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Cross-Network Synergies Fundamental to Sustained Global Ocean Carbon Observing

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Key Points:

- Sustained ocean carbon observing networks enable improved understanding, model validation, and evaluation of new technologies
- The growing need for carbon cycle information in a changing ocean motivates capitalizing on cross-network coordination and collaboration
- Ocean carbon observing networks should co-design cross-network priorities, collaborate on network design, and ensure data interoperability

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Abstract The ocean's critical role in absorbing anthropogenic carbon dioxide (CO_2) and the resulting changes in the ocean carbon cycle are monitored by global-scale observing networks, including the Global Ocean Ship-based Investigations Program (GO-SHIP), Surface Ocean CO_2 Observing Network (SOCONET), and Biogeochemical-Argo (BGC-Argo). Given the scale of the challenge to characterize the evolving ocean carbon cycle, no single network is sufficient; a coordinated, collaborative, cross-network approach is essential. This manuscript describes the overarching research questions driving these three networks and details their inherent synergies and dependencies, such as GO-SHIP and SOCONET delivering reference-quality measurements for validation of other in situ and satellite-based data, GO-SHIP providing opportunities for float deployment, and BGC-Argo filling gaps with high-frequency autonomous data. We provide recommendations for optimizing these relationships and an intra-network strategy moving forward. As representatives of the science committees for these networks, we are committed to sustaining and enhancing the collaborative structure necessary to fill critical knowledge gaps in ocean carbon cycle research, improve climate prediction, and enable future ocean ecosystem forecasting.

Plain Language Summary The ocean plays a vital role in absorbing human-caused emissions of carbon dioxide, but this process is changing the ocean's carbon cycle. Monitoring these vast global ocean changes requires a coordinated approach involving three major ocean observing networks: GO-SHIP, SOCONET, and BGC-Argo. This paper details how to maximize synergies across these networks to close critical knowledge gaps, improve climate prediction, and enable ocean ecosystem forecasts.

1. Introduction

The ocean plays a pivotal role in the global carbon cycle, taking up 25%–30% of the carbon dioxide (CO_2) emitted to the atmosphere by human activity over the last several decades (Friedlingstein et al., 2025; Gruber et al., 2019). This added CO_2 is changing marine carbonate chemistry, with implications for marine organisms, ocean biogeochemical cycles, and future carbon sink capacity of the ocean (Canadell et al., 2021; Feely et al., 2023; Fox-Kemper et al., 2021). Carbon-climate and carbon-ecosystem feedbacks are likely to further impact ocean

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chemistry, but the timing and magnitude of these feedbacks are highly uncertain (Müller et al., 2023). Detecting and understanding this uptake and the associated change in carbonate chemistry requires a parallel and collaborative effort of robust and sustained observing, modeling, and research. Sustained observations serve unique roles, providing the critical records for documenting change and the physical platforms and baseline understanding that supports research, validates models, and evaluates the potential of new technology to enhance existing climate records (Trenberth et al., 2002).

The Global Ocean Ship-based Investigations Program (GO-SHIP), the Surface Ocean CO_2 Observing Network (SOCONET), and the biogeochemical mission of the Argo profiling float network (BGC-Argo) are three observing networks of the Global Ocean Observing System (GOOS) providing sustained, global-scale observations of ocean carbon relevant variables. They are all community-driven networks developed by international groups of ocean scientists to address specific research and stakeholder needs (Sabine et al., 2010). They provide a considerable amount of climate-quality data that are able to differentiate the climate signal from natural background variability. GO-SHIP and SOCONET include reference-quality measurements, meaning they are sustained, trusted, and metrologically well characterized (traceable, comparable, and representative; Thorne et al., 2018). The complementary nature of GO-SHIP and BGC-Argo's depth-resolved observations with SOCONET's air-sea interface data is essential. Together, the networks provide critical research infrastructure and trusted data records for addressing key uncertainties in the ocean carbon cycle and are summarized briefly here.

GO-SHIP is a coordinated, international effort that reoccupies a subset of hydrographic sections initiated during the World Ocean Circulation Experiment (WOCE) in the 1990s in all ocean basins, nominally every decade and in some cases more frequently. GO-SHIP carries on the legacies of hydrographic measurements in WOCE and carbon measurements in the Joint Global Ocean Flux Study. GO-SHIP collects climate-quality, metrologically-characterized reference measurements of physical and chemical variables across all ocean depths in sections spanning the ocean continent to continent. These measurements are used to characterize full water column ocean properties and document basin- and global-scale changes in circulation and ventilation; property transports; and heat, freshwater, oxygen, and anthropogenic carbon content (Sloyan et al., 2019; Talley et al., 2016). As well as providing reference data for other networks, the research vessels that conduct GO-SHIP cruises also deploy and/or operate many of the instruments and sensors managed by the other networks, including Argo and SOCONET. These research cruises often venture into remote locations and enable testing of new sensors, approaches, and measurements. Biological measurements were recently added to select hydrographic surveys to begin a sustained record of ocean biogeography, with a focus on plankton ecosystems (Figure 1; Clayton et al., 2022). Since 2004, the Global Ocean Data Analysis Project (GLODAP) has compiled internally-consistent biogeochemical data collected from GO-SHIP and other cruise efforts into data products, improving data access for use in a variety of applications such as model and sensor validation (e.g., Lauvset et al., 2024; Tanhua et al., 2021).

