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A tri-national initiative to advance understanding of coastal and ocean acidification in the Gulf of Mexico/Gulf of America

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The Gulf of Mexico's (also recognized by the United States government as the Gulf of America; herein referred to as "the Gulf") valuable and diverse marine, coastal, and estuarine environments sustain many habitats, species, and economically important fisheries that are vulnerable to open ocean and coastal acidification (OOCA), including shellfish, coral reefs, and other carbonate reefs and seafloor. OOCA poses an economic threat to the Gulf's economy, which is estimated to have a combined value of $2.04 trillion (US) per year across Cuba, Mexico and the United States (U.S.). Scientists from Cuba, Mexico, and the U.S. co-organized and co-hosted the first Gulf International Ocean Acidification Summit on Oct. 18-19, 2022 in Mérida, Yucatan, Mexico to exchange information and begin development of a new tri-national network to address the socioeconomic and ecological impacts of OOCA in the Gulf based on common needs. The meeting included representatives from government agencies, universities, research institutes, non-governmental organizations, and was sponsored by the Furgason Fellowship of the Harte Research Institute at Texas A&M University-Corpus Christi. Discussions focused on each country's challenges, including known and potential socioeconomic vulnerabilities and biological and ecosystem responses to OOCA. Shared priorities were identified for observational, biological, environmental needs, socioeconomic research, outreach, and communications. Priority geographic locations for the study and short and long-term monitoring of OOCA were identified based on the group's knowledge of oceanographic conditions and vulnerable regions. Longer-term actions that will help support multinational collaborations include: identifying shared data and information platforms; standardizing chemical and biological sampling methodologies; coordinating communications with regulatory agencies and resource managers; and coordinating monitoring activities, collaborative research projects, and tri-national comparisons and synthesis of findings. We present guidance from this effort for an integrated, multinational approach to understanding the causes and consequences of OOCA in the Gulf.

KEYWORDS

coastal acidification, ocean acidification, tri-national, Gulf of America, Gulf of Mexico

1 Introduction

The Gulf, the ninth largest ocean basin in the world, is home to highly diverse marine, coastal, and estuarine environments, including ecosystems that contribute significantly to the economy of the three nations surrounding the Gulf (the U.S., Mexico, and Cuba; Figure 1). The Gulf is home to multiple species potentially susceptible to OOCA impacts such as shellfish, coral reefs, mesophotic corals, phytoplankton and other economically important fisheries. These organisms occupy a variety of habitats in the Gulf, including carbonate reefs and seafloor environments that can change as a result of acidification. The Gulf is highly biodiverse, with over 15,000 described species (Felder and Camp, 2009). This number is likely underestimated due to limited surveys on the slope and in deepwater regions.

Understanding, predicting, and responding to local and global stressors and responsive changes within the Gulf requires an integrated geographical approach due the interconnectedness of its waters through the current systems of the central, deep Gulf, estuaries, the shelves, and inshore/offshore flows (Morey et al., 2003; Oey et al., 2005; Martínez-López and Zavala-Hidalgo, 2009). Therefore, developing a tri-national network to exchange information and address the socioeconomic and ecological impacts of ocean and coastal acidification in the Gulf, based on mutually understood needs or shared needs, is of utmost importance.

Open ocean and coastal acidification (OOCA) throughout the Gulf is due to elevated atmospheric carbon dioxide (CO_2) as well as other chemical, biological, and physical processes (Osborne et al., 2022). Approximately one quarter to one third of annual CO_2 emissions are absorbed by the ocean, which lowers seawater pH (an indicator of ocean acidification). Coastal acidification is caused by a combination of ocean acidification and land-based pollution sources (for example, regional excess nutrient inputs to estuaries or coastal waters that can lead to eutrophication, hypoxia, and remineralization) that can contribute to localized acidification. Harmful algal blooms, freshwater inflows, biological production and respiration, anaerobic respiration, calcium carbonate ($CaCO_3$) dissolution, other benthic inputs, and episodic storm events have all been shown to contribute to or are affected by coastal acidification (Cai et al., 2021; Hicks et al., 2022; Hall et al., 2024; Zhang and Xue, 2022). Riverine systems are poorly buffered, have variable total alkalinity, and are often high in $p\mathrm{CO}_2$ (Cai et al., 2011; 2021). A long-term time-series of OOCA does not currently exist in the Gulf (Hu, 2019); however, several studies have documented that OOCA is occurring in both the open Gulf and within estuarine environments (Hu et al., 2015; Robbins and Lisle, 2017; Kealoha et al., 2020; Osborne et al., 2022).

