NOAA Oceanic and Atmospheric Research

Ocean Carbon Observing Science Plan

FY25 to FY35

Cover: *A CTD rosette is raised up to NOAA Ship PISCES. CTD stands for Conductivity, Temperature, Depth measurement instrument.*
Credit: Commander Jeremy Adams, NOAA Corps

NOAA Oceanic and Atmospheric Research
Ocean Carbon Observing Science Plan
FY25 to FY35

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EXECUTIVE SUMMARY

The impacts of the post-industrial increase in atmospheric carbon dioxide (CO_2) levels (IPCC, 2021; Friedlingstein et al., 2024) are accelerating, including rising ocean and atmospheric temperatures; melting sea-ice; sea level rise; and increased frequency and intensity of extreme weather events (e.g. hurricanes, flooding, droughts, wildfires, extreme heat). The year 2023 had the highest global annual average temperature in NOAA's 174-year climate record (1850-2023), about 2.43 °F (1.35 °C) above the pre-industrial average (1850-1900), as measured over land and ocean (Lindsay and Dahlman 2024). In the United States, there were 28 weather and climate disasters in 2023 that each had losses exceeding $1 billion USD (NOAA NCEI 2024a). There is now a strong need for increased innovation, partnerships, and observing system co-design with end users and decision makers to accelerate adaptive action.

Our changing ocean both mitigates and is impacted by increasing atmospheric CO_2. Impacts to aquatic health, including acidification and deoxygenation, threaten ocean and freshwater ecosystems and the vital services they provide, jeopardizing the nearly 2.3 million jobs in the fishery sector and over $321 billion in U.S. economic activity in 2022 alone (NMFS 2024). At the same time, the ocean mitigates climate impacts by absorbing excess heat and human-emitted CO_2. Recent estimates of the social cost of carbon, or the cost of the damage done by each additional ton of carbon emissions, in the U.S. vary from $3-$190 per metric ton CO_2 (Asdourian and Wessel 2023; EPA 2023). Given 37.4 billion metric tons of CO_2 emitted in 2024 (Friedlingstein et al. 2024), of which approximately 25% is absorbed annually by the ocean, the estimated value of natural ocean carbon uptake is between $28-1776.5 billion per year. Increasing public awareness of the impacts of climate change has accelerated the emerging climate solutions industry, which includes efforts aimed at enhancing the ocean's role in CO_2 uptake through marine carbon dioxide removal (mCDR) (Smith et al., 2024). Trusted and timely observations of carbon system dynamics in economically vital marine and freshwater ecosystems are needed to enable informed action by decision makers and resource managers. Sustained and expanded ocean, coastal, and Great Lakes carbon observing will help support the development of future climate projections, adaptation and mitigation strategies, and policies that inform decision makers and advance the blue economy.

NOAA Oceanic and Atmospheric Research (OAR) is uniquely positioned to provide critical ocean and Great Lakes carbon observations, data, products, and services to end users. The intent of this Science Plan is to outline OAR's goals related to ocean carbon observing, set priorities, and enable coordination with intra-agency, interagency, and international partners. The three goals of this 10-year Science Plan support OAR's long term vision to advance carbon cycle science; improve ocean, coastal, and Great Lakes models and product development; provide useful and societally relevant information; and develop capacity to drive innovation. These goals are:

GOAL 1

Observe Changes in the Ocean Carbon Cycle

GOAL 2

Enhance Ocean Carbon Data Management, Models and Services for Society

GOAL 3

Expand Ocean Carbon Opportunities and Community Engagement

Each goal is divided into prioritized research questions with associated actionable objectives. This document uses "ocean carbon observing" for brevity, which is considered to be inclusive of open ocean, coastal, and Great Lakes carbon observing. Overall, this Science Plan seeks to guide OAR's support of innovative ocean carbon cycle observing and science, address community needs through the co-design of ocean carbon products and services, as well as provide trusted and timely ocean carbon information to the nation and the world.

Close up of sensors on a Biogeochemical (BGC) Argo Float. Credit: Kathy Tedesco

Authorship

Representatives from OAR's labs and programs authored this plan. Leadership was provided by the Global Ocean Monitoring and Observing Program (GOMO) in partnership with the Ocean Acidification Program (OAP). Executive Steering Committee members represented the Climate Program Office (CPO), Ocean Exploration Program (OER), Air Resources Laboratory (ARL), Atlantic Oceanographic and Meteorological Laboratory (AOML), Geophysical Fluid Dynamics Laboratory (GFDL), Global Monitoring Laboratory (GML), Great Lakes Environmental Research Laboratory (GLERL), and Pacific Marine Environmental Laboratory (PMEL). To address the data management needs of ocean carbon research identified in the report, OAR partnered with representatives of the National Centers for Environmental Information (NCEI) within the NOAA National Environmental Satellite, Data, and Information Service (NESDIS). International perspective was provided through consultation with the International Ocean Carbon Coordination Project (IOCCP) and the Global Ocean Observing System (GOOS) Biogeochemistry Panel to align this plan with current international efforts as well as intergovernmental drivers such as the Global Climate Observing System Implementation Plan and the Global Greenhouse Gas Watch (G3W) Implementation Plan.

Acknowledgments

We, the Executive Writing Team, extend our thanks and gratitude to all contributing authors for their time and subject matter expertise in developing this Science Plan, from the outlining stage to the review process. We would also like to thank Dr. Rik Wanninkhof (AOML) for his extensive insight, consultation, and input to shaping this Science Plan. We are grateful to the reviewers, OAR lab and program directors, OAR Ocean's Portfolio, OAR leadership, Ocean Carbon and Biogeochemistry Scientific Steering Committee, and NOAA and interagency working groups (CCIWG, NOA-WG, IWG-OA, GHG Technical Team, mCDR Task Force) for their valuable expertise and feedback on this plan. We thank Melissa Hiatt for her work in designing and providing Figures 4 and 8, as well as modifying Figure 3. Additionally, we thank Andrea Fassbender for providing Figure 6C. We appreciate Alec Pelton for his assistance with Appendix B: Ocean Carbon Observing Directives and Authorizing Language. We also thank Andrea Badder for her guidance and support in the publication process. Finally, we thank the University of Southern California Sea Grant (NOAA award NA24OARX417C0060-T1-01), Woods Hole Oceanographic Institute (NOAA award NA24OARX417C0090-T1-01), and Mississippi-Alabama Sea Grant Consortium (NOAA award NA24OARX417C0069) for their financial support of the Knauss Fellows working on this project.

This is PMEL contribution number 5716.

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INTRODUCTION

Ocean, Coastal, and Great Lakes Sustained Carbon Observations

The ocean serves as an important sink of atmospheric CO_2, absorbing about 30% of total human-driven CO_2 emissions (Ciais et al. 2013; Gruber et al. 2019) and more than 90% of anthropogenic heat since the Industrial Revolution (NOAA NCEI 2024b; NOAA NCEI 2024c). As the largest active carbon reservoir, with 45 times more carbon than the atmosphere and 18 times more than terrestrial plants and soils, the ocean regulates atmospheric CO_2 levels (**Figure 1**) on time scales of decades to millennia (Revelle and Suess, 1957; Broecker, 1982; DeVries, 2022). Given the long timescales over which these processes operate, sustained ocean observations are critical to provide accurate knowledge about natural and anthropogenic sources and sinks of CO_2. Simultaneously, providing ocean, coastal, and Great Lakes carbon (hereafter termed 'ocean carbon') information on accelerated timelines is imperative for end users, natural resource managers, and decision makers.

The ocean covers 71% of the Earth's surface and is inextricably linked to global climate systems. While the uptake of CO_2 by the ocean reduces the accumulation of this greenhouse gas in the atmosphere, slowing the rate of climate change, it also increases the acidity of seawater (ocean and freshwater acidification), which endangers marine and aquatic organisms and impacts overall ocean health (Doney et al., 2009 a & b; Phillips et al., 2014, Weiss et al., 2018; Doney et al., 2020; Feely et al., 2009, 2023; Jiang et al., 2023; Fassbender at al., 2023). This can change the ecosystem services provided by the ocean (Cooley et al. 2022). Approximately 40% of the US population lives in coastal counties (Agardy et al. 2015). The American blue economy contributed $476.2 billion, or 1.8%, to the nation's GDP in 2022 (Bureau of Economic Analysis 2024; Nicolls et al. 2020), encompassing sectors such as fisheries, tourism, shipping, and energy. In addition, the Laurentian Great Lakes are the largest surface freshwater ecosystem on the planet and provide essential resources to more than 38 million people in the Great Lakes basin (Fergen et al. 2022). Trusted and timely observations of carbon system dynamics, as well as associated data, products, and services, in these economically vital ecosystems are critical to enabling informed policies, decisions, and action.

Robust and systematic observing of ocean carbon cycles is essential to quantify the uptake, transport, transformation, and storage of natural and anthropogenic CO_2, as well as discern the underlying mechanisms of change. This not only helps us better understand Earth systems, but also improves our models and informs decision making, leading to enhanced efficacy of mitigation and adaptation strategies. Over the past 30 years, significant progress has been made in establishing sustained ocean and coastal carbon observing networks through federally-funded scientific programs (e.g., NOAA, NSF, NASA, DOE, USGS, EPA, etc.), community-level capacity development, and co-design with partners and end users. However, limitations of both observational capabilities and associated modeling impact our ability to assess how physical, chemical, and biological carbon cycles are changing within ocean systems.

Trends in ocean carbon uptake, as estimated independently by observational products and global ocean biogeochemical models (GOBMs), are divergent, which limits our ability to accurately quantify the global carbon budget and its uncertainties in annual reports (see Surface

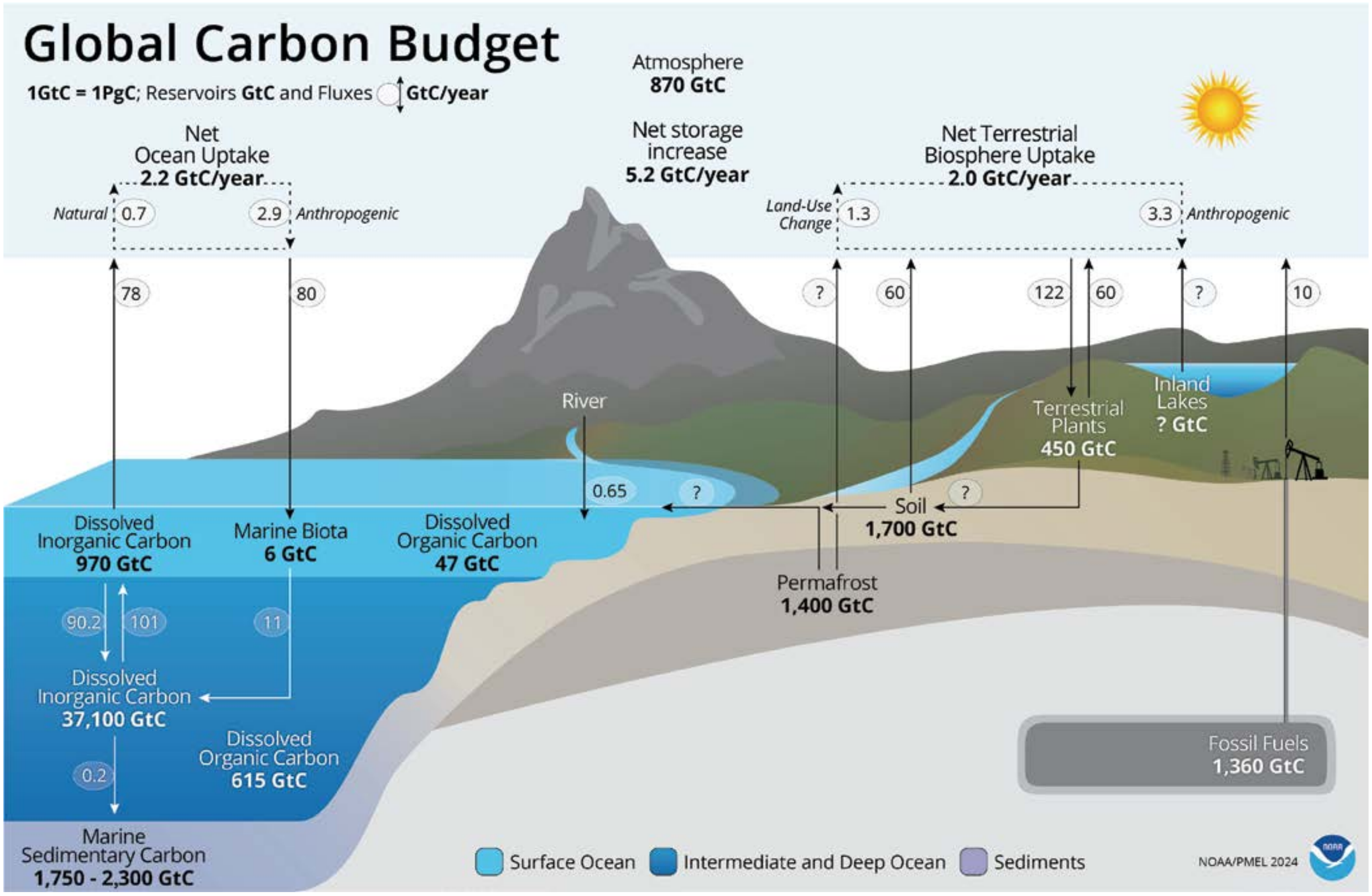


***Figure 1:** The Global Carbon Budget for 2022 (after Cai et al., submitted for publication). The ocean CO_2 sink was 2.9±0.4 Gt C yr^{-1} between 2014–2023 (26% of total CO_2 emissions) (Friedlingstein et al. 2024). The arrows with question marks indicate that values are unknown but believed to be small.*

Observations and Model Estimates of Global Air-Sea CO_2 Flux callout box, **Figure 2**). Recent evidence that the ocean carbon sink may be slowing due to climate-induced changes in the ocean (Müller et al. 2023; DeVries et al., 2023; Gruber et al., 2023) underscores the necessity of improved integration of observations and models (i.e., through data assimilation and observing system design) in order to better predict the future impacts of climate change. Additionally, ocean warming, marine heatwaves, and ocean circulation changes may drive ocean systems into new states where our current understanding of the ocean carbon uptake may decrease in accuracy (Heinz et al. 2021).

To address the wide range of pressing needs and societal challenges, a sustained global ocean carbon observing system is required (see Observing System Design callout box). An integrated system would enable improved understanding of the ocean's role in regulating global climate, routine assessment of the ocean's uptake of CO_2, and low-latency monitoring of marine ecosystem changes and their potential economic implications. These activities, alongside ocean carbon efforts conducted by other NOAA line offices, federal agencies, and international partners, will support climate resilience planning and policies, assessments of the feasibility of human intervention in the ocean carbon cycle, and blue economy innovations.

Surface Observations and Ocean Model Estimates of Global Air-Sea CO_2 Flux

Introduction

The Global Carbon Budget (GCB) presents an annual update of the global ocean anthropogenic CO_2 sink (GtC yr^{-1}) that is widely used among carbon cycle researchers. For the period since 1990, the GCB ocean sink ($S_{OCEAN)}$ estimate represents an average of a mean of multiple global ocean biogeochemistry models (GOBMs) and a mean of multiple gap-filled time-varying products based on global compilations of seawater fugacity of CO_2 (fCO_2) measurements (**Figure 2**; Friedlingstein et al. 2024). The fCO_2-based sea-air CO_2 flux estimate from the products is generated from gas exchange-wind speed parameterizations, reanalyses of wind speed and atmospheric pressure data, and gap filling of available direct observations of fCO_2 (via ships, moored buoys, and uncrewed surface vehicles [USVs]) using objective mapping or machine learning methods. It should be noted that all of these elements (i.e., the gas exchange parameterization, ancillary products, and gap filling methods) have significant sources of uncertainty that need to be quantified (Ford et al. 2024). The global estimate for sea-air CO_2 flux from observation-based products is then corrected by estimates of the flux of carbon from rivers to ocean and ocean burial such that it represents the uptake of anthropogenic CO_2 by the global oceans, in order for it to be comparable with GOBMs. Current GOBMs do not include a flux from rivers to ocean. Instead the anthropogenic CO_2 flux from GOBMs is estimated from the difference between a pre-industrial simulation and hindcast simulations spanning several decades up to the present.

Challenges

Despite a much greater number of fCO_2 measurements in the most recent decade compared to the two decades prior to the year 2000, the mean of GOBMs and the mean of products used in these estimates has diverged in recent years, such that they differed by approximately 0.3 GtC in 2023, roughly 10% of the global sink estimate. The spread of the individual models and data products is notably larger (i.e., >1 GtC in 2023) such that individual GOBM estimates overlap with individual data product results. Differences in global and regional estimates from various approaches could be related to a number of factors including data gaps, seasonal biases, biases in climate products used to estimate the observational fCO_2 flux and biases in the GOBM estimates. Recent studies also indicate that data gaps and gap-filling methodologies can also bias trends particularly in data sparse regions (Hauck et al. 2023). Furthermore, the mean annual river flux is largely unconstrained and significantly impacts global comparisons of observational products and GOBMs.

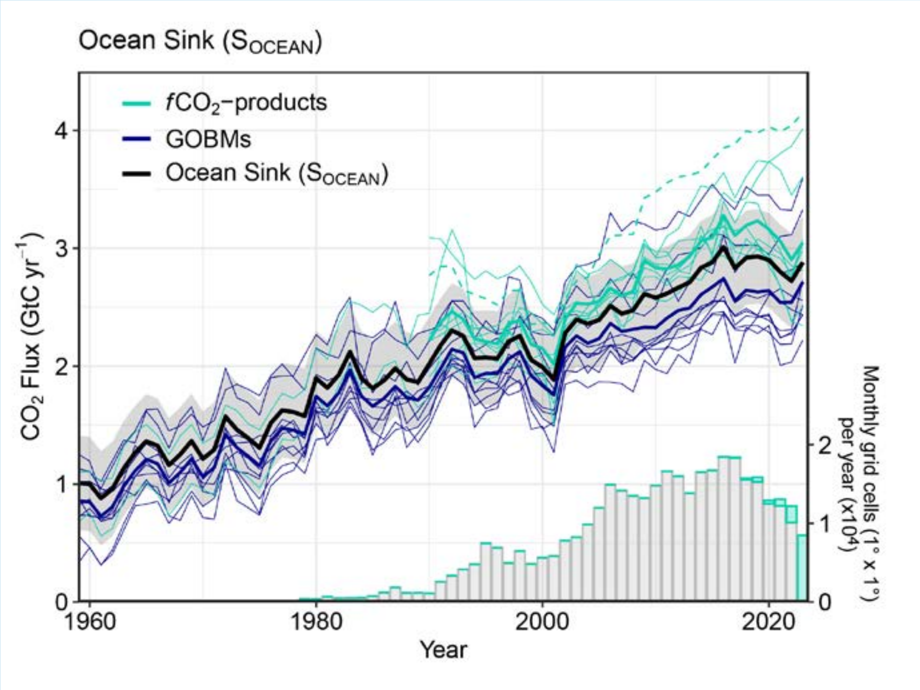


Figure 2: *Reproduced from Friedlingstein et al., 2024. The thick royal blue line represents the GOBM mean and the thick cyan line represents the* fCO_2 *product mean. Thin lines of either color represent individual GOBMs and products. Bar-plot in the lower right illustrates the number of monthly gridded values in the SOCAT v2024 database (Bakker et al., 2024). Grey bars indicate the number of grid cells in SOCAT v2023, and coloured bars indicate the newly added grid cells in v2024.*

Strategic Solutions

This Science Plan emphasizes research activities to determine where to sustain and routinely reassess the most effective positioning of existing and new fCO_2 observations made by ships and autonomous platforms (**objectives 1.1.1 – 3, 1.2.1, 1.2.3, 1.3.1**) to estimate and reduce uncertainties in all elements of the fCO_2 measurement approach (e.g., Ford et al. 2024). Assuming that regions with sparse observations contribute disproportionately to the differences between GOBMs and products (Hauck et al. 2023), filling observational gaps is an important first step to constrain uncertainty. Another important activity is to continue to investigate the river flux estimate, including potential interannual variability in the flux of organic carbon via rivers which could impact both the overall magnitude of the discrepancy and the trend of the product estimates but not the GOBMs (**objective 1.2.4**). This is critical given that the current estimates of the river flux span a wide range (i.e., ~0.2 to 1 GtC yr^{-1}) and are equivalent to the magnitude of the divergence between the GOBM mean and the data product mean (e.g., Liu et al. 2024). Overall, focus should be given to both quantifying and reducing uncertainties in observation-based estimates as well as GOBMs and other models that assimilate observations (**research question 2.2**).

NOAA Oceanic and Atmospheric Research

NOAA's Oceanic and Atmospheric Research (OAR) line office, also known as NOAA Research, plays a central role in providing sustained ocean carbon observations. OAR's mission is to "Conduct research to understand and predict the Earth system; develop technology to improve NOAA science, service, and stewardship; and transition the results so they are useful to society" (OAR Strategy 2020-2026). The science conducted by OAR programs, laboratories, and cooperative institutes, in collaboration with other NOAA line offices, academic institutions, and federal agencies (NSF, DOE, NASA, USGS, EPA, etc.), is foundational to the core NOAA mission and is aligned with Congressional and NOAA priorities of "reducing impacts to extreme weather and water events, exploring and understanding the ocean and maximizing the sustainable economic contributions of the American blue economy, understanding the changing climate, and advancing innovation" (OAR Strategy 2020-2026).

