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Abstract

This landscape analysis examined U.S. federal sustained, *in situ* ocean carbon observing efforts, identifying spatiotemporal gaps in the global coverage of these observations. A range of observational platforms were analyzed, including research vessels, ships of opportunity, moorings, autonomous surface vehicles (ASVs), and biogeochemical profiling floats. Despite extensive coverage by OAR alone in regions like the North Pacific, North Atlantic, Tropical Pacific, and Tropical Atlantic, notable gaps remain in southern hemisphere oceans, the Indian and Arctic Oceans, and the Laurentian Great Lakes. U.S. federal agencies have additional ocean carbon observation efforts throughout the global ocean, filling some of these gaps, yet observational efforts remain heavily biased toward the North Pacific and North Atlantic. Furthermore, high frequency ocean carbon observations of the deep ocean are lacking in most ocean basins. These gaps impact accurate quantification of ocean carbon reservoirs and fluxes, necessitating augmented and/or additional observational efforts, especially in under-sampled climate critical regions (e.g., polar oceans) and the deep ocean. This analysis emphasizes the need for technological advancements to overcome depth and seasonal biases, such as ice-related limitations in the Arctic Ocean, Southern Ocean, and Great Lakes. Although OAR is uniquely positioned to augment observations in some under-sampled climate critical regions, and to develop technology to overcome sampling limitations, this analysis also highlights the importance of collaboration across U.S. federal agencies and international partners to develop a more comprehensive global ocean carbon observing system. Ultimately, this work begins to answer some of the research questions within goal 1 of OAR's Ocean Carbon Observing Science Plan and recommends coordinated and regionally targeted ocean carbon observing augmentation for improved ocean carbon cycle quantification.

Introduction

NOAA Oceanic and Atmospheric Research (OAR) Ocean Carbon Observing Strengths

One of OAR's strengths lies in its long-term investments of sustained global ocean observations covering the open ocean, coasts, and Great Lakes. Within OAR, sustained ocean carbon observations are collected within every ocean basin, from the sea surface to the sea floor. These sustained observing efforts include U.S. GO-SHIP, Surface Ocean CO_2 Reference Observing Network (SOCONET) (with measurements from research vessels, autonomous surface vehicles [ASVs], moorings, and ships of opportunity [SOOPs]), BGC-Argo, Coastal Ocean Acidification (OA) Cruises, and the NOAA Ocean Acidification Observing Network (NOA-ON). Many of OAR's observing and research efforts are conducted in partnership with other NOAA line offices and federal agencies, including the National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), Department of Energy (DOE), Environmental Protection Agency (EPA), United States Geological Survey (USGS), Office of Naval Research (ONR), among others. Some programs supported by OAR (e.g. U.S. contributions to OneArgo and Global Ocean Ship-based Hydrographic Investigations Program [GO-SHIP]) receive 50% or more of their funding from other agencies (NSF).

Additionally, other NOAA line offices and U.S. agencies have independent sustained, campaign-based, and/or short term ocean carbon observing and research efforts. Some of these efforts use unique (e.g., different from OAR) platforms, assets, and techniques to collect ocean carbon measurements, including remote sensing (NASA and NOAA's National Environmental Satellite, Data, and Information Service [NESDIS]) and sediment traps to measure biological carbon export (NASA and NSF). Other agencies and NOAA line offices also fill spatiotemporal gaps that OAR currently does not. For instance, NASA and NESDIS remote sensing operations provide spatially broad, high frequency atmospheric carbon observations over the global ocean that help estimate air-sea CO_2 flux. NSF's Southern Ocean Carbon and Climate Observations and Modeling project (SOCCOM) uses biogeochemical profiling floats to measure interior carbon in the Southern Ocean. Furthermore, NOAA's National Ocean Service (NOS) supports a network of coastal buoys, fixed shore platforms, Wave Gliders, underwater gliders, and shore based sampling efforts that complement OAR's coastal North American carbon sampling efforts. Both the partnerships described above and the independent efforts described here are critical to comprehensively sampling the global ocean by leveraging strengths of each agency and line office. However, despite this global coverage, clear gaps in ocean carbon data remain. More comprehensive sampling of carbon throughout the global ocean is critical to improving accurate quantification of the global ocean carbon cycle. Enhancing ocean carbon observations, which are used for climate projections, ocean acidification forecasts, and global carbon accounting, will better inform policy and management decisions.

