Ocean acidification in the Gulf of Mexico: Drivers, impacts, and unknowns

Emily Osborne [a,*], Xinping Hu [b], Emily R. Hall [c], Kimberly Yates [d], Jennifer Vreeland-Dawson [e], Katie Shamberger [f], Leticia Barbero [a,g], J. Martin Hernandez-Ayon [h], Fabian A. Gomez [a,i], Tacey Hicks [f], Yuan-Yuan Xu [a,g], Melissa R. McCutcheon [b], Michael Acquafredda [j], Cecilia Chapa-Balcorta [k], Orion Norzagaray [h], Denis Pierrot [a], Alain Munoz-Caravaca [l], Kerri L. Dobson [j], Nancy Williams [m], Nancy Rabalais [n], Padmanava Dash [o]

[a] Atlantic Oceanographic and Meteorological Laboratory, National Oceanographic and Atmospheric Administration, Miami, FL, USA
[b] Harte Research Institute for Gulf of Mexico Studies, Texas A&M University-Corpus Christi, USA
[c] Mote Marine Laboratory, Sarasota, FL, USA
[d] US Geological Survey, St. Petersburg, FL, USA
[e] Gulf of Mexico Coastal Ocean Observing System Regional Association, Texas A&M University-Corpus Christi, TX, USA
[f] Department of Oceanography, Texas A&M University, College Station, TX, USA
[g] Cooperative Institute for Marine and Atmospheric Studies, Rosenstiel School for Marine and Atmospheric Science, University of Miami, Miami, FL, USA
[h] Autonomous University of Baja California, Mexico
[i] Northern Gulf Institute, Mississippi State University, MS, USA
[j] Ocean Acidification Program, National Oceanographic and Atmospheric Administration, Silver Spring, MD, USA
[k] Instituto de Recursos, Universidad del Mar, Puerto Angel, Oaxaca, Mexico
[l] Center for Environmental Studies in Cienfuegos, Cuba
[m] College of Marine Science, University of South Florida, Saint Petersburg, FL, USA
[n] Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA, USA
[o] Department of Geosciences, Mississippi State University, MS State, MS, USA

A B S T R A C T

Ocean acidification (OA) has resulted in global-scale changes in ocean chemistry, which can disturb marine organisms and ecosystems. Despite its extensively populated coastline, many marine-dependent communities, and valuable economies, the Gulf of Mexico (GOM) remains a relatively understudied region with respect to acidification. In general, the warm waters of the GOM are better buffered from acidification compared to higher latitude seas, yet long-term acidification has been documented in several GOM regions. OA within the GOM is recognized as spatially variable, particularly within the coastal zone where numerous physical and biogeochemical processes contribute to carbonate chemistry dynamics. The historical progression of OA within the entire GOM is difficult to assess because only a few dedicated long-term monitoring sites have recently been established, and full-water column observations are limited. However, environmental drivers on smaller scales that affect GOM acidification were found to include freshwater, nutrient, and carbonate discharge from large rivers; ocean warming, circulation and residence times; and episodic extreme weather events. GOM marine ecosystems provide essential services, including coastline protection and carbon dioxide removal, and habitats for many marine species that are economically and ecologically important. However, organismal and ecosystem responses to OA are not well constrained for the GOM due to a lack of studies examining the specific effects of OA on regionally relevant species under contemporary and projected conditions. Tackling the vast number of remaining scientific unknowns in this region can be coordinated through regional capacity networks, such as the Gulf of Mexico Coastal Acidification Network (GCAN), working to achieve a system-wide understanding of Gulf OA and its impacts. Here we synthesize the current peer-reviewed literature on GOM acidification across the ocean-estuarine continuum and identify critical knowledge, research, and monitoring gaps that limit our current understanding of environmental, ecological, and socioeconomic impacts from acidification.

1. Introduction

As atmospheric carbon dioxide (CO_2) concentrations have risen due to human activities, ocean time-series have shown a concomitant increase in CO_2 concentrations in the surface ocean (e.g., Dore et al., 2009; Bates et al., 2014; Friedlingstein et al., 2021). Increasing atmospheric and seawater CO_2 have caused a long-term decline in seawater pH (represented by an increase in hydrogen ion activity (a_H); pH $= -$ log (a_H)) that has been termed "Ocean Acidification" or OA (e.g., Caldeira & Wickett, 2003; Feely et al., 2004; Orr et al., 2005; Doney et al., 2009).

OA also coincides with other changes to the marine carbonate system, including a reduction in carbonate ion concentration ($[CO_3^{2-}]$), which is often expressed using the term Ω for calcium carbonate saturation state. OA has broad ranging negative implications for marine ecosystems, especially for marine calcifiers that are sensitive to changes in seawater pH and Ω with respect to aragonite (Ω_{ar}) and calcite (Ω_{ca}) (Orr et al., 2005; Hoegh-Guldberg et al., 2007; Iglesias-Rodriguez et al., 2008; Kleypas & Yates, 2009; Andersson and Gledhill, 2013; Waldbusser et al., 2014; Eyre et al., 2018; Doo et al., 2020; Doney et al., 2020). It is estimated that the global surface ocean has experienced a 0.1-unit reduction in mean surface pH since industrialization, with continued declines anticipated as anthropogenic CO_2 emissions continue to increase (Sabine et al., 2004; Orr et al., 2005; Feely et al., 2009). In addition to increasing atmospheric CO_2 as a driver of anthropogenic OA, other natural and anthropogenic environmental drivers and biogeochemical processes can dramatically alter seawater carbonate chemistry, particularly within the coastal ocean (see section 2.2). Local coastal processes, collectively referred to as coastal acidification, occur concurrently with atmospherically-driven OA, and include changes in freshwater and nutrient input, land use changes, biological activity, etc. and often co-occur representing compound stressor events (e.g., Cai et al. 2011; Duarte et al., 2013; Jewett et al., 2020; Osborne et al., 2019; Cai et al., 2020; Gruber et al., 2022). For the purpose of this manuscript, we often use the term "OA" to refer to carbonate chemistry changes associated with both ocean and coastal acidification.