Much of the research on OOCA in the Gulf has primarily focused on US waters (Hu, 2019). The shelves of the northern Gulf (a tropical-subtropical region) are dominated by rivers and eutrophication (Laurent et al., 2017), with localized coral reefs in the Florida Keys and Flower Garden Banks in Texas (Gil-Agudelo et al., 2020), mesophotic reefs (30–150 m; Turner et al., 2017) and karst geology in the southern FL peninsula. Historically, the National Oceanic and Atmospheric Administration (NOAA) leads the effort to monitor OOCA across the Gulf through the Gulf Ecosystems and Carbon Cruises (GOMECC) and Ship of Opportunity-OA (SOOP-OA) programs. The data obtained demonstrate the importance of ocean circulation, temperature seasonality, and the influence of rivers on carbon chemistry dynamics in the Gulf (Wang et al., 2013; Wanninkhof et al., 2015; Kealoha et al., 2020). In Mexican waters, the XIXIMI program has conducted total alkalinity (TA) and dissolved inorganic carbon (DIC) measurements in the southern Gulf offshore waters since 2010. Data from the XIXIMI expeditions show similar vertical structures in the DIC and TA profiles over time in the central and southern Gulf, comparable to the Caribbean profiles generated during the World Ocean Circulation Experiment (WOCE) in 1994. Like the northern Gulf, these regions exhibit high TA/DIC ratios, indicating a strong buffering capacity against acidification (https://www.ncei.noaa.gov/products/world-ocean-circulation-experiment Gledhill et al., 2008). The Research Network of Marine-Coastal Stressors in Latin America and the Caribbean (Red de Investigació n Marino-Costera; REMARCO) has established a network across the Caribbean and Latin America to increase measurements of OA (Espinosa, 2023). Despite these efforts, existing programs do not provide robust temporal coverage at subannual or subseasonal water column carbon chemistry scales, especially in the central Gulf region.

Cuba, while bordering the Gulf, is the largest island in the Caribbean. Its surrounding waters are generally oligotrophic, coral

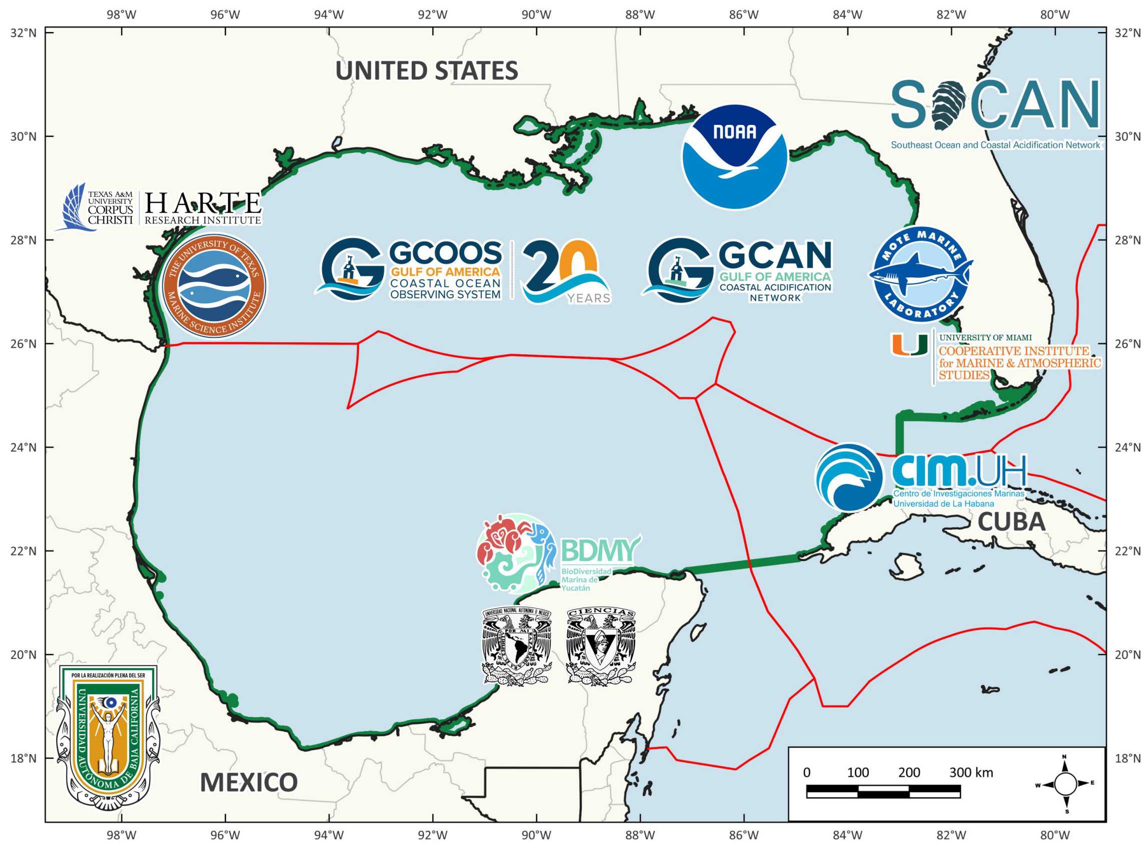

FIGURE 1
Map of the Gulf and surrounding nations. Red lines indicate exclusive economic zones of each nation. Green boundary line indicates official Gulf boundary. Representative logos from participating institutions are included.

reef ecosystems dominate its nearshore habitats, and studies indicate an increase in OOCA (Gledhill et al., 2008). The productive Yucatan Peninsula coast is characterized by karstic geology and submarine groundwater discharges (SGDs), deep water upwellings in the northeast, and seasonal wind-driven upwelling along the coast. Different seasonal conditions affect OOCA. Cold fronts typically approach from the north in the fall and winter and are accompanied by elevated values of dissolved inorganic carbon and total alkalinity near the coast. OOCA is also affected by geophysical characteristics, including the influence of SGD, oxidation of organic matter, and dissolution of carbonate minerals (Barranco et al., 2022). Monitoring efforts that encompass seasonal variability would help broaden understanding of the carbonate system dynamics in these regions.