This landscape analysis seeks to identify the "who" and "where" of United States *in situ* global ocean carbon observing, analyzing where gaps in these efforts remain. Aircraft and satellites collecting atmospheric carbon measurements (and other parameters necessary for carbon flux calculations) were not included in this analysis focused on *in situ* observations. This study was used to inform OAR Ocean Carbon Observing Science Plan Goal 1 research questions, objectives, and suggested actions which addresses filling observational and knowledge gaps (Kelly et al. 2025). While this analysis focused on information related to Goal 1, landscape analyses of ocean carbon data, models, products, and services (as related to Goal 2) and communication, outreach, education, and capacity development (as related to Goal 3) may be performed separately in the future.

Methods

Data on all known federal ocean carbon observing efforts were collected using information available online (webpages, reports, data repositories, etc.). Only sustained, *in situ,* inorganic ocean carbon (*fugacity* of carbon dioxide, pH, total alkalinity, and dissolved inorganic carbon) observing efforts were considered in this analysis. Here, "sustained" is defined as occurring (or planned to occur) for five or more years, even if no longer sustained as of 2025. For each observing effort, the following data was collected: sampling agency, NOAA line office (if applicable), name of sampling effort, length of time the sampling effort has been sustained, platform, depth(s) sampled, and region(s) sampled.

All known OAR sustained ocean interior carbon observations (**Table 1**), OAR surface ocean observations from moorings and ASVs (**Table 2**), and NOAA and partner Surface Ocean CO_2 Atlas (SOCAT) v2024 observations (**Table 3**) were included in this analysis. Observations collected between 30°N and 30°S were considered within the Tropical Atlantic or Tropical

Pacific based on the SOCAT definition for tropical oceans. Observations collected above the Aleutian Islands (for the Pacific Ocean) or above 60°N (for the Atlantic Ocean) were considered within the Arctic Ocean, and samples below 60°S were considered the Southern Ocean. Furthermore, **Tables 1 and 2** include both coastal and open ocean observations together, while **Table 3** groups all coastal observations together without delineation by ocean basin due to SOCAT methodology.

In **Tables 1 and 2**, quantification of an "observation" was platform specific. For BGC-Argo, one profile counted as one observation, and all profiles as of November 4th, 2024 were considered. For OAR contributions to U.S. GO-SHIP and Ocean Acidification Program (OAP) Coastal Ocean Acidification Cruises (West Coast Ocean Acidification [WCOA], East Coast Ocean Acidification [ECOA], Gulf of Mexico and East Coast Carbon [GOMECC]), one station was considered one observation. For Rainier Integrates Charting, Hydrography, and Reef Dynamics (RICHARD) and National Coral Reef Monitoring Program (NCRMP) cruises conducted in partnership with OAP, one carbonate chemistry sample (a discrete sample collected by scientific divers) was counted as one observation. For each buoy with MAPCO2 systems and/or pH meters, and ASVCO2 systems on Saildrones, underwater gliders, and Wave Gliders, one day deployed counted as one observation, and data available online as of November 4th, 2024 were considered .