Measurements of surface ocean partial pressure or fugacity of CO_2 (pCO_2 or fCO_2) have been collected for over 60 years on ships, including on GO-SHIP surveys, merchant vessels, and more recently on autonomous surface platforms such as buoys and uncrewed surface vehicles (USVs; Wanninkhof et al., 2019). However, the formalization of these efforts into SOCONET only occurred within the last few years. SOCONET was developed as the first GOOS network organized around an essential ocean variable (EOV) in order to maintain consistent measurement and data requirements across the diverse range of measurement platforms. This is particularly important for the reference-quality measurements of SOCONET, which are traceable to the same certified reference standards used by the atmospheric CO_2 observing networks (Wanninkhof et al., 2025). These atmospheric and ocean surface in situ observing networks are critical inputs for developing air-sea CO_2 flux maps proposed by the World Meteorological Organization's Global Greenhouse Gas Watch (Carmichael et al., 2024). The ultimate goal of SOCONET is that sustained measurements of surface ocean pCO_2 and marine boundary layer (atmospheric) CO_2 serve to constrain monthly-resolved global air-sea CO_2 exchange (Wanninkhof et al., 2019). Recognizing the need for global synthesis of surface ocean pCO_2 observations to generate estimates of ocean CO_2 flux (Takahashi et al., 2009), the pCO_2 observing community developed the Surface Ocean CO_2 Atlas (SOCAT), a quality-controlled, gridded data synthesis product (Bakker et al., 2025; Pfeil et al., 2013) updated annually. SOCAT is the primary data product used to create observing-based estimates of the seasonal to decadal exchange of CO_2 between the ocean and the atmosphere (e.g., DeVries et al., 2023). The Global Carbon Budget, an annual assessment of carbon sources and sinks, uses these observing-based estimates along with model simulations to quantify the overall ocean carbon sink and its variations over time (Friedlingstein et al., 2025). The Global Carbon Budget is therefore dependent on SOCONET delivering observations, SOCAT

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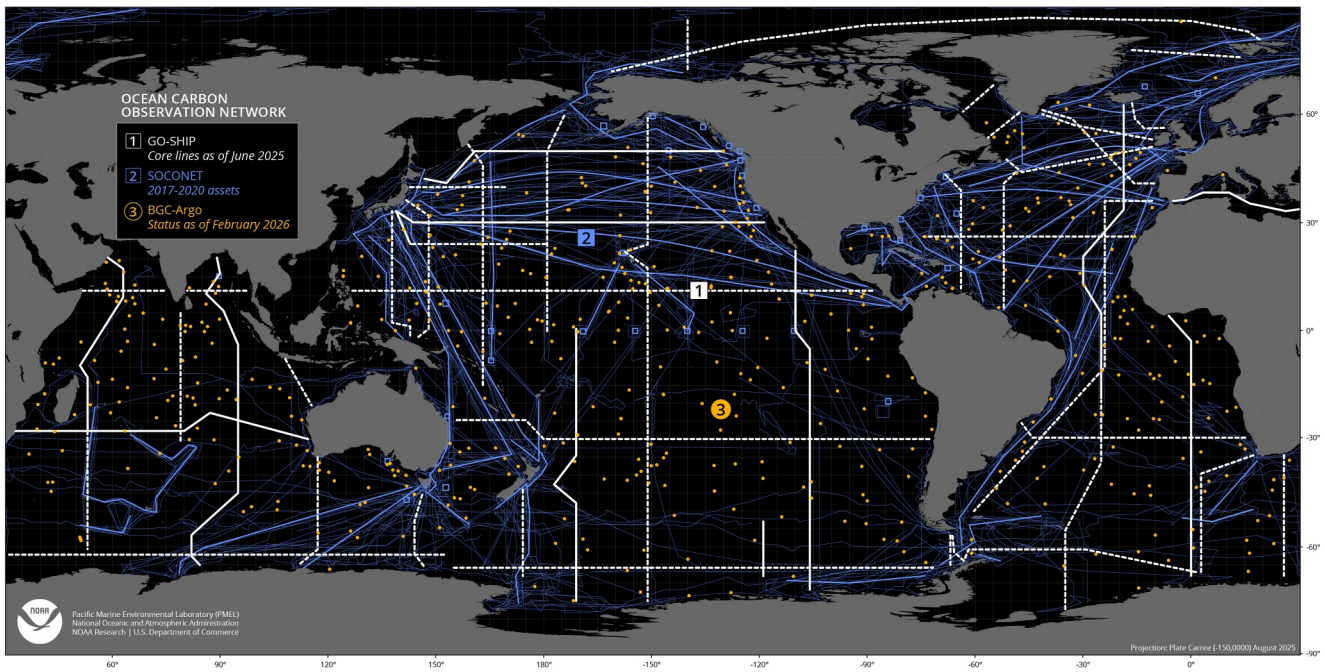


Figure 1. Schematic of current GO-SHIP (white), SOCONET (blue), and BGC-Argo (orange) networks. GO-SHIP lines shown are the 53 core reference lines as of June 2025, including the 13 lines with Bio-GO-SHIP measurements (solid lines represent cruises with Bio-GO-SHIP measurements; the remaining cruises are the dotted lines). SOCONET assets (lines represent research vessels, ships of opportunity, and USVs; squares represent buoys) can change from year to year. SOCONET is represented here by measurement locations from 2017 to 2020, with thicker blue lines over the regions of repeat occupations and the thin blue lines as single occupations. BGC-Argo floats are approximate locations of all floats with active pH measurements as of February 2026. Note that to visualize the status of all three networks in one map, each network representation is a different time period (GO-SHIP: decadal, SOCONET: 4 years, BGC-Argo: float location in February 2026). Online resources such as OceanOPS (ocean-ops.org) provide capability to map these different networks based on different metadata criteria, including time. Credit: NOAA Pacific Marine Environmental Laboratory.

creating the data product, and the SOCAT-based mapped pCO_2 and flux products. Beyond its use for quantification of air-sea CO_2 fluxes, the SOCAT data product also forms the basis for many global analyses of surface ocean carbonate chemistry, including ocean acidification (e.g., Feely et al., 2023; Jiang et al., 2023).

