# International Ocean Carbon Coordination Project

# Progress Report for SCOR, August 2024

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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.

Thanks to the excellent work of several members of the IOCCP SSG and a wider IOCCP community within the Joint Study Group on WMO Greenhouse Gas Monitoring (SG-GHG), the Greenhouse Gas Watch Implementation Plan (G3W IP), which includes several ocean-carbon related activities, has been approved by the WMO Technical Commission for Infrastructure in April 2024, and by the Executive Council of WMO in June 2024. IOCCP continues its work with and within GOOS structures and in partnership with our sponsors (SCOR, US NSF, US NOAA, IOC-GOOS, EU OceanICU), to implement specific actions of the G3W IP for the benefit of our community. In the past 12 months and into the future we strongly focus on formalizing and strengthening SOCONET, developing coordination structure for regional and global observational efforts to integrate $N_2O$ measurements with existing GOOS observing networks, and transitioning SOCAT funding structure into one that's sustainable and resilient. All these activities stem from the IOCCP-coordinated, community-developed *Declaration on Operationalising the Surface Ocean Carbon Value Chain*, published in January 2024 as an outcome of a series of community workshops held at the Flanders Marine Institute (VLIZ) in Oostende, Belgium and online (6-9 November 2023).

Motivated by an increased intensity of requests for specific ocean-carbon related information from a variety of stakeholders, which is not necessarily matched with an investment in the delivery value chain (observing capacities, data management capacities, information creation capacities) necessary to fulfil these requirements, IOCCP initiated a community-wide effort to develop a Global Ocean Observing System Carbon Plan based on 3 high level mandates: the Global Greenhouse Gas Watch Implementation Plan, the 2022 Global Climate Observing System (GCOS) Implementation Plan and the Integrated Ocean Carbon Research (IOC-R) Report. Each of these documents describes specific needs developed by our stakeholder community (scientific community across GOOS elements, national and international policy makers, funders of the ocean carbon observing system, industry, others….) and IOCCP in collaboration with the observing system implementers works to develop an actionable, costed Carbon Plan clearly describing the workload (and its cost) related to delivering the requested information. When completed (final draft planned for June 2025) this Carbon Plan will serve as a 3-5 year roadmap for IOCCP and its partners with regards to delivering products along the ocean carbon observing value chain.

In our efforts to find synergies across the interface between biogeochemical ocean observations and modelling efforts, the IOCCP in close collaboration with Xiamen University (China) and Mercator Ocean International (EU), held an important and fruitful Scoping Workshop in May 2024, which was aimed at identifying the most urgent needs of both communities with regards to an efficient and fit-for purpose creation and use of relevant ocean biogeochemistry observations. This activity allowed to identify some of the existing discrepancies between model simulations and field observations, and specific recommendations were developed aimed at increasing the model skill by directing the spatio-temporal data collection efforts as well as enhancing predictions through specific model refinements. We plan to apply these recommendations when working across the observations-modelling interface in the framework of implementing the G3W IP as well as developing the GOOS Carbon Plan.

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

## Declaration on Operationalizing the Surface Ocean Carbon Value Chain

In early November 2023, over a hundred ocean carbon scientists from around the world met at the Flanders Marine Institute (VLIZ) in Oostende, Belgium, to review the status of the Surface Ocean Carbon Value Chain and decide on specific improvements to the structure, process and resulting delivery of critical information. The community has been ready to update its mode of operation for a few years and the recently announced, WMO-led Global Greenhouse Gas Watch (GGGW) programme served as a direct trigger for this important gathering. IOCCP and its partners were discussing the current operating model throughout 2023 and managed to consolidate our commitment as well as specify our needs during this broadly attended meeting. As an outcome of these discussions culminating at the workshop in November 2023, we, the community, have expressed our collective ambition to completely transform our ability to deliver an integrated global surface ocean carbon monitoring system, helping countries to better understand and manage the causes of climate change in a timely and efficient manner. This IOCCP-led Declaration is available from our website here and its main points are as follows:

We, the 100+ ocean experts and stakeholders specialising in surface ocean carbon measurements and quantification of ocean carbon uptake, representing Europe, Australia, Asia, North America, South America and Africa, assembled at the Flanders Marine Institute (VLIZ) in Oostende, Belgium and online (6-9 November 2023) to assess the status of the multi-component community effort capable of measuring, storing, synthesising and mapping of the surface ocean carbon information, call for concerted international and intergovernmental efforts to create a robust, resilient and sustainable surface ocean carbon observing system. We envisage and expect that such a system, the so-called surface ocean carbon value chain, will meet the ever-increasing demands for ocean carbon data and information needed to inform national and intergovernmental policies on climate change and mitigation efforts, with the Paris Agreement being the most pressing commitment.

The United Nations Framework Convention on Climate Change (UNFCCC) mandates action upon the Global Climate Observing System Implementation Plan (GCOS IP), which in turn details the need to routinely monitor the ocean carbon uptake as essential for understanding the global climate change impacts and its future projections in support of climate policy making. The global ocean carbon research community has a long-lasting recognition of the importance of measuring key ocean carbon Essential Climate Variables (ECVs) in support of the GCOS IP coordinated under the Global Ocean Observing System (GOOS). Over the past three decades, this community of experts and stakeholders has developed a multi-component system capable of measuring, storing, synthesising and mapping ocean-related carbon parameters, enabling their use in the annual Global Carbon Budget, model projections, and inversion systems.

