Ocean Decade
Vision 2030
White Papers

Challenge 5:
Unlock ocean-based solutions to climate change

The United Nations
Decade of Ocean Science
for Sustainable Development
(2021-2030)

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Ocean Decade Vision 2030 White Papers

Challenge 5: Unlock ocean-based solutions to climate change

Enhance understanding of the ocean-climate nexus and generate knowledge and solutions to mitigate, adapt and build resilience to the effects of climate change across all geographies and at all scales, and to improve services including predictions for the ocean, climate and weather.

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The Intergovernmental Oceanographic Commission (IOC) of UNESCO, extends its sincere appreciation to the co-chairs and members of the Working Group for their leadership and commitment in the process of drafting and authoring the present document.

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Contents

Acronyms

BBNJ	Biodiversity Beyond National Jurisdiction
CDR	Carbon Dioxide Removal
DCC	Decade Collaborative Centers
DCO	Decade Coordination Office
GOOS	Global Ocean Observation Systems
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
mCDR	marine Carbon Dioxide Removal
NbS	Nature-based Solutions
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	UN Framework Convention on Climate Change

1. EXECUTIVE SUMMARY

1.1 Introduction and Scope of the White Papers

This White Paper has been prepared as part of the Vision 2030 process being undertaken in the framework of the UN Decade of Ocean Science for Sustainable Development. The Vision 2030 process aims to achieve a common and tangible measure of success for each of the ten Ocean Decade Challenges by 2030. From a starting point of existing initiatives underway in the Ocean Decade and beyond, and through a lens of priority user needs, the process determines priority datasets, critical gaps in science and knowledge, and needs in capacity development, infrastructure and technology required to ensure that each Challenge can be fulfilled by the end of the Ocean Decade in 2030.

The results of the process will contribute to the scoping of future Decade Actions, identification of resource mobilization priorities, and ensuring the ongoing relevance of the Challenges over time. The process identifies achievable recommendations that can be implemented in the context of the Decade, or more broadly before 2030 to achieve the identified strategic ambition and indicators that will be used to measure progress.

This White Paper is one of a series of ten White Papers all of which have been authored by an expert Working Group. Accompanied by an Outcomes Report authored by the Decade Coordination Unit, this White Paper was discussed at the 2024 Ocean Decade Conference before being finalized and published.

1.2 Strategic Ambition of Ocean Decade Challenge No. 5

By 2030, success for Ocean Decade Challenge number 5 will be marked by a move toward a more sustainable and climate-resilient ocean that aligns with the United Nations' sustainable development goals. Crucially, the success of Challenge 5 is intricately linked to the outcomes of Challenges 1 to 4, which focus on understanding climate-ocean interactions, controlling marine pollution, conserving biodiversity, and ensuring sustainable food production.

Success will include the fulfillment of critical science and knowledge gaps with respect to climate adaptation and mitigation. Both approaches need to be addressed in parallel. Key mitigation approaches include the development of marine renewable energies, reduction in marine pollution, the development of blue carbon ecosystems, and marine carbon dioxide removal (mCDR). Adaptation approaches include increased ocean literacy and awareness; co-designed governance and co-operation; improved risk reduction policies; and improved predictive capability of ocean, climate, and weather forecasts.

Challenge 5 was reported as one of the most commonly cited Challenges for knowledge uptake in the Decade. However, important gaps remain in terms of the geographical scope of the actions under this and other challenges.

1.3 Key Recommendations to Achieve the Strategic Ambition

The following recommendations have been identified to ensure that the strategic ambition is fulfilled, and success achieved for Ocean Decade Challenge No. 5 if implemented by 2030:

- It is recommended to increase research into marine renewable energy, ways of reducing marine pollution, and ways of expanding vegetated coastal ecosystems which will enable global-scale implementation.
- Controlled field testing of marine carbon dioxide removal (mCDR) must be co-designed and implemented with invested communities, modeled, and monitored.
- Ocean stewardship, improved ocean literacy, and ocean-based solutions to climate change must be enhanced by a movement towards co-designed governance and cooperation, as well as capacity development among the academic sector, traditional and indigenous knowledge holders, and users.

- Adaptive governance and management should be supported by decision support tools for the assessment of vulnerability and risk to coastal communities and marine industries, and for developing climate change adaptation pathways.
- Equity in implementation: Prioritize fairness and inclusivity in the execution of mitigation and adaptation measures to ensure all stakeholders benefit equitably.

1.4 Key Milestones and Indicators for the Strategic Ambition

The key milestones and indicators that will be used to measure the achievement of the strategic ambition include:

- By 2026, Improved climate prediction and modelling capabilities to support public needs at different scales.
- By 2028, Increased number of ocean and climate forecasts and projections available to users.
- By 2030, Increased number of co-developed ocean-based solutions, including CDR technologies and adaptation activities.
- By 2030, Increased implementation and effectiveness of monitoring policies aimed at reducing overfishing, pollution, and biodiversity loss, as well as minimizing the potential negative effects of mCDR activities.

2. INTRODUCTION

2.1 Background and context of the Challenge

The challenge to "Unlock Ocean-Based Solutions to Climate Change" is a pivotal component of the United Nations Decade of Ocean Science for Sustainable Development (2021-2030)[1]. It aims to deepen our understanding of the intricate interplay between the ocean and climate driven by the imperative to tackle climate change, a defining crisis of our era.

This challenge is founded on several key factors: first, climate change impacts have been observed in marine environments, including increasing temperatures, sea-level rise, ocean acidification, deoxygenation and extreme weather events imperiling ecosystems, economies, and societies worldwide (IPCC, 2021). Given the ocean's pivotal role in the Earth's climate system, addressing its capacity to regulate climate and provide ecosystem services that are relied upon by people worldwide becomes paramount.

The ocean acts as a vast carbon sink (25%±2% of the total anthropogenic CO_2 emissions from the early 1960s to the late 2010s (Gruber et al., 2023)), absorbing heat and carbon dioxide, thereby slowing climate change on land to some extent. However, these processes trigger unintended consequences, including ocean acidification and deoxygenation, posing severe risks to marine life, ecosystems and communities reliant on the ocean for their livelihoods (Doney et al., 2009, 2020). Understanding the ocean's intricate relationship with climate is crucial for harnessing its potential as a solution to climate change.

