Ocean Acidification Research for Sustainability

A Community Vision for the Ocean Decade

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Intergovernmental Oceanographic Commission

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

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OARS Ocean Acidification Research for Sustainability

GOA-ON Global Ocean Acidification Observing Network

IAEA Ocean Acidification International Coordination Centre OA-ICC

OAP NOAA Ocean Acidification Program

PML Plymouth Marine Laboratory

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Foreword

Peter Thomson
United Nations
Secretary-General's Special
Envoy for the Ocean

Over the past three years, the global community has begun work on the UN Decade of Ocean Science, to give us the Science we need for the Ocean we want. It remains imperative to emphasise that scientific research and evidence must be the basis of effective national and international policy needed for human security on this planet.

In pursuit of reliable science, we look to the Global Ocean Acidification Observing Network, known as GOA-ON, for global leadership on ocean acidification research and for continuing facilitation of coordination of efforts, knowledge sharing, and capacity building. Building upon GOA-ON›s foundation, I am delighted to witness the progress of the UN Decade-endorsed programme: Ocean Acidification Research for Sustainability (OARS). OARS offers a vision of how we can develop and utilise scientific evidence to provide societally relevant future predictions, raise public awareness of ocean acidification and shape effective policy. I extend my best wishes to all involved in the OARS programme and encourage the use of these white papers as a guide to advancing ocean acidification research and action.

Peter Thomson
22 February 2024

Preface

Vladimir Ryabinin
Executive Secretary of the Intergovernmental Oceanographic Commission of UNESCO

In 2010, the Intergovernmental Oceanographic Commission of UNESCO hosted in Paris the first "Ocean in a High CO2 World" Symposium. Since then, the IOC-UNESCO's commitment to globally lead, facilitate, and coordinate the research and observation of ocean acidification has been only strengthening, and the scope of activities has been constantly broadening. Adoption in 2015 of the UN 2030 Agenda with the Ocean Sustainable Development Goal 14 opened a new page in this work. IOC became the custodian agency for informing the world about progress in achieving of the Sustainable Development Goal Target 14.3: Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels. Finally, in 2021, a new era in this work arrived when IOC-UNESCO started to coordinate the implementation of the UN Decade of Ocean Science for Sustainable Development, guided by the vision of "the science we need for the ocean we want."

Modern leadership is in partnership, and the Ocean Decade has taken the cooperation in ocean sciences to new heights. The global ocean acidification research community responded to the Decade call by co-designing a pioneering UN Decade programme entitled "Ocean Acidification Research for Sustainability" (OARS). The programme is led by three partners: Plymouth Marine Laboratory (UK), University of Washington (USA), and IOC-UNESCO. OARS provides the blueprint to foster cooperation of ocean acidification research, improve understanding of the impacts of the phenomenon and, ultimately, develop approaches for mitigating its effects by acting on sources and identify adaptation approaches.

The OARS white papers in this publication summarize where the global community currently is on this path and what should be done in the future to include the ocean acidification dimension for combatting the degradation of ocean health under various anthropogenic stressors including the changing climate.

Let me invite you to join the OARS community, along with the IOC and its partners, and become a part of the vibrant Ocean Decade movement. Working together, we will provide society with the observational and scientific evidence to sustainably monitor, mitigate, and adapt to ocean acidification at local, regional, and global scales.

Vladimir Ryabinin
22 February 2024

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Co-designing Ocean Acidification Research for Sustainability

Co-leads of OARS

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Ocean Acidification is a global phenomenon, resulting from the absorption of atmospheric carbon dioxide (CO_2) by the world's ocean. As human activities, particularly the burning of fossil fuels, release more CO_2 into the atmosphere, a significant portion is absorbed by the ocean, leading to a decrease in seawater pH and changes in other carbonate chemistry parameters. This shift towards acidity poses severe threats to marine life and human livelihoods.

Addressing the causes and consequences of ocean acidification is imperative for the preservation of marine life and the overall health of the planet and society. By understanding, mitigating, and adapting to the impacts of ocean acidification, we can strive to safeguard the health and resilience of our ocean and the countless species that depend on them, including humans. In 2004, at the first Ocean in a High CO_2 World Symposium[1], the ocean acidification community joined together to identify pressing knowledge gaps and to assess the existing understanding of ocean acidification (OA). Shortly followed by a landmark publication by The Royal Society of the UK (The Royal Society, 2005), the field of ocean acidification observing and research expanded rapidly.

Awareness of ocean acidification is a first step, but in order to be able to combat its impacts we have to develop new strategies, addressing the causes, and ways to mitigate and adapt to the consequences. During the subsequent two decades an enormous amount of fundamental research has been undertaken, vastly expanding our understanding of the topic. However, with this increasing understanding we also revealed greater complexities and details that required yet further studies. Initially considered to be a relatively simple, largely open ocean, chemical phenomenon, it became clear that the influence of ocean acidification reaches into almost every part of the marine system, from ocean gyres and the deep ocean to shallow coastal bays and estuaries. It can be exacerbated and accelerated by other biogeochemical processes, widespread in coastal areas, such as nutrient cycling and eutrophication. We have seen how it touches upon the fundamental ecological and physiological processes that underpin the survival of marine life, threatening whole ecosystems and those human livelihoods that depend upon them.

Twenty years on from that initial recognition of Ocean Acidification as a global environmental threat, fundamental research and observations continue, but there remains much still to be done in terms of broadening the scope and depth of our knowledge. Due to inequities in the access to resources, capacities and

1 SCOR/ IOC Planning Committee: https://tos.org/oceanography/assets/docs/17-3_scor_ioc.pdf

capabilities, large parts of the 'world's ocean and seas remain unstudied and unmonitored in terms of ocean acidification. Widely applied, practical solutions for mitigating and adapting to the impacts are still lacking. Recognizing this, the global ocean acidification science community, led by the Global Ocean Acidification Observing Network (GOA-ON), responded to the call of the UN Decade of Ocean Science for Sustainable Development[2], and put forward a roadmap for **the ocean acidification science we need for the ocean we want** (Dobson et al 2022). This vision, the Ocean Acidification for Sustainability (OARS) programme[3] was formally endorsed by UN Ocean Decade in 2021. This programme provides a blueprint for action to deliver towards the SDG target 14.3, "Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels".

In order to deliver the OARS vision of **providing society with the observational and scientific evidence needed to sustainably identify, monitor, mitigate and adapt to ocean acidification; from local to global scales**, seven Outcomes[4] were defined. This Technical Report sets out, for the benefit of the whole ocean community, scientists, science communicators, policy makers and stakeholders, the relevant outputs, activities, and enablers that will be required for these Outcomes to be achieved. The following chapters outline how each one of us can contribute to tackling the ocean acidification crisis.

The OARS Outcomes and the following chapters

The Ocean Acidification Research for Sustainability programme aims to deliver seven Outcomes by the end of the decade:

1. Quality Data

The global science community will be equipped to provide the high quality, high quantity and high-resolution ocean acidification data needed.

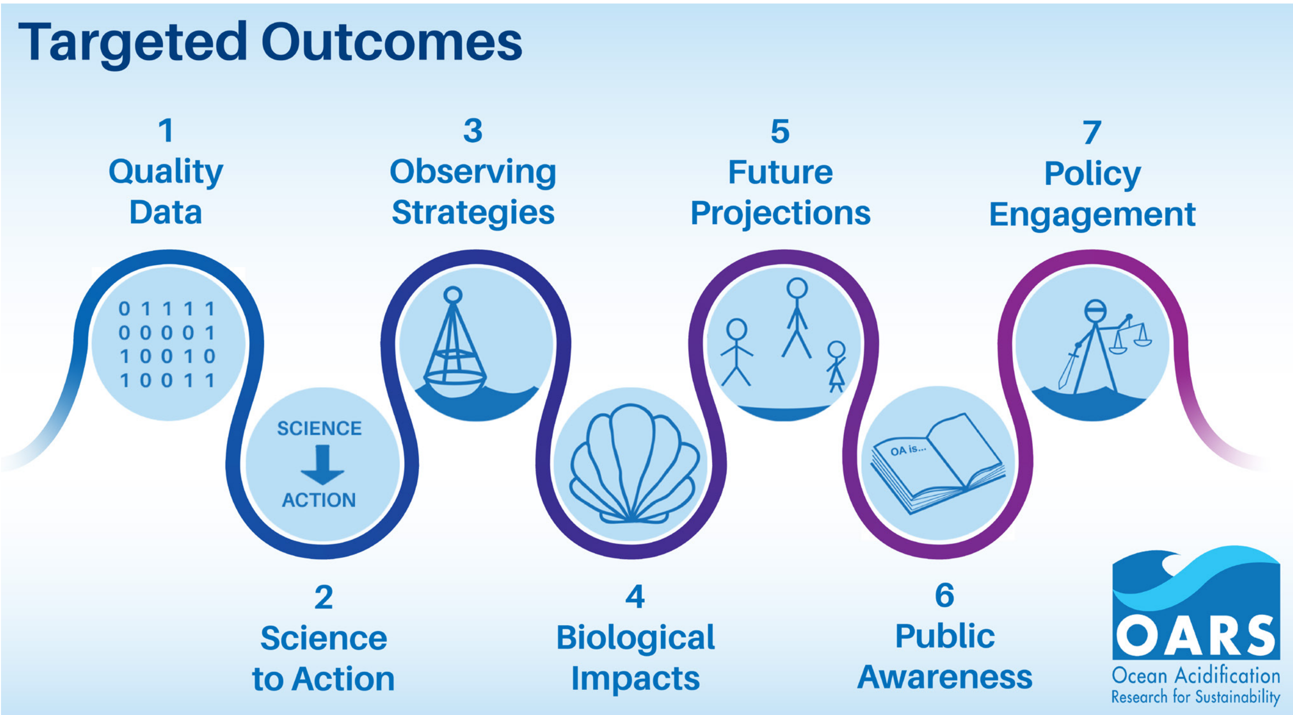

Figure 1: Overview of the seven OARS *Outcomes*.

2 UN Decade of Ocean Science for Sustainable Development : https://oceandecade.org
3 Ocean Acidification Research for Sustainability (OARS): http://goa-on.org/oars/overview.php
4 OARS proposal: See http://www.goa-on.org/oars/docs/oars-proposal.pdf

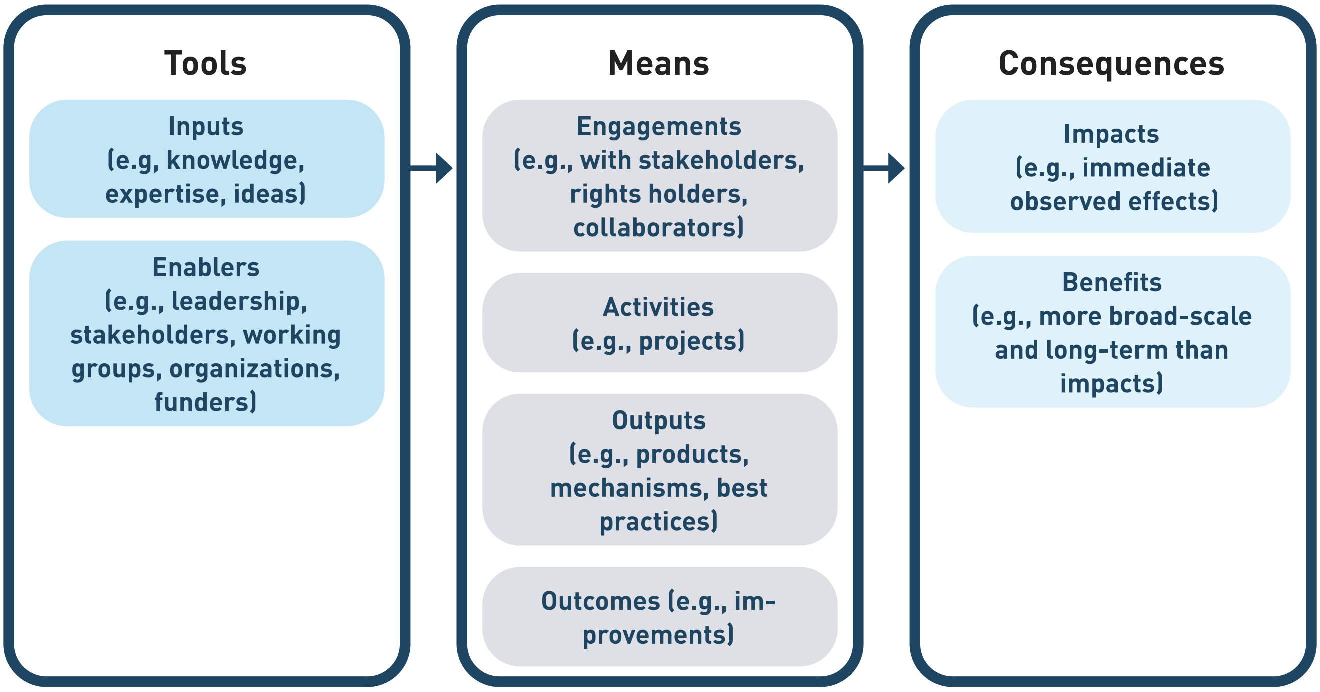

Figure 2: The framework provided by the ToC process: by identifying the positive consequences (impacts and benefits), which each OARS Outcome is aiming to achieve by 2030, the "co-champions" and their working groups are able to identify the means (engagements, activities, outputs, and outcomes) and tools (inputs and enablers) needed to facilitate achievement of those positive consequences, ultimately providing them with a pathway to success (Figure adapted from Dobson et al., 2022).

2. Science to Action

Specific data and evidence needed for mitigation and adaptation strategies, from local to global, will be clearly identified and provided.

3. Observation Strategies

Long-term ocean observing systems will be co-designed and implemented by scientists, funders and end-user partnerships.

4. Biological impacts

The risks and severity of ocean acidification impacts on marine organisms and ecosystems will be better understood and used to support the protection of marine life.

5. Future projections

Societally relevant predictions of the impacts of ocean acidification will be freely available.

6. Public Awareness

The public will be more ocean acidification literate, aware of its causes and impacts.

7. Policy Engagement

Countries and regions will routinely include measures to reduce ocean acidification in their respective national legislation.

By employing a Theory of Change (ToC) framework (Oberlack et al., 2019) for each Outcome, and with the co-design of science in mind, this technical report contains seven papers describing a detailed vision for each OARS Outcome **(Figure 2)**.

Transformative, transdisciplinary OA research requires collaborative implementation of a co-designed vision. The following principles provide the framework for each Outcome paper: (1) focusing on the science, (2) building a good team with strong leadership, (3) outcome-driven structure, (4) effective communication, and (5) measuring success (Dobson et al. 2023). The Outcome paper drafting process was led by experts from within the OA scientific community who have been identified as "co-champions" to direct each of the seven OARS Outcomes in outlining the actions necessary for their delivery. To do this, co-champions formed working groups with experts and representatives relevant to the respective Outcome, comprising OA specialists, non-governmental organizations, inter-governmental organizations, and funding agencies.

The vision for *Outcomes 1-7* as detailed over the course of this technical report will initiate the implementation phase of OARS in a coherent and inclusive manner, aiming to engage a broader community in producing and using ocean acidification research for sustainability.

If after reading this technical report you are inspired to undertake some of the activities and actions described, there are 3 practical ways to link your efforts to the overarching OARS programme and join us in tackling ocean acidification:

1) Volunteer to join one of the seven OARS Outcome working groups. To apply, potential candidates are requested to send a short CV (2 pages maximum) and a 1 page letter of interest describing which working group you would like to join, your motivation for self-nominating and the skills you would look to provide, to secretariat@goa-on.org.

2) Submit your current or proposed activities and actions for official endorsement the UN Ocean Decade action process[5] and link your action to the OARS programme.

3) Submit a voluntary commitment to undertake OARS relevant work *via* the OARS Commitment process[6]. In doing so we will be able to provide visibility for your efforts and celebrate your contributions with the rest of the ocean acidification community. We also would expect that great visibility of your commitments may inspire other to also act and join the global effort to minimize and address the impacts of ocean acidification.

5 UN Ocean Decade: https://oceandecade.org
6 OARS Committments: https://oars-commitments.org

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OARS Outcome 1:

The global science community will be equipped to provide ocean acidification data and evidence of known quality

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A major goal of the UN-endorsed OARS Programme (Ocean Acidification Research for Sustainability) is to build the capacity required to ensure that the world has ocean acidification (OA) science capability on a global scale. The mission of OARS *Outcome 1* is to enable the global scientific community to provide adequate OA data and data synthesis products to allow determination of the progress and trends of acidification throughout the world's ocean. To reach this goal, scientists and stakeholders need the resources and capacity to make sustained observations of known quality, and to integrate these data into national, regional, and global synthesis products.

Integrating OA data across the myriad of observing platforms and systems that are used globally requires that the observations are made using standardized methods with recognized calibration procedures and are accompanied by adequate supporting information including an assessment of data quality information (metadata). These data should then be made widely available, according to the FAIR (Findability, Accessibility, Interoperability, and Reusability) principle, and can then be combined and analyzed using commonly agreed methods and data analysis techniques. Determination of OA trends requires that the data provision is part of a globally coordinated, sustained, long-term observation network, with regional and/or global data compilation.

The infrastructure required to achieve this goal is already well-developed for many parameters, however, there are some restrictions and vulnerabilities that need to be addressed so that all relevant physical, chemical, and biological OA observations contribute to a globally integrated data delivery system. Increasing the capability of the OA community globally will be achieved via resource and capacity development, mentoring of early career scientists, facilitating data sharing, growing regional data management capabilities, increasing communication through meetings and workshops, and allowing for holistic approaches while considering all stakeholder perspectives.

Five Pillars will form the foundation for increasing the availability of data and data products to the global OA community, each with a Working Group and Action Plan:

O1P1. Sustained and integrated physical, chemical, and biological observations

O1P2. Submission and archiving of quality-controlled data within national and regional data centers

O1P3. Production of data synthesis products tailored to end-users

O1P4. Capacity building and mentoring

O1P5. Communication and collaboration building

O1P1. Maintain, sustain, and enhance high-quality integrated d physical, chemical and biological observations (Coordinated with *Outcomes 3* and *4*)

Assessments of the state and trend of OA require sustained observing programmes of physical, chemical, and biological parameters and derived products. The Global Ocean Acidification Observing Network (GOA-ON)[7] defined "climate" and "weather" measurement quality goals, where "climate" quality data are of a quality sufficient to assess long term trends with a defined level of confidence, thereby allowing detection of the long-term anthropogenically-driven changes in hydrographic conditions and carbon chemistry over multi-decadal timescales. "Weather" quality data are sufficient to identify relative spatial patterns and short-term variation, and support mechanistic interpretation of the ecosystem response to and impact on local, immediate OA dynamics. Both "climate" and "weather" quality data are required to achieve OARS *Outcome 1* goals.

Long-term, ship-based, open ocean time series such as the Bermuda Atlantic Time Series (BATS)[8], the Hawaii Ocean Time Series (HOT)[9], and several moored autonomous time series have been making climate-quality measurements for enough time such that long-term OA trends emerge from the natural variability. Time series measurement programmes in coastal areas where the natural temporal variability is high are generally not long enough or frequent enough for any long-term trend to emerge just yet. There are, however, a few coastal sites where long-term physical, chemical, and biological co-located measurements allow assessment and attribution of OA trends and drivers.

In conjunction with OARS *Outcome 3*, an evaluation of the capability of the existing observing capacity will be made. This will consider which variables need to be measured and the required accuracy and spatial and temporal resolution as well as what platforms are required in order to deliver the data products needed to determine the progress and trends of OA throughout the world's ocean.

Increasing the number of locations and ecosystem types where such long-term observations are made will allow the assessment of local and regional responses, and will contribute to the understanding of spatial differences in a global context. Reliable sensors, tools, resources, and human capacity that are required to achieve this objective include standard operating procedures (SOPs), appropriate reference materials (RMs), agreements on measured parameters, common methods for analyzing time series data, increased capacity of qualified personnel, and required analytical equipment.

