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Building ocean acidification research and policy capacity in the wider Caribbean region: a case study for advancing regional resilience

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To meet scientific, policy, and community goals, there is a critical need to strengthen research capacity, increase monitoring, and inform adaptation and mitigation policies to enhance resilience against ocean acidification (OA) and associated multi-stressors in the Caribbean. In 2023, an OA Needs Based Assessment survey of ocean professionals was conducted, engaging 59 participants from across the wider Caribbean to evaluate regional challenges and opportunities in OA research and monitoring. To understand differences in OA research capacity related to training and funding, we divide the respondents into four groups: those that have received 1) training and funding, 2) training only, 3) funding only, and 4) neither training nor funding. Results indicate regional strengths include awareness of local oceanic conditions, access to nearshore sites, and strong social support networks in ocean research. Regional barriers include limited technical capacity and funding to conduct oceanographic research and monitoring, and in particular, carbonate measurements. The four training and funding groups vary significantly, suggesting that access to training and funding are important factors to increasing the amount of access that respondents have to different types of equipment, the number of different types of measurements they conduct, the number of different habitats they research, and the amount of experience they have conducting OA research. This study also demonstrates the community-led efforts to address local OA challenges by presenting a case study on the formation of the Global Ocean Acidification Network (GOA-ON) OA Caribbean Hub that was founded by local leaders (co-authors of this study) who were inspired through the survey process and engagement that was conducted by co-authors. This study provides examples of avenues and challenges to build OA capacity for research and monitoring from the ground up within the wider Caribbean to advance towards global sustainability goals.

KEYWORDS

OA, sustainable development goals, capacity building, regional networks, Caribbean, OA training, OA funding, OA research

Introduction

As global climate continues to change, the ocean has absorbed around one-third of anthropogenic carbon dioxide emissions, causing the carbon content within the ocean to increase along with atmospheric carbon dioxide (CO_2) concentrations (Caldeira and Wickett, 2003; Doney et al., 2009). The absorption of CO_2 by the ocean leads to ocean acidification (OA) due to higher concentrations of hydrogen ions (decreased pH; increased acidity) and decreased availability of carbonate ions, which impacts marine ecosystems and organisms (Friedlingstein et al., 2022; Gruber et al., 2023).

Globally, ocean pH has decreased by 0.1 pH units over the past century, corresponding to a ~26% increase in acidity (IPCC, 2023). While OA is a global issue, local variability and its specific effects necessitate measuring it at the community scale. Localized approaches help to understand drivers and synergies, develop targeted adaptation and mitigation strategies, and create predictive capabilities to identify early warning signs for timely decision making (Cross et al., 2019).

In response to the rising threat, OA monitoring and research has been set as a priority for global policy frameworks. These include the international Kunming-Montreal Global Biodiversity Framework Target 8 and the national and regional frameworks within the U.S. (Federal Ocean Acidification Research and Monitoring Act of 2009, FOARAM Act, U.S. Code under Title 33, Chapter 50), European Union (Marine Strategy Framework Directive), and North-East Atlantic's Oslo and Paris Conventions (OSPAR) Commission (Galdies et al., 2021; Grabb et al., 2024). To achieve widespread global OA measurements, the United Nations Sustainable Development Goal (SDG) 14 (*Conserve and sustainably use the oceans, seas and marine resources for sustainable development*) aims to address and increase measurements of OA through its Target 14.3 (*Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels*) and Indicator 14.3.1 (*Average marine acidity (pH) measured at agreed suite of representative sampling stations*) (United Nations, 2024; See Appendix B for list of acronyms and policies). The SDG 14.3.1 methodology provides written guidance on how to conduct and collect OA observations, including identifying designated parameters to measure for OA (United Nations, 2024).

However, many countries lack the resources, policy, and technical capacity to monitor OA (Cooley et al., 2022), particularly Small Island Developing States (SIDS), which depend heavily on ocean resources for their livelihoods and economies (Meléndez and Salisbury, 2017; Grabb et al., 2024). Increasing the global capacity for OA research can help preserve ocean-based ecosystem services (i.e. coastal protection, food security, economies, and health) that directly support human livelihoods and provide up-to-date information and tools to assess these marine resources under changing climates (Gill et al., 2017; Hughes et al., 2017; Miloslavich et al., 2019). Depending on a number of factors including the future demand for shellfish and the extent of economic sectors that OA can impact, OA is predicted to result in an annual loss between US $6 billion (Narita et al., 2012) to US $400 billion (Moore and Fuller, 2020) globally. Under future climate scenarios, increased capacity for measuring, monitoring, and reporting OA must be a global and regional policy priority in order to inform mitigation, adaptation and resilience plans and to meet climate goals.

OA in the Caribbean

The Caribbean region consists of nearly 30 SIDS, yet is often discussed as the wider Caribbean region, which includes all countries and territories bordering the Caribbean Sea and Gulf of Mexico (Cartagena Convention, Article 2). Seventy percent of the

Caribbean population lives on the coast and relies on marine ecosystems for food security, coastal protection, the tourism industry, and cultural practices (Meléndez and Salisbury, 2017). The region is also a global marine biodiversity hotspot and one of the most diverse marine regions in the Atlantic (Roberts et al., 2002). Coastal ecosystems include coral reefs, seagrass beds, mangroves, rocky shorelines, and sandy beaches (Roberts et al., 2002; Miloslavich et al., 2010). However, climate stressors like OA threaten these ecosystems and associated resources (Gledhill et al., 2008; Cooley et al., 2022). For example, the categories of Caribbean species that had the highest commercial values in 2020 have the potential to be negatively affected by OA (Doney et al., 2009). Surface aragonite saturation state within the Caribbean has also declined by ~3% since pre-industrial levels (Gledhill et al., 2008; Meléndez and Salisbury, 2017), which can affect the availability of carbonate ions. This can negatively affect behavior, growth, survival, and larval development across a broad range of marine species, especially those that have larval stages requiring calcification, which can be further restricted if their larval development occurs during a tightly constrained time frame (Fabry et al., 2008; Spalding et al., 2017). In addition to the physiological challenges, OA also exacerbates other environmental stressors, including ocean warming, harmful algal blooms, and deoxygenation (Siedlecki et al., 2021).

Systematic remote sensing and *in situ* carbonate system measurements in the Caribbean SIDS began only in the past two decades, leaving significant gaps in both spatial and temporal data coverage. Despite these limitations, existing studies have successfully captured an OA signal across the region (Gledhill et al., 2008; Bates, 2012; Meléndez and Salisbury, 2017; Land et al., 2019; Meléndez et al., 2020). On a regional scale, remote sensing and model-based data indicate a ~10% increase in surface OA from 1992-2015, with significant spatial and temporal variability (Meléndez and Salisbury, 2017). At a local scale, the first long-term OA time series within Caribbean SIDS was established in 2009 at La Parguera Marine Reserve, Puerto Rico (Meléndez et al., 2020). This collaborative initiative between federal and state programs monitors nearshore carbonate dynamics along with other chemical, biological, geological, and physical parameters. La Parguera MAPCO$_2$ buoy is the only coastal buoy in the U.S. National Ocean Acidification Observing Network (NOAON) within the Caribbean Sea. In the wider Caribbean region, the CArbon Retention In A Colored Ocean (CARIACO) time series measured CO_2 concentrations within the Cariaco Basin off of Venezuela between 1995 and 2017, and observed some of the highest rates of decreasing pH compared to other ocean time series around the world (-0.0025 pH yr^{-1}) (Bates et al., 2014). The Research Network of Marine-Coastal Stressors in Latin America and the Caribbean (Red de Investigación Marino-Costera; REMARCO) has also established a network across the Caribbean and Latin America to increase measurements of OA, resulting in two countries (Colombia and Cuba) reporting data within the Caribbean Sea to SDG 14.3.1 and six countries (Colombia, Costa Rica, Cuba, Dominican Republic, Panama, and Venezuela) with monitoring stations for carbonate parameters within Caribbean Sea (Espinosa, 2023). These efforts to establish monitoring stations at various locations across the Caribbean Sea have provided enough data to show that OA is occurring throughout the region, yet more widespread, routine, and robust monitoring across the wider Caribbean region is needed to drastically increase the spatial and temporal OA data coverage. Higher resolution OA data throughout the region is necessary to understand the local variability in OA and inform local and regional decisions about mitigation and adaptation approaches.

Two significant sea level and climate monitoring networks were also established in the Caribbean in 1997 and measured physical parameters along with pH. However, they did not measure additional carbonate chemistry components to constrain the carbonate system and provide data on OA. The first was under the World Bank funded Caribbean Planning for Adaptation to Climate Change (CPACC) Project, during which 18 stations were established in 12 countries between 1997 and 2001. The second network consisted of the Coral Reef Early Warning System (CREWS) stations established in 11 countries over the period of 1997–2016 with funding provided by the U.S. National Oceanic and Atmospheric Administration (NOAA). These networks have faced challenges due to the lack of technical support and funding for routine maintenance and repairs, which were especially needed following severe damage from storm events and hurricanes (Hendee et al., 2016). Despite some advances in establishing OA monitoring programs, the limited number of functional monitoring sites, challenges with environmental conditions, and significant regional and local variability underscore the need for expanded capacity to help establish and strengthen observation and monitoring efforts to fully understand OA dynamics across the wider Caribbean region (IOC-UNESCO, 2024b).

