreover, adaptation financing frameworks often inadequately capture the ocean-climate nexus that defines many SIDS economies and vulnerability profiles (Hoegh-Guldberg et al. 2019). Existing financing structures tend to prioritize sectoral approaches despite the interconnected nature of coastal resilience, fisheries, marine ecosystems, tourism, food security and disaster risk management within island systems. This fragmentation creates challenges for developing integrated investment pipelines capable of addressing cascading and compound climate risks. For atoll nations, where critical infrastructure, freshwater lenses, ecosystems, and settlements are concentrated within narrow coastal zones, the distinction between ocean governance and climate adaptation becomes increasingly inadequate.

Access to climate finance for solutions with high carbon storage potential is a persistent challenge for SIDS. One commonly cited challenge identified by UN-OHRLLS (2015) relates to eligibility criteria for official development assistance (ODA). Despite high levels of exposure to climate-related risks, significant debt-servicing burdens and limited fiscal space, several SIDS face constraints in accessing concessional finance because eligibility is often influenced by income-based classifications, including middle-income country status. This challenge has contributed to growing support for complementary measures such as the Multidimensional Vulnerability Index (MVI), which seeks to capture vulnerabilities that may not be reflected by gross national income (GNI) per capita alone. Proponents of the MVI argue that reliance on GNI per capita as a primary eligibility criterion may not fully reflect the climate, environmental and economic vulnerabilities faced by many SIDS, potentially limiting access to concessional financing in some cases. A shift from GNI per capita to MVI would potentially save an estimated 1.5 per cent of GDP in interest payments per year for non-LDC SIDS (UNDP 2020).

5.5.2 Structural barriers

Perhaps one of the most persistent barriers confronting SIDS is the disconnect between the scale and urgency of climate impacts and the complexity of international climate finance access modalities. While multilateral climate funds have expanded adaptation windows and readiness support, many SIDS continue to face high administrative requirements relative to their institutional size and human resource capacity (UN-OHRLLS 2015). The preparation of funding proposals for major financing entities often requires extensive technical studies, environmental and social safeguard assessments, economic analyses, procurement planning, monitoring frameworks and stakeholder consultations. For small administrations with limited technical personnel, these requirements can consume already constrained institutional capacity and delay implementation timelines.

This challenge is compounded by high turnover within government ministries and implementing entities, which contributes to institutional memory loss and weak continuity across project cycles (Betzold 2015). In many SIDS, a small number of technical officers are simultaneously responsible for climate negotiations, donor coordination, reporting obligations under the Paris Agreement, project implementation and domestic policy development. As a result, climate finance access is not solely constrained by funding availability, but also by the absorptive and administrative burdens associated with navigating fragmented international financing systems.

Human capacity and administrative constraints are also recognized as barriers to accessing climate finance (UN-OHRLLS, 2015). The cost incurred by climate change ministries and their equivalents to develop full funding proposals is recognized as a constraint for accessing climate finance quickly and at scale. Combined with the time required to develop such proposals, Direct Access Entities with multiple priorities face data limitations in and other administrative constraints. SIDS often face the challenge of a public sector characterized by civil servants fulfilling multiple roles. Public sector officials are often required to manage multiple portfolios, limiting their ability to also facilitate the introduction of highly specialized and capital-intensive technologies. In addition, the integration of new technologies requires consultation with Indigenous Peoples and local community governance systems that operate in target communities. The structural barriers and limited fiscal space of SIDS have necessitated the development of innovative financing mechanisms to fill funding gaps. An example is the use of debt-for-nature swaps that have been employed to protect coastal ecosystems and to facilitate climate adaptation. Debt-for-nature swaps are designed to cancel or restructure a portion of sovereign debt for the purposes of directing resources towards payment for environmental conservation efforts.

