OARS Outcome 1 White Paper

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 oceans. 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 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. GOA-ON 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), the Hawaii Ocean Time Series (HOT), 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, considering which variables need to be measured and at what accuracy, at what spatial and temporal resolution and what platforms are required in order to deliver the data products needed to determine the progress and trends of OA throughout the world's oceans.

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 parameters to be measured, 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 programmes are required. While some SOPs already exist (e.g., Dickson et al. 2007, Riebesell et al. 2011), including those modified for low-cost methods (www.goa-on.org/resources/kits.php), 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 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 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 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), 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 research on OA trends advances.

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 what platforms are required in order to deliver the data products needed to determine the progress and trends of acidification throughout the world's oceans.
- Ensure adequate traceable RM for the community:
  - Provide a future long-term solution for a more resilient production of seawater RMs for the carbonate system, with one lab providing RM (most probably the National Institute of Standards and Technology (NIST, USA).
  - Equip regional laboratories to produce and distribute secondary reference materials, which are ultimately dependent on the values of the primary RMs.
  - Develop SOPs for the preparation of in-house standards, including the assignment of values and uncertainties.
  - The ultimate goal would be to have multiple RMs for different environmental conditions.
  - Increase the chemical species that are certified (i.e., pH, fCO_2, and isotope ratios $^{12}C/^{13}C$).
- 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 Outcome 3).

Enablers

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

- Modellers to evaluate the adequacy of the measuring network to achieve the Outcome 1 goals, and recommend cost-effect improvements
- Providers of reference material, in particular the National Institute of Standards and Technology (NIST, USA)
- Laboratories producing and distributing secondary reference materials on a sustained basis
- Experienced scientists willing to develop SOPs
- 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

O1P2. 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.

Utilising the International Oceanographic Data and Information Exchange (IODE) 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 Goal (SDG) indicator 14.3.1 Data Portal, a tool for the submission, collection, validation, storage and sharing of OA 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 adviser 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) tools and implemented in relevant data centres, data repositories, data management units
- ERDDAPP system installed in data centres, data repositories, and data management units
- ERDDAPP user surface developed to allow use for different purposes (i.e., SDG indicator 14.3.1)
- ERDDAPP 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 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 SOCAT, GLODAP 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.

The Surface Ocean CO_2 Atlas (SOCAT) and Global Ocean Data Analysis Project (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 gaps
- 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 recognise the need for data management and provision of data synthesis products as an integral part of any carbon observing programme.
- Stakeholders to visualise, 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 visualisation tools.

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, to regional to 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 programme; therefore, capacity building is a vital component of achieving the 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 OA monitoring, 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 programme 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 programme is substantially funded through grants and donations, with assistance from NGOs 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 programme, 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 programme and associated lab to 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 ready access to 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) 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.

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) and the GOA-ON Pier-2-Peer programme. Pier-2-Peer has matched 92 mentor-mentee pairs within the OA community since 2016, providing new insight or extending the learning from hands-on training event. As of January, 2023, 35 of those mentor-mentees are in very active partnerships. In some instances, the Pier-2-Peer 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 (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 programme
- Development of a sustainable mentoring programme, 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.

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, the Observing Air-Sea Interactions Strategy (OASIS), Global Ocean Observing System (GOOS) and World Meteorological Organization (WMO). 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 financial and environmentally responsible way, while allowing contributions from all partners

Enablers

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