Expanding OA monitoring throughout the Caribbean will be crucial to inform mitigation and adaptation strategies tailored to vulnerable local communities across the region. To achieve this access to resources such as sustained funding, training opportunities, collaborations, and regional networks are needed to strengthen OA research and monitoring (Miloslavich et al., 2019; Whitefield et al., 2021). Additionally, integrating place-based knowledge into scientific research and capacity-building efforts is essential, as it will provide vital insights, enhance adaptation strategies, and strengthen engagement throughout the community (Cross et al., 2019; Miloslavich et al., 2022).

Global initiatives to share ocean research capacity

Programs have been developed across regions to share research capacity amongst ocean professionals, yet few are focused on ocean carbonate chemistry measurements and even fewer are designed for and/or implemented within the Caribbean. In other regions of the world, networks have been established to help share OA research capacity, including the Global Ocean Acidification Network (GOA-ON) (Newton et al., 2015). GOA-ON is a collaborative international network designed to improve understanding of global OA conditions and ecosystem responses to OA. GOA-ON also works to acquire, exchange, and consolidate data and knowledge necessary to optimize modeling for OA and its impacts. GOA-ON has a dedicated Secretariat that coordinates over 1,000 members from over 100 countries and territories, as well as the UN Ocean Decade endorsed program Ocean Acidification Research for Sustainability (OARS) (Dobson et al., 2023; IOC-UNESCO, 2024a). To achieve a global approach that addresses local OA needs, GOA-ON has facilitated the grassroots formation of regional hubs that are purposefully built by local ocean professionals. GOA-ON and its partners also coordinate the Pier2Peer mentorship program (led by NOAA and The Ocean Foundation, TOF) and GOA-ON in a Box Kits (led by TOF), which are low-cost kits used for collecting weather-quality ocean acidification measurements. The Pier2Peer program awards scholarships for small projects and five have been awarded within the wider Caribbean (two in Mexico, one in Costa Rica, and one in Honduras). The Kits have been distributed to scientists in over 25 different countries with ongoing training and support including a few countries within the wider Caribbean (i.e. Mexico, Panama, Jamaica, and Colombia). Best practice guides for science, monitoring, and mentorship have also been developed as resources by the international OA community such as the Practical Best Practices to Ocean Acidification Monitoring (Currie et al., 2024) and the Guide for Developing Mentoring Programs for the International Ocean Community (Lang et al., 2024). These resources offer insights to OA measurements and mentoring programs that can also be translated to communities within the Caribbean.

OA policy and collaborations in the Caribbean

Given the major threat of OA to the Caribbean, policy and community efforts have been made to address OA within the region. For example, the IOC-UNESCO Subcommission for the Caribbean and Adjacent Regions, IOCARIBE, developed a Regional Action Plan on Ocean Acidification for Latin America and the Caribbean (Laffoley et al., 2018). This Action Plan highlighted priorities throughout the region for science, policy, communication, and outreach, and provided a framework of priorities to support collaboration and funding to prioritize OA research and monitoring. Following this, the Scientific and Technical Advisory Committee (STAC) to the Protocol Concerning Specially Protected Areas and Wildlife in the wider Caribbean region (SPAW Protocol, STAC8, December 2018 in Panama with TOF staff) and the Cartagena Convention (COP15, June 2019 in Honduras) signed a Memorandum of Understanding to work with TOF to address OA within the Caribbean region. REMARCO also recognizes OA as a major threat within the region and supports collaborative actions to measure OA, develop policies to reduce CO_2 emissions, and disseminate scientific information to inform policy and decision making.

Another well-established and highly productive network within the region that focuses on OA research and policy efforts is the GOA-ON Latin American and Caribbean OA Regional Hub (LAOCA). Since LAOCA primarily includes Spanish-speaking countries from Latin America, Central America, and the Caribbean, its meetings are often conducted in Spanish to accommodate the majority of its members. However, this can create challenges for non-Spanish-speaking Caribbean countries and territories, which have broad linguistic diversity (Ferreira, 2012) with English being the unofficial language of tourism (which is the largest industry) throughout the Caribbean. Beyond language barriers, the Caribbean SIDS face unique socio-cultural, logistical, and capacity-related challenges (Allahar, 1993; Fanning et al., 2021) that may not align with the priorities of LAOCA. Compared to larger Latin American countries, SIDS often have fewer resources and face distinct vulnerabilities that may not align with the broader regional priorities, potentially limiting their influence in policy discussions and capacity-building initiatives.

Despite these differences, LAOCA's progress serves as an excellent example of how regional collaboration can advance OA research and policy. Acknowledging this success, an opportunity was identified to establish a dedicated OA hub tailored to the unique needs of the wider Caribbean region, where many nations are SIDS. A new hub within the wider Caribbean region would address not only linguistic accessibility and the unique priorities of the region's islands but also foster complementary collaboration with LAOCA, REMARCO, and other existing regional networks to build on their successes and enhance collective efforts in addressing OA impacts across Latin America and the Caribbean.

In recognizing this need to establish an OA network within the Caribbean, the Caribbean Ocean Acidification Community of Practice (CoP) was formed in 2021. The CoP was developed following the 2021 UNESCO Intergovernmental Oceanographic Committee Assembly and the accepted IOCARIBE Decision. The CoP consisted of a core task team of members from the U.S. (i.e., NOAA Ocean Acidification Program (OAP), NOAA's Office of Oceanic and Atmospheric Research International Activities Office, and TOF) and the Caribbean (i.e., representatives from university partners, government, and non-profit/non-governmental organizations). The goals of the CoP were to increase connectivity and engagement and to identify and strengthen current OA research and capacity gaps within the region. The CoP brought together individuals with deep knowledge, strong connections, and a vested interest in the region. It played a key role in advancing OA research, addressing capacity gaps, and laying the foundation for long-term regional networks, such as the GOA-ON OA Caribbean Regional Hub and the Caribbean Coastal Acidification Network (CariCAN).

To better understand the unique regional needs and priorities of the wider Caribbean region, our co-author at TOF led members of the CoP to design an OA Needs Based Assessment survey in 2022. This survey aimed to evaluate OA research capacity and identify priorities and challenges related to OA research as well as strategies to strengthen the region's ability to address these challenges effectively.

In this paper, we present the results of the OA Needs Based Assessment survey, which indicate the current state of OA activities, including strengths and barriers in conducting OA research and monitoring in the wider Caribbean. We evaluate the OA research aspects that benefit from OA training and funding and present a case study on the establishment of the GOA-ON OA Caribbean Hub, which was initiated following the engagement from this survey. Finally, we provide a brief discussion on the challenges along with recommendations for sustained research, capacity building, and policies that support OA efforts in the wider Caribbean moving forward.

Methods

Survey design

The survey was designed by the CoP in collaboration with TOF to leverage their existing survey design which has been implemented in other regions as part of their OA capacity building efforts (Valauri-Orton et al., 2025; See Appendix A for survey). All survey questions were written in English. The survey was designed to: 1) assess the current state of OA sampling methodologies and ocean observing capacity for the region, and 2) identify regional priorities and areas for improvement and resource focus. A non-probability purposive sampling framework (Carr et al., 2021; Lune and Berg, 2017) was developed to select cases with the following criteria 1) ocean professional currently conducting ocean observations (with a demonstrated focus on OA parameters) and 2) individuals conducting broader water quality monitoring and oceanographic research within countries and territories that have waters bordering the Caribbean Sea. Therefore, this was a targeted survey that is not generalizable with an unknown probability of selection into the sample.

The survey assessment and follow-up activities within this study encompassed the wider Caribbean region (Cartagena Convention, Article 2). Responses from individuals located in the mainland U.S. were not included in the analysis per request of the Caribbean community members who participated in these efforts, given that the intent of this study was to understand the barriers to increasing OA capacity that are unique to the wider Caribbean. The mainland U.S. has had access to an abundance of resources in comparison to the rest of the wider Caribbean and typically does not face the same socio-cultural, logistical, and capacity-related challenges as the other countries and territories within the wider Caribbean, including the U.S. Territories (Allahar, 1993; Fanning et al., 2021). The sampling frame included individuals in the U.S. territories of Puerto Rico and U.S. Virgin Islands because Puerto Rico maintains the only MAPCO2 buoy currently collecting data in the region and both territories have research institutions that conduct OA research in collaboration with others within the region and act as funding pathways for other institutions in the wider Caribbean.

The survey distribution and follow-up activities were facilitated by the co-leads of this study (Grabb and Lord) during their tenure as Sea Grant Knauss Fellows at NOAA OAP in 2023. The survey was distributed between February and June of 2023 via email contact and the Google Forms survey platform. Efforts were made to distribute the survey widely amongst ocean professionals within all countries and territories within the wider Caribbean region; the survey was distributed through direct emails to contacts within the Caribbean by identified research institutions, academic departments, professors, and other ocean professionals with special attention to reach at least several representatives from each country and territory in the wider Caribbean. We also distributed the survey via snowball sampling through existing networks (i.e. the CoP, NOAA Southeast and Caribbean Regional offices, the UNESCO Intergovernmental Oceanographic Commission Subcommission for the Caribbean and Adjacent Regions (IOCARIBE), Caribbean Coastal Ocean Observing System (CARICOOS), United Nations Environmental Program Specially Protected Areas Protocol (SPAW)), at conferences in the Caribbean, through virtual presentations to Caribbean members, and through survey respondents' networks. Survey respondents were given up to five months (February to June) to respond and reminders were sent monthly to encourage respondents to fill out the survey and share it throughout their networks. Additional outreach was focused on encouraging responses from professionals within countries with low or no response rates, for example those within the Eastern Caribbean where there is limited existing research expertise. While snowball sampling methods enabled the survey to be sent to broad groups of ocean professionals, they restricted the ability to track the exact number of people who received the survey and determine the response rate, which is a limitation of the study.