The Gulf of Mexico (GOM) contains a wide range of ecosystems that provide important services and play a critical role in supporting the Gulf coast, United States, and international economies. For example, according to NOAA Fisheries in 2019, GOM commercial seafood landings revenue in the United States was $1.4 billion and accounted for 15% of the total national landings revenue. Of the total GOM commercial landings in 2019, shellfish contributed almost 73% of the revenue. GOM ecosystems are subject to multiple local (e.g., overfishing, eutrophication, hypoxia, and oil spills) and global (e.g., ocean warming and acidification) anthropogenic stressors. GOM US shellfisheries are particularly vulnerable to OA impacts because of a combination of environmental (e.g., eutrophication and high river input), biological (e.g., low diversity of shellfish fishery harvest), and social factors (e.g., low political engagement in OA and climate change and relatively low science accessibility; Ekstrom et al., 2015). Although an open ocean GOM
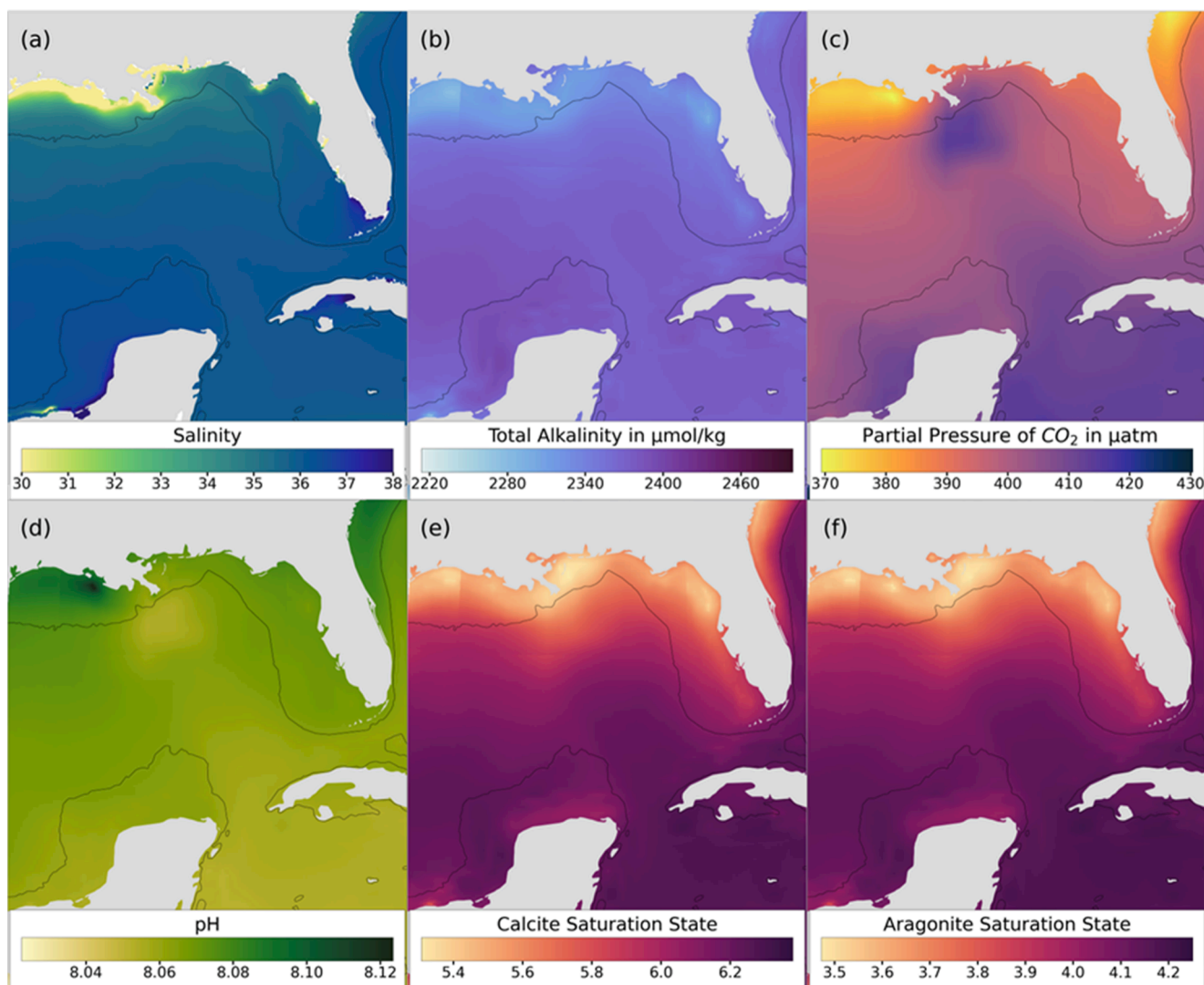
Fig. 1. Modelled mean (2014–2020) GOM surface values of (a) Hybrid Coordinate Ocean Model (HYCOM) salinity, (b) total alkalinity (μmol/kg), (c) partial pressure of CO_2 (pCO$_2$, μatm), (d) pH, (e) calcite saturation state, and (f) aragonite saturation state. Carbonate system parameters presented are a public data product that is produced by calculating the average of the datasets generated by the NOAA/AOML ACCRETE (Acidification, Climate, and Coral Reef Ecosystems Team; https://www.coral.noaa.gov/accrete/oaps.html; downloaded the dataset on June 12th, 2021). The western Gulf coast is excluded from this analysis because ACCRETE does not calculate values for the region. The black lines indicate 200 m isobath. Map colorbars were created following Thyng et al. (2016).

time-series station analogous to those that have documented OA in other ocean basins (e.g., Hawaii Ocean Time-series (Dore et al., 2009) and Bermuda Atlantic Time Series (Bates et al., 2012, 2014)) does not exist for the GOM (Hu, 2019), several studies have demonstrated that acidification of GOM estuaries (Hu et al., 2015; Robbins and Lisle, 2017), coastal and open GOM surface waters (Kealoha et al., 2020a), and subsurface waters (e.g., Cai et al., 2011; Hu et al., 2018; Wang et al., 2020) has occurred over the last 10–40 years. Broadly, the GOM has a relatively high Ω due to a high total alkalinity to dissolved inorganic carbon ratio and warm ocean temperatures (Fig. 1). Despite this, model simulations also show significant net decline in GOM surface ocean pH from 1863 to 2003 (Andersson et al., 2019), as well as continued GOM surface water acidification and declining Ω this century, further threatening GOM ecosystems (Community Earth System Model (https://www.cesm.ucar.edu/); Dee et al., 2019; Laurent et al. 2018).

Despite confirmation of acidification in multiple GOM regions, several factors make investigating the impacts of OA challenging. For example, the northern GOM receives large freshwater and nutrient influxes that enhance carbonate chemistry variability. Outflow from the Mississippi and Atchafalaya River system, in particular, may be masking or ameliorating long-term surface water CO_2 partial pressure (pCO_2) increases in coastal and open ocean waters of the central GOM (Kealoha et al., 2020a; Duarte et al., 2013; Gomez et al., 2021). The lack of a long-term time series station makes it difficult to attribute changes in carbonate chemistry to OA (Doo et al., 2020); and the absence of data in much of the deep GOM prevents the assessment of changing saturation horizon depths (the depth at which carbonate dissolution is favored; see section 3.1) and impacts on important deep-sea coral ecosystems. OA impacts on GOM ecosystems are largely unknown due to limited biological impact studies on regionally relevant species to date. In addition, GOM waters extend across three different countries, complicating coordination of data collection and deposition into accessible databases.

The complexity of the GOM region requires international partnerships to achieve a system-wide understanding of OA. Scientific capacity building groups, including the Gulf of Mexico Coastal Acidification Network (GCAN) and Global Ocean Acidification Observing Network (GOA-ON) North American Hub are instrumental in coordinating the GOM OA research community. GCAN initiated this synthesis to identify research and monitoring gaps and provide the foundation and guidance for establishing priorities to address them, catalyze transdisciplinary (Yates et al., 2015) and international collaboration, facilitate community engagement, and inform risk and vulnerability assessments of acidification impacts on the GOM. Here, we summarize our current understanding of the drivers of acidification across multiple science sectors of the GOM (Table 1). We highlight potentially vulnerable organisms and ecosystems, identify gaps in knowledge, and identify directions for future research and international collaboration.

2. Regional extent of the GOM

The GOM is an extensive marginal sea spanning approximately 1.6 million km^2 (Fig. 2). The GOM receives effluent from dozens of river systems, provides a continuum of coastal wetlands and estuaries, and is home to two US National Marine Sanctuaries. Nearly one-third of the basin consists of shallow continental-shelf waters that bound the deep basin that reaches a maximum water depth of 4400 m. Below we define geophysical characteristics of GOM regions with reference to regionally specific environmental drivers of carbonate chemistry dynamics described in greater detail in Section 3.0.

2.1. Open GOM

The open GOM, consisting of its continental slope and deep basin, makes up approximately 70% of the GOM by area. The 200-meter isobath is commonly used as a delineation between the open GOM and the the continental shelf (section 2.2). Seawater exchange

Table 1
Synthesis table of contents.