5.5.3 Innovative financing mechanisms

Debt-for-nature swaps have been explored by SIDS as an innovative financing opportunity (Seychelles in 2015, Belize in 2021, Barbados in 2022, Bahamas in 2024). The Seychelles Conservation and Climate Adaptation Trust (SeyCCAT), for example, is recognized internationally for its leadership in innovative financing for marine conservation. SeyCCAT also serves as a national platform for blue-finance innovation, facilitating partnerships, strengthening fiduciary systems and supporting the development of new financing models that link conservation outcomes with climate and economic benefits. Its model blends public, private and philanthropic capital to deliver long-term impact. Key mechanisms include:

- Debt-for-nature swap proceeds, which capitalized SeyCCAT and established a sustainable revenue stream for conservation.

- The Seychelles Sovereign Blue Bonds, which feed into the Blue Grants Fund that finances projects across conservation, climate adaptation and sustainable blue economy development.

- Exploration of emerging instruments is ongoing, including blue carbon credits, biodiversity finance mechanisms and sustainability-linked financing.

To date, SeyCCAT has supported national efforts to map, assess and monitor BCEs, including the 159,920 hectares of seagrass that store 18.9 million tons of organic carbon – equivalent to 69 million tons of CO2.

Another example of a debt-for-nature swap is the 2021 Government of Belize Debt Conversion for Marine Conservation, facilitated through bond buy-back and the issuance of a blue bond. The swap was implemented through a US$364 million loan from The Nature Conservancy (TNC) (UNDP 2023). The initiative reduced the debt held by Belize by the equivalent of an estimated 12 per cent of GDP (OECD 2024). The debt swap involved exchanging debt restructuring for the allocation of US$4.2 million for marine conservation and the expansion of biodiversity protection zones to cover 30 per cent of ocean area by 2026 (Jiang and Cao 2024; The Nature Conservancy 2021). While debt-for-nature swaps serve as a viable innovative financing mechanism for SIDS with high debt burdens, significant transaction costs and the required technical assistance also prevent them from being more widely adopted by SIDS governments (Tkachenko et al. 2024).

In the Pacific, the Fiji Sovereign Blue Bond (US$8.7 million) was issued in 2023. The bond is designed to channel private investment into high-priority marine conservation and ocean-focused climate adaptation initiatives across Fiji. The Blue Bond focuses on four priority areas:

1) Nature-based solutions.
2) Scaling up the aquaculture sector in Fiji.
3) Integrated planning solutions for coastal urban development.
4) Enhancing wastewater treatment systems.

The ocean financing instruments funded by the bond are aligned with the taxonomy framework developed by the Fiji Development Bank in collaboration with international actors such as the Climate Bonds Initiative and supported by the United Nations Development Programme (UNDP). Notably, the bond issuance was paired with a pipeline development initiative, the Blue Accelerator Grant Scheme, to fund early-stage, bankable blue economy project concepts.

The Bahamas Blue Carbon Project leverages spatial mapping combined with innovative financing and robust MRV of BCEs. The initiative generates revenue from non-traditional sources to leverage the carbon storage potential of seagrass ecosystems and mobilize resources through market and sovereign mechanisms. The Bahamas established a public-private partnership to verify seagrass protection initiatives, generate carbon credits and re-invest into a national investment fund. According to the Climate Vulnerable Forum and Vulnerable Twenty Group (2024), this initiative leverages a cloud-based system, Sentient All-Domain Augmented Response (SADAR) Natural Capital Monetization (NCM) to employ AI and geospatial data to track carbon sequestration. These examples demonstrate the potential for innovative financing initiatives to support projects centred on nature-based coastal protection, sustainable aquaculture and coastal resilience.

Despite their growing prominence, innovative financing mechanisms are not a universal solution for addressing the climate and ocean financing needs of SIDS. Instruments such as debt-for-nature swaps and blue bonds often involve complex legal, financial and institutional arrangements that require specialized expertise and extensive technical assistance throughout project design, negotiation and implementation. Transaction costs can be substantial relative to the size of many SIDS economies, potentially limiting cost-effectiveness and scalability. In addition, successful examples have often depended on unique political, financial or

environmental circumstances, raising questions about their replicability across different SIDS contexts. The relatively small size of many transactions may also constrain their capacity to meet the scale of adaptation and resilience investment required. While these mechanisms can play an important complementary role in mobilizing resources, their effectiveness depends on supportive policy environments, sustained capacity-building efforts and continued access to technical and financial support from development partners.