From inception in the early 2000s, Argo was envisioned as a global-scale network providing float-based profile data of temperature and salinity for detecting climate signals and providing ocean state estimates for ocean and climate models (Argo Steering Team, 1998). A part of Argo's ambition has been to contribute to data-assimilating ocean and climate forecast models, so the network was designed with data delivery infrastructure able to serve highly-resolved profile data from floats with minimal latency. BGC-Argo is building out a global array of floats measuring profiles from the ocean surface to 2 km depth carrying sensors for six biogeochemical parameters: oxygen, chlorophyll, nitrate, pH, optical backscatter from suspended particles, and downwelling irradiance (Owens et al., 2022). The goal of maintaining an array of 1,000 globally distributed floats measuring biogeochemical parameters (Biogeochemical-Argo Planning Group, 2016) is currently 53% implemented for five and six sensor floats carrying pH with a nearly uniform and global distribution (Figure 1). The array delivers quality controlled data with unrestricted access in near real-time across all seasons of the year at ∼10-day intervals. In addition to the global array of multi-sensor floats, arrays of floats equipped with fewer biogeochemical sensors are developing and will augment the BGC-Argo mission. BGC-Argo captures the variability between decadal GO-SHIP occupations and provides the opportunity to understand seasonal to interannual processes driving primary productivity, plankton carbon stocks and bloom phenology, carbon cycling and export, ocean deoxygenation and oxygen deficient zones (e.g., Sharp et al., 2023), and ocean acidification (Claustre et al., 2020; Sarmiento et al., 2023), serving as important constraints on biogeochemical models.

One common goal across these three networks is to address global-scale questions about the ocean carbon cycle and how it is changing. No observing network alone can address every aspect of the ocean carbon cycle because each network has different temporal and spatial coverage, sampling frequency, observing platform payload,

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measurement specifications and maturity, and motivating scientific questions. These differences dictate the niche each network plays in ocean carbon cycle research and represent opportunities where networks can provide added value to one another.

The scale of the challenge to characterize the ocean carbon cycle motivates capitalizing on every opportunity for cross-network coordination and collaboration. Here we describe the overarching research questions driving the mission of these networks, the synergies and dependencies across the networks, and recommendations for enhancing these synergies and intra-network strategy going forward. Implementation or strategic plans (Biogeochemical-Argo Planning Group, 2016; IOC of UNESCO and the International CLIVAR Project Office, 2009; Wanninkhof et al., 2019) and science reviews (Claustre et al., 2020; Talley et al., 2016) on the individual networks exist in other contributions. The focus of this contribution is to highlight how these three networks collaborate now and can expand collaboration in the future to enhance ocean carbon research.

2. Network Attributes and Design

GO-SHIP, SOCONET, and BGC-Argo are mature or emerging global-scale networks that currently meet or are actively working toward all network attributes as defined by the Observations Coordination Group (OCG) of GOOS that coordinates the operations of active global ocean observing networks (Table 1). In this contribution we focus on synergies between the three global-scale networks striving to implement operational aspects of sustained observing. Several other relevant networks, such as the Global Ocean Acidification Observing Network (GOA-ON), OceanSITES, and the Surface UNcrewed (SUN) Fleet are not detailed here because they significantly leverage carbon observations coordinated through GO-SHIP, SOCONET, and BGC-Argo. However, these other networks provide emerging contributions to the ocean carbon community. GOA-ON makes significant contributions to ocean carbon cycle knowledge through its globally-distributed community of practice and capacity building efforts in measurement collection and data management, which have resulted in expanded coastal observations of the ocean carbonate system (Tilbrook et al., 2019). As a network of practice and interaction, GOA-ON provides in-roads to a more globally-distributed network of scientists collecting ocean acidification observations, a resource that the three other networks could better utilize to help address geographical observing gaps and expand the number of scientists making ocean carbon measurements. The SUN Fleet is another more recently-designated emerging network of USVs that has the potential to play a significant role in expanding ocean carbon data collection (Patterson et al., 2025). Air-sea CO_2 observations collected on USVs are also a part of the EOV-based (rather than platform-based) SOCONET. Future advancements in ocean carbon sensor technology may lead to increased synergies across a wider number of ocean observing networks.

In addition to global-scale observing, several other network attributes are consistent across GO-SHIP, SOCONET, and BGC-Argo (Table 1). All networks conduct routine, systematic ocean carbon measurements and deliver Findable, Accessible, Interoperable, and Reusable (FAIR) data. Two of the three networks currently deliver routine metadata to OceanOPS: the international coordination center for tracking, monitoring, and supporting the GOOS networks. Each has a leadership structure that develops and tracks progress toward multi-year strategies. This includes a significant time commitment dedicated to coordinating activities that ensure a network supported by numerous scientists and research grants operates in a sustained and organized manner. In addition to measuring carbon EOVs, the interdisciplinary nature of each network has resulted in the collection of additional EOVs and Essential Climate Variables (ECVs) that aid in the interpretation of the carbon data and contribute to validation of satellite data products and to broader research efforts (Table 2). SOCONET was established to focus on the collection of surface seawater pCO_2 but—motivated by the requirements of the Global Greenhouse Gas Watch—is also working with atmospheric networks to harmonize measurement best practices to make it possible to fill major data gaps in atmospheric greenhouse gas ECVs over the ocean. Argo is a network that was first established to collect physical EOVs, with biogeochemical measurements incorporated later on as sensor technology development broadened the range of possible measurements. Bio-GO-SHIP is a new initiative incorporating biological measurements on GO-SHIP cruises that will, among other goals, contribute to research on the biological carbon pump (Clayton et al., 2022). Bio-GO-SHIP measurements provide supporting variables for GOOS biological and ecological EOVs such as plankton biomass and diversity but are not required parameters on GO-SHIP cruises at this time.