The Loop Current, which enters through the Yucatan Channel and exits through the Straits of Florida, dominates the mesoscale circulation of the central Gulf in the top ca. 1000 m (Oey et al., 2005; Candela et al., 2019). All nations bordering the Gulf are influenced by the Loop Current and the anticyclonic eddies that detach from it periodically. They are transported west and southwest, demonstrating the region's oceanographic interconnectedness (Hamilton et al., 1999). The upper layer is also influenced by near-surface freshwater discharge from rivers; water mass hydrographic and biogeochemical properties are altered through water density differences, mixing, and bathymetry, and are spatially variable and dynamic (Portela et al., 2018; McKinney et al., 2021; Cervantes-Díaz et al., 2022). Over the past several decades, human interactions have led to changes and impacts on natural resources throughout the Gulf, including fisheries resources, recreational facilities, offshore oil drilling, land use changes, and changes in organism and ecosystem diversity.

OOCA poses an economic threat to the Gulf's economy, which is estimated to be worth $2.04 trillion per year across Cuba, Mexico, and the US (Shepard et al., 2013). According to National Marine Fisheries (2024), the Gulf's commercial seafood landings for revenue in 2022 in the US was $921 million, accounting for 17.4% of national landings and 15.6% of the total revenue. Of the total Gulf commercial landings in 2021-22, shellfish contributed $66 million and almost 7% of the revenue. Recreational finfish fisheries accounted for catches of 580,375 individuals, which corresponds to 52% of the US total (National Marine Fisheries Service, 2024). Oyster fisheries alone brought in an estimated revenue of $76.9 and 93.4 million in 2023 and 2022, respectively (https://www.fisheries.noaa.gov/foss/f?p=215:200:3384444710405). Mexico's 2023 Statistical Yearbook of Aquaculture, published by the Fisheries National Commission of Aquaculture and Fisheries (CONAPESCA), indicates that the value of the Gulf's fisheries was approximately $440 million, with oyster production

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contributing \$3.4 million (Comisión Nacional de Acuacultura y Pesca, 2023). Major fisheries for Cuba include export of spiny lobster, penaid shrimp, and tuna. Since 1992, average annual value of fishery export in Cuba is ~\$107 million annually (Adams et al., 2000).

The Gulf ecosystems are subject to multiple local (e.g., overfishing, eutrophication, hypoxia, and oil spills) and global (e.g., ocean warming and acidification) anthropogenic stressors. The Gulf U.S. shell fisheries are particularly vulnerable to ocean and coastal impacts because of a combination of environmental (e.g., eutrophication and high river input), biological (e.g., low diversity of shellfish fishery harvest), and social factors (e.g., low political engagement in OOCA, ocean warming, and relatively low science accessibility; Ekstrom et al., 2015). In Mexico, the lack of long-term surveys of environmental conditions and biological communities, limited enforcement of fishery regulations, overexploitation, and coastal eutrophication and pollution threaten ecosystem health (Caso et al., 2014). Socioeconomic risks from ocean and coastal acidification impacts to fisheries' species are largely unknown. In addition to elevated carbon dioxide (CO_2) in the atmosphere, acidification in the region is influenced by a complex interplay of processes and multiple stressors such as increasing water temperature, changing ocean circulation, runoff of both river water and excess nutrients, as well as regionally low oxygen over the shelf, harmful algal blooms (HABs), storms, and oil spills. For example, blooms of *Sargassum* spp. have been problematic throughout the Caribbean. However, more recent studies show blooms persisting throughout the Gulf as well (Zhang et al., 2024). Decaying *Sargassum* spp. blooms could contribute to localized OOCA events (Liu et al., 2024) but may also have positive effects under OOCA on coral physiology (Lankes et al., 2025).

The Gulf seawater chemistry is highly complex but remains relatively under-studied concerning acidification (Osborne et al., 2022). Critical knowledge, research, and monitoring gaps limit our current understanding of environmental, ecological, and socioeconomic impacts needed to improve models for predicting acidification and its consequences. The diversity of habitats found in the Gulf spanning multiple climatic zones and the connection between bordering nations' ocean and coastal resources through ocean circulation and migration makes international collaboration critical to understanding the influence of acidification, its causes, and impacts in the Gulf. A shared, multi-national vision of a Gulf that is prepared to respond and adapt to ocean acidification united an international team of scientists from the US, Cuba, and Mexico to organize and conduct the Gulf's first International Ocean Acidification Summit.

