

# International Ocean Carbon Coordination Project

## Progress Report for SCOR, September 2025



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## EXECUTIVE SUMMARY

In the past 12 months the IOCCP continued to support the development of a global network of ocean carbon and biogeochemistry observations, coordinate the development of globally acceptable strategies and provide technical coordination developing operating methodologies, practices and standards, homogenizing efforts of the research community and scientific advisory groups.

To strengthen opportunities for an appropriate global implementation of the marine biogeochemistry observing system, the IOCCP, through close collaboration with GOOS, has started efforts to create dedicated structures in the WMO's implementation mechanisms, allowing for clear definition of requirements for observations, observing system capabilities, and provision of guidance on the most important and achievable priorities for addressing the gaps between the identified requirements and capabilities. That effort is a part of a wider commitment of the ocean observing community to work with the WMO members states on defining and prioritizing the way forward for ocean monitoring. The IOCCP has initiated the community engagement in order to undertake WMO's Rolling Review of Requirements (RRR) process for the requirements related to biogeochemical phenomena. We have engaged the SOCONET-SOCAT-SOCOM value-chain community in order to start co-design the identification of current requirements, capacities and gaps. IOCCP fulfilling its role as GOOS Biogeochemistry Panel, plays a role of a community coordinator and WMO's point of contact for these efforts, engaging expert groups to provide detailed technical input on requirements and gap analysis.

The IOCCP continues to make specific, targeted efforts towards implementing a community-developed model for production, certification and distribution of critically needed reference materials (RMs) for the seawater carbonate system. This model, centered around 3 regional hubs, was proposed in 2021 when the fragility of the production system of the seawater RMs for the carbonate system depending on one single laboratory (SIO, USA) heavily impacted the global community. The largest progress is being made in the context of working with GOA-ON and ICOS-OTC as well as national metrological Institutes in Europe, and integrating the work of oceanographic community with those. The overall objective is to ensure coherent traceability chains and procedures for measurement results of the four measurable variables of the seawater CO<sub>2</sub> system. This will stabilize supply, ensure metrological certification, and strengthen the resilience of the ocean carbon observing system. The Euro-African Hub will support the oceanographic community and emerging mCDR initiatives with trustworthy, verifiable data, and drive innovation in software, BPs, uncertainty evaluation, and data traceability. By fostering standardization, regulatory alignment, and capacity sharing, this activity will support the foundation for global assessments such as the annual Global Carbon Budget or Global Stocktake.

IOCCP community has significantly contributed to the ocean community-wide effort towards development of a framework for a set of ocean indicators allowing for translating of the ocean science and data into practical metrics, guidance, and tools, informing on the state and health of the ocean that can be directly applied by policymakers, practitioners, and the public. The development of the ocean indicators framework extends the functionality of the Essential Ocean Variables (including for biogeochemistry), so that they can be incorporated into a broader set of assessments undertaken at varying scales and therefore deliver some clear guidance in terms of national monitoring and reporting. Building on the Essential Variable frameworks, this initiative addresses a critical gap in the international discussion on the ocean's role in the broader environmental context.

These most impactful recent developments, as well as other activities developed, lead or contributed to by IOCCP are described in more detail in the remainder of this report.

# PROJECTS & MAJOR ACTIVITIES

## **Towards Integrated Ocean Data Architecture**

In the past year the IOCCP was significantly involved in conceptual and technical discussions with key partners around developing a vision for an integrated ocean data architecture. The SSG members (Jones, Lange, Garçon) as well as the Project Office, were tasked with contributing the input from the ocean biogeochemistry landscape towards a wider vision co-created by experts from the International Oceanographic Data and Information Exchange (IODE), the joint WMO-IOC Operational Center for Ocean Observing (OceanOPS), the GOOS Observations Coordination Group (OCG), the Ocean Biodiversity Information System (OBIS), the Ocean Decade's Data Coordination Group as well as GOOS Panels for Biology/Ecosystem and Physics.

Since 2016, when IOCCP published a Position Paper on ocean biogeochemistry data management, some of our efforts continue to be focused on integration with other disciplinary data streams. Therefore, the goal of this multi-partner activity, which is to enhance coordination and discuss integration and scalability of the ocean data digital architecture across parameters and platforms, provide us with an opportunity to further our long-term focus. Expected outcomes are to improve data sharing, management and accessibility, as well as to align technical developments around broad adoption of open architectures and federated system approaches (ODIS, WIS2.0, ERDDAP™).

To kick-start this long-term process, the IODE/GOOS Data Workshop was held in VLIZ, Ostend, Belgium (30 September - 2 October 2024) and a post-workshop working group was created to synthesize and recommend implementation routes for ocean data architecture reflecting current needs, opportunities, challenges and threats.

At the workshop the key objectives were to:

- Identify roles and synergies of all partners involved clarifying the mandates, responsibilities, and connections with respect to all Essential Ocean Variables (EOVs).
- Develop a joint vision for an ocean data architecture structure which would allow to establishing an integrated, FAIR and CARE aligned system to support the ocean digital ecosystem.
- Draft technical foundation
- Define coordination mechanisms between all partners and beyond to evolve and mature the architecture
- Outline next steps for meeting future user needs

It's also important to note that this specific effort responds, on technical level, to some of the UN Ocean Decade Vision 2030 Challenge 8, which lists the following ambitions to be put in place by 2030:

- The enabling environment [Infrastructures, Tools, Services and Content], for the creation of and access to an increasing number of digital representations and (twin) applications of the Ocean
- All observations, datasets, data products, information and knowledge outputs should be shared and easily available to all.
- A global Digital Atlas with at minimum 10 societally relevant global base-layers & minimum 10 local use cases (prioritizing SIDS and LDCs).