SOCATv2024 was used to create **Table 3**. Coastal observations were categorized separately in the SOCAT Live Access Server (PMEL), thus samples in each ocean basin represent open ocean samples. This SOCAT methodology also combines South Pacific, South Atlantic, and Southern Ocean samples, categorizing them all as Southern Ocean because of the limited number of observations in each ocean basin. In this analysis, samples per ocean basin were also normalized by the number of 1°x1° grid cells per ocean basin as defined by SOCAT (Pfeil et al. 2013). Furthermore, this normalization only addresses surface area, not volume of each ocean basin. Finally, SOCAT data includes observations collected by NOAA and our partners, not just OAR, due to the granularity of attribution within the SOCAT Live Access Server.

For interagency analyses (**Figure 2**), efforts were counted multiple times if sampling efforts occurred in multiple ocean basins.

Results and Discussion

OAR Ocean Interior Carbon Measurements

The North Pacific, North Atlantic, Tropical Atlantic, and Tropical Pacific were the most well sampled ocean regions by OAR, in terms of ocean interior inorganic carbon (**Table 1**). These measurements largely consisted of U.S. coastal observations, where several OAR efforts are focused (e.g., WCOA, ECOA, GOMECC, OAR Biogeochemical (BGC) Argo). Other efforts, like OAR's contribution to U.S. GO-SHIP, collected samples in the open oceans, yet accounted for a relatively small fraction of total observations in the North Pacific, North Atlantic (13% and 14%, respectively; **Table 1**). In contrast, GO-SHIP in the Tropical Atlantic and Tropical Pacific accounted for 26% and 41% (respectively) of OAR interior carbon observations in these basins. While these observations provide valuable interdecadal (GO-SHIP) and bi-decadal (Coastal OA

Cruises) information, high frequency ocean interior measurements (e.g., BGC-Argo) are more sparse.

Table 1: OAR sustained ocean interior carbon observations per ocean basin. U.S. GO-SHIP observations include only those provided by OAR.

Ocean Basin	Ocean carbon observing effort			Total ocean carbon interior observations
	BGC Argo	U.S. GO-SHIP	OAP Coastal OA Cruises	
Tropical Atlantic	289	599	1436	2324
North Atlantic	887	213	553	1653
Tropical Pacific		407	580	987
North Pacific		111	706	817
South Atlantic		237		237
Arctic Ocean			211	211
South Pacific		157		157
Indian Ocean		128		128
Southern Ocean				0

The South Pacific, South Atlantic, and Indian Ocean interiors have been sampled 7-13x less by OAR, relative to the North Atlantic Ocean. U.S. GO-SHIP has been the only OAR effort in these ocean basins. Again, while this inter-decadal climate-quality information is highly valuable, sustained higher frequency information is lacking and inhibits precise quantifications of ocean interior carbon sinks and fluxes. Lastly, few OAR efforts have collected ocean interior measurements in the Arctic ocean (the Gulf of Alaska Ocean Acidification Cruise in 2022, Bering Arctic Subarctic Integrated Survey in 2022, and sustained Ecosystems and Fisheries-Oceanography Coordinated Investigations), and OAR does not currently have any sustained ocean interior sampling efforts in the Southern Ocean. Therefore, these ocean basins may be considered gaps in OAR's ocean interior carbon observing efforts, though it is important to note that interagency efforts contribute to filling some of these gaps (see below).

OAR surface ocean observations from moorings and ASVs

Examining OAR surface ocean carbon observations from moorings and ASVs (Saildrones, underwater gliders, and Wave Gliders), the Tropical Pacific was the most observed region. Efforts in this region included 15 long term moored buoys (e.g., the TAO array) that have been providing sustained surface ocean observations since 2004 (**Table 2**; PMEL Carbon Program). The next most observed regions by OAR were the North Pacific and North Atlantic. OAR has several coastal ocean mooring arrays along North American coasts, yet few open ocean moorings exist (four as of 2023). Therefore, the surface ocean in these open ocean regions was relatively undersampled by these technologies.