The observational element, which provides data from merchant and research vessels, moorings as well as sailing boats and uncrewed surface vehicles, is referred to as SOCONET (the Surface Ocean CO2 Observing Network). SOCONET delivers data to the community-driven data quality control and synthesis element known as SOCAT (the Surface Ocean CO2 Atlas). SOCAT, in turn, is used for global mapping that fills observational gaps via machine learning approaches and other statistical methods involving satellite-borne information and is undertaken by individual investigators loosely coordinated through SOCOM (the Surface Ocean pCO2 Mapping Intercomparison). These activities together are referred to as the surface ocean carbon value chain and form an ocean contribution to the state of the Global Carbon Budget, including an estimate of the ocean carbon uptake, which is reported annually to UNFCCC by the Global Carbon Project (GCP) and through the WMO State of the Climate Report.

Despite the long-standing success in delivering critical information, the surface ocean carbon value chain is configured as a loose affiliation of observing and data synthesis elements that lack formal integration and operates on unstable, short-term research-based funding streams. In addition, sub-optimal support for coordination activities translates to limited formal presence of the elements of the surface ocean carbon value chain as part of GOOS, which in turn slows down GOOS' efforts to deliver the essential information needed. In recent years, recognition of the fundamental value of accurate, systematic and robust ocean carbon information has increased significantly across managerial and policy-making scales, and as a result demands for data products continue to increase. A need to supply routine air-sea CO2 flux data to the World Meteorological Organization's Global Greenhouse Gas Watch (GGGW), the need to integrate new technology and to broaden the scope to other greenhouse gases, will potentially overwhelm an already acutely stressed system, and therefore we find it timely to review the operating model of the surface ocean carbon value chain.

Our collective ambition, founded in the GCOS IP, is to completely transform our ability to deliver an integrated global ocean carbon monitoring system, helping countries to better understand and manage the causes of climate change in a timely and efficient manner. In recognition of this ambition, over 100 experts and stakeholders representing Europe, Australia, Asia, North America, South America and Africa gathered in Oostende, Belgium and together committed to:

- Formalise the structures of SOCONET to create a robust and resilient GOOS network bringing together surface ocean $CO_2$ observing efforts,
- Develop a clear pathway to securing a robust, resilient and scalable SOCAT data management system for the long term,
- Support and quantitatively underpin the efforts above with observing system experiments using SOCOM methods, satellite observations and models to optimise the current observing design.

In the Declaration, we request that all national and regional funding agencies and structures, global and regional intergovernmental agencies, space agencies and groupings, as well as global and regional coordination bodies take note of this commitment and work with the scientific community to realize this ambition via the following actions:

- Stabilize support for existing high accuracy data collection elements of SOCONET via dedicated, long-term sustainable funding mechanisms and internationally agreed rules to measure within country's Exclusive Economic Zones (EEZ),
- Support a SOCONET coordination structure via dedicated, long-term sustainable funding mechanisms,
- Equip all oceanographic research vessels with high quality surface ocean carbon observing instruments and support their operation,
- Coordinate the use of emerging autonomous surface technologies and sailing boats to obtain data from remote, traditionally hard to reach places such as the Southern Ocean,
- Develop funding mechanisms to support SOCAT as the data platform for quality-controlled surface ocean data
- Support a dedicated surface ocean GHG observing system design activity with regular evaluation and refinement of the design,

- Support innovation in surface ocean air-sea CO2 flux mapping techniques (SOCOM) and routine releases of ocean CO2 flux products,
- Support development, innovation and availability of relevant satellite-borne data products, to stabilise support of annual carbon assessments
- Address lack of capacity in the surface ocean carbon value chain through training and new career opportunities as well as incentives for contributing to the global network,
- Develop a review process to ensure that we innovate and develop the surface ocean carbon value chain in response to new information, science challenges, technological innovations and changes in the global carbon cycle.

We focused on implementing the actions listed in the Declaration throughout the 2024 and will continue these efforts for 2025 and most probably beyond, as the regional extent of individual tasks create a complex environment for global coordination. We hope that our partners and stakeholders will work with us to realize this ambition.

## Greenhouse Gas Watch Implementation Plan

Thanks to the excellent work of several members of the IOCCP SSG and a wider IOCCP community within the Joint Study Group on WMO Greenhouse Gas Monitoring (SG-GHG), the Greenhouse Gas Watch Implementation Plan which includes several ocean-carbon related activities has been approved by the WMO Technical Commission for Infrastructure in April 2024, and by the Executive Council of WMO in June 2024.

With that step, the G3W Implementation and Pre-Operational Phase (G3W-IPP, 2024-27) has officially started. The WMO flagship-level scenario estimated for G3W at $1 billion over the financial period 2024-2027 was a target for the resource mobilization discussed at the 44$^{th}$ WMO Financial Committee in June 2024. To realize the G3W ambitious goals, WMO is seeking support from various donors, including members, climate funds, philanthropy, and private sector. Contributions to the G3W trust-fund are open to all entities to enable firstly to resource the WMO Secretariat with support staff assisting on the G3W implementation priorities.