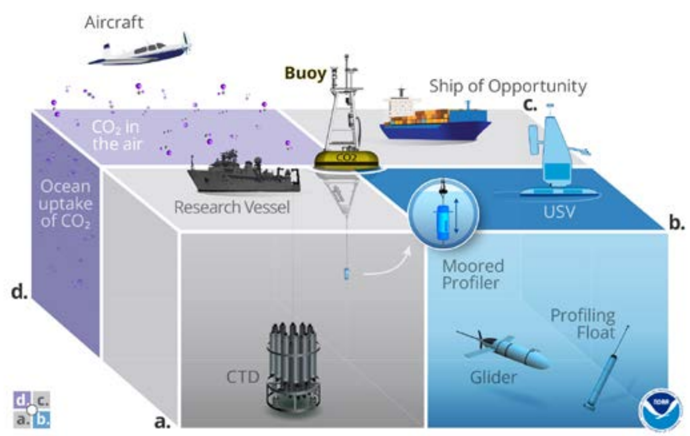


Figure 3: *OAR supports the use of **(a)** oceanographic platforms (CTD-equipped research vessels, profiler-equipped moored buoys), **(b)** autonomous platforms (gliders, floats, surface vehicles), **(c)** commercial ships of opportunity (SOOP), and **(d)** aircraft vertical profiles to collect ocean carbon and air-sea flux observations, which support global products, models, and projections. Modified from Sutton and Sabine 2023.*

In the United States, legislation and federal strategies define ocean carbon observing, research, and reporting as a high national priority (see Appendix B: Observing Directives). Key steps to achieve the goals outlined in relevant legislative and executive strategies include coordination and formalization of observing networks and synthesis projects, support for ship-board and autonomous observations, improved integration between observations and models, development of new and improved technologies, regional prioritization, and assessment of mitigation techniques.

In support of federal legislation and national and international priorities, OAR provides between 25-50% of global sustained carbon observations (parameter dependent) from the sea surface to the seafloor in the ocean (Feely et al. 2023; Kelly et al. 2025). Such observations are essential to determine how much carbon is absorbed from the atmosphere and to understand the role the ocean plays in regulating global climate (**Figure 3**). Surface water CO_2 fugacity (fCO_2) measurements from research and commercial vessels, buoys, and other autonomous platforms can be used to determine the amount of atmospheric CO_2 absorbed by the ocean on seasonal scales. This information allows scientists to evaluate the variability in carbon exchange between the ocean and atmosphere to provide meaningful projections of future atmospheric CO_2 levels. Co-located sampling of at least two carbonate chemistry parameters (e.g., fCO_2, pH, total alkalinity [TA], dissolved inorganic carbon [DIC]), allows for documentation of changes in aquatic carbonate chemistry. Ocean interior carbon observations from research vessels, autonomous underwater platforms, stationary platforms, and discrete monitoring programs help to monitor changes in the storage and transport of CO_2 and the impacts of changing carbonate chemistry on marine ecosystem health, such as ocean acidification (OA; see Ocean Acidification callout box). Measurements of atmospheric CO_2 and O_2 provide critical constraints on the global ocean sink (see Ocean Constraints callout box). In addition, OAR airborne CO_2 measurements have been shown to provide robust top-down constraints on regional-scale air-sea exchange (Long et al., 2021; Jin et al. 2024).

The other 50-75% of global ocean carbon observations are made by other U.S. agencies, research institutions, academic scientists, and international observationalists. While OAR collects ocean carbon samples in almost every ocean basin, the Tropical Pacific, Tropical Atlantic, North Pacific, and North Atlantic are the most well sampled regions (Kelly et al. 2025). Other U.S. agencies fill critical observing gaps in some of these regions under-observed by OAR, yet southern hemisphere oceans (South Pacific, South Atlantic, and Southern Ocean) and the Indian Ocean are relatively undersampled by both OAR and other U.S. agencies. Furthermore, for all ocean basins, the deep ocean (below 2,000 m) remains undersampled due to technological limitations. As laid out in this Science Plan, OAR will work with our intra- and interagency partners to fill observing gaps and work towards strategically sampling the global ocean by leveraging strengths of each agency.

TAO Mooring. Credit: NOAA PMEL

Science Plan Design

Motivation, Aim, and Scope

The motivation behind the development of this **NOAA OAR Ocean Carbon Observing Science Plan** is the vital need to observe and monitor our changing ocean. These critically important observations form the foundation of the ocean carbon value chain, from which a broad range of societally relevant products and assessments that inform decision makers are built (**Figure 4**). Given increasing national and international global carbon observing directives, there is also a strong need for increased communication of OAR carbon observing priorities and activities.

The aim of this Science Plan is to outline OAR's goals related to ocean carbon observing, set priorities, and provide coordination across OAR and with intra-agency, interagency, and international partners. The scope of this plan covers all OAR-supported observations and modeled estimates of ocean carbon uptake, transport, and storage, including *in situ* aquatic and air-sea carbon flux measurements. A strategic approach is necessary to meet these needs, address societal challenges, monitor and predict the global carbon cycle, and thereby provide critical information to end users and decision makers.

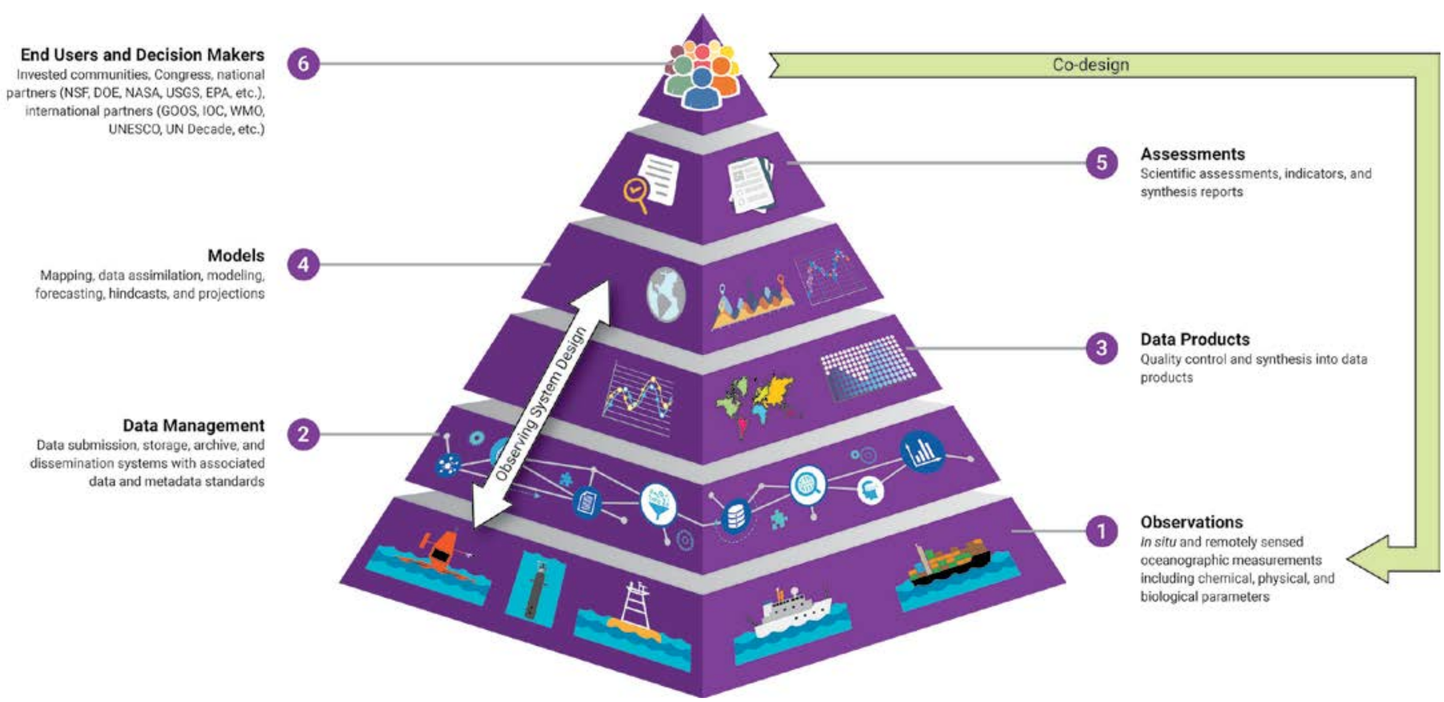
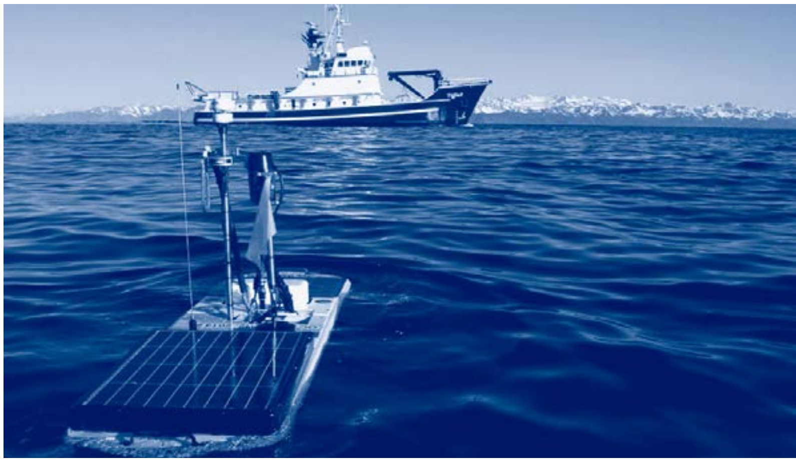


Figure 4: *The ocean carbon value chain where both ocean carbon observations and data management support products, models, assessments, and, ultimately, end users and decision makers. In turn, the upper levels of the pyramid inform, improve, and amplify the impact of observations through observing system design and community co-design of observational objectives. Goal 1 of this Science Plan addresses level 1 of the pyramid, goal 2 addresses levels 2-5, and goal 3 addresses level 6. Modified from Bakker and Guidi et al. 2020.*

Vision and Strategic Scientific Approach

NOAA OAR Ocean Carbon Observing Science Plan provides a vision to advance carbon cycle science, improve ocean models and products, provide useful and societally relevant information, and develop human capacity to drive innovation. The three goals outlined here represent the highest priorities for ocean carbon observing that OAR will seek to achieve over the next 10 years. Reflecting OAR's research-centered mission, each goal is separated into research questions that have been developed by OAR's subject matter experts, partners, and collaborators. Research questions are ordered based on scientific priority. The objectives, nested under each research question, are the steps required for OAR to achieve its goals and answer these questions. Specific suggested actions related to each objective are provided in Appendix A: Roadmap. The objectives are prioritized in terms of estimated timeframe, order of operations, and scientific urgency in the Prioritization, Timeline, and Long-Term Vision section of this document. It is important to note that successful completion or significant progress towards each goal and objective in this plan is dependent on the availability of both personnel and financial resources (see Resource Requirements). Finally, this Science Plan will be reviewed, revised, and updated at the mid-cycle (five year) time point to ensure alignment with the latest cutting edge ocean carbon cycle science and associated scientific priorities.



Autonomous glider with sensors. Credit: Evans Wiley, NOAA

Goal 1: Observe Changes in the Ocean Carbon Cycle	Goal 2: Enhance Ocean Carbon Data Management, Models, and Services for Society	Goal 3: Expand Ocean Carbon Opportunities and Community Engagement
Quantify the ocean's role in the global carbon cycle by assessing carbon reservoirs, sources, and sinks from the surface to the seafloor and by filling critical observation and knowledge gaps.	Serve as a trustworthy source of ocean carbon data, models, products, and information by improving ocean carbon data management practices, refining ocean carbon cycle models, and increasing the utility and timeliness of related products and services for society.	Collaborate with the global community to advance ocean carbon observing, develop human capacity to drive innovative science that is relevant to society, support outreach to external communities, and foster ocean literacy.

Related Strategic Priorities

This Science Plan exists in a complex ecosystem of agency, national, and international strategic, research, science, and implementation plans that include ocean carbon observations and research (**Figure 5**). This plan identifies scientific foci for OAR's contributions to achieving the goals and objectives of existing strategies and plans. In particular, the recommendations herein will allow OAR to meet its Mission and the goals of the OAR Strategy 2020-2026, including, (1) Explore the Marine Environment, (2) Detect Changes in the Ocean and Atmosphere, (3) Make Forecasts Better, and (4) Drive Innovative Science.

Overall, this plan represents the bottom-up priorities and urgent needs of the scientific community and is informed by top-down priorities in national and international carbon observing strategic documents. Improved engagement and co-development across OAR will advance OAR's position as a global leader in providing ocean, coastal and Great Lakes carbon observations, data, models, products, and services to the nation and the world.

NOAA Ship Bell Shimada. Credit: Stephen de Blois, NOAA NMFS/WCR

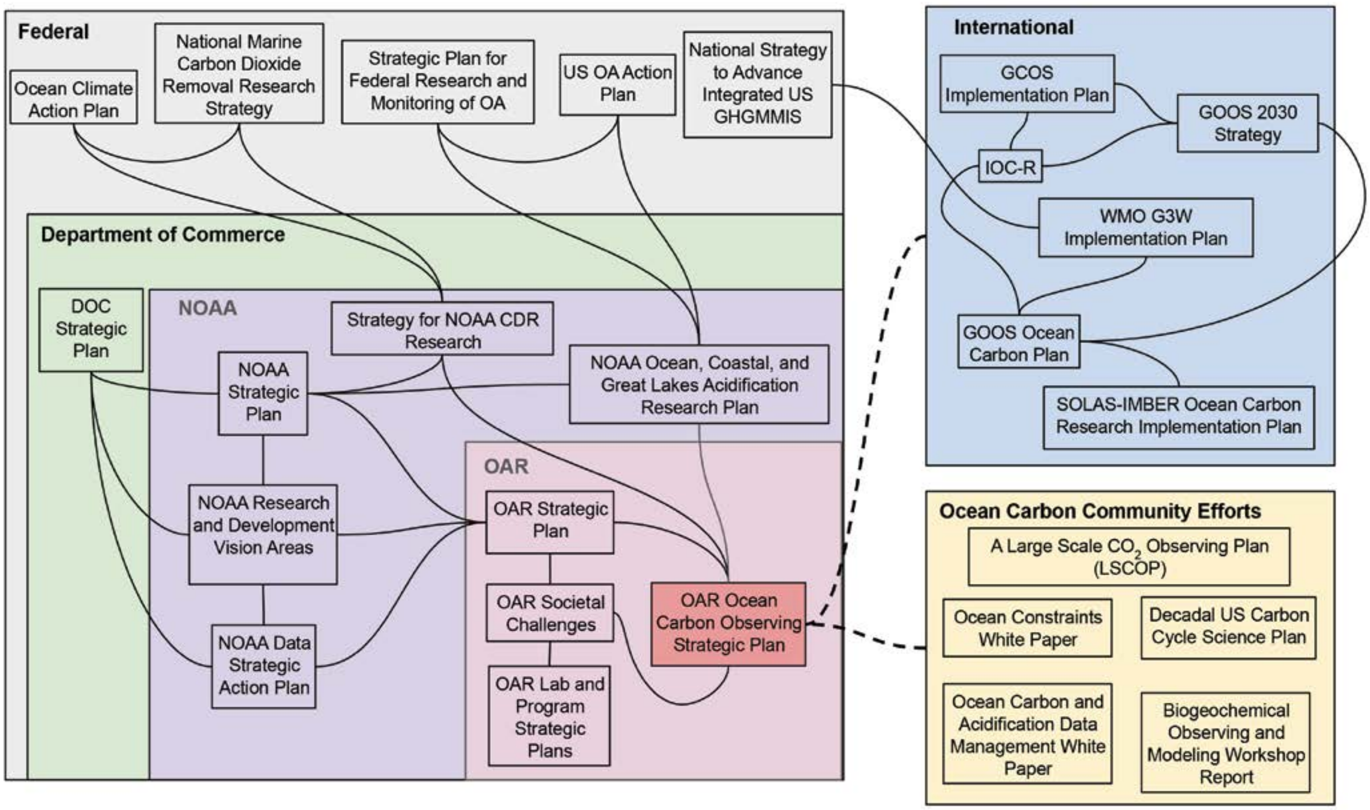


Figure 5: *National, international, and community-level strategic documents that address ocean carbon observing. Lines connect plans that inform or reference each other. Dashed lines connect groups of international or community plans to the NOAA OAR Ocean Carbon Observing Science Plan.*

Observing System Design

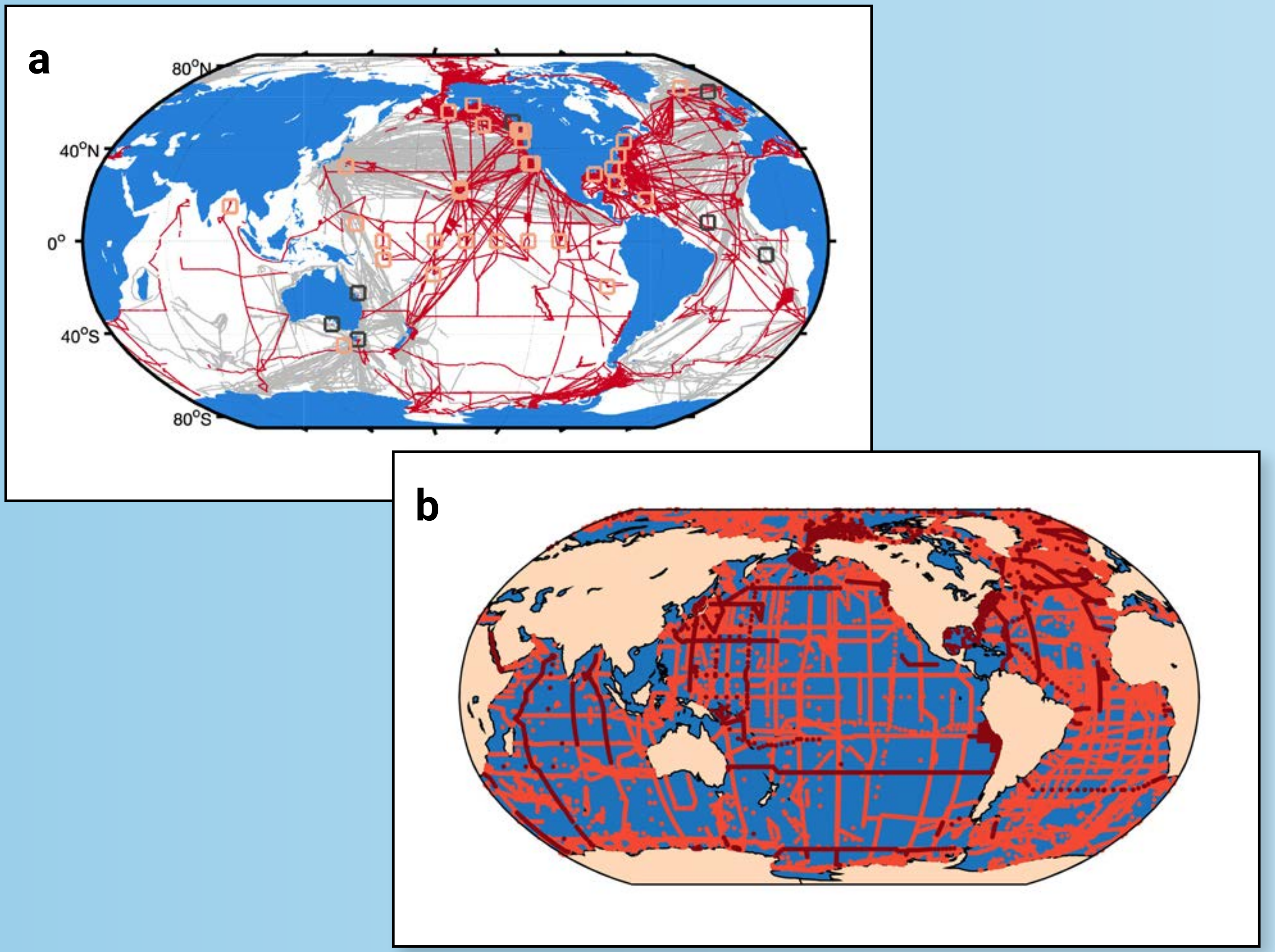


***Figure 6**: **(a)** Map of the SOCAT version 2023 surface ocean fCO_2 observations from 2010 to 2022. Lines represent ships of opportunity, USVs, and GO-SHIP cruises (NOAA-led lines in dark red and non-NOAA in light gray). Squares represent moored buoys (NOAA-led buoys in light red and non-NOAA in dark gray). **(b)** Map of GLODAP version 2024 cruise observations in the global oceans from 1989 through 2023. Each line represents a suite of surface-to-bottom stations along the transect. Dark red lines represent observations newly added to GLODAPv2.2023 (Lauvset et al. 2024). Both maps show certain regions of the globe are under-observed (Southern Hemisphere Oceans and the Indian Ocean) while others are only observed seasonally (Arctic and Antarctic). Note large lake systems, such as the Great Lakes are not represented and available data are seasonally biased and spatially and temporally sparse.*

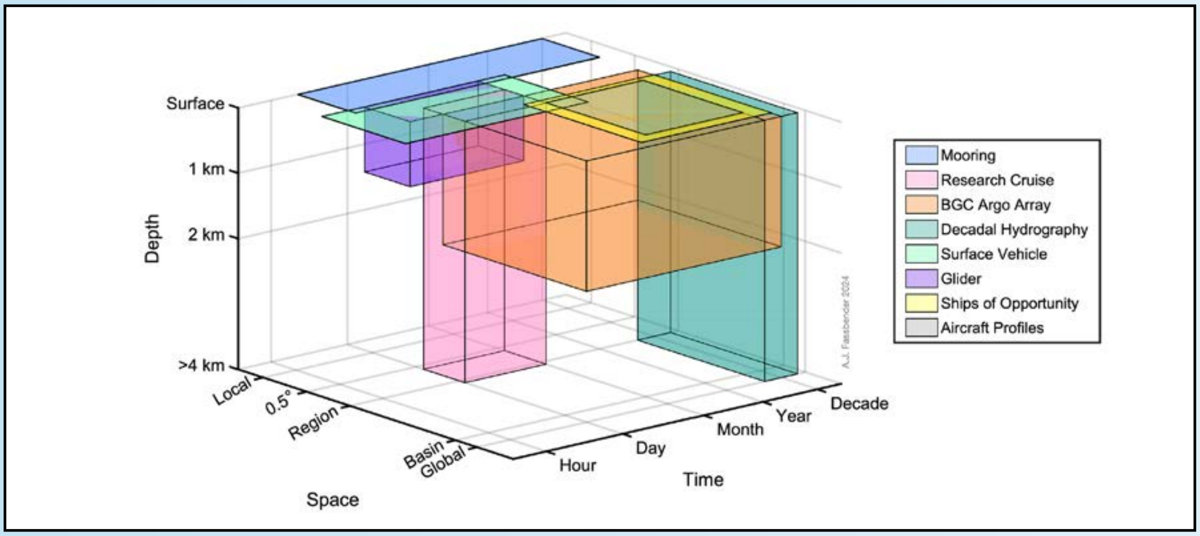


Figure 6c: *Schematic diagram illustrating the spatial, temporal, and depth scales at which ocean observing platforms provide carbon observations (Credit: Andrea Fassbender).*

Challenges

The global ocean carbon observing system is composed of largely independent networks (e.g., GO-SHIP, OneArgo [including BGC-Argo], NOAA-ON, SOCONET, etc.; Kelly et al. 2025), as well as research-driven scientific and infrastructure projects that feed into data synthesis products, repositories, and archives (e.g., SOCAT, SOCCOM, GO-BGC, GLODAP, CODAP-NA, OCADS, etc.). Each network faces design challenges in terms of balancing the spatial or temporal frequency of observation versus measurement quality given their unique set of observing platforms and requirements related to their core, often unique, mission (**Figure 6a-c**). This challenge has led to an ocean carbon observing system that is often sparse and both seasonally and spatially biased.