Responses were removed if the entirety of the survey was not complete or if participants identified their location in the mainland U.S. or outside of the wider Caribbean region. The participants were not compensated. Due to the unknown probability of selection into the sample, there are no survey weights, and these results do not represent the entirety of the marine research community in the Caribbean region. The non-probability sampling has limitations, and this work cannot claim generalizability to the entire population of regional researchers. Purposive and snowball sampling may be biased based on existing network access of individuals, with some researchers being left out (Lune and Berg, 2017). Purposive sampling was used to narrow the sampling frame to identify researchers studying ocean acidification and adjacent oceanographic research, therefore not allowing generalizability for all marine researchers in the region. Snowball sampling was used to leverage the social networks of researchers in the region and identify respondents that were difficult to reach, however the networks do not represent the full population of researchers in the region. Despite the limitations of the sample size and the ability for representativeness in statistical analysis, this OA Needs Based Assessment provides descriptive results in an understudied area of research in a data poor region and may be used to inform future funding and policy mechanisms for OA research.

Survey analysis

Survey responses were anonymized, translated into English, and processed using Microsoft Excel and Python programming languages for data analyses and visualization. The survey design included a combined use of quantitative (multiple choice) and qualitative questions (open-ended), so mixed-methods were used for analysis (Creswell and Creswell, 2017), combining both quantitative and qualitative data for more context. The quantitative questions included multiple choice answers where respondents could select all that applied. For the qualitative portion of the survey questions, the responses were open-ended and analyzed using inductive coding based on the themes presented in the responses and the literature (Carr et al., 2021). For questions with multiple categorical responses (i.e. number of different types of equipment accessible, number of different types of measurements conducted, etc.), the total number of responses for each category was quantified to facilitate further quantitative analysis. Based on answers about receiving training or funding, survey respondents were classified into four groups: respondents that have received 1) training and funding (T&F), 2) training only (T), 3) funding only (F), and 4) neither training nor funding (N). For those questions that had quantitative answers the average and standard deviation were calculated for the respondents within each of the four training and funding groups. To compare the significance between averages of each training and funding group, ANOVA single-factor p-values (<0.05) were calculated, followed by Tukey t-test p-values (<0.05) to determine individual variation.

To emphasize transparency in data collection and distribution, all survey responses were anonymized and shared with participants, and have since been reported at international conferences, regional meetings, community gatherings of ocean professionals, and with interested partners within the region. Anonymized responses to the multiple-choice questions are provided in Appendix C with personalized responses removed to protect anonymity. All data has been archived in the password-protected NOAA Google Drive platform.

Results and discussion

The findings presented here are based on the OA Needs Based Assessment survey, associated engagement, and the specific case study on establishing the GOA-ON OA Caribbean Hub. Given the limited sample size in relation to all ocean professionals within the wider Caribbean, this survey offers the viewpoint of those that participated; Most of the respondents have a working knowledge of OA, are involved in ocean research, and are connected in some way to a broader community, given the methods used to distribute the survey (see Methods). The survey results were self-reported and, therefore, may contain biases. The results presented suggest trends across survey participants, yet additional follow-up studies are needed to further investigate the cause of these trends and confirm if the smaller sample size in this study is representative for broader groups throughout the Caribbean. Regardless, these survey results and this study offer insights into the current state of ocean research and a case study on establishing a network dedicated to OA within the wider Caribbean that has not been published previously. It also lays the groundwork for follow-up investigations on OA research, policy, and capacity needs within the wider Caribbean while offering a model for other regions to follow.

Survey respondent demographics

A total of 76 ocean professionals responded to the survey. Of these, 59 were from the wider Caribbean (excluding the mainland U.S.) and were included in the analysis (Appendix C). The remaining 17 respondents - 10 from the mainland U.S. and 7 from other regions outside the Caribbean - were excluded. Representatives from the mainland U.S. were excluded in the survey responses and engagement activities per request from the Caribbean community members who participated in the survey engagement, and therefore, references to the wider Caribbean within this study will exclude the mainland U.S. The purpose of this request was to tailor the survey, capacity building efforts, policy recommendations, and follow-up actions to the priorities of the countries and territories within the wider Caribbean region (including U.S. territories), which differ socio-economically from the mainland U.S (Allahar, 1993; Fanning et al., 2021). The respondents from the wider Caribbean (n=59) were from 25 different countries and territories (Figure 1, Appendix C). Almost half of the participants (47.5%) were from academic and research institutions (n=28), 23% of them work in governmental roles (n=14), 22% work at non-governmental organizations (n=13), and one works for a private company (Supplementary Figure S1).

Of the 59 respondents, 79% currently conduct ocean monitoring. 40% of the respondents monitor biological parameters, with 23% conducting chemical monitoring, 26% conducting physical monitoring, and 13% conducting socioeconomic monitoring. A majority of the respondents have a working knowledge of OA (63%), while nearly a third (31%) lack the resources and instruments necessary to study and monitor OA, and another third (32%) are able to conduct their research but noted that they have limited resources. Another large portion (20%) of the respondents have some knowledge of OA but would like to learn more and potentially build a research and monitoring program (Figure 2; Appendix C).

The current state of OA research in the Caribbean

Ocean professionals in the Caribbean rely on nearshore marine environments due to their accessibility, and therefore, their strengths, interests, and expertise focus mainly on nearshore environments. Across the region, respondents are most concerned about coral reef health (58%) and water quality (51%) within their local marine environments. Over half of the respondents conduct research in nearshore environments (59%) compared to a much

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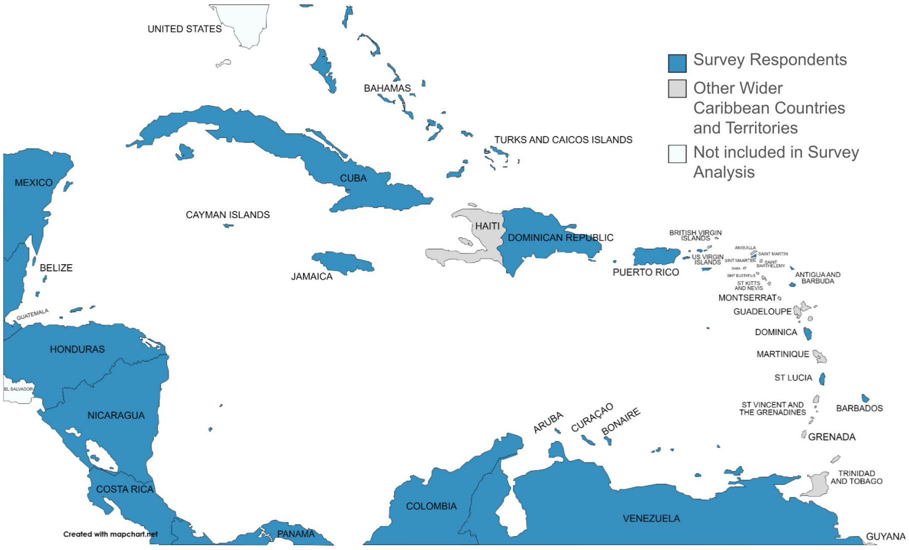

FIGURE 1
Map indicating countries and territories in the wider Caribbean where survey respondents reside (blue), the countries and territories that do not have survey respondents (grey), and those that are not included within the survey analysis (white, mainland U.S., excluded to focus survey on needs specific to wider Caribbean excluding mainland U.S.).

smaller fraction that work in the open ocean and offshore environments (22%). The most frequently studied ecosystems are coral reefs (64%), yet respondents also monitor other nearshore environments such as mangroves (49%), estuaries and bays (40%), and seagrasses (35%) (Figure 3). Other concerns for ocean health expressed by respondents, include harmful algal blooms (31%), sargassum inundation (27%), ocean acidification (21%), overfishing (22%), and climate change impacts such as hurricanes and sea level rise (29%) (Appendix C).

Respondents collect a wide range of ocean measurements, the most common include temperature (74%), salinity (68%), pH (66%), and dissolved oxygen (54%) (Figure 4). These parameters can be collected with methods that are easy to use, affordable, and require minimal training (Wang et al., 2019; Busch et al., 2016; Bittig et al., 2018), such as thermometers, refractometers, electrodes, optodes, and spectrophotometers. Chlorophyll measurements and water depth are conducted by 42% of respondents, and 36% of participants measure nutrients even though relatively affordable methods are available that require little expertise (Wernand, 2010; Beaton et al., 2012; Leeuw et al., 2013; Busch et al., 2016; Clinton-Bailey et al., 2017).