Finally, conventional climate mitigation strategies alone are insufficient to meet the targets of the Paris Agreement (IPCC 2021, UNFCCC 2015). Ocean-based carbon dioxide removal approaches such as carbon sequestration through blue carbon ecosystems, human derived manipulations of nutrients or alkalinity could offer innovative avenues to mediate climate change, resulting in so called negative emissions. These solutions can complement terrestrial actions and expand our toolkit for mitigating climate change (Duarte et al., 2021).

[1] www.oceandecade.org/

2.2 Overview of Current Work in the Ocean Decade

The Ocean Decade is currently overseeing (November 2023) 152 actions related to Challenge 5. Twenty programmes and 90 projects are contributing in some way to Challenge 5. The Ocean Decade Progress Report 2022-2023, in an analysis of the distribution of endorsed Decade Programmes and Projects, lists eight programmes and 42 projects that contribute to Challenge 5 (UNESCO-IOC 2023). The geographical scope of the Programmes is mostly global, with most programmes under this challenge focused on observations and co-design of observations, reducing stressors (sustainable fisheries, sound, pH, oxygen and others), emissions management, blue carbon ecosystems, mCDR and forecasting/prediction. These specific actions are coordinated by the Decade Coordination Unit (IOC-UNESCO), with several Decade Collaborative Centers (DCC) and Coordination Offices (DCO) providing support to the DCU. These include the DCO for Ocean Observing, the DCC for Ocean Prediction, the DCC for Ocean-Climate Solutions (Ocean Visions 2023), and the DCC for Ocean-Climate Nexus and Coordination Amongst Decade Implementing Partners in P.R. China, all addressing different aspects of Challenge 5.

Challenge 5 was reported as one of the most commonly cited Challenges for knowledge uptake in the Decade (UNESCO-IOC 2023). However, important gaps remain in terms of the geographical scope of the actions under this and other challenges.

2.3 Importance and Relevance of the Challenge for Sustainable Development

Harnessing ocean-based solutions to tackle climate change holds immense significance for sustainable development on multiple fronts. First, it is crucial for enhancing climate resilience, particularly in the context of vulnerable coastal communities and ecosystems. Developing management strategies that account for the interconnectedness of oceans and climate and that address mitigation and adaptation is vital to strengthening the resilience of these regions (IPCC, 2019). Second, marine biodiversity is of paramount importance to the functioning of marine ecosystems and the services they provide to society. A thriving ocean ecosystem not only sustains marine life but also plays a key role in climate regulation, ensuring food security, livelihoods, and overall ecological stability. Consequently, safeguarding and effectively managing these ecosystems through ocean-based solutions such as the restoration of disturbed and destroyed ecosystems is essential for sustainable development (UN 2023).

Third, attaining this challenge offers substantial economic potential, especially through the growth of the blue economy sectors encompassing renewable energy, sustainable fisheries, and marine tourism. These sectors can serve as engines of economic growth while simultaneously mitigating the effects of climate change (World Bank and United Nations Department of Economic and Social Affairs 2017).

Lastly, fostering global partnerships and interdisciplinary collaboration, which are fundamental principles of the Ocean Decade, promotes international cooperation and shared knowledge, contributing to global peace, security, and the advancement of the Sustainable Development Goals (SDGs) (UN 2023).

2.4 Methodology for strategic ambition setting

Challenge 5 presents an important opportunity to harness the potential of ocean-based solutions to reduce the impacts of climate change. To succeed, we must prioritize scientific rigor, invest in research and innovation, and promote international collaboration to mitigate, adapt to, and build resilience against climate change while benefiting both humanity and the planet. Co-production of solutions with local and indigenous communities is essential.

Effectively addressing Challenge 5 in the Ocean Decade involves setting a strategic ambition that guides research, innovation, and action. However, it is crucial to acknowledge the uncertainties and potential side effects of ocean-based climate solutions, such as carbon dioxide removal, among others. There has been a growing focus on ocean-based CDR approaches in recent years. However, there is high uncertainty about the potential impacts of these approaches and there are little to no regulations on the safety and effectiveness of this research (Boyd et al., 2023, Loomis et al., 2022). Some of the potential consequences of CDR include nutrient depletion for natural plankton to support cultivated phytoplankton, and alteration in plankton diversity and abundance with unknown ecosystem impacts (Oschlies et al., 2010). Therefore, a cautious, scientifically rigorous approach is necessary, focusing on inter- and transdisciplinary research (Smith et al., 2020), pilot projects (Johnson and Brown, 2019), risk assessments (Jones et al., 2021), adaptive management (Garcia et al., 2018) and fostering strong connections between the scientific community and policymakers (UNESCO-IOC 2021).

The monitoring, reporting, and verification (MRV) of marine carbon dioxide removal (mCDR) is also imperative, and the efficacy of these technologies must be tested through pilot studies before scaling up to larger testing and application (Loomis et al., 2022). Similarly, these technologies can only be upscaled if the pilot studies indicate that they do not have negative ecosystem impacts (NASEM, 2022, Boyd et al., 2023). Codes of conduct and monitoring frameworks for the detection, attribution, and determination of side effects of mCDR have been published (Boyd et al., 2023, Loomis et al., 2022, Cooley et al., 2022) and must guide the development of these technologies.

3. STRATEGIC AMBITION SETTING

3.1 Analysis of user needs and priorities

Identifying and classifying the needs of users within the ocean-climate nexus can be a complex task, as it involves understanding the diverse range of stakeholders, their goals, and how they intersect with both ocean and climate-related issues. The science required to provide solutions to reduce the impacts of climate change on land and in the ocean must include mitigation and adaptation approaches tailored to local and regional capabilities (Figure 1).