A combined representation of current GO-SHIP, SOCONET, and BGC-Argo network coverage is illustrated in Figure 1. GO-SHIP reference hydrographic lines with full-depth, physical and chemical measurements are

Earth's Future

10.1029/2026EF008722

Table 1
Status of Each Network's Attributes, Commitments, and Benefits as Defined by the GOOS Observations Coordination Group

OCG Network Attribute	GO-SHIP	SOCONET	BGC-Argo
Scale	Global	Global, with some regional gaps	Global, with some regional gaps
EOVs and ECVs	Several (see Table 2)	Several (see Table 2)	Several (see Table 2)
Sustained	Typically through short-term (~5 years or less) research grants; global surveys date back to the 1990s WOCE effort or earlier	Typically through short-term (~5 years or less) research grants; observations date back to 1957, improving in quality and spatial distribution since 1990s	Typically through short-term (~5 years or less) research grants; observations date back to 2002
Community of practice	International GO-SHIP Committee, as well as national committees and councils	SOCONET Steering Committee	OneArgo Executive committee and BGC-Argo Mission Team
Network mission and targets	IOC of UNESCO and the International CLIVAR Project Office (2009), Hofmann and the IMBeR Scientific Steering Committee (2016), Sloyan et al. (2019)	Wanninkhof et al. (2019, 2025); targeted 2026 release of SOCONET Implementation Plan	Biogeochemical-Argo Planning Group (2016), Roemmich et al. (2019), Thierry et al. (2025)
FAIR data	Ocean Carbon Data System (OCADS), CLIVAR and Carbon Hydrographic Data Office (CCHDO), GLODAP	SOCAT	Argo Global Data Assembly Centers (Coriolis, USGODAE)
OceanOPS-integrated metadata	Yes, operational	No, in process	Yes, operational
Standards and best practices	Hood et al. (2010)	Wanninkhof et al. (2025)	Bittig et al. (2019)
Capacity sharing	CCHDO accepts and manages data from non-GO-SHIP cruises, PIs share cruise planning software and routinely coordinate ancillary measurement efforts and sensor platform deployments	Project-level technical capacity building and exchange	Open-source toolboxes for data access, visualization and products
Environmental stewardship	GO-SHIP Committee discusses ways to mitigate impacts	Many new SOCONET platforms use solar, wind, or wave power; SOCONET SC plans to assess the current environmental stewardship strategies of commercial partners. Many platforms are ships of opportunity, for example, merchant ships.	Autonomous floats provide an alternative to some shipboard observations, minimizing the carbon footprint; implementing retrievable end-of-life floats (currently 4% at global scale; up to 70% in some marginal seas)

Note. GO-SHIP and BGC-Argo are considered mature GOOS networks and SOCONET is an emerging network. Note that only the main data endpoints are listed under FAIR data, however, the networks' data are archived at many National Oceanographic Data Centers.

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Table 2
EOVs and Essential Climate Variables (Those Not Already Listed Under the Carbon or Supporting EOVs) That are Measured on Each of the Three Global Ocean Carbon Observing Networks

	Carbon EOVs	Supporting EOVs	Supporting ECVs	Measurement temporal scale	Measurement spatial scale
GO-SHIP	Inorganic carbon (at least two of four: DIC, TA, pH, pCO_2), dissolved organic carbon*, stable carbon isotopes*	Temperature, salinity, oxygen, nutrients, transient tracers, surface currents, subsurface currents, plankton biomass and diversity*	Surface pressure, surface air temperature, surface air water vapor, surface wind speed and direction	Nominally decadal, sometimes more frequent	Full water column basin-scale repeat hydrographic lines with stations nominally every 30 nautical miles (closer across gradients and bathymetric features)
SOCONET	Inorganic carbon (pCO_2)	SST, SSS	Atmospheric CO_2*, surface wind speed and direction*, surface pressure, surface air temperature*, surface air water vapor*	Minutes to hours, some with coverage over an annual cycle	Air-sea interface using fixed stations, regional-scale cruises, and basin-scale crossings
BGC-Argo	Inorganic carbon (pH), ocean color, particulate matter	Temperature, salinity, oxygen, nutrients, plankton biomass, subsurface currents	Downwelling irradiance	10-day intervals with coverage over an annual cycle	Global distribution of water column profiles to 2,000 m depth

Note. DIC = dissolved inorganic carbon; TA = total alkalinity; pCO_2 = partial pressure of CO_2; SST = sea surface temperature; SSS = sea surface salinity. * signifies desired variables that are sometimes collected but not required by the network.

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repeated ideally at the decadal time scale at minimum, with some cruises repeated at a higher frequency and some not occupied in over a decade. Bio-GO-SHIP measurements have been conducted on approximately 13 hydrographic lines beginning in 2023. SOCONET has large gaps in every ocean basin in the Southern Hemisphere, in the Arctic Ocean and in some shelf seas. BGC-Argo is currently operating at approximately half of the network's target of 1000 floats measuring pH at any given time. SOCONET and BGC-Argo collect continuous observations at high-frequency, from minutes to hours for SOCONET and profiles every 10-day for BGC-Argo. Figure 1 illustrates the persistent coverage gaps that limit our ability to resolve multi-scale ocean carbon dynamics. Overcoming these limitations is fundamental to addressing the complex research questions regarding the ocean's evolving carbon cycle.

3. Observing Network Contributions to Global Ocean Carbon Research Questions

Systematic observations sustained over the long-term are a critical element of any research effort to understand the ocean carbon cycle and how it is changing. Observing networks generate long-term records, providing important historical context for targeted, time-limited investigations like process studies (e.g., NASA EXPORTS, Siegel et al., 2016). These historical records show interior ocean carbon accumulation and surface ocean CO_2 uptake consistent with rates of atmospheric CO_2 increases over the last several decades (DeVries et al., 2023; Müller et al., 2023). The capability to detect decadal-scale trends in carbon export and the feedback between ocean acidification and calcification are emerging (Barrett et al., 2025; Liniger et al., 2025). Continuation and expansion of these networks are necessary to track the ocean response to climate forcing and provide this information for operational needs, such as routine climate assessments (e.g., Friedlingstein et al., 2025) and future ocean ecosystem forecasts that inform policy and society.