The rapid development of new low-cost reliable sensors as well as SOPs and best practices for making OA-relevant physical, chemical, and biological observations are required by well-equipped laboratories and observing platforms that make "climate" quality measurements and also by those laboratories who make "weather" quality measurements. In many cases, the expertise and capability to make OA observations are only just beginning to be developed, and well-established SOP methodologies suitable for those observing programme are required. While some SOPs already exist (e.g., Dickson et al. 2007, Riebesell et al. 2011), including those modified for low-cost methods (e.g., GOA-ON in a Box Kits[10]), in some cases updates are clearly needed (e.g., OA sensor quality-assurance (QA) SOPs, best practices for collecting and analyzing biological samples, etc.). There is also a need to improve in situ ocean carbonate system sensor technologies by

7 Global Ocean Acidification Observing Network (GOA-ON): goa-on.org
8 Bermuda Atlantic Time Series (BATS): bats.bios.asu.edu
9 Hawaii Ocean Time Series (HOT): hahana.soest.hawaii.edu/hot
10 GOA-ON In a Box Kits: www.goa-on.org/resources/kits.php

improving measurement accuracy to meet GOA-ON's climate-quality measurement targets, lowering costs, improving ease of use, and making required sensor refurbishments and recalibrations more accessible to the entire global community (coordinated with OARS *Outcome 3*).

The utilization of appropriate RMs by all laboratories and observing platforms will enable measurements made using different methodologies to be integrated, using statistical techniques. Equitable and practical access to relevant RMs, along with training in quality control (QC) management and metadata reporting, is therefore a key component for realizing this goal.

There is a large demand in the OA observing community for training (and re-training) in data QC techniques. Community-developed best practices for level 1 Primary QC (i.e., data QC completed by data collector prior to data analysis and submission to data archive) of OA chemical data do not currently exist. Standardized data QC protocols are typically developed for use within lab groups, with some transfer of knowledge through formal and informal collaborations between groups. Given the recent expansion of scientists collecting OA observations, there is a need for community-developed information that is accessible online to aid in learning and putting into practice data QC techniques. This online package should include QC techniques for OA chemical data, data QC best practices such as flagging conventions, and how to estimate data uncertainty. To advance the development of these tools, a team of experts in data QC methods will need to be coordinated and supported to host workshops and develop this content for the community.

Common methods for analyzing time series data allow trends from different locations to be legitimately compared, thereby contributing to a global assessment of the state of change of the OA status of open ocean and coastal waters. A product of OARS *Outcome 1* will include published best practices for characterizing long-term trends in OA time series observations to facilitate global time series comparisons and communicate OA trends within and outside the scientific community. The organizations supporting coordination efforts within the ocean carbon and biogeochemistry community, such as GOA-ON and the International Ocean Carbon Coordination Project (IOCCP)[11], should support regular forums for sharing results and new techniques in trend analysis. These forums are essential, so the community can revisit and update these best practices as observational records increase in length and number and as research advances on OA trends.

Outputs and Products

- Evaluate the capability of the existing observing capacity considering which variables need to be measured, at what uncertainty, at what spatial and temporal resolution, and which platforms are required in order to deliver the data products needed to determine the progress and trends of acidification throughout the world's ocean.
- A long-term and resilient system for the provision of adequate, traceable Reference Materials (RM, commonly referred to as Certified Reference Materials, CRMs) to the carbon observing community globally. Such a system will most likely consist of several regional hubs (e.g., American, Euroafrican, and Asia Pacific) in partnership with National Metrology Institutes (NMIs). This would enable the separation of the certification function from the production and distribution of RMs. Development of associated SOPs for the preparation of secondary and in-house standards will be required to ensure equitable and practical access to RMs. Ultimately, multiple RMs for different environmental conditions, and different chemical species (i.e., pH, fCO_2, and isotope ratios $^{12}C/^{13}C$) will be available.
- Develop SOP methodologies for lesser resourced labs, including for OA sensor QA, and collecting and analyzing biological samples.
- Improve in situ ocean carbonate system sensor technologies by improving measurement accuracy to meet GOA-ON's climate-quality measurement targets, lowering costs, improving ease of use, and making required sensor refurbishments and recalibrations more accessible to the entire global community (coordinated with OARS *Outcome 3*).

11 International Ocean Carbon Coordination Project (IOCCP): www.ioccp.org

Enablers

The primary enablers for this Pillar are the global network of observationalists and ocean acidification scientists who comprise GOA-ON.

Important partners include:

- Modelers to evaluate the adequacy of the measuring network to achieve the OARS *Outcome 1* goals and recommend cost-effect improvements.
- Providers and certifiers of RM, in particular the National Metrology Institutes (NMIs), including the National Institute of Standards and Technology (NIST, USA)[12] and the European Association of National Metrology Institutes (EURAMET).[13]
- Laboratories producing and distributing in-house and working RMs on a sustained basis.
- Experienced scientists willing to develop SOPs, including from The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP).[14]
- Sensor developers to improve the availability of high quality and/or low-cost sensors for OA relevant physical, chemical, and biological parameters.
- Sensor manufacturers to produce, refurbish, maintain, and recalibrate instruments.

01P2. Submission and archiving of quality-controlled data

The production of OA data and data products that are available to a variety of stakeholders and end-users requires that data and associated metadata arising from observation programmes globally are made readily available to the community.

Utilizing the International Oceanographic Data and Information Exchange (IODE)[15] structure of National Oceanographic Data Centres (NODC), IODE Associate Data Units (ADU) and IODE Global Data Assembly Centre (IODE GDAC) will reduce cost, and avoid the proliferation of data centers, and allow compatibility with providers of other ocean data. The IODE already hosts the Sustainable Development Goals (SDG) 14.3.1. Data Portal, a tool for the submission, collection, validation, storage and sharing of OA[16] data and metadata submitted towards the SDG indicator 14.3.1: Average marine acidity (pH) measured at agreed suite of representative sampling stations.

An international OA data integration/ingestion system is envisioned to provide primary and secondary data quality control guidelines and tools that are implemented by data originators and submitted to relevant data centres. The GOA-ON Data Portal for metadata can be enhanced to provide a one-stop OA data shop.

OA data and metadata should follow the FAIR Guiding Principles for scientific data (Wilkinson et al., 2016), i.e., be Findable, Accessible, Interoperable and Reusable. Incorporation of coastal data, particularly those from indigenous peoples, may require additional CARE (Collective Benefit, Authority to Control, Responsibility, Ethics) (Carroll et al. 2020).

Outputs and Products

Specific activities identified to achieve sustainable OA data management globally include:

- Communication between relevant data centres, data repositories, and data management units is maintained, and an OA data management advisory group is supported and maintained.
- Agreement on appropriate controlled vocabulary.
- Agreement on appropriate metadata requirements.
- Primary QC guidelines and tools are developed and distributed to the OA community.
- Automated primary QC guidelines and tools are being developed based on the Ocean Carbon and Acidification Data System (OCADS)[17] tools and implemented in relevant data centres, data repositories, data management units.
- Installment of Environmental Research Division's Data Access Program (ERDDAP) system in data centres, data repositories, and data management units.

12 National Institute of Standards and Technology (NIST, USA): www.nist.gov
13 European Association of National Metrology Institutes (EURAMET): www.https://www.euramet.org
14 The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP): www.go-ship.org
15 International Oceanographic Data and Information Exchange (IODE): www.https://www.iode.org
16 Sustainable Development Goals (SDG): www. sdgs.un.org/goals
17 Ocean Carbon and Acidification Data System (OCADS): www.ncei.noaa.gov/products/ocean-carbon-acidification-data-system

- ERDDAP user surface developed to allow use for different purposes (i.e., SDG indicator 14.3.1).
- ERDDAP user surface mirrored in interested data centres, data repositories, and data management units, e.g., GOA-ON Data Portal.

Enablers

National, regional, and global data managers, database managers, and data centres are the main enablers of this Pillar. Data providers will also need to be engaged so that the appropriate metadata and data are recorded and archived in accordance with the recommended data policies.

Important partners include:

- IODE and the associated NDUs and ADUs.
- GOA-ON Data Portal manager.
- Data managers and data providers willing to contribute to Working Groups on controlled vocabulary and metadata requirements.

O1P3. Production of data synthesis products tailored to end-users (Coordinated with OARS *Outcomes 2* and *5*)

Ultimately, OA data will be used by a variety of end-users and stakeholders for a variety of purposes, usually by adding value to the data themselves. We recommend that current data products that are critical to characterizing OA conditions of the past, present, and future, such as The Surface Ocean CO_2 Atlas (SOCAT)[18], Global Ocean Data Analysis Project (GLODAP)[19], and SDG indicator 14.3.1, be fully supported and maintained and that an effort is made to integrate all OA data across observing platforms into one gridded product while retaining information about different measurement uncertainties.

SOCAT and GLODAP are integral parts of the OA data management system, including the production of value-added products. Both of these synthesis activities are vulnerable due to lack of sustained funding and indeed they rely on many hours of "volunteer" labor from scientists and data managers globally. A long-term funding model is urgently required.

There is also a need to organize workshops to determine what end-users need and how to build the capability to create additional tailored data synthesis products. Potential new data synthesis products include:

- Regional indicators of biological health and OA exposure, such as duration and extent of exposure to corrosive conditions for calcifying organisms.
- Time series products, including time series data analysis and data visualization tools.
- Global and regional maps of carbonate system parameters.
- Early-warning OA forecast systems.

Outputs and Products

Provide OA information to support the needs of end-users by:

- Evaluation of existing capacity to produce needed data products and Evaluation of gaps and existing capacity to produce needed data products.
- Partnerships to develop a funding model to ensure the sustainability of SOCAT and GLODAP.
- Organization of stakeholder workshops to identify additional end-user needs.

Enablers

Data managers, and data system designers and managers are the main enablers contributing towards this Pillar.

Important partners include:

- SOCAT data management team.
- GLODAP data management team.
- Funders to recognize the need for data management and provision of data synthesis products as an integral part of any carbon observing program.
- Stakeholders to visualize, utilize, and assess the data synthesis products which can best assist their particular application.
- Software and IT experts to interpret stakeholder needs, to design and produce novel data synthesis products and visualization tools.

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18 Surface Ocean CO_2 Atlas (SOCAT): https://socat.info
19 Global Ocean Data Analysis Project (GLODAP): https://glodap.info

O1P4. Capacity building and mentoring

Achieving the mission of determining the progress and trends of OA globally requires that data providers, managers, and other stakeholders have the resources and capacity to make the observations of known quality, and to integrate these data into synthesis products, as described above. Capacity building will be required at all levels, to ensure that all stakeholders have the necessary tools to fully contribute. As new technologies and procedures are developed and introduced to the OA community, training, tools, and resources should be included to ensure uptake and appropriate use. Capacity building should be an integral part of OA observing and data management.

Resources and tools for underutilized laboratories

The magnitude, rate, and consequences of OA vary spatially due to different drivers, both natural and anthropogenic. It is, therefore, necessary to observe, manage, and mitigate on scales from local, regional, and global, from coastal to open ocean, and from the surface to deep waters. Equitable access to OA observing allows regions to manage their own coastal environments as well as to contribute to the globally integrated system. Many regions lack the local expertise, resources, and infrastructure required to implement an OA observing program; therefore, capacity building is a vital component of achieving the OARS *Outcome 1* goals. In addition, many laboratories around the globe that study tangentially related topics to OA (e.g., aquaculture) may be uniquely suited to monitor OA, yet do not have the necessary capacity (either equipment, knowledge, or SOPs) that makes OA measurements feasible. As the OA observing field develops, capacity building may also be required for more developed observing programmes on specific topics, such as data and metadata management.

The GOA-ON in a Box kit program has allowed opportunities for institutions, ministries, and organizations to produce OA data with associated training and support for staff time to carry out planning, active monitoring, and data processing. Seventeen kits have been distributed to 16 countries, and to date, a number of these kit recipients have successfully uploaded OA observations to the SDG indicator 14.3.1 data portal, providing weather-quality observations in regions where data were sparse or nonexistent. The GOA-ON in a Box program is substantially funded through grants, donations, and staff time support from many organizations, including the Government of Sweden, U.S. Department of State, National Oceanic Atmospheric Administration Ocean Acidification Program, and Oceans and Fisheries Canada, with facilitation assistance from non-governmental organizations, such as The Ocean Foundation. As this approach limits the number of kits that can be distributed, a sustainable funding model is necessary. Dedicated SOPs for the GOA-ON in a Box kits are being developed, including associated videos, templates, and resources. These SOPS are closely aligned with those of the wider observing program, allowing integration of data if appropriate quality control methods are followed.

On-going training and mentoring workshops are required as trainees progress from setting up a monitoring program and associated lab to conducting QC and submitting data to regional and global databases following FAIR and CARE principles. This can be accomplished through targeted workshops that provide an intensive period of learning for a select number of recipients or through perennial media resources such as written and video guides. Capacity building in sensor maintenance and easily accessible spare parts are also required to ensure that initiatives that increase monitoring do not wind down after the initial support. While workshops can help advance specific goals, such as the first hands-on experience with making high-quality measurements or providing coaching for data QA/QC, the travel and staff time is often costly. Resource materials can reach a broader audience, but they require upfront staff time and periodic revisions to align with current best practices. Resources and upskilling are needed to assist regions to utilize relevant data and data products to manage their own coastal environments. Such databases and data products should be part of the global system (Section **O1P3**), and therefore appropriate for local and regional needs.

The IOC OceanTeacher Global Academy (OTGA)[20] is a comprehensive internet-based training platform which builds equitable capacity related to ocean research, observations, and services in all IOC Member States. An OA module has been developed, which could be expanded to include other aspects of OA observing and data management. Other training materials have been developed by a variety of institutes. A directory of such training material could be developed, maintained, and extended as new resources become available.

20 IOC OceanTeacher Global Academy (OTGA): www.https://classroom.oceanteacher.org

Mentoring is an effective part of capacity development, where experts provide tailored assistance to an individual or a small group of trainees. There are several existing mentoring projects such as the Partnership for the Observation of the Global Oceans (POGO)[21] and the GOA-ON Pier2Peer program[22]. Since 2016, there have been over 250 members of the OA Community from 60 different countries involved with Pier2Peer, providing new insights or extending the learning from hands-on training events. As of September 2023, 65 mentor-mentees are in active partnerships. In some instances, the Pier2Peer Scholarship program has provided funds to allow mentor-mentee pairs to focus on data analysis in preparation for submission and publication.

Capacity Building for more established labs

As the OA observing and data management communities expand their operations to address the needs and opportunities outlined above, training and upskilling will be required by many practitioners to ensure that they are able to effectively contribute. Advanced training workshops are a useful approach for training specialists in data management and data synthesis approaches.

The changing production, distribution and use of RMs (informally known as CRMs) (Section **O1P1**) for analytical QC will need associated training for users to ensure the on-going provision of known-quality OA data. The uptake of standardized metadata (including harmonized vocabularies and the extent of metadata required) to ensure data are FAIR (Section **O1P2**) requires training, templates and other resources.

Outputs and products

The following are essential components for successful capacity building:

- Development of a sustainable funding model for the GOA-ON in a Box program.
- Development of a sustainable mentoring program, considering novel ways to deliver to a large number of mentees with a smaller pool of mentors.
- Engagement with industry and technology developers to encourage the development of low-cost sensors.
- A directory of existing training materials.
- Production of additional training material as gaps are identified.
- Efficient utilization of the OTGA OA training course, including expansion to include regional and ecosystem-specific modules.
- Online training tool for QA/QC of OA data.
- Co-development of training material for new initiatives such as metadata requirements and RM utilization.

Enablers

Much of the expertise needed to deliver these Capacity Building outputs already exists, however often the same small group of people are contributing. A key activity is to expand the group of experts, utilizing the different perspectives that a wider group can contribute, particularly those with specific regional knowledge.

Experts are required to assemble and develop training materials, using traditional methods such as written and audio-visual material as well as novel approaches such as interactive and e-learning. Experts are also required to deliver the training, both in-person and remotely. Specific skills that are required include expertise in observing methodology, QC, and data management, plus project managers, editors and producers of audio-visual and online material.

O1P5. Communication and collaboration building

Communication by the OARS Programme to the wider stakeholder community should be done as part of an overall strategy, to which the observing and data management components will contribute. Additionally, the WG1 observing and data management components will need to communicate and collaborate both within their own communities, and with the wider OA community.

21 Partnership for the Observation of the Global Oceans (POGO): www.pogo-ocean.org
22 GOA-ON Pier2Peer program: www.goa-on.org/pier2peer/pier2peer.php

The organizations supporting coordination efforts within the OA community, such as GOA-ON and IOCCP, should continue to support regular forums that facilitate on-going communication within the OA observation and data community. These forums are essential so the community can revisit and update SOPs, best practices, and data and information products as OA observations and research expands and advances. Communication tools such as newsletters, websites, and email updates are effective for one-way delivery. Workshops, working groups and conferences are required for effective discussion and feedback.

A strategy is required to ensure effective participation by a wide variety of contributors, particularly with wide geographical representation. Providing data and data synthesis products that track OA throughout the ocean will also require communication and collaboration building beyond the OA community, including partners such as the G7 Future of the Seas and Oceans Initiative[23], the Observing Air-Sea Interactions Strategy (OASIS)[24], Global Ocean Observing System (GOOS)[25], and World Meteorological Organization (WMO)[26]. If these products are to be co-designed in a way that serves the entire global community, new partnerships will also need to be developed through appropriate forums with researchers, institutions, policymakers and other stakeholders from under-resourced countries as well as with Indigenous communities.

Outputs and products

The following are essential components for successful communication and collaboration building:

- Support for communication tools and materials that help the community to visualize and contribute to the development of scientific information documents, policy documents, databases, observing networks, best practices, innovative technologies (such as sensors, buoys, floats, remote sensing algorithms, etc.), new model domains and projections, data visualization, synthesis and analysis tools and reports, educational and training materials, outreach materials, etc.
- Develop a strategy to communicate in a financially and environmentally responsible way, while allowing contributions from all partners.

Enablers

Communication experts are needed to design and produce products to disseminate information to a wide range of stakeholders using traditional and new communication tools.

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26 World Meteorological Organization (WMO): www.public.wmo.int/en

OARS Outcome 2:

Identify Data and Evidence Needs for OA Mitigation and Adaptation Strategies, From Local to Global

science
↓
action

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How does *Outcome 2* contribute to OARS objectives and to the UN Decade of Ocean Science?

Ocean warming, acidification and deoxygenation have gained increasing recognition across international and domestic policy platforms, including the UN Framework Convention on Climate Change, the UN Sustainable Development Goal Agenda, the Convention on Biological Diversity and the national climate strategies or ocean policy (Fullam et al., 2021). To date, international science coordination has emphasized the need to enhance coastal observations and establish regional baselines, to contribute to global indicators, and to develop research around keystone species (Tilbrook et al., 2019).

While this work must continue across different scales, governments and end-users need examples of targeted information that they can use to support discrete choices about localized mitigation, adaptation, and preparedness strategies in the face of ongoing climate change. This is especially true when setting management targets, tailoring responses, and establishing tradeoffs to potential interference of ecosystem services and marine resources that human communities depend on at local and coastal scales. Through OARS, the OA science and research community has the unique opportunity and emerging set of tools, to co-construct observations and develop regional baselines together with coastal communities. This also includes engaging end users of information more directly in mitigation and adaptation actions and supporting community priorities (including sociocultural and economic) by targeted OA monitoring and research.

It is the vision of OARS that increased regional, national, and local understanding of climate-related changing ocean conditions will enable enhanced management and policy prioritization. This in turn will lead to more impactful outcomes including effective fisheries and aquaculture resilience strategies, well-informed ecosystem restoration and conservation choices, evaluation of blue carbon projects, evaluation of nature-based solutions, marine carbon dioxide removal strategies and promotion of pollution controls, marine spatial planning and marine management.

However, achieving impactful outcomes through appropriate policy goals and management tools, requires a better understanding of the data, evidence, accuracy, evaluation, and spatial and time scales required for leveraging the correct policy or management tool to address a specific problem.

For example, some outcomes may include helping policy and decision makers communicate more clearly the regional and local impacts of climate change on marine ecosystems and resources, thus expanding relevant financing for adaptation efforts and accelerating policies aimed at reducing global greenhouse gas and carbon dioxide emissions. In addition, enhanced communication can also facilitate societal support for emerging policies to fight climate change impacts.

Achieving more specific and localized outcomes will require site specific information in assessing local conditions (including for example the prevalence and type of interactions of multiple - stressors and source attributions) and evaluating the best interventions or management responses.

To attain OARS objectives across the Ocean Decade it is critical that the global research community increases guidance on and summarizes the type of data and information that is available — or that requires development — to support specific decision-making outcomes. This guidance will also identify pathways for targeted discrete outcomes and expansion of coastal observations where regional baselines do not currently exist.

A guiding framework for OARS *Outcome 2* includes the following preliminary questions

1) What are climate and ocean policy leaders or decision makers charged with achieving, managing or regulating?

2) What are the policy, management or regulatory frameworks that presently (or can evolve to) integrate ocean knowledge into their decision-making?