2 Materials and methods

2.1 Meeting purpose and scope

Thirty-one participants from the US, Cuba, and Mexico met in Mérida, Yucatán, Mexico, from October 18-19, 2022, for the first "Gulf International Ocean Acidification Summit". Organizing institutions included: Harte Research Institute (HRI), Texas A&M University-Corpus Christi; the Gulf of America Coastal Ocean Observing System (GCOOS, a Regional Association of the U.S. Integrated Ocean Observing System); Gulf of America Coastal Acidification Network (GCAN); Centro de Investigaciones Marinas, Universidad de La Habana (CIM-UH); Centro de Estudios Ambientales de Cienfuegos (CEAC); UMDI-Sisal, Facultad de Ciencias, Universidad Nacional Autónoma de México (UNAM); Instituto de Investigaciones Oceanológicas, Universidad Autonoma de Baja California (IIO-UABC); and Kalanbio A.C. – Mexico. Meeting participants included representatives from government agencies, universities, research institutes, non-governmental organizations, and graduate students. The primary meeting objectives included: fostering communication among international colleagues; sharing information on OOCA science, identifying gaps, research, and monitoring needs; and exploring approaches and opportunities for collaboration.

Prior to the in-person meeting, GCAN hosted a virtual coordination meeting that included activities to prioritize topics for discussion at the in-person meeting based on common needs across the nations. The results of the discussion were used to develop the summit's agenda. Participants were also asked to join a virtual meeting to introduce each other as a group, identify other stakeholders who may wish to participate, provide summaries of each participant's information needs related to OOCA for the organizing committee, and to allow participants to assist with determining what was required to ensure a productive meeting that met the overall objectives.

The meeting in Mérida, Mexico, began with a social activity and introductory presentations from the sponsors and representatives of each of the three countries, covering meeting goals, potential outcomes, and brief overviews of the state of the science, gaps, and challenges from each country. These presentations were followed by topic-specific breakout sessions and group discussions on gaps, challenges, common regional issues, and scientific and geographic priorities related to: exposure to OOCA and region-specific special considerations affecting exposure; biological response to OOCA, including species, habitats, and ecosystem-level responses; and known and potential socioeconomic vulnerabilities. Due to the varying levels of expertise among the participants, protocols for sample collection, analysis, and QA/QC were discussed, as were the challenges of using optical sensors for continuous monitoring (sensor availability, cost, and deployment locations). The final group discussion focused on approaches for developing a tri-national network for ocean acidification and acknowledging the shared commitment to working toward this goal. The group agreed upon short-term actions to begin facilitating the development of this network, including establishing pathways and platforms to facilitate group communication, increasing awareness of the tri-national effort to stakeholders, policy-makers, and managers, and building on existing collaborative efforts and networks such as GCAN. Additionally, the group identified shared priorities for observational, biological, and socioeconomic research; outreach and communications; priority geographic locations for study; and longer-term actions needed to facilitate multi-national collaboration such as: identification or development of shared data and information platforms; standardization of chemical and biological methods; joint training activities for research and monitoring practices and procedures; coordinated interaction and communication with regulatory agencies and resource managers for guidance to science; and coordination of monitoring activities, collaborative research experiments, and tri-national comparison of results.

2.2 Anticipated outcomes

In addition to working toward development of a tri-national network to foster collaboration among the three nations on ocean acidification research and monitoring, other anticipated outcomes from this meeting included: co-development of a report by the participant group describing meeting topics and discussions in detail; development of a tri-national Gulf regional gap analysis to assist with identifying nation-specific as well as shared research and monitoring gaps; development of a multi-national Gulf socioeconomic risk and vulnerability assessment/report; and development of special topical work groups to facilitate international collaborative research activities, training opportunities, and funding needs.

3 Results

3.1 Preliminary meeting

During the virtual meeting with participants, the highest priority communication needs were identified as exchanging experiences with colleagues related to science and working with stakeholders, learning different perspectives across regions and sectors on OOCA's impacts, and developing a tri-national network to facilitate multi-national collaboration on OOCA research and monitoring.

3.2 Meeting introductions

Social activities were conducted at the beginning of each day of the summit to provide an opportunity for participants to meet, engage in informal conversation, and to begin working together as a team. For example, one group activity included all participants working together to map the Gulf on the floor with a rope. Participants were grouped by region (U.S., Cuba, or Mexico) and the rope was placed in the shape of the coastline adjacent to their county (Figure 2). Then participants were asked to work together across regions to evaluate and improve the map as a way to facilitate interaction and conversation. Introductions were provided on the meeting agenda, the summit organizing institutions (GCOOS and HRI), GCAN, state of the science on ocean and coastal acidification, and summaries of recent or ongoing research cruises that encompass most of the Gulf. After introductions, participants were asked to participate in topic-specific group discussions on gaps, challenges, common regional issues, scientific and geographic priorities related to three different themes including: 1. exposure to ocean acidification and region-specific special considerations influencing their vulnerability; 2. potential biological responses to ocean acidification including specific species, habitats, and ecosystem responses; and 3. known and potential socioeconomic vulnerabilities. A final group discussion focused on approaches for developing a tri-national network for OOCA and acknowledging the shared commitment to working toward this goal.