IOCCP continues its work with and within GOOS structures and in partnership with our sponsors (SCOR, US NSF, US NOAA, IOC-GOOS, EU OceanICU), to implement specific actions of the G3W IP for the benefit of our community:

**Action O1**: Create an exhaustive inventory of existing surface based GHGs measurements.
**Action O2**: Develop GHG monitoring standards and revise and reconcile existing GHG measurement requirements.
**Action O3**: Develop a roadmap for longer-term GHG observing activities.
**Action O8**: Formalize and enhance a sustained surface ocean CO2 observational network.
**Action O9**: Deliver routine global gridded products of air-sea CO2 flux.
**Action O11**: Liaise and prioritize with CEOS-CGMS for indirect GHG observations from space (required to infer GHG fluxes).
**Action P1**: Identify data-stream needs on prior emission and absorption of CO2.
**Action D1**: Data management life cycle stage 1; from raw instrument data to characterized product acceptable for international data exchange
**Action D2**: Data management life cycle stage 2; Getting observational data from providers to operational centres for assimilation

In the past 12 months we strongly focused on the following tasks:

### *Action O1: Create an exhaustive inventory of existing surface based GHGs measurements.*

The activities under this action include:

- Conducting survey of the greenhouse gas observations (concentration, column measurements, and fluxes) from existing networks and programmes for atmospheric and ocean measurements with the following attributes: variables, measurement methods, quality of observations (including quality control of measurements), sampling frequency and data access.
- Evaluating available information about GHG observations in databases (Observing Systems Capability Analysis and Review (OSCAR), Surface Ocean CO2 Atlas (SOCAT), Marine Methane and Nitrous Oxide (MEMENTO), and other GOOS and relevant data and metadata repositories.
- Performing a comprehensive literature and online review to identify additional long-term and campaign datasets not included in the existing databases and data repositories.
- Carrying out a gap analysis comparing the variables and coverage needed for the inversion models (actions P1-P3) to the variables currently measured and their coverage.

### *Action O8: Formalize and enhance a sustained surface ocean CO2 observational network.*

The activities under this action include:

- Designing a governance structure for a sustained Surface Ocean CO2 Network (SOCONET).
- Implementing sustained infrastructure for existing and new SOCONET reference measurements, including utilizing existing and new vessels and new autonomous platforms.
- Expanding observations in data-poor regions as informed by past and ongoing Observing System Experiments (OSEs).
- Developing optimal observing design using results from OSEs.
- Developing recommendations for the infrastructure necessary to incorporate CH4 and N2O observations at critical locations.

The measures of success are:

- Established governing body for SOCONET.
- Roadmap for sustained funding for surface ocean CO2 observations.
- Plan for addressing observing gaps in data-poor regions.
- Increased observational coverage in data-poor regions.
- Initiation and evaluation of value of CH4 and N2O observations at critical sentinel sites and regions (e.g., areas of high concentration and flux such as continental margins, areas of methane clathrate (frozen methane) vulnerability and exposure, and high latitudes).

The implementation of this activity is done through several stages, with initial emphasis in 2024 on governance design, implementation and expansion of the observing infrastructure will take place through the whole period of 2024–2027, while the design of the observing system for CH4 and N2O will take place at a later stage (2026–2027) in collaboration with the satellite community. When feasible, measurements of G3W should be paired with, concurrent and integrated with the observation of other Essential Ocean Variables in order to enable understanding and modelling of processes that control fluxes. Extensive and persistent observing gaps, such as in high-latitude regions during winter and the Indian Ocean basin, are known sources of error to ocean CO2 flux estimates and could be addressed in the near-term with existing technology while design of a tiered observing network is being developed, and critical sites for CH4 and N2O monitoring are identified.

### *Action O9: Deliver routine global gridded products of air-sea $CO_2$ flux.*

The activities under this action include:

- Formalizing the Surface Ocean CO2 Atlas (SOCAT, www.socat.info) through development of a governance structure;
- Making efforts to develop infrastructure capable of delivering global gridded products more frequently than annually.
- Working towards interoperability with products from other ocean carbon networks that require validation.
- Modernizing computing infrastructure to adapt to the evolving needs of scientists and users.
- Coordinating with MEMENTO (Marine Methane and Nitrous Oxide database) to assess potential for shared, leveraged or interoperable infrastructure necessary for CH4 and N2O data synthesis products.
- Conducting OSEs using mapping intercomparisons (Surface Ocean pCO2 Mapping intercomparison, SOCOM) and models to determine optimal tiered observing network design to reduce flux uncertainties, including assessment of the SOCOM capabilities or modelling infrastructure regarding adaptation and expansion to include CH4 and N2O to estimate sensitivity of these GHGs.
- Developing a roadmap for SOCOM, including a plan for:
    - Sustained delivery of ocean CO2 flux and other GHGs flux products required as prior estimates for data assimilation systems,
    - Regular intercomparisons of mapping products, ocean models, and inversions.

The measures of success include:

- Established governance structure for SOCAT - as part of GOOS infrastructure under the GOOS Biogeochemistry Panel/ IOCCP.
- Sustained funding for surface ocean GHG data management and products.
- Defined spatial coverage and frequency of surface ocean CO2 observations.
- Demonstrated clear pathway for timely, integrated, seamless, and interoperable dataflow in the G3W.

The SOCAT governance structure development has been and continues to be a matter of priority in 2024. Enhancement of SOCAT is to be implemented in 2025–2027, while the observing network experiments for SOCOM and associated flux uncertainty assessments can be conducted in parallel with the governance development during 2024–2025. SOCOM roadmap is to be developed in 2027.

## Surface Ocean $CO_2$ Observing Network – formalizing the network structures and developing an implementation plan.

Urgent, deep and sustained emission reductions are needed to peak and reduce greenhouse gas (GHG) emissions, to reach net zero by 2050, as agreed by the 196 Parties to the Paris Agreement. The concentrations of GHGs in the atmosphere are regulated by both emissions and uptake by the land and ocean. However, ocean $CO_2$ uptake varies significantly in time and space and a large number of high-quality continuous measurements is needed to monitor and predict the ever-changing scales and patterns of the air-sea interactions and to monitor and predict any adverse impacts of this uptake such as ocean acidification. A key activity that addresses the fate of human-produced and natural carbon released to the atmosphere is a loose affiliation of observing platforms (from merchant and research vessels, moorings as well as sailing boats and uncrewed surface vehicles) that lack formal integration and coordination which translates to limited presence of the surface ocean carbon observing system as part of information delivery to UNFCCC assessments, WMO's Global Greenhouse Gas Watch or WMO's State of the Climate Report amongst other critical management and policy making bodies and processes.