Strategic Solutions

This Science Plan recommends three key actions to improve the observing system of ocean carbon networks. First, OAR should sustain and strengthen support for its contributions to existing global ocean observations across relevant observing networks (**research questions 1.1, 1.2**). Second, OAR intends to strengthen support for co-design and use of model-based and statistical approaches and experiments (e.g., OSE, OSSE, ensembles, Bayesian, data assimilation, etc.) to evaluate and compare simulated observation networks. These reconstruction experiments can be used to propose optimal sampling strategies, allowing acquisition of the requisite data to monitor and forecast ocean carbon system dynamics across time scales and applications while minimizing costs (**objectives 1.1.3, 1.1.5, 1.2.1, 1.2.2, 1.2.4**). Third, OAR plans to support strategic workshops to connect the leadership of the ocean observing networks with the observing system design modeling community in order to ensure that model-based recommendations are incomparable and that observing system design is fit for purpose (**objectives 3.1.3, 3.1.4**).

Credit: Adobe Stock

SCIENCE PLAN

Goal 1: Observe Changes in the Ocean Carbon Cycle

Quantify the ocean's role in the global carbon cycle by assessing carbon reservoirs, sources, and sinks from the surface to the seafloor and by filling critical observation and knowledge gaps.

NOAA OAR observations and models contribute greatly to our understanding of the global ocean carbon cycle. Sustained climate-quality observations and model comparisons (see Goal 2) provide critical insights on how carbon reservoirs and fluxes change with time, though key uncertainties remain. Improving estimates of the changing ocean carbon sink and long-term uptake trends will enhance our understanding of other key aspects of the global carbon cycle, including terrestrial sources and sinks of carbon with respect to the atmosphere. While Goal 1 focuses on improving the observational component of global carbon cycle estimates, Goal 2 addresses the modeling component.

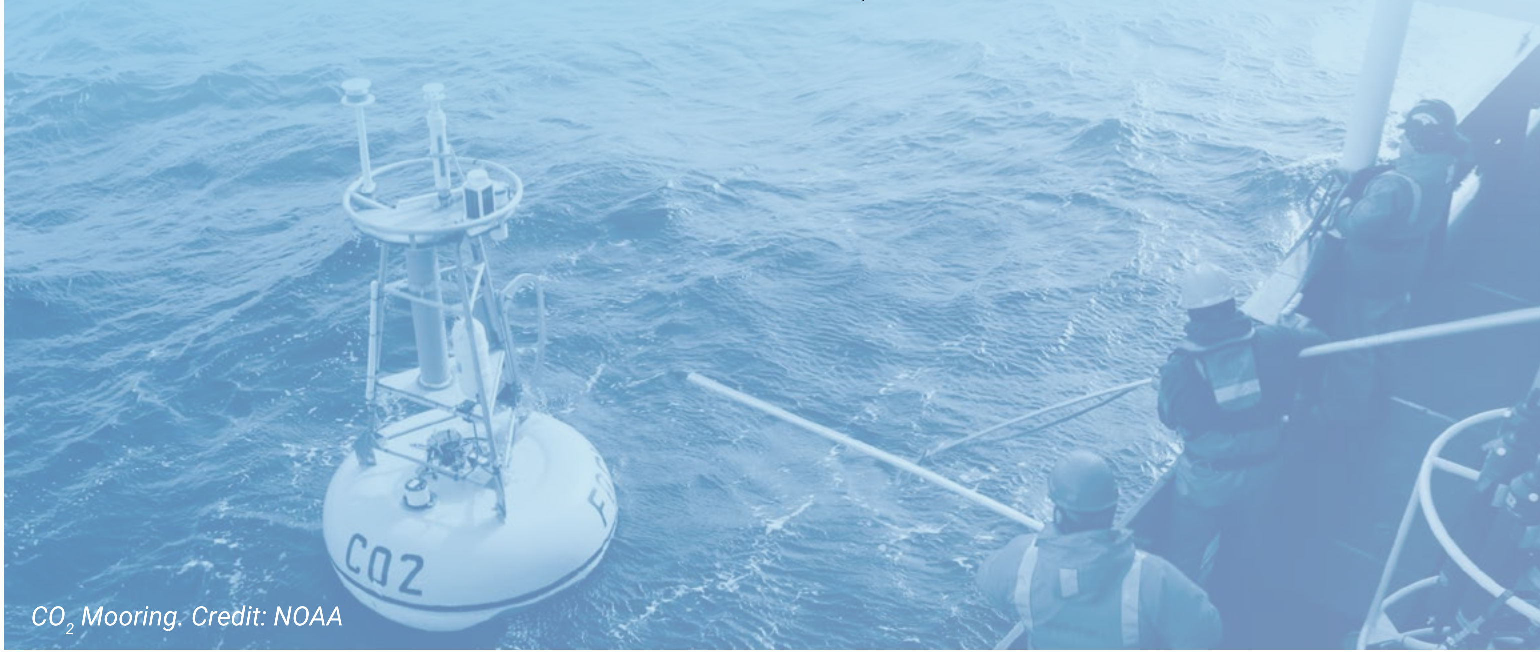
Through the objectives outlined in this goal, OAR aims to sustain and strengthen the existing global ocean, coastal, and Great Lakes observations. This includes and prioritizes maintaining support for the existing observing networks, including planned cruises, moored buoys, and autonomous surface and subsurface platforms (such as uncrewed surface vehicles, profiling floats, and underwater gliders). In addition, this plan recommends comprehensive studies of the optimal spatiotemporal distribution of current and potential observational activities and assets to inform future observing system design (see Observing System Design callout box). The overarching aim of these activities is to reduce uncertainties, particularly those due to spatiotemporal and knowledge gaps, in estimates of the ocean sources and sinks of carbon to improve our understanding of how climate change influences their long-term evolution.

Ocean Constraints and Atmospheric O_2 / N_2 Observations

Introduction

A fundamental question in observing the global carbon cycle is how well we can quantify inventories for and fluxes between the atmospheric, terrestrial, and oceanic reservoirs (**Figure 1**) to determine how anthropogenic CO_2 moves through the earth system. The quantification of the anthropogenic CO_2 flux between the atmosphere and ocean is termed the global ocean carbon constraint, which enables both better understanding of regional ocean carbon cycling as well as global carbon fluxes between the atmospheric and terrestrial reservoirs. Additionally, policy-relevant carbon budgets (e.g., the Global Carbon Budget) require assessing anthropogenic perturbations relative to natural baselines, which require these global-scale estimates.

There are several largely independent methods to determine the fluxes between the atmosphere and ocean (**Table 1**). These methods are particularly powerful for defining the role of the ocean in modulating atmospheric CO_2 rise due to fossil fuel combustion. Here, we focus on the atmospheric O_2/N_2 approach (**Figure 7**) that is based on measurements of the long-term trends in atmospheric CO_2 and O_2, and exploits the distinct O_2/CO_2 exchange ratios for fossil fuel, ocean sink, and land sink components (Keeling and Shertz 1992; Keeling and Manning 2014). This approach provides an important anchor point for long-term global constraints. The ocean carbon sink derived from it has been used to adjust results from GOBMs in previous IPCC reports to a common baseline (Watson et al. 2001).



CO_2 Mooring. Credit: NOAA

***Table 1**: Observation-based ocean constraint approaches including the atmospheric O_2/N_2 method. See DeVries et al. (2023) for a more comprehensive description of each approach and the component fluxes.*

Constraint	Advantages	Disadvantages
fCO_2 products	Based on seawater fCO_2 observations and captures all flux components	99% machine-generated data and highly sensitive to air-sea gas exchange parameterizations
Atmospheric O_2/N_2	Direct measure of the ocean sink (S_{ocean})	Interannual variability and other drivers of O_2 sea-air flux make short term assessments difficult
Atmospheric inverse models and airborne profiles	Direct measurement of the impact of net flux of CO_2 across the sea-air interface on atmospheric gradients	Few measurements directly over the ocean and biases due to land processes
Ocean interior carbon measurements (e.g. eMLR-C*)	Integrated assessment of the ocean sink (S_{ocean})	Decadal scale changes

Challenges

O_2/N_2 estimates rely on an atmospheric network of exacting observations requiring an accuracy two to three orders of magnitude greater than corresponding CO_2 observations. To date, the method has largely been used for decadal global ocean constraints. These scales can be decreased to basin and biannual resolution with a denser atmospheric network and improved atmospheric transport models. Moreover, the uncertainty in the results based on O_2/N_2 measurements can be decreased with more measurements. Additionally, better quantification of natural O_2 fluxes and ocean deoxygenation on interannual and decadal timescales is needed to improve the ocean sink estimates from O_2/N_2. This work is already underway through BGC-Argo and GO-SHIP.

Strategic Solutions

The global atmospheric O_2/N_2 network is largely in place, but its sustainability and needed augmentation for reduced uncertainty are under threat. Only a few laboratories have skilled personnel to routinely make the measurements, and a new model for sustained support is needed (**objective 1.1.1**). O_2/N_2 measurements can be expanded and incorporated into established observational networks, such as SOCONET (**objective 1.1.4**). Observing system analyses focused on how to expand the scope of the atmospheric O_2/N_2 network and expected returns with respect to increased resolution of time and space scales are warranted (**objective 1.1.3**). To address the correction of the O_2/N_2 measurement to account for ocean deoxygenation, ongoing efforts in studying the ocean O_2 cycle should include efforts dedicated to this correction (**objective 1.2.3**).

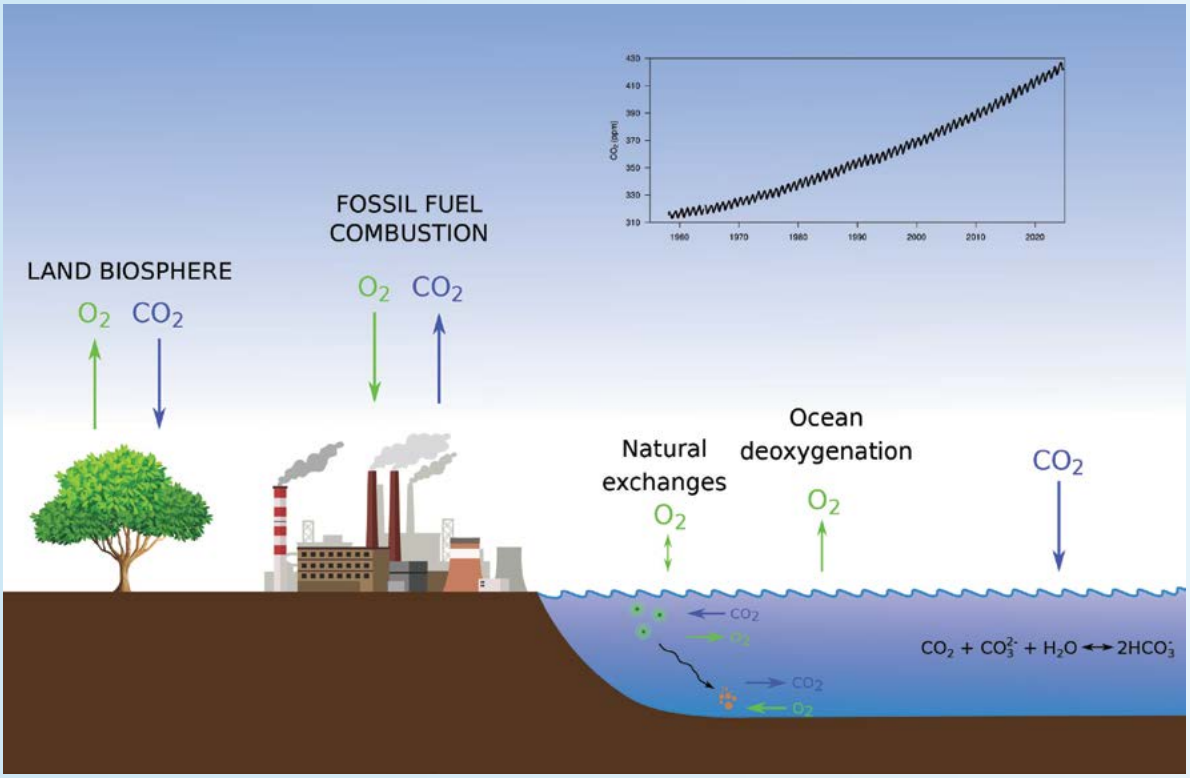


Figure 7*: Diagram of the major fluxes of O_2 and their coupling to CO_2 as used to determine the ocean carbon sink. Fossil-fuel burning and the land sink for CO_2 are tightly coupled to O_2 fluxes in well-known proportions. In contrast, the ocean sink for CO_2 is driven by inorganic reactions in seawater, with no impact on O_2. Atmospheric O_2 is however also influenced by natural exchanges of O_2 across the air-sea interface, as well as by long-term ocean O_2 outgassing, tied to ocean deoxygenation from warming and circulation changes. The O_2/N_2 method uses measurements of the global trends in O_2 and CO_2. Prior estimates of fossil and ocean O_2 components to simultaneously quantify the ocean and land carbon sinks are required to balance both the O_2 and CO_2 budgets.*

Research question 1.1: What actions are needed to better quantify and reduce spatiotemporal sources of uncertainty in estimates of the ocean carbon cycle?

The existing ocean carbon network of cruises, moored buoys, profiling floats, and uncrewed systems is critical to estimate the global ocean carbon cycle and thus needs to be maintained and enhanced. At present, ocean carbon observing assets are often deployed on an opportunistic basis such that major temporal and spatial gaps still exist over large expanses of the global ocean, particularly those regions and seasons that are seldom visited by research or commercial activities, or in the deep ocean, which requires time- and resource-intensive research cruises (see Observing System Design callout box). Gaps exist in the oceans of the global south; the Indian, and Arctic Oceans; and temporally in the winter at mid and high latitudes when ice and rough seas make observations challenging (Kelly et al. 2025). Furthermore, many regional and global carbon budgets have systematically excluded the Great Lakes due to observational sparseness relative to their spatial and temporal heterogeneity (Cavarallaro et al. 2018). These spatiotemporal gaps introduce significant uncertainty into estimates of the ocean carbon cycle and budget. Furthermore, monitored regions that are also highly dynamic, such as the North Atlantic and Tropical Pacific, may require observing system redesign and/or augmentation. The objectives in this question lay out an ordered and collaborative process for augmenting observing assets where they are needed most and promoting an efficient observing system design to reduce uncertainty related to undersampling. In completing these actions, collaboration and co-design should occur iteratively between observationalists, modelers, and end users (see Goal 3).

- **Objective 1.1.1:** Continue to maintain the present ocean carbon observing assets to provide continuity with past measurements and answer critical questions regarding the ocean carbon cycle.
- **Objective 1.1.2**: Identify and quantify primary sources of uncertainty in observations of carbon Essential Ocean Variables/Essential Climate Variables (EOVs/ECVs) and estimations of the ocean carbon cycle.
- **Objective 1.1.3:** Make use of model-based and statistical approaches and experiments to determine optimal sampling strategies and where observational augmentation would be most valuable.
- **Objective 1.1.4:** Expand observations where needed and promote efficiencies to the existing observing system to improve the quantification of carbon cycling throughout the water column, both nearshore and offshore, as well as fluxes at the sea surface.
- **Objective 1.1.5:** Improve quantification of the global ocean carbon cycle by continuously updating estimates using a variety and evolving combination of approaches.

Research question 1.2: How can OAR work towards filling current knowledge gaps that prohibit fully constraining the ocean carbon cycle?

Scientific gaps in our understanding of certain ocean processes impact our estimates of the global carbon cycle and budget, introducing additional uncertainties in these estimates often through simplified parameterizations of poorly understood or complex ocean processes. For instance, ocean circulation is a key driver of ocean carbon distribution and flux, yet knowledge gaps about ocean circulation, and in particular changes thereof, remain. Other ocean carbon cycle related knowledge gaps include interactions between freshwater, terrestrial, coastal zone, and open ocean systems; microbial carbon transformations; the biological carbon pump (see Biological Carbon Pump callout box); and how climate change impacts all of the above (see Ocean Acidification callout box). The objectives within this question address making progress towards filling these critical yet outstanding scientific knowledge gaps regarding ocean carbon. This will require collaborations among biological, chemical, and physical oceanographers.

- **Objective 1.2.1:** Improve knowledge of ocean circulation and air-sea CO_2 flux to reduce uncertainty in ocean carbon model parameterizations.
- **Objective 1.2.2:** Use observations to research biological carbon transformations and fluxes towards better understanding and constraining the biological component of the ocean carbon cycle.
- **Objective 1.2.3:** Study how climate change interacts with the ocean carbon cycle to determine long-term change and to parse out impacts and interactions between natural variability and anthropogenic change.
- **Objective 1.2.4:** Study how large freshwater systems such as the Great Lakes, submarine groundwater discharge, and riverine-to-ocean inputs affect global carbon dynamics.

Research question 1.3: What new platforms, sensors, and/or technological improvements to OAR's observing assets are needed to monitor trends in the ocean carbon cycle?

Technological challenges currently restrict our ability to sample ocean, coastal, and Great Lakes carbon, resulting in undersampling of certain ocean regions, depths (deep ocean), seasons (e.g., winter), and conditions (e.g., storms). Regional environmental conditions limit many of the currently available technologies from being used universally (i.e. between marine and freshwater systems). Challenges also exist at the intersection between the private sector and government, particularly regarding the need for industry production of economical sensors that meet research needs, as well as supply chain issues for federally-supported observations.

The objectives in this question focus on collaborative development of new and improved technology to fill these critical observing gaps.

- **Objective 1.3.1:** Identify and develop new and improved technologies (e.g., sensors, platforms, supersites, etc.) and technological advancements necessary to detect changes in the global carbon cycle.
- **Objective 1.3.2:** Strengthen public-private partnerships and support dialogues with industry that are mutually beneficial for the transition and development of new technologies.
- **Objective 1.3.3:** Contribute to the development standard procedures for intercomparison studies of sensors, systems, and measurements from different platforms in collaboration with national and international partners.