3) What can policy makers, decision makers or marine resource users do with OA information at different spatial and temporal scales?

4) What outcomes or decisions can bespoke OA information help inform?

5) What is the quality of data and how much is needed to support different outcomes or decisions?

Inputs into OARS *Outcome 2* from otherOARS Outcomes

Activities that increase or strengthen OA knowledge for specific actions (mitigation, adaptation and restoration) are represented across multiple OARS Outcomes. These efforts must be undertaken in parallel to engaging stakeholders and end-users who must agree to, co-design and apply mitigation and adaptation actions. These activities include, but are not limited to:

- Building baselines to measure coastal variability and trends in physical and chemical parameters.
- Monitoring and understanding functional biodiversity and ecological interactions.
- Conducting species-specific research to determine vulnerability and adaptation potential of significant species (particular for ecosystem engineers, foundation species, or species of economic or cultural importance).
- Conducting ecosystem vulnerability assessments (to move beyond species-specific studies).
- Conducting nationwide or regional vulnerability assessment to identify the risks that ocean warming, acidification, and loss of oxygen pose to socio-economic-systems: including coastal and marine resources and the economy and social dynamics of coastal communities.
- Improving knowledge of biological impacts to marine species and ecosystem functioning within the region, along with locally appropriate adaptation actions or interventions.
- Exploring how land-based pollution, including nitrogen and wastewater inputs, interact with or exacerbate coastal acidification and deoxygenation trends.

- Enhancing climate response and preparedness and strengthening predictive models.
- Developing, testing, and deploying nature-based solutions — including shell dissolution techniques and restoration of mangrove, seagrass, salt marsh, and kelp forest — and evaluating their net effect on ecosystems.
- Exploring aquaculture techniques that aim to predict and mitigate corrosive conditions.

Outputs from OARS *Outcome 2*

To support all OARS outcomes and advance primary inputs, the *Outcome* 2 approach must help articulate to policy makers, decision-makers and marine resource users what can be achieved with the existing data and information available vs. what actions or decisions require additional data from monitoring and research, increased accuracy, or existing modelling frameworks. A road map is also necessary to determine how to prioritize different actions in different oceanic regions.

In parallel, *Outcome* 2 activities must solicit policy, management and information needs and marine use priorities across a broader community of stakeholders. Indeed, this two-way information exchange is the foundation of *Outcome* 2 and will guide the work plan over the next several years.

Outcome 2 will be the preliminary link between stakeholders and all OARS Outcomes. It will aim to: (1) provide direction for other Outcomes to assess what knowledge is required, and how best to deliver it; and (2) serve as a critical translator of science knowledge for real life application.

To accomplish these aims, *Outcome* 2 will:

- Support and enhance institutional process understanding to streamline stakeholder needs around climate and ocean information.
- Develop new tools to identify and channel ocean data/information/reporting requirements for policy, governance, and marine resource users.
- Optimize the translation and transfer of science applications to accelerate stakeholder uptake and utilization.
- Codesign processes for streamlining/ mapping "stakeholder needs to stakeholder action."
- Establish metrics to evaluate success of knowledge delivery and uptake.

Preliminary products

To support ongoing work, case studies and collaborations across OARS activities and expanding membership, the *Outcome* 2 working group members will begin a preliminary mapping exercise to help illuminate data and information needs associated with 6 discrete decision-making categories including:

1) Documenting change and informing risk.
2) Assessing food security and resilience of seafood economies.
3) Assessing best applications of marine management tools.
4) Assessing carbon sequestration potential or ecosystem resilience options with habitat conservation and restoration (nature -based solutions).
5) Assessing local remediation and adaptation strategies through reduction of land-based pollution.
6) Assessing the potential risks, benefits, and monitoring/ evaluation needs for marine carbon dioxide removal (mCDR) strategies.

The preliminary mapping exercise will produce an ***"OA Information for Decision Making" cheat sheet (see Appendix A)***. The cheat sheet will serve as a basic rubric for broadly categorizing data and evidence needs across 6 decision-making categories.

The rubric is meant to serve as a jumping off document decision tree for beginning discussions across policy, decision makers, marine resource users and scientists. These discussions will help illuminate priorities for co-designing specific OA science and research projects (data and evidence) for discrete purposes. Additionally, the rubric is meant to help organize other OARS Outcome working groups to co-design projects or case studies that are applicable to their activities, aims and charges.

Once developed, the "***OA Information for Decision Making***" rubric should take on more dynamic qualities under OARS.

The "***OA Information for Decision Making***" rubric should evolve as it incorporates additional projects or case studies, thus providing users of this tool more concrete examples. Additionally, the rubric should help outline ongoing data and evidence needs required for achieving specific outcomes, as prioritized by global constituency of OARS partners.

Preliminary outreach

Over 2023-2024, the *Outcome 2* working group will seek to expand its membership and core audience. The goal is to engage with a global constituency that represents marine resource managers, climate policy leads, Tribal and First Nation governments, commercial and subsistence fisheries and aquaculture leads, and civil society initiatives focused on nature-based solutions, innovative mariculture, water quality and coastal zone health and the climate-ocean policy nexus. It will do this through specific invitations to engage in the *Outcome 2* work made through the OA Alliance, partner academic institutions, governments, intergovernmental organizations and NGOs, as well as a series of regionally coordinated webinars and workshops.

In parallel to these efforts, the Outcome 2 working group will shepherd the creation of a running list of identified "shovel ready" OA monitoring or research projects that have discrete management or adaptation application built into their proposals. This list will be made publicly available to help drive funding support.

Preliminary markers of success

Finally, it is important that the *Outcome 2* working group outlines how it will measure success, both as a working group and OA information uptake on a larger scale. This could include a myriad of metrics:

- Discrete metrics might include perspective diversity of *Outcome 2* working group members; investments made in projects outlined by working group; co-benefits of potential actions taken; development of OA indicators through *Outcome 2*.
- Short-term metrics might include the increased development of OA policies (national and local) through the development of OA Action Plans, or increased commitments made to OA knowledge curation across international fora. This could also include specific OA or OARS recommendations being taken up by the respective bodies of the 2030 Agenda for Sustainable Development, the UNFCCC. Ocean Dialogue or Convention of Biological Diversity Implementation of National Action Plans.
- Longer-term metrics might include reductions of CO_2 concentration in the atmosphere; increased level of biodiversity (or population size for key species); increased resilience demonstrated across specific ecosystems; increased integration across climate-ocean policy priorities; OA eferenced in in national climate preparedness reports, though it is acknowledged that these larger and longer-term metrics are complicated and will be harder to quantify OARS relative contributions.

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Appendix A: "OA Information for Decision Making" rubric (as as of January 2024).

How the "OA Information for Decision Making" Rubric Will Be Used:

This rubric was created by OARS 2 working group members and broadly categorizes the potential application of OA data and evidence associated with 6 discrete decision-making categories.

- Documenting change and informing risk.
- Assessing food security and resilience of seafood economies.
- Assessing best applications of marine management tools.
- Assessing carbon sequestration potential or eco-system resilience options with habitat conservation and restoration (nature-based solutions).
- Assessing local remediation and adaptation strategies through reduction of land-based pollutions.
- Assessing the potential risks, benefits, and monitoring/ evaluation needs for marine carbon dioxide removal (mCDR) strategies.

The rubric is meant to serve as a jumping off document/ decision tree for initiating conversations between the OARS research community and policy makers, decision makers, marine resource or other stakeholders about their discrete data and evidence needs for specific project applications at regional or local scales.

These conversations (taken on as 1-1 meetings, workshops, webinars, or established more broadly through OARS programming) will help illuminate the OARS programme's priorities for co-designing specific OA science and research projects (data and evidence) for discrete purposes. The rubric is meant to help organize other the OARS programme's Outcome working group members around co-design of projects or case studies that are most applicable to their activities, aims and charges.

Once published through this white paper, the ***"OA Information for Decision Making"*** rubric will take on more dynamic qualities under OARS.

This will include:

Posting the rubric on the OARS website, and establishing "how to use" guidance for three user groups:

- OARS researchers.
- Policy makers and government marine resource managers.
- Non-government stakeholder communities.

Establishing and posting case-studies, providing more details for existing projects identifying data and evidence needs for specific purposes under each category.

Annual review and evolution of the rubric, accounting for new case studies and updating the rubric based upon lessons learned broadly across the OARS community. This includes better understanding the best uses for, and applicability of, the rubric in helping science and policy practitioners co-identify key data and evidence needs for OA mitigation and adaptation efforts required for achieving specific outcomes, as prioritized by global constituency of OARS partners.

About the "OA Information for Decision Making" Rubric

The rubric currently reflects broadly categorizes of information needs, instrumentation and tools associated, and the potential application of OA data and evidence associated with six discrete decision-making categories.

- Documenting change and informing risk.
- Assessing food security and resilience of seafood economies.
- Assessing best applications of marine management tools.
- Assessing carbon sequestration potential or ecosystem resilience options with habitat conservation and restoration (nature-based solutions).
- Assessing local remediation and adaptation strategies through reduction of land-based pollutions.
- Assessing the potential risks, benefits, and monitoring/ evaluation needs for marine carbon dioxide removal (mCDR) strategies.

It is acknowledged by OARS 2 working group members that identifying OA data and evidence needs for specific place-based applications will require additional determinations of time scale and frequency of data needed alongside a number and decision-making factors.

As case studies are developed and posted on the OARS website alongside this rubric, they will reveal and explain which timescale category is being applied to determine data and evidence needs.

To help OARS practitioners best determine discrete OA data and evidence needs for specific place-based applications, case studies will also illuminate which decision-making factors are informing priority projects. There will be several different variables at play when policy makers, marine managers or stakeholders are determining which data should be prioritized to guide their decision-making.

These might include effort or difficulty, time scale requirements, cost, alignment with existing policy or management goals or mandates, degree of potential social, economic, environmental harm (risk) or benefit ascribed to a given project or action.

It will be important to understand and share how each case study project has categorized the need for data, evidence and action taking across a particular decision-making outcome. This will include some analysis of the costs and benefits of generating science for discrete applications, alongside side weighing the costs and benefits of taking "no regret" actions now, while awaiting ongoing data and evidence to underpin specific management or regulatory changes.

Finally, through the development of case studies, it will be important to understand and communicate the "readiness" of the OA science practitioner community to deliver the data, evidence and information being requested and to identify where further investments are needed.

Decision Making Category	What Information Is Needed Instrumentation or Tools Required	What It Tells You What It Might Inform
Documenting change and informing risk to human communities (social, economic, or cultural reliance on impacted resources and ecosystems).	Global monitoring of ocean warming, acidification and deoxygenation trends reported through IPCC, UN SDG 14.3.1 or other regional climate-ocean observing bodies. Regional ocean and coastal observing and monitoring systems/ satellite observations of chemical and physical environment. Regional trends or projections of ongoing ocean warming, acidification and deoxygenation caused by atmospheric CO_2 and GHG emissions.	Information to understand regional climate-ocean change dynamics across ocean basins. Informs coastal variations/ divergences from a baseline. Projections can be integrated to inform more holistic climate risk or vulnerability assessments. Projections can inform policy and financing needs associated with risk and vulnerability assessments. Information can increase calls for urgent and drastic reductions of CO_2 emissions.
Assessing food security and resilience of seafood economies.	Robust baselines for both stock and stressor(s). Hindcasting, forecasting and modelling of ocean and coastal conditions integrated into fish stock assessments coupled with biological and ecological research. Satellite observations that help predict exposure of corrosive conditions, undersaturation or prolonged temperature increases. Highlight hot spots and vulnerable areas that have more compounding stressors/ seasonality changes, or resilient areas that have higher potential to buffer negative impacts of OA and create better conditions for species growth and survival. Illuminate locations or episodes of increased stress or vulnerability. Lab research and experimentation to illuminate biological and physiological impacts to keystone species, or multiple stressors on ecosystem function. Lab research and experimentation to examine adaptation potential and thresholds of keystone species.	Information to support climate resilient regional fisheries and aquaculture strategies. Information to support shellfish hatchery growing practices. Information can be integrated into annual fishing quota determination (or annual projections of stock assessments).
Assessing best applications of marine management tools.	Robust baselines for both ecosystem and stressor(s). Place based monitoring & research + hindcasting, forecasting and modelling of coastal conditions. Multiple stressor modelling in areas of high priority (estuaries and bays; fisheries/ aquaculture growing operations; reef systems). Coastal and marine habitat mapping. Research to identify: (1) place-based wild species, community resources or commercial practices that may be at risk; (2) areas where additional management, conservation, restoration, or regulation schemes are needed to support resilience; (3) techniques or actions that could remediate harm or build resilience.	Information to support targeted regulations, seasonal closures, conservation measures like Marine Protected Areas (MPAs), and shared -use planning tools like Marine Spatial Planning (MSP). Information can be integrated into ecosystems-based management strategies. Local actions that can improve resilience across marine ecosystems—planning or targeted conservation measures—and have multiple beneficial outcomes,

Decision Making Category	What Information Is Needed Instrumentation or Tools Required	What It Tells You What It Might Inform
Assessing carbon sequestration potential or ecosystem resilience options with habitat conservation and restoration (nature -based solutions).	Robust baselines for both ecosystem and stressor(s). Place based monitoring & research to evaluate the sequestration potential of blue carbon ecosystems. Scientifically supported methodologies accounting for the potential sequestration potential of blue carbon ecosystems. Place based monitoring & research to evaluate where and how marine vegetation and coastal wetlands are beneficial for remediating impacts of OA and support ecosystem resilience. Coastal and marine habitat mapping.	Information to evaluate the potential for blue carbon ecosystems to support sequestration goals (mitigation). Information to guide the use of natural shorelines and coastal or marine habitat to support ecosystem resilience (remediation). Local actions that can improve resilience across marine ecosystems—through blue carbon or nature-based solutions—and have multiple beneficial outcomes.
Assessing local remediation and adaptation strategies through reduction of land-based pollutions.	Robust baselines for both ecosystem and stressor(s). Multiple stressor modelling in areas with high coastal/ terrestrial activities or significant marine resources (estuaries and bays; fisheries/aquaculture growing operations; productive reef systems). Research to identify local sources of land-based pollution like nutrients (including nitrates) that enter the ocean through wastewater, stormwater, and agriculture run-off additionally contribute to OA and eutrophication.	Information to guide terrestrial and coastal activities including the reduction of land-based pollution. Actions to reduce these local land-based pollutions that contribute to OA and eutrophication can reduce impacts on species and improve ecosystem function. Additionally, understanding interactions between stressors may help identify which immediate actions can be taken to increase resilience or speed ecosystem recovery.
Assessing the potential risks, benefits, and monitoring/ evaluation needs for marine carbon dioxide removal strategies. ***Information to identify best conditions for mCDR, potential risks, potential conflicts, as well other regulator, socio-economic and cultural contexts for decision-making.***	Monitor of natural carbon system biological communities and biological pumps baselines (incl. seasonal and interannual fluctuations): necessary to identify target levels and results of actions. Outline, prioritize, and conduct the research and evaluation needed to assess the implications of different mCDR approaches/ techniques. Investigate and identify which approaches and techniques can be more useful across different scales, under different conditions and for distinct desired outcomes. (e.g.Ecosystems-habitats, climatic regions and seasons) Monitor and research approaches and techniques (results and implications-impact) in situ	Information to identify best conditions for mCDR, potential risks, potential conflicts, as well other regulator, socio-economic and cultural contexts for decision-making. Information to determine how mCDR strategies affect OA, how much mCDR strategies affect OA-sensative species and ecosystems, and how OA might affect different desired outcomes of mCDR strategies. Co-construction of solutions for social acceptability, but also to maximize the impact and durability of socio-economic adaptation measures, whilst respecting the cultural context and supporting or encouraging (according to the different realities) a culture of stewardship of the local and regional environment.

OARS Outcome 3:

Co-design and implement observation strategies

Co-Champions:

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Introduction

Building upon efforts of the Global Ocean Acidification Observing Network (GOA-ON), the Ocean Acidification Research for Sustainability (OARS) Programme, endorsed by the UN Decade of Ocean Science for Sustainable Development, further enhances ocean acidification capacity, increases observations of ocean chemistry changes, identifies the impacts on marine ecosystems on local and global scales, and provides society and decision makers with the information needed to mitigate and adapt to ocean acidification. GOA-ON and its partners propose to broaden the network's scope and expect to achieve a set of seven *Outcomes* **(Figure 1)** through OARS by 2030. Collectively, this will help regions and national governments better understand the dynamics of climate related ocean changes across different geographic and spatial scales, which is essential for improving understanding of key vulnerabilities and adaptation potential to climate change. While mechanisms are being established to strengthen ocean mitigation and adaptation measures across relevant UN and international conventions, capacity for generating tailored information for local management, policy response and preparedness remains a significant barrier to advancing necessary adaptation efforts.

To help break down this barrier, OARS *Outcome 3* will contribute to co-design and implement observation strategies in collaboration with data/information producers and end-users, supported by capacity building, to ensure vulnerable areas are adequately monitored and baseline information for newly developed carbon removal strategies is provided. To have the capability to effectively co-design activities, all interested stakeholders involved in that co-building of observing systems need an effective knowledge

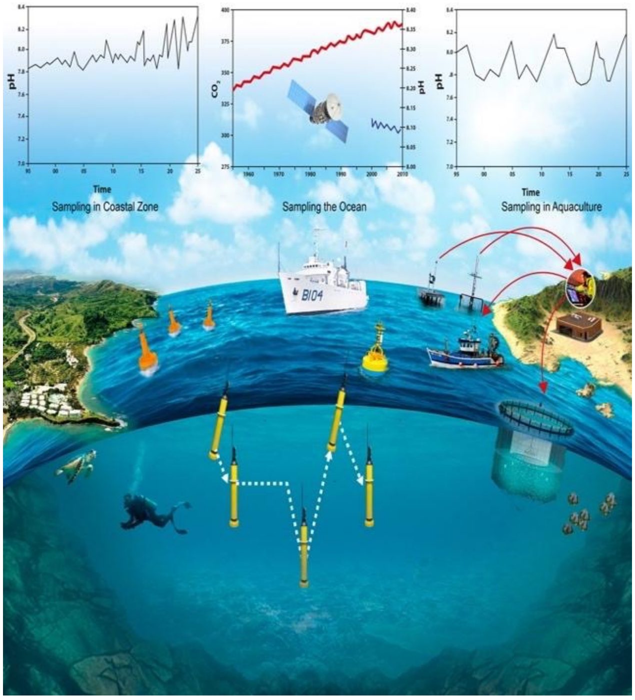

Figure 3: Integrated programs are recommended to better understand present day carbon cycle dynamics.

to engage more effectively. Stakeholders need to understand how the natural and human systems work and how they interact. Without this key understanding, there will not be any willingness for action. We witness a current plethora of individual monitoring activities operating over different spatial and temporal scales, all with different objectives and approaches. Only targeted co-built observation strategies will guide successful coral reef restoration, fisheries and aquaculture resilience strategies, innovative nature-based projects, carbon removal strategies, land-based pollution controls and climate responsive marine spatial planning and conservation efforts **(Figure 3)**.

Interdisciplinary and integrated programs based on ship-based hydrography, Voluntary Observing Ship (VOS) lines, time-series moorings, floats, gliders, and autonomous surface vessels with sensors for partial pressure of carbon dioxide (pCO_2), pH, and ancillary variables (Fabry et al., 2008) are recommended to better understand present day carbon cycle dynamics, quantify air-sea carbon dioxide (CO_2) fluxes, and determine future long-term trends of CO_2 in response to global change forcings (changes in river inputs, hydrological cycle, circulation, sea-ice retreat, expanding oxygen minimum zones (Borges et al., 2010.

The success of OARS *Outcome 3* will depend on close communication and interaction with activities conducted under OARS *Outcomes 6* (Public awareness) and *7* (Political engagement). Collaboration between actions under OARS *Outcomes 1* (Quality data) and *3* is indispensable. Focusing on the scientific community to provide ocean acidification data and evidence of known quality via capacity development, mentoring of early career researchers, and facilitating data sharing are fundamental steps to implement fit for purpose observation strategies (OARS *Outcome 3*). A close collaboration with OARS *Outcome 4* will allow us to design observation strategies that are relevant for the forecasting of biological impacts, and with OARS *Outcome 5* to provide appropriate data and information necessary for the development of societally relevant predictions and projections.