Section	Topic	Section	Topic
1.0	Introduction	4.0	GOM ecosystem and marine species sensitivity to OA
2.0	Regional extent of the GOM	4.1	Salt marshes
2.1	Open GOM	4.2	Seagrass beds
2.2	Continental Shelf Regions	4.3	Mangroves
2.3	Estuarine and Wetland Regions	4.4	Coral reefs
3.0	Carbonate chemistry dynamics and drivers of OA in the GOM	4.5	Shellfish
3.1	GOM Carbonate Chemistry and OA Overview	4.6	Finfish
3.2	Air-Sea CO2 Exchange	4.7	Sea urchins
3.3	Ocean warming	4.8	Sponges
3.4	Ocean Circulation	4.9	Phytoplankton and harmful algal blooms (HABs)
3.5	Riverine influence	4.10	Calcifying plankton
3.6	Episodic Storm Events	4.11	Microbes
3.7	Submarine groundwater discharge	5.0	GOM OA Monitoring Gaps
3.8	Eutrophication and Hypoxia	6.0	Conclusions and next steps

between the open GOM and the Atlantic Ocean and Caribbean Sea occurs only through the narrow passage of the Florida Straits and the Yucatán Channel, respectively (Fig. 2). Ocean inflow to the GOM is transported through the Yucatán Channel giving rise to the Loop Current (see section 3.4), the dominant physical oceanographic feature within the basin (DeHaan and Sturges, 2005; Delgado et al., 2019). The northern extent of the Loop Current is highly variable and can episodically influence northern GOM coastal waters and shed large anticyclonic eddies that propagate westward (Furey et al., 2018).
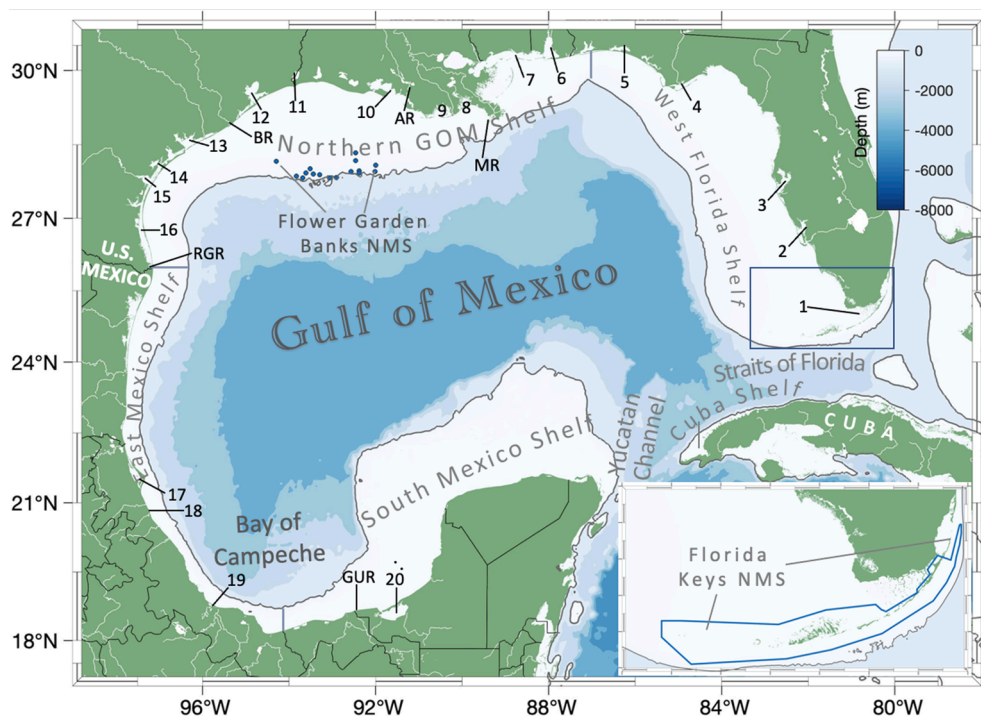
2.2. Continental shelf regions

Approximately 30% of the GOM is comprised of continental shelf, defined as areas shallower than 200 m water depth. 33 rivers flow into the GOM with drainage areas covering 60% of the United States, 40% of Mexico, and a small area in northwestern Cuba (Yáñez-Arancibia and Day, 2004). Respective shelf regions are described individually below.

The Florida Keys are an arc of small islands that extend from Miami, FL southwest into the GOM, spanning ∼ 240 km (Hoffmeister and Multer, 1968). Freshwater is delivered to this region via Florida Bay from the southern Everglades, creek systems and canals, and submarine groundwater discharge (McIvor et al., 1994; Corbett et al., 1999; Stalker et al., 2009). Freshwater inputs cause large seasonal variations in temperature, salinity, turbidity, and carbonate chemistry on the reefs, especially those nearshore.

The West Florida Shelf extends across a large latitudinal gradient from Pourtales Terrace within the Florida Straits to De Soto Canyon offshore of Pensacola, FL in the Florida panhandle and is known for its low bathymetric gradient (Davis, 2017). The West Florida Shelf is influenced by the Loop Current, seasonal upwelling (Weisberg and He, 2003; He and Weisberg, 2003) and submarine groundwater discharge (Kroeger et al., 2007).

The Northern GOM Shelf (also referred to as the Large River Province*)* is geographically bounded by the De Soto Canyon (near the Alabama-Florida border) and US-Mexico border. The width of the continental shelf increases from east to west, with a narrower area near the Mississippi River mouth (Goodwin, 1989). Mississippi-Atchafalaya River discharge is the major driving force for shelf physics and biogeochemistry, with smaller rivers playing a role in localized areas particularly during flood events (DiMarco et al., 2012; Rebich et al., 2011; Dzwonkowski and Park, 2012).

Fig. 2. Map of the GOM identifying major regions discussed in this review. The solid gray line represents the 200 m isobath, defined as the boundary between the coastal continental shelf region and open GOM regions. The continental shelves are broken down geographically and are described in detail within Section 2.2. Selected major rivers, bays, and estuaries are identified as follows: MR-Mississippi River, AR-Atchafalaya River, BR-Brazos River, RGR-Rio Grande River, GUR-Grijalva-Usumacinta River; Estuaries: 1-Florida Bay, 2-Charlotte Harbor, 3-Tampa Bay, 4-Apalachicola Bay, 5-Pensacola Bay, 6-Mobile Bay, 7-Mississippi Sound, 8-Barataria Bay, 9-Terrebonne/ Timbalier Bays, 10-Atchafalaya/Vermilion Bays, 11-Sabine Lake, 12-Trinity-San Jacinto Estuary (Galveston Bay), 13-Colorado-Lavaca Estuary (Matagorda Bay), 14-Mission-Aransas Estuary, 15-Nueces Estuary (Corpus Christi Bay), 16-Laguna Madre (including both the upper and lower portions and Baffin Bay), 17-Laguna de Tamiahua, 18-Laguna de Tuxpan, 19-Laguna de Alvarado, 20-Laguna de Terminos. The extents of the two US national marine sanctuaries (NMS), Flower Garden Banks (dark blue dots) and Florida Keys (dark blue box and inset map), are also shown. Figs. 2-4 were created using the MatLab package M_Map (Pawlowiz, 2020).

The East Mexico Shelf includes the area offshore of Tamaulipas, Veracruz, and Tabasco states, and spans to the southern end of the Bay of Campeche (Fig. 2; Zavala-Hidalgo et al., 2003). This shelf becomes increasingly narrower from north to south (from 100 km to 30 km) before widening again toward the Yucatán Shelf to the east (Dubranna et al., 2011). The Grijalva-Usumacinta River directs freshwater input into the Gulf in the southernmost Bay of Campeche.

The South Mexico Shelf, a large karst substrate plain, extends approximately 250 km from shore (Ruiz-Castillo et al., 2016; Bauer-Gottwein et al., 2011). Fractures and passages facilitate submarine groundwater discharge through point or diffuse sources (Gallardo and Marui, 2006; Valle-Levinson et al. 2011). Submarine groundwater discharge and upwelling along the east edge of the shelf are the major sources of nutrients that support productivity there (Estrada-Allis et al., 2020).

The Cuba Shelf is comprised of a steep and narrow shelf bordering Cuba and was defined by the Caribbean plate colliding with the North American and South American plates (Davis, 2017). The Loop Current is dominant in controlling the coastal currents on the northwestern Cuba shelf, where upwelling is frequent (Le Hénaff et al., 2020).

2.3. Estuarine and wetland regions

The GOM has over 200 estuaries, some of which are protected by barrier islands and form lagoons, accounting for most lagoonal systems in North America (Dürr et al., 2011). GOM estuaries include river-dominated (northern Gulf), semi-arid (western Gulf), and groundwater-fed (southern and eastern Gulf) physiographic environments. Estuaries often contain extensive seagrass beds as well as surrounding coastal wetlands, which are important areas of high primary productivity that sequester a large fraction of blue carbon (Breithaupt et al., 2012; Chmura et al., 2003; Hopkinson et al., 2012; Windham-Myers et al., 2018), i.e., carbon sequestered in vegetated coastal habitats (Mcleod et al, 2011). The GOM is also home to more than half of the North American tidal wetlands. Broadly, wetlands found along the

northern and eastern Gulf coasts are dominated by salt marshes, while on the western Gulf coast, mangroves dominate and account for 80% of the mangrove environments found in North America (Windham-Myers et al., 2018). Coastal erosion in the area due to natural and human activities (such as storm events, sea level rise, damming, dredging, and coastal development) also affects salt marshes and threatens the sustainability of many GOM wetland areas (Allison et al., 2010; Bulseco et al., 2019; FitzGerald., 2008; McTigue et al., 2019; Weston, 2014; Zhong and Xu, 2011; Luo et al., 2019; Lewis et al., 2014).