The following high-level integrated tools, systems and services are hoped to be developed and in place by 2030:

- A federated global Ocean Data Discovery & Access Service (DDAS) with map viewer + Ocean Data Helpdesk and distributed Data Ingestion Service;
- A global Technical and Organizational Structure for Ocean Forecasting;
- A user-friendly reference global Digital Atlas of the Ocean;
- Set of platforms & mechanisms to easily store & exchange ocean information & knowledge;
- Enhanced Capacity Development & Training resources/facilities tailored to user-needs.

Through technical and strategic presentations and discussions, the meeting participants identified the following high-level needs:

- Strengthening the importance of data sharing as cross-cutting priority across structures and activities, including significant strengthening of a linkage between what is developed at technical level and decision-making and governance implementation at high international and national level
- Data management and sharing need to be recognized as essential in all communities of practice and relevant data management practices need to be sufficiently communicated and implemented
- Emphasis on training and creating employment opportunities of skilled staff in the ocean observing/data management landscape needs to be strengthened at all levels of stakeholders
- A shared vision across all the partners needs to be supported for implementation to avoid fragmentation in the disciplinary, geographical and political context
- An emphasis needs to be put on building data synthesis products to deliver directly to the needs of users and stakeholders
- Collective access to and benefits of sharing the data need to be available to all participants including currently under-capacitated global south
- Data licencing and restrictive usages protocols need to be developed or acknowledged and implemented.

The [full meeting report](#) contains a detailed description of the existing infrastructure elements, the ideas and planning suggested towards the ocean data architecture, as well as an initial list of agreed actions of which the most consequential was to establish and start the work of the IOC Data Architecture Working Group with membership including all involved partners. IOCCP is represented by Veronique Garcon and Nico Lange, and the group has been working on the following tasks:

- Map the data flows across disciplines
- Select showcase pilots that demonstrate data flows testing robustness of the system
- Address global capacity
- Develop joint (cross-partners) budget strategy including partnerships with private sector
- Communicate on the proposed data architecture across stakeholders to gain feedback and motivate co-design
- Assess the technical resources required, including computing power
- Assess human resource needs
- Consider system capacity for handling of the model data in an integrated/connected fashion

Dissolved Oxygen is currently considered as one of the showcase pilots and IOCCP will continue to be involved in strategic discussions as well as working on technical level with data providers to develop solutions enabling digital transformation across all biogeochemical EOVS in the 2030 perspective.

## **Ocean Biogeochemical Cycles as an Application in the WMO's structure**

The WMO Integrated Global Observing System (WIGOS) consists of multiple components which observe many different geophysical variables across the Earth System. By working together to collect and share their observations in the WIGOS framework, WMO Member countries gain access to the international observations needed in the activities undertaken to fulfil their mandates in monitoring the Earth System and delivering services. To this date ocean biogeochemistry observations have very limited presence in the WIGOS framework and the few parameters that are included, are loosely scattered across many Application Areas (AAs) as supporting measurements, which diminishes the description of impact which measuring of these parameters has on our ability to monitor the Earth System.

To strengthen opportunities for an appropriate global implementation of the marine biogeochemistry observing system, the IOCCP, through close collaboration with GOOS, has started efforts to create dedicated structures in the WMO's implementation mechanisms, allowing for clear definition of requirements for observations, observing system capabilities, and provision of guidance on the most important and achievable priorities for addressing the gaps between the identified requirements and capabilities.

That effort is a part of a wider commitment of the ocean observing community to work with the WMO members states on defining and prioritizing the way forward for ocean monitoring. The ocean is one of the six Earth System Application Categories within the overall framework of the WMO Rolling Review of Requirements (RRR). It encompasses seven key application areas for the ocean application domain: 1) Ocean Forecasting and Real-Time Monitoring, 2) Coastal Forecasting, 3) Oceanic Climate Monitoring and Services, 4) Tsunami Monitoring and Detection, 5) Marine Environmental Emergency Response, 6) Maritime Safety (from ports to open ocean), and 7) Ocean Biogeochemical Cycles. The Ocean Biogeochemical Cycles (OBC) AA is currently dormant and has been since its creation a couple of years ago.

The IOCCP has initiated the community engagement in order to undertake WMO's Rolling Review of Requirements (RRR) process for the requirements related to biogeochemical (BGC) phenomena. We have engaged the SOCONET-SOCAT-SOCOM value-chain community in order to start co-design the identification of current requirements, capacities and gaps. IOCCP plays a role of a community coordinator and WMO's point of contact (PoC) for this task, engaging expert groups to provide very technical input on requirements and gap analysis.