A formalized and coordinated surface ocean $CO_2$ reference network (SOCONET), integrated within relevant elements of IOC-UNESCO and WMO, will be the backbone of constraining understanding of the carbon cycle, effective mitigation actions, as well as monitoring, reporting and verification (MRV) efforts to properly incorporate ocean sinks in global carbon assessments and stocktakes as well as implementing and reporting on marine carbon dioxide removal interventions. The climate quality ocean observational data will feed directly into carbon monitoring systems to aid in accurate and timely assessments of surface ocean carbon levels, carbon uptake by the ocean, carbon exchange with the atmosphere, and changes thereof. A uniquely designed and distributed surface ocean $CO_2$ reference network will be a tightly coordinated activity to create monthly air-CO2 flux maps, assess surface ocean health as it pertains to ocean acidification; and to quantify ocean mitigation potential to reduce atmospheric CO2 increases.

In the past 12 months we have made continuous effort to help our community consolidate efforts around SOCONET by providing global coordination around the following tasks:

### *SOCONET Steering Committee*

- Perform an initial stocktake of current SOCONET operators to allow further effective coordination, development of governance structure and operating requirements.
- Based on community input received before, during and after the series of Workshops on Surface Ocean $pCO_2$ Observations, Synthesis and Data Products held in late 2023, lead the establishment of the SOCONET Steering Committee (SC)
- Lead the SC efforts towards identification of key science and policy stakeholders for a Surface Ocean $CO_2$ Observing Network (SOCONET) to allow for efficient co-design of an ocean carbon observing system.
- Organize and support monthly conference calls with the SOCONET SC focusing on progress of work regarding key priorities.
- Organize and co-moderate the First SOCONET Steering Committee Meeting (2-3 days, to be held in Q1-Q2 2025)
- Draft the agenda and produce and disseminate meeting reports for the SOCONET SC meeting and conference calls.

### *SOCONET Implementation Plan*

- Coordinate and provide oversight for the drafting and preparation of the SOCONET Implementation Plan
- Identify path forward for developing an observing network design exercise to be included in the SOCONET Implementation Plan
- Coordinate the development, operation and governance of the SOCONET Task Teams for: Standard Operating Procedures, Training and Capacity Building and Liaison with Satellite Community.

### *Formal integration of SOCONET into the IOC-UNESCO GOOS Observation Coordination Group*

- Prepare and deliver a formal application for SOCONET to become a formally recognized observing network under the GOOS Observations Coordination Group
- Establish/(formalize?) connections and initiate interaction with other relevant observing networks through the GOOS OCG and OceanOPS
- Engage with IOC and WMO and their relevant bodies like GOOS and GGGW, respectively, to assure international and intergovernmental recognition of SOCONET.

### *Coordination Activities*

- Provide inter-sessional oversight for SOCONET activities.
- Oversee development of project planning documentation and schedules.
- Develop and/or review SOCONET presentations as necessary (e.g., for annual IOC-UNESCO General Assembly, annual GOOS SC Meeting, etc.).

## Global Ocean Observing System Carbon Implementation Plan

Motivated by an increased intensity of requests for specific ocean-carbon related information from a variety of stakeholders, which is not necessarily matched with an investment in the delivery value chain (observing capacities, data management capacities, information creation capacities) necessary to fulfil these requirements, IOCCP initiated a community-wide effort to develop a Global Ocean Observing System Carbon Plan responding to 3 existing high level mandates: the Global Greenhouse Gas Watch Implementation Plan, the 2022 Global Climate Observing System (GCOS) Implementation Plan and the Integrated Ocean Carbon Research (IOC-R) Report. Each of these documents describes specific needs developed by our stakeholder community (scientific community across GOOS elements, national and international policy makers, funders of the ocean carbon observing system, industry, others) and IOCCP in collaboration with the observing system implementers works to develop an actionable, costed Carbon Plan clearly describing the workload (and its cost) related to delivering the requested information. When completed (final draft planned for June 2025) this Carbon Plan will serve as a 3-5 year roadmap for IOCCP and its partners with regards to ocean carbon observing value chain.

On top of specific work around delivery to the Global Greenhouse Gas Watch described earlier in this report, during this reporting period we have been involved in the following activities related to the other two mandates: two actions from the 2022 Global Climate Observing System (GCOS) Implementation Plan that identify IOCCP as an implementing body or that require IOCCP support or coordination:

### *Action B8: Coordinate observations and data product development for ocean $CO_2$ and $N_2O$*

The activities under this action include:

- Development of a strategy and implementation plan to operationalize the data production and delivery of surface ocean $CO_2$ information.
- Coordination the existing nitrous oxide ($N_2O$) ocean observations into a harmonised network.

IOCCP activities during the past 12 months:

- IOCCP facilitated development of SOCAT governance structure, including linkages to SOCONET governance,
- IOCCP collaborated with partners developing funding opportunities for SOCAT support
- New IOCCP SSG member coordinating $N_2O$ and $CH_4$ discussions between SOCAT and MEMENTO on potential leveraged infrastructure and coordinating activities to build a harmonized $N_2O$ network will be appointed by 1 October 2024.