3.3 Breakout session 1: exposure

The exposure breakout session consisted of four subgroups focusing on identification of knowledge gaps, measurement protocols, communications, and solutions. Geographic gaps for OOCA research and monitoring were identified as:

- nearshore and estuarine measurements (<10 m depth),
- the deep-water region of the Gulf,
- Usumacinta River outflow and impacts,

FIGURE 2
The social activity involved participants being asked to form the shape of the Gulf.

- Veracruz Region and National Park, and
- ocean and coastal impacts to the karst environments of Florida and the Yucatan Peninsula.

OOCA measurement priorities were identified as:

- all countries needing higher temporal and spatial resolution measurements to pair with biological studies and address resource management issues,
- establishing laboratories with the capacity to integrate chemical and biological studies,
- need for identifying OOCA indicator species that are charismatic and relatable to the public,
- ensuring the availability of reference samples, especially in Mexico and Cuba, and
- making sure the sampling and analytical methodology is standardized (by establishing best practices) for chemistry and biology measurements.

Communications priorities were identified as:

- conveying OOCA information to non-experts in understandable terms,
- emphasizing that although OOCA is underemphasized as a problem in the Gulf, the system has been shown to have some of the fastest acidification rates measured as declining carbonate saturation states,
- a need for a transdisciplinary approach to communicating OOCA issues,
- improving efforts oriented toward stakeholder outreach through interaction with local and regional groups, and
- expanding awareness through student education programs.

Potential solutions identified included:

- collaboration and development of common communication strategies and practices,
- using the expertise within the summit's participants to share best practices for OOCA studies,
- implementing training activities to promote professional development in the field of OOCA that are oriented toward early career researchers,
- initiate laboratory inter-comparisons across nations, and develop sampling kits to train people for sample collection and expanding monitoring through citizen science,
- identify common (Gulf-wide) indicator species and establish baselines of biological responses to OOCA,
- developing an approach for elevating perception of impact such as designing a multi-national sampling effort and strategy for the most impacted areas and events,
- exploring collaboration with the National Association of Marine Labs (NAML) for help with obtaining and distributing certified reference materials, and
- identifying or developing cost-effective alternatives for pH measurements.

3.4 Breakout session 2: biological response

The biological response breakout session was broken out into three subgroups covering gaps, challenges, and solutions. Knowledge gaps were identified as

- OOCA impacts on marine fish and shellfish,
- studies on other Gulf marine organisms (e.g. megafauna), and
- research on food web implications from plankton to higher species.

Challenges were identified as:

- no standardized methods across regions and
- difficulty of studying physiological effects on larger coastal and marine organisms.

Solutions were identified as:

- the need to identify common species of interest across nations and involve fisheries regulatory agencies in the process to provide guidance for biological research focus and
- the need for vulnerability models for species groups.

3.5 Breakout session 3: socioeconomic considerations

The socioeconomic session was divided into two subgroups, centered on knowledge gaps and potential activities. The socioeconomic impacts of OOCA throughout the Gulf can be linked to recreational tourism (diving, hotel occupancy along the coast, etc.), ecotourism, shellfish farming, and commercial, recreational, and subsistence fishing. The total economic value of fisheries is well-studied by each country surrounding the Gulf, but the current or future estimates if impacted by OOCA have not been assessed. Additionally, socioeconomic impacts are likely to differ among nations and regions (such as states in the U.S. and Mexico and provinces in Cuba), and specific evaluation and assessment are required. The gaps the workshop participants identified include:

- need for assessing potential socioeconomic impacts and potential values within each region,
- a pressing need for public, community leader, managers, and policy maker education about OOCA, particularly in Mexico and Cuba, and
- development of educational content in English and Spanish to promote public and stakeholder education.

Potential activities include:

- mining socioeconomic data from each country to evaluate the realized or potential effect of OOCA and updating as a tri-national effort,

- identifying socio-economists who understand the effects of OOCA on economic value,
- implementing community listening sessions,
- increasing partnership development (e.g., working with organizations that function as liaisons),
- targeted public engagement, and
- creative communication.

3.6 Development of a tri-national network

The final group discussion focused on approaches for developing a "Tri-National Network for OOCA" and acknowledging their shared commitment toward this goal. The group agreed upon short- and long-term actions to begin facilitating the development of the network, including establishing pathways and platforms to facilitate group communication, increasing awareness of this tri-national effort, and building on existing collaborative efforts (Table 1). Additionally, the group identified shared priorities for observational, biological, and socioeconomic research, including environmental justice needs; outreach and communication; and pursuing funding and longer-term actions needed to facilitate multinational collaboration. Priority locations within each region for monitoring and research were also identified (Table 2).