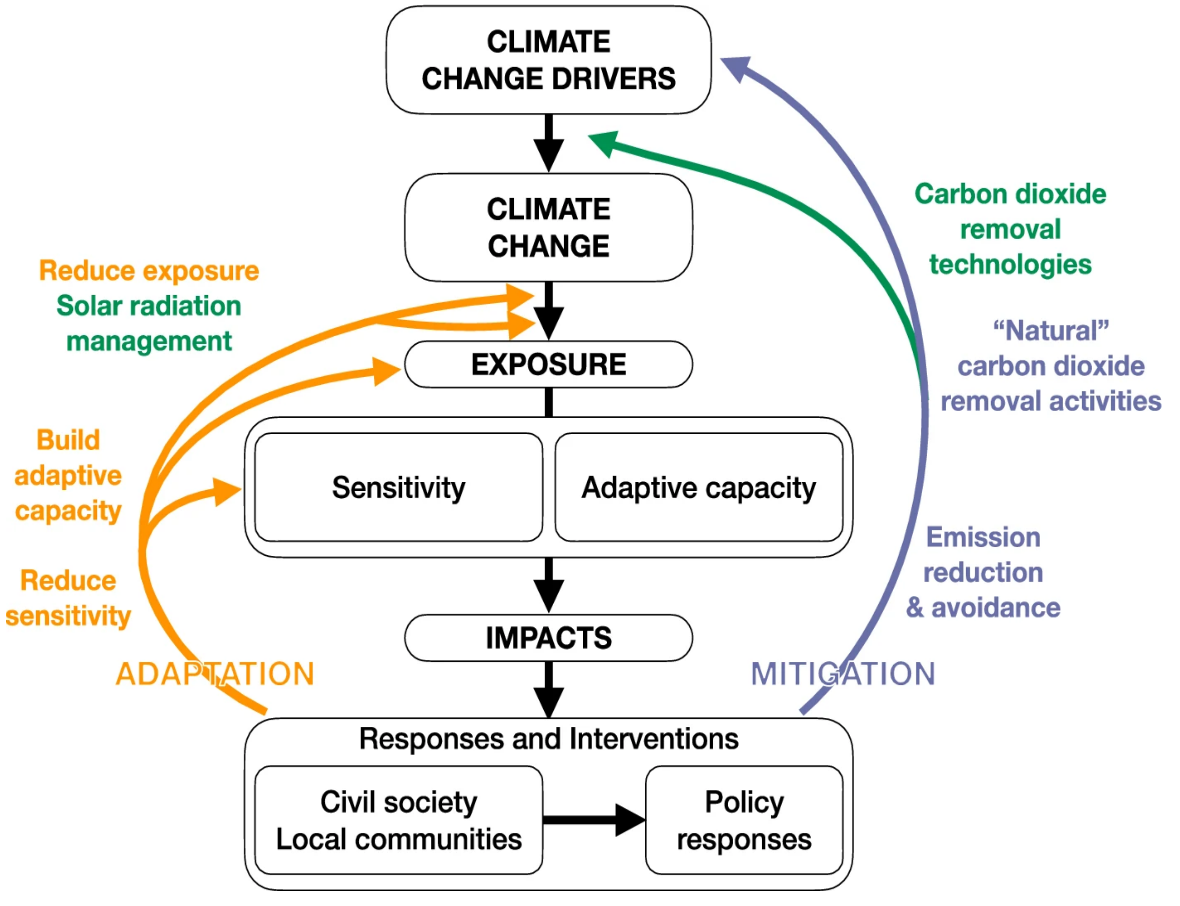

Figure 1: *Mitigation (blue) and adaptation (gold) and interventions to address the impacts of climate change. Interventions with a technological focus (sometimes collectively termed ''geoengineering'') are shown in green (Adapted from Trebilco et al., 2021 (https://link.springer.com/article/10.1007/s11160-021-09678-4/figures/2)*

High level agreements that have already, or will likely soon commit nations to several obligations related to the ocean-climate nexus and ocean solutions include:

- UNFCCC and Paris Agreement
- The Kunming-Montreal Global Biodiversity Framework (GBF)
- The Agreement on Marine Biodiversity of Areas beyond National Jurisdiction (BBNJ Agreement) or High Seas Treaty.
- The resolution at the UN Environment Assembly (UNEA-5) to End Plastic Pollution and forge an international legally binding agreement by 2024.
- 2030 Agenda for Sustainable Development

These regulations and frameworks may introduce conflicts between the various rights and stakeholders and those undertaking the regulation.

The primary beneficiaries of ocean-based solutions to mitigate, adapt and build resilience to the effects of climate change are populations threatened by the effects of climate change. These solutions will likely be provided by a set of commercial enterprises or government actors and regulated by an agent appointed by the relevant statutory authority. These groups have a shared mutual interest in satisfying themselves that these solutions are a) certified, b) effective, c) verifiable, d) economically viable and e) do not harm other components of the ocean system.

As an example, a wide range of legislation is in place that governs the legality of carbon dioxide removal interventions designed to address climate change. Arcusa & Sprenkle-Hyppolite (2022) provide an overview that suggests that the regulatory system is incredibly complex ('at least 30 standard developing organizations proposing at least 125 standard methodologies for carbon removal from 23 different CDR activities and selling 27 different versions of certification instruments in voluntary and compliance markets'). Further, they suggest that some activities have multiple regulators while others have none. They suggest that marine solutions are subject to a less comprehensive regulatory regime than land-based methods.

Multilateral Commissions and other regional management bodies can help set legally binding instruments for nations to implement the previously mentioned agreements, but they need science-based solutions to provide directions. International/intergovernmental science organizations have a role to play in developing best practices (including data management and sharing, and capacity development) for measurement of variables that show the status and impacts of mitigation and regulation.

Partnerships between the various actors in each region will be required. For example, Morgera et al., (2023) make ambitious recommendations on implementing Strategic Ecosystem Assessments at the regional level through fair research partnerships, mutual capacity-building and technology co-development between least and well-developed states (termed the Global North and South) to fill key knowledge gaps and ensure ecologically meaningful management of BBNJ, including for climate change mitigation.