**Action B10: Identify gaps in the climate observing system to monitor the global energy, water and carbon cycles**

Discussions with members of the modelling community around this activity started in November 2023 during the series of workshops in Ostende and continue by email and online meetings. In close collaboration with colleagues in the modeling community focused on optimizing observing systems, a wide spectrum of aspects is being taken into account in order to develop a comprehensive, integrated global ocean carbon observing system design. The design will focus on the observations needed to answer fundamental global-scale questions about the ocean carbon cycle including the following from the IOC-R report:

- Will the ocean uptake of anthropogenic $CO_2$ continue as primarily an abiotic process?
- What is the role of biology in the ocean carbon cycle and how is it changing?

A workshop attended by observing networks and relevant colleagues in the modelling community is planned for mid-2025 and an actionable recommendations from this workshop will hopefully inform the design strategy and will include:

- a summary of existing networks' (primarily GO-SHIP, SOCONET, BGC-Argo) missions, implementation plans, and network designs
- a clear cross-network strategy, describing the roles of each network and dependencies across networks, including satellite oceanography,
- recommendations on integrating designs across networks and identification of priority network enhancements and technology development to fill gaps.

## Carbonate System Reference Materials

High-quality measurements of the seawater carbonate system allow us to quantify and understand the oceanic uptake of atmospheric carbon dioxide ($CO_2$) and monitor ocean acidification. Those seawater carbonate system measurements rely on the availability of reference materials (RMs). The COVID-19 pandemic highlighted the fragility of the production system of the seawater RMs for the carbonate system, currently depending on one single laboratory. With that in mind, a new model for seawater RMs for the carbonate system, centered on regional hubs, was proposed (as reported in two previous IOCCP reports) to create a more resilient system. The proposed new model for seawater RMs for the carbonate system requires unprecedented involvement of National Metrology Institutes (NMIs) on a global level. The integration of the new model into the global metrology landscape will help to produce the RMs that are comparable and metrologically traceable to the International System of Units.

Building on the past activities addressing these challenges, IOCCP has continued to make progress on and undertake new initiatives in close collaboration with our partners according to the three main lines of work agreed by the IOCCP SSG:

- Regular communication around seawater carbonate system RMs and standards
- International community coordination around requirements for sustained global production and supply of seawater carbon standards
- Standard Operating Protocol for production of secondary reference materials

Based on extensive work described in previous reports, IOCCP's Maribel Garcia-Ibanez co-led a book chapter on the future strategy for a resilient production and certification of seawater RMs for the carbonate system. That book chapter depicts the new model for seawater RMs for the carbonate system, centered on regional hubs, first proposed during the IOCCPworkshop in Spring 2022.

IOCCP fostered dialogue with the NMI of France, LNE, where Paola Fisicaro is leading the work on characterizing Tris buffers to be used in inter-comparison exercises for France, and on TA traceability and stability in artificial and natural seawater. It was established that the production of RMs for TA and DIC is not sustainable and too expensive for many NMI's including LNE. Those European NMIs (LNE

-France-, PTB -Germany-, and INRIM -Italy-) are working on the seawater carbonate system RM developemnt, focusing on pH, TA, and pCO2, but are not interested in working with DIC. The European Association of National Metrology Institutes was contacted to help our community coordinate RM development efforts in Europe.

A new call for proposals (co-funded by the European Commission) for carbonate system RM development will be opened in 2024 to help fund efforts in European NMIs. At the same time, IOCCP is in close contact with the most active partner in this theme, namely US NIST (represented in our community by Regina Easley) and its exciting to know that NIST expects to be able to release first batches of Certified RMs in 2026-2027.

To foster the creation of the Eurafrican Hub, IOCCP has established collaboration with JPI Oceans Ocean Carbon Capacities Knowledge Hub. JPI Oceans Ocean Carbon Capacities is willing to act as a focal point to catalyze activity and resources for coordinating the establishment of a European capacity to produce the carbonate system RMs required for ocean measurements of anthropogenic carbon and coastal ocean acidification. The creation of the Eurafrican hub presents some challenges, such as the identification of institutions that lead the effort, the difficulty of coordinating different countries with different capacities, and the need to identify or develop a mechanism to financially contribute to (subsidy) production in order to replicate the original production/certification/distribution model operating from Scripps, US. But it also comes with some advantages, such as the existence of the European Metrology Network for Climate and Ocean Observation, which was established in 2014 by EURAMET to improve the quality of Essential Ocean Variables by increasing linkages to the International System of Units and improving measurement accuracy, among other objectives. An overview of the status of the establishment of the Eurafrican hub was presented during the GOA-ON Ocean Acidification Week in late 2023 and is available via the GOA-ON YouTube channel for further consultation.

The dramatic reduction in the supply of RMs during the pandemic forced many groups to produce in-house, secondary “interim” RMs, which is a challenging task since there are no standard protocols for their production yet, which results in non-uniform production and potentially unknown uncertainty. IOCCP has established dialogue with Andrew Dickson (SIO, USA) and Tobias Steinhoff (ICOS-OTC, GEOMAR, Germany) to try and coordinate the creation of standard operating procedures (SOPs) for preparing in-house, secondary RMs. Andrew Dickson funded by NOAA works on development of such SOP’s with focus on US-based labs. Dickson’s SOPs will contain instructions on how to prepare a batch of 100-200 bottles (250 mL) with 1 year of stability. This SOP will have an associated document containing instructions on how to perform homogeneity and stability tests, uncertainty estimation, and value assignment by comparing to SIO RMs. Tobias Steinhoff is developing the SOPs as part of the European Research Infrastructure Euro GO-SHIP, which will be publicly available. We hope to be able to coordinate the two efforts and recommendations for the benefit of the rest of global community.