In order to constrain the carbonate system and OA, two of the four carbonate measurements are needed (i.e. dissolved inorganic carbon (DIC), total alkalinity (TA), pH, or partial pressure of carbon dioxide (pCO_2)), therefore requiring researchers to measure another carbonate parameter in addition to pH. Of the other carbonate parameters besides pH, 32% of respondents are measuring TA, 14% are measuring pCO_2, and 15% are measuring DIC (Figure 4). A total of 34% of respondents are measuring two or more of these four carbonate parameters (i.e., pH, DIC, TA, and/or pCO_2), and this percentage could be related to the pending distribution of low-cost sensors and/or complex laboratory methods that require specific training and lab infrastructure for DIC, TA, and pCO_2 measurements (Pardis et al., 2022; Li et al., 2023; Currie et al., 2024). Underlying this need for training and infrastructure to enhance the ability to make carbonate chemistry measurements are the required funds for the initial investment in establishing labs that can conduct these measurements and the continued financial support to maintain the equipment, workforce, and on-going research and monitoring.

While respondents often highlighted awareness of local oceanic conditions as a strength, they also recognized the need for additional formal technical scientific training and support in advanced chemical and physical monitoring techniques. Many respondents expressed a strong commitment to ocean research, motivated by both local knowledge and the desire to contribute to broader scientific understanding. One participant highlighted several strengths of their research program: "long standing relationships with local communities, close network of local scientists, and access to talented students". Underlying most of the barriers that respondents identified to building and enhancing OA research and monitoring efforts were limitations in training to achieve greater technical capacity and access to sufficient funding, which is needed to sustain research, purchase equipment, and increase overall resources.

The role of training and funding

Training and continuous funding acquisition are paramount to advancing global observations by increasing scientific expertise, instrumentation, data management, and infrastructure to conduct ocean measurements (Venkatesan et al., 2019). For countries with limited resources to conduct oceanographic research, long-term

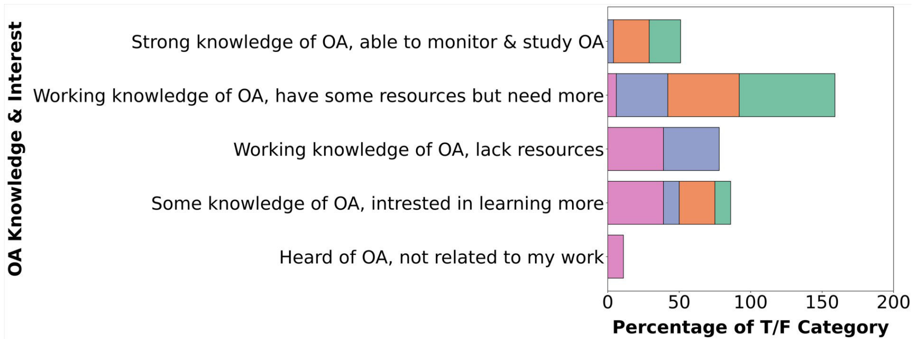

FIGURE 2
Ocean acidification knowledge and interest of survey respondents (y-axis) for each of the training and funding (T/F) categories (training only in blue, n=28; funding only in orange, n=4; training and funding in green, n=9; neither training nor funding in pink, n=18), displayed by percentage of each respective category normalized to the sample size for each training and funding category (x-axis).

monitoring of OA can be particularly challenging, especially for nations with coral reef ecosystems, such as those within the wider Caribbean, where carbonate chemistry budgets add complexity. Due to the lack of resources and sustained funding, baseline assessments for acidification conditions across the Caribbean are deficient (Meléndez and Salisbury, 2017) with only one sustained time series that continues to measure CO_2 within the Caribbean (La Parguera, Meléndez et al., 2020). The one other previous time series (CARIACO) within the region measured the highest rates of decreasing pH compared to any other ocean time series around the world (-0.0025 pH yr^{-1}) (Bates et al., 2014) and was one of only three total time series (CARIACO, Bermuda Atlantic Time-series Study, BATS, and Hawaii Ocean Time-series, HOT) that have been funded by the U.S. National Science Foundation for over two decades to measure ecology and biogeochemistry in ocean waters (Muller-Kargo et al., 2019). Unfortunately, in 2017 the CARIACO time series was discontinued due to budget constraints even though BATS and HOT continue to be funded to date, thus limiting data collection within the Caribbean (Kusek, 2019).

In this study, over half of the survey respondents (62%) indicated that they have received some amount of training on OA across a wide range of techniques. Of the 62% that have received training, the majority have learned techniques such as conducting pH analysis in the lab (86%), collecting bottle samples for lab analysis (81%), and/or conducting alkalinity analysis in the lab (70%). Techniques that respondents have received less training on include deployment of autonomous sensors (38%); data offloading, quality control, and analysis (30%); and pCO_2 analysis in the lab (27%). Fewer trainees have received training on OA biological effects and modeling aspects, such as designing biological experiments (19%), running analysis and analyzing results (14%), monitoring the effects of OA on species *in situ* (11%), and using

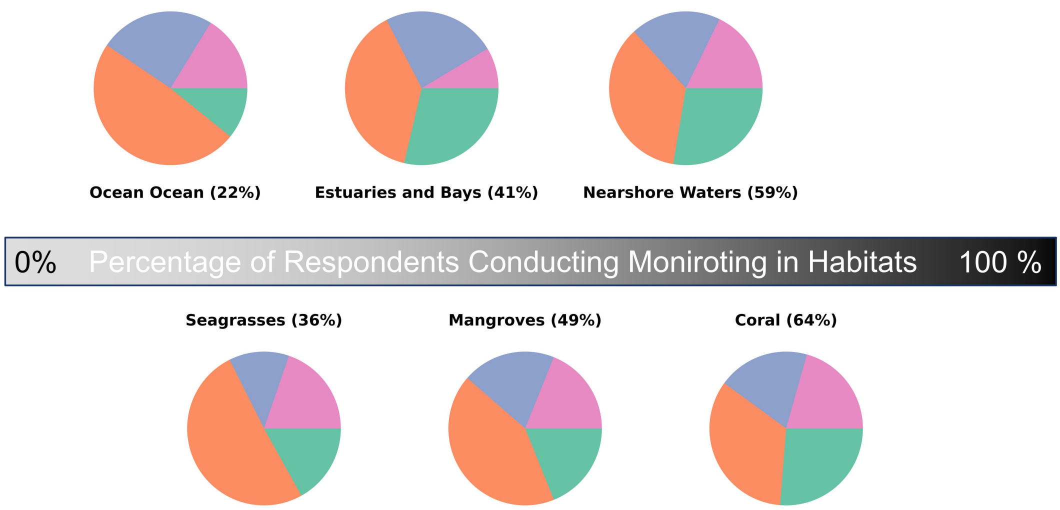

FIGURE 3
Percentage of respondents that are currently conducting monitoring in different habitats (indicated by percentage next to parameter), listed along the continuum from lowest (left, 0%) to highest (right, 100%). Pie charts show the percentage of each training and funding (T/F) categories (training only in blue, n=28; funding only in orange, n=4; training and funding in green, n=9; neither training nor funding in pink, n=18) normalized to the sample size for each respective category.

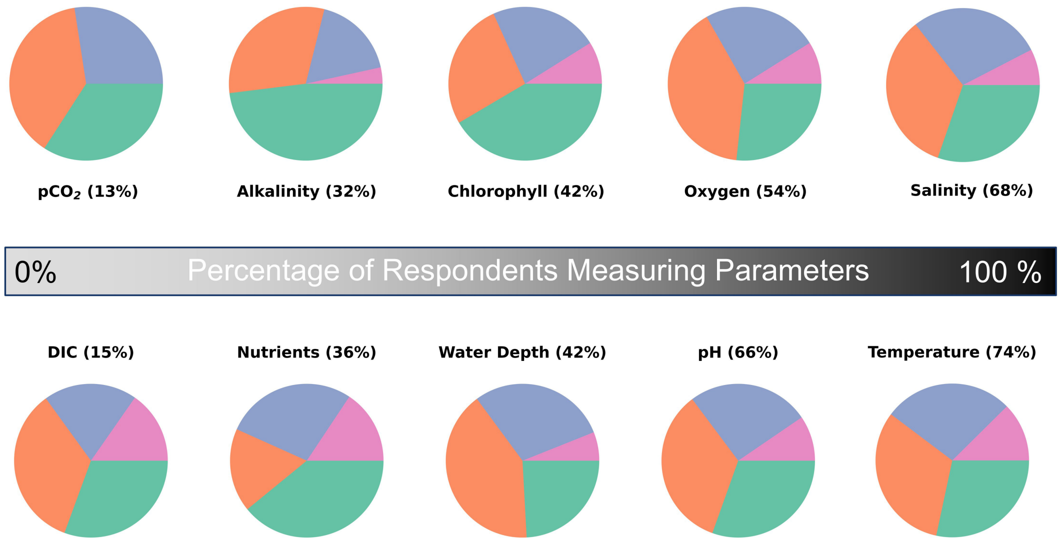

FIGURE 4
Percentage of respondents that are measuring specific parameters in coastal or offshore waters (indicated by percentage next to parameter), listed along the continuum from lowest (left, 0%) to highest (right, 100%). Pie charts show the percentage of each training and funding (T/F) categories (training only in blue, n=28; funding only in orange, n=4; training and funding in green, n=9; neither training nor funding in pink, n=18) normalized to the sample size for each respective category.

computer models to understand OA (11%) (Appendix C). While exposure to some OA training has been accessible by majority of the survey respondents, this study did not explore the type of training, quality, or quantity of training received nor what type of training would be most beneficial to respondents in the future.