An example of a fast-growing ocean-based solution, offshore renewable energy, holds immense potential to allow nations to meet their reduced emissions targets but may also negatively impact marine biodiversity and fishing activities co-located near installations. This potential conflict between offshore renewables and fishing has a range of impacts to consider, such as damage to fishing gear or property, restricted access to high value fisheries, crowding around installations or alternative fishing grounds, and loss of fishing revenue and income that affect livelihoods (Chaji & Werner, 2023). Balancing priorities and user needs is likely to vary regionally and will involve many sectors.

3.1.1 Mitigation approaches

It is important to note that marine mitigation can only meaningfully contribute to remedying climate warming if it is combined with extensive efforts to reduce emissions. mCDR or other negative emissions technologies (NETs) are not the first-line solution to climate change; mitigation of at least 80% of emissions must be the priority. It is only after massive reductions that NETs make practical sense (Ho, 2023).

In addition, a critical understanding of the human dimensions of marine mitigation approaches is necessary for generating durable and just ocean-based solutions to the climate crisis. Human dimensions include governance, policy, regulation, economic, livelihood, supply chain, and social and relational components such as perception and acceptability, for which the harms and co-benefits of marine mitigation, intended and unintended, must be identified and deliberated (e.g. Hoegh-Guldberg et al., 2023, Ocean Visions 2023). Key scientific outputs addressing the human dimensions of marine mitigation could include: spatial analyses to understand where technical, economic, social, infrastructure, and political conditions make mitigation feasible and where there may be conflicts; implications of scaling for supply chains, work force and livelihoods, and sustainability; development of model international and domestic (where applicable) legal and regulatory frameworks that accelerate field testing and account for procedural and distributional justice; and co-creation of knowledge around community and practitioner perception of the co-benefits and risks and their acceptability (NASEM 2022, Ocean Visions 2023, Smith et al., 2023).

Marine Renewable Energy

Fossil fuel dependence contributes significantly to environmental degradation and severe climate change impacts on the climate system. In this context, renewable energy emerges as a key mitigation strategy to not only mitigate climate change impact on the marine ecosystem but also foster economic growth and energy security on a global scale. The shift towards renewable energy sources is in progress across numerous regions worldwide, with renewables emerging as the second-largest contributor to global electricity production, after coal (Bosch et al., 2017).

Renewable energy sources encompass a diverse array of technologies, each harnessing a different natural process to generate sustainable power. Solar photovoltaic and wind power are two of the most competitive and low-cost options, with their combined global potential comprising an amount beyond that required to sustain ambitious mitigation strategies and limit warming below 2°C (Bosch et al., 2017, Clarke et al., 2022). Hydropower is a long-standing and widely adopted renewable energy source, with the best conversion efficiencies among all known energy sources, although its future mitigation potential depends greatly on the minimization of the environmental and social impacts.

The exploration and implementation of ocean renewables represent a grand challenge in the renewable energy sector. From offshore wind farms to wave energy technologies and tidal energy systems, these sources present vast and largely untapped potential. Beyond offering a clean and consistent power source, these technologies emphasize the importance of diversifying our energy portfolio. As the ocean renewables sector progresses, it not only holds promise for mitigating the impacts of climate change but also for catalyzing economic growth and fostering resilience in the ever-changing energy landscape.

Reducing Marine Pollution

Marine pollution is strongly interconnected with the other planetary crises of climate change and biodiversity loss. Combating marine pollution is a global challenge that needs a global approach if it is to be mitigated (UNEP 2021). Increasing population and changes in consumption patterns are driving larger waste generation. Limited waste management capabilities in some countries result in significant percentages of this waste finding its way to the ocean. This waste creates additional stress on marine organisms that are also feeling the stress of climate change. Reducing marine pollution can help give organisms more time to adapt to their changing environment, creating a more resilient ecosystem structure.

The production of products that ultimately lead to marine pollution is also a source of greenhouse gasses that contribute to climate change. Reducing waste and better managing the waste we already have, can have multiple benefits, including providing another pathway to reduced emissions.

Blue Carbon

Vegetated coastal ecosystems (mangrove forests, seagrass meadows, and tidal marshes) are characterized by disproportionately high levels of carbon sequestration (Macreadie et al., 2019; 2021) The term "blue carbon" has been applied to these ecosystems, which have drawn global attention for their role in climate change mitigation efforts (Lovelock & Duarte, 2019). Fundamental aspects of blue carbon sequestration, however, remain unresolved. These include questions about the extent to which disturbance, or restoration of these ecosystems results in the release or uptake of greenhouse gasses, how a changing climate is affecting carbon stores within mature blue carbon ecosystems, and the role of macro algae in blue carbon cycling (Macreadie et al., 2019; 2024). Low-cost diagnostic tools are lacking to set baselines and precisely track rates of sequestration in blue carbon restoration and conservation projects (Wedding et al., 2021). Finally, the impact of sea level rise on the resilience of coastal vegetative ecosystems is unclear. However, the crucial role of blue carbon ecosystems is not only for climate change mitigation, but also in achieving biodiversity conservation goals, renders the valuation of blue carbon ecosystems important even though it is challenging and disputed (Wedding et al., 2021; McHarg et al., 2022).

Marine Carbon Dioxide Removal

In addition to drastic reductions in emissions, negative emissions technologies that remove existing atmospheric carbon dioxide will be needed at the gigaton scale to achieve the climate targets set by the Paris Agreement (IPCC 2022). Some marine solutions are currently ready for large-scale deployment, such as ocean-based renewable energy and decarbonization of ocean transport, but purposeful sequestration of atmospheric CO_2 into the ocean is more of a challenge (Ho, 2023, Hoegh-Guldberg et al., 2023).

Carbonate chemistry in seawater allows the ocean to absorb vast amounts of carbon. Without the natural ocean carbon sink, atmospheric CO_2 levels would be almost 100 ppm higher than today. Thus, if human intervention could practically increase this capacity by removing and durably storing ocean carbon, excess carbon may be drawn down from the atmosphere to mitigate climate change. Ocean CDR pathways, including ocean alkalinity enhancement, forms of direct atmospheric removal with ocean storage, and nutrient fertilization, among others, are currently low in technological readiness (Hoegh-Guldberg et al., 2023), and need to undergo extensive testing to evaluate their effectiveness and potential side effects. Controlled field testing must be co-designed and implemented with invested communities, modeled, and monitored for the long-term (NASEM 2022, Hoegh-Guldberg et al., 2023, Ocean Visions 2023) before we can determine whether additional carbon sequestration can practically be engineered at the necessary scales.