3. Carbonate chemistry dynamics and drivers of OA in the GOM

GOM carbonate chemistry dynamics are influenced by a complex interplay of increasing carbon inventories due to anthropogenic OA and other diverse environmental and anthropogenic drivers that are described within this section (Fig. 3). The availability of GOM carbonate chemistry data, major GOM OA observing programs, and limitations in data availability are described within this section. These observations, collected by the United States, Mexico, and Cuba, represent observations by governments and academic programs, often in collaboration. Collectively, these measurements provide a foundation for the current understanding of OA in the GOM region. GOM carbonate chemistry observing efforts are characterized in detail within the Supplementary Information. Based on these available data and published scientific literature, processes driving OA in the GOM are summarized here, noting that a number of remaining unknown or unobserved drivers likely exist in addition to those discussed here.

3.1. GOM carbonate chemistry and OA overview

Discrete measurements of total alkalinity (TA), dissolved inorganic carbon (DIC), and pH within the GOM have often been carried out as part of projects evaluating specific geographic areas and processes affecting the local carbon cycle (e.g., limited coastal zones or single estuarine systems). As a result, data coverage has historically been
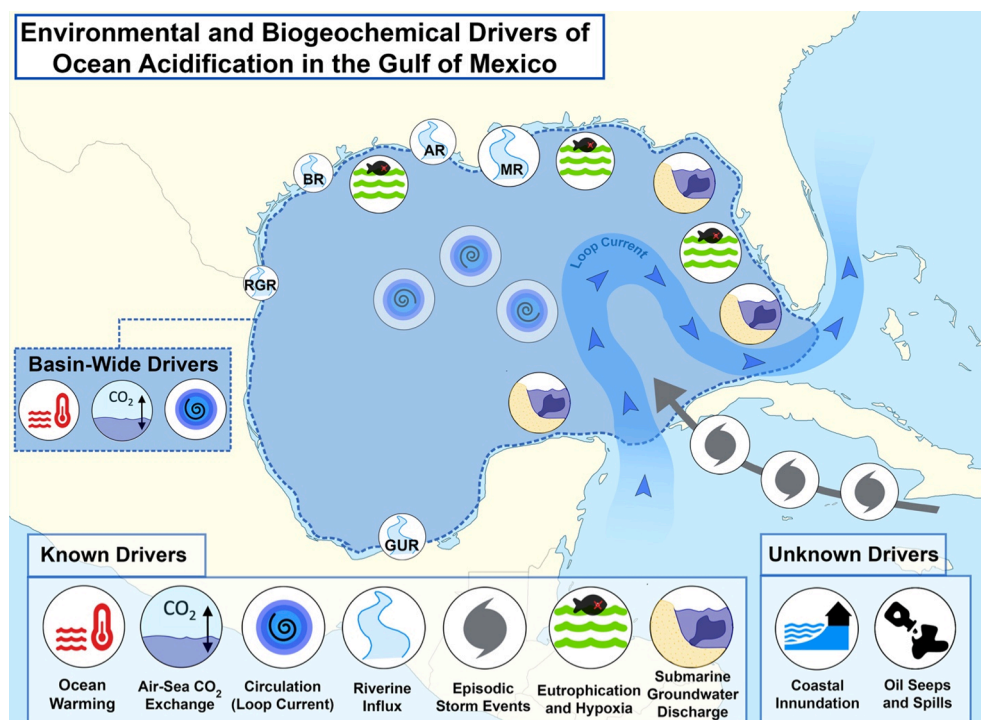
Fig. 3. Schematic showing the major environmental and biogeochemical drivers of OA in the GOM and their known spatial coverage. Basin-wide drivers (air-sea CO_2 exchange, warming, and circulation) affect the entire basin across the open-ocean to coastal ocean continuum. The general flow of the major ocean circulation system, the Loop Current, and anti-cyclonic (warm core) and cyclonic (cold core) eddies, are depicted. The five major rivers flowing into the GOM are identified (size of symbol relates to the volume of flow), however numerous other rivers and estuarine systems provide freshwater flow into the basin. In addition to known drivers, which are synthesized in sections 3.2–3.8, several unknown drivers (oil seeps and spills, and coastal inundation) are discussed.

uneven both spatially and temporally, with heavy observational biases towards the northern GOM Shelf (Fig. 4) and during the summer months. For example, out of the million underway observations of surface ocean partial pressure of CO_2 (pCO_2) in the Gulf from 1996 to 2020, only 4% were collected from the southwestern region south of 25.5 N latitude and west of 88 W longitude (https://www.socat.info/). Data availability and intercomparability is inconsistent for a variety of reasons, including but not limited to different instrumentation, seasonal weather limitations for sample collection, and national government restrictions on data publication. Concerted efforts are required to make all existing data accessible for GOM-wide assessments.

In the US, the National Oceanic and Atmospheric Administration (NOAA) supports the only sustained effort to monitor Gulf-wide OA through its Gulf of Mexico Ecosystems and Carbon Cruises (GOMECC) and Ship of Opportunity-OA (SOOP-OA) program. GOMECC cruises initiated in 2007 and SOOP-OA observations in the GOM initiated in 2008 with two NOAA research vessels presently outfitted with underway surface pCO_2 instrumentation. Data from these programs demonstrate the importance of ocean circulation, temperature seasonality, and riverine influence to GOM carbonate chemistry dynamics (e.g., Wang et al., 2013; Wanninkhof et al., 2015; Kealoha et al., 2020a). Within Mexican waters, Mexico's XIXIMI program has collected TA and DIC measurements in the southern GOM offshore waters since 2010. Data across the XIXIMI cruises indicate similar vertical structures of DIC and TA profiles over time in the central and southern regions of the GOM, comparable to Caribbean profiles generated during World Ocean Circulation Experiment (WOCE) in 1994. Similar to the northern GOM, the central and southern regions show high TA/DIC ratios indicating strong buffering capacity (i.e., the capacity of seawater to buffer against acidification) and high Ω_{ar} values between 3 and 4 (J. Martin Hernandez-Ayon, written communication, Autonomous University of Baja California, Mexico, 22 June 2022). Despite extensive efforts, these programs do not provide robust temporal coverage on sub-annual to sub-seasonal time-scales of water column carbonate chemistry, particularly within the central GOM region.

Coastal observing projects and time-series within the GOM have permitted finer time-scale evaluations of Gulf carbonate chemistry dynamics. In particular, extensive carbonate chemistry measurements have been collected across the northern GOM coastal region, revealing highly variable and elevated TA values associated with riverine input from the Mississippi-Atchafalaya river system (Cai, 2003). As such, the northern GOM shelf (section 2.2, Fig. 2) and the north central portion of the open GOM (section 2.1, Fig. 2) have carbonate chemistry that is distinct from regions which are not directly influenced by the Mississippi-Atchafalaya River System. Surface water TA/salinity ratios in regions influenced by the Mississippi-Atchafalaya River System are among the highest found in any ocean (Jiang et al., 2014). Associated elevated DIC values are quickly drawn down by high phytoplankton production stimulated by nutrient input, primarily from agricultural landscape-derived dissolved inorganic nutrients (Guo et al., 2012, Huang et al., 2013). This results in a high TA/DIC ratio corresponding to an increased buffering capacity (Frankignoulle, 1994; Egleston et al., 2010), and as a consequence, surface seawater Ω_{ar} remains elevated (~4) as river water flows both along the shelf and offshore. This region showed a minimal decrease in surface Ω_{ar} based on differences between surveyed data in the late 2000′s and early 2010′s (Wanninkhof, 2015) and based on model simulations (Gomez et al., 2021).