OARS *Outcome 3* embraces the three pillars of the Framework for Ocean Observing (FOO, 2012), namely: Requirements, Observations, and Data science to ensure the completion of the "ocean observing value chain". However, FOO does not capture all the desired elements for co-design. This is why OARS decided to use the "Theory of Change" (see section below "To Be Transformative") first setting the desired long-term goals and then working backwards. OARS *Outcome 3* specifically ambitions to build capacity for people responsible for funding/commissioning monitoring/observations ('funders'), and for those people who could contribute to the application of monitoring on the ground (e.g., environmental managers, related industries such as aquaculture fishing, NGOs - the 'practitioners'). Targeted capacity development activities for these stakeholders will be key since they constitute the missing links in the value chain despite the significant role they have to play in realising integrated, sustainable, long-term observing activities.

In this position paper, we will describe our outcome vision of OARS *Outcome 3*, then the anticipated impacts and benefits with respect to the UN Ocean Decade, the environment and society. We will then provide a tentative list of outputs and products to be delivered to reach the expected outcomes along with the engagement activities that will create the outputs and products. We will point to the funding needs from international bodies to support this work, indeed vulnerable areas need to be adequately monitored as part of a comprehensive climate preparedness and response. Finally key inputs and enablers needed along the road to support activities and to ensure success to deliver the outcomes will be presented.

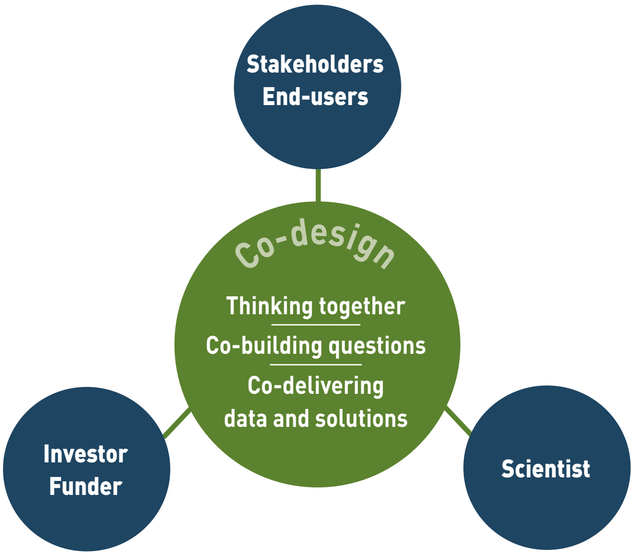

Figure 4: Co-design: Changing our way of thinking.

To be transformative, one needs to think differently

Scientists are used to setting up scientific questions, formulating and testing hypotheses, and carrying out the work. In the UN Decade of Ocean Science for Sustainable Development, we need to be transformative, meaning we have to change our way of thinking. We need to envision the whole value chain; this means identifying the stakeholders, investors, end-users, and co-building with them the questions, identifying what are the potential factors limiting the collection of data or implementation of solutions, and ultimately delivering the relevant data bases and solutions **(Figure 4)**. We can no longer promote the status quo and simply relabel, we need to try to change and position ourselves. Thinking differently can be eased using the "Theory of Change": First setting the desired long-term goals and then working backwards from these to identify all the conditions (outcomes) that must be in place (and how these relate to one another causally) for the goals to occur. These outcomes then provide the basis for identifying what type of activity or intervention will lead to the outcomes identified as preconditions for achieving the long-term goal. Through this approach, the precise link between activities and the achievement of long-term goals is more fully understood. This leads to better planning, in that activities are linked to a detailed understanding of how change actually happens. It also leads to better evaluation, as it is possible to measure progress towards the achievement of longer-term goals that goes beyond the identification of program outputs. The new way of thinking is switching from the sequences "Root causes - Problem - Consequences" to those of "Means - Desired Result - Impact" to ultimately follow those of "Impacts - Benefits - Outputs - Outcomes -Activities - Engagement" (Clark and Taplin, 2012).

Vision of outcomes

Despite the many Intergovernmental Panel on Climate Change (IPCC) reports, the impacts of ongoing ocean warming, acidification and deoxygenation are often under-recognized by policy and decision-makers, misunderstood or not incorporated across mainstream climate mitigation or adaptation priorities. This disconnect between science and policy response poses a substantial risk to coastal community resources and seafood economies that humans depend upon. It also undermines the effectiveness of more mainstream ocean conservation and management tools like marine protected areas, ecosystem and habitat restoration efforts, nature-based solutions, and climate-resilient fisheries.

Ocean acidification, the related biogeochemical changes, and related impacts are caused by human activities, therefore people must also be part of the solution. Educating people now should be a call to arms for engaging people in addressing this challenge of ocean change. While increasing ambition to reduce carbon dioxide emissions is paramount for mitigating OA, there are actions that governments and regional coordinating bodies can and should be taking now that will allow for increased adaptation and resilience of vulnerable ecosystems and species, further bolstering the ability of human communities to cope with future change. Despite the importance to our lives on Earth, we have explored only 5% of the Earth's ocean and conducted sustained observations in far less of it. The way nations are investing as a consortium in the International Space Station to discover the origins of life should be duplicated for observing the ocean.

Teaching people about the value of the ocean for human wellbeing, how to preserve our ocean, and being curious, will hopefully direct humans towards inventing a route for a habitable planet in the future. The human biogeochemical footprint on the planet is now so large that the future quality and sustainability of environmental resources will be determined by societal choices rather than natural variability. At the same time, it is critical to understand how natural Earth Systems will respond to this anthropogenic forcing. Understanding the interactions between the pressures of humans and natural changes in marine ecosystems will be the basis for society to make educated decisions, and to be able to maintain, manage, and improve ocean and human health. Only when acknowledging that human activity is driving the delivery of ocean services will their provision be maintained. Therefore, an envisaged outcome of co-designing ocean acidification observation is to provide data and information tailored for educational use, the implementation of marine management and policy action. While the academic sector is required to engage in developing knowledge that is "co-designed and co-produced" with those who use research in governments, business, and civil society, keeping a high profile on the rules of ethics and maintaining principles of bottom-up inspiration and scientific excellence is indispensable. Credibility and independence of the OARS research community are important attributes and should remain so.

In order for co-development and co-building to work better, it needs to be a cycle, i.e., by co-developing observing systems alongside other key groups (other academics from different disciplines, funders, industry, public, decision makers, etc.), we will build these other stakeholders' knowledge of ocean acidification. By growing this knowledge these groups will then be better equipped to engage in future co-development systems, creating better outcomes with more learning opportunities, and the cycle goes on gaining strength with every cycle. Communicating co-design blueprint, capacity training and educating people about the facts of ocean acidification science and policy will be fundamental priority tasks for our OARS *Outcome 3*.

Most of the capacity for conducting ocean research and observations is concentrated in developed countries and in the Northern Hemisphere (IOC-UNESCO, 2020), and many of the best practices for conducting ocean acidification research were developed assuming access to a robust laboratory and costly equipment. In recent years ocean acidification expertise has been greatly enhanced through the work of many partners, including the International Atomic Energy Agency Ocean Acidification International Coordination Centre (IAEA OA-ICC), GOA-ON, National Oceanic Atmospheric Administration Ocean Acidification Program (NOAA OAP), and The Ocean Foundation (TOF).

To improve accessibility of conducting research a group including the IAEA OA-ICC, GOA-ON, NOAA OAP, TOF, and IOC developed recommendations for creating a low-cost kit capable of collecting "weather quality" OA measurements as defined by GOA-ON. With funding support from the U.S. Department of State and the Government of Sweden, TOF created a kit list based on these recommendations. This kit, nicknamed "GOA-ON in a Box", enables users to obtain pH and alkalinity data through sensor deployment and analysis of discrete samples. To date, TOF has procured and shipped out 17 kits to 16 countries.

Another program key to expanding capacity is the Pier2Peer program, which pairs scientists new to studying ocean acidification with more experienced scientists. With funding from U.S. Department of State, the Government of Sweden, and NOAA OAP, TOF administers a small grants fund in support of this program to enable mentor and mentee pairs to collaborate on research and develop the skills and capacities of mentees and their institutions.

More than 500 scientists have also participated in hands-on training courses hosted by TOF, NOAA OAP, the IAEA OA-ICC, and IOC. Training in ocean observations has also been provided since 2001 by the Partnership for Observation of the Global Ocean (POGO) and the Scientific Committee on Oceanic Research (SCOR) through the provision of fellowships allowing early-career scientists from developing countries to receive training in practical skills and methods for ocean observing, data processing/management and modelling. Of course, training in itself is not sufficient, and a long-term vision, sustained funding, and the development of international partnerships and collaboration are required to truly develop the capacity (human resources/expertise and infrastructure) for long-term, routine OA monitoring in coastal developing nations worldwide.

In order to enable enduring capacity, partners are now seeking to establish regional training centers and use the regional hub structure of GOA-ON to ensure in-region support. For example, TOF and NOAA recently established the Pacific Islands OA Centre (PIOAC), hosted jointly by The Pacific Community and the University of the South Pacific. The Centre will host a spare parts inventory to enable quicker replacement of lab materials, maintain two GOA-ON in a Box kits for training purposes, provide data management and chemistry coaching to partners in the region, and support sensor repair and maintenance. This Centre was established in partnership with in-region partners and was specifically designed to meet community needs. POGO also supports regional and global projects that enable collaboration and sharing of best practices. On a regional scale, POGO supports a Working Group on ocean acidification monitoring in the Gulf of Guinea, which is also collaborating with TOF and GOA-ON to provide training and OA kits to the participating countries. A global project on deoxygenation, ocean acidification and productivity, supported by POGO with funding from the

Nippon Foundation (NF), and conducted by NF-POGO alumni, provides funding for bimonthly sampling of selected biogeochemical parameters in 17 countries. A partnership with GOA-ON and TOF could enable the expansion of the measurements to the full suite of OA parameters and their integration into existing global datasets.

In brief, OARS *Outcome 3* will include two main pillars:

1) The people that should be part of the co-building process, their roles and their needs. One may question what the specific development needs for the actual process of co-developing are. Do participants need specific skills to be able to do co-building and what skills do they have in their chosen discipline? Is co-development a skill or expertise in itself, on top of being a scientist, politician, stakeholder, funding manager? Targeted observations must be fit for purpose to ensure coastal managers, policy makers and climate advisors are equipped to advance meaningful and quantifiable adaptation strategies along the coastline that are responsive to human needs. This will require clear identification of stakeholder networks and providing accessible avenues for seeking their engagement and understanding their needs.

2) The practical process of actually implementing co-building in creating a sustainable, effective observing system involves identifying the barriers that prevent co-development and what needs to be done to overcome these barriers. It means understanding the factors that limit the collection of data such as access to instrumentation, appropriate maintenance, technological capacity, institutional capacity and financing – especially in developing countries or in regions that are more dependent on ocean and marine resources. There is a crucial need to strengthen policy commitments and increase awareness about the various applications for targeted OA data and information. This will help promote incentives for sensor developers and companies to reduce prices, to actively encourage multiple producers of sensors to accelerate sensor distribution and minimise costs by easing the knowledge transfer, and to collaborate to reduce maintenance costs and improve access to and sharing of monitoring opportunities.

These two pillars are the prerequisite foundation to create an enhanced global OA observing network by increased observing capability and geographic distribution of monitoring.

Benefits and impacts

The ultimate benefits and impacts will be increased observation capabilities in place globally to derive an improved understanding of global climatic trends, e.g., ocean pH and oceanic carbon uptake. This information, necessary to the development of societally relevant projections, will also enable the assessment of proposed carbon removal strategies.

Co--locating observations of different parameters (physical, biological, chemical, environmental, social, economic) will provide us with a much more holistic appreciation of the fundamental processes, relationships and drivers which underpin marine socio-ecological systems and better understand the impacts of ocean acidification, in the context of other stressors (both climate driven and local human activity). For example, a methodological concept that serves as a basis for the development of alert systems on the development of corrosion conditions in the fishing sector where mollusk farming activities are carried out will benefit this sector.

Such breadth of data collection will also facilitate the creation and application of Digital Twins to better manage complex environmental challenges (e.g., creating and maintaining climate smart marine protected areas, managing fisheries, supporting marine spatial planning, etc.).

An additional benefit will be a common and mutually agreed upon knowledge base to support international policy debate and science-based political vision by designing a forward-looking climate decarbonization policy. By co-designing with stakeholders, common goals will be agreed upon, possibly favouring access to funding. Raising funds is critical, in particular for vulnerable areas to plan their climate response.

Specifically, the increased collection of good/usable data respecting the "FAIR" (Findable Accessible Interoperable Reproducible) and "CARE" (Collective Benefit, Authority to Control, Responsibility, Ethics) principles and building of reliable databases with internationally agreed standard treatment (e.g., quality checks, quality flagging, adjustment procedures) will ease the comparison of results between international research groups to deliver globally consistent baseline information. Again, specific attention will be paid to proactively designing and implementing new observation strategies to ensure vulnerable areas are adequately monitored.

Outputs for achieving co-designed ocean acidification observation by data producers and users

Delivering the outcomes mentioned above requires a suite of key outputs to be produced. Some will be produced in synergy with outputs derived from other OARS Outcomes.

The very fundamental one is to ensure a sustainable production and distribution system for Reference Materials (RMs, commonly referred to as Certified Reference Materials, CRMs) and for the development of secondary and in-house standards (OARS *Outcome 1*). The COVID pandemic with shortage of RMs highlighted the need to have in place a fully sustainable production and worldwide distribution system.

The delivery of our outcomes also implies the advancement of sensor technology towards a lower cost of equipment and of instrument maintenance, a prerequisite to expanding OA observing in developing countries. The need to install low-cost underwater sensors with the ability to measure pH, temperature, and salinity in conjunction with the analysis of historical data generated by coastal programs is highlighted, which is proposed to be a tool to generate information on the variables of the CO_2 system and evaluate the potential impacts that acidification can have in natural systems as described by Alin et al. (2013).

Stakeholders of the fishing sector have expressed the need to have in place alert systems so that they can make decisions on their activities. An alert system should be based on good performance with respect to improving data collection, data quality control, and verification of modeled results with algorithms. However, the system must be able to adapt to the problems identified in user feedback, and valuable information because it is derived from user experience in the real world (National Science Foundation, 2007; Newman et al., 2012). This is where the coastal monitoring system should offer the oyster producer for instance information (visualization of observed data and modeling aimed at a non-specialized audience through for instance a web interface) on environmental monitoring (pH, temperature, and aragonite saturation, Ωarag), making it a potential tool in decision-making. These decisions can be translated into short-term actions, such as adequate control of the seawater use system, or they could impact medium- and long-term actions, for example, the adoption of practices to deal with suboptimal conditions for bivalve development. Considering that the success of these digital platforms is based on training for their proper use, which would provide useful feedback, it is necessary to evaluate the ability of potential users to adapt to this newly available technology (Dehnen-Schmutz et al., 2016). In addition, considering for example that the oyster farming industry in different parts of the world is potentially susceptible to the influence of cold, undersaturated, and acidic waters, either in the short term (for example, coastal upwelling on the West coast of the North Pacific), or in the long term (for example, OA), knowing the opinions and the degree of knowledge of oyster farmers on the potential effects of OA on their industry is necessary to evaluate their potential use of the available information. The challenge is to identify the missing information this sector has on this topic, and thus be able to address this problem, but with appropriate strategies to promote community participation in this topic of OA among stakeholders.

Evaluating the openness of aquaculture producers (e.g., oyster farmers) in adopting new information technologies and their perception of the effects of OA in the aquaculture industry is also needed. The fishing sector has fish mortality problems and the causes of these problems are uncertain; they might be due to management problems or diseases. We should be aware that the issue of OA is another addition to their list of challenges, making the needs assessment of the fishing sector even more delicate.

Coordination of OA monitoring with other ocean and atmospheric observation systems should be favoured. This would allow us to better understand the key biogeochemical-physical interactions and feedback between the ocean and atmosphere which regulate climate and global change. Similarly, deploying observing platforms that couple OA monitoring with biological monitoring would harness the power of existing biological time-series (link with OARS *Outcome 4*). All Essential Ocean Variables (EOVs) from observing systems could be managed/stored in a way that allows us to access both types of data simultaneously. This will require an improved dialogue between siloed entities that are focussed on climate change monitoring on one hand and those focused on biodiversity monitoring on the other hand. One may call for a specific joint IPCC-Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) report on the fate of our future ocean which would demonstrate these international bodies work in concert to yield useful joint products. Collaborating with other UN Ocean Decade programs (such as the Ocean Biomolecular Observing Network, OBON, Marine Life 2030, and others) would also facilitate the linkage between OA and biodiversity monitoring.

There should be wider, systematic access to community-approved best practices and calibration protocols. These products can be easily delivered by publishing guidelines, best practice peer-reviewed documents, and by making available open access training materials to build capacity in people to engage in co-development.

In line with stakeholder-oriented co-design, and linking to OARS *Outcome 7*, co-development could become a legal requirement in statutory environmental monitoring. OA monitoring could be for instance a mandatory observing requirement of Marine Protected Areas and aquaculture activities. Similarly, in areas of potential marine intervention for carbon dioxide removal (CDR hereafter), there could be baseline OA observing activities that would provide evidence-based guidance on the development and implementation of such projects. It will be important for the scientific community to preserve key baseline observations in regions off-limits to CDR interventions, for tracking the background OA signal and impacts (e.g. at Hawaii Ocean Time Series (HOT) Station ALOHA or BATS Stations). Carbon Capture and Storage (CCS) initiatives carry out some monitoring for leakage from geological sub-sea CCS and this has potential for cross-over benefits for OA.

Finally, all observations/research based informational products useful for decision making, e.g., time series analysis tools and mechanisms visualizing the impacts of OA on marine life are instrumental to deliver the desired outcomes. Visuals are the backbone of efficient messaging to society so we should aim to always deliver high quality informative visuals to communicate and capture society's attention.

Planned engagement activities

As was mentioned before OARS *Outcome 3* embraces the three pillars of the Framework for Ocean Observing (FOO). The three pillars include Requirements, Coordination of observations, and Data management and information products **(Figure 5)**. The FOO is the ideal framework to structure engagement activities and it provides valuable guidelines for assessing ocean observing problems. The "loop" that is executed when applying the FOO principles to a certain observing objective (e.g., seasonal cycle of coastal pH off California) is also called the "ocean observing value chain". The value chain is a concept adopted from economics that describes a process in which a system

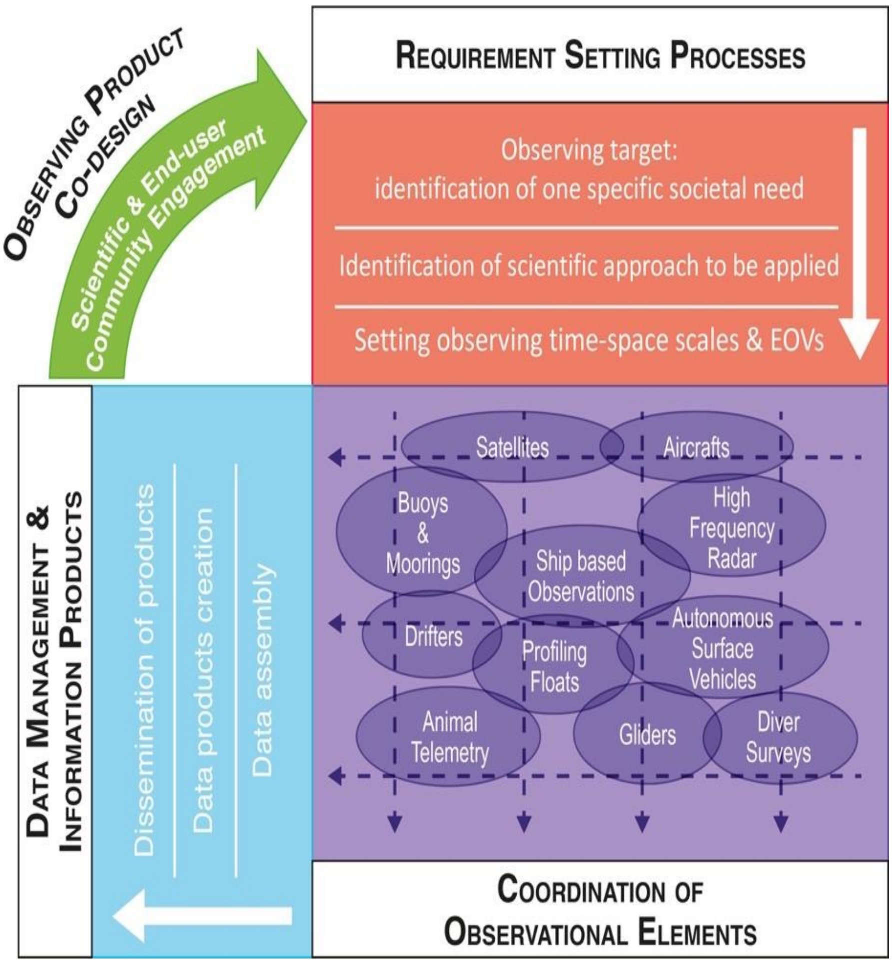

Figure 5: Conceptual structure for an ocean observing value chain designed to match the original structure of the Framework for Ocean Observing (FOO). Adapted from the FOO, 2012.

is organized through subsystems, each adding value with inputs, transformation processes, and outputs.