When categorizing the respondents into four groups based on the training and funding received, we find that around one in six have received both training and funding (15%), nearly half received training only (47%), a small portion received funding only (7%), and nearly a third have received neither (31%) (Supplementary Figure S2). There is a significant difference between these four groups in relation to the amount of access to different types of equipment (ANOVA, p-value < 0.001), types of measurements conducted (ANOVA, p-value < 0.001), number of habitats researched (ANOVA, p-value = 0.041), and OA experience level (ANOVA, p-value = 0.025) (Table 1).

There is a major funding gap for Caribbean SIDS to meet their ocean-based Nationally Determined Contributions (NDCs) and ocean acidification scientific research projects lack funding and policy support, requiring additional allocation of domestic resources and leveraging of international climate finance and private sector funds (VanderZwaag et al., 2021; Mohan, 2023). In this survey, responses suggest that funding may play a significant role in the different types of equipment and ecosystems that ocean professionals can access for ocean monitoring. For example, access to different types of equipment is significantly higher (tukey-t test, p-value < 0.001) when both funding and training are provided compared to providing neither (Table 1; Supplementary Figure S3). Funding may be more of a driver than training to increase access to different types of equipment (Tukey-t test p-value, T&F v T < 0.001, F v N = 0.041) (Table 1; Supplementary Table S1), however the group that has received funding only is small (n=4) and therefore follow-up studies are required to confirm these trends. Funding alone is correlated with higher diversity of habitats in which ocean professionals conduct ocean monitoring (tukey-t test p-value, T v F = 0.043, F v N = 0.035) (Table 1, Supplementary Table S1, Figure 3). Compared to receiving neither option, providing either training and/or funding to ocean professionals significantly increases the different types of measurements that they can conduct to monitor the ocean (tukey-t test p-value, T v N = 0.001, F v N = 0.012, T&F v N = 0.001) (Supplementary Table S1). While OA experience is significantly different between the four training and funding groups (ANOVA p-value = 0.025), a specific combination of training and funding is not driving this variation (Supplementary Table S1). There is a higher average level of OA experience within the training and funding (4 +/- 0.8 out of 5) and funding only (4.3 +/- 0.4 out of 5) groups compared to those that only received training (3.5 +/- 0.7 out of 5) or neither training nor funding (3.1 +/- 1.1 out of 5) (Table 1). This suggests that funding may be slightly more impactful to increase OA experience than training, although additional research is necessary to investigate the types of training and funding that would be most beneficial to the community and confirm this trend since the groups that received funding were the smallest in sample size (4 respondents received funding only and 9 received training and funding). This small sample size also suggests that there is only a small proportion of ocean practitioners within the Caribbean that has received funding compared to training for OA research and monitoring, further supporting the conclusion that additional funding support is needed in the region. One participant noted that “most problems are related to financial

TABLE 1 Table indicating the average amount of access to different types of ocean observing capabilities based on the max value for each of the capabilities.

Amount of Access to Different Types of Ocean Observing Capabilities	Max value	Entity	Training and Funding (T&F) (n=9)	Training (T) (n=28)	Funding (F) (n=4)	Neither (N) (n=18)	ANOVA p-value	Tukey t-test (p-value < 0.05)
Training techniques	11	Avg	4.89	4.04	1.75	0.00	*6.485E-5	T&F v. N (0.000) T v. N (0.000)
		Std Dev	1.59	2.15	2.05	0.00		
Access to Equipment	17	Avg	11.56	5.75	9.75	4.39	*3.025E-5	T&F v. T (0.000) T&F v. N (0.000) F v. N (0.041)
		Std Dev	1.71	3.87	3.56	3.32		
Types of Measurements Conducted	10	Avg	6.22	4.89	6.50	1.67	*0.000	T&F v. N (0.001) T v. N (0.001) F v. N (0.012)
		Std Dev	2.94	2.81	0.50	2.49		
Habitats researched	6	Avg	3.11	2.50	5.00	2.33	*0.041	T v. F (0.043) F v. N (0.035)
		Std Dev	1.97	1.57	0.71	1.80		
OA Experience Level	5	Avg	4.00	3.54	4.25	3.11	*0.025	
		Std Dev	0.82	0.68	0.43	1.05		

Averages and standard deviations are displayed for the four training and funding categories along with the ANOVA p-value for the difference between the four training and funding categories. The Tukey t-test indicates which group-to-group comparisons between the different training and funding categories (T&F, Training and Funding; T, training only; F, funding only; N, neither training nor funding) are significantly different (p-value < 0.05) with the p-value stated in parenthesis. For example, when considering the number of training techniques each group on average has access to, the T&F group varies significantly from the N group with a p-value of 0.000 and is therefore listed in the table as "T&F v. N (0.000)".

capacity including the ability to hire qualified staff, maintain equipment, instruments and facilities and opportunities for training in data collection and data management." Unfortunately, even though this study found that training and funding are critical for capacity building, only 22% of the survey respondents have received funding for OA research. While 62% have received training, around 76% of those who have received training did not receive funding, which would make it difficult to conduct and sustain the techniques that were learned during training and highlight the limited nature of funding within the Caribbean for OA research.

This study showcases the need for both training and funding to be provided to make a significant impact on research capacity, which has also been shown in previous studies (e.g. Venkatesan et al., 2019; VanderZwaag et al., 2021; Mohan, 2023). While both increased training and funding are necessary, training can be passed on through various formal and informal avenues while funding requires continuous investment to sustain the workforce, maintain equipment, and support on-going research and monitoring. Training and funding are especially important for complex techniques that require specific lab infrastructure, such as TA, DIC, and pCO2, which are needed in addition to pH to constrain the carbonate system (Pardis et al., 2022; Li et al., 2023; Currie et al., 2024). Therefore, this study suggests that financial support for OA research may be a factor in increasing the amount and diversity of equipment available, measurements conducted, habitats research, and level of OA expertise. Future studies should be conducted to confirm these trends across a broader group of ocean professionals throughout the Caribbean and investigate which training and funding resources would be most impactful for the region.

Application of OA measurements to SDG requirements

Clearly, gaps remain in regional OA research and monitoring, making it difficult for Caribbean nations to not only meet their ocean-based NDCs (Mohan, 2023), but also contribute to the indicator methodology required under international data reporting obligations for UN SDG Target 14.3 (*Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels*). Of the survey respondents, 64% are aware that OA monitoring is required to meet the SDG Indicator 14.3.1 (*Average marine acidity (pH) measured at agreed suite of representative sampling stations*). However, only 37% of participants could name the entity responsible for submitting the required OA monitoring data for their nation. This result highlights a gap between the OA data collection and submission process, which could be due to many different factors which we did not investigate in this study. This gap does, however, suggest that communication and engagement could be strengthened either within and/or across nations to better familiarize ocean professionals and researchers collecting OA data with the governmental entities submitting the data on the SDG Indicator 14.3.1 Data Portal. While SDG 14.3 is considered a target, it does not account for a scientifically verifiable baseline, nor contain binding elements, which could make it more effective (Houghton, 2014; Loewe and Rippin, 2015; Recuero Virto, 2018). The SDG Indicator 14.3.1 is one of the quantifiable aspects of SDG Target 14.3 that can produce scientific data to inform practitioners of OA trends across temporal and spatial scales. Regions with more OA monitoring and research capabilities, such as many regions within the Global North, maintain a record of incorporating OA mitigation and adaptation strategies into their local and regional policies (Grabb et al., 2024). However, there is a comparable lack of OA research capacity and regulation frameworks addressing OA within SIDS and the Global South (Grabb et al., 2024). Given that the wider Caribbean region includes a few dozen SIDS that rely heavily on the marine environment (Meléndez and Salisbury, 2017), the wider Caribbean is an example of a region that could benefit from increasing research capacity to address SDG Indicator 14.3.1 by expansion of OA data collection and research dissemination. Although further research is required to investigate the factors underlying this gap, this study suggests that additional access to OA training and funding may help ocean professionals increase OA research capacity to contribute to SDG Indicator 14.3.1 and conduct more OA measurements using a larger variety of instrumentation across a wider range of habitats including offshore and deep-sea ecosystems (Bell et al., 2023). Training and funding opportunities may help increase the ability to meet policy commitments such as NDCs and the SDG Indicator 14.3.1, yet additional efforts are also required to strengthen conduits to apply OA science to inform mitigation, adaptation, and policy decisions, which were not investigated within this study.