In the past 12 months, the IOCCP (Maciej Telszewski) participated in 3 workshops (June and September 2025) to engage with PoCs and Coordinators of other oceanic, atmospheric and terrestrial application areas and facilitate our work towards completing the transition of information included in (or missing from) the EOVS Specification Sheets to WMO structures. Outcomes of this participation include familiarizing with the existing guidance related to handling of the WMO's Observing System Capability Analysis and Review (OSCAR) database, identifying technical and personnel needs for completion of the OBC application area, initiation of direct interaction with the Joint Expert Team on Earth Observing System Design and Evolution as well as other ESAC Coordinators and provision of input relevant to marine biogeochemistry to the WIGOS 2050 Vision drafting group. Several technical aspects

were workshopped, and results of these discussions will help IOCCP deliver the OBC requirements and gap analysis benefiting from past experiences and lessons learned in the process.

The aim for the next 12 months is to complete the RRR process for at least two of the phenomena with entry level of operational service delivery, and therefore allow operational services to engage with the identified requirements. The two phenomena are: GHG Fluxes (linked to the WMO Global Greenhouse Gas Watch (G3W)), and Ocean Acidification (linked to the GCOS climate indicator). IOCCP in close collaboration with the EU BioGeoSea project, will be leading this task, ensuring that requirements in terms of BGC EOVs for these services are embedded in the OSCAR database and the WMO Statements of Guidance for the Earth System Application Category - Ocean.

## **Global Greenhouse Gas Watch: Data Integration and Optimal Observing Design**

The IOCCP (lead by SSG Members Sutton and Sanders as well as project director Telszewski) and a wider IOCCP community continue to coordinate the ocean community around implementation of the G3W. In the past 12 months specific focus of these efforts was on data sources integration and optimal design of the observing system.

The first of the two priority activities identified for the current phase of the G3W implementation, was specification of the output products, global centers requirements, comparison protocols, data exchange requirements and data architecture. All that across terrestrial, atmospheric and oceanic domain with an ambitious goal of integration allowing efficient interoperability.

To advance with these tasks a dedicated G3W Global Data Providers Workshop was organized in Geneva, Switzerland on 4-7 March 2025. The workshop built on the preparatory work conducted by the dedicated Task Team (including the IOCCP) over November 2024 - March 2025. Members of the Task Teams on G3W Modelling and G3W Data and a limited number of TT Networks and invited experts participated in this workshop. The workshop focused on some fundamental work including:

- Detailed description/characteristics of the output of the domain-specific G3W systems, requirements to the spatial and temporal resolution, requirements for the input data, comparison protocols and evaluation of the model performance.
- Requirements for the global centers that can deliver identified products and provisions for their integration in a WMO Integrated Processing and Prediction System (WIPPS)
- Identification of the data streams (input data, including observations and priors; data exchange for the models intercomparison and quality control, output data) and their characterization
- Initial considerations about architecture and requirements for the data flow for the inclusion in WIPPS.

IOCCP contributed with clear indication of the current status of the surface ocean carbon observing data management structure (SOCAT) and description of efforts aimed at filling the observational gaps using statistical approaches and models (SOCOM). In both cases limitations and potential gaps in the context of G3W requirements were indicated.

The second priority activity identified for the current phase of the G3W implementation relates to designing an integrated, optimal, cross-domain observing system, which is a fundamental requirement for data assimilation, modelling and verification. A global GHG observing system spanning across all

Earth system domains (land, ocean, atmosphere, and cryosphere) consisting of surface-based and space-based efforts, is complex and for a large part disconnected. It includes a variety of initiatives and collaborations among international organizations, government agencies, research institutions, and private sector. Implementation of such observing system requires development of a common set of monitoring approaches and principles applied across observing networks for integration.

To advance this work a dedicated G3W Network Design Workshop was prepared and will be held in Geneva, Switzerland on 7-9 October 2025. IOCCP (Sutton, Sanders, Telszewski) has coordinated the preparatory work of the ocean community and will convene an ocean session attended by invited ocean experts representing relevant observing networks and optimal design practitioners.

The workshop will build on the preparatory work conducted by the Task Team over July-September 2025. The workshop will combine limited number of presentation and discussion sessions focused on the outputs of preliminary work of the Task Team and related studies to come up with the recommendations on the G3W network design. Initial priority is on carbon dioxide. Studies related to other greenhouse gases (in our case nitrous oxide and methane) will be also briefly discussed.

The cross-domain GHG community will attempt to define whether and how a tiered network structure can be adopted. Such structure has already been developed for SOCONET. The cost-efficient design of the observing system is sought after for the implementation of WMO member countries and international community, utilizing common monitoring principles across domains. While the strategies for the development of the satellite segment of the GHG observing system are well established, the surface (including over the ocean) network design need further optimization.

The topics addressed by the workshop include:

- Cross-domain system optimization based on the results of model intercomparisons and satellite data utilization,
- Cross-domain optimization based on the footprint analysis,
- Optimization of the surface ocean observing network,
- Results of the Observing System Simulation Experiments, including benefits and impact of the optimized network.

During the preparatory work for the TT Networks Workshop, the IOCCP contributed with clear indication of the current status of the surface ocean carbon observing system (SOCONET) and description of efforts aimed at filling the existing gaps. Current technical, logistical and coverage limitations in the context of G3W requirements were indicated.