For the Arctic and Southern Oceans, observations were relatively more sparse. Saildrone missions have occurred but are seasonally biased away from winter. High frequency surface ocean carbon observations (excluding underway measurements from research vessels and ships of opportunity [SOOPs]) have not been collected in the South Atlantic and Indian Oceans. SOOPs, other NOAA line office efforts, and U.S. agency efforts fill some of these gaps, yet some ocean basins remain under-observed (see below).

Table 2: Sustained OAR surface ocean carbon observations. ASVCO2 measurements include those collected from Saildrone, underwater glider, and Wave Glider missions.

Ocean Basin	Observing Effort		Total Observations
	Buoys	ASVCO2	
Tropical Pacific	40920	401	41321
North Pacific	25374	369	25743
North Atlantic	10954	289	11243
Tropical Atlantic	7766		7766
Arctic Ocean	2383	790	3173
Southern Ocean	2164	48	2212
South Pacific		11	11
South Atlantic			0
Indian Ocean			0

NOAA and partner contributions to SOCATv2024 fill some surface ocean observing gaps

Some of these gaps in surface ocean carbon data have been filled by underway fugacity of carbon dioxide (fCO_2) sampling on SOOPs according to data extracted from SOCATv2024. It should again be noted that the following analysis only considers open ocean observations, as coastal observations were categorized separately and not delineated by ocean basin. The Southern, South Pacific, and South Atlantic Oceans will be excluded from this analysis, as SOCAT categorization methods group the limited number of observations from the South Atlantic and South Pacific with the Southern Ocean, artificially inflating the number of observations (see methods). The SOCATv2024 announcement highlighted the severe undersampling in these southern hemisphere ocean basins (Bakker et al. 2024; **Figure 1**), which is partially due to fewer ship operations occurring in the southern hemisphere. Therefore, although the numbers for these ocean basins may be misleading in this analysis, other evidence points to undersampling in the Southern hemisphere ocean basins.

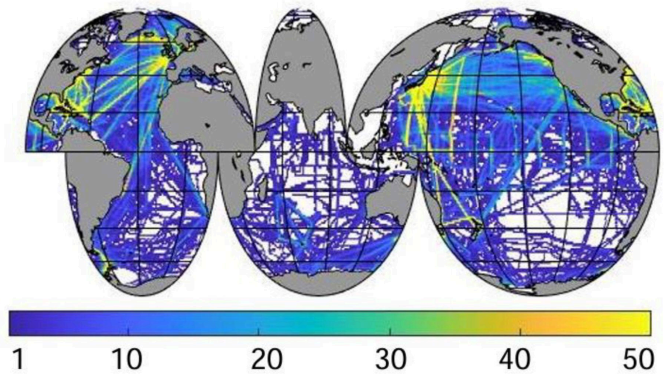

Figure 1: The number of individual months with 1°x1° gridded surface ocean *f*CO2 values between 1970 and 2002. Reproduced from Bakker et al. 2024.

According to data extracted from SOCATv2024 and normalized by the number of 1°x1° grid cells per ocean basin, the Tropical Pacific, Tropical Atlantic, and North Atlantic Oceans were the most sampled surface oceans by NOAA and partners (**Table 3**). This is similar to the findings from OAR mooring and ASV observations (**Table 2**), though those observations were not normalized to account for the difference in basin sizes.

The Indian and Arctic Oceans were the least sampled ocean basins in this analysis (**Table 3**). The Indian Ocean is generally agreed upon as an undersampled region by the ocean carbon observing community, while sampling in the Arctic remains a challenge due to accessibility and sea ice. Surprisingly, the North Pacific was the third least sampled ocean basin, with approximately 1.9x fewer observations per 1°x1° grid cell than the North Atlantic. However, these numbers only include open ocean, not coastal data, which likely account for a significant portion of observations. This may indicate that the open ocean in the North Pacific is relatively undersampled compared to other ocean basins.