## 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 $CO_2$ Atlas - SOCAT, and Global Ocean Data Analysis Project - GLODAP), as well as new and emerging data synthesis products as needed (GO2DAT, METS RCN, MEMENTO, SPOTS).

Surface Ocean $CO_2$ Atlas (SOCAT)

The latest update of the community-led Surface Ocean CO2 Atlas, version 2024, has delivered 38.6 million, quality-controlled, in situ surface ocean fCO2 (fugacity of CO2) measurements collected between 1957 and 2023 with an estimated accuracy of < 5 μatm. Version 2024 of the community-led Atlas (SOCAT; www.socat.info) shows that data collection has declined to levels similar to those a decade ago with poor data coverage south of 20°N. The number of monthly, 1° latitude by 1° longitude gridded fCO2 values is used as a measure for the open ocean CO2 observing effort, as it is not affected by changes in the reporting frequency (e.g. from every minute to every second) nor by changes in the coastal ocean data collection effort.

SOCAT fCO2 measurements are key for quantification of ocean CO2 uptake at regional and monthly scales, providing vital information for climate policy. However, in addition to the decline in observations, the integration, quality control and accessibility of data products by SOCAT is at risk from persistent funding shortfalls, with SOCAT now relying on a single regional hub (NOAA-PMEL, Seattle, USA). At a time where the importance of constraining ocean CO2 uptake is well recognized by the WMO Global Greenhouse Gas Watch and the UNFCCC Global Stocktake, there continues to be an urgent need for sustained and expanded funding of accurate surface ocean CO2 observations and their synthesis.

Despite its importance, open ocean fCO2 data collection in SOCAT is in sharp decline. The number of fCO2 data sets per year decreased by 35% from 2017 to 2021, and the number of monthly grid cells with fCO2 decreased at a similar rate (33% from 2017 to 2021). The main reason for this decline is the lack of funding for data collection, processing and synthesis.

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 included 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.

The IOCCP continues to be involved in several activities developed in the last couple of years aimed at aiding the situation:

In the short term

- Include the specific personnel and financial requirements for SOCAT in presentations (and following discussions) for the GOOS leadership presenting at the IOC and WMO executive bodies.
- Investigate the potential for securing appropriate funds at the EU JPI Oceans to cover the immediate staff requirements for SOCAT minimal maintenance.

In the long term:

- A new European hub for SOCAT is needed to complement the US-based group based at NOAA PMEL (Seattle) and led by Kevin O'Brien.
- One challenge is that there are very few organisations where the necessary expertise in marine carbon science and scientific data synthesis co-exist which is rather necessary for successful hub operation.
- Discussions with IODE will culminate during the GOOS Data Meeting in Ostend, Belgium in late September 2024, regarding their potential for providing long-term support for SOCAT

based on coordinated dataflows via NODCs. IODE coordinates the global network of NODCs offering a truly global solution, as for example with SDG 14.3 reporting on pH for ocean acidification. This has potential to create hubs outside of Europe and North America.

Global Ocean Data Analysis Project (GLODAP)

The Global Ocean Data Analysis Project (GLODAP) is a synthesis effort providing regular compilations of surface-to-bottom ocean biogeochemical bottle data, with an emphasis on seawater inorganic carbon chemistry and related variables determined through chemical analysis of seawater samples. IOCCP continues to financially and organizationally support GLODAP development as the product serves not only as the most accurate record for its 13 variables but its dramatically increasing significance lies in its value as validation data for autonomous sensors mounted on a variety of platforms including AUV's, floats and moorings. Maciej Telszewski is a member of the GLODAP Reference Group.

Released in October 2023, GLODAPv2.2023 is an update of the previous version, with the major following changes: data from 23 new cruises were added, data coverage was extended until 2022. GLODAPv2.2022 includes measurements from more than 1.4 million water samples from the global oceans collected on 1108 cruises. The added cruises are from 2002 to 2021, with the majority being more recent than 2018. This update consists of:

- 5 cruises from Marine Institute Ireland
- 3 time series datasets in the Arctic Ocean
- A dataset from the Greenland-Scotland ridge including multiple stations in the Irminger and Iceland Seas over the years 2002-2006, and the Iceland standard section at 64°20'N
- 4 Japanese cruises in the Northwest Pacific Ocean
- 1 CHINARE (2008) cruise from the Arctic (Chukchi Sea)
- An update of the Irminger and Iceland Sea time series with new data from 2014 – 2019
- 1 Line-P cruise (2015)
- 3 LowpHOX cruises from Coastal Ecosystem and Environmental Change lab (ECCO-Lab) in Chile
- 1 Discovery cruise in the Southern Ocean
- A20 and A22 occupations from 2021
- The 2018 OVIDE cruise

All new data in GLODAPv2.2023 include seawater $CO_2$ chemistry, and additionally, 8 new cruises include halogenated transient tracers. Salinity and oxygen data can be obtained by analysis of water samples (bottle data) and/or directly from the CTD sensor pack. These two measurement types are merged and presented as a single variable in the product. For salinity 48% Of the 23 new cruises included both CTD and bottle data in the original cruise files, and for oxygen 57 % of the new cruises were oxygen was included had both CTD and bottle data. Only 14 of the 23 new cruises had oxygen data at all. For all these cruises the two data types were found to be consistent. These new data have higher proportion of cruises with both bottle and CTD measurements than GLODAPv2.2022 (39 % for both salinity and oxygen). For oxygen the remaining cruises have only CTD data, while for salinity 22% have only CTD data and 30 % have only bottle data.