Interest in GOA-ON hub

This study identified the opportunity to create a coordinated regional effort in the wider Caribbean to support OA capacity building and facilitate the sharing of OA research findings and methodologies. Indicated by previous studies on OA, a key recommendation to address OA is to create a strong regional monitoring network to inform policy actions (Chan et al., 2016; Whitefield et al., 2021). Therefore, as a case study to explore possible mechanisms to build capacity through a regional network for OA research and monitoring within the Caribbean, this study explored the option to establish a regional GOA-ON OA Caribbean Hub. 39% of the survey respondents were already GOA-ON members, however, when all survey respondents were asked if they thought a regional GOA-ON OA Caribbean Hub would be beneficial, 78% responded "Yes", 17% responded "Maybe", and only 2% responded "No". The majority of respondents felt that strong benefits of a regional GOA-ON OA Caribbean Hub included increased access to equipment (88%), capacity building (85%), regional organization and communication (83%), development of policy and decision-making resources (81%), help with SDG Indicator 14.3.1 reporting (75%), data sharing (66%), and collaborations and joint activities (54%). Survey respondents also had the opportunity to indicate if they were interested in future leadership opportunities in capacity building efforts.

GOA-ON regional hubs are built from the ground up with local community leaders to ensure alignment with regional goals and they are also provided with staff support from the GOA-ON Secretariat to facilitate meetings and connect GOA-ON members and Hubs to opportunities within the international network (Newton et al., 2015). Previously established GOA-ON regional hubs have demonstrated that benefits similar to those expressed by the survey respondents are achievable (Newton et al., 2015). For example, through opportunities within the GOA-ON network, many regional hubs have benefited from OA trainings and workshops, Pier2Peer mentorship and scholarships, increased access to technical equipment (i.e., GOA-ON in a Box Kits), increased opportunities for research funding, and international collaborations. While the needs within each GOA-ON regional hub are unique, the successes to establish and sustain OA monitoring and research within other regional hubs serve as examples for the potential resources that can be developed through the GOA-ON network.

GOA-ON OA Caribbean hub formation

To inform the Caribbean OA research community of the needs assessment results, the survey results were shared via email to respondents, presented during virtual meetings with Caribbean community members, and presented at a conference in the Caribbean where local OA practitioners were engaged in further conversations and discussions. Following these engagements, those interested in leadership positions for future capacity building networks were encouraged to attend an initial virtual meeting in May 2023, which was facilitated by the co-leads of this study, who were Sea Grant Knauss Fellows at NOAA OAP. After several virtual informational meetings where the survey results were presented, the Caribbean OA community leaders (who are co-authors of this study) decided to establish and lead monthly meetings to design the goals, scope, and direction of a collaborative network. Upon learning about the opportunities that GOA-ON regional hubs have provided other regions, the Caribbean OA community leaders decided to pursue the formation of a GOA-ON OA Caribbean Hub in November 2023 by creating and agreeing upon terms of reference and naming the steering committee members (https://www.goa-on.org/regional_hubs/caribbean/about/introduction.php). The GOA-ON OA Caribbean Hub was formed with two co-chairs hailing from Jamaica and the U.S. Virgin Islands, and five additional steering committee members located in Belize, Commonwealth of Dominica, Cuba, Puerto Rico, and the U.S. Virgin Islands. The GOA-ON OA Caribbean Hub welcomes members from the wider Caribbean region, including U.S. Territories, and as of February 2025 had 28 members from 14 different countries and territories.

The steering committee designed the GOA-ON OA Caribbean Hub goals to address the needs of the wider Caribbean region that were expressed in the needs assessment. The goals of the hub are to: (1) Grow involvement within the Caribbean OA community and promote activities within the hub; (2) Encourage coordination of efforts and collaboration with organizations and projects involved in ocean acidification observations, impacts, and data delivery; (3) Promote the awareness of the OA Caribbean Hub to the public, policymakers, and scientific community; and (4) Engage national and international funding agencies to support the activities of the OA Caribbean Hub.

Since its establishment, the GOA-ON OA Caribbean Hub has interacted with other GOA-ON regional hubs to learn about successful regional initiatives for building and sustaining OA research and monitoring capacity. Like other hubs, the OA

Caribbean Hub has GOA-ON secretariat support to assist with connections throughout the international network as well as two seats on the GOA-ON Executive Council to help increase international networking and knowledge sharing with other GOA-ON regional hubs and international partners (Newton et al., 2015). The GOA-ON OA Caribbean Hub also has a dedicated early career steering committee member who sits on the International Carbon Ocean Network for Early Career (ICONEC) steering committee. International partners and networks have expressed interest in engaging with the OA Caribbean GOA-ON Hub including IOCARIBE, CARICOOS, UN Environmental Program (UNEP) SPAW, Caribbean Fishery Management Council, International Atomic Energy Agency (IAEA), and IOC-UNESCO.

Within a year of establishment, the GOA-ON OA Caribbean Hub maintained monthly steering committee meetings and made progress towards increased collaboration and expansion of its network with sessions at both 2023 and 2024 GOA-ON OA Week, a presence at international conferences such as the CariCOOS 2023 General Assembly, and facilitation of an OA workshop for regional collaboration on OA research. The Hub has worked to disseminate OA research updates and funding announcements via a monthly newsletter and created a policy brief in 2024 to communicate OA issues in the Caribbean to better inform local officials.

At the same time the GOA-ON OA Caribbean Hub was forming, there was also a strong push to establish the Caribbean-based Coastal Acidification Network (CariCAN) for the U.S. territories within the Caribbean: Puerto Rico and the U.S. Virgin Islands. While the Hub itself did not directly lead to the creation of the CariCAN, the growing momentum for OA research driven by researchers and NOAA's programs like CariCOOS and OAP helped facilitate its formation in 2024. Throughout the U.S., there are seven CANs that are regionally located and they are designed to bring together collaborative partnerships across scientists, academics, Tribal community leaders, industry professionals, and policymakers to build capacity for regionally-specific OA science and disseminate research for U.S. states and territories (McLaughlin et al., 2015; Cross et al., 2019; Gassett et al., 2021). Coupling the GOA-ON OA Caribbean Hub with the CariCAN will complement the international GOA-ON network with U.S. capacity building and funding opportunities to expand the reach beyond scientific sectors.

Continued policy and community directions for sustained future capacity

This study suggests that there is a need to strengthen the resulting actions from high level policies to increase tangible support for funding, training opportunities, and access to regional networks that can help sustain OA research and assist with the translation of this research into mitigation and adaptation policies. Example models of the successful, sustained future capacity required in the Caribbean can be seen in The Pacific Islands Ocean Acidification Center (PIOAC), as well as in collaborative actions in the Gulf of Guinea. Both examples were made possible by significant collaborative funding investments, and they are already yielding high returns in improving OA research and policy capacity. Policymakers play a crucial role in increasing the regional awareness around OA and can advocate for increased support for OA research and monitoring within the existing regional networks (i.e., IOCARIBE, SPAW, etc.) and international communities and organizations (i.e., GOA-ON, IOC-UNESCO, NOAA, IAEA, etc.). Continued support for the recently established GOA-ON OA Caribbean Hub, CariCAN, and associated efforts for training and capacity building can ensure reliable science is being produced across the region that can inform mitigation and adaptation policies.

The GOA-ON OA Caribbean Hub's policy brief produced in 2024 conveys OA data and possible OA mitigation solutions to regional policymakers to bolster efforts to include OA priorities in national and regional climate change policy. For example, the brief suggests policies should support increased collaboration, innovation, protection, and mitigation of OA. The ability to manage marine ecosystems and minimize the negative effects of OA and other stressors relies on targeted science that is conducted in collaboration with and supported by policy initiatives. Policies need to prioritize, fund, and direct sustained resources towards efforts to establish and reinforce robust monitoring programs at local and region-wide scales and support research efforts on OA impacts. Developing methods to convey OA data and solutions to policymakers at the regional and international levels requires collaboration amongst scientists and decision makers and open communication lines, which can further strengthen the scientific goals and ensure that scientific priorities also align with policy needs. Additional science-policy coordination and engagement with the communities can also help distribute resources for OA education.

Conclusion

The results of the wider Caribbean OA Needs Based Assessment Survey reflect the challenges to develop sustained regional OA monitoring projects that are designed *by the community for the community* to enhance research capacity in a data poor region. This study indicates that training to achieve greater technical capacity supported by sustained funding is essential to build research capacity at the community level. Since OA has unique local impacts that need continuous monitoring to understand natural variation, addressing OA requires sustained financial investment and commitment across communities and sectors, including policy and decision makers, to combat OA at a global scale (Weller et al., 2019). Dedicated support and funding for staff time is essential since many actors are involved in a variety of initiatives and commitments. Leaders within the Caribbean (including co-authors of this study) have stepped up to pioneer the field of OA within their communities in addition to many other responsibilities and need continued financial support and resources to carry on these efforts. External research collaborations, training, and funding initiatives should prioritize community needs by investing in grassroots leadership, co-designing and co-developing collaborative projects from the onset, and ensuring that the resources remain within the local community to sustain the initiatives. Only by creating policies that empower local community members and commit resources that align with their priorities can we begin to address the impacts of OA and meet climate goals.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

Ethics statement

Ethical approval was not required for the study involving humans in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and the institutional requirements.