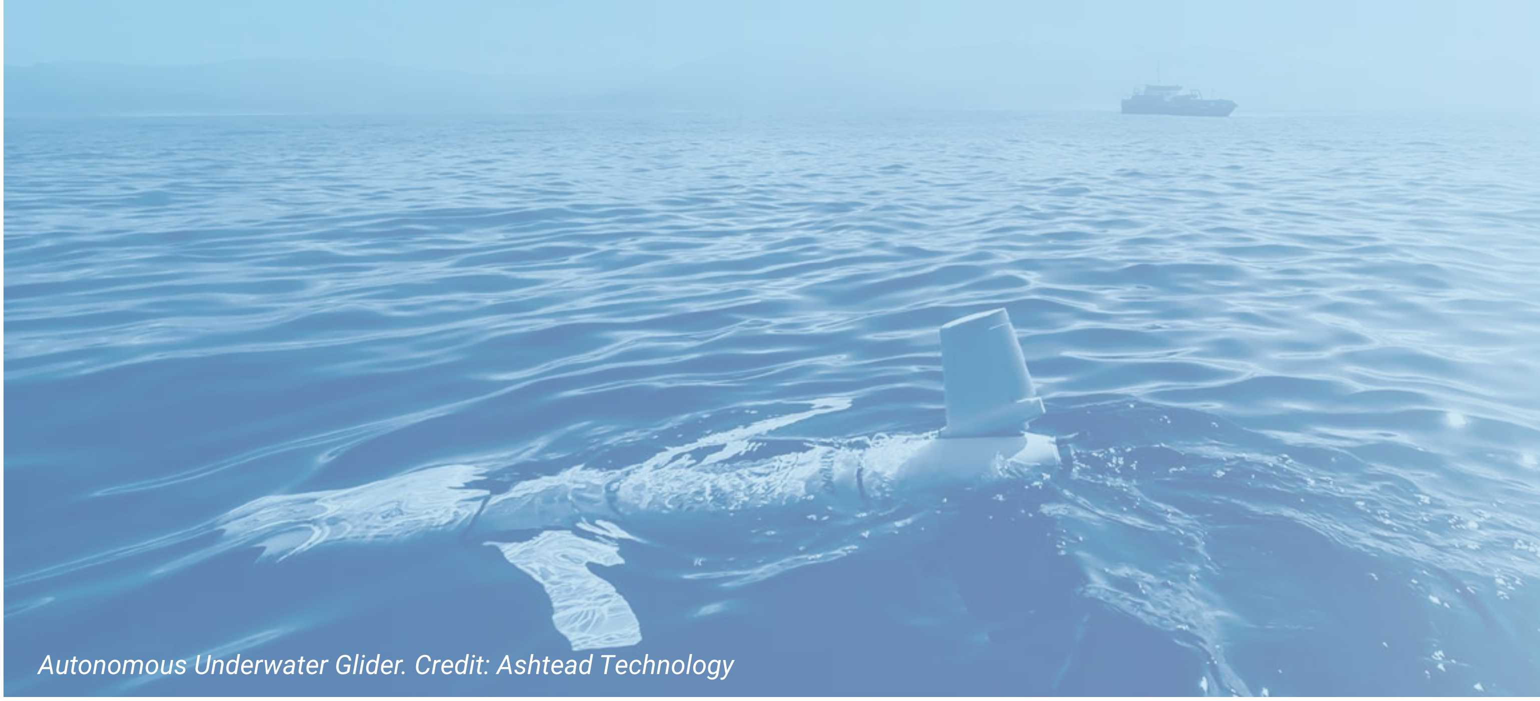
Ocean Acidification

Introduction

Ocean Acidification (OA) is caused by oceanic uptake of anthropogenic carbon dioxide from the atmosphere and is compounded by ocean processes, such as biological activity and physical ocean changes (Feely et al., 2008, 2024; Doney et al., 2009 a and b, 2020). The same chemical and biological processes influence freshwater acidification and, here, are considered part of the OA challenge. OA presents most prominently as a global feature through declines in surface ocean pH and carbonate saturation states, which are expected to continue into the future (IPCC, 2019; Jiang et al., 2019; Feely et al. 2023). Though OA is a global phenomenon, local conditions vary due to spatial, biological, and oceanographic drivers, creating complexities in predicting conditions and determining socioeconomic implications of coastal ecosystem changes. Notably, studies show that OA signals are amplified in subsurface waters below the euphotic zone, a region that is economically important for many marine fisheries (Cai et al. 2011; Feely et al. 2018; Arroyo et al. 2022; Fassbender et al. 2023; Müller and Gruber, 2024). Thus, OA observing presents distinct challenges that need to be addressed with the ocean carbon observing system.

Challenges

While many global ocean carbon observing platforms provide information relevant to OA research, there is further interest in capturing the impacts of acidification on ecosystems and human communities resulting from the physical and chemical changes. Consequently, OA observing systems should target ecologically relevant areas, such as continental shelves and



Autonomous Underwater Glider. Credit: Ashtead Technology fisheries hotspots, and include biogeochemical and biological parameters in order to provide information relevant to coastal managers and researchers.

Monitoring biologically relevant parameters requires consistently measuring two of the four carbonate system parameters (Figure 8a; pH, TA, DIC, or fCO_2) to fully resolve the system and estimate saturation states. Finally, technology for measuring these parameters is evolving. At the same time, perennial difficulties exist concerning stable sensor production to enable long-term access to quality sensors.

Strategic Solutions

Efforts to augment existing ocean observing platforms with additional carbonate system sensors (Figure 8 b-d) can ensure OA is being observed in tandem with other variables needed to fully resolve carbonate system changes and ecosystem responses. In particular, co-location of chemical and biological parameters enhance our collective understanding of OA impacts when coupled with biogeochemical and ecological models (**objectives 2.1.2, 2.3.3**).

Co-development of observing systems with data users will ensure increased impact and utility of these networks (**objectives 3.1.2, 3.1.3**). Cooperative efforts to identify the needed OA data products will help inform observing system design from the outset. These systems may include "weather-quality" sensors (sensors accurate enough to identify short-term variations and local patterns) and affordable system design.

Continued investment in ocean carbon observing technology tailored to coastal ecosystems is imperative to improve OA observing capabilities (**objectives 1.3.1, 1.3.2**). The development of accurate, precise, and stable sensors for surface and subsurface platforms (Figure 8 b-d; buoys, ships, and autonomous platforms) will ensure carbon parameter changes can be discerned at the temporal resolution desired by end users (**Figure 8 e-g; objectives 1.3.1, 1.3.2**). One way in which OAR plans to support a steady supply of sensors will be by enhancing public-private partnerships to transfer sensors developed in academic or federal research laboratories to private industry for long-term production and sale to the community (**objectives 1.3.2, 3.1.5**).

Changes in coastal zone carbonate systems typically occur on timescales of hours to seasons, making long-term, incremental OA changes more difficult to discern. Detection of these large, high-frequency variations can be captured with lower-quality and lower-cost sensors that are more affordable compared to the higher-quality, more expensive sensors necessary to resolve climate signals in open ocean and coastal regions (Carter et al. 2019; **objectives 1.1.3, 1.3.2, 2.2.2**). Pairing these "weather-quality" measurements with "climate-quality" carbon observing stations, which provide measurements precise enough to detect long-term change, strengthens the utilization of lower resolution sensors (Newton et al., 2015). Thus intertwining regional and global systems will act as a force multiplier for carbon observing overall.

a

pH

pH is a measure of theacidity of seawater based on how many free hydrogen ions (H^+) there are. Increasing levels of carbon dioxide (CO_2) in the ocean create more free H^+ ions, resulting in lower pH.

fCO_2

The seawater fugacity of carbon dioxide (fCO_2) is a measure of the amount of CO_2 in seawater. Seawater fCO_2 increases as atmospheric CO_2 levels rise and CO_2 is absorbed by the ocean.

DIC

Dissolved inorganic carbon (DIC) is a measurement of how much non-biological carbon is in seawater. Inorganic carbon includes carbon dioxide, bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}).

TA

Total alkalinity (TA) is a measure of the ocean's ability to buffer CO_2. It represents the concentration of HCO_3^-, CO_3^{2-}, and other ions in seawater that can neutralize H^+ ions created during acidification.

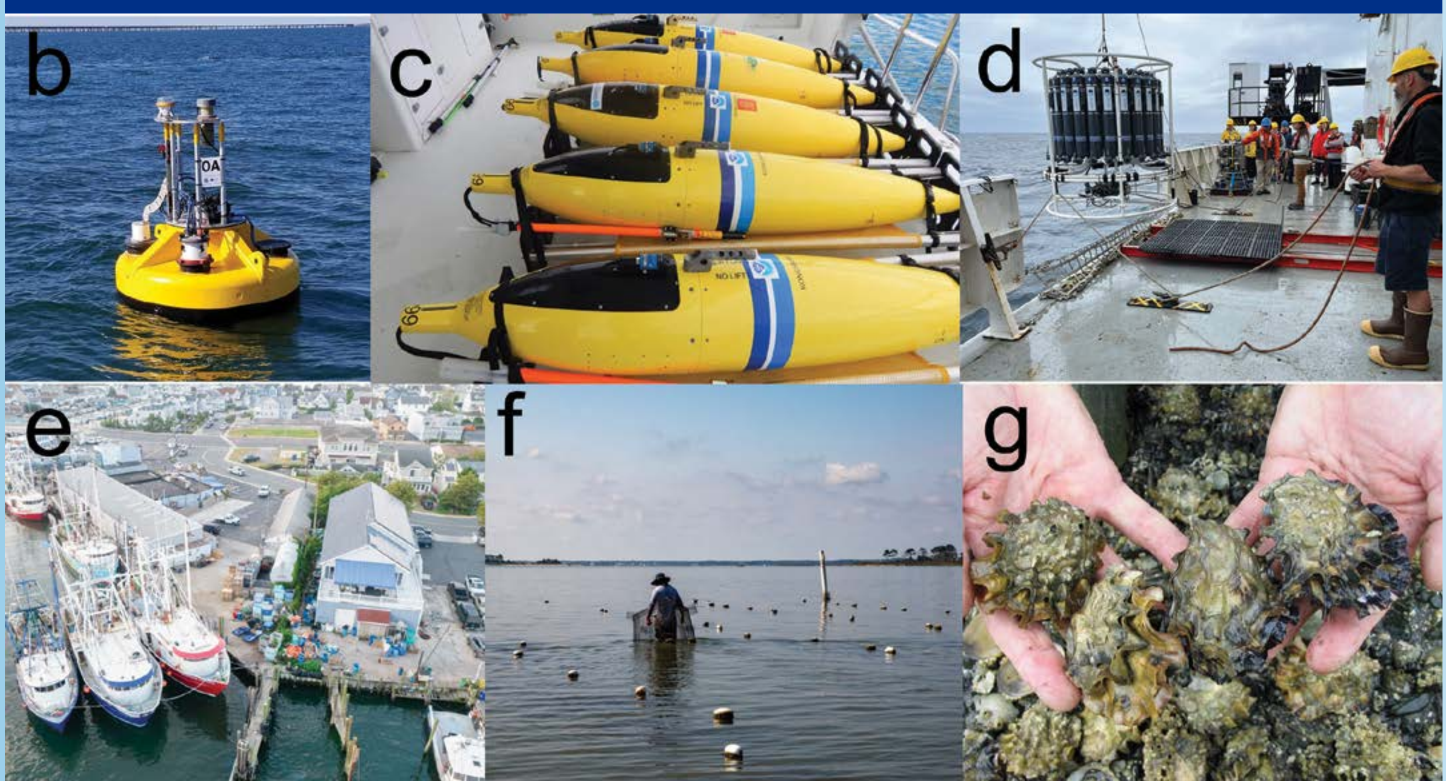


Image Credit: NOAA OAP

Figure 8 (left) *: Ocean acidification observing needs, tools, and impacted communities.* ***(a)*** *The four carbonate system parameters; measurement of at least two parameters is needed to fully resolve the carbonate system.* ***(b-d)*** *Platforms used to measure the four carbonate system parameters:* ***(b)*** *coastal ocean acidification buoy (credit: NOAA PMEL),* ***(c)*** *underwater buoyancy gliders (credit: NOAA AOML),* ***(d)*** *a package of oceanographic sensors and sampling equipment deployed from a research cruise (credit: NOAA OAP).* ***(e-g)*** *Coastal resources vulnerable to OA:* ***(e)*** *a coastal fishing port (credit: Mid-Atlantic Regional Council on the Ocean, MARCO),* ***(f)*** *a coral reef in the Pacific Remote Islands (credit: NOAA Fisheries), and* ***(g)*** *farmed oysters (credit: NOAA Fisheries).*

Biological Carbon Pump

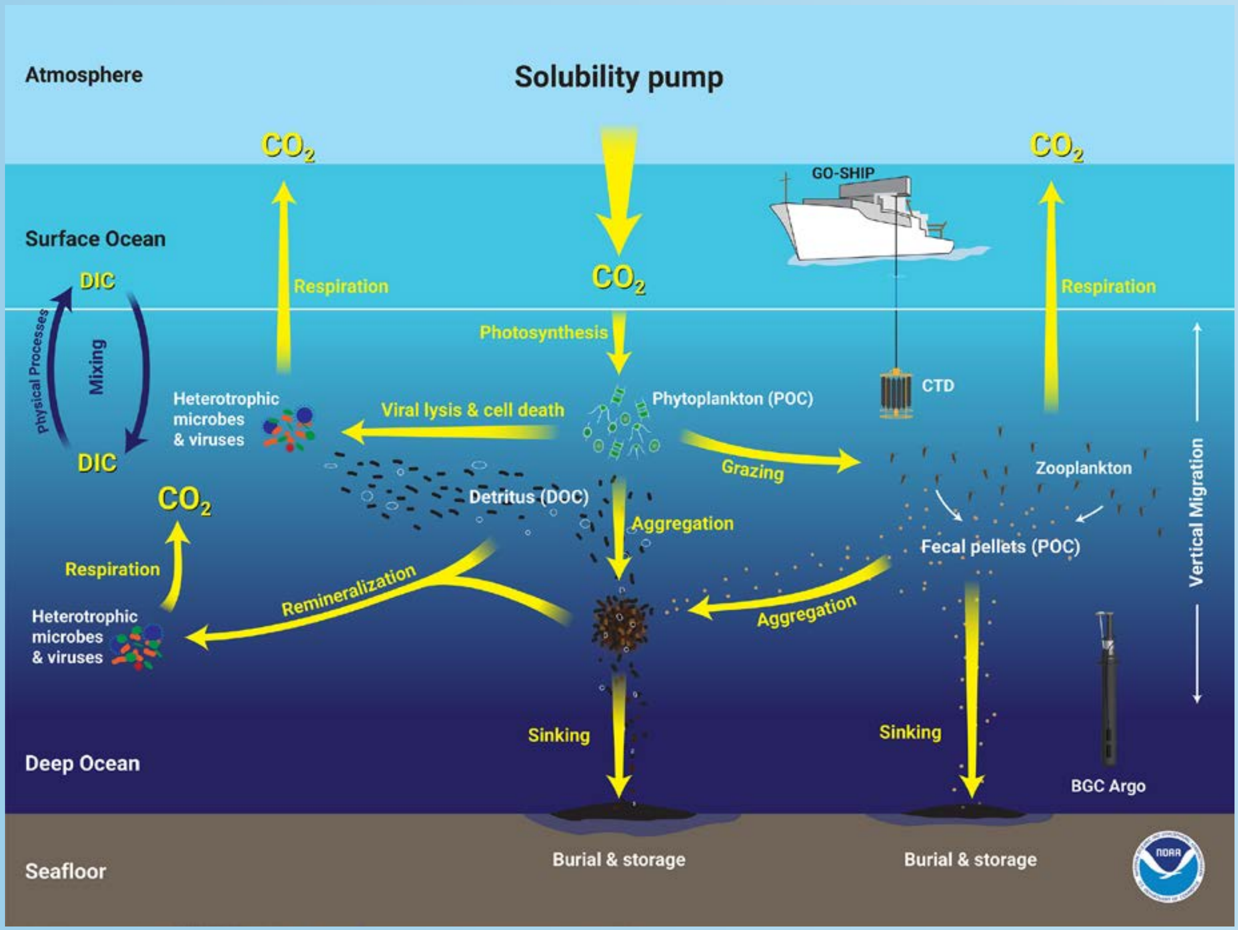


Figure 9: *Illustration of the biological carbon pump (BCP) and OAR observing technologies used to measure its components. Yellow arrows indicate the movement of carbon through the various biological processes, including export to the seafloor. Black arrows represent physical processes that impact both organic and inorganic carbon cycling. (Credit: Melissa Hiatt)*

Introduction

The Biological Carbon Pump (BCP) is a process that transports biologically produced organic and inorganic carbon from the surface to intermediate and deep waters of the ocean. While the soft-tissue component of the BCP refers to the movement of organic material though the water column, the inorganic carbonate component operates through the export of biogenic calcium carbonate particles from the surface and their dissolution at depth. Both components of the BCP play a key role in long-term carbon cycling, carbon storage, and regulation of atmospheric CO_2. (**Figure 9**). Biological carbon cycles on relatively rapid timescales (daily to seasonal) and plays an important role in controlling the vertical distribution of DIC, TA, pH, nutrients, and fCO_2 throughout the global oc eans. Phytoplankton take up DIC from the surface ocean during photosynthesis, producing particulate and dissolved organic carbon and lowering surface ocean fCO_2. When these cells die via grazing or other means, the organic material sinks (gravitational pump), or is transported (migration pump and mixing pump) to intermediate waters where much of it is remineralized, supporting mesopelagic and deep ecosystems and increasing DIC, nutrient concentrations, and fCO_2. Some organic material continues to deeper depths, with approximately 2-3 GtC yr^{-1} reaching the seafloor on average (Middleburg et al. 2019). Surface productivity is then sustained by the return of these remineralized nutrients, along with DIC, to the surface by physical processes. An efficient BCP depletes available nutrients in the surface ocean (lowering fCO_2) as soon as these remineralized nutrients are made available. Assessing and monitoring the BCP and its role in the ocean carbon cycle requires a complex accounting with multiple tracers and coordinated activities between biological, chemical, and physical observationalists and modelers.

Challenges

While the solubility pump is a primary driver of surface ocean carbon uptake at present, significant uncertainty remains in our understanding of how ocean circulation and biological changes may be impacting the ocean carbon sink magnitude and variability (Henson et al. 2022). Aside from biogeochemical and biological observations collected as part of NSF-funded ocean time series stations (e.g. BATS, HOT), ocean and coastal Long-term Ecological Research (LTER) sites, and measurements made by BGC-Argo profiling floats, and *in situ* campaign efforts by NASA (EXPORTS with NSF, PACE validation, etc.) sustained observations of the BCP are scarce. Regions such as the Indian Ocean, Southern Ocean, and North and South Pacific Oceans are undersampled with regard to key BCP measurement parameters, such as thorium-234 (^{234}Th; Ceballos-Romero et al. 2022; **Figure 10**). Additionally, depth thresholds for annual and multi-year export vary by region, resulting in the need for high resolution vertical sampling from the surface to the deep ocean. Temporally, primary productivity and export efficiency change on rapid timescales (days), dependent on phytoplankton community composition, mixed layer depth, grazing activity, food web structure, nutrient availability, physical oceanography dynamics (e.g., eddies), short term particle injection events, and other physical and biogeochemical oceanographic conditions (e.g., Boyd et al. 2019; Xing et al, 2020). Overall, spatiotemporal gaps impede our understanding of changes to the magnitude and efficiency of all components of the BCP and impact our ability to estimate the global carbon budget's sources and sinks and to predict future change. Improved observations of the BCP are necessary to gain a better understanding of its spatiotemporal variability and extend our understanding of BCP processes from decadal to longer time scales.

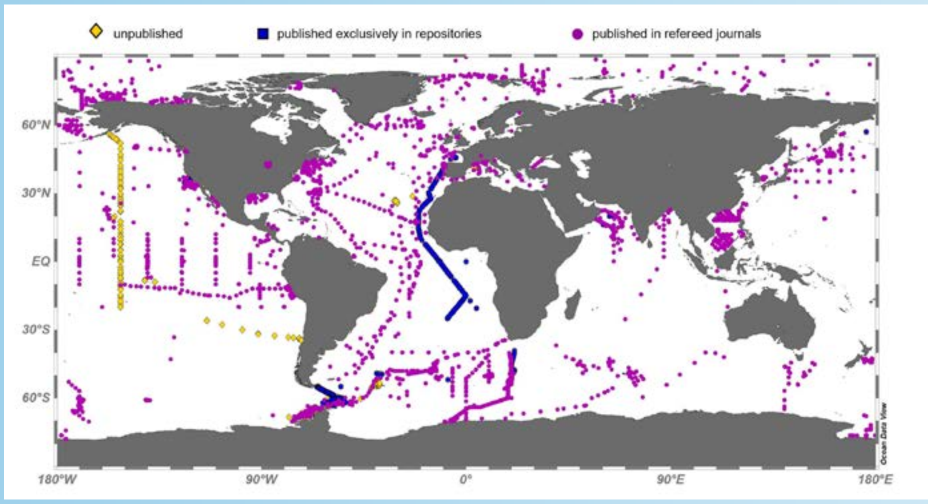


***Figure 10**: Reproduced from Ceballos-Romero et al. 2022. Map showing a global oceanic compilation of particulate organic carbon export measurements (^{234}Th) from 5000 sampling locations collected over a period exceeding 50 years.*

Strategic Solutions

To improve our understanding of the BCP and more fully constrain the ocean carbon cycle, this Science Plan supports the expansion of ship-based sampling of biological parameters based on community recommendations (Boss et al. 2018; SCOR Working Group 154, 2020) through such programs as the pilot Bio-GO-SHIP project (Clayton et al. 2022) (**objectives 1.1.4, 1.2.2**). OAR also plans to support the use of ocean carbon and other tracer observations to understand how biological carbon export, remineralization, dissolution, sequestration, and BCP efficiency changes with natural and anthropogenic variability (**objectives 1.1.3, 1.2.1, 1.2.3**). In addition, OAR intends to work toward filling knowledge gaps regarding how ocean acidification impacts biogenic processes related to organic and inorganic carbon flux and vice versa (**objectives 1.2.2, 1.3.1**).