Riverine influenced carbonate chemistry dynamics in coastal waters are difficult to parameterize in numerical models and the enhanced buffering capacity and elevated saturation state observed in the north central GOM is not captured by the NOAA/AOML ACCRETE (Acidification, Climate, and Coral Reef Ecosystems Team; https://www.coral.noaa.gov/accrete/oaps.html) data product (Fig. 1). Simplified biogeochemical calculations do show an increased resistance to anthropogenic OA and an absence of a weak buffering area, or Minimum Buffer Zone, in the northern GOM compared to estuaries that receive river water with lower weathering products (Hu and Cai, 2013; Cai et al. 2021). Consistent with their enhanced buffering capacity due to high TA and high biological DIC removal, coastal and open GOM surface waters in the north central GOM region show no long-term pCO_2 trends, despite
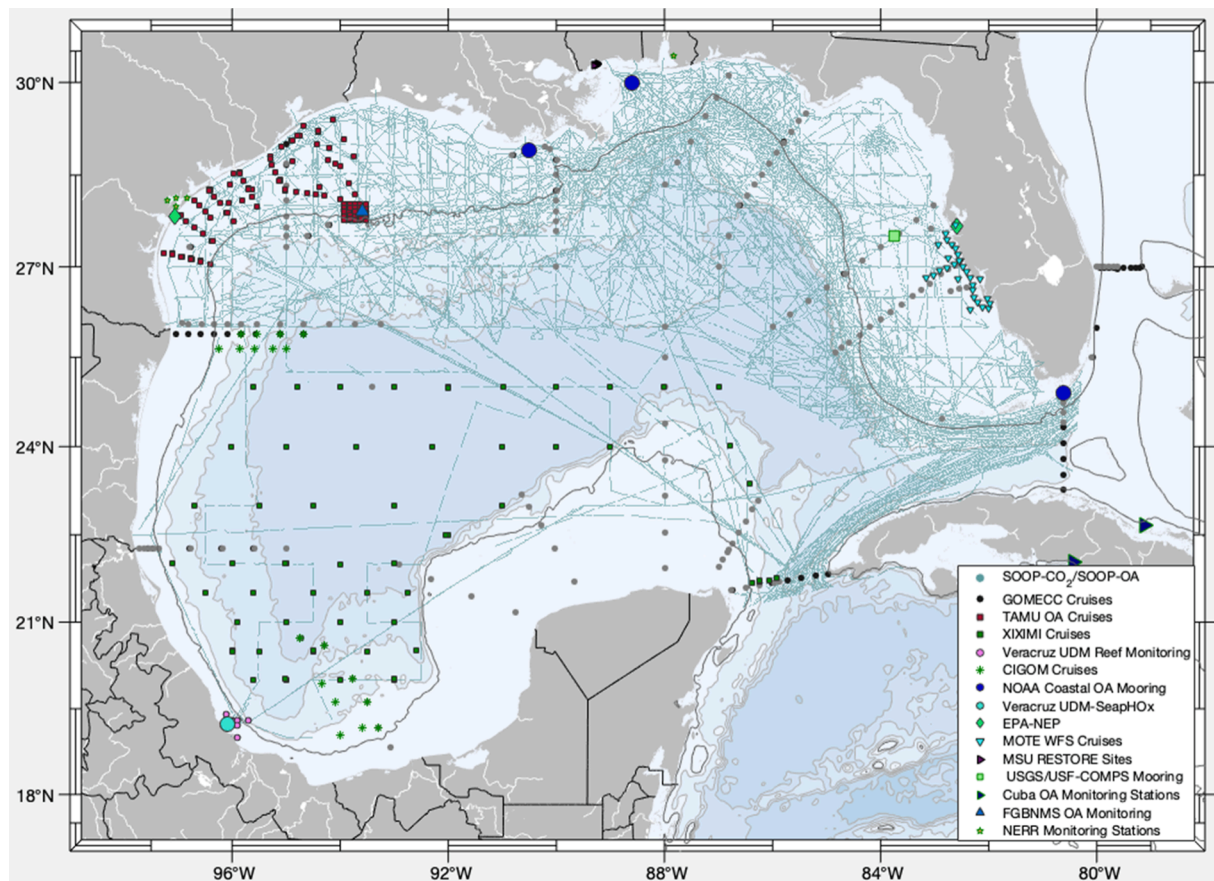
Fig. 4. Available carbonate chemistry datasets (published and unpublished/collected by authors of this manuscript) across the GOM region. See Supplementary Information for a detailed description of datasets. SOOP surface water underway CO_2 fugacity surveys (dark green lines, SOCAT V2020), GOMECC-3 2017 cruise transects (black circles); Texas Shelf and Flower Garden Banks cruises (dark red squares, K.E.F. Shamberger, written communication, Texas A&M University, 22 June 2022); XIXIMI project cruises (green squares, J.M. Hernández-Ayon, written communication, Autonomous University of Baja California, Mexico, 22 June 2022); Veracruz Reef System National Park stations (green circles C. Chapa Balcorta, written communication, Instituto de Recursos, Universidad del Mar. Puerto Angel, Oaxaca, Mexico, 22 June 2022); Malla Fina campaign off the Mexico east and south shelf for the CIGOM project (green *, O. Norzagaray, written communication, Autonomous University of Baja California, Mexico, 22 June 2022, note some overlap with the GOMECC-3 stations); the three blue circles are MAPCO2 buoys offshore from coastal Louisiana (28.9°N, 90.5°W, from 2017 to the present), Mississippi coast (30°N, 88.6°W, from 2009 to 2017), and Cheeca Rocks in Florida Keys (24.9°N, 80.6°W, from 2011 to the present); the turquoise circle represents the SeapHOX monitoring station at off Veracruz, Veracruz (19.23°N, 96.0°W); the two green diamonds are the two National Estuary Program funded estuarine acidification sites (Port Aransas Ship Channel, TX, and Tampa Bay, FL); the cyan triangles on the FL west coast are estuarine (Tampa Bay, Charlotte Harbor, and San Carlos Bay) and coastal OA sampling stations (E. Hall, written communication, Mote Marine Laboratory, Sarasota Florida, 22 June 2022); and the dark blue triangle overlapping with the Flower Garden Banks is the OA monitoring station based on seasonal discrete sampling (X. Hu, written communication, Texas A&M University, Corpus Christi, Texas, 22 June 2022, Hu et al. 2018).

significant increases in surface water pCO_2 over the last ~ 20 years in adjacent GOM regions that are less impacted by Mississippi-Atchafalaya outflow (Kealoha et al., 2020a; Gomez et al., 2021). This may suggest that the northern GOM could remain a favorable environment for surface water calcifying organisms longer than other US coastal areas where river discharges have lower alkalinity (Miller et al. 2009). It is also possible that river-enhanced variability in the carbonate chemistry system is masking long-term CO_2 trends. A combination of carbonate chemistry records that are longer than the OA 'time of emergence' (e.g., Sutton et al., 2019; Turk et al., 2019; Doo et al., 2020) and improved understanding of natural variability in this highly variable region (e.g., Carter et al., 2019) will help resolve the long-term impact of major river inputs on OA in the northern GOM.

Based on a 1996–2017 synthesis, the northwest and southeast open GOM surface water pCO_2 is increasing at similar rates (1.63 and 1.70 µatm yr^{-1}, respectively; Kealoha et al., 2020a) as other northern hemisphere ocean margins (1.93 µatm yr^{-1}; Wang et al. 2017) and ocean basins (e.g., 1.72 µatm yr^{-1} at the Hawaii Ocean Time-series (HOT; Dore et al., 2009; Bates et al. 2014) and 1.69 µatm yr^{-1} at the Bermuda Atlantic Time Series (BATS; Bates et al., 2012, 2014)). Increasing surface

CO_2 in the northwest and northeast open GOM are likely due to atmospherically-driven anthropogenic OA, while the southeast trend may be driven by a combination of OA, warming, and possibly a decrease in net ecosystem production (Kealoha et al., 2020a). Surface water CO_2 is increasing on the northwestern GOM shelf and West Florida Shelf at faster rates than in the open GOM (Robbins et al., 2018; Kealoha et al., 2020a). High rates of pCO_2 increase (2.35–3.20 µatm yr^{-1}) in GOM coastal waters are also consistent with several studies showing enhanced acidification of some coastal ocean areas compared to the open ocean, due to higher warming and/or shifts towards net heterotrophy, superimposed on atmospherically-driven OA (Bates et al., 2014; Cyronak et al., 2014; Reimer et al., 2017; Robbins et al., 2018; Kealoha et al., 2020a). However, warming also partially compensates for OA-induced declines in Ω (e.g., Salisbury et al., 2018), hence, the long-term trends of Ω need to be further explored in the GOM.