Outcomes of both activities will contribute to the next phase of the GGGW implementation which is to combine gap analyses across observations, data management and modelling Task Teams and to provide the G3W leadership with clear recommendations on priorities regarding stakeholder and WMO member states focus.

## **Development of tiered structure for the Surface Ocean CO<sub>2</sub> Observing Network**

In our current role as coordinators of the Surface Ocean CO<sub>2</sub> Observing Network (SOCONET), in the past 12 months the IOCCP experts (Sanders, Sutton, Telszewski) collaborated with the SOCONET's interim Steering Committee members to develop and describe specific guidelines for SOCONET reference-quality measurements (referred to as Tier-1 measurements also in the context of GGGW), which are the observational cornerstone for surface ocean fCO<sub>2</sub> to quantify sea-air CO<sub>2</sub> fluxes with

sustained delivery of reference quality datasets in support of efforts such as the Global Carbon Budget, Global Greenhouse Gas Watch and other assessments and activities.

The requirements developed for SOCONET-Tier 1 are to perform high-quality observations with an accuracy of  $<2 \mu\text{atm}$  in  $f\text{CO}_2$  and  $<0.2 \text{ ppm}$  ( $\mu\text{mol mol}^{-1}$ ) in mole fraction in dry air, and implementation of these measurements in a coordinated framework. This approach and these accuracies are necessary to constrain global annual sea-air  $\text{CO}_2$  fluxes to  $0.2 \text{ Pg C}$  ( $1015 \text{ g C}$ ) or uncertainties of less than 10% of the current annual global sea-air  $\text{CO}_2$  flux.

The work of this expert group resulted in development of a SOCONET community-approved guiding document entitled First steps to implement SOCONET-Tier 1 measurements and data delivery, which was published by IOCCP in April 2025 here: <https://zenodo.org/records/15681842>

The authors (including current and past IOCCP experts) provide the practical considerations to establish uniform presentation, documentation, and (meta)data delivery. The document incorporates ideas and common practices in place by established operators with the goal of providing a unified outward-facing presence of the entities providing high-quality measurements. It provides the first practical implementation steps with the recognition that several other critical activities need to take place to implement SOCONET, including network design, establishing formal cooperation agreements; industry, academic, and (multi)-government partnerships; and technology development. The document is focused on Tier 1 operations, but much of the practices will likely be adapted for non-Tier 1 measurements, once experience is gained in incorporating the procedures by the established groups.

Considerations outlined in this document are a subset of much broader requirements setting that will be developed in a form of a SOCONET Implementation Plan overseen by SOCONET under the coordination of IOCCP.

## **Coordination of the Nitrous Oxide ( $\text{N}_2\text{O}$ ) EOVS with Methane ( $\text{CH}_4$ ) observations**

The oceans are a fundamental component of the global climate system and are a net source of tropospheric  $\text{CH}_4$  and  $\text{N}_2\text{O}$  at the global scale, although local to regional budgets may include both source and sink components. There are far fewer measurements of dissolved  $\text{CH}_4$  and  $\text{N}_2\text{O}$  than of dissolved  $\text{CO}_2$  and while there is substantial international coordination with regard to  $\text{CO}_2$  analysis, calibration, and data reporting, no such coordination yet exists for  $\text{CH}_4$  and  $\text{N}_2\text{O}$ . Given the increasing prominence of climate change on scientific and societal agendas, greater coordination among the marine  $\text{CH}_4$  and  $\text{N}_2\text{O}$  scientific community to provide more targeted measurements and increase the quality and interoperability of  $\text{CH}_4$  and  $\text{N}_2\text{O}$  observations is particularly timely.

Until recently there has been no formal coordination of observations across the  $\text{CH}_4$  and  $\text{N}_2\text{O}$  scientific community. In response to this, the IOCCP has appointed a new SSG member (Gregor Rehder) responsible for Non- $\text{CO}_2$  GHG parameters. A major goal of this appointment is the integration and homogenization of research related to oceanic and coastal measurements of  $\text{N}_2\text{O}$  and  $\text{CH}_4$ , including an update of the current EOVS description for  $\text{N}_2\text{O}$ , and driving the development of a sustainable scientific network and data stream for oceanic measurements of these important non- $\text{CO}_2$  greenhouse gases.

An important activity in the last 12 months was the preparation and distribution of common, combined gaseous  $\text{CH}_4$  and  $\text{N}_2\text{O}$  standards to 12 international laboratories, with the aim of improving and

standardizing calibration. A subsequent intercomparison of discrete seawater samples included the use of these standards and revealed the variability between laboratories. While there were some encouraging results from the intercomparison, such as the agreement between individual laboratories using contrasting techniques, overall a large range was observed in CH<sub>4</sub> and N<sub>2</sub>O concentration data generated by the participating laboratories. Such analytical discrepancies weaken our collective ability as a community to evaluate temporal–spatial variability in marine CH<sub>4</sub> and N<sub>2</sub>O. The discrepancies also highlighted the need for standard operating procedures (SOPs) for CH<sub>4</sub> and N<sub>2</sub>O analyses to facilitate standardization of sampling, measurement, and calibration, as well as the reporting of data and accompanying metadata in common repositories. Only when all these points will be at least partially met, the development of a combined N<sub>2</sub>O-CH<sub>4</sub> EOVS Specification Sheet will make sense.