A common challenge across mCDR pathways is that the natural cycling of carbon creates large fluxes to and from the ocean surface and atmosphere, as well as high rates of transformation between inorganic and organic carbon pools in the water column. Though theoretical arguments suggest more carbon uptake could be achieved through human interventions, determining if and how much additional ocean carbon uptake has occurred due to specific human activities is extremely difficult. There is a great need for the development of observational technologies and modeling capacity to support robust and standardized monitoring and carbon accounting (NASEM 2022,). High priority development is needed to improve understanding of how user communities use monitoring instrumentation and data, and what these communities might need in the future; improve ocean chemistry baseline measurements; innovate more robust sensor designs; and develop more robust model designs to improve carbon life cycle accounting (NASEM 2022, Hoegh-Guldberg et al., 2023, Ocean Visions 2023). Improved capacity for making measurements in under-sampled areas is also needed.

mCDR pathways have the potential to benefit ocean ecosystems by mitigating ocean acidification, but each also carries potential negative ecosystem impacts that must be investigated and considered in a risk analysis framework that compares them to the status quo (Hoegh-Guldberg et al., 2023, Smith et al., 2023). Science delivered to meet Challenge 5 could include the impacts of pH and saturation state changes on marine ecosystems, nutrient redistribution, changes to net primary productivity, and changes throughout the water column, including deep ocean impacts (NASEM 2022, Smith et al., 2023). Unintended consequences are also anticipated (NASEM 2022), and the knowledge base on both intended and unintended impacts needs strengthening (Gattuso et al., 2021).

3.1.2 Adaptation and Building Resilience

Adaptation is a critical component in unlocking ocean-based solutions to climate change (Figure 2). The global ocean and inland waters collectively contribute to the diets of over 3.3 billion people, supplying them with at least 20% of their protein intake, and supporting the livelihoods of 60 million people. Coastal communities, where 40% of the global population resides within 100 kilometers off the coast (UNR Seas), heavily depend on the improved predictive capability of ocean, climate, and weather models for sustainable planning and resilience.

Human adaptation comprises an array of measures that reduce harm or exploit opportunities from climate change (Cooley et al., 2022). Indeed, many adaptation approaches can deliver benefits both for mitigation and for reducing climate change impacts (Bindoff et al., 2019), at a variety of scales. Adaptation strategies in oceans and coastal ecosystems continue to be based primarily on theory because of limited evidence about implemented solutions and their success across regions, particularly in low-income nations (Cooley et al., 2022).

There is a continued need for improved modelling capabilities at different timescales, ranging from days for short-term extreme events, to seasonal prediction for tactical management, to decadal variability prediction for resilient strategies across different sectors and long-term climate predictions for strategic planning, resource management, and policy development.

However, advancing ocean, weather, and climate prediction capabilities encounter various challenges. These include improving understanding and simulating local-scale ocean processes, understanding complex interactions among different climate system components, reducing uncertainties in prediction, and bridging gaps in observation networks spatially and throughout the ocean interior. Additionally, there are computational infrastructure challenges for data intensive ocean and coastal models, and a need for global collaboration in data sharing and model development.

One priority is the need for shorter-term forecasts of extreme events such as marine heatwaves, hypoxic and anoxic events, ocean acidification, hydrogen sulphide plumes or harmful algal blooms. For areas with operational forecasting systems, it is important that these forecasts are co-developed, easily accessible and understood by users to inform their behavior and decision-making. This is because, despite significant improvements and efforts in weather forecasting and climate prediction, end users may not be aware of how to access forecasts and apply them to their daily lives and decisions. The challenge should therefore aim to bridge the gap between end users of climate forecasts and predictions and access to relevant data products.

To navigate this challenge effectively, researchers and policymakers must employ adaptive and resilient strategies that acknowledge the inherent uncertainties in climate models and projections. This involves continually refining models based on new data, advancements in scientific understanding, and improved computational capabilities. Additionally, fostering collaboration among scientists, policymakers, and stakeholders is crucial to developing holistic and informed strategies that can withstand the uncertainties associated with long-term climate modeling.

Ocean literacy – that is, enhanced understanding of the ocean, sustainable ocean use, and the climate-ocean nexus – will be an important element in achieving climate mitigation and sustainable development goals but requires the development and implementation of dedicated strategies to improve societal connections to the ocean (Kelly et al., 2022). Ocean stewardship, and ocean-based solutions to climate change, will also be enhanced by a movement towards co-designed governance and co-operation between users, including local and indigenous communities (e.g. Karrasch et al., 2017; Lyons et al., 2023). Adaptive governance and management can be supported by decision support tools for the assessment of vulnerability and risk to coastal communities and marine industries, and for developing climate change adaptation pathways (e.g. Fulton et al., 2020).

'Climate-smart' marine spatial planning - including transboundary marine spatial planning to accommodate climate-driven species redistribution - is also critical for supporting sustainable ocean management and governance (Frazão Santos et al., 2024; see also Figure 2). However, there is currently a low level of confidence in how to implement this solution to support adaptation (Figure 2). Integrated Coastal Zone Management is also central to robust adaptation planning in busy ocean spaces that are subject to climate change impacts, however there is also relatively high uncertainty in how to implement this solution in a way that is equitable, efficient and will reduce risk (Figure 2).

The ability to adapt to sea-level rise, and cope with future coastal risks and associated social conflict depends on immediate mitigation and adaptation actions. Adaptation planning needs to increase significantly in most coastal regions over the next few decades (Cooley et al., 2022). Effective responses to rising sea level require locally applicable combinations of decision analysis, public participation, and conflict resolution approaches; together, these can anticipate change and help adapt to and address the challenges due to rising sea level (Cooley et al., 2022). Updating sea-level projections for local and regional scales and reducing uncertainties are also key adaptation measures to sea-level rise. Providing scientific support to have local-scale sea-level projection for low-lying low-income countries with less research capability will be crucial. For example, projections from coarse global climate models or IPCC projections are not resolved sufficiently for Southeast Asian countries such as the Philippines, Indonesia and Vietnam. Developing countries often lack the resources to implement large-scale mitigation projects, making adaptation the more immediate and critical strategy for their survival.