5.6 ENABLING CONDITIONS FOR TECHNOLOGY TRANSFER

The transfer and deployment of ocean-based climate technologies in SIDS are influenced by a range of enabling conditions spanning policy, finance, institutions, capacity and access to technology. Evidence from the UNFCCC Technology Executive Committee highlights that effective technology transfer depends on supportive enabling environments, including clear regulatory frameworks, skilled human resources, access to finance, institutional coordination, technology information and international cooperation (UNFCCC TEC 2022). At the same time, developing countries, including many SIDS, continue to face challenges related to limited technical capacity, inadequate financing, weak institutional arrangements and constraints in accessing and adapting technologies to local contexts. This section examines these barriers and enablers in the context of SIDS, with particular attention paid to the factors that may influence the effective transfer, adoption and scaling of ocean-based climate technologies and OCI capabilities.

5.6.1 Economic and financial enablers

The growing costs associated with climate risk monitoring and adaptation technologies also risk widening a "resilience divide" between SIDS with stronger institutional access to external financing and those with more limited implementation capacity (World Bank 2021; ITU and WMO 2023). Technologies such as high-resolution satellite imagery, light detection and ranging (LiDAR) mapping, ocean observation systems, and digital early warning infrastructure are increasingly necessary for adaptation planning and risk reduction. However, the long-term maintenance, calibration, licensing and operationalization costs associated with these technologies remain substantial. Without predictable grant-based support and long-term technical partnerships, there is a risk that technological modernization efforts become financially unsustainable after initial project cycles conclude. To accelerate adaptation and resilience efforts, facilitating access to climate finance can unlock and accelerate the progress of SIDS against their already ambitious targets in relevant national policy documents. Greater incorporation of financing needs for coastal resilience and blue economy is recognized as a missing component in creating the enabling policy environments for increasing SIDS resilience (Global Center on Adaptation [GCA] 2025). Between 2030 and 2050, an estimated US$2 trillion in climate finance will be required to meet the mitigation potential of ocean-based climate technologies (Hoegh-Guldberg et al. 2023).

5.6.2 Institutional and organizational enablers

While several technological systems and innovations are technically feasible and have the potential to monitor carbon capture initiatives in SIDS contexts, each requires human and institutional capacity to support long-term viability and sustainability. Due to their small population size, limited land area and expansive maritime zones, SIDS are also constrained by limited private sector engagement. Regional cooperation can help to lower transaction costs through the pooling of resources (Meddeb 2022). Peer-to-peer learning opportunities have also strengthened capacity-building in SIDS at the regional or subregional level (Kaur and Tennant 2024), filling gaps in formalized education or training and sharing lessons learned to address challenges common to SIDS, as well as catalysing the strengths and synergies identified through these types of exchanges.

5.6.3 Technical enablers

The potential co-benefits of OCI systems are highly dependent on the context, shelf depth and other criteria which rely on accurate bathymetry data. These data are often costly to obtain, requiring specialized marine vessels, LiDAR and data processing. The costs of data acquisition are often prohibitive, resulting in higher financial risks for investors. Singh, Linnér and Singh (2025) highlight the lack of historical data, specifically for marine resources in SIDS, as well as limited access for local authorities.