During this past 12 months an overview of the oceanic CH<sub>4</sub> and N<sub>2</sub>O data repository known as the Marine Methane and Nitrous Oxide database (MEMENTO) was performed to assess the collective ability of the scientific community to determine the spatial variability of marine CH<sub>4</sub> and N<sub>2</sub>O distributions. MEMENTO established in 2009 is now sufficiently mature to support descriptions of the broadscale surface distributions of CH<sub>4</sub> and N<sub>2</sub>O. Machine-learning mapping also recently identified the various contributions of physical and biogeochemical predictor variables for CH<sub>4</sub> (e.g., depth, primary production) and N<sub>2</sub>O distributions (e.g., chlorophyll, sea surface temperature, apparent oxygen utilization, and mixed-layer depth).

Shallow marine environments and oxygen-deficient zones are widely recognized as deserving of greater attention because they have high CH<sub>4</sub> and N<sub>2</sub>O concentrations with inherently high uncertainties that complicate any assessment of their emissions to air. This inherent complexity of shallow marine environments clearly warrants a strategically coordinated approach to optimize the value of future integrated CH<sub>4</sub>/N<sub>2</sub>O monitoring. Issues to consider include identifying the locations of complementary sampling sites, standardizing sampling strategies and techniques, and agreeing on the use of common ancillary measurements that set the broad biogeochemical context.

To increase the value of the promoted coupled (N<sub>2</sub>O/CH<sub>4</sub>) observing system, we encouraged the Global Carbon Project with its objective of developing a complete picture of the global carbon cycle including interactions and feedbacks, to expand its scope to include CH<sub>4</sub>/N<sub>2</sub>O data. The recent Global Carbon Project N<sub>2</sub>O budget reported emissions from the open ocean, inland waters, estuaries, and coastal zones. Low-oxygen oceanic regions associated with eastern- boundary upwelling zones and the coastal ocean were identified as key regions with significant N<sub>2</sub>O variability requiring more detailed assessment via measurement campaigns and model analyses. Contribution to the Global Carbon Project and similar initiatives will identify areas of synergistic CH<sub>4</sub> and N<sub>2</sub>O research for oceanographers and other Earth observation scientists. Furthermore, field observations alone are insufficient to improve the robustness of Earth system models, and leveraging laboratory-based microbial process studies is highly recommended.

The success of any coordinated CH<sub>4</sub> and N<sub>2</sub>O observing system relies heavily on having uniformly high confidence in the various resulting datasets and their interoperability, which should be clearly defined in the EOVS Specification Sheet. We therefore identify three key initiatives that are paramount to ensuring this:

- The first is to develop and adopt standard operating procedures (SOPs) to help obtain intercomparable CH<sub>4</sub> and N<sub>2</sub>O datasets of the highest possible accuracy and precision. Currently, there is no consensus definition of high-quality CH<sub>4</sub> and N<sub>2</sub>O measurements. However, an analytical agreement of  $\leq 1\%$  is considered achievable for the laboratories

conducting repeat oceanographic surveys and time-series observations. For context, an analytical agreement of  $\leq 1\%$  would permit the ocean's response to the increasing tropospheric  $\text{CH}_4$  and  $\text{N}_2\text{O}$  mole fractions to be resolved on timescales of 10 and 5 years, respectively. These values are based on the changes in surface ocean  $\text{CH}_4$  and  $\text{N}_2\text{O}$  concentrations that are predicted to occur due to the ongoing increase in tropospheric  $\text{CH}_4$  and  $\text{N}_2\text{O}$  mole fractions at a seawater temperature of 20C and a salinity of 35 g kg<sup>-1</sup> and assuming all sources and sinks remaining constant. In a recent marine  $\text{CH}_4$  and  $\text{N}_2\text{O}$  intercomparison exercise it was concluded that the diversity of analytical procedures employed by the participants was a major cause of high variability between the reported concentrations, highlighting an urgent requirement for  $\text{CH}_4$  and  $\text{N}_2\text{O}$  SOPs. Consequently, these SOPs are now being compiled by the scientific community.

- The second is increased regularity of intercomparison exercises through the periodic distribution of consensus material, i.e., water samples in which  $\text{CH}_4$  and  $\text{N}_2\text{O}$  concentrations are known with high confidence, obtained by pooling analyses from several laboratories with demonstrated analytical capability. These will help the scientific community to monitor data comparability and accuracy, particularly in the case of highly elevated concentrations of  $\text{CH}_4$  and  $\text{N}_2\text{O}$ , i.e., those exceeding atmospheric equilibrium concentrations by at least an order of magnitude.
- The third activity calls for the production of global data products for dissolved  $\text{CH}_4$  and  $\text{N}_2\text{O}$  measurements. To date, the MEMENTO database has been very successful at compiling  $\text{CH}_4$  and  $\text{N}_2\text{O}$  datasets and making them readily accessible to the modeling community. However, the MEMENTO database has not yet yielded a global data product that includes publicly accessible quality-controlled dissolved  $\text{CH}_4$  and  $\text{N}_2\text{O}$  datasets. The international marine carbon science community has widely embraced such an approach for  $\text{fCO}_2$ , by submitting data to the Surface Ocean  $\text{CO}_2$  Atlas (SOCAT), which was initiated in response to the need for a quality-controlled, publicly available, global surface  $\text{CO}_2$  dataset. Due to fewer measurements, a similar data product for marine  $\text{CH}_4$  and  $\text{N}_2\text{O}$  would be needed every  $\sim 5$  years. We consider the production of global data products for dissolved  $\text{CH}_4$  and  $\text{N}_2\text{O}$  to be essential for supporting future global modeling efforts and to enhance field observations.