4 Discussion

The Gulf is a semi-enclosed oceanic basin of approximately 1.6 million km^2 that connects Mexico, the US, and Cuba (Turner and Rabalais, 2019). These nations are aware of risks to the Gulf, including the degradation of coastal areas that support local communities, loss of habitat and marine and coastal natural resources; overfishing; increasing harmful algal blooms; hypoxia; vessel groundings on coral reefs; coastal subsidence; energy exploration (including oil spills); increased production in coastal areas; increases in the frequency of environmental changes in the ecosystem (such as fluctuations in abundance and distribution of fish, birds and mammals due to anthropogenic stressors linked to climate change); and the need for climate change monitoring (UNIDO, 2014). OOCA, currently understood as both a water quality and a climate change issue (Doney et al., 2009; Wallace et al., 2014), is increasing throughout the Gulf estuaries, coasts, and open ocean (Wanninkhof et al., 2015; Robbins and Lisle, 2017; Osborne et al., 2022; Jiang et al., 2024), yet the connectivity of populations and communities throughout the Gulf has not been fully evaluated. Developing a tri-national network to foster collaboration among the three nations on OOCA research and monitoring is imperative to understand the Gulf's oceanographic and biological interconnectedness.

TABLE 1 Short- and long-term action items for a tri-national OA network.

Short-term action items
Continuation of tri-national network communications
Follow-up meetings
Search for funding for international collaborations
Long-term action items:
Identification or development of shared data and information platforms
Standardization of analytical methods
Joint training activities for research, monitoring practices, and protocols
Coordinated interaction and communication with regulatory agencies and resource managers to identify and guide scientific needs
Coordination of monitoring activities, collaborative research experiments, and tri-national comparison of results

TABLE 2 Priority locations for pilot studies within each region.

U.S.	Cuba	Mexico
Florida Keys	Guanahacabibes MPA	Veracruz MPA
Northwest Gulf	La Habana	Laguna de Términos MPA
Florida Shelf	Cayo Santa María MPA	Celestún MPA
		Alacranes MPA

MPA, Marine Protected Areas.

During this first International OA Meeting, participants concluded that exposure to OOCA is poorly understood, particularly in shared waters and adjacent national coastlines. Several research and monitoring gaps were identified; although some previous studies within each region have been conducted and published, they were either short-term or lacked a broader context. For example, only a handful of studies on nearshore and estuarine measurements throughout the Gulf have been published, and these are predominantly in the U.S. (e.g., Cai et al., 2011; Hu et al., 2015; Robbins and Lisle, 2017; McCutcheon and Hu, 2022; Hall et al., 2024; Martínez-Trejo et al., 2024). Some coral reefs, like the Flower Garden Banks, and the northern Gulf (e.g., Mississippi River outflow), have been relatively well-studied (e.g. see Hall et al., 2020; Osborne et al., 2022; and references therein). However, studies in deep Gulf waters (>300 m depths) are generally limited because of difficult access and high costs. In addition, benthic landers are promising for deep water acidification studies at the sediment-water interface (Berelson et al., 2019). The Grijalva-Usumacinta River System provides the highest freshwater inflow into the southern Gulf, yet the impact on OOCA is poorly understood. Studies in that system are only beginning to evaluate changes in carbon cycles (Soria-Reinoso et al., 2022). The coast and shelf of the state of Veracruz in the southwestern Gulf has the main commercial port in Mexican waters, an extensive network of coral reef systems that includes endemic species of fishes and is one of the largest marine protected areas in Mexico. Studies on high population centers that are popular fishing and recreational areas, like the Grijalva-Usumacinta River System and the state of Veracruz, can serve as models to promote and enhance public awareness, motivate effective management for current or projected OOCA impacts, with the ultimate goal of protecting or restoring ecosystems (Duarte et al., 2008). Other poorly understood systems include karst environments. Much of the geology in the Gulf (east of Louisiana in the U.S., Cuba, and Mexico) is karst. These systems are unique in that the dissolution of carbonate rocks can increase TA and DIC, yet how these systems influence OOCA is uncertain (Patin et al., 2021; Barranco et al., 2022; Martínez-Trejo et al., 2024). Limited *in-situ* studies have been conducted in coral reef ecosystems in the Gulf (e.g. Crook et al., 2012; Dee et al., 2019; Guan et al., 2020; Lawman et al., 2022).

To tackle these gaps, participants determined that all three nations need higher temporal and spatial resolution measurements. Short term or temporally infrequent data collections can provide some information (e.g. Hall et al., 2024), however frequent and sustained data collection (e.g. from *in situ* sensors) can more effectively capture key parameter measurements under variable environmental conditions, allowing for a better characterization of daily to seasonal trends in carbonate chemistry across a range of estuarine, coastal and marine settings (Rosenau et al., 2021). The group also recognized that higher temporal and spatial resolution measurements should be paired with biological studies. A unified set of indicator species that are charismatic and relatable to the public would contribute to developing management responses to OOCA (Ducarme et al., 2013). Many species of coral have been well studied for the effects of OOCA (e.g. Lunden et al., 2014; Kurman et al., 2017; Muller et al., 2021; Bove et al., 2022), yet corals are distributed in isolated locations throughout the Gulf and OOCA exposure and impacts do not exist entirely throughout the Gulf. Other, less-studied, yet ecologically and economically relevant organism studies are needed. Impacts of OOCA on marine fish species and food web interactions throughout the Gulf are limited (Osborne et al., 2022). A challenge is that there are currently no standardized methods to assess the effects of OOCA on marine organisms across the Gulf regions. Common species of interest that are found across the Gulf should be identified, and fisheries regulatory agencies should be involved to guide biological research focus (e.g. Galindo-Cortes et al., 2019). Lastly, OOCA vulnerability models are needed for species groups to support ecosystem-based management decisions across nations (Ekstrom et al., 2015; Ocaña et al., 2019).