Some activities come under only one pillar, while others fall under the combination of two pillars. Here is the list of planned engagement activities:

- Support for enhanced networks is paramount in tackling local, national, regional, and global specific OA issues.
- The development of autonomous, programmable, low-cost instruments with the necessary electronics and sensors to measure pH and temperature of seawater.
- The development and strengthening of the capacity to monitor, document, and analyze the changes in pH and Ωarag, in the effects on the coastal ecosystem through the development of an underwater pH, salinity, and temperature sensor.
- Identification of potential funders and development of diverse sources of funding (e.g., for instruments and maintenance and/or return to companies for maintenance) are critical to delivering the above-mentioned outputs. OARS should liaise with the corporate world through, for instance, the World Ocean Council or the Global Association of Risk Professionals to activate the private sector in "natural capital" so that they set up venture capital funds to invest in ocean climate solutions sourced from ocean science institutions. Insetting is a way for companies to harmonize their operations with the ecosystems they depend upon and transition to a more sustainable business model. OARS could team up with companies to build insetting projects along companies' value chains that are designed to generate GHG emission reductions and carbon storage, and at the same time create positive impacts for communities and ecosystems.
- A transformative thinking means creating an innovative synergy between the private and public sectors, including philanthropic foundations. Ocean prediction and forecasting systems should include all biogeochemical EOVs and this should be widely supported like weather forecast. This falls perfectly within the UN Decade Ocean Prediction Decade Collaborative Center mission.
- Present exemplars include the Ponant Science capacity building platform R/V Commandant Charcot icebreaker which sails in the Arctic and Antarctic, the GOA-ON Pier2Pier program, and the Partnership for Observation of the Global Ocean (POGO) to list a few. By engaging with these stakeholders, increased accessibility to funding is expected. Active participation of private sector partners (e.g., Aanderaa Data Instruments AS) in capacity-building events will certainly favor companies' awareness and potential reduction in the cost of equipment and in instrument maintenance for developing countries.
- To maximize the use of infrastructure, it is timely to stop breaking up all observing networks and to promote greater integration between the global OA observing network and other observing networks, focusing on related measurements.
- The development and validation of proxy algorithms of the aragonite saturation state using hydrographic data that is intended to be applied in sites where aquaculture is practiced.
- Generate relevant information to evaluate the changes and trends of ocean acidification on the coasts that are useful for the aquaculture sector.
- Provide advice and experience on these issues to other groups from different countries, starting in priority regions most vulnerable to acidification.
- Generate environmental information on vulnerable regions that will support future research related to the potential impacts of climate variability and change on natural and socioeconomic systems, know the degree of interest and availability of aquaculture producers (e.g. oyster farmers) around the world to adopt digital platforms to obtain environmental information (coastal monitoring system) and evaluate their perception of OA.
- A platform will be provided enabling continued communication and more open access between different stakeholders to ensure governmental, private, and UN support to OA observing efforts and the application of the produced data and information. Planned exemplars include for instance dissemination of an ad-hoc stakeholder questionnaire for aquaculture companies in Mexico, and increased production and dissemination of Chilean CEAZAmar Bulletin types to contribute to the education of the younger generation and general public globally.
- The development of cheaper and more readily available RMs (increased access) should be undertaken along with the promotion of adherence to international standards (link with OARS *Outcome 1*)

- The development of capacity and mentoring of early career scientists (link with OARS *Outcome 1*), of the general public (link with OARS *Outcome 6*), of policymakers (link with OARS *Outcome 7*) and of stakeholders and funders (OARS *Outcome 3*) is definitely a transverse fundamental action within OARS.
- Upcoming exemplars include the GOOD/OARS International Summer School in Chile SS2023 in November 2023, and initiatives to be co-led with the Ocean Teacher Global Academy (OTGA), GOA-ON, TOF, and POGO.
- The world of databases needs to be reshuffled to ultimately build harmonized, interoperable, reliable, and open access databases which can be used for climate science, and this means improving data infrastructure.
- Development of the capacity of countries to measure and report OA data as part of the SDG indicator 14.3.1 process and to achieve the SDG target 14.3 should be our UN Decade endeavor.

Key inputs and enablers

Key **inputs** to support these engagement activities will require intellectual resources (expertise and strategic vision), data and information, dedicated commitment from members of our scientific community and of the private sector, availability of equipment, infrastructure, and funding. We will have to consider possible strategies for implementation, e.g., either prioritize some key actions to lead globally, then, when achieved, move on to others, or pragmatically push for certain actions in some parts of the world and others in other parts, making sawtooth plan progression. Pragmatism is key since actions need to be initiated **now** and produce results.

To achieve proper delivery of *Outcome 3*, key natural **enablers** include both OARS co-chairs, all OARS co-champions, and their working group members, GOA-ON and OARS support secretariat, and all possible funders from the public and private sectors. Everyone is an ocean stakeholder so ultimately all nations should invest in ocean observation as a consortium, the way they do in the International Space Station. Humankind has been determined to understand the origins of life on planet Earth. Similarly, humankind should show an unwavering will to build the future trajectory of Earth's climate toward sustainability, habitability, and well-being. It is not enough to know where we come from, we also need to shape where we go. And within a healthy and resilient ocean, sustainable and productive, clean and safe, predicted, transparent and accessible, inspiring and engaging, lies our future.

Conclusion and perspective

Following this roadmap, WG OARS *Outcome 3* efforts will be instrumental in meeting our ultimate challenge: contributing to designing policies for balancing the needs of human development with environmental protection to preserve the ocean from irreversibly turning sour.

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OARS Outcome 4:

Increase understanding of ocean acidification impacts to protect marine life by 2030

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OARS *Outcome 4* and how it contributes to the Ocean Acidification Research for Sustainability (OARS) objectives and to the Ocean Decade

One of the proposed Outcomes of OARS is to «increase understanding of ocean acidification impacts to protect marine life by 2030". Reaching the full understanding of the biological response to ocean acidification (OA) is a formidable task that requires a combination of approaches including biological observations, laboratory and field-based experimentation, and modeling, to generate information that can be used interchangeably and broadly. The **vision of OARS Outcome 4** is a healthy ocean sustained through policies and management actions based on accurate and timely information on the impact of OA on marine life. **A focus on timely action will allow us to prioritize data needs and gaps, data valuation, analyses, observations, and research and generate new knowledge** to be used by other Outcomes. OARS *Outcome 4* will also evaluate existing practices and the development of new best practices and contribute to capacity building.

The persistent increase in atmospheric CO_2 from anthropogenic sources is the main driver of OA in the ocean. An overwhelming body of evidence documents OA with an implication that there are potentially significant impacts on marine species and ecosystems. These impacts are intertwined with local expressions of marine life and physical, chemical, and geological drivers. Generally, in the global ocean, upwelling, downwelling, advection and changes in temperature such as with seasons and long-term warming play a major role in modulating and also driving variability in local partial pressure of CO_2 (pCO_2), pH and other parameters of the carbonate system. In the coastal zone, variability in pCO_2 and pH are directly driven by biological and environmental processes. Processes such as river run-off, stratification, and tides influence the chemical and biological processes that affect air-sea exchange of gasses and feedback. Short- and long-term changes in biodiversity can also alter the carbonate cycle of aquatic environments. Understanding these linkages and feedback is required to characterize past scenarios of ocean states, assess present status and trends, and to project possible future scenarios and to recommend management actions to protect marine life.

Outcome 4 is central to the OARS objectives as it bridges between observed and projected chemical changes, biological impacts, and societal consequences.

The complexity of bridging chemical and biological changes associated with OA is often underestimated. Today, projections of OA rely mainly on proxy variables like pH, saturation state, temperature, salinity, and simplistic thresholds to speculate about the status and trends of biodiversity and ecosystem services. However, the impacts of OA on ecosystems are complex and dependent on multiple other conditions. There is a need to consider factors such as adaptation of organisms to local chemical variability, evolutionary processes, ecological interactions, and the modulating role of other environmental drivers or stressors **(Figure 6)**. Global, regional, and local impacts of OA on biology and ecology, whether gradual or stepwise, are not fully resolved. Experimental work often oversimplifies these processes, for instance by focusing on single species and stressors, short-term responses that focus on single life-history stages and responses within a single generation, and static conditions that do not incorporate natural variability. Yet focusing on comprehensive, real-world conditions that encompass multiple life-history stages, responses across generations, and in the context of species interactions is important to fully understand ecosystem-scale changes that ultimately affect ecosystem services.

Results from experimental work and from *in situ* observing efforts are not always well integrated into synthesis and modeling efforts. Conversely, the requirements of modelers for particular datasets and data formats are not well understood or communicated to observers and experimentalists. Ocean observing

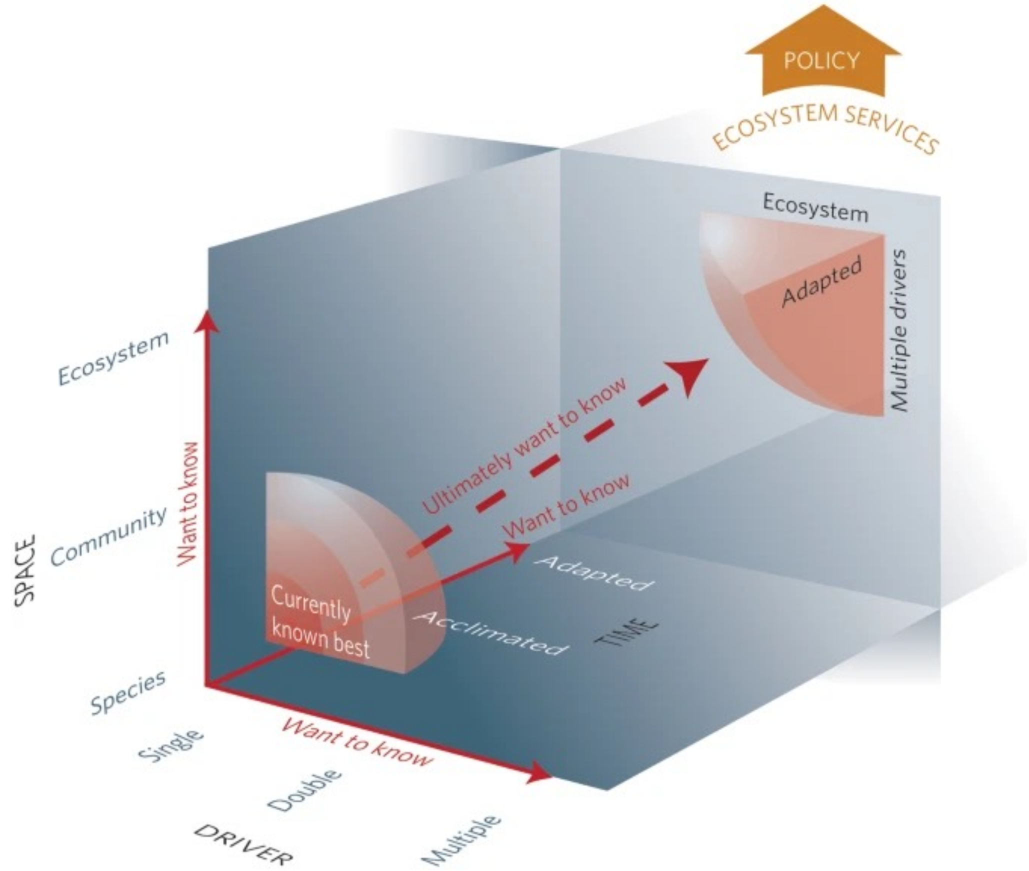

Figure 6: Biological response to ocean acidification: Present state of knowledge and knowledge needs. Most information on the biological impacts of ocean change currently available is on short-term response of single species/strains under the influence of a single driver. *Source:* Riebesell et al., 2015.

data and information delivery systems are often focused on one or a handful of physical and biogeochemical Essential Ocean Variables (EOV)[27] (*Global Ocean Observing System,* n.d.). Historically, however, these observing systems have not included biology and ecosystem EOVs, observations of interactions between organisms and the environment, or observations of interactions among organisms. Although similar marine biology and ecosystem EOV sub-variables are often collected using different methods by different groups, the data are most often managed independently by different observers, and many results are not curated using accepted data management standards. This hinders data sharing, if the data is shared at all. Thus, most marine species and much of the ocean's ecosystems remain under-represented in open databases like the Ocean Biodiversity Information System (OBIS) and the Global Biodiversity Information Facility (GBIF). Further, databases of environmental parameters, including OA parameters (e.g., SDG 14.3.1 data portal)[28], are not linked with other databases, in particular databases that house marine life information (e.g., OBIS and GBIF). To some extent, this has led to slow progress models. Models are simple and lack forecasting skill, leading to assessments about marine life and ecosystem services that are often speculative.

A consequence of all this is that at present, although data are being generated about OA changes and separately about some ecological changes, we are not able to evaluate whether a local resource or ecosystem service is changing, whether it is changing because of a local driver or multiple stressors, or due to larger-scale oceanographic or climate-scale changes.

There is a need to link the entire OA community with those who have a shared interest of protecting and conserving biodiversity in the face of global changes. OARS plays a key role in promoting actions to address the need for broader, more diverse, inclusive, and interdisciplinary collaboration and co-design. There is a need to facilitate inclusion of all researchers interested in monitoring and OA research networks around the world. At present, many early career and international researchers find that much of the science community remains exclusive, based on perceived membership, or requires invitation to the groups or networks that already exist. One problem is that this creates an incentive for parallel networks. The broader benefits of inclusion are improved collaboration, effective sharing of information, fewer duplicate repetitive studies, and an ability to address questions of much larger scale and scope. OARS can facilitate and foster an inclusive network of scientists that is open and accessible to all who are interested. Inclusion of more countries and professionals is a requirement in the quest of diversification in OA research.

Among strategies to strengthen cohesion and relevance of the OA community are active communications between OARS working groups and developing effective links between the biologica oceanographic community and the biogeochemical community engaged in OA research. Priorities in data and information needs will be defined in close collaboration with OARS *Outcome 2* ("Identify data and evidence needs for mitigation and adaptation strategies, from local to global"). Members of the *Outcome 4* working group will be involved in a stakeholder workshop organized by the *Outcome 2* working group. Results of these discussions will guide the work to achieve Outcome 4. The information generated by this working group, jointly with *Outcome 1* ("Enable the scientific community to provide OA data and evidence of known quality") will be central for OARS and will contribute to the improved ability to forecast future changes, drive information-based actions and increase awareness and science capacity, including in developing countries.

OARS *Outcome 4* has a high probability of success because it builds on existing communities including the Early Career Ocean Professionals (ECOPs), the Global Ocean Acidification Observing Network (GOA-ON), the Marine Biodiversity Observation Network (MBON), and the Marine Life 2030 Ocean Decade Program. It will develop stronger links with the Ocean Decade Ocean Best Practices System (Ocean Practices), Digital Twins of the Ocean (DITTO) and observing efforts such as Observing Air-Sea Interactions Strategy (OASIS). It will be important to continue to link these and other communities, such as marine protected area management and planning groups, through ongoing dialogue.

A major benefit of collecting biological information jointly with OA chemical observations is the ability to address major aspects of Sustainable Development Goal (SDG) 14. Specifically, it will directly address SDG 14.3: "Minimize and address the impacts of OA, including through enhanced scientific cooperation at all levels" (SDG Target 14.3). OARS *Outcome 4* will also allow the design of models and the improvement of ocean system components forecasts, including marine life. This entails improving digital twins, which are digital representations of real-life conditions that are used to model the ocean and to understand past, present, and future conditions. These can be scaled to address local to global user needs and will be helpful in advancing our understanding of OA processes and impacts on marine life, in a way that can help management interactions.

27 Essential Ocean Variables: https://goosocean.org/what-we-do/framework/essential-ocean-variables
28 SDG 14.3.1 Data Portal: https://oa.iode.org

Preliminary list of key outputs and products

The OARS *Outcome 4* working group will work in close collaboration with *Outcome 2* and *Outcome 7* working groups ("Develop strategies and solutions to enable countries and regions to include measures to reduce OA in their respective legislation") to engage stakeholders including resource managers, observing system planners and coordinators, and scientists in the co-design of a **priority roadmap** to achieve the vision of OARS. This roadmap will identify the OA Knowledge needed for Decision Making, including information on the data resolution and quality needed for a successful implementation of the needed actions. Working with the *Outcome 7* working group (influence of OA knowledge to guide political decision making) we want to ensure that OA is part of the conversation within international and national decision-making structures e.g., the Convention of Biological Diversity, IPBES (Intergovernmental Panel on Biodiversity and Ecosystem Services), and the UN Framework Convention on Climate Change (UNFCCC). Importantly, OARS *Outcome 4* will ensure an optimal use of existing information to avoid delaying the needed actions to address and minimize the impact of OA.

The second step will be an evaluation of the existing data and information gaps, and identification of the factors responsible for these information gaps (e.g., data sharing, poor communication between communities, time, funds, lack of capacity or best practices). The *Outcome 4* working group will **summarize existing information** (e.g., synthesis, relative thresholds), **generate new knowledge** on biological impacts from existing information (e.g., combining data from chemical and biological observation), and provide **clear recommendations for research and capacity building** that will be shared with other OARS Outcomes.

Examples of outputs in this process include:

An inclusive and diverse community

- Actively includes and promotes researchers at different career stages and from around the world and promotes an interdisciplinary community.
- Promotes and hosts interaction between social and natural scientists.
- Develops an ethics statement and works with the community to adopt these guidelines.
- Establishes better linkage between local and regional groups interested in ecosystem services and role of carbonate system changes.

Summary of existing information (scientific articles, policy documents, database)

- A comprehensive inventory of coastal, estuarine, and ocean observing programs that conduct co-located and simultaneous carbonate system and biological observations and findings related to OA impacts.
  - This will be done jointly with the Global Ocean Acidification Observing Network (GOA-ON), the Global Ocean Observing System (GOOS) and the Ocean Biodiversity Information System (OBIS) (e.g., GOOS BioEco Metadata Portal).
  - Understanding how biological data are curated, formatted, and shared.
  - Advance adoption of data formatting standards and sharing practices.
- Evaluation of existing literature on OA biological impacts in close coordination with:
  - The Ocean Acidification International Coordination Centre (OAICC) bibliographic and biological response databases.
  - The International Ocean Carbon Coordination Project (IOCCP).
  - The Global Ocean Observing System (GOOS).
  - The Ocean Biodiversity Information System (OBIS).
  - The Marine Biodiversity Observation Network (MBON).
  - Ocean Decade programs: Marine Life 2030, SUPREME, OASIS, ECOPs, OceanPractices, and others.
- Identification of baselines for biodiversity at key sites.
  - Establish a process that follows the Framework for Ocean Observing that identifies needs.
  - For example, ongoing OBIS monitoring at UN World Heritage sites.

New knowledge from existing information (scientific articles, policy documents, database)

- Integration of efforts to collect biological observations with OA chemical observations, and vice-versa, using the GOOS Framework for Ocean Observing.
- Identifying data repositories and enabling access, including cross-linking data records of different EOVs collected simultaneously but archived separately.
- Development of synthesis products, theoretical frameworks, biological relative thresholds, and indicators based on existing information, and integrating biological complexity.
- To avoid delaying needed actions, existing information on the impact of OA on marine life and ecosystem services will be communicated to key relevant stakeholders, including the public. A collaboration with communicators will allow to identify the best information to drive change and actions strategically and efficiently.

Recommendations for research and capacity building (best practices, scientific articles, policy documents)

- Developing lists of benefits of observing and applications, consequences for inaction, and guidelines for action in areas where ocean observing has traditionally not been a priority.
- Definition of standards for recording and sharing biological data.
- Implementation of best practices for biological observations to detect and compare OA impacts across marine species and ecosystems.
- Development of best practices for the identification of locally relevant biological indicators integrating environmental, ecological, and evolutionary complexities.
- Development of best practices for laboratory and field-based experimentation integrating the right level of complexity **(Figure 6)**.
- Guidelines for the research and observing community to address information needs, including identifying funding sources.
- Recommendations for improved modeling and forecasting, including models that account for:
  - Species interactions and adaptation.
  - Land-ocean exchanges including freshwater inputs.
  - Ocean-atmosphere exchanges.
  - Improve projection of vulnerability and resilience to OA at all temporal and spatial scales, identification of geographic priorities, and
  - Promote the development of Digital Twin prototypes to help assess the state of the ocean.
- Capacity development materials that explain or allow use of common and standard methods for biological observation and data management standards, including Darwin Core for taxonomic data and Extended Measurements or Facts (e.g., OBIS).