The benefits of pursuing the three activities described above have already been clearly demonstrated for carbon system measurements in the ocean. The intercomparability and high accuracy and precision of carbon system measurements were achieved by streamlining methodological approaches, universally adopting agreed-upon SOPs, production of reference material, and following community-driven quality control procedures. It is encouraging to see the marine  $\text{CH}_4$  and  $\text{N}_2\text{O}$  community beginning to move in a similar direction.

## **Carbonate System Reference Materials**

In the past 12 months the IOCCP SSG experts (Garcia-Ibanez, Rehder, Sanders) as well as the Project Office continued to make progress on implementing a new model for seawater reference materials (RMs) for the carbonate system, centered on 3 regional hubs which was proposed since the fragility of the production system of the seawater RMs for the carbonate system, currently depending on one single laboratory (SIO, USA), was proposed in 2021.

The largest progress is being made in the context of working with GOA-ON and ICOS-OTC as well as national metrological Institutes in Europe and integrating the work of oceanographic community with those. The overall objective is to establish an integrated network of metrology and oceanographic

institutes to ensure coherent traceability chains and procedures for measurement results of the four measurable variables of the seawater CO<sub>2</sub> system. The specific objectives are:

- to combine metrological and oceanographic expertise in gas analytic, electrochemistry, and chemical analysis to develop coherent, SI traceable primary calibration procedures and reference materials for measuring variables of the seawater CO<sub>2</sub> system with the expanded uncertainties required by requirements listed in GOOS EOVS, GCOS ECV and soon WMO RRR specifications in the framework of the global observing system.
- to identify and minimize systematic measurement errors contributing to observed inconsistencies between the four variables of the seawater CO<sub>2</sub> system by performing measurements of each variable in artificial seawater solutions at selected national metrology institutes and with coherent, calibrated instruments at oceanographic institutes, and by analyzing the metrological coherence of the corresponding complex traceability chains of the variables.
- to establish a sustainable metrological network at the European level for the provision of certified reference materials (CRMs), calibration services, and calibration procedures for end-users to ensure metrologically consistent measurement results of the four variables of the seawater CO<sub>2</sub> system, also embedding European partners in the foreseen international CRM production and certification framework of the ocean carbon observing community.
- to implement the developed calibration and measurement procedures for the measurement of the four variables of the seawater CO<sub>2</sub> system in oceanographic practice by engaging with relevant oceanographic institutions publishing respective guidelines, for instance IAPSO Best Practice Study Groups, and the Ocean Best Practice System, and to support transfer of optimized calibration and measurement procedures, and knowledge on CRM production to interested companies supplying oceanographic institutes with equipment and materials.

To foster the creation of one of the three proposed hubs, namely the Eurafrican Hub, IOCCP has engaged in collaboration with 27 partners from Europe and Africa to develop and implement a long term strategy to produce, certify and distribute the carbonate system RMs required for ocean measurements of anthropogenic carbon and coastal ocean acidification. This will reduce dependence on a single RMs supplier (SIO, USA), stabilize supply, ensure metrological certification, and strengthen the resilience of the ocean carbon observing system. The Hub will support the oceanographic community and emerging mCDR initiatives with trustworthy, verifiable data, and drive innovation in software, BPs, uncertainty evaluation, and data traceability. By fostering standardisation, regulatory alignment, and capacity sharing, this activity will support the foundation for global assessments such as the annual Global Carbon Budget or Global Stocktake in ocean carbon monitoring and climate verification infrastructures.

Currently, the proposal undergoes a review process at the European Commission and therefore details of the developed strategy and plan for implementation can't be shared. We will report on the outcomes as soon as they will become available. If the EC decides to fund this initiative, IOCCP will be very well positioned to co-coordinate the implementation of the 3-hub model globally and also to help strengthen the accessibility of carbonate system RM's amongst partners based in Africa. Alternatively, should the Commission decide to prioritize other opportunities, we will focus on attracting attention to this priority need within the European funding landscape.

At the same time, IOCCP is in close contact with the most active partner coordinating the development of an American Hub, namely US NIST (represented in our community by Regina Easley) where plans

continue to be for NIST to be able to release first batches of Certified RMs (with Pacific and/or Atlantic water source) in 2026-2027.

## **Contribution to the Global Ocean Indicators framework**

In the past 12 months the IOCCP SSG experts (Garçon, Sutton, Telszewski) have significantly contributed to the ocean community-wide effort towards development of a framework for a set of ocean indicators allowing for translating of the ocean science and data into practical metrics, guidance, and tools, informing on the state and health of the ocean that can be directly applied by policymakers, practitioners, and the public.