Here we discuss how GO-SHIP, SOCONET, and BGC-Argo measurements contribute to these research gaps by focusing on the distribution and drivers of ocean carbon (3.1) and potential climate feedbacks (3.2). For a more in-depth review of ocean carbon cycle research gaps, refer to the Integrated Ocean Carbon Research report (IOC of UNESCO, 2026).

3.1. What Are the Controls and Distribution of Natural and Anthropogenic Carbon in the Ocean on Seasonal to Multi-Decadal Time Scales?

Characterizing the processes by which carbon enters the ocean, is transformed, stored, and eventually re-enters the atmosphere, is necessary to understand present and future habitat suitability and the ocean's ability to continue to dampen the buildup of CO_2 in the atmosphere. This requires knowledge of the natural variability of the carbon cycle, and how it changes as anthropogenic CO_2 increases. The sustained monitoring provided by the ocean carbon observing networks supports a significant amount of this research (e.g., DeVries et al., 2023; Gruber et al., 2019).

GO-SHIP reference measurements of the ocean interior are foundational to understanding ocean carbon distribution and change. The colocated measurements of biogeochemical properties provided by GO-SHIP allow estimation of the calibration fields (Bittig et al., 2018; Carter et al., 2021; Williams et al., 2017) needed for BGC-Argo (Maurer et al., 2021) and the decadal anthropogenic carbon accumulation estimates (Gruber et al., 2019; Müller et al., 2023) that complement the contemporary total surface ocean CO_2 flux estimates derived from the SOCONET record (e.g., Müller et al., 2025). Transient tracer information, which is nearly uniquely provided by GO-SHIP, allows both reconstructions and projections of anthropogenic carbon distributions (e.g., Carter et al., 2025) and can ensure that these estimates remain viable for the near future despite ongoing changes to the ocean carbonate system (i.e., ocean acidification). GO-SHIP also collects many of the colocated sets of three or more carbonate system measurements that are essential for testing how effectively seawater pCO_2 information from SOCONET and seawater pH information from BGC-Argo can be converted into other metrics for ocean acidification and carbonate chemistry (e.g., Carter, Sharp, García-Ibáñez, et al., 2024; Fong & Dickson, 2019; García-Ibáñez et al., 2022). GO-SHIP reference measurements also make it possible to quantify coastal carbon exchange with the open ocean and extend anthropogenic carbon content estimates into coastal waters where societal concerns about impacts are most acute (Feely et al., 2016, 2024).

The different measurement timescales of GO-SHIP and BGC-Argo are highly complementary in resolving interior ocean carbon cycle processes from the seasonal to decadal scales. For example, measurements made on GO-SHIP and similar cruises over the last three decades are being used alongside more highly-resolved

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BGC-Argo-derived records to develop empirical relationships and train machine learning mapping algorithms that generate spatially- and temporally-resolved climatological distribution of inorganic carbon and oxygen. For example, Sharp et al. (2023) illustrates that together, the GO-SHIP and BGC-Argo data sets provide a much clearer view of ocean deoxygenation. GO-SHIP provides the reference-quality information that validate BGC-Argo and other autonomous measurements, while higher-resolved BGC-Argo observations provide new opportunities to constrain sub-decadal (seasonal to interannual) variability of the ocean carbon cycle.

The surface ocean coverage of SOCONET and associated atmospheric measurements constrain the variability in surface pCO_2 and air-sea CO_2 exchange across a variety of time scales. Annually-updated machine learning products based on SOCONET observations, via SOCAT, show interannual to decadal variability in addition to the long-term trend in the ocean CO_2 sink. Ocean conditions, primarily circulation, mixing, and sea surface temperature, drive significant regional and seasonal to interannual variability in surface ocean pCO_2. However, the relatively small global average disequilibrium between atmospheric and surface ocean CO_2 that drives ocean uptake (~4 µatm between 1980 and 2021, Fay et al., 2024) dictates the need for accurate pCO_2 measurements for quantifying air-sea CO_2 flux. Annual bottom-up estimates of the ocean CO_2 uptake derived from SOCONET and global ocean biogeochemical models, along with decadal-scale GO-SHIP-derived interior ocean anthropogenic carbon estimates, provide several approaches to ocean CO_2 sink constraints and are used in tandem to seek ways to improve the different approaches (e.g., Hauck et al., 2020). Top-down inversion approaches to constraining global CO_2 fluxes between the atmosphere, ocean, and terrestrial boundaries are also seeking SOCONET-based products as ocean priors and as direct input. By directly measuring surface ocean and atmospheric marine boundary layer CO_2 using the same certified reference gases as the atmospheric CO_2 network, SOCONET provides a traceable approach connecting surface ocean response to atmospheric forcing.

Emerging efforts to assess the ocean's capacity to take up additional carbon through marine Carbon Dioxide Removal (mCDR) approaches are dependent on these three networks to characterize global ocean baseline carbon variability and change. Without constraint of this baseline, it will not be possible to validate additionality from mCDR interventions at scale. Ocean observing networks could support future mCDR monitoring, reporting, and verification activities (Boyd et al., 2023). Alternatively, if ocean models are ultimately the primary tools for estimating additionality, those models must be validated with data and information from sustained observing networks (Findlay et al., 2025).

3.2. How Are Climate Feedbacks Changing Ocean Carbon Uptake?

Warming, changes in circulation, ocean acidification, reduced buffer capacity, changing ecosystem dynamics, changes in sea ice extent, and increasing frequency and intensity of extreme events, such as marine heatwaves and their compound effects, have the potential to impact ocean CO_2 uptake and storage. The extent to which climate feedbacks are changing ocean carbon uptake is believed small but with significant uncertainty and increasing importance in the future. Each network provides unique contributions to better understand the relationship of carbon to changing ocean physics, biogeochemistry, and biology.