Ultimately, some of the key outcomes envisioned through these broader collaborations include:

- Data from new OA studies that specifically expand our understanding of:
  - How biological and ecological processes respond to OA within a multi-stressor environment over spatial and temporal scales that are relevant to the rate of environmental change,
  - The consequences of OA on complex marine systems and whole ecosystems,
  - The modulating role of human interventions on OA and their impact (e.g., implementation of various marine carbon dioxide removal (mCDR) approaches, including ocean alkalinity enhancement), and
  - The impact of OA on the function and value of those services provided by biological systems to humans.
- Tools and methods for exploring OA impacts on marine organisms, biological processes, populations, habitats, and ecological interactions from genomes to ecosystems.
- Digital tools to synthesize complex biological knowledge and information to visualize, interpret, and gain better conceptual understanding of how biological systems (individuals to ecosystems) work and how they will respond to OA (e.g., Digital Twins).
- Tools and methods to observe and measure biology (abundance, distribution, and processes) over different spatial and temporal scales (e.g., remote sensing, sensors, genomics, imaging, AI/ML) to increase our ability to monitor the response of biology to environmental change.

- Fully integrated (federated) data systems that allow the free flow of data to users, allowing all relevant biological data to be easily discovered and accessed, together with any associated environmental and socioeconomic data.

- Generate synthesis products/indicators formatted in ways that are useful to decision processes and that are co-designed with stakeholders.

Some of these products will be developed in collaboration with other OARS Outcomes and with a broader biology and biogeochemistry community. The efforts should be guided by the general OARS Outcomes.

Priorities and timeline for these outputs and products will be developed in close collaboration with the OARS *Outcome 2* working group and will be based on (1) data needs for action and decision making as well as (2) data availability, (3) the possibility to gather new information in a timely fashion; and (4) the complexity of developing and implementing best practices.

Outcome 4 will also contribute to a reflection on how to evaluate OARS success led by *Outcome 2* focusing on indicators of greenhouse gases, emissions, uptake by the ocean, and marine ecosystem health (e.g., atmospheric CO_2, functional biodiversity, etc.).

Research and outreach activities

An inclusive and diverse community

- promote activities that engage a diverse and interdisciplinary community.

- activities will include natural and social scientists to collaborate jointly with stakeholders and co-design solutions.

Stakeholder workshop (2023, collaboration with OARS *Outcome 2*)

Achieving *Outcome 4* requires developing a **roadmap** that keeps the vision and initial outputs in focus. The OARS *Outcome 4* champions will work in close collaboration with OARS *Outcome 2* to plan and conduct a stakeholder workshop to identify biological data needs and priorities for decision making, and to develop solution implementation. Several members of the OARS *Outcome 4* working group will be directly involved and will share with other members. One of the co-champions of the *Outcome 2* working group (Richard Bellerby) is also directly involved in *Outcome 4* ensuring efficient communication between Outcomes.

The list of possible and desired research and outreach activities can be expected to be very long, and it will be necessary to focus on the preliminary outputs while identifying other priorities. These activities should be viable in the short-term (2022-2023 timeframe) while the Ocean Decade OARS program works with the Ocean Decade and other groups to identify resources, and some intermediate range goals for 2024-2030.

Among the viable first steps that may be achieved with limited funding and on a voluntary basis are activities that directly address some of the key outputs listed in above (Preliminary list of key outputs and products). For example:

Evaluation of the existing data and literature to identify locally relevant thresholds and test new hypotheses (2023-2024)

OBIS and GBIF, other databases holding biological data should be mined to understand where time series observations may be available with which to evaluate changes and thresholds related to OA and other stressors.

Also, the Ocean Acidification International Coordination Centre (OA-ICC), the IOCCP, and other groups host bibliographic databases compiling scientific articles published on OA and ocean carbonate systems. They also have a database of biological responses. These resources can be used to test new hypotheses and identify thresholds (e.g., Vargas et al., 2022). Synthesis and meta-analysis exercises can be time consuming, and we will first focus on case studies. A broad survey of the community will help identify who may already be doing such fundamental meta-analyses.

We will take advantage of a virtual "Meta-analysis training" organized by the OA-ICC in February 2023. The purpose of the event is to use the OA-ICC databases to work on several meta-analysis projects and train participants in the use of these resources. Twelve experienced researchers will be selected, trained and locally relevant projects focusing on the identified priorities will be developed. The OARS *Outcomes 4* working group members will provide mentoring during the process and several scientific articles can be expected by the end of 2024.

Inventory of coastal, estuarine, and ocean observing programs (2023-2024)

A working group will be built to conduct a comprehensive inventory of coastal, estuarine, and ocean observing programs that conduct co-located and simultaneous carbonate systems and biological observations and findings related to OA impacts. The group should work in close coordination with GOOS and OBIS to complement and augment the inventory of biology and ecosystem EOV observing programs, and documents which also collect carbonate parameter data (https://bioeco.goosocean.org/). These assessments can be used to plan case studies and combined with experimental observations, to test new hypotheses.

Members of this working group will be selected from among the OARS *Outcome 4* working group members, the GOA-ON biology working group as well as in other relevant initiatives (e.g., the International Atomic Energy Agency's Coordinated Research Project "Evaluating the Impact of Ocean Acidification on Seafood – a Global Approach" involving 17 countries).

The process should include activities that synthesize knowledge based on biological and acidification observations. This includes identifying data repositories and cross-linking data records of different EOVs. An inventory will need to include an assessment of data formats and management processes used.

An important activity will be to explore the use of observation data to identify performance curves and develop biological indicators and thresholds that consider ecological and environmental complexity and yet simple to understand and useful.

Identifying priorities and strategies for modeling and forecasting (2023)

- A workshop will be organized including members from communities of experimental biology, observation, and modelers that consider the integration of biology with environmental changes including the contribution of land/freshwater ecosystems on OA and its impact on marine life. Specifically, it will address:

  1) biological interactions

  2) response to multiple stressors

  3) impacts of management on the environment and biological responses

  4) interactions among all factors.

Capacity building for common and standard methods, data management standards, and applications in management (2023)

Develop and share capacity building materials that explain or allow the use of common and standard methods and data management standards, including Darwin Core (e.g., OBIS). This can be done through a training workshop for Darwin Core data formatting and sharing of biological data via OBIS; Darwin Core format for taxonomic data and Extended Measurements or Facts. Such training can also include specific recommendations for OA biological observations from Widdicombe et al. (2022) and focusing on five fundamental ecosystem traits and their suite of observable indicators (Figure 7): 1) calcified organisms and calcification, 2) autotrophs and primary production, 3) heterotrophs and secondary production, 4) biodiversity and community structure, and 5) genetic and epigenetic adaptation.

These efforts may identify biological monitoring that is already taking place across the world (e.g., status monitoring, MPAs, fisheries, citizen science projects, etc.) and provide suggestions on where to add chemical monitoring efforts. A planning effort will need to be conducted to facilitate co-locating biological, chemical, and other EOV observations. This will require identification of specific biology and ecology EOVs needed to address local and global user needs, and to develop a forecasting ability.

The various working groups will also identify data and best-practice gaps as well as reasons (e.g., funds, capacity, technical) behind those gaps. This will provide science policy recommendations that can be communicated to the relevant stakeholders.

Over the long term, actions and implementation of solutions will require long-time series of co-located chemical and biological observations and new experimental projects using a wide range of approaches and emerging technologies (e.g., Free Ocean CO_2 Enrichment (FOCE) experiments). OARS *Outcome 4* will provide some guidance and best practices on strategies to fill up gaps in data needed for management and policy.

Key inputs to support activities and outputs

To enable the viable short-term activities, OARS *Outcome 4* members will work to identify and collaborate with key experts to address activities, set up realistic timelines and dates for workshops, and resources needed to implement:

- Engage early career groups including the Ocean Decade ECOPS in developing messaging about the importance of links between marine life and OA.

- Meetings or workshops that bring together members with the relevant expertise (e.g., biological, or chemical observation, experimentalists, ecologists, physiologists, evolutionary biologists, modelers, etc.)

Calcifying Organisms and Calcification	Autotrophs and Primary Production	Heterotrophs and Secondary Production
Relative prevalence and success of calcifying organisms Changes in biomass, abundance of biocalcifying species compared to non-calcifying species inorganic to organic biomass ratios	**Biomass/standing stock** Total chl a concentrations, phytoplankion cell abundance; microphyto-benthos blomass; blomass of macroalgae and seagrasse	**Biomass/standing stock** Biomass per Individual; numbers of individuals; average body sizes; percent cover quantification of abundance and blomass of major functional or species groups
Calcified biostructure morphology Weight, density, damage or abnormality, dissclution severity, or strength calcified biostructure	**Productivity** Carbon fiocation rates, planktonic, macroalgal or seagrass growth rates	**Productivity** Gross estimates of pelagic and benthic secondary production from in-situ techniques to algorithms
Rates of calcification Rates of calcification or dissolution	**Phenology** Timing of blooms orother rapid growth periods	**Phenology** Quantification of changes in the phenology of secondary producers
Biodiversity and Community Structure		
Taxonomic diversity and community composition Identification, quantification (number or blomass) of speces, spedfic taxonomic or functioral groupa present within a community or assemblage at any ghen time		
Functional or trait diversity Identification, quantification (number or blomass) of functional, ecological or behavioral traits		
Genetic Adaptation		
Neutral genetic variation Classic molecular markers (eg, allozymes, mkrosatellites or mtDNA); high-throughput sequencing approaches		
Mutation rates High-throughput sequencing technologies of few loc or whole genomes		
Functional genetic variation Quantitative trait locus (QTL) analysis genome-wide association studies (GWAS); restriction-site associated DNA tags (RAD-seq); RNA secuencing (RNA-seq)		

Figure 7: *Five fundamental ecosystem traits and their observable indicators. Source: Widdicombe* et al., 2023.

- Survey or other method of identifying programs that have in the past, or are, collecting biological and chemical data.
- Close communication with other OARS Outcomes to ensure communication with other scientists (e.g., social science) and stakeholders.
- Close communication across the whole OA community and broader collaborations across communities, particular biological and biogeochemical observation and research programmes relevant for OA, in a purposeful interdisciplinary manner.

Key enablers of success

A minimum of resources, people, and time commitment are required to achieve our short-term goals including the development of a roadmap in collaboration with the OARS *Outcome 2* working group and the short-term activities. Going beyond this to achieve other outputs requires substantial people, coordination, and funding.

It will then be important to develop strategies to have useful interactions between OARS, Marine Life 2030, and other relevant Ocean Decade programs (e.g., DITTO, Ocean Practices, SUPREME, OASIS, iDOOS, Challenger 150) as well as OA initiatives such as GOA-ON and the OA-ICC.

We can take advantage of existing initiatives to train and involve volunteers and Early Career Ocean Professionals interested in the success of the Ocean Decade. For example, the OA-ICC and IOCCP have capacity building programs. Several trainings are planned for 2023 that fits OARS *Outcome 4* goals including a meta-analysis workshop that will fund 12 participants to work on a synthesis project. Other sources of fundings will be explored to organize workshops and meetings.

Further, we need:

- The academic community to understand, engage and support these programmes and deliver the research required.
- Funders of academic research to provide resources for this work. Not just formal funding agencies but also philanthropic investment.
- Industry to engage through the development of new technologies but also those industries that already work in the marine sector and can help with our work (e.g., fisheries, aquaculture, marine tourism and recreation, oil and gas, maritime transport/ships of opportunity) by providing facilities, knowledge, and resources.
- Local communities to provide their knowledge of their own marine systems, undertake activities in their own lives that reduce the potential impacts on marine systems and to call for better decision making, and political action required to better protect and manage the marine environment.
- Educators and communicators (teachers, journalists, film makers, people from the creative arts) to help inform the public on the threats of OA on marine life and what they can do about it (linked to *Outcome 6* ("Increase public awareness of OA, its sources and impacts").
- Policy makers to recognize and use the information generated to support environmental legislation (link to *Outcome 7*).

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OARS Outcome 5:

Provide appropriate data and information necessary to the development of societally relevant predictions and projections

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Motivation & Vision

The anthropogenically forced increase in atmospheric carbon dioxide is accompanied by a commensurate trend in the carbonate system of the global ocean, a phenomenon called ocean acidification, recognized by the IPCC to be "highly certain". As such, surface pH has been shown to be highly predictable at the global scale for a given emissions scenario within global Earth System Models (ESMs) well into the future. In coastal environments, local processes can modulate or exacerbate this trend, and these processes occur on spatial scales that are not well represented in ESMs. As a result, prognostic information from advanced prediction to support decisions facing coastal communities subject to ocean acidification impacts is largely lacking. Some regions do benefit from this kind of prognostic information, but it is largely inaccessible by non-experts because the data size is large, uncertainty measures are difficult to generate, and interfacing with it is complicated.

The UN Ocean Decade offers an opportunity to advance, globalize, and enable access to regional climate information through broadening our capacity, expanding our capabilities, and investing in the resilience of coastal communities. Several large endeavors are already well underway to bring forecasting and climate information to coastal communities and more localized scales (CoastPredict, OceanPredict, GOOS). Within this effort, it is of particular importance to include and expand our focus to include ocean acidification to enable communities to build resilience around this important aspect of ocean health.

A lot of attention has been focused on the predictability of warming and heat waves both within research and applications (Jacox et al. 2020), but considerably less effort has been applied to understanding the commensurate and often more severe consequence of ocean acidification. In addition, relatively fewer observations exist to monitor ocean acidification variables. Ocean acidification variables are likely more predictable than physical variables. Ocean acidification variables also evolve differently within downscaled projections than global ESMs on climate timescales within coastal settings (Siedlecki et al. 2021), which makes downscaled products necessary for localized projection. The ocean acidification community is deeply rooted in attribution science, scenario planning, and working with stakeholders. In coastal regions, the community has close ties to stakeholder groups who are actively engaged (Cross et al., 2019). Research and products already exist that help inform decisions around the globe making those who are looking for stakeholder engagement as part of their forecasting or projection efforts well advised to partnering with this engaged community of practice **(Table 1)**. But ocean acidification is not happening in a vacuum and those same engaged stakeholders need tools to inform decisions about the many changes and challenges they are experiencing in the changing coastal environment. As such, Outcome 5 will focus on the complete product of delivering climate information relevant to many sources of ecological stress, with the main focus of optimizing the design, delivery and utilization of bespoke knowledge ocean acidification products.

Table 1: A subset of examples of model forecasting and projection OA variable-based products that already exist and help inform decisions around the globe.

Project description	Region	Decision the model supports	Timescale	Paper and or project website
East coast estuary historical simulation	Chesapeake Bay, USA	Nutrient mitigation for the watershed into the bay	Climate	
J-SCOPE	Northern CCS, USA	Fisheries management	Seasonal	Siedlecki et al. 2016; Kaplan et al. 2016; J-SCOPE website[29]
East coast projections with NWA ROMS	NWA shelf, USA	Regional OA action planning for MA, NJ, and ME	Climate (>2050)	Siedlecki et al., 2021
West coast historical simulation	Southern CCS, USA	Nutrient mitigation and sewage treatment remediation actions in the S-CCS	Climate	Kessouri et al., 2021
Alkalinity enhancement	Austrialia, Great Barrier Reef	OA mitigation	Climate	Mongin et al., 2020
FutureMares	North Atlantic and European Seas	Nature Based Solutions	Statistically downscaled CMIP6/Monthly/ Climate	Project underway https://www.futuremares.eu
CE2COAST	European Seas and Chile	Fisheries, MSP, Nature-Based Solutions, Windfarms	Seasonal to Climate	Project underway Ce2coast.com https://www.ce2coast.com

29 J-SCOPE website: https://www.nanoos.org/products/j-scope/

Table 1: *continued*

Project description	Region	Decision the model supports	Timescale	Paper and or project website
European Seas climate projections	European seas	Marine Spatial planning and MPA	Climate	https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-marine-properties; https://cds.climate.copernicus.eu/cdsapp#!/software/app-marine-spatial-planning-explorer
ACLIM	Bering sea			
DOM/OCCAS	Indian Ocean	Regional OA projections	Climate	Project underway Sarma et al., 2023 https://moes.gov.in/schemes/dom?language_content_entity=en

Our Vision

Ocean predictions and projections on the local scale to support decisions will require us to employ new technologies such as digital twins, machine learning, high resolution local predictions, and regional earth system models that seamlessly interface with large scale model output. Equitable, easy access to these ocean forecasts and projections in our everyday life will result in a more climate savvy public changing people's behaviors, increasing public awareness, expanding knowledge and perceptions, and contributing to the UN SDGs. The data will allow for mitigation of climate change impacts on coastal communities as well as the natural environment like coastal acidification driven by eutrophication. These tools will allow to contrast different scenarios within a multi stressor framework and therefore to develop more realistic plans for the management of marine resources. The production of these projections and associated data products will enable better marine resource management decisions. These tools will allow for implementation of ocean acidification adaptation and mitigation strategies, and integration of this information into other adaptation and mitigation strategies like marine carbon sequestration and removal, thus enhancing our international capabilities.

How does this fit within OARS and the UN SDG goals?

The UN Ocean Decade program "Ocean Acidification Research for Sustainability" (OARS) alongside GOOS: CoastPredict will provide a roadmap to achieve this vision. *Outcome 5* activities are informed by stakeholder needs identified in *Outcome 2*, biological response products in *Outcome 4*, and will require strong data provision from *Outcome 1* and *Outcome 3* to inform and test model development. In return, it will identify gaps in global observations strategies, and this promotes optimal resource investment in ocean acidification monitoring. The provision of knowledge that is usable and understandable requires good communication with *Outcome 6*, and further to science policy equip nations and society to mitigate and adapt to ocean acidification with *Outcome 7*.

Ocean predictions and projections on the local scale to support decisions will require us to employ new technologies such as digital twins, machine learning, high resolution local predictions, and regional earth system models.

No tool currently exists that delivers localized ocean climate information which spans the timescales of short-term forecasts all the way to projection space. This is in part because of lack of access to the model data, regional capacity, and in part due to lack of knowledge about how regional climate data could be consumed. All of those barriers are traversable and the goal of this Outcome's activities.

Products and outputs expected from *Outcome 5*

To achieve this Outcome, key products will need to be produced including new modeling innovations as well as tools to apply existing global simulations to local scales, all while ensuring equitable access to the bounty of climate information produced. Development of innovative technologies that both integrate and guide autonomous real time observations including artificial intelligence, machine learning, digital twins, data assimilation, and future innovations will also be required. Collaboration with other UN decade activities with similar objectives like DITTO, CoastPredict, OceanPredict, and GOOS is vital to the success of this Outcome. In many cases, these other programmes are not considering ocean acidification in their prioritization and thus it is up to our community to voice our potential as well as work toward its inclusion in these important activities.

Delivery of this information at hyper-localized scales will require additional visualization tools, which likely will demand the inclusion of a new community of practice and expertise in other disciplines like social science and data visualization.

Best practices will need to continue to be established for making near-term predictions, long-term projections of ocean acidification and other marine ecosystem stressors to support community decisions, and provision of localized ocean acidification climate information including novel applications of existing global ESMs. Some stakeholder groups like marine resource management, have been the target of these kind of activities on decadal to century scale downscale projection (Drenkard et al. 2021; Tommassi et al., 2017) on seasonal to decadal scales. These best practice recommendations have been US centric and rely heavily on large compute resources like High Performance Computer (HPC). There is a need to continue to develop best practices with developers of tools from broad international communities and to consider alternative approaches in order to ensure inclusive practices and continue to build capacity. Among these alternative approaches, emulators trained on data and/or regional model outputs could provide a targeted low-cost tool allowing the expansion of modelling tools also in region where access to HPC is limited or non-existent. Furthermore, this will also allow to limit the CO_2 emissions associated from running energy intensive models on HPC that are not entirely fueled by fossil-free energy.

The long-term need for these kinds of tools and regional climate information at hyper local and temporal scales requires that capacity is established to broadly support development of these models and tools locally but also that capacity exists to enables local users to access near-term prediction and future scenario projection outputs. As such, educational and training workshops in all regions of the world will need to be provided. This will entail the development of modular educational activities that can augment existing scientific meetings and summer schools to be deployed globally.