The regional buffering effect of the Mississippi-Atchafalaya outflow has resulted in no long-term significant surface ocean OA trend within this GOM sub-region (Kealoha et al., 2020a; Gomez et al., 2021). While Mississippi-Atchafalaya river outflow increases the buffering capacity of northern GOM surface waters, this same shelf region experiences

seasonal bottom-water hypoxia and acidification driven by eutrophication, due to stratification and downward flux of organic matter, and subsequent decomposition by bacterial respiration, which threatens critical benthic ecosystems (Cai et al., 2011; Hu et al., 2017; Wang et al., 2020). For example, a 2016 severe mortality event on the East Bank coral reef within the Flower Garden Banks National Marine Sanctuary in the northern GOM may have been associated with benthic hypoxia and acidification (Le Hénaff et al. 2019, Kealoha et al. 2020b). In addition to seasonal bottom-water acidification, results from three cruises conducted between 2007 and 2017 indicate a rapid decrease in pH and Ω_{ar} in subsurface waters (~100–250 m) near the Flower Garden Banks over that decade. These decreases are larger than those observed in other tropical and subtropical waters and may indicate enhanced acidification of GOM subsurface waters (Hu et al., 2018). Acidification of GOM surface and subsurface waters has been demonstrated, but many GOM regions lack time-series data that are long enough to detect OA-driven changes in carbonate chemistry.

In addition to the ocean and coastal measurements, US Environmental Protection Agency's National Estuary Program (NEP) funded high-resolution monitoring stations in both Tampa Bay and Mission-Aransas Estuary (Galavotti et al., 2021). As microtidal estuaries in the subtropical climate, both monitoring stations exhibited lower pCO2 and higher pH and generally smaller fluctuations in both parameters, compared to their higher latitude counterparts that are mostly of macrotidal conditions (Rosenau et al., 2021; McCutcheon et al., 2021). A complex interplay of temperature, biological activity, freshwater inflow, and tide level on diel to seasonal time-scales are all at play in these GOM estuarine systems (McCutcheon et al., 2021). Of the approximate 200 estuaries distributed across the GOM region, only a handful have been characterized with respect to carbonate chemistry dynamics to date.

3.2. Air-sea CO2 exchange

Air-sea CO2 fluxes in the open GOM and most coastal waters display strong seasonal variability characteristic of a temperature-controlled system (Kealoha et al., 2020a). CO2 uptake prevails during winter-spring and CO2 outgassing prevails during summer, the latter except in the Mississippi-Atchafalaya river plume area (Gomez et al., 2020). Over a million surface pCO2 measurements have been made in the GOM (Bakker et al., 2016) but they skew heavily towards the northern region (Supplementary Fig. 1), and there is somewhat limited coverage in the winter months, particularly in the open GOM. As a result, most flux studies have focused on US coastal regions along the West Florida Shelf (Robbins et al., 2014, 2018; Chen et al., 2016) and the Louisiana-Texas shelf (e.g., Lohrenz et al., 2010, 2018; Cai et al., 2003, 2013, Huang et al., 2015a,b, Hu et al., 2018; Supplementary Fig. 1). These studies suggest that the northern GOM shelf acts as an annual sink for CO2, absorbing from 0.25 to 1 mol m^{-2} yr^{-1}, and link this pattern to large biological CO2 uptake during spring-summer, and relatively cold conditions during winter (Huang et al., 2015a; Lohrenz et al., 2018; Gomez et al., 2020; Kealoha et al. 2020a). While a recent modeling study by Gomez et al. (2020) also suggested the West Florida Shelf is an annual carbon sink, two recent observational studies indicate this region is actually a weak carbon source (Robbins et al., 2018, Kealoha et al., 2020a). Preliminary results from the coast of Veracruz indicate the East Mexico Shelf behaves as a carbon source both in summer and winter (I. Espinoza-Ramirez, written communication, Autonomous University of Baja California, Mexico, 22 June 2022). Basin-wide, the limited dataset included in the Takahashi (2009) climatology indicated that the GOM basin was a small annual source (0.21 mol C m^{-2} year^{-1}). However, a substantial increase in surface pCO2 data collection since 2008 (~200,000 data points in 2 years), mostly in the northern and central part of the Gulf, point toward the Gulf as a weak annual sink (−0.02 mol C m^{-2} year^{-1}; Pierrot et al., 2011). Further, in the most recent studies, estimated annual average fluxes suggest that the GOM basin is a neutral to weak carbon sink (Xue et al., 2016; Fennel et al., 2019; Gomez et al.,

2020; Kealoha et al., 2020a). Air-sea CO2 fluxes in the GOM may differ significantly from year to year due to variability in wind, temperature, precipitation, and strength of the Loop Current (Muller-Karger et al., 2015). Ocean warming reduces the solubility of gases; however, previous research shows that the direct impact of increasing atmospheric CO2 concentrations plays a primary role over this secondary factor (Lohrenz et al., 2018; Kealoha et al., 2020a).

3.3. Ocean warming

Ocean warming influences ocean carbonate chemistry via gas solubility, stratification and other changes in upper ocean mixing and transport (Gruber, 2011), and rates of biogeochemical and biological processes that are temperature dependent. Temperature also plays an important role in controlling surface water pCO2 and pH distributions through its influence on seawater carbonate system thermodynamic equilibria (Cai et al., 2020). Seasonal changes in GOM surface pCO2 and Ω_{ar} are significantly modulated by sea surface temperature (SST) (e.g., Hu et al., 2018; Wanninkhof et al., 2019; Gomez et al., 2020; Kealoha et al., 2020a). The influence of temperature on pCO2 seasonality is the strongest in the open GoM region (Kealoha et al., 2020a), and weakest over the northern GOM shelf where river input is a major driver of pCO2 variability.

Multiple studies have documented significant increasing trends in GOM water temperature. Surface warming, as derived from satellite SST, ranged from 0.017 to 0.030 °C yr^{-1} (1981–2012) in the open GOM (Muller-Karger et al., 2015). A seasonal trend analysis based on satellite SST revealed the greatest warming during the early rainfall season (April-July) in the northern GOM (>0.04 °C yr^{-1}), and during the late rainfall season (August-November) in the western GOM (~0.03 °C yr^{-1}) (Glenn et al., 2015). A simple calculation indicates that a rapid 1 °C warming in the open GOM surface layer, neglecting changes in air-sea CO2 flux, would elevate pCO2 ~ 13.5 μatm and Ω_{ar} of 0.025 units, and decrease pH by ~ 0.013 units. These estimations are based on the average DIC, alkalinity, temperature and salinity and air-sea flux conditions derived by Gomez et al. (2020). Since ocean warming due to climate change is a slow process (multidecadal), we could expect CO2 flux adjustments (decrease in CO2 uptake or increase in CO2 outgassing) moderating the magnitude of those temperature-driven pCO2, pH, and Ω. Further, on the northern GOM shelf, bottom waters have experienced warming at a higher rate (~0.05 °C yr^{-1}) than surface waters, a signature that can contribute to increasing bottom water hypoxia and acidification (Turner et al., 2017). Observations also show that GOM deep basin warming is occurring at a rate of 0.018 °C per decade (Ochoa et al., 2021).