The original data, their documentation and DOI codes are available at the Ocean Carbon and Acidification Data System of NOAA NCEI (https://www.ncei.noaa.gov/access/ocean-carbon-acidification-data-system/oceans/GLODAPv2_2022/, last access: 15 August 2022). This site also provides access to the merged data product, which is provided as a single global file and as four regional ones – the Arctic, Atlantic, Indian, and Pacific oceans – under https://doi.org/10.25921/1f4w-0t92 (Lauvset et al., 2022). These bias-adjusted product files also include significant ancillary and approximated data, which were obtained by interpolation of, or calculation from, measured data.

In February 2025, IOCCP will organize a technical workshop for GLODAP Reference Group to work on a major, decadal dataset update (from v2 to v3). This workshop will be co-sponsored by NORCE (Norway) and ICOS-OTC (EU). During this in-person only workshop, experts will work to agree on the adjustments that will be applied to all the cruises (9 parameters per cruise for more than 1100 cruises). In comparison to the regular annual updates, the corresponding discussions will be much more detailed as the Reference Group will make use of an additional inversion exercise on top of the annual crossover analysis. The former is the main differences between GLODAP annual "updates" and decadal "version" releases.

Synthesis Product for Ocean Time Series (SPOTS)

After more than a decade of collective efforts of IOCCP, US Ocean Carbon and Biogeochemistry Program and efforts of the many scientists worldwide who secured funding and dedicated their careers to collecting and sharing the data, in April 2024 the Synthesis Product for Ocean Time Series (SPOTS) including data from 12 major fixed ship-based time-series programs was published.

The related stations represent unique open-ocean and coastal marine environments within the Atlantic Ocean, Pacific Ocean, Mediterranean Sea, Nordic Seas, and Caribbean Sea. The focus of this pilot has been placed on biogeochemical essential ocean variables: dissolved oxygen, dissolved inorganic nutrients, inorganic carbon (pH, total alkalinity, dissolved inorganic carbon, and partial pressure of CO2), particulate matter, and dissolved organic carbon. The time series used include a variety of temporal resolutions (monthly, seasonal, or irregular), time ranges (10–36 years), and bottom depths (80–6000 m), with the oldest samples dating back to 1983 and the most recent one corresponding to 2021. Besides having been harmonized into the same format (semantics, ancillary data, units), the data were subjected to a qualitative assessment in which the applied methods were evaluated and categorized.

The most recently applied methods of the timeseries programs usually follow the recommendations outlined in the report from the Bermuda Time Series Workshop (2013) co-organized by US OCB and IOCCP as an initial effort to kick-off the global coordination of ship-based time series with regards to sampling methodology, data quality control and management as well as data submission into discoverable centres. Recommendations from this report are used as the main reference for "method recommendations by prevalent initiatives in the field". However, measurements of dissolved oxygen and pH, in particular, still show room for improvement. Additional data quality descriptors include precision and accuracy estimates, indicators for data variability, and offsets compared to a reference and widely recognized data product for the global ocean: the GLobal Ocean Data Analysis Project (GLODAP).

Publishing SPOTS marks an important milestone in IOCCP's efforts to coordinate globally scattered, often completely disconnected ship-based time series observatories. This initial pilot exercise will hopefully serve as a magnet for up-to 200 ship-based time series to join and share their often multidecadal data collections in otherwise completely under sampled coastal regions. Generally, SPOTS at its current stage indicates a high level of continuity in measurement quality within time-series programs and a good consistency with the GLODAP data product, even though robust comparisons to the latter are limited. The data are available as (i) a merged comma-separated file that is compliant with the World Ocean Circulation Experiment (WOCE) exchange format and (ii) a format dependent on user queries via the Environmental Research Division's Data Access Program (ERDDAP) server of the Global Ocean Observing System (GOOS). The pilot increases the data utility, findability, accessibility, interoperability, and reusability following the FAIR philosophy, enhancing the readiness of the ship-based biogeochemical time series.

It also facilitates a variety of applications that benefit from the collective value of biogeochemical time-series observations and forms the basis for a sustained time-series living data product, complementing already well established products for the global interior ocean carbon data (GLODAP), global surface ocean carbon data (SOCAT), and perhaps somewhat suspended at the moment global interior and surface methane and nitrous oxide data (MarinE MethanE and NiTrous Oxide, MEMENTO product). Aside from the actual data compilation, the pilot project produced suggestions for reporting metadata, implementing quality control measures, and making estimations about uncertainty. These recommendations aim to encourage the community to adopt more consistent and uniform practices for analysis and reporting and to update these practices regularly. The detailed recommendations, links to the original time-series programs, the original data, their documentation, and related efforts are available on the SPOTS website. This site also provides access to the data product.

## Enhancing Integration of Biogeochemical Observations and Modelling

In our efforts to find synergies across the interface between biogeochemical ocean observations and modelling efforts, the IOCCP in close and generous collaboration with Xiamen University (China) and Mercator Ocean International (EU), held a Scoping Workshop in Xiamen, China on May 21-23, 2024, which was aimed at identifying the most urgent needs of both communities with regards to an efficient and fit-for purpose creation and use of relevant ocean biogeochemistry observations. The event was attended by around 48 participants and was led by Dr. Fei Chai (Xiamen, China) and Dr. Véronique Garçon (Paris, France).

Ocean circulation models and Earth System Models (ESMs) now incorporate the carbon cycle and other biogeochemical (BGC) processes, and can make estimations of the ocean's uptake, transport, and storage of carbon dioxide. However, insufficient observations hinder BGC model development, leading to large uncertainties and limited forecasting skill.