The full SOCATv2024 data set, including all observations, has a few differences from the NOAA subset of SOCATv2024 (**Table 3**). Notably, the North Atlantic and Tropical Atlantic were 3.3x and 3.2x more sampled than the Tropical Pacific (respectively), and the Arctic Ocean was 2.3x more sampled than the Indian Ocean. Furthermore, the North Pacific was relatively more sampled than the Tropical Pacific, in contrast to NOAA and partner SOCAT data. The relative increase in North Atlantic, Tropical Atlantic, North Pacific, and Arctic Ocean observations may be due to SOOP and other research operations funded by other nations.

Table 3: The total number of open ocean and coastal observations in SOCATv2024 made by NOAA and partners, and all SOCATv2024 observations, per ocean basin. This data was also normalized by the approximate number of 1°x1° grid cells per ocean basin. South Pacific and South Atlantic observations were categorized as Southern Ocean measurements due to SOCAT methodology. Within each ocean basin listed observations are considered open ocean, as

coastal observations were categorized separately. *Indicates that observations have not been considered in this analysis.

Ocean Basin	NOAA and partner observations	All observations in SOCATv2024	Approximate 1°x1° grid cells per ocean basin	Number of observations per 1°x1° grid cell (NOAA and partners)	Number of observations per 1°x1° grid cell (all)
Coastal*	5,779,569	28,909,653	6093	949	4745
Tropical Atlantic	464,531	2,623,497	1429	325	1836
Tropical Pacific	2,335,901	4,436,769	7710	303	575
North Atlantic	755,793	4,903,691	2557	296	1918
Southern Ocean*	3,115,120	9,970,037	14617	213	682
North Pacific	289,410	1,511,114	1817	159	832
Indian	232,962	416,963	2212	105	189
Arctic	405,484	2,706,107	6194	65	437

Federal sampling efforts fill some of OAR's sampling gaps

Clear gaps remain in OAR's global ocean observing efforts, including high-frequency open ocean interior measurements in all ocean basins and surface ocean observations in the North Pacific, North Atlantic, and southern hemisphere open oceans. While these gaps exist in NOAA efforts, other U.S. agencies and international observing groups contribute to filling some of these gaps. It should be noted that not all sampling efforts are equal (i.e., the number of samples collected, sampling frequency, number of observing assets, etc., is different for each observing effort).

Examining the number of U.S. federal, sustained ocean carbon observing efforts across each ocean basin, the North Pacific and North Atlantic were the most sampled regions, with 23 and 18 sampling efforts in each, respectively (**Figure 2**). This was expected, as this analysis focused on Federal efforts, many of which occur in North American coastal waters. However, several of these efforts also include open ocean samples.