Furthermore, immediate adaptations to challenges such as harmful algal blooms causing fishing-area closures, can be informed by public communications and education along with early-warning forecasts. These types of adaptations are more efficient in building trusted relationships and effective coordination among involved parties and are inclusive of diversity in a coastal community. Adaptation of climate change requires the collective action of all members of society. This means bringing together public sectors and private partners, civil society, and marginalized groups like women, youth, indigenous peoples, migrants, displaced persons and affected communities.

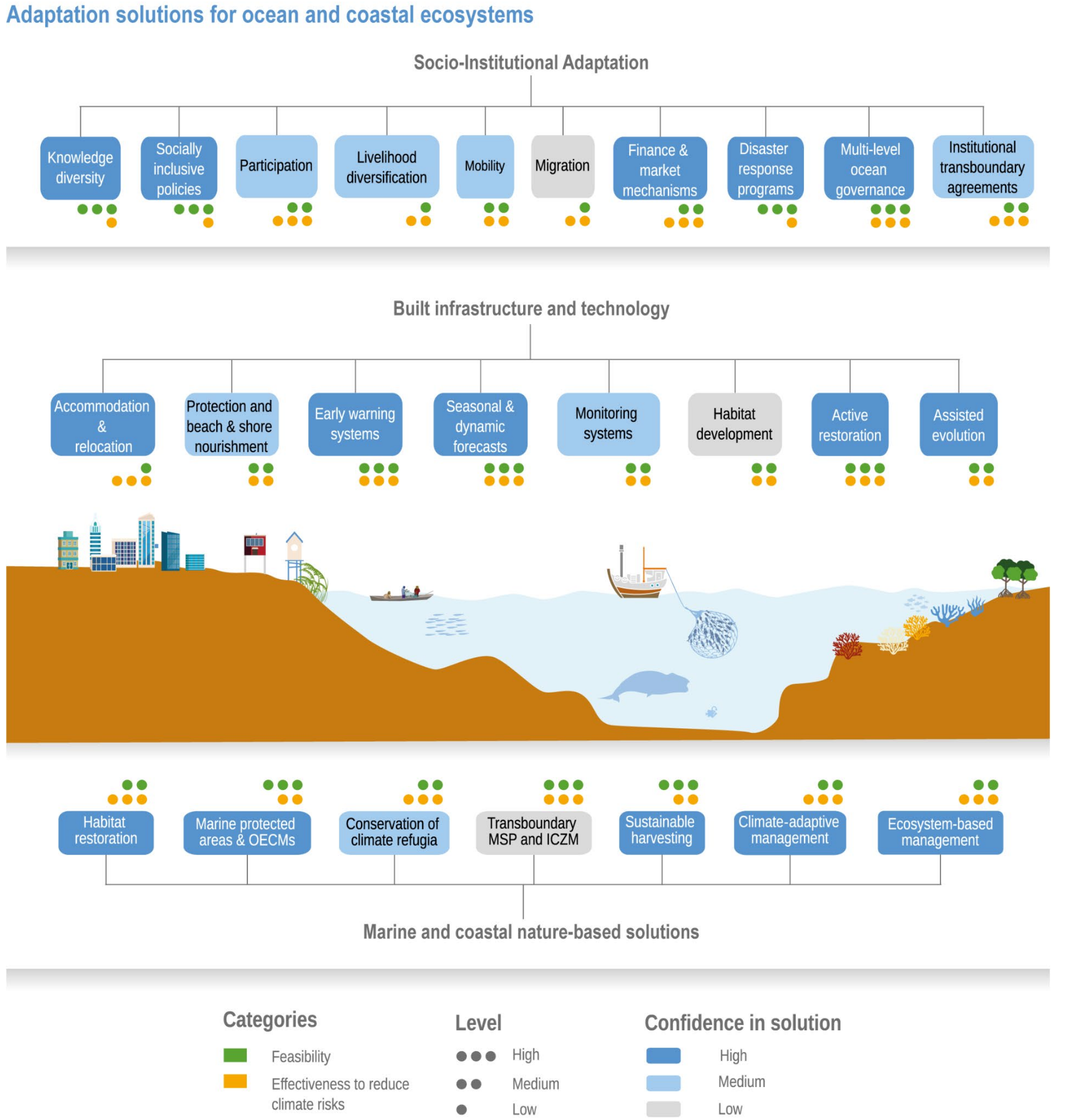

Figure 2. *Adaptation solutions for ocean and coastal ecosystems to address climate change risk in ocean ecosystems and communities. Box color indicates confidence in the solution's potential to reduce risk. The figure is adopted from IPCC AR6 WGII chapter 3. https://www.ipcc.ch/report/ar6/wg2/figures/chapter-3/figure-3-023*

3.2 Definition of the strategic ambition for the Challenge

We can ask the question: What does success look like for mitigating, adapting, and building resilience to climate change taking into account the role of the ocean and its effect on the climate?

This will be defined in terms of the provision of data, knowledge, infrastructure, personnel capacity, governance frameworks and societal engagement to enable mitigation of climate change - maintaining global temperatures below 1.5˚C warming by 2100 and to adapt to/be resilient to anticipated levels of climate change. This is summarized in Table 1.