Downscaling of Coupled Model Intercomparison Project 5 (CMIP5) model projections suggest a significant decline of Loop Current transport this century, which could have a cooling effect in the surface layers of the open GOM (Liu et al., 2015). However, the same modeling study predicts an accelerated warming on the northern GOM shelf during summer (>4°C by 2090 under the IPCC RCP8.5 scenario), likely linked to ineffective mechanisms to dissipate surface heating. These temperature changes can have a significant impact on pH, pCO2, and air-sea CO2 fluxes, and could eventually shift the northern shelf from a carbon sink to a carbon source (Gomez et al., 2020). However, a direct quantification of the temperature impact on OA trends is only possible for a few areas of the GOM with sufficient data. For example, while anthropogenic OA is likely the cause of long-term surface water pCO2 increases in the northwest and northeast open GOM, approximately 25% of the southeast open GOM pCO2 increase was attributed to increasing SST (0.03 °C yr^{-1}) (Kealoha et al., 2020a). Similarly, ~40% of the pCO2 increase on the West Florida Shelf was attributed to increasing SST (0.07 ± 0.04 °C yr^{-1}) (Kealoha et al., 2020a). Quantification of the impact of increasing ocean temperatures on other carbonate chemistry parameters (e.g., pH and Ω) and in subsurface waters of the GOM is largely limited by data availability.

3.4. Ocean circulation

The Loop Current is the main circulation feature in the open GOM, transporting warm, oligotrophic, and well-buffered waters (surface alkalinity around 2,370 μmol kg^{-1} and $\Omega_{Ar} > 3.5$) from the Caribbean Sea into the GOM, and eventually to the US East Coast once Loop Current waters exit the GOM and join the Gulf Stream (Wang et al., 2013; Wanninkhof et al., 2015). Loop Current waters are also characterized by relatively small seasonal and interannual carbon system variability, mainly driven by temperature (Gomez et al., 2020). The northward penetration of the Loop Current, and associated mesoscale eddy shedding, exhibits large spatiotemporal variability which greatly impacts circulation on the outer shelves (e.g., Weisberg et al., 2005; Oey et al., 2003). This modulates water exchange between shelves and the open GOM region, influencing carbonate chemistry across the basin (e.g., Wang et al., 2013; Wanninkhof et al., 2015). Downscaling of future projections from the CMIP5 suggest that the Loop Current transport will be reduced by 25% this century, causing a cooling trend in the northern open GOM during spring (Liu et al., 2015). It is expected that changes in Loop Current transport will have a direct impact in cross-shore export and carbonate chemistry, probably affecting OA patterns, but no ocean-biogeochemical model study has evaluated future scenarios specifically for the GOM.

Circulation over the northern GOM inner shelf is wind- and buoyancy-driven (e.g., Zavala-Hidalgo et al., 2014; Zhang et al., 2014). The buoyancy forcing is mainly linked to a strong cross-shore salinity gradient, resulting from downwelling favorable (easterly) winds compressing the Mississippi River plume against the coast, thus inducing a geostrophic westward flow during fall-spring (Wiseman et al., 1997). Upwelling-favorable (westerly) winds during summer disturb this pattern, spreading the Mississippi River plume eastward and offshore (e. g., Morey et al., 2003; Zhang et al., 2014). This wind seasonality, along with the seasonal change in river discharge, contributes to a strong variability in salinity, nutrients, plankton biomass, oxygen, and carbonate chemistry, and modulates the export of low-salinity and highly productive waters offshore (e.g., Morey et al., 2003; Huang et al., 2015a; 2015b; Lohrenz et al., 2018; Le Hénaff et al., 2019). El Niño–Southern Oscillation (ENSO)-induced interannual anomalies in winds, precipitation, and river discharge further increase variability in ocean chemistry and offshore export at interannual timescales (Gomez et al., 2019).

Over the Yucatan, East Mexico, and West Florida inner shelves, which are regions less influenced by river discharge than the northern GOM, surface circulation is mainly wind-driven (Cochrane and Kelly, 1986; Zavala-Hidalgo et al., 2014). Prevailing easterly winds on the Yucatan shelf promote coastal upwelling and enhanced phytoplankton biomass year-round (Zavala-Hidalgo et al., 2006; Estrada-Allis et al., 2020). Modeling results show a clear upwelling signature in the carbonate system variables, with high DIC and TA waters spreading northwestward to the open Gulf (Gomez et al., 2020). Over the East Mexico shelf, seasonal changes in alongshore winds promote downwelling and a southward surface flow during fall-winter, and the opposite pattern (upwelling and northward flow) during spring-summer (Zavala-Hidalgo et al., 2006). This seasonal variability drives a southward transport of low salinity and plankton-rich waters from the Texas shelf during winter, which significantly influences biogeochemistry off eastern Mexico (Zavala-Hidalgo et al., 2006). On the west Florida inner shelf, coastal winds also vary seasonally, promoting downwelling and northward flow during summer, and upwelling and southward flow during winter (Yang and Weisberg, 1999). The Florida Keys act as a barrier for the southward flow, so a return northward flow can develop over the middle and outer West Florida Shelf during upwelling conditions (Liu and Weisberg, 2005). The Loop Current influences thermocline and nutricline depths near the West Florida Shelf break, modulating the temperature and chemistry of upwelled waters onshore (Weisberg and He, 2003).

3.5. Riverine influence

Freshwater influx from rivers exerts significant influence on GOM biogeochemistry, particularly within the northern GOM shelf region. Thirty-three major river outlets exist along the GOM coastline (Kumpf et al., 1999; Ward and Tunnell, 2017) with an enormous freshwater inflow flushed into the northern GOM via the Mississippi-Atchafalaya river system. Rivers deliver freshwater, dissolved loads of chemicals, and suspended particles, which have been shown to alter the physical and chemical dynamics along the GOM coast. GOM rivers have a wide range of alkalinity levels, which are dependent on the drainage basin mineralogy and relative abundance of freshwater (Cai, 2003; Lohrenz and Cai, 2006; Cai et al., 2010). The impact of freshwater input on GOM carbonate chemistry is further modulated by the volume and rate of freshwater discharge, and physical mixing processes that affect residence time in lagoonal estuaries, and stratification of the water column in offshore areas (Cai, 2003).

Land-based chemical weathering along the Mississippi-Atchafalaya introduces carbonate alkalinity (HCO_3^- and CO_3^{2-}) that significantly alters the carbonate chemistry of the northern GOM shelf. An 80-year examination has shown that alkalinity export from the Mississippi River (and its three main tributaries, the upper Mississippi, the Missouri, and the Ohio Rivers) has increased (Raymond and Cole, 2003; Raymond et al., 2008). In fact, an empirical orthogonal function (EOF) analysis of data (sea surface salinity, sea surface temperature, sea surface pCO$_2$, temperature-normalized sea surface pCO$_2$) from 1996 to 2017 indicates surface water CO$_2$ variability on the northern GOM shelf is primarily associated with river input, though seasonal changes in temperature also have a significant influence (Kealoha et al., 2020a). The effect of Mississippi-Atchafalaya outflow on GOM carbonate chemistry is not restricted to coastal waters. Although seasonal SST changes dominate surface water pCO$_2$ variability in the open GOM, about half the observed variance in northern open GOM surface water CO$_2$ is associated with river input. In fact, transport of Mississippi-Atchafalaya outflow can influence open GOM carbonate chemistry hundreds of kilometers offshore (Kealoha et al., 2020a).

The influence of freshwater influx on carbonate chemistry is especially prominent in estuaries. The GOM has the world's largest lagoonal estuaries (Dürr, 2011), which are drowned river valleys partially separated from the GOM by barrier islands that span from humid to semi-arid climate zones (Montagna et al., 2013). Estuaries typically receive direct riverine inflow that is naturally low in pH and calcium ion concentration ([Ca^{2+}]), creating undersaturated conditions ($\Omega < 1$) in lower salinity regions (i.e., oligohaline to mesohaline, or salinity 0.5–18, Montagna, 2013) of an estuary (Beckwith et al., 2019). For example, in the Mississippi Sound, data collected over the natural oyster reefs since 2018 show a strong seasonal variability with lower pH during winter (8.00 ± 0.04) and spring (7.86 ± 0.10) compared to summer (8.14 ± 0.16) (Sankar et al., submitted). Seasonal bottom-water acidification, mostly due to increased freshwater influence in spring, threatens economically and ecologically important benthic ecosystems, particularly calcifying systems such as oysters.