Following a clear call from the OceanObs'19 Conference Statement it became clear that development of ocean indicators is necessary for regular reporting on the state of the ocean, its variability and change, identification of knowledge gaps and observing system gaps that limit our capacity to respond to society's needs for ocean information. While playing this multi-faceted scientific and technical role, indicators are also key communications tools for the general public, enhancing ocean literacy and the engagement of citizens.

To assure science-driven and science-based development of an ocean indicator framework considering major aspects of the ocean, a global multi-disciplinary and transdisciplinary Indicators Task Team lead by the Ocean Observations Physics and Climate Panel under the GOOS umbrella was established with an aim to develop and publish a perspective framework proposing rationale for the global ocean indicators framework which would invite broad participation and engagement into the future. The group was tasked with the following:

- to develop a list of characteristics and criteria for ocean indicators,
- to provide topical classifications for the indicator framework,
- to provide a targeted set of pilot indicators and their definitions for each topical multidisciplinary classification from global to regional scale
- to provide a long-term perspective and guidance on the evolving developments of an indicator framework (e.g. methodologies, best practices, involvement of services, etc.)
- to synthesize and promote the initiative through a high-level publication

The group worked very intensely since December 2024 to fulfil the tasks listed above, with an ultimate goal to publish the initial framework allowing for wide adoption and improvements. Key foci included:

- ocean indicator definition and criteria, aimed at refining the definition of an ocean indicator, assuring clear framing of a future indicator framework. Also the number of indicators needed to be limited to obtain a clear focus of an initial framework. Existing initiatives and already established indicators were discussed as a need for interconnectivity and not doubling the efforts. Consideration of upcoming scientific advancements was encouraged to allow flexibility of the framework to assure state-of-the-art. These considerations allowed the development of a set of criteria for an ocean indicator.
- ocean indicator purpose and application areas, aimed at development of a topical framing of the framework across Ocean interfaces (Human, Atmosphere, Cryosphere, Land and Biosphere), considering the many aspects of the Ocean drawing on the various scientific disciplines and the

Global Ocean Observing System. Three out of nine pilot indicators developed, were provided and described by IOCCP experts in collaboration and consultation with a wider community centered around ocean acidification, ocean deoxygenation and net community production.

- Spatial and temporal scales, aimed at tackling a challenge of resolving different time and space scales for a single indicator. In essence the question of how the specific use of one indicator differs across different application areas, which usually have varying time and space boundaries and requirements.

This work resulted in a manuscript entitled *Global Ocean Indicators: Marking Pathways at the Science-Policy Nexus* which has been submitted to the Journal of Marine Policy in June 2025 and accepted after minor revisions in September 2025. Publication is expected in October 2025. The development of the ocean indicators framework extends the functionality of the Essential Ocean Variables (including for biogeochemistry), so that they can be incorporated into a broader set of assessments undertaken at varying scales and therefore deliver some clear guidance in terms of national monitoring and reporting. Building on the Essential Variable frameworks, this initiative complements existing climate (GCOS) and biodiversity (BIP) indicators, addressing a critical gap in the international discussion on the ocean's role in the broader environmental context. Strengthening collaboration among academia and international organizations will now be essential to broaden the use of these indicators and incorporate them into global frameworks and services.

IOCCP will continue to work with a variety of stakeholders and partners to use the above framework for practical development of tools for public, management and policy-making. In the next 12-24 months our involvement in the EU BioGeoSea project will allow for implementation of practical solutions in a number of European basins. This effort is planned to be scalable and implementable beyond the European landscape.

## **Global data synthesis activities**

IOCCP continues to contribute to overcoming challenges and to developing strategic actions related to the established global data synthesis products (Surface Ocean CO<sub>2</sub> Atlas - SOCAT, and Global Ocean Data Analysis Project - GLODAP), as well as new and emerging data synthesis products as needed (GO<sub>2</sub>DAT, METS RCN, MEMENTO, SPOTS).

### Surface Ocean CO<sub>2</sub> Atlas (SOCAT)

The latest update of the community-led Surface Ocean CO<sub>2</sub> Atlas (SOCAT), version 2025 was published in June 2025 despite funding struggles described in past reporting periods. This critically impactful effort continues as a community-driven activity with scatted support based on research rather than operational streams. IOCCP (mainly Jones, Sanders and Telszewski) continues to work across the observing value chain to engage partners, users and stakeholders in discussions leading to changing the fundamental funding regime as described in the Oostende Declaration in late 2023.

The annual mean growth rate of atmospheric carbon dioxide (CO<sub>2</sub>) was 3.77 ppm (μmol mol<sup>-1</sup>) in 2024, a record high rate, highlighting the urgent need for quantification of the ocean carbon sink. Since 2011, the community-led SOCAT ([www.socat.info](http://www.socat.info)) offers an annual public update of global in situ oceanic fCO<sub>2</sub> (fugacity of CO<sub>2</sub>) measurements. Version 2025 adds 451 new data sets and updates 44 data sets from ships, yachts, uncrewed surface vehicles (USVs), moorings and drifting platforms. Version 2025