The Science Plan recommends the implementation of a sustained BGC-Argo array that is integrated shipboard biological carbon and ocean tracer measurements (GO-SHIP) to constrain both carbon export production and the physical processes that impact the BCP (**objectives 1.1.3-4, 2.3.3**). A sustained global BGC-Argo array will aid and spatially expand estimates of the magnitude, variability, and long-term trends of organic and inorganic biogenic carbon production and export. In the past, many carbon production estimates had to be integrated over the annual cycle to quantify carbon export. New methods have been developed to reduce the latency of float-based, *in situ* carbon export estimates from one year to 10 days (Huang et al., 2022), lending new insights to regional BCP importance (Huang et al., 2023) and efficiency (Huang et al., 2024). Persistent global BCP estimates will be used to identify where spatiotemporal augmentation to current BCP observing assets would be most valuable, especially in climate-critical regions (**objectives 1.1.3, 1.1.5, 1.2.2, 1.3.1, 2.2.2, 2.3.3, 3.1.3**). Overall, both shipboard and autonomous measurements will enable OAR to provide critical information capable of assessing both marine ecosystem change and potential climate mitigation strategies like mCDR (**objective 1.3.1**).

Goal 2: Enhance Ocean Carbon Data Management, Models, and Services for Society

Serve as a trustworthy source of ocean carbon data, models, products, and information by improving ocean carbon data management practices, refining ocean carbon cycle models, and increasing the utility and timeliness of related products and services for society.

Societally important applications of ocean carbon data include global carbon accounting, Earth system and global biogeochemical modeling, climate projections, ocean acidification forecasts, and more. An emerging need also includes robust baseline carbon system observations and the creation of models and products appropriate for assessing changes in the ocean carbon cycle, due to both climate change and potential climate mitigation activities (see mCDR callout box). With accelerating impacts of climate change on ocean ecosystems, the provision of useful and timely carbon data is critical for the development of novel metrics and markers that can be used to monitor ocean health and evaluate mitigation and adaptation strategies. Fundamental to achieving these objectives is ocean carbon data management. Data management is critical to all parts of the ocean carbon value chain (**Figure 4**), from observations to models, products, and services and is fundamental to all parts of this Science Plan (see Data Management callout box). Overall, the questions and objectives outlined under this goal seek to ensure the ocean carbon observing system provides useful data for modeling, forecasting, projecting, and product development, and these products are fit-for-purpose and adequately serve societal needs including mitigation and adaptation.

Data Management

Introduction

The ocean is a vast system and data collected from individual research projects, programs, and cruises need to be compiled into regional and global data products before they can be used to support synthesis assessments. Data management plays a crucial role in bridging the gap between field observations and subsequent research based on these data. Specifically, effective data management enables long-term preservation of data, facilitates interoperability, compatibility, and integration, and enables data discovery and access (de La Beaujardière et al. 2010). By encouraging compliance with uniform and complete metadata standards, proper data management also ensures that data is fully comprehensible, which is essential to determine whether data are appropriate for a given application. NOAA OAR supports data repositories (OCADS, CCHDO, Argo DAC, and GDAC), databases, and data products (SOCAT, GLODAP, CODAP, WOD) that contain ocean carbon data. By working to improve data management of these systems, OAR intends to facilitate the use of ocean carbon data in models, products, and services.

Challenges

Data findability, accessibility, interoperability, and reusability (FAIR principles) are persistent challenges in management of data used in ocean carbon research. Inconsistent formatting of ocean carbon data and metadata leads to a lack of interoperability, in part caused by differing data management practices of numerous data assembly centers (DACs) distributed across the globe. In some cases lack of DOIs and missing metadata (or components within) impede findability, accessibility, and attribution. In addition, the lack of consistent quantification of

Credit: Adobe Stock

uncertainty across ocean carbon cycle methods and products remains a challenge for DACs. Addressing carbon data management needs is critical to improving the oceanographic research-based products and services NOAA provides.

Strategic Solutions

This Science Plan aligns with and supports community efforts toward improving data management (Jiang et al. 2024). OAR will work with partners, including NESDIS/NCEI, to ensure an accessible, trusted, and timely ocean carbon data architecture that is tailored to serving the data needs of the research community, and supports documentation, attribution, archive, integration, and dissemination (research question 2.1). This modernized ocean carbon data management system will promote greater efficiency in the existing observing system and allow the creation of high-quality data products for the ocean surface and subsurface (**objectives** 1.1.4, 2.2.2, 2.3.1). Applying common and broadly agreed-upon data management practices, including metadata standards with controlled vocabularies, will enable data findability, usability, and accessibility. International partnerships are key to ensuring the success of this system through data interoperability across DACs. OAR will collaborate with international partners to support the development of a global network of DACs (**objectives** 2.1.2, 3.1.4). Furthermore, OAR plans to contribute to the development of next-generation data submission interfaces, leveraging the latest technologies to simplify data submission. In addition, OAR aims to support both the co-development of ocean carbon data management system objectives as well as training for data creators, data practitioners, and end-users (**objectives** 2.1.4, 2.3.1-2, 3.1.3), thereby improving the usability of OAR-generated data and increasing the value of our observations.

Research question 2.1: How can OAR support ocean carbon data management guided by the FAIR principles to better bridge the gap between observations, models, and products?

Sound data management supports data integrity that underscores scientific integrity. The following objectives describe how OAR plans to support the advancement of standard community practices that improve ocean carbon data management, especially in terms of interoperability, usability, and accessibility. Ultimately, this will streamline data aggregation and ingestion to improve model outputs.

- **Objective 2.1.1:** Ensure OAR-supported ocean carbon data are properly documented, quality assured/controlled (QA/QC), and preserved to facilitate integration and harmonization of all data contributing to the measurement of common Essential Ocean Variables and Essential Climate Variables.
- **Objective 2.1.2:** Increase ocean carbon data interoperability by supporting improvements in data submission and assembly, metadata templates and display interfaces, controlled vocabularies, and data access portals.
- **Objective 2.1.3:** Sustain data management efforts to ensure all ocean carbon data from OAR investments are safeguarded in a long-term archive with version control capabilities, documented with rich metadata leveraging controlled vocabularies, and accompanied with stable data citations equipped with DOIs.
- **Objective 2.1.4:** Support ocean carbon data management community efforts to discuss challenges; improve interoperability; ensure data producers only need to submit their data once, and data users can easily find, access, and use data and products through a unified data access interface; collaborate and co-design projects; and co-create best practices for data management.
- **Objective 2.1.5:** Assess needs and develop novel data management capabilities for new ocean carbon data types.

Research question 2.2: What societally relevant ocean carbon data products, models, reconstructions, forecasts, and projections need to be enhanced or developed?

OAR aims to provide assessments of and improvements to current global and Earth system models. Critical to this process will be the creation of global and regional four-dimensional (e.g., latitude, longitude, time, depth) gridded data products that are based on direct observations and can be used for model validation, tuning, and setting boundary conditions. In addition, OAR plans to assess, improve, and produce new coastal models, forecasts, and projections for improved understanding of ocean acidification, mCDR, and changes in carbon cycling in the coastal zone.

- **Objective 2.2.1:** Facilitate interactions between observationalists and modelers to identify community needs, overcome challenges related to observational data assimilation and integration into models, and co-develop solutions in order to improve global and regional ocean carbon models.
- **Objective 2.2.2:** Develop integrated global and regional data synthesis products for the ocean surface, subsurface, and coastal ocean by combining data from a variety of observing platforms (ships, profiling floats, moored buoys, uncrewed systems, etc.) with gap-filling techniques to ultimately support improved models, ocean health assessments, refined carbon budgets, and better management of living marine resources.
- **Objective 2.2.3:** Provide seasonal-to-decadal ocean carbonate system models, reconstructions, and projections/forecasts at

global and regional scales to meet societal needs (e.g., global carbon budgets, national greenhouse gas inventories, ocean acidification forecasts, mCDR, etc.).

Research question 2.3: How can OAR best provide ocean carbon data as a product or service to better monitor ocean carbonate chemistry, ocean health, and changing ecosystems?

Culturally, ecologically, and economically valuable species and ecosystems will be impacted by changes in ocean carbonate chemistry, ranging from long-term trends such as ocean acidification to active interventions such as mCDR activities. NOAA OAR plays a critical role in providing timely and trusted ocean carbon data to relevant end-users. OAR will work toward improving data access, co-designing products with end-users, supporting rich ocean carbon metadata, co-locating measurements, and researching impacts of the carbonate system on biological communities to better observe and monitor ocean health and ecosystem changes.

- **Objective 2.3.1:** Enhance data and product usage and impact by soliciting input from end users about what ocean carbon information is most valuable to them and co-developing products that are reliably delivered.
- **Objective 2.3.2:** Improve the accessibility and timeliness of data and product delivery to the ocean carbon community and other end-users.
- **Objective 2.3.3:** Ensure carbon data are co-collected with a suite of biological, chemical, and physical measurements and that all critical metadata is provided to end-users in order to enhance the usefulness and impact of the carbon data.
- **Objective 2.3.4:** Support the development of ecosystem indicators for key long-term and active carbon cycle processes and/or interventions.

Marine Carbon Dioxide Removal

Introduction

While drastic reduction in carbon dioxide (CO_2) and other greenhouse gas emissions is the most important factor in averting the worst of the climate crisis, there is increasing interest in assessing whether CO_2 can be durably removed from the atmosphere (IPCC Sixth Assessment Report, 2023). One method by which CO_2 can be removed from the atmosphere is marine carbon dioxide removal (mCDR), defined as methods that purposefully enhance the ocean's ability to draw down CO_2 from the atmosphere or upper hydrosphere, thereby durably removing it from the atmosphere for extended periods of time (100s to 1,000s of years; Ocean Climate Action Plan 2023). These methods include both biological (nutrient fertilization, artificial upwelling/downwelling, and macroalgal cultivation and aquaculture) and inorganic (ocean alkalinity enhancement and electrochemical) pathways (National Academy of Sciences 2021, Strategy for NOAA Carbon Dioxide Removal Research 2023, National Marine Carbon Dioxide Removal Research Strategy 2024). NOAA, along with the White House Office of Science and Technology Policy, co-chaired a Fast Track Action Committee comprised of 14 US agencies to write a National Marine Carbon Dioxide Removal Research Strategy that will accelerate ethical and responsible progress on the foundational research necessary to inform US government decisions about potential implementation by 2030 (National Marine Carbon Dioxide Removal Research Strategy 2024). NOAA's role in mCDR is to support accountable research to inform potential future deployment decisions and use existing assets to provide the data and models that are required for adequate assessment of the baseline conditions against which mCDR activities should be compared. Additionally, NOAA's public, private, and interagency relationships and ocean planning infrastructure should be applied to engage with communities and end users potentially impacted by planned mCDR activities (Strategy for NOAA CDR Research, 2023).

Challenges

Marine carbon dioxide removal research is in early stages, with foundational knowledge still needed to inform decisions about potential scaling. The fast-paced growth of the mCDR research field in universities and industry necessitates public-private partnership to ensure responsible stewardship of ocean resources. Many challenges remain around robust measurement, monitoring, reporting, and verification (MMRV) capabilities, which are critical to establishing the efficacy, additionality, leakage, and durability of pathways broadly, as well as for each mCDR approach. This will require a robust global ocean carbon observing system that determines the background baseline concentrations, as well as local and regional observing capabilities to detect mCDR-induced perturbations to the system. Alongside increasing the observational capabilities driving robust MMRV, studies of the efficacy and effects of mCDR pathways should take advantage of existing models while more tailored regional models are developed. New models specific to mCDR activities should be developed that predict and track the effects of perturbing the ocean carbon cycle. Additionally, more research is needed to understand the potential effects of mCDR on ocean resources that are economically, culturally, and ecologically important, in order to inform future decision making about scaling mCDR activities. Lastly, effective communication about mCDR research, development, and scaling activities is critical to enabling informed public decision making for mCDR technologies.

Strategic Solutions

This Science Plan emphasizes the need to sustain large-scale global carbon observation networks (e.g., SOCONET, GO-SHIP, OneArgo) in collaboration with interagency (DOE, NSF, EPA, etc.) and intra-agency (e.g., IOOS, NESDIS, etc.) partners, which are critical to advance the foundational understanding of the ocean carbon cycle in order to support informed decision-making, establish local and regional baselines before perturbation by mCDR activities, and ultimately to provide critical information (**objective** 1.1.1). Regional coastal observing networks (e.g., GOA-ON, NOA-ON, and IOOS regional networks) are useful in bridging near-field and far-field observations. These efforts must be supported and expanded, as robust local observing enables researchers to track the efficacy, durability, and ecosystem impacts of mCDR activities if implemented at scale (**objectives** 1.1.3, 1.1.5, 1.2.1, 1.3.1). Opportunities and frameworks for industry engagement, such as through programs like NOAA IOOS Ocean-Based Climate Resilience Accelerators, should be explored to determine how internal and external investment in the rapidly growing field of mCDR may help advance ocean carbon observing capabilities (**objectives** 1.3.2, 3.1.5).

This Science Plan also addresses expanding ocean carbon observing networks to improve carbon cycle models for predicting, scaling, and tracking the effects of mCDR on the ocean carbon cycle, including the solubility pump, biological carbon pump, air-sea gas exchange, and transport processes. A suite of modeling frameworks will be needed for responsible and successful modeling studies including, but not limited to: physical transport models, biogeochemical and ecosystem models from regional-to-global scales, micro-to-local-scale process models to study key mCDR-related processes, and global Earth System Models (ESMs) that include data assimilation (**objective** 2.1.5). Existing model frameworks could be adapted to suit mCDR needs (**objective** 2.2.3), in addition to development of new fit-for-purpose models. Ultimately, this will enable the exploration of the feasibility, efficacy, potential risks, and co-benefits of mCDR.

Furthermore, NOAA holds a unique position as a reputable source of carbon cycle information with robust ability to communicate ocean carbon science to end users. As such, NOAA has a unique role in supporting responsible mCDR research, ensuring that communities are informed, valued, and respected throughout scientific activities (**objective** 3.2.3). Building robust mCDR MMRV approaches and ecosystem assessments is the foundation of a trustworthy mCDR sector (**objectives** 1.1.3, 2.3.4, 3.1.3). OAR can help build the trust of interested communities by ensuring that the effects (impacts and co-benefits) and the efficacy of mCDR pathways are well understood, characterized, and communicated (**objective** 3.1.2). Finally, progress on activities such as efficacy and feasibility assessments, carbon cycle perturbation foundational research, data management protocols, and community engagement could be areas of potential interagency collaboration via the NOAA-Department of Energy Memorandum of Agreement on mCDR research and development (U.S. Department of Energy and NOAA 2024; **objectives** 1.2.3, 2.1.5, 3.1.3).

Goal 3: Expand Ocean Carbon Opportunities and Community Engagement

Collaborate with the global community to advance ocean carbon observing, develop human capacity to drive innovative science that is relevant to society, support outreach to external communities, and foster ocean literacy.

NOAA OAR is an internationally renowned, reliable, and clear source of ocean carbon knowledge that provides subject matter expertise to policy makers, the general public, students, the private sector, and other end user communities. In order to maintain this stature, OAR must enhance multiple lines of communication, collaboration with the global ocean observing community, training and capacity development, and increasing ocean carbon literacy of the general public. In all of these engagements, OAR strives to target a wide range of communities to ensure that their voices shape the science supported by OAR. The questions and objectives in this goal address improving the delivery of societally relevant, innovative science outcomes through capacity development, outreach, and education.

Research question 3.1: How can mutually beneficial collaboration, coordination, and co-design be improved between OAR and the national and international carbon observing community, end users, industry, non-governmental organizations (NGOs), and academic institutions to expand our capacity for innovation and more effectively carry out our mission with regard to ocean carbon observing?

To address this question, OAR will engage in targeted, intentional, meaningful communication with external partners. Ultimately, expanded partnerships will improve OAR engagement with the broader ocean carbon observing community, driving innovative science that is useful to society. This question also focuses on finding ways to improve coordination of ocean carbon programs and projects within OAR. This co-design and collaboration is integral to all goals within this Science Plan, and should not be viewed as a standalone endeavor, but rather an iterative process.

- **Objective 3.1.1:** Establish an annual meeting between OAR labs, programs, and both current and future NOAA working groups (e.g., NOAWG, CDR Task Force, GHG Technical Team, etc.) focused on ocean carbon observing, data synthesis, and products to improve connection and dialogue.
- **Objective 3.1.2:** Meaningfully solicit feedback from and involve end users, Indigenous and Tribal nations, and those with environmental justice concerns to co-design and tailor observing systems, data management, products, and services to meet community needs.
- **Objective 3.1.3:** Maintain and increase local and global observing and research capacity

by partnering and co-designing research and observing initiatives with oceanographic organizations (throughout academia, cooperative institutes, research institutions, NGOs, government, entities funded for mCDR research, etc.) both domestically and abroad. This includes identification of synergies and redundancies.

- **Objective 3.1.4:** Work with the Global Ocean Observing System (GOOS) and the International Ocean Carbon Coordination Project (IOCCP) to support meetings between steering committee members of international carbon observing networks (e.g. GO-SHIP, SOCONET, OneArgo, etc.) to coordinate observing system design and assess cross-network scientific objectives.
- **Objective 3.1.5:** Engage with the private sector on objectives of this Science Plan, including, but not limited to, technology development and production, data access, expanding observations, and other topics.

Research question 3.2: How can OAR improve communication of societally relevant science to policy makers, end users, and the general public, and continue to serve as a reputable and authoritative source of ocean carbon information?

To address this question, OAR aims to translate our ocean carbon observing information such that it is accessible to non-technical audiences, ultimately enhancing ocean carbon and climate science literacy. The objectives listed below will further elevate OAR's reputation as the authority on high quality, accurate, sustained coastal and open ocean observations. This question also includes educating students about ocean carbon and related career opportunities, potentially inspiring the pursuit of related STEM careers and/or ocean stewardship. This will be done in partnership with other external carbon programs, including the Ocean Carbon and Biogeochemistry (OCB) Program, U.S. CLIVAR, the U.S. Carbon Cycle Science Program, and others.

- **Objective 3.2.1:** Establish a NOAA-wide website for timely dissemination of authoritative and societally-relevant ocean carbon information, including OAR efforts and scientific findings.
- **Objective 3.2.2:** Increase ocean carbon science literacy of the public by engaging in outreach and education activities and developing targeted outreach and education materials.
- **Objective 3.2.3:** Host proactive briefings with congressional representatives.

Research question 3.3: In what ways can OAR educate, recruit, train, and retain students and postdocs, developing capacity and expertise in the ocean carbon observing field to drive innovative science?

OAR needs highly qualified personnel to carry out our mission to drive innovative science that is useful to society. Therefore, answering this question requires finding ways to train and recruit undergraduates, graduate students, and postdocs to OAR labs, Cooperative Institutes, and programs, as well as partner academic, public, and private institutions. This will be done in collaboration with NOAA partners such as the Office of Education as well as external partners (e.g. UCAR, NRC, etc.).

- **Objective 3.3.1:** Recruit and train a skilled OAR workforce by maintaining and increasing participation of labs and programs conducting ocean carbon observing and research in NOAA training programs and career pipelines.
- **Objective 3.3.2:** Develop and provide pathways and frameworks for success and retention of current workforce.
- **Objective 3.3.3:** Provide continuing education and training opportunities for current workforce.

Research question 3.4: How can OAR partner with Indigenous communities and Tribal nations to co-develop ocean carbon observations, products, and services that provide timely information about ocean conditions in support of traditional use of ocean resources?

Indigenous communities are significantly impacted by changing ocean conditions, particularly with regard to ocean acidification, which can affect traditional practices like subsistence harvesting. OAR's ocean carbon research programs have established relationships with Indigenous communities and Tribal nations to co-develop ocean carbon observations, products, and services that provide critical information to support these communities and their traditions. These communities possess deep, place-based knowledge of the ocean environment, and collaboration can lead to more effective scientific outcomes and culturally relevant ocean carbon services. This engagement must be a respectful, committed, and mutually beneficial two-way knowledge exchange, ensuring that the voices and priorities of Tribal nations are heard and respected. To avoid overburdening these communities, OAR efforts should focus on leveraging existing partnerships and mentors. NOAA's Tribal Relations Team plays a crucial role in facilitating and guiding the growth and maintenance of these important relationships.

- **Objective 3.4.1:** Maintain and further develop trusting, long-term relationships with Indigenous communities and Tribal nations to foster a mutual exchange of knowledge, understand and integrate Indigenous knowledge of ocean change, and share relevant Western ocean carbon science.
- **Objective 3.4.2:** Co-design and tailor ocean observing assets, products, and services to meet needs of Indigenous communities and Tribal nations.
- **Objective 3.4.3:** Incorporate CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics; Carroll et al. 2020) data governance principles and environmental justice considerations in ocean carbon observing related co-design processes.

Prioritization, Timeline, and Long-Term Vision

This Science Plan covers a ten-year period from 2025 to 2035. The goals, research questions, and objectives described here provide the basis of OAR's sustained effort of delivering valuable ocean carbon data, products, models, and services that will continue in the long term. This Science Plan also suggests short- to medium-term ocean carbon observing and research actions (see Appendix A: Roadmap) towards improving the sustained observing system and achieving the long-term vision of this plan, which includes:

- implementation of an improved observing system design that fills observational gaps;
- technological advancements that can sample challenging-to-observe seasons and conditions;
- measurable improvements in agreement across independent methods used to estimate and constrain the ocean carbon sink;
- and an expanded biological carbon observing system;
- creation of co-designed and fit-for-purpose ocean carbon products and services.

Ultimately, these achievements will produce a comprehensive global ocean carbon observing system capable of addressing emerging scientific questions and providing information needed for ocean-based solutions.