Addressing these gaps requires increased funding. Funding for marine research in Mexico, Cuba, and the U.S. could come from various sources, including government agencies, private foundations, and international organizations. Participants agree that shared strategies and best practices can be established effectively despite funding limitations. Collaboration on best practices for methods of OOCA sampling and analyses, including standard protocols for biological sampling, is imperative for cross-nation studies. There are currently several best practices manuals for studies on OOCA (e.g. Dickson et al., 2007; Riebessel et al., 2011; Boyd et al., 2019; Sutton et al., 2022); however, some institutions do not have access to the materials, instruments, and methods described in these manuals. To define these best practices throughout the Gulf, joint training activities and shared students can be utilized to grow human capacity. Programs like international internships and fellowships offered by universities or non-government organizations can increase participation (Torres et al., 2017; Sharma, 2024).

Another potential action to overcome these gaps is to begin collaborative interlaboratory comparisons on sampling and carbonate chemistry analyses across nations. Shared data and the usefulness of these measurements will depend on data quality and consistency. Historically, interlaboratory comparisons for OOCA analyses have been conducted throughout the U.S. using certified reference materials provided by the Dickson Lab; however, these comparisons have not occurred since 2017 (Bockmon and Dickson, 2015). Likewise, laboratories across the U.S., Mexico, and Cuba have not performed interlaboratory comparisons. As previously stated, many institutions lack the proper equipment and materials to perform interlaboratory comparisons. Organizations like the Global Ocean Acidification Observing Network (GOA-ON) have created low-cost kits for collecting ocean acidification measurements. The GOA-ON in a Box kits have been distributed to scientists in sixteen countries in Africa, Pacific Small Island Developing States, and Latin America, and can be used to train people in the measurement, collection of OOCA indicators and expanding monitoring through citizen science (Valauri-Orton et al., 2025).

There will be socioeconomic impacts from OOCA throughout the Gulf, including tourism and commercial, recreational, and subsistence fishing sectors. Understanding socioeconomic impacts due to OOCA in the Gulf can be improved by better defining the economic values of impacted sectors within each region. The total value of fisheries is well-studied by each country surrounding the Gulf (e.g. Sánchez-Gil et al., 2004; Valle et al., 2011; Ekstrom et al., 2015; Anuario Estadístico de Acuacultura y Pesca 2023), but not the species-specific potential losses if impacted by OOCA. Additionally, valuation of resources may differ depending on the country leading the study and available data (Adams et al., 2004). Understanding the impacts of OOCA on tourism remains a challenge to define.

Another challenge is public education and awareness about OOCA as it relates to the potential impacts on socioeconomic activities. Evaluating and identifying regions or environmental conditions that are conducive to OOCA is critical to mitigating its impacts, yet is hindered by a lack of a sense of urgency in the general public and a lack of media coverage (Tiller et al., 2019). Multiple efforts throughout the US are working toward better public awareness (which are also directed and coordinated with managers and policy-makers), such as the Coastal Acidification Networks, the Ocean Acidification Alliance, NOAA Ocean Acidification Program, the National SeaGrant Programs, and others (Cook and Kim, 2019; Cross et al., 2019; Hall et al., 2020; Osborne et al., 2022). While these efforts are starting to extend across nations, they remain insufficient in certain regions. For example, the Global Ocean Acidification Network (GOA-ON) is an international collaborative network that monitors ocean acidification in marine environments to understand its causes and impacts. It supports the development of mitigation and adaptation strategies. The network encourages the formation of regional centers, such as the North American and Caribbean Hubs, where EUA, Mexico, and Cuba are all included, to collect comparable data and support predictive models. In addition, in Mexico, the Mexican carbon Program (PMC) also seeks to coordinate scientific activities related to carbon cycle studies carried out, act as

Mexico's scientific counterpart to similar programs in other countries, develop and promote scientific research related to the carbon cycle in the country, and systematize scientific information on carbon.