Author contributions

KG: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. NL: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. KD: Conceptualization, Investigation, Methodology, Project administration, Writing – review & editing. D-AG-S: Investigation, Methodology, Writing – review & editing. EE-B: Investigation, Methodology, Writing – review & editing. MF: Investigation, Methodology, Writing – review & editing. SL: Investigation, Methodology, Writing – review & editing. GK: Conceptualization, Investigation, Methodology, Project administration, Resources, Writing – review & editing. MM: Conceptualization, Investigation, Methodology, Writing – review & editing. JM: Investigation, Methodology, Writing – review & editing. AM: Investigation, Methodology, Writing – review & editing. JN: Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. AP: Investigation, Methodology, Writing – review & editing. AV-O: Conceptualization, Investigation, Methodology, Writing – review & editing. JV: Investigation, Methodology, Writing – review & editing. CV: Investigation, Methodology, Writing – review & editing. EW-F: Conceptualization, Investigation, Methodology, Project administration, Resources, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2025.1595911/full#supplementary-material

References

Allahar, A. L. (1993). Unity and diversity in caribbean ethnicity and culture. *Can. Ethnic Stud. (XXV)* 1, 70–84.

Bates, N., Astor, Y., Church, M., Currie, K., Dore, J., Gonaález-Dávila, M., et al. (2014). A time-series view of changing ocean chemistry due to ocean uptake of anthropogenic CO2 and ocean acidification. *Oceanography* 27, 126–141. doi: 10.5670/oceanog.2014.16

Bates, N. R. (2012). Multi-decadal uptake of carbon dioxide into subtropical mode water of the North Atlantic Ocean. *Biogeosciences* 9, 2649–2659. doi: 10.5194/bg-9-2649-2012

Beaton, A. D., Cardwell, C. L., Thomas, R. S., Sieben, V. J., Legiret, F.-E., Waugh, E. M., et al. (2012). Lab-on-chip measurement of nitrate and nitrite for *in situ* analysis of natural waters. *Environ. Sci. Technol.* 46, 9548–9556. doi: 10.1021/es300419u

Bell, K. L. C., Quinzin, M. C., Amon, D., Poulton, S., Hope, A., Sarti, O., et al. (2023). Exposing inequities in deep-sea exploration and research: results of the 2022 Global Deep-Sea Capacity Assessment. *Front. Marine Sci.* 10. doi: 10.3389/fmars.2023.1217227

Bittig, H. C., Steinhoff, T., Claustre, H., Fiedler, B., Williams, N. L., Sauzède, R., et al. (2018). An alternative to static climatologies: Robust estimation of open ocean CO_2 variables and nutrient concentrations from T, S, and O_2 data using Bayesian neural networks. *Front. Mar. Sci* 5. doi: 10.3389/fmars.2018.00328

Busch, J., Bardaji, R., Ceccaroni, L., Friedrichs, A., Piera, J., Simon, C., et al. (2016). Citizen bio-optical observations from coast- and ocean and their compatibility with ocean colour satellite measurements. *Remote Sens.* 8, 879. doi: 10.3390/rs8110879

Caldeira, K., and Wickett, M. E. (2003). Anthropogenic carbon and ocean pH. *Nature* 425, 365. doi: 10.1038/425365a

Carr, D., Boyle, E. H., Cornwell, B., Correll, S., Crosnoe, R., Freese, J., et al. (2021). "Art and Science of Social Research: with Ebook," in *Quizitive, Writing for Sociology Tutorials, and Author Videos* (WW Norton & Company).

Chan, F., Boehm, A. B., Barth, J. A., Chornesky, E. A., Dickson, A. G., Feely, R. A., et al. (2016). *The West Coast Ocean Acidification and Hypoxia Science Panel: Major Findings, Recommendations, and Actions* (Oakland, California, USA: California Ocean Science Trust).

Clinton-Bailey, G. S., Grand, M. M., Beaton, A. D., Nightingale, A. M., Owsianka, D. R., Slavik, G. J., et al. (2017). A lab-on-chip analyzer for in situ measurement of soluble reactive phosphate: improved phosphate blue assay and application to fluvial monitoring. *Environ. Sci. Technol.* 51, 9989–9995. doi: 10.1021/acs.est.7b01581

Cooley, S., Schoeman, D., Bopp, L., Boyd, P., Donner, S., Ghebrehiwet, D. Y., et al. (2022). "Oceans and Coastal Ecosystems and Their Services," in *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Eds. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (Cambridge University Press, Cambridge, UK and New York, NY, USA), 379–550. doi: 10.1017/9781009325844.005

Creswell, J. W., and Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches* (Sage publications).

Cross, J. N., Turner, J. A., Cooley, S. R., Newton, J. A., Azetsu-Scott, K., Chambers, R. C., et al. (2019). Building the knowledge-to-action pipeline in North America: Connecting ocean acidification research and actionable decision support. *Front. Marine Sci.* 6, 356. doi: 10.3389/fmars.2019.00356

Currie, C., Sabine,, Lowder, K., Hassoun, A. E. R., Meléndez, M., Chu, S., et al. (2024). *Practical Best Practices for Ocean Acidification Monitoring (1.1)* (The Ocean Foundation). doi: 10.5281/zenodo.13876198

Dobson, K. L., Newton, J. A., Widdicombe, S., Schoo, K. L., Acquafredda, M. P., Kitch, G., et al. (2023). Ocean acidification research for sustainability: co-designing global action on local scales. *ICES J. Marine Sci.* 80, 362–366. doi: 10.1093/icesjms/fsac158

Doney, S. C., Fabry, V. J., Feely, R. A., and Kleypas, J. A. (2009). Ocean acidification: the other CO2 problem. *Annu. Rev. Marine Sci.* 1, 169–192. doi: 10.1146/annurev.marine.010908.163834

Espinosa, L. F. (2023). *REMARCO – NETWORK FOR RESEARCH ON MARINE – COASTAL STRESSORS IN LATIN AMERICA AND THE CARIBBEAN* (UNEP(DEPI)/CAR).

Fabry, V. J., Seibel, B. A., Feely, R. A., and Orr, J. C. (2008). Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES J. Marine Sci.* 65, 414–432. doi: 10.1093/icesjms/fsn048

Fanning, L., Mahon, R., Compton, S., Corbin, C., Debels, P., Haughton, M., et al. (2021). Challenges to implementing regional ocean governance in the wider caribbean region. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.667273

Ferreira (2012). "Caribbean Languages and Caribbean Linguistics," in *Caribbean Heritage* (University of West Indies Press).

Friedlingstein, P., Jones, M., O'Sullivan, M., Andrew, R., Bakker, D., Hauck, J., et al. (2022). Global carbon budget 2021. *Earth System Sci. Data* 14, 1917–2005. doi: 10.5194/essd-14-1917-2022

Galdies, C., Tiller, R., and Martinez Romera, B. (2021). "Global Ocean Governance and Ocean Acidification," in *Life Below Water.* Eds. W. Leal Filho, A. M. Azul, L. Brandli, A. Lange Salvia and T. Wall (Springer International Publishing, Cham), 1–12. doi: 10.1007/978-3-319-71064-8_109-1

Gassett, P. R., OBrien-Clayton, K., Bastidas, C., Rheuban, J. E., Hunt, C. W., Turner, E., et al. (2021). Community science for coastal acidification monitoring and research. *Coastal Manage.* 49, 510–531. doi: 10.1080/08920753.2021.1947131

Gill, D. A., Mascia, M., Ahmadia, G., Glew, L., Lester, S., Barnes, M., et al. (2017). Capacity shortfalls hinder the performance of marine protected areas globally. *Nature* 543, 665–669. doi: 10.1038/nature21708

Gledhill, D. K., Wanninkhof, R., Millero, F. J., and Eakin, M. (2008). Ocean acidification of the greater Caribbean region 1996–2006. *J. Geophysical Research: Oceans* 113, 1–11. doi: 10.1029/2007JC004629

Grabb, K. C., Ghosh, A., Adekunbi, F. O., Williamson, P., and Widdicombe, S. (2024). "Ocean acidification: Causes, impacts, and policy actions," in *Reference Module in Earth Systems and Environmental Sciences* (Elsevier), B9780443140822000119. doi: 10.1016/B978-0-443-14082-2.00011-9

Gruber, N., Bakker, D. C. E., DeVries, T., Gregor, L., Hauck, J., Landschützer, P., et al. (2023). Trends and variability in the ocean carbon sink. *Nat. Rev. Earth Environ.* 4, 119–134. doi: 10.1038/s43017-022-00381-x

Hendee, J. C., Halas, J., Fletcher, P. J., Jankulak, M., and Gramer, L. J. (2016). Expansion of the coral reef early warning system (CREWS) network throughout the caribbean. *Proc. 13th Int. Coral Reef Symposium Honolulu*, 517–522. Available online at: https://coralreefs.org/wp-content/uploads/2019/01/Session-73-1-Hendee-et-al-CREWS-Expansion-13ICRS-Session73A-Final-1NS-1.pdf.

Houghton, K. (2014). *A Sustainable Development Goal for the Ocean: Moving from Goal Framing Towards Targets and Indicators for Implementation* (IASS Potsdam).

Hughes, T. P., Kerry, J., Alvarez-Noriega, M., Alvarez-Romero, J., Anderson, K., Baird, A., et al. (2017). Global warming and recurrent mass bleaching of corals. *Nature* 543, 373–377. doi: 10.1038/nature21707

IOC-UNESCO (2024a). *Ocean Acidification Research for Sustainability - A Community Vision for the Ocean Decade* (IOC-UNESCO). doi: 10.25607/YPE3-0H04

IOC-UNESCO (2024b). *IOCARIBE Medium-Term Strategic Science Plan, 2023–2029* (Paris: IOC Information document).