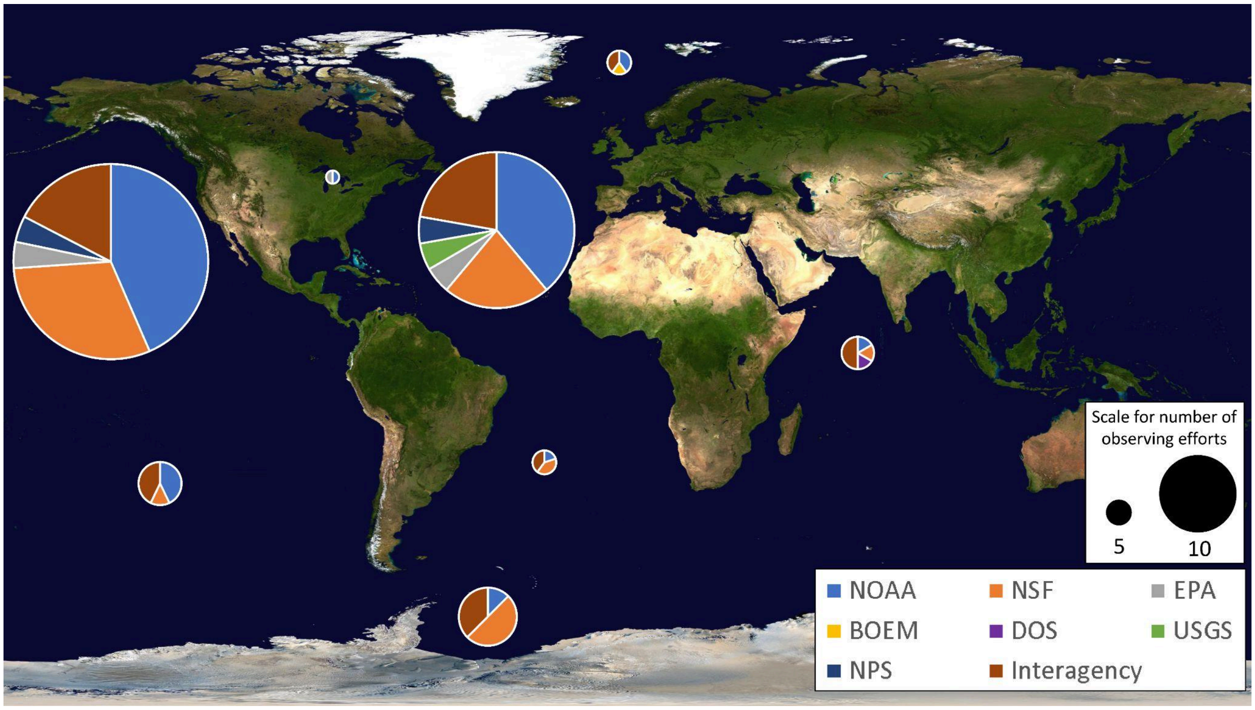

Figure 2: Sustained observing efforts and programs per ocean basin by an agency or interagency partnership (i.e., efforts conducted in partnership by two or more agencies) conducting the observing effort. If one effort collected measurements in multiple ocean basins, the effort was counted multiple times (once for each relevant basin). The size of the pie chart indicates the number of observing efforts, while color represents the agency conducting the observing effort(s).

In the North Atlantic and North Pacific Oceans, sustained open ocean efforts included: NSF's Global Ocean Biogeochemistry Array (GO-BGC), SOCONET, U.S. GO-SHIP (NSF and NOAA), and historically, the U.S. Joint Global Ocean Flux Study (JGOFS), and the World Ocean Circulation Experiment (WOCE) (**Table 4**). NSF's GO-SHIP, GO-BGC, efforts fill critical gaps in OAR's open ocean interior sampling in these regions. Maintenance and growth of the high-frequency deep observations by BGC-Argo is critical to continue providing valuable ocean interior data, yet GO-BGC is only funded by NSF through 2025. Furthermore, this technology is limited to measuring the upper 2000 m of the water column, thus technology that can reliably measure deeper high-frequency observations is needed (Goal 1 in Kelly et al. 2025). Therefore, while other agencies fill observational gaps in OAR North Pacific and North Atlantic open ocean data, important gaps remain.

The Arctic and Southern Oceans had 4.6x and 2.9x fewer sustained sampling efforts than the North Pacific. Many of these efforts occur in the summer season, as sampling under and around sea ice remains a challenge for sampling technologies. However, targeted efforts have been made to increase sampling of these hard-to-reach regions using profiling floats and autonomous surface vehicles (e.g., NSF's SOCCOM and OAR Saildrone missions).

In the Indian Ocean, where OAR efforts and NOAA SOCONET efforts are sparse, the Department of State (DOS), NSF, and interagency collaborations collect ocean carbon measurements. Even so, this region is undersampled relative to other ocean basins, and observational augmentation should be considered. Similarly, although NSF, BOEM, and interagency efforts fill some gaps in the Arctic, South Atlantic, and South Pacific Oceans, these basins have relatively few sampling efforts, especially considering their larger surface area.