Local observations and integrated products are key ingredients to the success of these activities as they are vital for model evaluation for development as well as trust building activities with stakeholders. Collaboration with the team working on *Outcome 1* will facilitate this objective. Observation-based products include the generation of maps, atlases, and indices, which will involve collaboration with the team working on *Outcome 4*. Regional partners need to be engaged for identifying observational data gaps and generating downscaled future projections on regional scales.

Regional forecasts and projections are developing tools that will require the generation of trust, especially in new implementations, as these products will be required over long timescales into the future. Trust needs to be established both in the potential capabilities of the tools and the abilities of the scientific community to achieve them. Building trust with communities of potential stakeholders around models, projections, and forecasts of ocean acidification variables will require the development community to develop new methods to quantify and communicate uncertainty with these new tools and decision support systems in mind. Some existing systems (e.g., Copernicus Marine Services, J-SCOPE, and others in **Table 1**) can be used as examples and be used to establish methods around best practices for this activity. In addition, partnering with real time observing networks (partner with *Outcome 1*), will be essential as weather forecasts and other atmospheric based products have the benefit of direct user experience to build trust, but without real time observations, stakeholders have no way to establish direct experiences with ocean conditions.

Delivery of this information locally will require additional collaborations between the model and tool developers with the private sector as well as social scientists to bring the visualization of these data sets into everyday life (e.g., Google maps). Funding mechanisms to support these kinds of collaborations currently are not easily accessible by the community and either need to be established or advertised broadly.

Research and outreach activities planned and needed - the roadmap to achieving this Outcome

Several key actions can be taken early in the decade to move toward the success of this Outcome and to develop concrete time horizons with broad community support and participation, including workshops, papers, and educational module development **(Figure 8)**. These activities will directly engage new collaborators, communicate the findings and methods necessary to globalize these products, and build trust through extended usage and transparency of the models themselves.

In order to motivate stakeholders, funders, and decision makers to support this activity broadly, establishing the clear added value of these computationally intense activities will be important early on. One approach involves collecting case studies or examples that exist already in this space, and not all these case studies need to pertain to ocean acidification necessarily to provide evidence. Focusing on achievable small scale success stories will provide a foundation and examples to build upon. For example, several existing predictable systems exist for ocean acidification variables on the west coast of the US on seasonal to decadal timescales (Siedlecki et al. 2016; Brady et al. 2020; Kessouri et al. 2021) and elsewhere **(Table 1)**. The collection and curation can be accomplished through regional workshops that rely on the GOA-ON hubs and networks of other sister programmes within the decade. An integrated paper on the topic or even regional summaries where appropriate would greatly benefit the continued development of these tools globally.

Several best practices workshop(s) in collaboration with other UN Decade programmes and organizations outside of the ocean acidification community would provide fuel early in the decade for the vision to be enabled globally. In partnership with GOOS/CoastPredict and the core focus area FLAME, best practices for downscaling ocean climate information need to be extended from Drenkard et al. (2021) to allow for broader participation in this endeavor. The generation of a body of work or paper documenting these ideals will serve the further development of this important activity.

In addition, the conversation with other communities with experience forecasting and projecting on smaller timescales is critical to learn from and guide us. Well established communities in weather, sea level rise, flooding, HABs, and other folks working on these shorter timescales. Relocatable forecast systems are also being operated like OPENCoastS[30] and SURF[31] which could be augmented for ocean acidification variables (Oliveira et al. 2020; Trotta et al. 2016; 2021) . Relocatable tools and methods also serve as a practical way to support the development of modelling capacity in various regions. Given the highly variable and localized issues associated with coastal acidification, research would need to be done on how to best include these variables rigorously in these flexible systems.

Broadening the community, we learn from will also be critical. This includes turning to the private sector and business community who have streamlined the process by which stakeholder information is integrated into product development like AGILE (Raharjo and Purwandari, 2020). Stakeholder co-designed tools exist for weather, surf, and wind forecasts whose process could inform the development of similar tools for the ocean acidification community. Boundary organizations will be necessary when these systems move into new regions as, especially those that exist in regions with long standing relationships with local stakeholders. Learning about these workflows and inviting the private sector into the process could speed up the process of co-design.

Stakeholders will continue to be critical to engage with as early and often as possible, which will require collaboration and coordination with OARS *Outcome 2* activities. In particular, a gap analysis with observational needs in collaboration with OARS *Outcome 1* and *2* could also identify new knowledge potential from existing data mining. By creating an inventory of existing tools, applications, models, and products for ocean acidification and development of new knowledge from existing data. Workshops will define which groups of stakeholders to focus on first. They will identify what are the main stakeholder data requirements. *Outcome 5* competence and ambition, alongside the high stakeholder relevance will be used in targeted funding meetings with, for example, research councils, government agencies, financial institutions, private companies, NGOs, philanthropists.

30 OPENCoastS: http://opencoasts.lnec.pt/index_en.php
31 Surf: https://www.surf-platform.org

Specific communities are needed to engage with and ensure the data provided is relevant to decisions that can be supported from the forecasts and projections. We will work closely with *Outcome 2* on this outreach to include:

- Marine resource/fisheries managers
- Conservation areas
- Wind farms
- Marine CDR industry
- Tourism
- Indigenous communities
- Blue carbon
- Aquaculture

Extending this work into new regions and sustaining it into the future will require additional capacity building in regional modeling, statistical downscaling, and using big data from global ESMs.

This could be achieved by offering training sessions at international and national conferences as well as summer schools on this topic. Educational materials will need to be developed and distributed as well as tutorial videos generated.

With marine carbon dioxide removal work on the rise, the incorporation of ocean acidification baselines into newly developed recommendations for CO_2 removal and nature -based solutions is vital.

A potential list of researchers involved in ocean acidification research may be prepared for carrying out capacity building activities in new regions.

Data needs

We will also require FAIR, open, and verifiable data from a variety of sources and in particular those available in real time for model evaluation through the platform in real time. This activity is vital to the development of trust with new communities surrounding these

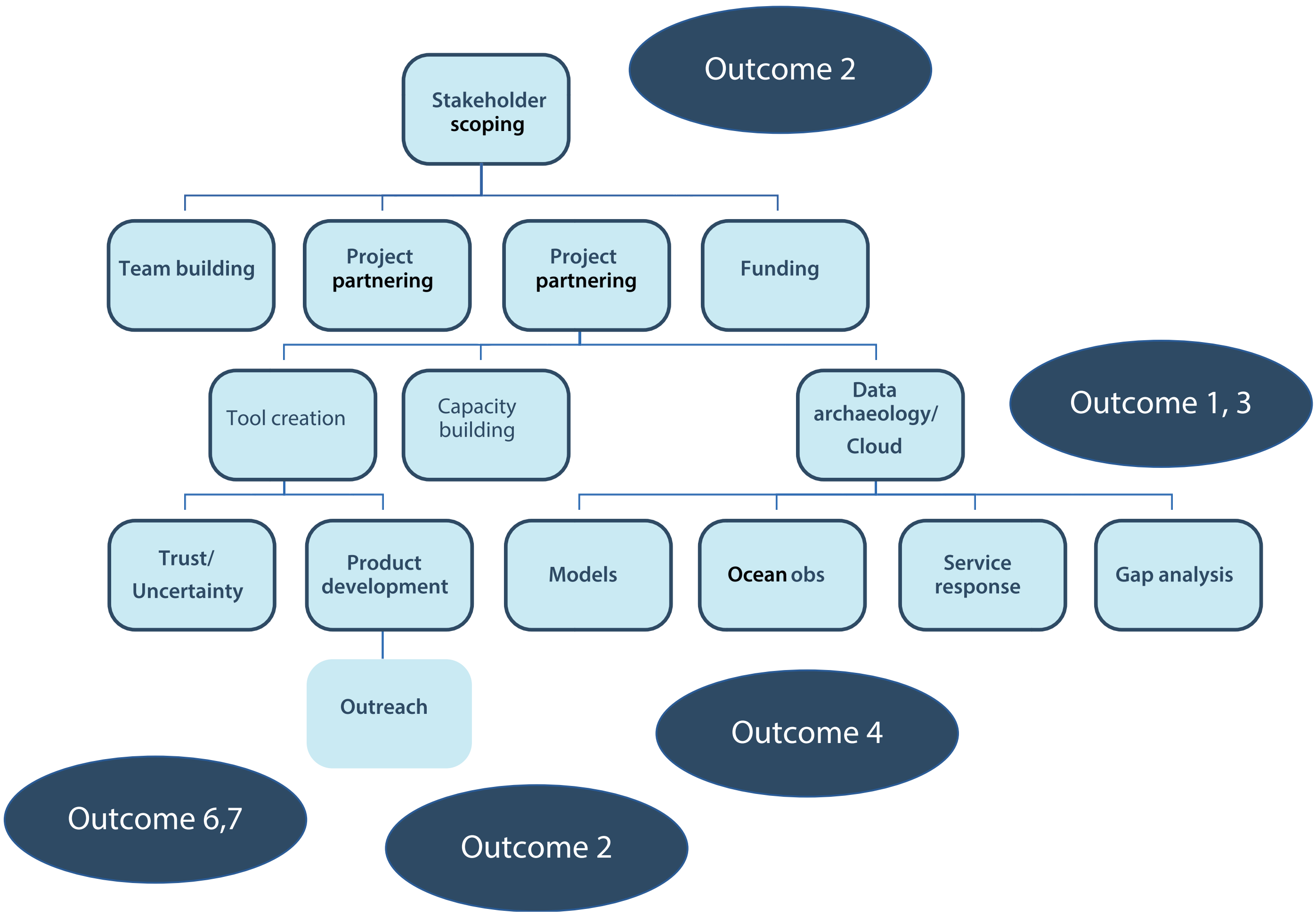

Figure 8: Early phase schematic of *Outcome 5* structure, sub-themes, and information pathways.

new tools. We will work closely with *Outcome 1* on this research need.

In addition, new analysis and products from observations will also be required for evaluation of the local climate information. This includes climatologies, regional trends, and local attribution of trends. As the ocean acidification community's data finally extends long enough in some regions to begin this activity, or regional statistical models emerge to extend existing hydrographic information, these products will begin to emerge and will help inform the regional climate trends in collaboration with *Outcome 3*.

Finally, as new tools emerge in underdeveloped regions, evaluation using local data sets will continue to be critical. Satellite products are often available even if no other data is being collected. Extending satellite products to include localized ocean acidification relationships will be vital in these emerging locations.

Membership

To enable these activities in both the short and the longer decade, OARS *Outcome 5* members will work to identify, collaborate, and engage with experts from a broad pool of topics including those listed in **Table 2**. We will identify additional members through boundary organizations, partner endeavors and programmes within the Decade, and through GOOS and GOA-ON regional associations and hubs.

The way forward

By the end of the Decade, through the activities described here and the combined power of the sum total of the Decade's activities, societally relevant predictions of the impacts of ocean acidification will be freely available. This will require new approaches and partnerships to support the computationally intense requirements to provide climate information at hyper-local scales. For example, innovative technologies that integrate autonomous real time observations and visualize the output will need to be developed. Best practices for forecasting and providing localized projections of climate are needed. Furthermore, equitable distribution pathways for seamless existence in everyday life will need to be identified and established. Finally, capacity and trust building with the next generation of scientists as well as stakeholders and end users.

Table 2: List of some potential partner organizations and programmes.

Expertise	Potential groups to engage
Global climate modelers (ESMs)	OceanPredict; DITTO
Downscaling	CoastPredict; Jupiter
Process based modeling	CoastPredict; Gordon conference; GEM
Visualization/map making	Geographers
Data Scientists	
Large Ensemble analysis/Uncertainty	OceanPredict
Real time delivery of quality-controlled biogeochemical data	GOOS
Ocean forecasting at various required scales for stakeholders	GOOS/CoastPredict; UNDRR[32]
Marine resource management and other key stakeholders' perspectives (*Outcome 2*)	OARS O2; boundary organizations like CFRF
Multimedia experts	

32 UNDRRR: https://www.undrr.org/theme/early-warning

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OARS Outcome 6:

Increase public awareness of ocean acidification, its sources, and impacts, achieved via ocean literacy and public outreach.

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Introduction

Atmospheric CO_2 is increasing in unprecedented ways due to anthropogenic activities such as the burning of fossil fuels, deforestation, cement production, and large-scale land-use changes (Friedlingstein et al., 2020). The ocean absorbs the atmospheric CO_2 alleviating the greenhouse effect. However, this CO_2 absorption is changing seawater chemistry by lowering the pH and carbonate ion (CO_2^{3-}) levels. This causes a fundamental shift in ocean chemistry, known as ocean acidification (Doney et al., 2020; Hassoun et al., 2022). Ocean acidification (OA) is threatening the overall structure of marine ecosystems (Beaufort et al., 2011; Gattuso and Hansson, 2011; Riebesell et al., 2013; IPCC, 2021) and resources on a global scale (IGBP et al., 2013). For example, OA effects cause a decline in shellfish calcification and growth rates (Talmage and Gobler, 2010; Wittmann and Pörtner, 2013), as well as of shell-forming marine plankton and benthic organisms including mollusks (Kroeker et al., 2013; Vargas et al., 2013), echinoderms (Dupont et al., 2010; Bednaršek et al., 2021), pteropods (Bednaršek et al., 2019), and corals (Beaufort et al., 2011; Kornder et al., 2018; Cornwall et al., 2021). The latter have already disappeared or are significantly damaged in some coastal areas around the world, including Indonesia, Hawaii, the Caribbean, Fiji, the Maldives, and Australia (Erez et al., 2011). A 30% decline or damage of coral reef ecosystems is estimated worldwide, with predictions that as high as 60% of global coral reefs may disappear by 2030 (Hughes et al., 2003), which will alter the ecological goods and services provided by these ecosystems (Moberg and Folke, 1999) thus affecting the more than 3 billion people who directly depend upon coral reefs for their livelihoods and food security (Hilmi et al., 2019).

OA is therefore a significant global concern that is threatening the livelihoods of billions of people relying on marine resources, as well as the future of crucial marine functions that are maintaining the current global climate system. Even with the availability of funding resources and a consensus for improved and coordinated OA governance, Hassoun et al. (2022) found that a lack of OA literacy (Fauville et al., 2013) can lead to a lack of consistent OA policies (Harrould-Kolieb and Hoegh-Guldberg, 2019) and OA regional governance (Galdies et al., 2020). We cannot engage with issues we don't understand and OA literacy is key to informing the public and authorities about the complex consequences of OA and solutions to mitigate and adapt to future global changes.

What is the problem?

While the ocean provides tremendous services and value to humans (e.g., Costello et al., 2020; Worm et al., 2006), human activities are compromising its capacities to provide these services (IPCC, 2019). To avoid catastrophic consequences of anthropogenic impacts on the ocean, it is urgent to address these threats (Gattuso et al., 2015). As argued by Sterling (2001), "the difference between a sustainable or a chaotic future is learning". In order for citizens to be responsibly involved in marine environmental issues such as OA, they need to understand the value and role of the marine environment, as well as how human activity is affecting, or potentially diminishing, the marine environment. Ocean literate people understand the influence the ocean has on them and their influence on the ocean. Ocean literacy helps demonstrate the value of ocean science for sustainable economy and policy, helping to create a common baseline of understanding and a common set of values among societal actors and stakeholders (Eparkhina et al., 2021).

The original definition of ocean literacy covers three dimensions: (i) having knowledge about the functioning of the ocean, (ii) being able to communicate about the ocean in meaningful ways, and (iii) taking informed and responsible actions regarding the ocean and its resources (Cava et al., 2005). Lately, the concept of ocean literacy has been attracting more attention from the research community. Scholars argue for expanding the reach of ocean literacy beyond these three dimensions and suggest six dimensions (Brennan et al., 2019) and even ten dimensions such as activism, emotional connections, and adaptive capacity (McKinley et al., 2023).

Previous research has revealed a low level of knowledge about the ocean among the public; citizens have limited marine understanding (Guest et al., 2015), hold serious misconceptions about the ocean (Ballantyne, 2004), and have little understanding of marine environmental issues and protection (Eddy, 2014). To change this, it is not enough to provide information (Bray and Cridge, 2013; Clayton et al., 2015). Research has shown that focusing on a personal connection,relevance of the information, and agency of the learners is more efficient than sharing facts (Kollmuss and Agyeman, 2002; Bamberg and Möser, 2007). Also, direct experience of an environmental issue is more powerful than second-hand information (Spence et al., 2011).

However, experiencing environmental issues that take place in the ocean is complicated. Few people have the ocean in their backyard and exposure to the ocean is rarely a significant part of formal education in secondary schools. First-hand exploration of the ocean is a challenge in terms of time, safety, and budget (Fauville et al., 2018). Even for citizens living by the ocean, most of the marine environment remains hidden under the surface and far away from the coastline, leading to a situation where only a small fraction of the marine biodiversity and processes can be encountered and experienced directly. As expressed by Longo and Clark (2016,), "the ocean is commonly viewed as something far removed from human society. In some way, it is deemed 'out of sight, out of mind'".

When it comes to increased OA literacy, the research is in its infancy. Teaching OA is made difficult by the lack of general scientific literacy, an unprepared field of education, the complex and invisible nature of this issue, and the lack of personal connection with the ocean (Fauville et al., 2020). The educational strategies developed thus far to address this issue have been limited in their approach. Moreover, the strategies adopted to teach OA have lacked proper research on their impact on knowledge, attitude, and behavior related to the health of the ocean (Fauville et al., 2013).

How public awareness contributes to the overall OARS objective, the ultimate impacts and benefits with respect to the Ocean Decade, as well as the environment and society at large.

Outcome 6 is to "Increase public awareness of ocean acidification, its sources, and impacts, achieved via ocean literacy and public outreach". By taking steps to achieve this Outcome, distinct benefits will be realized:

a) **Increase Ocean literacy in general, and OA literacy in particular:** Ocean literacy has been recognized as an important skill of the 21st century in order to reach the sustainability goals set by the UN, including but not limited to SDG 14 (Life Below Water), to the 7 UNESCO essential principles of ocean literacy[33] and to the Ocean Decade Challenges[34]. As this is a global issue, it is critical to reach many sectors and demographics to create change, including policy and decision-makers, the public, industry, and young people. In collaboration with various national, regional, and international initiatives[35], strategies to improve ocean literacy among key targets will be developed. **It will be more widely understood that OA is directly linked to climate change and requires urgent attention.**

b) **Implement innovative strategies to overcome barriers to teaching OA:** OA is a complex issue grounded in chemical reactions and complex equations. Engaging communication will require emotional connection between the public and the ocean, to overcome this complexity and to trigger interest and involvement. This can be achieved, for example, through teaching about charismatic ocean fauna that are affected by OA (e.g., pteropods, corals, crustaceans, and molluscs). Storytelling and focus on heroes as model characters can be another approach to trigger emotional connection with the ocean. **More sectors of humanity will have a more innate understanding of why ocean change can have significant and relevant consequences.**

c) **Focus on positive actions rather than on negative impacts:** This can be conducted through science-based messages highlighting solutions or inspiring the audiences to suggest their own. Within this initiative, it is deemed important to engage with OA skeptics who obfuscate by citing uncertainties around OA. It is important to clearly explain uncertainties and highlight risks. This will require collaboration between sectors such as health, insurance, security, banks, and businesses that are ready to support the mitigation of OA in a tangible and sustainable way. There must be a much more visible connection between the science of OA and the public's lifestyle in order to help citizens make informed choices in relation to the ocean and its resources. ***In this way,* the public will see how positive changes in their daily life can help fight OA.**

d) **Work on key take-home messages to various audiences:** The messages will aim at four target groups: policy and decision-makers, general public, educators, and students. Appropriate language and narratives will be used to reach out to each of the target groups. Activities and tools will be designed for each target group but in such a way that they can be repurposed to another group if possible. **This will enable a common language and understanding between disparate sectors.**

e) **Tailoring indicators/metrics of progress and success:** In collaboration with various types of experts, we will provide metrics that can be regularly used during and beyond the UN Ocean Decade to monitor the progress of our activities and the success of the strategies implemented. **This will provide common knowledge of whether efforts are reaching the intended level of change.**

Preliminary list of key outputs and products that will need to be produced in order to deliver the desired *Outcome*.

In this outcome, we aim to provide the following outputs:

1) Various **communication strategies** will be proposed to reach our audiences. These strategies might include mainstream and engaging documentaries, animated short films (i.e., teacher at sea, citizen-science), participation in international short film festivals, Virtual or Augmented Reality (VR, AR), and celebrity interviews about OA to be shared on social media with catchy titles (e.g., What will OA do to Aquaman?).