Table 1: *Summary table linking 'science needed' with 'what success looks like'*

	PRIORITY DATASETS	KNOWLEDGE GENERATION	INFRASTRUCTURE	PARTNERSHIPS	CAPACITY	TECHNOLOGY
Challenge 5 in general	- Datasets and globally and locally relevant levels of all Essential Ocean Variables	- Vulnerability assessments for all coasts, based on academic, local and indigenous knowledge on management	- Long term observations are maintained, and regional coverage improved physical, chemical and biological observations are co-located; - Models are available at spatial and temporal scales relevant to predict future change.	- Global and regional observation systems, e.g. GOOS, Argo, Meteorological offices, private sector	- Marine managers, academic sector; - Private sector, indigenous and local knowledge.	- Access to observation technology, sustainable for all countries
Mitigation: Develop marine renewable energy	- Energy cost vs benefit; - Mapping of suitable areas for marine renewable energy.	- Improved knowledge of energy potential; - Understanding of potential unintended consequences; - Cost/benefit ratio.	- Cabled arrays to get power to shore; - Robust energy generation systems.	- Strengthened partnerships between social and ecological science researchers and the private sector developing and deploying field trials; - Improved communication and partnerships between legislators and policy makers and the private sector to enable better cross-sectoral understanding of parties' needs and concerns and accelerate implementation of controlled field trials.	- Finance; - Marine engineers; - Energy sector people.	- Innovation of more robust designs; - Innovation of more robust models.
Mitigation: Reduce marine pollution	- Finger-printing source of pollutants and their fate	- Better understanding of environmental sensitivities	- Marine debris collection systems	- Industries that generate marine debris; - Fishing industry.	- Finance private sector, in particular agriculture sector	- Efficient clean-up and recycling approaches

Mitigation: Restore and increase marine vegetation	- High quality, comprehensive and accessible biodiversity and carbonate system measurements	- Coastal ecosystem dynamics; - Improved knowledge of intended and unintended ecosystem impacts; - Spatial analyses of feasibility and use conflicts; - Improved understanding of implications of scaling of each marine NbS approach for supply chains, livelihoods, and economies; - Improved understanding of perceptions of risks, benefits, and acceptability; - Governance frameworks.	- Coastal development and regulations; - Robust MRV program.	- Blue carbon community; - Biodiversity community.	- Finance marine managers; - NGOs involved in blue carbon projects.	- Seed farms remote sensing technology to map coastal ecosystems
Mitigation: Marine Carbon Dioxide Removal	- High quality, comprehensive and accessible carbonate system measurements observations of the marine environment (biology) to determine the efficiency of the biological carbon pump	- Improved knowledge of intended and unintended ecosystem impacts; - Spatial analyses of feasibility and use conflicts; - Improved understanding of implications of scaling of each mCDR approach for supply chains, livelihoods, and economies; -Improved understanding of perceptions of risks, benefits, and acceptability governance frameworks.	- Robust MRV program; - Designated areas for mCDR testing.	- CDR companies	- Monitoring community development	- Innovation of more robust sensor designs; - Innovation of more robust model designs.
Adaptation: Increased ocean	- Data on existing and planned ocean literacy	- Improved understanding of how the impacts may alter behavior;	- Information coordination center	- Science media; - Science writers;	- Mass media	- Improved storytelling and scenario testing tools

literacy / awareness	activities, including scope, audience, ways of implementation.	- Ability to crowdsource solutions for adaptation.		- Educators in schools and universities.		
Adaptation: Co-designed governance and co-operation	- Data of existing governance structure related adaptation in open ocean and coastal areas	- Build on all available sources of information; - Co-designed management plans.	- Ocean conservation lobbyists	- NGOs, governments at all levels	- Connections to government bodies	- N/A
Adaptation: Improved risk reduction policies	- Data on existing and planned risk reduction policies, including how the ocean is accounted for, sectors, enforcement. Risk assessment support tools.	- Environmental information to inform policies	- Knowledgeable policy writing centers; - Climate-smart marine spatial planning; - Integrated ocean management.	- Policy makers; - Social science insurance companies.	- Improved assessment capacity	- Computing capacity
Adaptation: Improved predictive capability of ocean, climate and weather forecasts	- Observations of physical, biogeochemical and biological variables. Link with GOOS, GCOS	- Robust integrated models and underlying knowledge of drivers	- Computing facilities	- Operational weather forecasting community	- Higher resolution integrated models and data to support regional planning	- Computing capacity

3.3 Integration, synergies, and interdependencies with other Challenges

Achieving success in addressing ocean challenges, particularly Challenge 5, the climate-ocean nexus, entails seamless collaboration and integration across challenges, including marine pollution, biodiversity conservation, sustainable development, and equitable resource access. Such success creates a resilient ocean that aligns with the United Nations' sustainable development goals. Crucially, the success of Challenge 5 is intricately linked to the outcomes of Challenges 1 to 4, which focus on understanding climate-ocean interactions, controlling marine pollution, conserving biodiversity, and ensuring sustainable food production. For instance, a deeper comprehension of climate-ocean interactions (Challenge 1) is vital for informing climate-resilient solutions, while effective marine pollution control (Challenge 2) is imperative for maintaining the health and integrity of the ocean ecosystem. Enhancing community resilience (Challenge 6) is essential for fostering adaptive capacities in the face of climate change impacts, reinforcing the overarching resilience objectives. Expanding ocean observations (Challenge 7) provides critical data for understanding and responding to climate-related challenges, directly supporting the scientific foundation of Challenge 5. The creation of digital ocean representations (Challenge 8) facilitates advanced modeling and simulation, aiding in the development of innovative solutions for climate resilience. Promoting knowledge and skills (Challenge 9) ensures a well-equipped workforce capable of addressing the complexities of Challenge 5, while the transformation of humanity's relationship with the ocean (Challenge 10) establishes a sustainable and harmonious coexistence with this vital ecosystem.

4. MILESTONES AND INDICATORS

4.1 Key milestones to measure progress and success

The key milestones for challenge 5 connect with the common milestones found in the Vision 2030 process as illustrated below.

Milestone 1: Enhanced Ocean Data Accessibility and Availability

Improved understanding of the mitigation potential, development, environmental risks and safe scaling and deployment of effective mCDR technologies and nature-based solutions (NbS) approaches.

Improved ocean forecasting, climate prediction and modelling capabilities to support public needs at different scales.

Improved access to impact studies for environmental impacts, to set realistic targets for CO_2 removal using different technologies and to use available data required for all evaluation criteria.

Milestone 2: Advancement in Ocean Knowledge Sharing

Increased number of ocean and climate forecasts and projections available to users.