All three networks have established records essential to track potential changes to ocean carbon uptake with largely independent approaches. GO-SHIP based estimates of ocean interior carbon storage and SOCONET-based estimates of air-sea CO_2 exchange both suggest that the ocean sink over the last three decades has tracked increasing atmospheric CO_2 driven by the solubility pump. Tracking any deviation from ocean CO_2 uptake trends due to ocean climate feedback requires these high-quality, traceable measurements.

Whether the ocean CO_2 sink will continue as a mostly abiotic process requires proper account of all the different carbon pumps. BGC-Argo brings new and unique capabilities for understanding biological uptake, transfer, and storage of carbon, which is needed to track whether long-term possible changes in ocean biology may start impacting the ocean carbon sink trend and to identify the key physio-chemical drivers of these changes. For example, BGC-Argo may have future potential to characterize variability in the ocean carbon inventory and distinguish between natural and anthropogenic components of change. Regional-to global-scale quantification of net community production and organic matter export from BGC-Argo measurements would transform our understanding of the mechanisms and rates of carbon sequestration (Thierry et al., 2025; Yamaguchi et al., 2024). Just as GO-SHIP provides essential reference measurements to validate biogeochemical models (e.g., Hinrichs et al., 2023; Séférian et al., 2020) and float-based biogeochemical sensors and algorithms (e.g., Maurer

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et al., 2021), full implementation of Bio-GO-SHIP is required to ground truth these approaches to elucidating biological pump processes and long-term change.

Finally, the high-frequency capabilities of BGC-Argo and SOCONET provide opportunities to constrain event-scale dynamics, including changing frequency and duration of extreme events. e.g., these autonomous observing networks have been essential to studying potential impacts of marine heatwaves on ocean carbon (e.g., Bif et al., 2025; Mogen et al., 2022). These event-scale studies are primarily the result of observing assets having fortuitous encounters with marine heatwaves. As intensity, duration, and spatial coverage of these types of events change, BGC-Argo, SOCONET, and other autonomous observing networks must adjust to be responsive to the needs of characterizing event-scale drivers and impacts by, for example, increasing density in event-prone regions or re-directing autonomous assets to areas with emerging events.

4. Discussion

4.1. Optimizing Synergies and Dependencies Across Networks

GO-SHIP, BGC-Argo, and SOCONET are complementary observing networks that have provided significant improvement in constraining ocean carbon variability, change, and carbon cycle processes at different time and space scales. Some ocean carbon scientists are involved in more than one of the three networks, and as a result, have improved network outcomes by leveraging some cross-network synergies and dependencies. Here we discuss those synergies and dependencies and how they may be optimized.

One clear cross-network dependency is the reliance on GO-SHIP visiting remote locations to help SOCONET and BGC-Argo achieve global coverage. The repeat ocean basin crossings of GO-SHIP on research ships outfitted with underway CO_2 instruments, particularly in the Southern Hemisphere, fill spatial gaps in SOCONET that are not covered by research cruises or volunteer observing vessels primarily moving goods between ports that are most dense in the Northern Hemisphere. GO-SHIP cruises also provide BGC-Argo float deployment opportunities; 20% of Argo floats are deployed from GO-SHIP cruises. Known GO-SHIP tracks and the extensive planning that goes into each cruise allows time for coordination with BGC-Argo to assemble, test, and ship new floats and to train scientists and crew in float deployment.

The reference-quality measurements of GO-SHIP allow all BGC-Argo deployment opportunities to become measurement validation opportunities as well. Casts performed at float deployment locations provide validation measurements to ground truth float-based measurements of pH, oxygen, and nitrate and estimates of total alkalinity calculated from temperature and salinity. These validation casts are part of BGC-Argo standard operating procedures. SOCONET reference measurements have also supported validation for BGC-Argo derived surface ocean pCO_2 (Williams et al., 2017). Measurement intercomparisons between direct surface pCO_2 measurements from SOCONET and calculated pCO_2 from BGC-Argo have revealed a bias on the order of 6–11 µatm in float-derived surface ocean pCO_2 (Bushinsky et al., 2019), which has stimulated research into the source(s) of that bias (Bushinsky et al., 2025) and testing of new pH sensors (Wirth et al., 2024). Better constraint of the source (s) of the bias may lead to float-specific, regional, or global-scale correction routines that improve float-derived estimates of inorganic carbon variables. In addition, GO-SHIP cruises are among the only sources of reference-quality overdetermined carbonate chemistry measurements, which are essential for ongoing research quantifying and reducing the uncertainties in CO_2 system calculations (Carter, Sharp, Dickson, et al., 2024). Known and unknown uncertainties in those calculations may be contributing to uncertainties throughout CO_2 system derived estimates of ocean carbon, including float-derived pCO_2 and DIC. As Bio-GO-SHIP develops, their optical measurements of chlorophyll pigments and particulate organic carbon will similarly validate and enhance the BGC-Argo bio-optical measurements.

Research vessels serve as critical platforms for these types of sensor and measurement method evaluations (Sloyan et al., 2019). Air and surface seawater CO_2 instrument comparisons are now being conducted on several research vessels, including those supporting GO-SHIP cruises. These advanced air and ocean greenhouse gas measurement technologies are being tested to constrain and reduce measurement uncertainty with a potential outcome of filling gaps in marine boundary layer measurements over the ocean. SOCONET-derived ocean CO_2 sink estimates also depend on the wind parameterization studies conducted on research cruises (Wanninkhof, 2014 and references therein). More widespread deployments of paired underway surface pCO_2 and direct flux instrumentation on research vessels could also contribute to air-sea CO_2 flux research, including improving