The research questions within each goal were presented to a group of 25 subject matter experts from OAR labs/programs and academic partners who were asked to rank the questions by priority. Within each goal of this Science Plan, all research questions are presented in priority order; the first research questions within each goal (1.1, 2.1, and 3.1) are the highest priority questions to address. The prioritization order is based on the assumption that the financial and staffing resources necessary to accomplish these priorities will be available.

In addition to thematic priority of the research questions, it is important to consider temporal achievability when deciding which actions require attention and funding first. OAR and academic subject matter experts were asked to estimate the amount of time it will take to address each objective. To reflect this, within each research question the objectives have been sorted into short-term and medium-term objectives (**Figure 11**). Short-term objectives can make measurable progress within years one to four, and medium-term objectives will take five to eight years. While some objectives will need to be achieved sequentially, many are capable of happening simultaneously. The accomplishment of these short- and medium-term objectives will support progress towards the ten-year vision.

Generally, short- and medium-term objectives within the highest priority questions (1.1, 2.1, 3.1) should be addressed first, as they are achievable in a shorter time period given available resources. Some of these objectives are already in progress. Completing these readily achievable tasks within the highest priority questions will provide the foundational knowledge needed to begin addressing longer-term objectives. Each objective has a list of more specific suggested actions, which are an ordered list of short, medium, and long term actions that might be taken to meet Science Plan goals (see Appendix A: Roadmap). Implementation of this plan will be tracked over the next ten years. In addition, this Science Plan will be reviewed, revised, and updated at the mid-cycle

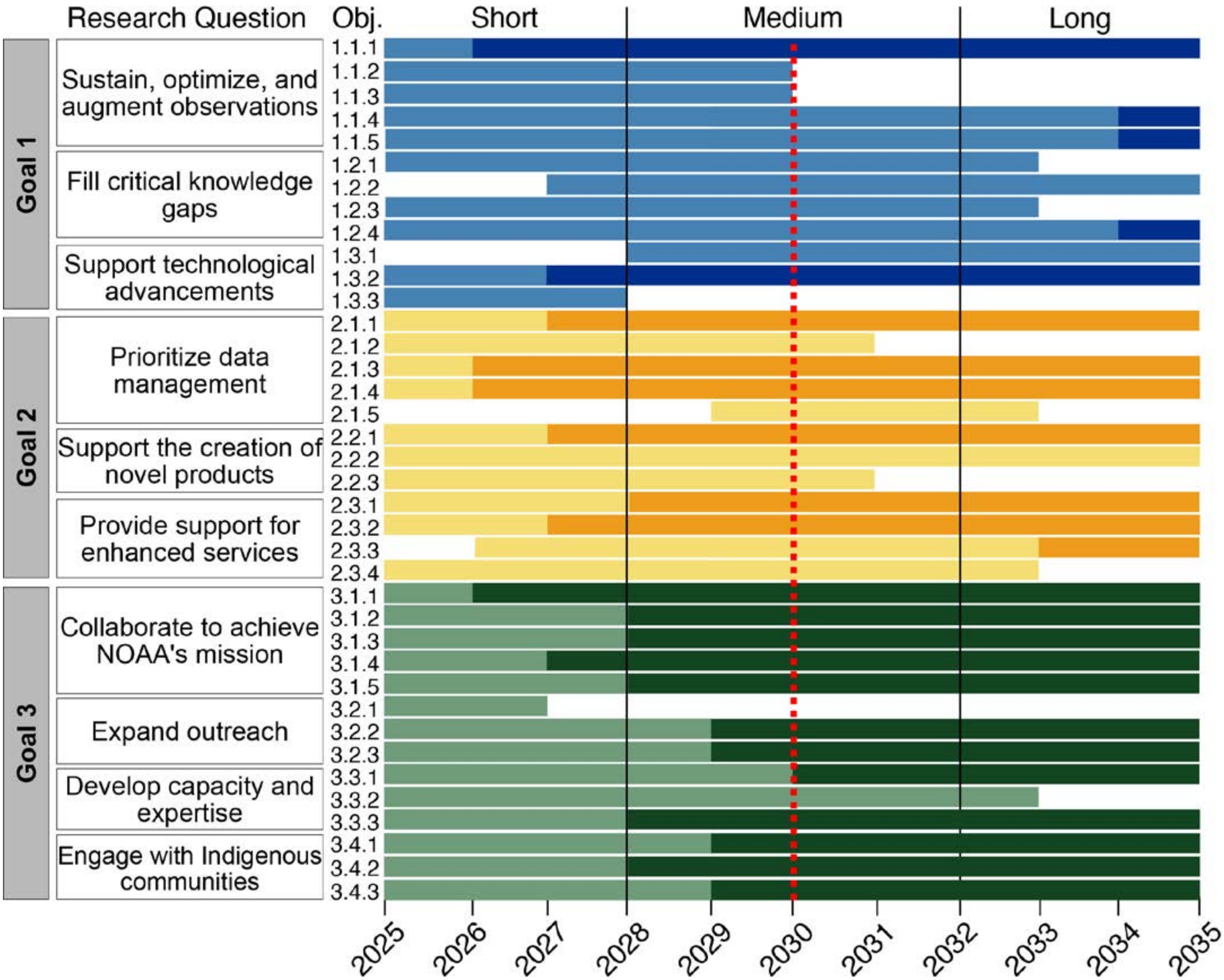


Figure 11: *Timeline for beginning and accomplishing the objectives of the Science Plan. Short indicates that work on this objective can begin within years one to three, and medium for years four through seven. Each goal is represented by a different color: goal 1 (blue), goal 2 (yellow/orange), goal 3 (green). The lighter color bars (light blue, yellow, light green) indicate that the objective will be accomplished or significant progress will have been made by its end year. Darker color bars (dark blue, orange, dark green) indicate that these objectives will be continuous once implemented. The red dashed line indicates the mid-cycle revision point for this Science Plan.*

(5 year) time point to assess progress towards the goals and address emerging scientific needs and priorities.

Research is an iterative process, meaning some results may create opportunities for further investigations. The prioritization and timelines presented here may not encompass the full span of time needed to fully address each question, but instead reflect how long it will take to achieve the first step in the process. The science will progress, and end user input at each stage will alter the path to success for each research question. This iterative process will produce a stronger carbon observing network over the next ten years.

RESOURCE REQUIREMENTS

This Science Plan includes actionable objectives that OAR is uniquely positioned to accomplish over the next 10 years, enhancing observing networks and advancing ocean carbon cycle science. However, the work outlined in this plan is contingent on Federal appropriations. Adequate financial and personnel resources will be necessary to carry out these objectives and accomplish each goal. It is important to note that OAR may be unable to fully achieve the goals and objectives in this plan with existing resources alone. Additional financial support and staff is not only necessary for some of these objectives, but would also greatly aid in accomplishing these critical, societally relevant scientific goals in a timely manner. Furthermore, OAR plans to leverage new and existing partnerships across NOAA line offices and with other agencies, academic institutions, NGOs, and the private sector in order to accomplish these objectives.

Considering FY24 funding levels and assuming flat budgets into the future, this plan details which objectives are [1] already underway and/or expected to have adequate resources to achieve within the 10 year timeframe of this plan, [2] expected to have resources to make progress towards but will need additional resources to fully complete, and [3] which will rely on new resources and partnerships to make significant progress towards. Of the objectives that will require more resources, priority that is laid out in the Prioritization, Timeline, and Long Term Vision section should be considered and used as a guideline for funding decisions. To this end, objectives in Appendix A: Roadmap have been tagged with [1], [2], or [3], as defined above, to indicate resourcing needs. Of 38 objectives, 18 were estimated to fall in category [1], 15 were estimated to fall in category [2], and 5 were estimated to fall in category [3]. Although OAR is unable to commit to completing every suggested action in Appendix A: Roadmap given future funding uncertainties, this plan provides concrete steps that OAR and its partner institutions can take to serve as a global leader in monitoring the role of the ocean in climate change and address emerging societal challenges over the next 10 years.

CONCLUSION

This Science Plan emphasizes OAR's commitment to conducting mission relevant global ocean carbon observations and research. The goals, research questions, objectives, and suggested actions prioritized within this plan are intended to guide collective efforts toward realizing a comprehensive global ocean observing system that will provide improved and expanded ocean carbon data, products, and services for societal benefit. Over the next 10 years, OAR will aim to make substantial progress towards fulfillment of this global vision for ocean carbon observing and research. In the short term, the knowledge gained from increased observational capacity will advance scientific understanding of the global carbon cycle and begin to reduce uncertainty of both ocean carbon observations and estimates of fluxes between reservoirs. This work will be used to develop critical products and services on ocean carbon-related topics, including ocean acidification, mCDR, and fisheries-relevant ecosystem health, to end users ranging from local communities to national and international policy and decision makers. In addition, OAR intends to invest in developing capacity for the future, including education and training, to support a changing and growing national workforce. Over the long term, this plan will help OAR to support a resilient and adaptive Nation, a thriving blue economy, and will allow the United States to continue to act as a global leader delivering critical ocean carbon information to the international community on a scale unmatched by any other Nation.

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APPENDIX A: ROADMAP

Introduction

This appendix contains specific actions OAR subject matter experts suggested to implement broader objectives, answer scientific questions, and accomplish goals laid out in this Science Plan. These suggested actions are intended to function as a roadmap for guiding OAR ocean carbon observing and research activities over the next 10 years. These actions are based on 2024 knowledge of ocean carbon science, status of the observing system, and technological capabilities, but may change as scientific and financial landscapes evolve over the next 10 years. This part of the document is subject to change and will be updated/amended at the midpoint of the plan's timeline (five years) based on evolving ocean carbon knowledge, technology, priorities, and resource availability.

Each objective and suggested action has been labeled with a timeline indicator in brackets to denote when work on these suggested actions can begin and/or measurable progress can be achieved. [Short] indicates that this objective or suggested action can be started within years one to four, [medium] within years five to eight, and [long] within year nine or later. Timeline indicators with an asterisk (*) denote that these objectives and suggested action will be continuous activities once implemented. **Figure 11** reflects this timeline, as well as a prediction of how long it will take to accomplish each objective. While the objectives can all be started within the 10-year timeframe of the plan, suggested actions lay out some of the next steps OAR will work towards to realize the plan's ten-year vision (see Prioritization, Timeline, and Long-Term Vision).

Successful implementation and accomplishment of objectives for all goals within this Science Plan can be measured based on suggested Outcomes and Outputs of Success, which are included at the end of each goal below.

Each objective and suggested action is also labeled with indicators of which callout boxes or other Science Plan themes are relevant. Callout box and themes are abbreviated as follows: [BCP] = Biological Carbon Pump, [DM] = Data Management, [mCDR] = marine Carbon Dioxide Removal, [O&M] = Observations and Models, [OSD] = Observing System Design, [OC] = Ocean Constraints, [OA] = Ocean Acidification, [CCD] = Co-design and Capacity Development.

Finally, each objective is labeled with an estimated level of funding resources required to achieve the objective within the 10 year timeframe of this plan. Estimated resource requirements are based on FY24 funding levels and assume a flat or slightly increasing budget (i.e., ~3% increase per year to account for inflation) into the future. The resource requirement levels are defined as follows: [1] = already underway and/or expected to have adequate resources to achieve, [2] = expected to have resources to make progress towards but will need additional resources to fully complete, and [3] = will rely on new resources and partnerships to make significant progress.

Suggested Actions

Goal 1:

Research question 1.1

- **Objective 1.1.1:** Continue to maintain the present ocean carbon observing assets to provide continuity with past measurements and answer critical questions regarding the ocean carbon cycle. [O&M, OC, CCD] [short*] [2]
  - Maintain people and financial resources needed to maintain these observing assets. [CCD] [short*]
  - Upgrade and replace mooring-based fCO_2 instrumentation. [O&M, OC] [short]
  - Upgrade and replace shipboard carbon measuring instrumentation. [O&M, OC] [short]
  - Solidify support for atmospheric O_2/N_2 measurements to ensure long-term continuity as part of a sustained observing system. [O&M, OC] [medium]
- **Objective 1.1.2:** Identify and quantify primary sources of uncertainty in observations of carbon Essential Ocean Variables/Essential Climate Variables (EOVs/ECVs) and estimations of the ocean carbon cycle. [O&M] [short] [1]
  - Assess the strengths, weaknesses, and complementarity of various methods and analyses for estimating fluxes associated with the ocean carbon cycle. [O&M] [short]
  - Determine relative contribution of spatiotemporal measurement distribution, analytical uncertainty, systematic errors due to parameterization, and/or physical transport to current uncertainty in carbon reservoir and flux estimates. [O&M] [short]
  - Update reasonable, acceptable, and quantitative uncertainty values for both climate-quality studies, models, and synthesis efforts, as well as shorter term weather-quality observing applications (see also Goal 3). These efforts should consider both uncertainties in direct measurements of the carbonate system and uncertainties in less direct flux estimates (e.g., individual estimates of inorganic and organic carbon export). [O&M] [short*]
- **Objective 1.1.3:** Make use of model-based and statistical approaches and experiments to determine optimal sampling strategies and where observational augmentation would be most valuable. [OSD, O&M, BCP, OC, OA, mCDR] [short] [2]
  - Conduct inter-comparability assessments of model-based testbed reconstruction experiments in collaboration with the global ocean carbon observing community. [O&M] [short]
  - Determine sampling distribution of surface-ocean tracers (e.g., fCO_2, DIC, TA, pH, etc.) needed to constrain the ocean carbon cycle. [O&M, OC, OSD] [short]
  - Determine optimal full water column sampling distributions of DIC, TA, pH, O_2, nutrients DOC, POC, and tracers from shipboard cruises and autonomous underwater platforms needed to better estimate natural and anthropogenic deep ocean carbon storage. [OSD, BCP] [short]
  - Determine augmentations to existing atmospheric O_2/N_2 observing network

needed to provide biannual and basin scale estimates of the ocean carbon sink. [O&M, OSD, OC] [short]

- Determine optimal sampling strategy for vertical aircraft profile campaigns needed to provide regional and basin scale estimates of air-sea CO_2 exchange. [O&M, OSD] [short]
- Determine what observations and observing system design(s) are needed for predictions of open-ocean, coastal, and freshwater acidification on seasonal to decadal timescales. [OSD, OA] [short]
- Assess the impact to ocean carbon sink estimates of increasing the spatiotemporal distribution of surface ocean fCO_2 measurements and atmospheric xCO_2 within the marine boundary layer by utilizing research ships, ships of opportunity, and autonomous platforms. [O&M, OC, OSD] [short]
- Determine sampling distribution of tracers of natural and anthropogenic carbon (e.g., DIC, $DI^{13}C$, nutrients, dissolved O_2, etc.) needed to assess the impact of changes in circulation on carbon storage and transport. [OSD] [short]
- Determine sampling distribution of deep ocean tracers of water mass age (e.g., ^{14}C, CFCs, SF_6, etc.) needed to constrain exchange between the surface and deep ocean. [OSD, OC] [short]
- Determine what frequency (interannual, year-round) of observations using paired air-sea interface and ocean interior observing assets in critical circulation zones (such as the Gulf Stream, Subtropical Mode Water formation region, and North Atlantic) is needed to improve understanding of the role of processes within these dynamic regions to the ocean carbon cycle. [OSD] [short]
- Determine what observations and observing system design(s) are needed for accurate MMRV of mCDR. [mCDR, OSD] [short]
- Determine what measurements (and modeling studies; see Goal 2) at regional and local scales would allow adequate prediction and observation of changes to the carbon system driven by mCDR testing and potential future deployment. [mCDR, O&M, OSD] [short]
- Determine what observations and observing system design will help reanalysis (e.g., OMIP models used in Global Carbon Project and RECCAP) and inverse models (e.g., CarbonTracker) constrain recent changes to the ocean carbon system. [O&M, OSD] [short]
- Determine what observations and observing system design would provide validation of coupled-carbon-climate Earth system model projections with a comprehensive group of ocean carbon constraints on natural and anthropogenic CO_2 uptake. [O&M, OC, OSD] [medium]

- **Objective 1.1.4:** Expand observations where needed and promote efficiencies to the existing observing system to improve the quantification of carbon cycling throughout the water column, both nearshore and offshore, as well as fluxes at the sea surface. [BCP, DM, O&M, OC, CCD] [medium*] [3]
  - Support biogeochemical observations (e.g., fCO_2, DIC, TA, pH, nutrients, dissolved O_2, POC, DOC, chlorophyll, etc.) on hydrographic transects (GO-SHIP) and shipboard research cruises (Coastal Acidification cruises) to improve observational spatiotemporal coverage. [OC, BCP] [short]
  - Ensure shipboard biogeochemical observations are interoperable with biogeochemical profiling floats (BGC-Argo) and other autonomous underwater platforms in order to provide adequate

calibration and validation of autonomous systems and improve cross-system efficiency. [BCP] [short]

- Collaborate with end users, including international observing networks, to implement this objective. [CCD] [medium]
- Develop capacity (e.g., resources and people) to expand the observing system. [CCD, O&M] [medium]
- Expand the atmospheric O_2/N_2 network to create a sustained observing system that provides biannual and basin scale estimates of the ocean carbon sink. [O&M, OC] [medium]
- Incorporate vertical aircraft CO_2 profiles over oceans into sustained observing systems to provide monthly to annual air-sea CO_2 exchange values from regional to basin scales. [O&M, OC] [medium*]

- **Objective 1.1.5:** Improve quantification of the global ocean carbon cycle by continuously updating estimates using a variety and evolving combination of approaches. [all themes] [medium*] [2]
  - Create a synthesis product that provides ocean constraints on air-sea CO_2 flux using all relevant and available observational data, including assimilating and inversion approaches, with separate estimates based on surface ocean fCO_2, deep ocean, and atmospheric measurements and rigorous uncertainty quantification. [O&M, OC] [short*]

Research question 1.2

- **Objective 1.2.1:** Improve knowledge of ocean circulation and air-sea CO_2 flux to reduce uncertainty in ocean carbon model parameterizations. [O&M, OSD, BCP, mCDR] [medium] [2]
  - Determine where to prioritize co-located, contemporaneous observations of air-sea CO_2 flux (e.g., direct flux measurements such a s eddy covariance together with surface fCO_2) to reduce biases in regional bulk air-sea CO_2 flux estimates. [O&M, OSD] [short]
  - Sustain, improve, and expand ocean circulation relevant observations (e.g., CFCs, SF6, DI14C, temperature, salinity, DI13C) to better parameterize anthropogenic carbon in models. [O&M] [medium]
  - Couple biogeochemical observations (e.g., fCO_2, DIC, TA, pH, nutrients, dissolved O_2, POC, DOC, etc.) with physical measurements (e.g., sea surface temperature, salinity, pressure, etc.) to parse out physical versus biological drivers of carbon parameters and fluxes, understand anthropogenically driven carbon cycle changes mechanistically, and establish more detailed baseline conditions for any future large scale mCDR activities. [BCP, mCDR, O&M] [medium]
- **Objective 1.2.2:** Use observations to research biological carbon transformations and fluxes towards better understanding and constraining the biological component of the ocean carbon cycle. [BCP, OSD, OA] [medium] [3]
  - Continue development of float-based productivity and export estimation methods. [BCP] [short]
  - Increase understanding of biogenic carbonate production and dissolution due to OA and how it relates to the ocean carbon cycle. [BCP, OA] [medium]
  - Assess biological carbon pump (BCP) observing system design across a range of parameters (e.g., primary production, net community production, POC flux, PIC flux, etc.). [BCP, OSD] [medium]

- Increase spatiotemporal density of organic carbon flux measurements and estimates in the surface ocean (<500-1000m) to better constrain organic carbon export, as well as the density of inorganic carbon measurements in the deep ocean (>1000m) to better constrain deep subduction and improve mechanistic understanding of the biological and solubility pumps. [BCP] [medium]
- Determine how fluxes and transformations of dissolved and particulate organic matter affect the transport of carbon throughout the ocean interior. [medium]
- Support research examining the response of microbial communities to human-driven changes in key ecosystem trends or processes (e.g., OA, BCP). [BCP, OA] [medium]
- Produce global estimates of net primary productivity, net community productivity, and carbon export using emergent approaches. [BCP] [long]
- Determine the role of microbial community structure, functional roles, emergent properties, net community production, net primary production, physiology (ballast, transparent exopolymer particle production, response to nutrient limitation, etc.), and diel vertical migration patterns in marine biogeochemical and carbon cycles, especially uptake and export efficiency. Characterize these differences across different spatial and temporal scales. [BCP] [long]

- **Objective 1.2.3:** Study how climate change interacts with the ocean carbon cycle to determine long-term change and to parse out impacts and interactions between natural variability and anthropogenic change. [O&M, OC, BCP] [medium] [2]
    - Partition surface ΔfCO_2, DIC, and TA changes over time (seasonal, annual, and longer time scales) as a result of anthropogenic carbon uptake, changes in circulation and mixing, changes in temperature, and changes in the buffer capacity of the oceans. [BCP, O&M, OC] [short]
    - Use subsurface measurements to determine how climate change processes affecting the global ocean circulation alter anthropogenic carbon uptake over time. [BCP, O&M] [medium]
    - Conduct investigations of the deoxygenation correction to the atmospheric O_2/N_2 approach leveraging observations collected by biogeochemical profiling floats (BGC-Argo) and hydrographic transects (GO-SHIP). [O&M, OC] [short]
- **Objective 1.2.4:** Study how large freshwater systems such as the Great Lakes, submarine groundwater discharge, and riverine-to-ocean inputs affect global carbon dynamics. [O&M, OSD, OA] [short*] [3]
    - Augment Great Lakes carbon observing system with additional assets (e.g., enhanced spatial and depth distribution of observations; Kelly et al. 2025). [OSD] [short]
    - Determine how changes in riverine input affect the dissolved and particulate carbon flux in the oceans. [O&M] [long]
    - Use the Great Lakes as case studies for future change in the ocean carbon cycle including ocean acidification. [O&M, OA] [long]