By addressing these issues, the overall goals of the workshop were: to identify effective strategies for incorporating observational data into models, enhancing their accuracy and reliability, and improving forecasting skills; to consider novel approaches for data collection and model development: autonomous platforms (e.g. BGC Argo, gliders, sail drones, wave gliders, etc.) and remote sensing techniques; to discuss the integration of BGC observations and predictions, through data assimilation, use of data for deep learning into models, emergent constraints, and digital twins of the ocean (DTO).

To achieve the above goals, participants worked to develop recommendations across four main topics:

1. BGC data for emergent constraints for future climatic scenarios

2. BGC data for model validation, such as the standards, practices, data formats, evaluation metrics in the ocean forecast community
3. Data assimilation to include BGC and Bio/Eco data into operational prediction/forecasting systems
4. DTO and machine-learning algorithms for BGC and marine ecosystems, including omics data.

### *BGC data for model validation*

Initial discussions focused on reviewing issues related to the BGC data use for model validation:

- Access to the data
  - FAIRness of data including data sharing and crediting
- Types of data needed
  - EOV data; Coastal data (e.g., riverine data); Flux data (e.g., air-sea, sediment-water column); Trace metals (Fe, dFe, ligand Fe, colloid Fe); DOC speciation (e.g., labile DOC, refractory DOC); Benchmark data sets.
- Impact of data processing on data meaningfulness for the model
  - seasonality/diel variation; data drifting (e.g., sensor aging); confusing cruise track repetition (lack of accurate time stamps); large dynamic range of the BGC parameters (spatially and temporally) is lost during processing and is challenging to make use of when not processed.
- Protocols for model output validation with in-situ data
  - Match the time when data have strong temporal variation; Extreme conditions with strong variability (e.g., Submesoscale eddies/storms; QC vs unQC); How should we deal with seasonality if we do annual model? How should we separate the data for training and validation? Random separation is not ideal.

Based on those discussions initial recommendations were developed (the final report will include them in a more comprehensive manner following post-workshop communications):

- Relatively high resolution models need to be used in order to determine appropriate time and space resolution for BGC measurements,
- Downscaling requires basin-specific knowledge to be incorporated into model development
- Use of experimentally optimized mix of Langrangian and Eulerian platforms seems to positively impact the accuracy of model outputs,
- With respect to 4D machine-learning (AI–based) output for additional input for validation: the consensus was to separate observing platforms to keep each platform attributed
- One should privilege quantitative skill performance assessment metrics such as Taylor diagram, $R^2$, RMSE, relative error, PDFs and EMDs, wavelets analysis to list a few and always use multiple-models with the same metrics.

It was mentioned that model validation should be a prior step before defining emergent constraints and the list of biogeochemical and biological/ecological EOVs that can be acquired from mobile platforms was reviewed in that respect.

### *Data assimilation: how to include BGC and Bio/Eco data into prediction/forecasting systems*

Discussions focused on challenges related to assimilation of biogeochemical/bio-ecological data were less conclusive mainly due to the need to overcome such fundamental challenges like computer-time restrictions preventing scientists from experimenting with these types of data:

- Identify and correct the systematic bias in the model – both physics and biogeochemistry
  - Cannot assess the assimilation results until the model has a systematic bias
- Joint Physical-BGC data assimilation
  - Physical-only data assimilation confuses vertical velocities and therefore creates artificial properties
- Different timescale of atmospheric forcings– operational forecast system
  - Coastal – shorter timescale, extreme events (e.g., typhoon, winter storms) – very short timescales
- A variety of data types are needed across higher trophic level
  - E.g. Zooplankton - critical and large gaps exist
- Frequency of data assimilation
  - A variety of frequencies in BGC data sources makes it extremely difficult for models to assimilate information into a coherent system (e.g. BGC-Argo at very high frequency and GO-SHIP at very low frequency)
- Lack of inter-platform consistency of data of the same parameter is very challenging for modellers and models
- Novel information sources would ideally be collected with data assimilation in mind
  - e.g. multi-omics data
- Bio-optical information – what are the prospects to include more than CHLa?
  - Low quality of satellite CHLa in coastal regions and lack of it in polar regions

### *Digital Twin of the Ocean and machine-learning algorithms for BGC*

- DTO is an operator/stakeholder-centred framework
- It is application-oriented, focused on "local" questions, and scenario construction. Political and economic needs are considered integral to the co-design
- A universe of multiple data components mimicked by as identical as possible modelling components (hence "twin"), developed in successive stages by different providers, and interoperable.
- DTO for BGC is still in the phase of identifying the twin components. Co-developed with DTO for physics
- Open tools and data availability is essential, but there is a risk of data security, asymmetry of access, and geopolitics (EEZ)
- New data streams (multi-omics, imagery) need to be included at design level to link effectively with model development and validation

It is rather early in the DTO methodology to develop recommendations related specifically to BGC data. Rather general comments need to be applied. A DTO is initially usually tailored to one given application, and therefore answering relatively narrow portfolio of questions related to posed problems. When the complexity progresses, it can be used to test "What if" scenarios along with a cost benefit analysis. DTO consists of individual models capable of representing avariety of domains (regional, global), using a variety of methods and complexity (individual based models, coupled physicalbiogeochemical models with or without data assimilation, E2E models). A catalogue of existing data/models "twins" should be developed for biogeochemistry as a first step. Followed by development of best practices for DTO development by creating regional working groups: for data fusion/downscaling, skill metrics, uncertainties attribution, and machine learning techniques.

Following the publication of the full workshop report by the organizers, the IOCCP will work with the modelling and interested part of the observing community to further the development of DTO's focused on issues central to our mission like observing system design or integration with bio-eco observing capacity.

# PUBLICATIONS

(with NSF/SCOR funding acknowledged)

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