33 Ocean literacy principles: https://oceanliteracy.unesco.org/principles/
34 Ocean Decade Challenges: https://oceandecade.org/challenges/
35 e.g., OARS Outcomes 2 and 7: http://www.goa-on.org/oars/outcomes.php

2) **Professional development** for Civil Society Organizations (CSOs) from coastal communities, Indigenous communities, traditional knowledge holders, and educators will be provided to give adequate knowledge to teach about the OA in classrooms (e.g., through knowledge exchange and training-of-trainers initiatives).

3) **Scientifically vetted take-home messages** underlining sources, impacts, solutions, and required actions will be co-created with science communicators, artists, and marketing experts.

4) We will promote the **use of high-tech tools** to improve OA awareness. The use of immersive technologies such as VR and AR have already been demonstrated to have potential to impact public environmental literacy (Fauville et al., 2020; Pimentel, 2022). These tools can help make the process of OA visible to the human eyes but also to develop empathy for the species negatively impacted by this problem. These species can be either animals the public is familiar with and feel connected with through, for example, their diet, or species that are not well known but can be discovered through ocean literacy (e.g., pteropods).

5) **Citizen-science campaigns** will be launched. In fact, all the aforementioned initiatives can be refined by mapping out various audiences' knowledge and launching citizen science campaigns. This kind of campaign could, for example, engage divers, CSOs from coastal communities, Indigenous communities, traditional knowledge holders, and students. Such campaigns may include students building a mini boat to sail on the open ocean or adopting a float that collects OA data that can be analyzed in school.

6) An **OARS Education website** will be developed to publish the materials generated from this Outcome and to collate any existing resources. OA scientists, educators, CSOs from coastal communities, Indigenous communities, and traditional knowledge holders from around the globe will be invited to interact with students using these materials.

7) We will create a **comprehensive OA training programme**, both virtual and in-person, that can be utilized globally.

Research and outreach activities that are needed to create the outputs and products listed in section 2.

The outreach activities utilized must be guided by a clear answer to each of these three questions:

- What are the expected learning outcomes? (i.e., what are the take-home messages we wish to deliver?)
- Who are the learners? (i.e., what is their socio-demographic profile, their lifestyle, their profession?)
- In which context is this outreach activity taking place (i.e., in school, at work, in the media, on the internet, outdoors, in science museums)?

Analysis of these answers will guide the implementation of an activity.

While OA is a psychologically distant issue due to its invisible nature and its distance in terms of impact, it is essential to invest in solutions that have the potential to decrease this distance. One way is to engage people in the issue. Strategies developed must give learners as much involvement as possible. This can be done during a series of activities with opportunities to get close to the marine environment first hand or to build and deploy tools to collect their own OA data. Moreover, the learning outcome should be grounded in practical solutions and actions that the learners can engage in. Solution-oriented education will help avoid generating a doom and gloom feeling and help develop a sense of ownership. The OARS efforts should also spread across various international networks of marine educators (e.g., Asia Marine Educators Association AMEA, European Marine Science Educators Association EMSEA, Canadian Network for Ocean Education CaNOE, International Pacific Marine Educators Network IPMEN, National Marine Educators Association NMEA, Latin American Education Network for the Ocean RELATO and Australian Association for Environmental Education AAEE) and the UN Decade programmes and projects addressing ocean literacy (e.g. Ocean Literacy with All OLWA and Scientists for Ocean Literacy).

The proposed OA literacy activities can engage people in an unusual and creative way and become widely spread via social media (e.g., TikTok, Instagram, Facebook, etc.), or in public areas (e.g., malls or pubs). There are also opportunities to develop instructional material for schools, train the teachers, and promote the inclusion of OA in the curriculum. No matter what tactics are used to educate people, these activities should be developed and tested in an iterative way with the audience they target to ensure that these learning tools address the needs of their specific learners. The strategies developed should also be investigated from a qualitative and quantitative perspective in order to develop an in-depth understanding of their impacts and try to improve the evaluation of activities in innovative ways (e.g., using indicators of success and progress).

Key enablers that would influence the likelihood of successfully delivering the Outcome.

The creation of OA literacy strategies and tools will require a multidisciplinary approach. Expertise from fields such as storytelling, art, marketing, journalism, social media, communication, and education are essential to make sure that the focus is not only on the scientific accuracy but also the mode of delivering the message. Moreover, in addition to academic science, Traditional Ecological Knowledge (TEK) must also be considered in developing the science base for OA literacy. Many coastal communities rely on the ocean for their livelihoods and are highly impacted by OA. It will be important to engage CSOs from coastal communities, Indigenous communities, and traditional knowledge holders from around the world, preferably with the support of their central or regional governments, to empower their voices and enhance awareness and actions.

As one of the programmes endorsed by the UN Ocean Decade, OARS will establish synergies with other Decade actions, towards a stronger joint impact. Among others, this will include collaborating with programmes Ocean Literacy With All, Decade of Ocean Empathy, and ECOP (Early Career Ocean Professional) Network Programme.

Finally, we need to take a critical look (e.g., through meta-analyses and systematic reviews) into systemic inequities embedded in the field of OA and environmental education in order to ensure diversity, equity, and inclusion in OA research (Hassoun et al., 2022) in our goal to increase OA literacy.

Key inputs that would be needed to support the activities and outputs described above.

There needs to be an increased focus on this specific Outcome, OA literacy, combining many perspectives and integrating several expertises. A forum to focus this activity is lacking, because the needed inputs span diverse disciplines. Sub-working groups, including CSOs from coastal communities, Indigenous communities, and traditional knowledge holders, need to be established to guide the outputs. Lastly, a way to institutionalize the activity, so the good bursts of energy don't wither on the vine after a year or so is needed. This will help sustain this outcome's outputs beyond the UN Ocean Decade.

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OARS Outcome 7:

Develop strategies and solutions to enable countries and regions to include measures to reduce ocean acidification in their respective policy and legislation.

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A Note from the Authors:
The goals of OARS can only be achieved through coordinated action at local to global scales. While the authors of this white paper have endeavored to set a vision for *Outcome 7*, success will be found only if the global ocean acidification community works together to shape and implement this shared vision. Therefore, please consider the objectives listed here a guiding framework and a list of possible actions for members of our community to take, but not as a strict roadmap or top down process.

OARS *Outcome 7* and how it contributes to the OARS objectives and to the Ocean Decade

The Ocean Acidification Research for Sustainability (OARS) Programme[36] is an endorsed programme of the United Nations (UN) Decade of Ocean Science for Sustainable Development. The OARS programme is structured around seven complementary Outcomes which are designed to provide systematic evidence of the impacts of ocean acidification (OA) on the sustainability of marine ecosystems, enhance ocean acidification capacity, increase observations of ocean chemistry changes, enhance the communication to policy makers and communities by providing the information needed to mitigate and adapt to OA, and to facilitate the development and evaluation of strategies to offset future impacts. This paper is focused on *Outcome 7*.

OARS *Outcome 7* is charged with developing strategies and solutions that enable countries and regions to include measures to reduce OA in their respective management, legislation, and policy frameworks. However, the development of adequate OA policy and legislation is hindered by: (a) lack of understanding by policy makers of the relevant science and how to evaluate related impacts and risks; (b) lack of understanding of possible response options, including mitigation and adaptation actions; (c) lack of clarity on how policy actions can assist; (d) lack of coherence in and between national climate policy and ocean policy; (e) lack of understanding of how OA policies support

36 GOA-ON Decade Programme OARS: http://www.goa-on.org/oars/overview.php./overview.php.

the implementation of international and multilateral environmental and humanitarian commitments, and (f) lack of financial and human resources and capacity, especially in smaller economies.

Actions under this Outcome, therefore, will work with governments and relevant stakeholders to close these gaps and support the ongoing development and adoption of management approaches, policies, and legislation that help governments understand, account for, address, and minimize the causes and impacts of OA. The **vision of OARS** *Outcome 7* is wide adoption and implementation of effective OA governance through policy and legislation with sustained resourcing in a diverse range of countries. This vision is supported by the implementation of the following five pillars **(Figure 9)**:

1) The latest science is understood by policymakers and referenced in international, regional, national, sub-national level government and intergovernmental outputs (e.g., laws, policies, strategies, briefings, media, etc.).

2) National inventories of OA impacts on different national assets are developed and implemented.

3) Policy practitioners are engaged with each other across jurisdictions and policy areas and share an understanding of how to develop and implement OA policy.

4) OA policy frameworks are integrated with national, multilateral, and international ocean, climate, and biodiversity policies, food security and development strategies, and other relevant policy / governance structures.

5) Sustained funding is available for implementation of OA policy and related activities, including monitoring of OA and its impacts.

Achieving this vision will require inputs from all other Outcomes of OARS. A detailed description of how the outcomes of OARS will work together to achieve this vision can be found in section 4 *(Outcome 4)* of this paper.

Figure 9: Current Constraints to Achieving of OARS *Outcome 7*.

Figure 10: UN frameworks whose mandates support, and are enhanced by, OA management and policy development. *Source:* OA Alliance.

Preliminary list of key outputs and products

In order to address and eliminate the current constraints hindering meaningful policy action **(Figure 10)**, we recommend the following list of key outputs that will strengthen the science to policy feedback loop and provide frameworks and structures to reduce barriers.

1) A range of written and visual products that clearly articulate the latest science, available in policy-relevant formats (e.g., regional vulnerability assessments, summaries of expected change, and potential impacts).

2) A framework to create national inventories of assets (e.g., particular ecosystems and economic activities) affected by OA, with links to existing sustainability, climate, food security, and biodiversity frameworks at policy-relevant scales guiding future ambition and action.

3) A network of policy makers, including bilateral and multilateral connections, particularly focused on south-south relationships and cooperations.

4) Comprehensive guidance, legal templates, samples, and training in OA policy frameworks that integrate with national ocean policies, national climate policies, national development strategies, or other existing policy structures of relevance.

5) A series of engagements to raise awareness with funding bodies on the need for OA policy and monitoring for climate adaptation and resilience building, and the need to ensure stable, multi-year funds are allocated for these purposes.

Example activities to support outputs

Delivering the above outputs will require locally, regionally, and internationally coordinated activities. The following list of example activities is not meant to be exhaustive, but rather illustrative of the types of activities we recommend are undertaken.

Example Activities:

1) Training for policymakers on designing OA policy and integrating with international and national frameworks.

2) Production and/or collation of templates, guidance, and samples of OA policy frameworks.

3) Analysis of legal frameworks at local, regional, and national scales to enable effective policy integration.

4) Engagement activities to raise awareness with funding bodies on the need for OA policy, OA monitoring, OA modeling, and research regarding OA impacts on biology, as well as the relation between OA and existing climate, development, food security, and biodiversity funding strategies.

5) Convening or research activities that bring disparate groups and frameworks together to align relevant actions across national and international frameworks.

Specific policy goals related to regional and country priorities will also guide activity planning and selection. Activities such as the ones listed above are already being conducted by several bodies, including The International Alliance to Combat Ocean Acidification, The Ocean Foundation, and The Commonwealth Blue Charter. Examples of their specific efforts can be found in **Boxes 1, 2**, and **3**, on page 65 and 66.

Key inputs to support activities and outputs

The design and implementation of effective ocean acidification policy will require guidance and input from the science community at the scale of the policy being designed. Policies will need to consider the projected *timing, scale, and scope* of impacts as well as the potential *risks* associated with inaction and *options* to reduce risks.

Therefore, the outputs of all other OARS Outcomes will be important inputs towards achieving *Outcome 7*. This is true for *Outcome 2* (Science to Action), *Outcome 4* (Biology Impacts), *Outcome 5* (Future Projects), the engagement generated through *Outcome 6* (Public Awareness), and the data developed through *Outcome 1* (Data Quality) and *Outcome 3* (Observing Strategies). While inputs will be required at the specific scales of each policy, we believe a set of standardized products and tools would serve as general inputs to *Outcome 7*. For example, we recommend the creation of policy-relevant scientific syntheses produced regularly at specified scales (e.g., international, basin-specific, convention-specific).

We believe many of these inputs are already in development or that the structure to acquire such inputs exists. For example, at the international level, UN climate- and ocean-related frameworks, such as the Convention on Biological Diversity and the Sustainable Development Goals are beginning to integrate OA monitoring, research, mitigation, and adaptation. **Figure 10** describes the relevant UN frameworks whose mandates support, and are enhanced by, OA management and policy development. Specifically, they include the UN Environment Assembly, the United Nations Framework Convention on Climate Change (UNFCCC) Ocean and Climate Change Dialogue and Global Stocktake, the UN Decade of Ocean Science for Sustainable Development and the UN 2030 Sustainable Development Agenda (SDG 14.3). Note this figure was produced prior to the finalization of the Kunming-Montreal Global Biodiversity Framework, of which target eight explicitly applies to ocean acidification.

There are also existing agencies and bodies working at the science-policy interface. Those groups working to provide countries with the latest scientific information relevant for ocean acidification at national and regional levels include the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) and the International Atomic Energy Agency Ocean Acidification International Coordination Centre (IAEA OA-ICC), both of which support GOA-ON and OARS with the aim to provide data and information addressing the challenges countries experience due to ocean acidification. More international partnerships, the status and trends of ocean acidification, as well as challenges, opportunities, and areas for future collaboration including all stakeholders in the field of ocean acidification action are listed in the background document of the Interactive Dialogue 3 for the UN Ocean Conference 2022.[37, 38]

37 Concept paper for Interactive dialogue 3: Minimizing and addressing ocean acidification, deoxygenation and ocean warming: https://sdgs.un.org/sites/default/files/2022-05/ID_3_Ocean_acidification_deoxygentation_warming.pdf

38 Concept paper for Interactive dialogue 3: Minimizing and addressing ocean acidification, deoxygenation and ocean warming: https://sdgs.un.org/sites/default/files/2022-05/ID_3_Ocean_acidification_deoxygentation_warming.pdf

Key enablers of success

Coordinating the delivery of activities and production of outputs will require human resources. Therefore, a key enabler of achieving *Outcome 7* will be funding explicitly allocated to this coordination.

While the outputs of each OARS outcome will enable success of the entire Programme, *Outcome 6* will particularly enable policy activities. A broader public base engaged in and interested in addressing ocean acidification will increase interest in implementing policies.

The most important enablers, however, are the broader ocean acidification community and the policy makers at local and national levels, who are taking the final decisions about the adoption of ocean acidification sensitive legislation and its enforcement. Conversations at the science/policy interface need to be happening at all scales. Scientists should be communicating with policymakers in their regions to ensure their findings are incorporated into planning processes, and to identify areas of collaboration. Essentially, *Outcome 7* can only be achieved when scientists and policymakers take coordinated approaches at regional and international scales, particularly as novel and potentially wide-reaching mitigation and adaptation strategies such as marine carbon dioxide removal are explored.

Box 1: Description of OA policy relevant action by The International Alliance to Combat Ocean Acidification.

INTERNATIONAL ALLIANCE TO
COMBAT OCEAN ACIDIFICATION

The International Alliance to Combat Ocean Acidification (OA Alliance) brings together governments and organizations from across the globe dedicated to taking urgent action to protect coastal communities and livelihoods from the threat of ocean acidification and other climate- ocean impacts.

Facilitated through the OA Alliance, gational, subnational, regional and tribal governments are proactively responding to the impacts of ocean acidification as they create OA Action Plans to effectively promote solutions and advance knowledge into action.

OA Action Plans include strategies for reducing carbon emissions and local land based pollution, strengthening monitoring nearshore to better understand and predict local conditions, investing in adaptive measures in partnership with industry or seafood dependent communities, and advancing information sharing strategies that help policy makers respond.

By creating an OA Action plan-in whatever form is chosen and in keeping with existing capacity-climate and ocean policy leaders and managers explore the following important questions:

1. What species, economies, communities and cultures are currently or will be impacted by ocean acidification in my region?
2. Does my constituency know about this issue? Are there steps that my jurisdiction can take to raise awareness?
3. Is there anything that my government can do now that will make a difference?
4. How should my government prioritize actions that maximize our resources?
5. How does ocean acidification fit into existing management frameworks?
6. How does action on ocean acidification support existing high-level multilateral commitments?

Box 2: Description of OA policy relevant action by The Ocean Foundation.

The Ocean Foundation

The Ocean Foundation's International Ocean Acidification Initiative (IOAI) was founded in 2003 to ensure scientists, policymakers, and communities have access to the resources and tools required to monitor, understand, and respond to ocean acidification. The IOAI assists international, regional, national, and subnational governing bodies with developing legislation and other legal frameworks to address ocean acidification. In 2019 the IOAI published The Ocean Acidification Guidebook for Policymakers, This guidebook compiles all existing legal frameworks that explicitly address or could be used to address ocean acidification. Each legal framework is annotated and guidance is provided for policymakers deciding how to construct their own legislation. The Ocean Foundation has also created template legislation and works with governments to customize this legislation to meet local needs and adhere to local policy structures. Additionally, The Ocean Foundation has worked with regional bodies such as The Cartagena Convention to introduce resolutions designed to enable regional coordination on ocean acidification. In addition to this policy work, The Ocean Foundation supports scientific capacity development through the provision of training, equipment.

Box 3: Description of OA policy relevant action by the Commonwealth Blue Charter.

The Commonwealth Blue Charter

The Commonwealth Blue Charter is an agreement by the 56 Commonwealth member countries and adopted at the Commonwealth Heads of Government Meeting in London, April 2018. The Charter of the Commonwealth provides the underlying principles for the Blue Charter, ensuring that the Commonwealth takes a fair, equitable, inclusive, and sustainable approach to ocean economic development and protection. Under the Blue Charter, Commonwealth countries agree to actively cooperate to tackle ocean-related challenges and meet commitments for sustainable ocean development, with particular emphasis on the UN Sustainable Development Goals (SDGs), especially SDG 14 (Life Below Water). Implementation of the Commonwealth Blue Charter is through Action Groups, which work to unlock the power of all Commonwealth nations and guide the development of tools and training. Each Action Group is member driven and led by one or more Champion countries. To date, 16 countries have stepped forward to champion 10 Action Groups.

New Zealand champions the Ocean Acidification Action Group, with the goal of improving the capacity of Commonwealth countries to address the impact of ocean acidification, particularly in small-island developing states. The Action Group shares knowledge, experience and best practices on tackling ocean acidification, with particular focus on improving understanding of the impacts and drivers of ocean acidification (beyond carbon dioxide and with an emphasis on coastal systems); monitoring, modelling and forecasts; and mitigation, adaptation and resilience measures.

In February 2019, New Zealand hosted the Commonwealth Ocean Acidification Action Group Workshop in its role as Champion of the Commonwealth Blue Charter Action Group on Ocean Acidification. Scientific experts and observers were joined by 23 government officials from 17 Commonwealth countries. During this meeting, attendees discussed how to enhance Commonwealth members' ability to address the impacts of ocean acidification by identifying strategies for marine monitoring, capacity development, ocean literacy, governance, and management. Through these discussions, participants recognised that most available ocean acidification resources require technical expertise and implementation capacity that are not readily accessible to policymakers and often not available in Commonwealth countries. As a result they developed A Policymakers' Handbook for Addressing the Impacts of Ocean Acidification, The Handbook addresses this gap by identifying and contextualizing existing resources to facilitate the identification and implementation of strategies to address ocean acidification.

Intergovernmental Oceanographic Commission

Ocean Acidification Research for Sustainability

A Community Vision for the Ocean Decade

Ocean Acidification Research for Sustainability, OARS, is an endorsed Ocean Decade Action for the UN Decade of Ocean Sciences for Sustainable Development (2021-2030). Building on the successful work of the Global Ocean Acidification Observing Network (GOA-ON), OARS fosters the development of the science of ocean acidification including the impacts on marine life and sustainability of marine ecosystems in estuarine-coastal-open ocean environments. The programme's activities aim to attain the Sustainable Development Goals Target 14.3 "Minimize and address the impacts of Ocean Acidification, including through enhanced scientific cooperation at all levels" and provides a roadmap for ocean acidification research for the next Decade.

The vision for all seven Outcomes 1-7 as detailed over the course of this technical report will initiate the implementation phase of OARS in a coherent and inclusive manner, aiming to engage a broader community in producing and using ocean acidification research for sustainability.

One planet
One ocean
ioc.unesco.org

Ocean Acidification Research for Sustainability
Global Ocean Acidification Observing Network
IAEA
Ocean Acidification International Coordination Centre OA-ICC
NOAA Ocean Acidification Program
PML Plymouth Marine Laboratory