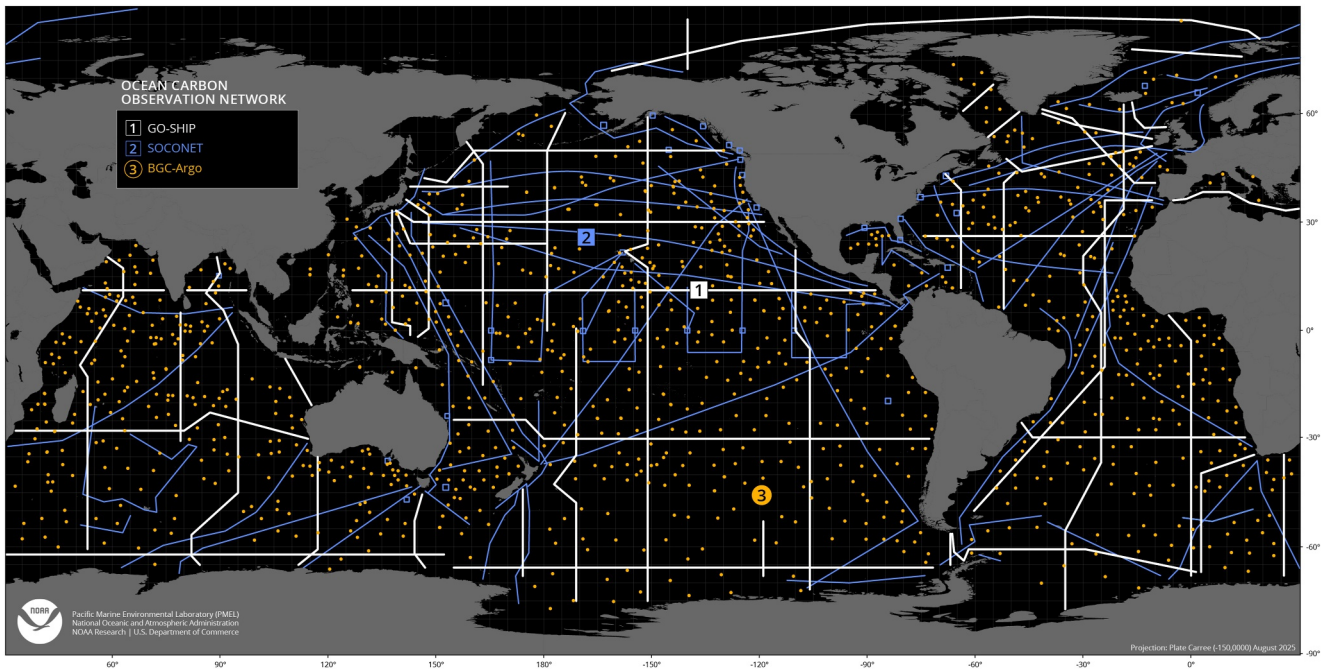


Figure 2. Schematic of a more optimal network design for GO-SHIP (white), SOCONET (blue), and BGC-Argo (orange). As in Figure 1, network timescales vary and represent minimum decadal repeat cruises for GO-SHIP, annual observations for SOCONET, and a snapshot view of an evenly-distributed BGC-Argo network. Enhancements relative to Figure 1 include Bio-GO-SHIP measurements on all 53 core GO-SHIP lines, a resurrection of past SOCONET platforms in the Southern Hemisphere, and a doubling of BGC-Argo to 1000 floats. Reference measurements of GO-SHIP and SOCONET in an optimal network are globally-distributed. BGC-Argo is also globally-distributed but has higher density compared to the reference networks. This schematic is conceptual based on our current understanding, but network plans should change over time as research activities advance our understanding of optimal network design. Credit: NOAA Pacific Marine Environmental Laboratory.

gas transfer velocity parameterizations and refining skin temperature corrections for bulk CO_2 flux estimates (Dong et al., 2021; Ford et al., 2024). Furthermore, BGC-Argo floats carrying wind sensors are being tested and might fill gaps in in situ wind observations necessary for air-sea flux, especially in remote areas like the Southern Ocean (Delaigue et al., 2026).

These cross-network sensor intercomparisons and measurement evaluations highlight the utility of a tiered network approach providing a framework for integrating measurements of differing quality from networks with (GO-SHIP and SOCONET) and without (BGC-Argo) reference-quality carbon measurements (Thorne et al., 2018). While reference networks are metrologically characterized, they are not as densely distributed as networks like BGC-Argo (Figure 2). A more formalized tiered network approach would benefit from a cross-network plan for routine intercomparisons and data sharing. While GO-SHIP and BGC-Argo have adopted best practices for float validation activities, SOCONET should provide public access to near real time metadata that make it possible to identify operating status of deployed assets with reference-quality measurements available for intercomparisons.

This level of cross-network integration would benefit additional synergies and dependencies between the three carbon networks and others. Data products from in situ ocean networks are validation assets for satellite oceanography, while satellite oceanography provides critical data for interpolating sparse in situ surface ocean observations as is done to create global CO_2 flux maps from SOCONET data (e.g., Landschützer et al., 2016). Merging satellite and BGC-Argo measurements can also extend the high-resolution satellite observations into the ocean interior (Fox et al., 2024) and into cloud- and ice-covered regions and high-latitude winters where satellite observations are not feasible (Ford et al., 2026). The open-ocean carbon networks also provide open-ocean boundary conditions contributing to coastal biogeochemical research and model development. In an observing system where all these data sources are accessible and interoperable, intercalibration between reference

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measurements and more widely-distributed measurements not traceable to a reference will be key to combining all these different data sources.

Measurement and data consistency, including uncertainty estimates, across the networks would allow for more seamless research across the wide range of different time and space scales this collection of networks represent. Idealized cross-network synergies would involve BGC-Argo providing sub-decadal interior observations between GO-SHIP occupations, SOCONET and BGC-Argo constraining the drivers of event-scale to interannual variability from surface through the mixed layer into the interior ocean, and satellites providing information for interpolating sparse in situ observations. Data from these global-scale networks combined with a variety of additional coastal data from regional cruises, gliders, and other autonomous platforms will be required to develop sought-after ocean ecosystem forecasting tools (Thierry et al., 2025).