Finally, the Laurentian Great Lakes only have two sustained sampling efforts: the Great Lakes Observing System, consisting of a few underway CO_2 sensors on ferry boats and moorings, and the EPA's Great Lakes Water Quality Monitoring Program. However, this sampling typically only occurs May to September, as observing assets are removed before ice formation. Furthermore, these efforts are not spatially extensive nor do they occur in all of the Great Lakes. More sampling in the Great Lakes that covers broader spatiotemporal scales is necessary for understanding aquatic carbon dynamics.

Table 4: List of federally supported sustained sampling efforts, including the agency conducting sampling, name of the effort, what ocean basins the samples are collected from, and where in the water column samples are collected.

Agency	Name	Acronym	Ocean Basin	Water column
Interagency (NSF and NOAA)	US Global Ocean Ship-based Hydrographic Investigations Program	US GO-SHIP	Global	Full
Interagency (NOAA, NSF, NASA, DOE, ONR, USGCRP)	US Joint Global Ocean Flux Study	JGOFS	North Atlantic, North Pacific, South Pacific, Indian Ocean, Southern Ocean	Full
Interagency (NOAA, NSF, USGCRP, international partners)	World Ocean Circulation Experiment	WOCE	Global	Full
Interagency (NOAA & BOEM)	Flower Garden Banks Long Term Monitoring	NA	North Atlantic	Surface
BOEM	Biogeochemical Assessment of the OCS Arctic Waters: Current Status and Vulnerability to Climate Change	NA	Arctic Ocean	Full
Interagency (BOEM, NPS, US Navy)	Pacific Regional Intertidal Sampling and Monitoring	PRISM	North Pacific	Surface

Department of State	OceAn pH Research Integration and Collaboration in Africa	ApHRICA	Indian Ocean	Surface
EPA	Coastal Ocean Acidification Monitoring	NA	North Pacific, North Atlantic	Surface
EPA	Great Lakes Water Quality Monitoring Program	NA	Great Lakes	Surface
NPS	Inventory and Monitoring Program (the ones below should maybe be lumped in)	NA	North Atlantic, North Pacific	Surface
NSF	Hawaii Ocean Time-series at Station A Long-term Oligotrophic Habitat Assessment	HOT at Station ALOHA	North Pacific	Surface to 4750m
USGS	Gulf of Mexico Sediment Trap with carbonate chemistry measurements	NA	North Atlantic	Surface to 50 m
NSF	Santa Barbara Coastal LTER	SBC LTER	North Pacific	Various
NSF	Georgia Coastal Ecosystems LTER	GCE LTER	North Atlantic	Surface
NSF	California Current System LTER	CCE LTER	North Pacific	Surface to 40 m
NSF	Plum Island Ecosystems LTER	PIE LTER	North Atlantic	Data not available
NSF	Palmer Antarctica LTER	PA LTER	Southern Ocean	Full
NSF	Moorea Coral Reef LTER	MCR LTER	North Pacific	Data not available
NSF	Bermuda Atlantic Time Series	BATS	North Pacific	Surface to 4200m
NSF	Global Ocean Biogeochemistry Array	GO-BGC	North Pacific, South Pacific, North Atlantic, South Atlantic, Indian, Southern Ocean	Surface to 2000 m