In addition to geospatial, quantitative data, and socioeconomic data, qualitative data are also needed to collect information acquired through interviews, focus group discussions and storytelling. In addition, co-designing the integration of innovations engages local communities (Havea et al. 2024; Lewis Paliszkiewicz and Roopnarine 2024; Oh-Seng, Klöck and Deenapanray 2025; Singh, Linnér and Singh 2025; Sena and Makino 2026) in site selection and management of climate adaptation technologies, and strengthens the long-term viability of interventions. Co-designing and multi-stakeholder engagement are aligned with global efforts such as the UNESCO-IOC

Ocean Decade priority areas to implement ocean literacy initiatives (UNESCO 2021). Equipment, facilities and infrastructure also require modification to take into consideration context-specific conditions (cyclone conditions, exposure to saltwater, wind shear, etc.). The integration of new technologies requires not only investment in human capacity to ensure that the technologies can be maintained and operated, but also support for education in areas where simulators and other types of equipment are lacking (Kaur and Tennant 2024).

Ocean-based climate technologies demand not only the increased adoption of technology, but also of nature-based solutions, as well as the integration of Indigenous practices. Traditional knowledge can be formally institutionalized into climate adaptation governance using legal spatial frameworks. Despite challenges in implementation (Mons et al. 2026), the Marine Coastal Spaces for Indigenous Peoples (Espacio Costero Marino de Pueblos Originarios [ECMPOs]) initiative has been a model that validates ancestral memory, biocultural conservation and customary resource management as formal, legally protected strategies to mitigate coastal environmental threats. The example of ECMPOs demonstrates the potential for local ecological knowledge to be integrated, enabling the empowerment of Indigenous leadership over marine management (Anbleyth-Evans et al. 2025).

Participatory mapping can support these processes through the identification of power imbalances, potential inequalities and vulnerable groups. Through this process, the level of trust, ownership and mutual understanding (Singh, Linnér and Singh 2025) can refine the introduction and dissemination strategy for new technologies. Close collaboration and engagement facilitate the identification of and alignment with the needs of target communities, in accordance with cultural contexts (Kaur and Tennant 2024), anticipate potential negative spillover effects on surrounding areas, and improve the identification of context-specific technologies and potential modification.

5.7 INTERNATIONAL COOPERATION

The strengthening of technology partnerships has been identified as a key contributor to developing the capacity of ocean-based climate technologies, particularly for SIDS (WEF 2024). Building human and institutional capacity in research and development through centres of excellence, research partnerships, regional systems of innovation, and scholarship are included in SIDS' national priorities to facilitate technology transfer and uptake. Scaling nature-based solutions can provide carbon sequestration and resilience benefits while generally presenting lower environmental risks than some more intervention-intensive approaches, with co-benefits extending from local communities (coastal resilience) to regional and global impacts. In some areas, incorporating nature-based solutions may also contribute to reversing biodiversity loss (Riisager-Simonsen et al. 2020).

Triangular approaches can also be integrated to facilitate technology transfer effectively. An example of a triangular approach is the Management and Conservation of Blue Carbon Ecosystems in Pacific Island Countries (MACBLUE) project. Financed by Germany through its International Climate Initiative (IKI) and implemented by the Secretariat of the Pacific Regional Environment Programme (SPREP) and the Pacific Community (SPC), the project centres on capacity-building and technology transfer (satellite remote sensing, GIS mapping, carbon-modelling capabilities) in Fiji, PNG, Solomon Islands and Vanuatu. This type of regional model operates on a shared foundation of common interest to ensure that the investments in data infrastructure, carbon accounting and MRV capacity are strengthened and remain under national and/or regional data governance.

Bolstering long-term technology partnerships should also be prioritized over short project-based interventions (UNCTAD 2025). Many technology transfer initiatives in SIDS remain dependent on externally driven pilot projects with limited continuity after funding cycles end. More durable partnerships involving regional organizations, universities, technical agencies and local institutions are needed to support sustained capacity development, technology localization and knowledge retention. Regional cooperation mechanisms can also help to pool technical expertise, reduce operational costs and support shared climate information infrastructure across geographically dispersed Island States.