Research question 1.3

- **Objective 1.3.1:** Identify and develop new and improved technologies (e.g., sensors, platforms, supersites, etc.) and technological advancements necessary to detect changes in the global carbon cycle. [O&M, OA, BCP, mCDR, DM] [medium*] [3]

- Improve calibration and validation of underway and profiling nutrients and dissolved O_2 to better understand particulate and dissolved nutrient stoichiometry (C:N:P:O) and the impacts of nutrient limitation on carbon cycling. [BCP, O&M] [medium]
- Improve sensors for carbon system measurements on autonomous platforms. [O&M] [medium]
- Develop platforms and sensors to monitor and analyze trends in regions that are under sampled due to technological challenges (e.g., within sea ice, deep ocean, freshwater). [O&M] [medium]
- Develop two-carbon and multi-parameter sensors that can be integrated into surface and underwater platforms (e.g., TA/pH, TA/ $f\mathrm{CO}_2$, or $f\mathrm{CO}_2$/DIC). [mCDR, O&M, OA] [medium]
- Facilitate research into novel approaches to quantify ocean carbon cycle uncertainty. [O&M, DM] [medium]
- Improve methods to measure particulate organic carbon flux (e.g., improve indirect estimate capabilities of assets such as Underwater Vision Profilers (UVP's) and advance radioisotope methods) for estimating particle fluxes. [BCP, O&M] [long]

- **Objective 1.3.2:** Strengthen public-private partnerships and support dialogues with industry that are mutually beneficial for the transition and development of new technologies. [CCD, DM, O&M, OA, BCP, mCDR] [short*] [1]
    - Continue to develop and improve carbon system sensors. [BCP, mCDR, O&M, OA] [short*]
    - Support dialogues with industry that are mutually beneficial for technology development (e.g., carbon sensor design), data accessibility, etc. [BCP, CCD, DM, mCDR, O&M, OA] [short*]
    - Train SOOP crews to maintain and repair underway sensors. [CCD, DM] [short*]
    - Determine what bottlenecks hinder development, production, and proliferation of platforms and sensors and develop strategies to overcome these bottlenecks. [CCD] [short]
    - Demonstrate to industry partners the need for and benefits of increased production of carbon sensors and observing platforms. [CCD] [short]
    - Support the production and use of carbon-sensor equipped autonomous underwater platforms capable of sampling in open-ocean and coastal waters. [BCP, CCD, mCDR, O&M, OA] [short]
- **Objective 1.3.3:** Contribute to the development of standard procedures for intercomparison studies of sensors, systems, and measurements from different platforms in collaboration with national and international partners. [O&M] [short] [1]

Outcomes & Outputs of Success

Performance measures

- A rigorous quantification of the uncertainties in observation-based estimates of the ocean carbon cycle has been performed, peer-reviewed, and made publicly available.
- The number of new carbon observing assets (sensors and platforms) being deployed increases and existing assets are maintained and, if necessary, redistributed strategically to

reduce uncertainty and improve understanding of the carbon cycle in the open and coastal ocean and the Great Lakes.

- The number of accurate ocean carbon measurements increases, meeting community and international standards.
- Estimates of the global ocean carbon cycle and associated parameterizations are improved via regular updates with new observations.

Milestones

- Existing ocean carbon observing measurements and assets are sustained and maintained to continue supporting ocean carbon cycle research.
- Model-based and statistical approaches and experiments have provided recommendations on the placement and collection of regional ocean carbon observations to reduce uncertainty in carbon cycle estimates.
- Underlying drivers of the differences between and among observational and model-based estimates of the ocean carbon sink have been identified and are being ameliorated.
- New observations are being used to create a global ocean constraint product, with planned updates on a bi-annual basis, and improve estimates of the global carbon cycle.
- OAR-funded scientists continue to disseminate cutting edge information and advancements in ocean carbon cycle science with the broader community through national and international presentations and high-impact peer-reviewed publications.
- Improving mechanistic understanding of processes including air-sea CO_2 flux, biological carbon transformations and fluxes, influence of climate change, and riverine-to-ocean, needed to constrain and model ocean carbon cycling.
- Outdated ocean carbon observing assets have been upgraded to cutting-edge models.
- Progress is being made toward the development of new observing technologies (sensors and platforms) for open and coastal ocean and the Great Lakes carbon cycle measurements.
- Regular engagement with private sector technology partners is being supported.
- Documentation of community standards for ocean carbon sensor and platform intercomparison studies has been performed.

Goal 2:

Research question 2.1

- **Objective 2.1.1:** Ensure OAR-supported ocean carbon data are properly documented, quality assured/controlled (QA/QC), and preserved to facilitate integration and harmonization of all data contributing to the measurement of common Essential Ocean Variables and Essential Climate Variables. [DM, O&M] [short*] [1]
    - Support QA/QC of discrete observing samples collected by local and regional partners to ensure their work is able to be integrated into broader observing networks. [DM, O&M] [short*]
    - Co-develop a consistent data flow between the observational, data management, and QA/QC communities including considerations of appropriate treatment of QC flags. [DM] [short]
    - Develop strategies for integrating and harmonizing data from the different observing assets, sensors, and platforms measuring the same EOVs/ECVs. [DM, O&M] [medium]

- **Objective 2.1.2:** Increase ocean carbon data interoperability by supporting improvements in data submission and assembly, metadata templates and display interfaces, controlled metadata vocabularies, and data access portals. [DM, O&M, OA] [short] [2]
    - Ensure each carbon (meta)dataset's citation is linked to a permanent, dereferenceable, and unique identifier (e.g. a DOI, etc.). [DM] [short]
    - Streamline ocean carbon data submission by developing common and minimal but rich metadata templates as well as submission interfaces that enable pre-population of information using unique data identifiers (e.g., DOIs, etc.) to ultimately support lower-effort submissions. [DM] [short]
    - Support the creation of a global ocean carbon data management network, consisting of regional hubs, to ensure that scientists only need to submit their data once, making all ocean carbon data findable and accessible through a unified, federated data portal. [DM, O&M] [medium]
- **Objective 2.1.3:** Sustain data management efforts to ensure all ocean carbon data from OAR investments are safeguarded in a long-term archive with version control capabilities, documented with rich metadata leveraging controlled vocabularies, and accompanied with stable data citations equipped with DOIs. [DM] [short*] [1]
- **Objective 2.1.4:** Support ocean carbon data management community efforts to discuss challenges; improve interoperability; ensure data producers only need to submit their data once, and data users can easily find, access, and use data and products through a unified data access interface; collaborate and co-design projects; and co-create best practices for data management. [DM, CCD] [short*] [2]
    - Establish and facilitate annual to biannual meetings, in either new or existing forums, between data managers, data producers (observers), and data users (modelers) with a specific focus on the needs of ocean carbon data and related metadata. [DM, CCD] [short*]
    - Support training and workshops for the research community from all sectors (NOAA scientists and our partners in academia, industry, etc.) to introduce effective tools, techniques, and data management best practices. [DM] [short*]
    - Regularly update and document best practices in ocean carbon data management. [DM] [short*]
    - Support open source tool development for ocean carbon data management and data dissemination. [DM] [short*]
- **Objective 2.1.5:** Assess needs and develop novel data management capabilities for new ocean carbon data types. [DM, BCP, mCDR, OSD] [medium] [2]
    - Leverage existing data processing systems, such as that already in place for Argo, to efficiently develop data systems for new networks (e.g., such as the BGC glider network) with the aim of providing near-real time delivery and QC of data. [BCP, DM, OSD] [medium]
    - Develop data management methods for data collected from mCDR field testing and potential future scaling. [DM, mCDR] [medium]
    - Develop novel data management methods for process studies [DM] [medium]

Research question 2.2

- **Objective 2.2.1:** Facilitate interactions between observationalists and modelers to identify community needs, overcome challenges related to observational data assimilation and integration into models, and co-develop solutions in order to improve global and regional ocean carbon models. [CCD, DM, O&M] [short*] [1]
  - Coordinate observationalists and data assimilation-based model developers to facilitate model and forecast improvements through meetings, networking events, and other venues. [CCD, DM, O&M] [short]
- **Objective 2.2.2:** Develop integrated global and regional data synthesis products for the ocean surface, subsurface, and coastal ocean by combining data from a variety of observing platforms (ships, profiling floats, moored buoys, uncrewed systems, etc.) with gap-filling techniques to ultimately support improved models, ocean health assessments, refined carbon budgets, and better management of living marine resources. [O&M, DM, OC, BCP, OA] [short] [2]
  - Support the development of routine global gridded products of air-sea CO_2 flux that incorporate time-varying estimates of uncertainty. [DM, O&M, OC] [short]
  - Continue to develop global-scale time-varying productivity and export estimates from gridded products based on *in situ* observations. [BCP] [short]
  - Support the development of routine global gridded products of four-dimensional ocean biogeochemistry that incorporate time-varying estimates of uncertainty. [BCP, DM] [short]
  - Lead and coordinate the development of global coastal ocean integrated data products, e.g., CODAP-Global, GLODAP, SOCAT. [BCP, DM, O&M, OA] [medium]
  - Support the development of routine global gridded products for the subsurface ocean by leveraging gap-filling techniques and incorporating data from both discrete bottle-based products and neural network-based products. [DM, O&M] [medium]
  - Improve uncertainty quantification in gap-filling products used for estimating the global ocean carbon cycle. [DM, O&M] [medium]
- **Objective 2.2.3:** Provide seasonal-to-decadal ocean carbonate system models, reconstructions, and projections/forecasts at global and regional scales to meet societal needs (e.g., global carbon budgets, national greenhouse gas inventories, ocean acidification forecasts, mCDR, etc.). [O&M, OC, mCDR, OA] [short] [1]
  - Provide, enhance, and/or improve seasonal-to-decadal ocean carbon models (e.g., inverse, global biogeochemical, earth system, etc.), and projections/forecasts to constrain near- and long-term carbon budgets, determine the impact of the “natural system” on the year-to-year atmospheric increase of CO_2, and accurately track contributions to the Global Stocktake (e.g., national greenhouse gas inventories). [O&M, OC] [short]
  - Provide, enhance, and improve nested OA forecasts at global and regional scales, and on daily to decadal timescales as appropriate, for end users (e.g. shellfish growers), resource managers, and policy makers. [OA] [short]
  - Expand modeling at global, regional, and local scales to allow adequate prediction and observation of changes to the carbon system driven by mCDR testing and

potential future deployment. [mCDR] [medium]

- Develop global and regional nested models and/or simulations that are able to investigate and/or predict how enhanced atmospheric CO_2 uptake driven by mCDR pathways will affect the ocean carbon cycle (solubility pump, biological carbon pump, air-sea gas exchange, sources and sinks, etc.). [mCDR] [medium]
- Develop global and regional models that are able to predict how certain forms of terrestrial CDR techniques, such as direct air capture, might affect air-sea carbon equilibrium driven by a decrease in atmospheric CO_2. [mCDR] [medium]

Research question 2.3

- **Objective 2.3.1:** Enhance data and product usage and impact by soliciting input from end users about what ocean carbon information is most valuable to them and co-developing products that are reliably delivered. [DM, CCD] [short*] [2]
  - Engage with local and regional natural resource managers and policy makers to ensure NOAA data and data synthesis products are being utilized to address critical issues. [CCD] [short*]
  - Produce a living document or webpage with case studies of impactful ocean carbon products and assessments, including descriptions of the observing systems providing data that is updated and publicly released regularly. [CCD] [short]
  - Engage with the remote sensing community (NESDIS and NASA) to support the use of *in situ* observations in satellite calibration and validation. [CCD] [medium]
- **Objective 2.3.2:** Improve the accessibility and timeliness of data and product delivery to the ocean carbon community and other end-users. [CCD, DM] [short*] [1]
  - Ensure data and product delivery on web portals and formal program websites is timely, transparent, and reliable. [CCD, DM] [short*]
  - Provide timely notifications regarding release dates for relevant and significant ocean data products to the ocean carbon community. [CCD, DM] [short*]
  - Connect existing web portals to enhance access to data products. [CCD, DM] [medium]
- **Objective 2.3.3:** Ensure carbon data are co-collected with a suite of biological, chemical, and physical measurements and that all critical metadata is provided to end-users in order to enhance the usefulness and impact of the carbon data. [BCP, O&M, OA] [medium*] [2]
  - Document natural variability in ocean ecosystems with co-located biological (including Essential Biodiversity Variables [EBVs]), chemical, and physical ocean observations to establish baseline understanding of different environments, focusing on regions that are under-observed (subsurface, mesopelagic, wintertime) or climate critical (Tropical Pacific, subpolar, strongly impacted by ocean acidification, etc.). [BCP, O&M, OA] [medium]
  - Perform shipboard, laboratory, and *in situ* biological rate measurements and experiments to identify biomarkers of environmental change and ecosystem health. [BCP, O&M, OA] [medium]
- **Objective 2.3.4:** Support the development of ecosystem indicators for key long-term and active carbon cycle processes and/or interventions. [OA, mCDR] [short] [1]

- Support further investigations and developments of OA biogeochemical indicators, indicator species, and related health metrics (gene expression, stress, etc.). [OA] [short]
- Investigate the effects of mCDR on biological species and develop relevant ecosystem impact indicators as appropriate. [mCDR] [short]

Outcomes & Outputs of Success

Performance measures

- Improvements to ocean carbon data products and models results in greater convergence of independent ocean carbon budget metrics, reduced uncertainty, and increased quantification of the direct and indirect effects of anthropogenic carbon on ocean change.
- Global and regional ocean models demonstrate improvements in the ability to produce (1) annual estimates of carbon uptake by region and/or ocean provinces, (2) reliable forecasts and projections of subregional carbon dynamics including episodic processes (e.g. acidification events, hypoxia, etc.), and/or (3) local-to-global impacts of proposed mCDR activities.
- Carbon data are used to deliver routine metrics of ocean health, in particular regarding ocean acidification status and potential impacts on biological communities to regional end users.

Milestones

- High quality, QA/QC'ed, transparent, and assimilation-ready ocean carbon data products for the ocean surface and subsurface are made publicly available on a routine and timely basis for use by national and international partners.
- The process for submission of ocean carbon data with metadata templates that use controlled vocabularies is user friendly, easily accessible, and globally interoperable.
- OAR-funded ocean carbon data is supported by a trusted data architecture that provides dissemination, documentation, attribution, and archive.
- Early dialogues, collaboration, and co-design of objectives in addition to cross-functional training opportunities for the ocean carbon observing, modeling, and data management communities are supported by OAR.
- Use of OAR-funded ocean carbon data products and services results in greater recognition of NOAA's leadership in the ocean change space.

Goal 3:

Research question 3.1

- **Objective 3.1.1:** Establish an annual meeting between OAR labs, programs, and both current and future NOAA working groups (e.g., NOAWG, CDR Task Force, GHG Technical Team, etc.) focused on ocean carbon observing, data synthesis, and products to improve connection and dialogue. [CCD] [short*] [1]
- **Objective 3.1.2:** Meaningfully solicit feedback from and involve end users, Indigenous and Tribal nations, and those with environmental justice concerns to co-design and tailor observing systems, data management, products, and services to meet community needs. [CCD] [short*] [1]
  - Identify key end users for targeted communication and collaboration. [CCD] [short]
  - Enhance collaboration between scientists and end users to co-develop priorities

  across all components of the ocean carbon value chain. [CCD] [short*]
  - Determine which culturally and economically important ecosystems and species may be impacted by changing ocean carbonate systems, including active interventions such as mCDR, that need additional investment of research to inform management. [CCD] [short]
  - Communicate the importance of ocean carbon observations and reducing uncertainty in forecasts and models to the broader scientific community, in the context of the ocean carbon value chain. [CCD] [short]
- **Objective 3.1.3:** Maintain and increase local and global observing and research capacity by partnering and co-designing research and observing initiatives with oceanographic organizations (throughout academia, cooperative institutes, research institutions, NGOs, government, entities funded for mCDR research, etc.) both domestically and abroad. This includes identification of synergies and redundancies. [All themes] [short*] [2]
  - Work with other agencies to co-design mCDR MMRV approaches and assessment procedures. Build avenues for private sector engagement into these procedures. [medium]
- **Objective 3.1.4:** Work with the Global Ocean Observing System (GOOS) and the International Ocean Carbon Coordination Project (IOCCP) to support meetings between steering committee members of international carbon observing networks (e.g. GO-SHIP, SOCONET, OneArgo, etc.) to coordinate observing system design and assess cross-network scientific objectives. [CCD, OSD, DM, O&M] [short*] [1]
- **Objective 3.1.5:** Engage with the private sector on objectives of this Science Plan, including, but not limited to, technology development and production, data access, expanding observations, and other topics. [CCD] [short*] [1]
- Expand engagements with the private sector (e.g.,Dialogues with Industry) to develop recommendations for collaboration between the public and private sectors to meet the needs of science and society. [CCD] [short*]

Research question 3.2

- **Objective 3.2.1:** Establish a NOAA-wide website for timely dissemination of authoritative and societally-relevant ocean carbon information, including OAR efforts and scientific findings. [CCD] [short] [2]
  - Establish oceancarbon.noaa.gov for one NOAA carbon branding and messaging. [CCD] [short]
  - Update oceancarbon.noaa.gov and OAR lab and program websites frequently with accessible, plain-language content to keep the general public and policy makers informed. [CCD] [short*]
- **Objective 3.2.2:** Increase ocean carbon science literacy of the public by engaging in outreach and education activities and developing targeted outreach and education materials. [CCD] [short*] [1]
  - Increase ocean carbon outreach through the development of targeted materials and participation in outreach opportunities for specific audiences. [CCD] [short*]
  - Include ocean carbon related topics in curricula by partnering with NOAA's Office of Education and other educational organizations. [CCD] [short*]
  - Provide opportunities to inspire student interest in ocean carbon and ocean

stewardship by investing and participating in ocean literacy educational programs, curriculum development, and teacher continuing education. [CCD] [short*]

- **Objective 3.2.3:** Host proactive briefings with congressional representatives. [CCD, OA, mCDR, O&M, BCP] [short*] [1]
    - Provide policy makers and industry partners with relevant information related to the impacts of OA, mCDR, and other human activities on marine ecosystems to make decisions that will build community climate resilience. [BCP, CCD, mCDR, O&M, OA] [short*]

Research question 3.3

- **Objective 3.3.1:** Recruit and train a skilled OAR workforce by maintaining and increasing participation of labs and programs conducting ocean carbon observing and research in NOAA training programs and career pipelines. [CCD] [short*] [2]
    - Increase visibility of NOAA training programs and career paths by participating in and supporting funding for outreach and education efforts with undergraduates, graduate students, and postdocs from a broad range of backgrounds. [CCD] [short*]
    - Develop training and communication materials that incorporate OAR supported scientific findings and can be shared broadly. [short*]
    - Reduce barriers to bringing on postdocs. [CCD] [long]
    - Incorporate citizen science initiatives into ocean carbon observing activities. [CCD] [long]
- **Objective 3.3.2:** Develop and provide pathways and frameworks for success and retention of current workforce. [CCD] [medium] [1]
    - Develop performance metrics that are more varied than first author publications to support and encourage scientists to engage in other societally relevant work (e.g., Tribal engagement, outreach and education, co-design, etc.). [CCD] [medium]
- **Objective 3.3.3:** Provide continuing education and training opportunities for current workforce. [CCD] [short*] [1]
    - Provide OAR workforce professional development opportunities, including leadership development. [CCD] [short*]
    - Conduct outreach and training to ensure accurate interpretations of pH and [H+] data (Fassbender et al. 2021). [OA, CCD] [short]

Research question 3.4

- **Objective 3.4.1:** Maintain and further develop trusting, long-term relationships with Indigenous communities and Tribal nations to foster a mutual exchange of knowledge, understand and integrate Indigenous knowledge of ocean change, and share relevant Western ocean carbon science. [OA, CCD, mCDR] [short*] [1]
    - Support and encourage OAR employees working on carbon to participate in tribal engagement trainings held by NOAA. [CCD] [short*]
- **Objective 3.4.2:** Co-design and tailor ocean observing assets, products, and services to meet needs of Indigenous communities and Tribal nations. [OA, OSD, CCD] [short*] [3]
    - Support collaborations between physical scientists, social scientists, and Tribal nations/Indigenous communities to inform ocean carbon observing asset placement and co-design products and services to meet Indigenous needs. [CCD] [short*]

- **Objective 3.4.3:** Incorporate CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics; Carroll et al. 2020) data governance principles and environmental justice considerations in ocean carbon observing related co-design processes. [DM, CCD] [short*] [2]
    - Continue to work with tribes to create systems for protecting and appropriately sharing Indigenous and Tribal ocean carbon data when incorporated into databases and long-term archive systems. [DM, CCD] [short*]

Outcomes & Outputs of Success

Performance measures

- An increased number of and broader set of collaborative activities between OAR carbon labs/programs and other NOAA line offices, research institutions, the private sector, end users, international partners, federal agencies, interagency working groups, NGOs, citizen scientists, and other partners are supported.
- The number of OAR scientists and programs partnering with Indigenous and Tribal end users to support ocean-related management and decision making increases.
- The number of impactful OAR ocean carbon science outreach products increase and increase and are disseminated to the public (including web stories, videos, lesson plans, and other outreach materials).
- Improved provision of ocean carbon products and services leads to an increased number of congressional engagements.
- The OAR ocean carbon workforce grows, including at labs, programs, and partner institutions, contributing to ocean carbon research and observing.
- Increased availability of training, continuing education, and professional development opportunities are provided for OAR staff working on ocean carbon.