Results from this meeting indicated a strong need for a tri-national network on OOCA. Since the summit, some progress has occurred, laying a foundation toward achieving some of the identified priorities. Short-term and long-term communication needs were determined. In the short term, a web page was developed by HRI (https://www.harteresearch.org/collaboration/trinational-initiative-mexico-and-cuba-0, accessed 03/29/25) including a linked page to the tri-national network on OOCA (https://gcoos.org/oa-trinational/, accessed 03/29/25) and multiple press releases were developed. In the long-term, priority international OOCA projects were agreed upon (Table 2). A more comprehensive Gulf of Mexico Ecosystems and Carbon Cycle (GOMECC) cruise began in 2017. It continued with the 2021 cruise, sampling international waters of Mexico and Cuba for the first time to establish an OOCA monitoring network to quantify the increase in near-surface water carbon dioxide and associated changes in inorganic carbon speciation (Barbero et al., 2019). Supported by NOAA OAP, GOMECC-5 is scheduled for the fall of 2025. A series of webinars were presented virtually and focused on establishing collaborative opportunities among the US Marine Biodiversity Observation Network (MBON), GCAN and the Southeast Ocean and Coastal Acidification Network (SOCAN) (https://gcoos.org/webinars2024/; accessed 3/25/25). The goal of building synergy across networks to advance science in support of resource management and the Blue Economy aligns with the goals of the tri-national OOCA network. Topics of discussion included advancing the state of MBON and OOCA science, identifying opportunities to bridge MBON and OOCA science, synthesizing lessons learned, and developing new partnerships. GCOOS has since opened membership to international collaborators. These initiatives are also synergistic with ongoing efforts to facilitate cross-national collaboration (Machlis et al., 2012; Ayala-Castañares and Knox, 2000; UNIDO, 2014; Zaldívar-Jiménez et al., 2017).

There has also been progress from each represented nation's policies on OOCA throughout the Gulf since this initiative occurred. In 2023, the US Ocean Acidification Action Plan was established, which outlines strategies for mitigation, adaptation, and resilience to OOCA (Interagency Working Group on Ocean Acidification, 2023). This plan also aligns with the International Alliance to Combat Ocean Acidification (OA Alliance), which the US joined in 2022. In this plan, the US commits to working with communities worldwide to share knowledge and build capacity to address the shared challenges of OOCA. The US has also added a new Coastal Acidification Network (The Caribbean CAN [Cari-CAN]) to its network within NOAA. Cari-CAN engages with international bodies like the UNESCO Intergovernmental Oceanographic Committee and other research networks to address OOCA. Cuba continues to be a part of the Research Network of Marine-Coastal Stressors in Latin America and the Caribbean (REMACO) project (www.remarco.org/en/cuba/, accessed 9/22/2025). This network aims to establish current levels of OOCA and promote policies aimed at reducing CO_2 emissions. Most recently, Cuba is participating in the project *Strengthening Regional Capabilities on the Application of Nuclear and Isotopic Techniques to Increase Knowledge about Stressors that Affect Marine and Coastal Sustainable Management* (ARCAL CLXXXIX; https://remarco.org/en/cuba/) as part of their participation in the Research Network of Marine-Coastal Stressors in Latin America and the Caribbean (REMARCO; https://remarco.org/en/). (Nuclear techniques refer to contaminant detection.) Data from Cuba is currently being uploaded to the United Nations SDG 14.3.1 Monitoring Portal and a monitoring tool developed by UNESCO's Intergovernmental Oceanographic Commission to share ocean acidification data (Grabb et al., 2025). Mexico is expected to publish an updated national policy for the sustainable management of Mexico's seas and coasts during the latter half of 2025: *Política Nacional para el Manejo Sustentable de Mares y Costas 2025* (https://sdgs.un.org/partnerships/publication-updated-national-policy-sustainable-management-mexicos-seas-and-coasts). This policy will serve as Mexico's Sustainable Ocean Plan, is part of the country's commitments to the High-Level Panel for a Sustainable Ocean Economy and preliminarily includes a focus on OOCA. Some initiatives will likely overlap between the three nations. Future efforts should support collaborative efforts that complement existing monitoring efforts and the understanding of the drivers of OOCA in the Gulf.

A trinational initiative involving the US, Mexico, and Cuba is crucial for understanding OOCA in the Gulf due to the shared nature of marine ecosystems and the transboundary challenges they face. The Gulf's diverse habitats and species, including shellfish and coral reefs, are vulnerable to OOCA, which poses significant ecological and economic threats. Collaborative efforts enable the pooling of resources, expertise, and data, leading to a more comprehensive understanding of acidification patterns and impacts across the entire Gulf region. Such cooperation fosters the development of unified strategies and policies to mitigate adverse effects, benefiting all nations involved.

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 author.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

EH: Investigation, Writing – review & editing, Methodology, Funding acquisition, Conceptualization, Writing – original draft.

XH: Writing – review & editing, Investigation, Conceptualization, Funding acquisition, Methodology, Project administration. JV: Writing – review & editing, Investigation, Methodology, Conceptualization, Project administration. KY: Methodology, Conceptualization, Project administration, Investigation, Funding acquisition, Writing – review & editing. MB: Methodology, Project administration, Conceptualization, Investigation, Funding acquisition, Writing – review & editing. JB: Funding acquisition, Conceptualization, Writing – review & editing, Project administration, Methodology, Investigation. LB: Conceptualization, Writing – review & editing, Methodology, Investigation. SH: Funding acquisition, Methodology, Project administration, Conceptualization, Investigation, Writing – review & editing. JH: Methodology, Writing – review & editing, Investigation, Conceptualization. NS: Conceptualization, Methodology, Investigation, Writing – review & editing. PG: Conceptualization, Methodology, Writing – review & editing, Project administration, Investigation.

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Conflict of interest

Author JV-D was employed by Ocean Associates, Inc.

The remaining 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.

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