Milestone 3: Building Capacity for Ocean Decade Challenges

Improved observational, experimental, modelling, and technological capacity to ensure the Ocean-Climate Nexus is maintained.

Milestone 4: Sustainable Policy and Governance Implementation

Development of a standardized and accepted framework for the monitoring of mCDR activities.

Development and implementation of a policy and governance framework to guide CDR research and technologies, assess potential side effects and minimize negative impacts.

Increased implementation and effectiveness monitoring of policies aimed at reducing overfishing, pollution, and biodiversity loss.

Avoidance of action-induced conflicts between climate, biodiversity and social well-being.

Seek solutions with sustainable (win-win-win) outcomes that do not undermine global biodiversity and the Sustainable Development Goals.

Milestone 5: Inclusive Stakeholder Engagement

Increased number of co-developed, co-produced and co-evaluated ocean-based solutions, including NbS, mCDR technologies and activities like forecasts.

Set a quantitative global goal for adaptation (e.g. climate funding for adaptation, number of vulnerable communities adapted, reduction of impacts/risks).

Milestone 6: Societal and Environmental Impact

Improvement in the health and integrity of the ecosystems affected by climate change.

Increased resilience of communities, ecosystems and sectors to the impacts of climate change.

Reduced vulnerability of communities and ecosystems to climate change.

Adoption and promotion of resource-efficient and sustainable practices.

Milestone 7: Increased Funding for Decade Actions

Increased climate finance for ocean-based solutions to achieve the global goal for adaptation.

Milestone 8: Diverse and Inclusive Decade Actions

Increased measurements of diversity, equity, and inclusivity in the milestones.

Number of new programmes and projects initiated that focus on addressing underrepresented topics or geographic regions.

Diverse allocation of resources. Percentage increase in the allocation of resources to Decade actions targeting underrepresented areas.

Number of partnerships established with organizations and stakeholders from underrepresented regions to foster collaboration and knowledge exchange.

Measurement of stakeholder satisfaction and feedback on the implementation of programmes and projects.

Milestone 9: Advancement in Ocean Technology and Innovation

Increased modeling capacity and technologies to support robust and standardized monitoring and carbon accounting.

Milestone 10: Enhanced Utilization of Ocean Science and Knowledge

Number of workshops, seminars or training sessions conducted to disseminate ocean solutions knowledge among diverse stakeholders, demonstrating the efforts to enhance public awareness and understanding of ocean-related issues.

Percentage increase in the utilization of available ocean data by research institutions, governmental bodies, and non-governmental organizations, indicating the growing reliance on existing data for scientific studies and decision-making.

Percentage increase in the integration of ocean science-based knowledge in sustainable development strategies, showcasing the influence of scientific knowledge on decision-making.

Number of sustainable practices and technologies derived from ocean science, indicating tangible contributions to sustainable development goals.

4.2 Indicators to track the achievement of the strategic ambition

The indicators used to track the progress achieved by Challenge 5 are 1) the number of knowledge products produced disaggregated by (i) type of product and (ii) inclusion of indigenous and local knowledge (generation of knowledge) and 2) Number of references to knowledge products by users disaggregated by type of use (IOC-UNESCO, 2023). In addition, we propose the following indicators to measure progress in achieving the strategic ambition:

Priority datasets to unlock or to generate:

- Registry/Number of mCDR activities and other ocean-based solutions
- Number (% of total) of impact studies associated with the mCDR activities, including feasibility and effectiveness assessments
- Oceanographic and atmospheric datasets at appropriate resolution to quantify the impact of climate change on the ocean's ability to absorb atmospheric carbon dioxide and determine the effectiveness of mCDR activities
- Integrated assessments of vulnerability and risks for different regions and sectors to the impacts of climate change and mCDR technologies
- Valuation of Ocean Climate services
- Seasonal and decadal-scale forecasts/predictions at appropriate scales
- Identification and quantification of carbon sequestration hotspots worthy of protection to prevent the release of carbon and greenhouse gases.

Knowledge to generate or to share

- Number of operational forecasts per continent/basin
- Knowledge and understanding to underpin the implementation of ocean management that is dynamic and adaptive to a changing environment and changing uses of the ocean (implementation plan, p.28-31)
- Knowledge of the ocean's role in climate regulation
- Improved understanding of the marine carbon cycle and the effects of human activities
- Knowledge of the potential, costs, risks, impacts and co-benefits of mCDR technologies
- Best practices from case studies successfully implementing adaptation options to climate change.

Infrastructure required to generate or share data or knowledge or to build capacity and skills

- Cloud infrastructure e.g. https://gallery.pangeo.io/repos/pangeo-gallery/cmip6/ with sustained support available to endorsed actions
- Number of platforms measuring ocean carbon and essential ocean variables related to mCDR.

Partnerships and financial or in-kind resources to generate and ensure uptake of knowledge

- Number of climate- and ocean-smart investments supporting ocean and nature-based solutions.

Capacity development and exchange needs

- Number of capacity building /development activities by type (i.e. mentoring programmes, exchange programmes, number/amount of travel support for ECRs
- Number of webinars/seminars/communication activities raising societal awareness of climate change, impacts and the role of the ocean in climate regulation
- Inclusion (and extent) of ocean-based solutions to climate change in policy and governance negotiations.

Technology and innovation solutions including those required for uptake of knowledge.

- Increased robustness and capacity of computational modelling systems (e.g. enhanced processing units and data centres).

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United Nations Decade of Ocean Science for Sustainable Development (2021-2030)

Proclaimed in 2017 by the United Nations General Assembly, the UN Decade of Ocean Science for Sustainable Development(2021-2030), provides a convening framework to develop the scientific knowledge and partnerships needed to catalyse transformative ocean science solutions for sustainable development, connecting people and our ocean. The Ocean Decade is coordinated by UNESCO's Intergovernmental Oceanographic Commission (IOC).

Established during the Preparatory Phase and to continue throughout implementation until 2030, the IOC's Ocean Decade Series will provide key documentation about this global initiative and aims to serve as a primary resource for stakeholders seeking to consult,monitor and assess progress towards thevision and mission of the Ocean Decade.

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