Milestones

- Ocean carbon products and services are co-developed with user communities and other oceanographic organizations.
- Positive feedback is received from communities invested in ocean carbon research during the routine lab and program review process.
- OAR ocean carbon activities are reported frequently to OAR and NOAA leadership (e.g., hot item posts for weekly reports, newsletters, etc.).
- OAR ocean carbon data and products are frequently cited in assessments, products, papers, etc., and are used by co-design partners and end users.
- OAR-funded scientists continue to disseminate cutting edge information and advancements in ocean carbon cycle science with the broader community through national and international presentations and high-impact peer-reviewed publications.
- New early career development opportunities are created, especially for graduate students, post-docs, and early career employees.
- Ocean carbon research and program staff in OAR labs, programs, and cooperative institutes are retained.

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APPENDIX B: OCEAN CARBON OBSERVING DIRECTIVES AND AUTHORIZING LANGUAGE

Summary

Ocean and coastal carbon observing is congressionally mandated through the Federal Ocean Acidification Research And Monitoring Act of 2009 (FOARAM), which requires federal agencies to monitor and conduct research on the processes and consequences of ocean acidification. Moreover, the Integrated Coastal and Ocean Observation System Act of 2009, and its reauthorization via the Coordinated Ocean Observations and Research Act of 2020, require federal agencies "to improve the Nation's capability to measure, track, observe, understand, and predict events related directly and indirectly to weather and climate, natural climate variability, and interactions between the oceanic and atmospheric environments, including the Great Lakes." In 2023, the White House Office of Science and Technology Policy's Ocean Climate Action Plan (OCAP) and the National Strategy to Advance an Integrated U.S. Greenhouse Gas Measurement, Monitoring, and Information System (GHGMMIS) called on federal agencies to ensure robust, sustained, and adequate ocean observations are in place to support critical initiatives including monitoring of natural systems emissions and removals (i.e., "sinks") and mCDR research.

Internationally, a suite of strategic, research, science, and implementation plans have been developed to address the goals of the Paris Agreement and the United Nations (UN) Decade of Ocean Science for Sustainable Development (2021-2030). These plans include the Intergovernmental Oceanographic Commission's (IOC) Integrated Ocean Carbon Research (IOC-R) plan, the Roadmap for the Implementation of the Global Ocean Observing System (GOOS) 2030 Strategy, the 2022 Global Climate Observing System (GCOS) Implementation Plan, and the World Meteorological Organization (WMO) Global Greenhouse Gas Watch (G3W) Implementation Plan. All four plans call for an enhancement of *in situ* ocean carbon observations to better quantify net flux of ocean carbon.

Strategic documents, directives and agreements

NOAA

NOAA FY22-26 Strategic Plan

OAR Strategy 2020-26

GOMO FY21-25 Strategic Plan

Ocean, Coastal, and Great Lakes Acidification Research Plan: 2020-2029

Strategy for NOAA CDR Research

The GFDL 5-10 Year Strategic Science Plan

Global Monitoring Division 2018-2022 Research Plan

PMEL Strategic Plan 2021-2030

AOML Strategic Plan 2022-2026

GLERL Strategic Plan 2024-2028

GLERL Implementation Plan 2024-2028

ARL Strategic Plan 2021-2026

OER Strategic Plan 2023-2027

CPO Strategic Plan 2024-2028

Sea Grant Strategic Plan 2024-2027

National Severe Storms Laboratory Strategic Plan 2021-2030

Weather Program Office Strategic Plan 2022-2026

NOAA Blue Economy Strategic Plan: 2021-2025

NOAA Education Strategic Plan 2021-2040

Department of Commerce

U.S. Department of Commerce Strategic Plan 2022-2026

National

National Strategy to Advance an Integrated U.S. Greenhouse Gas Measurement

Monitoring, and Information System

Ocean Climate Action Plan

The United States Ocean Acidification Action Plan

National Marine Carbon Dioxide Research Strategy

International

Global Ocean Observing System 2030 Strategy

The 2022 GCOS Implementation Plan

Integrated Ocean Carbon Research (IOC-R)

WMO Global Greenhouse Gas Watch (G3W) Implementation Plan

Paris Agreement

Declaration on Operationalising the Surface Ocean Carbon Value Chain

Venice Declaration for Ocean Literacy in Action

Research statutes, mandates, and authorizing language directing general oceans and climate research

National Sea Grant College Program (33 U.S. Code § 1123): The National Sea Grant College Program provides financial assistance for research, education, training, technology transfer, and public service. It supports state Sea Grant programs, the administration of the program, and strategic investments in ocean, coastal, and Great Lakes resources, developed in consultation with the Board and approved by sea grant colleges and institutes.

National Oceanographic Partnership Program (10 USC §§8931): This program is mandated to promote the national goals of advancing national security, economic development, environmental protection and stewardship, and science education through enhanced ocean knowledge. It coordinates and strengthens oceanographic efforts by fostering partnerships among federal agencies, academia, industry, and the oceanographic community, and by executing research projects that support these objectives through grants, contracts, cooperative agreements, and other mechanisms.

Integrated Coastal and Ocean Observation System Act (ICOOS Act), reauthorized via the Coordinated Ocean Observations and Research Act of 2020: authorizes activities to promote basic and applied research for developing, testing, and deploying advanced coastal and ocean observation technologies to address data gaps and enhance understanding of weather, climate, and ocean dynamics. It also supports efforts to conserve healthy ecosystems and restore degraded coastal environments.

America Competes Act: [P.L. 110-69] Title IV of this Act directs NOAA to coordinate with NSF and NASA to establish a coordinated program of ocean, coastal, Great Lakes, and atmospheric research and development (in collaboration with academic institutions and other nongovernmental entities) that focuses on the development of advanced technologies and analytical methods that will promote United States leadership in ocean and atmospheric science and competitiveness.

America COMPETES Reauthorization Act of 2010 (33 U.S.C §§ 893-893c): Authorizes the Administrator of NOAA, in consultation with the NSF and NASA, to establish a coordinated program for ocean, coastal, Great Lakes, and atmospheric research and development to advance U.S. leadership in science and competitiveness in applied technologies. The program focuses on identifying emerging research priorities, promoting U.S. leadership in oceanic and atmospheric science, and advancing transformative research and observations in collaboration with federal agencies, academic institutions, and the private sector.

Global Change Research Act of 1990 (15 U.S.C. § 2921 et seq): This act supports the development and coordination of a United States research program to understand, assess, predict, and respond to anthropogenic and natural processes of global change. (§2932) NOAA is a member of the Committee on

Earth and Environmental Sciences, which oversees federal global change research efforts to enhance their effectiveness and productivity, focusing on changes in the global environment that may affect Earth's capacity to sustain life.

National Climate Program Act (15 U.S.C. 2901-2908, at 2904(d) (4), et seq.): This act authorizes global data collection, monitoring, and analysis to provide continuous data on climate and environmental changes, and promotes increased international cooperation in climate research. The President, through the Environmental Protection Agency, is tasked with developing and proposing to Congress a coordinated U.S. policy on global climate change, considering research from key federal agencies (including NOAA) and scientific organizations.

National Oceanic and Atmospheric Administration Act of 1992 (15 U.S.C 1540): Authorizes cooperative institutes and agreements to promote scientific and educational activities to foster public understanding of NOAA or its programs.

National Environmental Policy Act (NEPA) of 1969: Requires federal agencies to consider the environmental impact of their projects and programs.

Coastal Zone Management Act (CZMA) of 1972 (as amended 1990) (16 U.S.C. § 1450 et seq.): Requires understanding and predicting long-term climate change, which may have large impacts in the coastal zone such as global warming and associated sea level rise.

Consolidated Appropriations Act of 2005, Pub. Law No. 108-447: "Establish[es] a Federal research program that examines ocean resources and their applications to human health." The Act aims to "…ensure that any integrated ocean and Coastal observing system provides information necessary to monitor, predict and reduce marine public health problems including: (A) baseline observations of physical ocean properties to monitor climate variation; (B) measurement of oceanic and atmospheric variables to improve prediction of severe weather events; …"

Federal Ocean Acidification Research and Monitoring Act of 2009, Pub. Law No. 111-11 (as passed in the Omnibus Public Land Management Act of 2009): Establishes an ocean acidification program within NOAA to conduct research, monitor ocean chemistry and biological impacts of ocean acidification, and coordinate with appropriate international ocean science bodies.

Secure Water Act of 2009, Pub. Law No. 111-11 (as passed in the Omnibus Public Land Management Act of 2009): NOAA shall provide the Secretary of the Interior with "access to the best available scientific information with respect to presently observed and projected future impacts of global climate change on water resources."

Omnibus Public Land Management Act of 2009: NOAA and DOI are directed to establish and lead an inter-agency panel to review current scientific understanding of climate change on the quantity and quality of U.S. water resources and develop strategies to improve observational capabilities, expand data acquisition, increase the reliability and accuracy of modeling and prediction systems to benefit water managers, and increase the understanding of the impacts of climate change on aquatic ecosystems. NOAA will establish an ocean acidification program and in collaboration with NSF and NASA will develop and coordinate an interagency plan that will assess impacts from ocean acidification. NOAA is authorized to perform research on marine ecosystem adaptation to ocean acidification, including coordinated interdisciplinary and international research, long-term monitoring, and research to develop adaptation strategies for marine ecosystems

Federal Water Pollution Control Act (Clean Water Act; 33 U.S.C. § 1251 et seq.): The principle statute governing water quality with the goal is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters.

U.S.C. § 883d, Improvement of methods, instruments, and equipments; investigations and research: To improve the efficiency of the National Ocean Survey and to increase engineering and scientific knowledge, the Secretary of Commerce is authorized to conduct developmental work for the improvement of surveying and cartographic methods, instruments, and equipments; and to conduct investigations and research in geophysical sciences (including geodesy, oceanography, seismology, and geomagnetism).

The Coral Reef Conservation Act of 2000: This Act is the primary driver for the CRCP activities by directing NOAA to develop and implement a national strategy and program for coral reef conservation and management that includes coastal uses and management; water and air quality; mapping and information management; research, monitoring, and assessment; international and regional issues; outreach and education; local strategies developed by the States and Federal agencies, including regional fishery management councils; and conservation, including how the use of marine protected areas to serve as replenishments zones will be developed consistent with local practices and traditions.

Oceans and Human Health Act: the Secretary of Commerce established an Oceans and Human Health Initiative to coordinate and implement research and activities of NOAA related to the role of the oceans in human health.

Magnuson Stevens Fishery Conservation and Management Reauthorization Act (1976, 1996, 2006): Provides for research to support fishery conservation and management, including but not limited to, biological research concerning the abundance and life history parameters of stocks of fish, the interdependence of fisheries or stocks of fish, the identification of essential fish habitat, the impact of pollution on fish populations, the impact of wetland and estuarine degradation, and other factors affecting the abundance and availability of fish.

National Aquaculture Act of 1980, (16 U.S.C. at 2801-2810): Directs Commerce to study, promote, and regulate the US aquaculture industry.

Harmful Algal Bloom and Hypoxia Research Control Act: mandates NOAA to develop research plans and assessments and examine alternatives to reduce, mitigate, and control hypoxia and HABs in coastal waters including the Great Lakes. Includes relevant OA-HAB research.

Infrastructure Investment and Jobs Act (aka Bipartisan Infrastructure Law): Title II directs NOAA to improve and enhance coastal, ocean, and Great Lakes observing systems.

Inflation Reduction Act: Title IV directs NOAA to accelerate advances and improvements in research, observing systems, modeling, forecasting, assessments, and dissemination of information to the public as it pertains to ocean and atmospheric processes related to weather, coasts, oceans, and climate.

FOARAM (33 U.S.C Ch. 50): requires federal agencies to monitor and conduct research on the processes and consequences of ocean acidification.

Permitting statutes - an informed permitting process requires sufficient research to inform regulators' decisions, with the following statutes giving NOAA a permitting role and requiring it to conduct relevant research:

- **Marine Mammal Protection Act:** Permits the Secretary of Commerce to support research in subjects which are relevant to the protection and conservation of marine mammals. funding
- **Marine Protection, Research, and Sanctuaries Act:** Directs the Secretary to undertake a comprehensive research program on the effects of ocean dumping, as well as human-induced changes in ocean ecosystems.
- **National Marine Sanctuaries Act:** Directs the Secretary to support, promote, and coordinate scientific research on, and long-term monitoring of, the resources and natural processes of marine Sanctuary areas.
- **Endangered Species Act:** Allows the Secretary to issue permits for scientific purposes or to enhance the propagation or survival of an affected species.

Data Management authorizing language and strategic documents

This Science Plan's data management approach is in line with:

- The White House Office of Science and Technology Policy (OSTP) memorandum, **"Increasing Access to the Results of Federally Funded Scientific Research" (February 22, 2013):** mandates open accessibility of research data for all federal funding agencies.
- The U.S. House of Representatives' **"H.R.4174 - Foundations for Evidence-Based Policymaking Act of 2018" (January 14, 2019):** requires data from all federal agencies to be accessible to support policymaking.
- The latest OSTP policy guidance, **"Ensuring Free, Immediate, and Equitable Access to Federally Funded Research" (August 25, 2022):** emphasizes unrestricted public access to federally funded research results, including both publications and scientific data, without embargoes or fees.
- NOAA's Data Strategy and Data Strategic Action Plan
- NOAA Public Access to Research Results (PARR) Plan

In addition, this Science Plan's data management approach will support cross-network plans such as the:

- GOOS OCG Cross-Network Data Implementation Strategy
- UNESCO IOC's Ocean Decade Data and Information Strategy

Authorizing and appropriations language directing mCDR research

- **Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM; 33 U.S.C Ch. 50):** SEC. 12402: “research on adaptation strategies and mitigation of impacts of ocean and coastal acidification and related co-stressors on marine ecosystems.”
- **CHIPS and Science Act:** Amended the FOARAM Act and added in additional language around mitigation of ocean acidification.
- **Infrastructure Investment and Jobs Act (aka Bipartisan Infrastructure Law):** emphasizes the importance of carbon capture, utilization, storage, and transportation infrastructure in reducing emissions from the industrial sector, which is responsible for nearly 25% of U.S. carbon dioxide emissions. It finds that large-scale deployment of these technologies is essential for achieving climate goals, driving regional economic growth, technological innovation, and high-wage jobs, while requiring a backbone system of shared carbon dioxide transport and storage infrastructure, supported by both federal and state initiatives alongside private investment.
- **FY 24 Appropriations Report Language (from Senate Report):** “National Oceanographic Partnership Program [NOPP].—The Committee provides $2,500,000 for NOPP to continue to facilitate interagency and public-private partnerships to advance ocean science research, development, and education. Within the funds provided, NOAA shall allocate no less than $500,000 to work with other appropriate Federal agency and industry partners to develop, test, and evaluate ocean-based carbon dioxide removal technologies.”
- **FY 23 Appropriations Report Language (from Joint Explanatory Statement):** “National Oceanographic Partnership Program (NOPP).—Within the funds provided for NOPP, NOAA is encouraged to work with other appropriate Federal agencies and industry partners to develop, test, and evaluate ocean-based carbon dioxide removal technologies.”
- **Consolidated Appropriations Act of 2021:** “Sec. 5002. Directs the Secretary of Energy to establish a Carbon Dioxide Removal Task Force and, in consultation with the heads of any other relevant Federal agencies, to prepare a report no later than 180 days after the date of enactment of this Act.”

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APPENDIX C: ACRONYM DEFINITIONS

AOML - Atlantic Oceanographic and Meteorological Laboratory

ARL - Air Resources Laboratory

BATS - Bermuda Atlantic Time-series Study

BCP - Biological Carbon Pump

BGC-Argo - Biogeochemical Argo

BOEM - Bureau of Ocean Energy Management

^{14}C - Carbon-14, or "radiocarbon"

CARE - Collective benefit, Authority to control, Responsibility, Ethics

CCD - Co-design and Capacity Development

CCHDO - CLIVAR and Carbon Hydrographic Data Office

CDR - Carbon Dioxide Removal

CO_2 - Carbon Dioxide

CFCs - Chlorofluorocarbons

CTD - Conductivity, Temperature, Salinity (instrument)

CLIVAR - Climate Variability and Predictability Program

C:N:P:O - Ratio of carbon to nitrogen to phosphorus to oxygen, or the "Redfield Ratio"

CPO - Climate Program Office

CODAP - Coastal Ocean Data Analysis Products

CODAP-NA - Coastal Ocean Data Analysis Products - North America

DAC - Data Assembly Center

DIC - Dissolved Inorganic Carbon

$DI^{13}C$ - Isotopic composition of DIC, carbon-13

$DI^{14}C$ - Isotopic composition of DIC, carbon-14

DOC - Dissolved Organic Carbon

DOE - Department of Energy

DOI - Digital Object Identifier

DOS - Department of State

DM - Data Management

EBV - Essential Biodiversity Variable

ECV - Essential Climate Variable

eMLR-C* - Extended multiple linear regression of the carbon tracer C*

EOV - Essential Ocean Variable

EPA - Environmental Protection Agency

ESM - Earth System Model

FAIR - Findable, Accessible, Interoperable, Reusable

***f*CO_2** - Fugacity of CO_2

FOARAM - Federal Ocean Acidification Research and Monitoring Act

G3W - Global Greenhouse Gas Watch

GCB - Global Carbon Budget

GCM - Global Climate Model

GCOS - Global Climate Observing System

GDAC - Global Data Assembly Center

GFDL - Geophysical Fluid Dynamics Laboratory

GHG - Greenhouse Gas

GHGMMIS - Greenhouse Gas Measurement, Monitoring, and Information System

GLERL - Great Lakes Environmental Research Laboratory

GLODAP - Global Ocean Data Analysis Project

GML - Global Monitoring Laboratory

GO-BGC - Global Ocean Biogeochemical Argo

GO-SHIP - Global Ocean Ship-based Hydrographic Investigation Program

GOA-ON - Global Ocean Acidification Observing Network

GOBM - Global Ocean Biogeochemistry Model

GOMO - Global Ocean Monitoring and Observing Program

GOOS - Global Ocean Observing System

GtC - Gigaton of Carbon

[H^+] - Concentration of hydrogen ions

HOT - Hawaiian Ocean Time-series

IOC - Intergovernmental Oceanographic Commission

IOC-R - Integrated Ocean Carbon Research

IOCCP - International Ocean Carbon Coordination Project

IOOS - Integrated Ocean Observing System

IPCC - Intergovernmental Panel on Climate Change

K-12 - Kindergarten through 12th grade

LSCOP - Large Scale CO_2 Observing Plan

LTER - Long-term Ecological Research

mCDR - Marine Carbon Dioxide Removal

MMRV - measurement, monitoring, reporting, and verification

N2 - Nitrogen

NASA - National Aeronautics and Space Agency

NCEI - National Centers for Environmental Information

NESDIS - National Environmental Satellite, Data, and Information Service

NGO - Non-Governmental Organization

NMFS - National Marine Fisheries Service

NOAA - National Oceanic and Atmospheric Administration

NOA-ON - NOAA Ocean Acidification Observing Network

NOAWG - NOAA Ocean Acidification Working Group

NOPP - National Oceanographic Partnership Program

NSF - National Science Foundation

O_2 - Oxygen

OA - Ocean Acidification

OAP - Ocean Acidification Program

OAR - Oceanic and Atmospheric Research

OCADS - Ocean Carbon Data System

OCAP - Ocean Climate Action Plan

OCB - Ocean Carbon and Biogeochemistry program

OER - Ocean Exploration Program

O&M - Observations and Models, in reference to the "Surface Observations and Ocean Model Estimates of Global Air-Sea CO_2 Flux" callout box

ONR - Office of Naval Research

OMIP - Ocean Model Intercomparison Project

OSD - Observing System Design

OSE - Observing System Experiment

OSSE - Observing System Simulation Experiment

PIC - Particulate Inorganic Carbon

PMEL - Pacific Marine Environmental Laboratory

ΔpCO_2 - Delta between the partial pressure of carbon dioxide (pCO_2) in the surface ocean and the overlying atmosphere

POC - Particulate Organic Carbon

RECCAP – REgional Carbon Cycle Assessment and Processes

SF6 - Sulfur hexafluoride

SOCAT - Surface Ocean CO_2 Atlas

S_{OCEAN} - Ocean Sink

SOCCOM - Southern Ocean Carbon and Climate Observations and Modeling

SOCONET - Surface Ocean CO_2 Monitoring Network

SOLAS-IMBER - Surface Ocean Lower Atmosphere Study-Integrated Marine Biogeochemistry and Ecosystem Research

SOOP - Ships of Opportunity

STEM - Science Technology Engineering Mathematics

TA - Total Alkalinity

^{234}Th - Thorium-234

QA - Quality Assurance

QC - Quality Control

UN - United Nations

UNESCO - United National Educational, Scientific, and Cultural Organization

USGS - United States Geological Survey

USD - United States Dollars

USV - Uncrewed Surface Vehicle

UVP - Underwater Vision Profiler

WMO - World Meteorological Organization

WOD - World Ocean Database

XCO_2 - Concentration of CO_2

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