contains 41.4 million, quality-controlled, in situ surface ocean  $f\text{CO}_2$  measurements with an estimated uncertainty of better than  $5 \mu\text{atm}$  collected between 1957 and 2024, which constitute the main SOCAT synthesis and gridded products. In addition, 8.2 million  $f\text{CO}_2$  values with an uncertainty of 5 -  $10 \mu\text{atm}$ , mainly from membrane-based sensors, are made separately available. Open ocean  $\text{CO}_2$  data submissions have stabilised, expressed by the number of monthly,  $1^\circ$  by  $1^\circ$  gridded, surface ocean  $f\text{CO}_2$  values in 2020 to 2023. Documentation of data sets has improved over time (reduction in D flags). SOCAT is key for quantification of ocean  $\text{CO}_2$  uptake and ocean acidification, providing vital information for climate policy. As the importance of constraining ocean  $\text{CO}_2$  uptake is well recognized by the WMO Global Greenhouse Gas Watch (G3W) and the UNFCCC Global Stocktake, there is an urgent need for sustained funding of accurate surface ocean  $\text{CO}_2$  measurements and their synthesis. The SOCAT synthesis effort remains at risk by reliance on a single hub and funding.

The IOCCP led the inclusion on SOCAT-specific personnel and financial requirements into the WMO G3W IP, which is an important step to allow WMO Member States to develop dedicated funding streams and mechanisms. Similarly, IOCCP leaders continue to include SOCAT-specific personnel and financial requirements into their funding proposals in Europe, North America and Australia. These research-based funding portfolio is suboptimal in the long term, but critical in the short term.

#### Synthesis of ocean products for ocean carbonate chemistry

In the past 12 months and beyond, the global ocean biogeochemistry community worked towards compiling an extensive catalogue of existing ocean carbonate chemistry data products, encompassing compilations of cruise datasets, derived gap-filled data products, model simulations, and compilations thereof. Current IOCCP members: Lange, Sutton and Telszewski joined a group of 70 collaborators from 50 institutions, many of whom served on the Panel in the past, to identify and access data products that best align with current research objectives, ultimately enhancing our understanding of the ocean's evolving carbonate chemistry.

Motivated by an ever-increasing need to monitor ocean carbonate chemistry to allow tracking the evolving ocean carbon sink, observing ocean acidification and its ecological impacts, and establishing a baseline for the marine carbonate system to assess the additional impacts of mCDR, the group (led by the US NOAA NCEI) has compiled an exhaustive catalogue of synthesis products pertaining to ocean carbonate chemistry, including cruise data compilations, gridded gap-filled data products, and other derived data products.

To enhance user access and raise awareness of available resources, identified products are organized based on verified end-user needs:

- Cruise data compilations (no gridding or gap filling).
- Time-series data products.
- Derived gap-filled (interpolated) products for the surface ocean, starting with products offering a climatological snapshot of the ocean, followed by those showing temporal changes.
- Derived gap-filled (interpolated) products for the subsurface ocean, also starting with products offering a climatological snapshot of the ocean, followed by those showing temporal changes.
- Multi-product analyses of two previous categories. These compilations also include hindcast model simulations of the ocean carbon cycle and biogeochemistry.

- Model output products projecting ocean carbon variables into the future (Here the term “model” refers to ocean biogeochemical models. If a statistical model or machine learning model is used for gap filling, the product is not categorized as a model output product in this compilation)

This compilation spans both regional and global scales, providing a holistic view of the current state of ocean biogeochemistry data aggregation. The work resulted in submission of an extremely comprehensive and well-defined to the Earth System Science Data, where a [pre-print is available](#) and is currently undergoing a discussion: <https://essd.copernicus.org/preprints/essd-2025-255/#discussion>.

The 60 synthesis and gridded data products compiled in this catalogue reflect enormous community-based efforts that have been made to advance understanding of the ocean's role in global carbon cycling. This synthesis provides a comprehensive overview of key data compilations and gridded data products essential for coastal and global ocean carbonate chemistry research. It highlights the key features of each product, serving as a resource for researchers seeking the necessary data for their work. Access links for all data products mentioned in the compiled catalogue are provided.

## **Best Practices for Oxygen EOY measurements**

In the past 12 months a large proportion of the IOCCP SSG team (Garçon, Lange, Atamanchuk, Jones, Telszewski) was involved in a series of online discussions which followed from earlier international workshops and a survey, aimed at compiling and developing an up-to-date portfolio of best practices for ocean oxygen measurements, streamlining metadata definition and data quality control levels applied across a variety of available data bases, and local, regional and global data products.

This work was largely coordinated by the UNESCO-IOC GO<sub>2</sub>NE working group, and led by Véronique Garçon. Collaborations included partners from a variety of organizations including IODE, WOD, WOA, EMODnet and individual observing networks.

For quite some time an urgency to combine all oxygen data acquired from eulerian and langrangian platforms in the coastal and open ocean into an open access database was clearly defined. The international community has agreed on a roadmap for the Global Ocean Oxygen Database and ATlas (GO<sub>2</sub>DAT) back in 2021, and recent efforts are focused on defining and implementing GO<sub>2</sub>DAT standards and best practices for calibration, adjustment protocols, data quality control protocols and quality flags, metadata specification and the most efficient data flow. The data flow discussions also included considerations on data sharing and availability, as significant amount of oxygen EOY observations are made in coastal waters and community consultation indicated that only a fraction of these data is publicly available.

A comprehensive description of these efforts including detailed technical specifications of proposed protocols was submitted to Environmental Research Letters in September 2025.

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