NSF	Ocean Observatories Initiative	OOI	North Pacific, North Atlantic, Arctic, South Atlantic, Southern Ocean	Varies by location, from surface to 130m
NSF	Southern Ocean Carbon and Climate Observations and Modeling	SOCCOM	Southern Ocean	Surface to 2000 m
NOAA	Biogeochemical Agro	BGC Argo	North Pacific, North Atlantic	Surface to 2000m
NOAA	East Coast Ocean Acidification Cruise	ECOA	North Atlantic	Full and underway surface
NOAA	Gulf of Mexico and East Coast Carbon Cruise	GOMECC	North Atlantic	Full
NOAA	West Coast Ocean Acidification Cruise	WCOA	North Pacific	Full and underway surface
NOAA	Surface Ocean CO2 Reference Observing Network	SOCONET	Global	Surface
NOAA	California Cooperative Oceanic Fisheries Investigations	CalCOFI	North Pacific	Full
NOAA	National Coral Reef Monitoring Program (includes RICHARD)	NCRMP	North Pacific, South Pacific, North Atlantic	Surface
NOAA	Mid-Atlantic Regional Association Coastal Ocean Observing System	MARACOOS	North Atlantic	Surface
NOAA	Great Lakes Observing System	GLOS	Great Lakes	Surface
NOAA	Alaska Ocean Observing System	AOOS	Arctic	Surface
NOAA	Caribbean Coastal Ocean Observing System	CARICOOS	North Pacific	Surface

NOAA	Central and Northern California Ocean Observing System	CeNCOOS	North Pacific	Surface
NOAA	Northwest Association of Networked Ocean Observing Systems	NANOOS	North Pacific	Surface
NOAA	Pacific Islands Ocean Observing System	PacIOOS	North Pacific, South Pacific	Surface
NOAA	Southern California Coastal Ocean Observing System	SCCOOS	North Pacific	Surface
NOAA	Southeast Coastal Ocean Observing Regional Association	SECOORA	North Atlantic	Surface

Conclusion and recommendations

This landscape analysis revealed spatiotemporal gaps in U.S. sustained ocean carbon observing efforts. However, it is important to first acknowledge that international groups may fill some of these observational gaps, though they were not included in this analysis. For U.S. federal efforts, southern hemisphere oceans (South Pacific, South Atlantic, and Southern Ocean), the Indian Ocean, and the Laurentian Great Lakes were relatively undersampled by OAR and other agencies, for both interior and surface ocean measurements. Intentional efforts to increase observations in these ocean basins, in collaboration between NOAA and other U.S. and international agencies, should be considered. Furthermore, although OAR sampling gaps also persist in the Southern Ocean, other U.S. agencies have made great strides towards filling these gaps (e.g., NSF SOCCOM). However, despite this region being one of the most important to observe, efforts remain seasonally biased due to sea ice (see below).

OAR is uniquely positioned to fill observing gaps in climate critical regions. While the Topical Pacific Ocean (both surface and interior) was the most sampled region by OAR, additional observations may be necessary to further resolve carbon cycling in this highly dynamic and critical region. With several existing efforts in this region, OAR should be well positioned to augment observations. Surprisingly, the North Pacific surface open ocean was also undersampled by NOAA and partners according to observations in SOCAT. Targeted efforts to fill observing gaps in this region should be undertaken as it is not only climate critical, but also relevant to the American Blue Economy as an ocean basin that supports U.S. fishing and other economically important activities.

OAR is also uniquely positioned to work towards developing technology that can aid in filling observational gaps identified by this analysis. For instance, though the Southern Ocean, Arctic Ocean, and Great Lakes are underobserved and seasonally biased due to ice, OAR intends to research technological solutions that may be able to overcome these challenges. For the

Southern Ocean in particular, OAR should also work with partners with extensive observing and research experience in this region (e.g., NSF) to aid in providing additional observations by leveraging existing strengths in uncrewed surface vehicles and other platforms. Finally, although the North Atlantic and North Pacific ocean interiors were relatively well sampled, high frequency ocean interior observations below 2,000 m remains a challenge. With the success of Deep Argo in measuring physical oceanography parameters up to 6,000 m, OAR is well positioned to further develop this technology for carbon observations. Therefore, OAR should utilize its unique observing strength to focus efforts on these spatiotemporal gaps.

Finally, strengthening and creating new partnerships with the U.S. federal and international ocean carbon observing communities will be critical to filling these gaps. A coordinated effort developing the global ocean carbon observing system will result in more comprehensive sampling that leverages agency-specific strengths to gain a better understanding of the global carbon cycle.

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