Interventions that align with traditional knowledge and incorporate aspects of Indigenous climate adaptation practices enable a hybrid approach that can combine the intergenerational practices of local communities with engineering solutions. These efforts enable the integration of cultural practices, knowledge of ecological boundaries, and traditional knowledge of ecosystems that are uniquely adapted to the local context. By anchoring technology transfer in enabling conditions that are conducive to knowledge-sharing and data access (Coelho 2022), and supported by human capacity developments, SIDS can facilitate the uptake of emerging innovations that are context-specific and sustainably implemented in the long term.

5.8 CONCLUSION

SIDS occupy a particularly important position within the ocean-climate nexus. Despite contributing less than 1 per cent of global greenhouse gas emissions, they are among the most exposed to the impacts of ocean warming, sea level rise, ocean acidification, extreme weather events and ecosystem degradation. Their vulnerabilities are amplified by geographic isolation, limited land area, dependence on climate-sensitive sectors, and constrained fiscal and institutional capacities. At the same time, SIDS possess globally significant ocean assets, including extensive EEZs and BCEs that provide opportunities for climate mitigation, adaptation and sustainable development.

Ocean-based climate technologies and innovations offer important pathways to strengthen resilience and support climate action in SIDS. Nature-based and hybrid approaches, including mangrove restoration, reef rehabilitation and integrated coastal protection systems, can generate multiple benefits for climate adaptation, biodiversity conservation and local livelihoods. Emerging technologies such as ocean observation systems, satellite monitoring, AI and digital climate services, and an OCI approach, can enhance decision-making, risk management and ecosystem monitoring. However, more experimental interventions, particularly mCDR technologies, require careful assessment, robust governance frameworks, community engagement and rigorous environmental safeguards before deployment at scale.

The successful transfer and implementation of ocean-based technologies in SIDS depends on enabling conditions that extend beyond the technology itself. Sustainable outcomes require investment in human and institutional capacity, data infrastructure, localized climate information systems, research partnerships and long-term operational support. Regional cooperation, peer-to-peer learning and technology partnerships can help overcome limitations associated with small populations, dispersed geographies and limited technical resources. It is equally important to integrate Indigenous knowledge, traditional governance systems and community co-design processes to ensure that innovations are socially acceptable, culturally appropriate and responsive to local priorities.

Persistent structural barriers continue to constrain the ability of SIDS to access and deploy ocean-based climate technologies. High debt burdens, limited fiscal space, restrictive financing criteria, administrative capacity constraints and fragmented climate finance mechanisms all hinder implementation. While innovative financing instruments such as blue bonds and debt-for-nature swaps demonstrate promise, they are unlikely to meet the scale of financing needs on their own. Greater access to predictable, grant-based adaptation and loss and damage finance, alongside reforms that recognize multidimensional vulnerability rather than income alone, will be essential.

Looking forward, scaling ocean-based climate technologies in SIDS requires a holistic approach that combines technological innovation, ecosystem stewardship, sustainable finance, capacity development and inclusive governance. By aligning ocean-based climate technologies with national priorities, local knowledge systems and long-term development objectives, SIDS can strengthen their resilience to climate change while advancing a sustainable and equitable blue economy. The experiences of SIDS also offer valuable lessons for the global community on integrated approaches to ocean governance, climate adaptation and sustainable development in an increasingly climate-constrained world.



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ACRONYMS

2D / 3D	Two-dimensional / Three-dimensional
AASI	Accelerating Adoption of Sensor Innovation
ABNJ	Areas Beyond National Jurisdiction
AI	Artificial intelligence
BAP	Best Aquaculture Practices
BBNJ	Biodiversity Beyond National Jurisdiction
BCE	Blue carbon ecosystems
BCP	Biological carbon pump
BGC-Argo	Biogeochemical Argo
C3S	Copernicus Climate Change Service
CAF	Development Bank of Latin America and the Caribbean (Corporación Andina de Fomento)
CBD	Convention on Biological Diversity
CDR	Carbon dioxide removal
CH_4	Methane
CHF	Swiss Franc
CO_2	Carbon dioxide
CSI	Certified Seafood International
DEP	Digital Earth Pacific
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
DOCCS	Direct ocean capture with carbon storage
ECLAC	United Nations Economic Commission for Latin America and the Caribbean
ECMPOs	Espacio Costero Marino de Pueblos Originarios (Marine Coastal Spaces for Indigenous Peoples)
EEZ	Exclusive economic zone
EIA	Environmental impact assessment
EMEC	European Marine Energy Centre
ENSO	El Niño–Southern Oscillation
EU / UKRI	European Union / UK Research and Innovation
FAIR	Findable, accessible, interoperable, reusable
FMRI	Future Marine Research Infrastructure