5. Cross-Network Strategy and Actionable Recommendations

In recent decades, the ocean carbon observing community has made progress building observing network infrastructure that will be foundational to optimizing cross-network synergies. Within-network best practices and infrastructure supporting all aspects of ocean carbon observing from the initial planning of data collection to the availability of the data products and their dissemination have improved measurement standards and procedures, data availability, and data and information synthesis products designed for research, policy, and operational end users. The networks have also made progress cultivating many cross-network synergies. Here we recommend several near-term actions that will build on this work and create a more integrated and efficient ocean carbon observing system able to support the growing need for carbon cycle information in a changing ocean.

Our strategy includes pursuing the following cross-network recommendations:

Observing network designs should consider the collective of ocean carbon observing networks. GO-SHIP, SOCONET, and BGC-Argo should undertake a collective effort to further define a vision for an optimal global open-ocean carbon observing system (Figure 2). This system-level design should define what the minimum quantity and quality of measurements are required to meet scientific and societal needs. Such efforts as "A Large-Scale CO_2 Observing Plan: In Situ Oceans and Atmosphere" were foundational in the design and implementation of ocean observing systems (Bender et al., 2002). As individual networks evolve to fulfill that design, networks should consult others on evolving individual network designs to help identify gaps to fill or areas of collaboration, extending the impact of individual networks and the collective observing system. These designs should also be co-developed with end users, including those using observations to model and to reconstruct ocean carbon conditions with ocean inverse, data assimilation, and machine learning models. In addition to informing the observing community of their needs, they can actively participate in design by utilizing models to simulate and assess the impact of changes in the observing network.

The networks should actively engage with international efforts seeking to ensure data interoperability, that is the automation of information exchange between data systems. Ease of use and access to network-produced metadata, data, and data products will facilitate validation activities needed to make data comparable across networks, make it easier to maintain existing data synthesis products, build new 4-dimensional data products that integrate information from multiple networks, and provide easy data access for validation of biogeochemical and ecosystem models and improved process-level understanding (IOC of UNESCO, 2024; Lange et al., 2023). In collaboration with OCG, OceanOPS, and each networks' respective data assembly centers, the networks should meet all requirements for metadata, near real time and delayed-mode data, and data best practices that will lead to interoperability (GOOS, 2024). That automation will streamline information exchange between the networks, providing more timely visibility of network gaps and crossovers and availability of data for cross-network measurement quality assessment and product development.

Utilize established GOOS forums to provide routine updates on progress in optimizing cross-network synergies. Annual OCG meetings are opportunities to share updates on best practices, data quality control and management, and data product development, benefiting the networks by identifying opportunities to share approaches and tools and avoid duplicative efforts. These meetings should also serve a connection to other networks with expanding

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and emerging carbon measurements, such as SUN Fleet and OceanGliders. In addition to existing OCG collaboration, there may be a need to create additional forums to facilitate discussions between the scientific carbon leadership of the three networks to make progress on cross-network priorities, such as holistic ocean carbon network design. GOOS should also bring together the networks and operational entities to align observing requirements with operational needs. For example, GOOS should enhance engagement with satellite governance through the Committee on Earth Observation Satellites to communicate priority satellite products utilized by the ocean carbon community, share status of in situ ocean data available for satellite validation, and better understand the satellite community's in situ ocean data requirements. More broadly, continued GOOS advocacy for a healthy system of ocean observing and research infrastructure is foundational to achieving operational and research needs.

Networks should establish new targets for cross-network synergies. The ideas for optimizing cross-network synergies and dependencies presented here are just a start. In strategic planning and target setting, each of the networks should discuss new and adapted activities and accuracy goals that are cross-network focused and iterate on those plans with other networks through routine OCG meetings.

Intra- and inter-network infrastructure should be strategically planned to be responsive to accelerating change, extreme events, climatic shifts, and unanticipated changes/phenomena. Any new cooperative framework should be designed to facilitate multi-network collaborations on timescales that can respond to event-scale ocean carbon cycle changes, in addition to long-term planning and target setting. For example, an observing system that can utilize existing GO-SHIP cruises to deliver BGC-Argo floats or redirect SOCONET USVs to a region with important emerging ocean carbon cycle implications, is a system that can deliver both sustained and responsive observations in a rapidly changing ocean. Achieving the full, responsive capability of this infrastructure, however, will require dedicated new resources.

Expand supporting infrastructure for ocean carbon observing networks. It is a challenge to sustain GO-SHIP, SOCONET, and BGC-Argo in the current funding model of using short-term research funds for networks aiming to become operational. The coordination of short-term funding commitments, the contingency planning during funding gaps, and the process of competing for limited research funding all consume a large amount of time. Meanwhile, overall capacity to maintain these observing networks is decreasing. For example, the U.S. Academic Research Fleet has decreased from 34 to 17 ships, with ocean research vessels retiring faster than the ability to construct new ones or the ability of other countries to add ships to the international research fleet. There are additional needs including: strengthening efforts for technical development to improve direct measurements of the carbonate system, supporting the international activities that facilitate cross-network data synthesis and co-ordination, and enhancing networks to be responsive to a rapidly-changing ocean. Sustained and new ocean infrastructure, including for the Arctic and Southern Hemisphere, is essential to the long-term success of the ocean carbon observing networks.

As representatives of the science committees of GO-SHIP, SOCONET, and BGC-Argo, we are committed to enhancing these cross-network synergies, sustaining the networks, and enacting new efforts that will contribute to filling knowledge gaps in ocean carbon cycle research and improving climate prediction and ocean ecosystem forecasting. We commit to the leadership and advocacy required within the networks to build understanding and support for doing this work. We believe this type of collaborative structure and implementation is required to meet the growing needs of the community.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

This article synthesizes the findings of published works cited in the manuscript. Data and software were not used, nor created for this research.

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