IPCC (2023). *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 1st edn* (Cambridge University Press). doi: 10.1017/9781009325844

Kusek, K. (2019). 21-Year CARIACO Ocean Time Series Ends: That's a Wrap! ¡Fin del Día!. *USF College of Marine Science.* Available online at: https://www.usf.edu/marine-science/news/2019/21-year-caricao-ocean-time-series-ends.aspx (Accessed May 27, 2025).

D. Laffoley, J. M. Baxter, F. A. Arias-Isaza, P. C. Sierra-Correa, N. Lagos, M. Graco, E. B. Jewett and K. Isensee (Eds.) (2018). *Regional Action Plan on Ocean Acidification for Latin America and the Caribbean – Encouraging Collaboration and Inspiring Action. Serie de Publicaciones Generales No. 99* (Santa Marta, Colombia: INVEMAR), 37pp.

Land, P. E., Findlay, H. S., Shutler, J. D., Ashton, I. G. C., Holding, T., Grouazel, A., et al. (2019). Optimum satellite remote sensing of the marine carbonate system using empirical algorithms in the global ocean, the Greater Caribbean, the Amazon Plume and the Bay of Bengal. *Remote Sens. Environ.* 235, 111469. doi: 10.1016/j.rse.2019.111469

Lang, F., Gwinn, J., Grabb, K., Valauri-Orton, A., and Spencer, G. (2024). *Guide to Developing Mentoring Programs for the International Ocean Community* (The Ocean Foundation). Available online at: https://oceanfdn.org/guide-to-ocean-mentoring.

Leeuw, T., Boss, E., and Wright, D. (2013). *In situ* measurements of phytoplankton fluorescence using low cost electronics. *Sensors* 13, 7872–7883. doi: 10.3390/s130607872

Li, H., Zheng, S., Tan, Q.-G., Zhan, L., Martz, T. R., and Ma, J. (2023). Toward citizen science-based ocean acidification observations using smartphone devices. *Analytical Chem.* 95, 15409–15417. doi: 10.1021/acs.analchem.3c03720

Loewe, M., and Rippin, N. (2015). The sustainable development goals of the post-2015 agenda: comments on the OWG and SDSN proposals. *SSRN Electronic J*, 1–92. doi: 10.2139/ssrn.2567302

Lune, H., and Berg, B. L. (2017). *Qualitative research methods for the social sciences* (Pearson Education Limited).

McLaughlin, K., Weisberg, S., Dickson, A., Hofmann, G., Newton, J., Aseltine-Neilson, D., et al. (2015). Core principles of the California Current Acidification Network: linking chemistry, physics, and ecological effects. *Oceanography* 25, 160–169. doi: 10.5670/oceanog.2015.39

Meléndez, M., and Salisbury, J. (2017). Impacts of ocean acidification in the coastal and marine environments of caribbean small island developing states (SIDS). *Caribbean Marine Climate Change Rep. Card: Sci. Rev.* 2017, 31–39.

Meléndez, M., Salisbury, J., Gledhill, D., Langdon, C., Morell, J. M., Manzello, D., et al. (2020). Seasonal variations of carbonate chemistry at two western atlantic coral reefs. *J. Geophysical Research: Oceans* 125, e2020JC016108. doi: 10.1029/2020JC016108

Miloslavich, P., Díaz, J. M., Klein, E., Alvarado, J. J., Díaz, C., Gobin, J., et al. (2010). Marine biodiversity in the caribbean: regional estimates and distribution patterns. *PloS One* 5, e11916. doi: 10.1371/journal.pone.0011916

Miloslavich, P., Seeyave, S., Muller-Karger, F., Bax, N., Ali, E., Delgado, C., et al. (2019). Challenges for global ocean observation: the need for increased human capacity. *J. Operational Oceanography* 12, S137–S156. doi: 10.1080/1755876X.2018.1526463

Miloslavich, P., Zitoun, R., Urban, E. R., Muller-Karger, F., Bax, N. J., Arbic, B. K., et al. (2022). "Developing Capacity for Ocean Science and Technology," in *Blue Economy*. Eds. E. R. Urban and V. Ittekkot (Springer Nature Singapore, Singapore), 467–504. doi: 10.1007/978-981-19-5065-0_15

Mohan, P. S. (2023). Implementing nationally determined contributions under the Paris Agreement: An assessment of ocean-based climate action in Caribbean Small Island Developing States. *Marine Policy* 155, 105787. doi: 10.1016/j.marpol.2023.105787

Moore, C., and Fuller, J. (2020). Economic impacts of ocean acidification: A meta-analysis. *Marine Resource Economics* 37, 201–219. doi: 10.1086/718986

Muller-Karger, F. E., Astor, Y. M., Benitez-Nelson, C. R., Buck, K. N., Fanning, K. A., Lorenzoni, L., et al. (2019). The scientific legacy of the CARIACO Ocean Time-Series Program. *Ann. Rev. Mar. Sci.* 11, 413–437. doi: 10.1146/annurev-marine-010318-095150

Narita, D., Rehdanz, K., and Tol, R. S. J. (2012). Economic costs of ocean acidification: a look into the impacts on shellfish production. *Climatic Change* 113, 1049–1063. doi: 10.1007/s10584-011-0383-3

Newton, J. A., Feely, R. A., Jewett, E. B., Williamson, P., and Mathis, J. (2015). *Global Ocean Acidification Observing Network: Requirements and Governance Plan* (IAEA, GOA-ON), 57.

Pardis, W., Grabb, K. C., DeGrandpre, M. D., Spaulding, R., Beck, J., Pfeifer, J. A., et al. (2022). Measuring protons with photons: A hand-held, spectrophotometric pH analyzer for ocean acidification research, community science and education. *Sensors* 22, 7924. doi: 10.3390/s22207924

Recuero Virto, L. (2018). A preliminary assessment of the indicators for Sustainable Development Goal (SDG) 14 "Conserve and sustainably use the oceans, seas and marine resources for sustainable development. *Marine Policy* 98, 47–57. doi: 10.1016/j.marpol.2018.08.036

Roberts, C. M., McClean, C. J., Veron, J. E. N., Hawkins, J. P., Allen, G. R., McAllister, D. E., et al. (2002). Marine biodiversity hotspots and conservation priorities for tropical reefs. *Science* 295, 1280–1284. doi: 10.1126/science.1067728

Siedlecki, S. A., Pilcher, D., Howard, E. M., Deutsch, C., MacCready, P., Norton, E. L., et al. (2021). Coastal processes modify projections of some climate-driven stressors in the California Current System. *Biogeosciences* 18, 2871–2890. doi: 10.5194/bg-18-2871-2021

Spalding, C., Finnegan, S., and Fischer, W. W. (2017). Energetic costs of calcification under ocean acidification. *Global Biogeochemical Cycles* 31, 866–877. doi: 10.1002/2016GB005597

United Nations (2024). Measure and report ocean acidification: Sustainable Development Goal 14.3.1 indicator. UN Sustainable Development Goals. Available online at: https://sdgs.un.org/partnerships/measure-and-report-ocean-acidification-sustainable-development-goal-1431-indicator (Accessed February 9, 2025).

Valauri-Orton, A., Lowder, K. B., Currie, K., Sabine, C. L., Dickson, A. G., Chu, S. N., et al. (2025). Perspectives from developers and users of the GOA-ON in a box kit: A model for capacity sharing in ocean sciences. *Oceanography* 38, 96–98. doi: 10.5670/oceanog.2025.135

VanderZwaag, D., Oral, N., and Stephens, T. (2021). *Research Handbook on Ocean Acidification Law and Policy* (Edward Elgar Publishing). doi: 10.4337/9781789900149

Venkatesan, R., Navaneeth, K. N., Vedachalam, N., and Atmanand, M. A. (2019). "Observing the oceans in real time—need for affordable technology and capacity development," in *OCEANS 2019 MTS/IEEE SEATTLE* (IEEE, Seattle, WA, USA), 1–7. doi: 10.23919/OCEANS40490.2019.8962684

Wang, Z. A., Moustahfid, H., Mueller, A. V., Michel, A. P. M., Mowlem, M., Glazer, B. T., et al. (2019). Advancing observation of ocean biogeochemistry, biology, and ecosystems with cost-effective *in situ* sensing technologies. *Front. Mar. Sci.* 6, 519. doi: 10.3389/fmars.2019.00519

Weller, R. A., Baker, D. J., Glackin, M. M., Roberts, S. J., Schmitt, R. W., Twigg, E. S., et al. (2019). The challenge of sustaining ocean observations. *Front. Marine Sci.* 6. doi: 10.3389/fmars.2019.00105

Wernand, M. R. (2010). On the history of the Secchi disc. *J. Eur. Optical Society-Rapid Publications* 5, 10013s. doi: 10.2971/jeos.2010.10013s

Whitefield, C. R., Braby, C. E., and Barth, J. A. (2021). Capacity building to address ocean change: organizing across communities of place, practice and governance to achieve ocean acidification and hypoxia resilience in Oregon. *Coastal Manage.* 49, 532–546. doi: 10.1080/08920753.2021.1947133