GCA	Global Center on Adaptation
GCP	Global Carbon Project
GDP	Gross domestic product
GEF	Global Environment Facility
GM	Green Marine
GNI	Gross national income
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program
GOA-ON	Global Ocean Acidification Observing Network
GOBM	Global ocean biogeochemistry model
GOOS	Global Ocean Observing System
G3W	Global Greenhouse Gas Watch (WMO)
GtC	Gigatonnes of carbon
ICES	International Council for the Exploration of the Sea
IEC	International Electrotechnical Commission
IKI	International Climate Initiative (Internationale Klimaschutzinitiative, Germany)
IOC	Intergovernmental Oceanographic Commission of UNESCO
IPCC	Intergovernmental Panel on Climate Change
ITMO	Internationally transferred mitigation outcome
ITU	International Telecommunication Union
JGOFS	Joint Global Ocean Flux Study
KPI	Key performance indicator
LDCs	Least developed countries
LEK	Local ecological knowledge
LiDAR	Light detection and ranging
LOC-NESS	Locking away Ocean Carbon in the North East Shelf and Slope
MACBLUE	Management and Conservation of Blue Carbon Ecosystems in Pacific Island Countries
mCDR	Marine carbon dioxide removal
mERW	Marine enhanced rock weathering
MRV	Measurement, reporting and verification
MSC	Marine Stewardship Council
MVI	Multidimensional Vulnerability Index
N_2O	Nitrous oxide

NAP	National Adaptation Plan
NBSAP	National Biodiversity Strategy and Action Plan
NCM	Natural Capital Monetization
NDC	Nationally Determined Contribution
OAE	Ocean alkalinity enhancement
oCDR	Ocean-based carbon dioxide removal
ODA	Official development assistance
OECD	Organisation for Economic Co-operation and Development
ONCE	Ocean negative carbon emissions (international programme)
OSSE	Observing System Simulation Experiment
pH	potential of hydrogen (acidity scale)
PforR	Program-for-Results (World Bank financing instrument)
PIC	Particulate inorganic carbon
POC	Particulate organic carbon
SADAR	Sentient All-Domain Augmented Response
SeyCCAT	Seychelles Conservation and Climate Adaptation Trust
SIDS	Small Island Developing States
SIOOC	Sistema Integrado de Observación del Océano Chileno (Chilean Integrated Ocean Observing System)
SOCAT	Surface Ocean CO_2 Atlas
SOCONET	Surface Ocean CO_2 Observing Network
SPREP	Secretariat of the Pacific Regional Environment Programme
SSP	Shared Socioeconomic Pathway
TEC	Technology Executive Committee (UNFCCC)
ILK	Indigenous and local knowledge
TNC	The Nature Conservancy
UNCLOS	United Nations Convention on the Law of the Sea
UNCTAD	United Nations Conference on Trade and Development
UNEP	United Nations Environment Programme
UNEP-CCC	UNEP Copenhagen Climate Centre
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change

UN-OHRLLS	United Nations Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States
USV	Uncrewed (unmanned) surface vehicle
WEF	World Economic Forum
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
WRI	World Resources Institute


UN environment programme
CTCN
UN Climate Technology Centre & Network
United Nations Climate Change
Technology Executive Committee
UN environment programme
copenhagen climate centre