In northwestern GOM estuaries, freshwater supply reduction due to the increase in damming activities for human and agricultural consumption is thought to have contributed to a reduction in alkalinity levels in the majority of estuaries, a phenomenon termed "dealkalization" (Hu et al., 2015). Coastal acidification is occurring in these estuaries, with pH values decreasing over the past few decades at rates (~0.0014 to 0.0180 pH units yr^{-1}, coastwide average pH 8.05 ± 0.38, Hu et al., 2015), comparable to or greater than those observed in the open ocean (pH declines at HOT and BATS are 0.0016 and 0.0017 pH units yr^{-1}, respectively; Bates et al., 2014) (Byrne et al., 2010; González-Dávila et al., 2007). In comparison, a decrease in pH has been observed in west Florida estuaries at a rate (0.00073 pH units yr^{-1}, average pH range of 7.89–8.17 (Robbins and Lisle, 2017), much lower than open ocean rates. The slower pH decrease in some of these estuaries was

attributed to possible carbonate platform dissolution and an increase in salinity, the latter of which may be caused by freshwater diversion and sea level rise. River influence often plays the dominant role in determining long-term temporal carbonate chemistry changes in areas such as estuaries that are directly affected by changing freshwater input (e.g., Cai et al., 2021).

3.6. Episodic storm events

Recent studies have demonstrated the potential for episodic storm events to influence coastal acidification through rainfall and runoff (Grey et al., 2012; Manzello et al., 2013; Hu et al., 2020; T. Hicks, written communication, Texas A&M University, College Station, Texas, 22 June 2022). In the northern GOM, riverine inputs dominate alkalinity distributions in the upper water column and Mississippi River TA is usually >2000 μmol kg^{-1} (Yang et al., 2015). In contrast, rainfall-derived episodic storm runoff typically exhibits very low alkalinity and thus exerts a strong influence on coastal acidification (Saba et al., 2019). Tropical cyclones have been shown to cause prolonged (days to weeks) disturbances in the carbonate chemistry of seawater in calcifying ecosystems, depressing Ω and pH due to high rainfall and runoff (Gray et al., 2012; Manzello et al., 2013; T. Hicks, written communication, Texas A&M University, College Station, Texas, 22 June 2022). Mobilization and degradation of large amounts of terrestrial carbon and nutrients from such storms can also allow for increased microbial respiration (Paerl et al., 2018; Steichen et al., 2020; Yan et al., 2020), influencing estuarine and coastal carbon cycling. However, variable disturbances on the carbonate chemistry of two adjacent estuaries were observed, despite similar freshening conditions following category 4 Hurricane Harvey, suggesting that chemical changes may not be uniform across coastal environments even on small spatial scales (Hu et al., 2020).

Few studies can report on the influence of tropical storms on estuarine carbon cycling (Hu et al., 2020; T. Hicks, written communication, Texas A&M University, College Station, Texas, 22 June 2022), despite the GOM's relatively high hurricane activity. Long-term decreases in alkalinity and pH have been documented for a number of estuaries in the northwestern GOM (Hu et al., 2015). As ocean acidification progresses, a shift towards more acidic conditions and lowered buffering capacity may also exacerbate the effects of storm events on estuarine biogeochemistry (Manzello et al., 2013). Furthermore, the frequency and intensity of tropical cyclones are also predicted to increase under climate change (Knutson et al., 2015). This may have implications for the magnitude of impact that episodic storm events have on coastal acidification, potentially increasing the amount of time needed for a system to recover (Steichen et al., 2020). However, enhanced mixing associated with increased tropical storm activity could reduce hypoxia and lessen bottom water pH declines (Rabalais et al., 2010). Long-term carbonate chemistry monitoring will be central to further investigating the interaction between tropical storms and coastal acidification, as well as predicting the future of critical estuarine and coastal ecosystems.

3.7. Submarine groundwater discharge

While submarine groundwater discharge (SGD) can be difficult to quantify, dedicated flux studies have shown SGD contributes significantly to biogeochemical processes in many coastal ecosystems across the globe (e.g., Santos et al., 2021). The limestone foundation (mostly from fossil mollusk and calcareous and coralline algae) on the GOM shelf is overlain by a subtropical carbonate platform and provides avenues for groundwater to discharge including unique surficial and subterranean karst features such as springs, sinkholes, and other avenues for seepage. The northeastern and eastern GOM have extensive SGD seepage that can change considerably over a range of temporal scales (tidal, seasonal, interannual) (Taniguchi et al., 2003; Santos et al., 2009). SGD also occurs along the northwest Yucatan Peninsula coast in association with the

crater ring formed by the Chicxulub meteorite impact (Bauer-Gottwein et al., 2011). It is likely that there are other SGD outlets along the Yucatan shelf that have simply not yet been characterized (Valle-Levinson et al., 2011). Blue holes (e.g., submerged springs and sinkholes) are common throughout the GOM and are regions where groundwater and seawater interact (Patin et al., 2021) and coastal karst aquifers also provide important links for SGD to the sea.

Groundwater discharge associated with carbonate platforms (both Florida and Yucatan) can increase calcium and carbonate ion concentrations due to dissolution of calcium carbonate as water moves through limestone (Beckwith et al., 2019). Groundwater alkalinity ranges in these regions are similar to seawater values to a few times higher (Gonneea et al., 2014; Liu et al., 2014; Beckwith et al., 2019). Although groundwater input is typically more dispersed along the coastline than riverine freshwater input, SGD can be especially important to the chemistry of estuaries that are shallow and have relatively long residence times. For example, groundwater discharge from springs, seeps, and spring-fed rivers along the Springs Coast of Florida elevate calcium and carbonate concentrations, and decrease nutrient concentrations, creating natural refuge environments from the effects of acidification, which are enhanced in seagrass habitats (Beckwith et al., 2019).

Groundwater can also be enriched in CO_2 due to organic carbon degradation. Many sources of groundwater discharge to the GOM bring elevated DIC (Moore, 2010; Patin et al., 2021), alkalinity (Murgulet et a., 2018, Liu et al., 2014), DOC (Santos et al., 2009), and nutrients (Patin et al., 2021; Ho et al., 2019; Slomp and Van Cappellen, 2004), which can contribute to coastal acidification. Along the Yucatan peninsula, SGD can have high alkalinity and even higher DIC relative to seawater, with low TA/DIC ratios that result in very low pH (6.70–7.30) and Ω_{ar} (0.30–0.97) (Crook et al., 2011). The variability of groundwater discharge rates and chemistry make it difficult to assess the degree of SGD impact on GOM-wide coastal acidification, with local scale impacts ranging broadly across the GOM.

3.8. Eutrophication and hypoxia

Anthropogenic eutrophication, marked by excessive plant and algal growth in estuaries and coastal waters, driven by the transport of terrestrial-derived nutrients is a long term, pervasive problem in the GOM. Thirty of 38 surveyed estuaries across the US GOM exhibited moderate to high eutrophic conditions in 1999 and 23 were predicted to develop worsening conditions over the next 20-years (Bricker et al., 1999). Based on eutrophication indicators including nutrient, dissolved oxygen, and chlorophyll, Environmental Protection Agency (EPA) reported fair (53% of locations) to poor water quality conditions (10% of locations) at 63% of 879 GOM coastal locations by 2006. Poor water quality locations were identified along the coasts of all five Gulf Coast US States (USEPA 2012).

In addition to affecting carbonate chemistry directly, freshwater discharge from rivers can create conditions that cause dramatic changes in seawater chemistry indirectly. An increasingly common effect of enhanced riverine nutrient delivery is coastal hypoxia, or low oxygen conditions that negatively affect marine species and ecosystems (Diaz and Rosenberg, 2008; Breitburg et al., 2018). Coastal hypoxia is widespread in the GOM and has been detected across the northern GOM and West Florida shelves (Diaz and Rosenberg, 2008; Bianchi et al., 2010; DiMarco et al., 2012; Heil and Muni-Morgan, 2021; Turley et al., 2021), as well as in GOM estuaries (Wetz et al., 2016; McCutcheon et al., 2019; Gledhill et al. 2020). The most well studied GOM hypoxic region is located on the northern GOM shelf where Mississippi-Atchafalaya river discharge, in combination with solar warming and low wind speeds, creates stratified conditions during summer months (Rabalais et al., 2001; Turner et al., 2008). Nutrients delivered by the rivers cause intense surface primary production (Rabalais et al., 1996; Lohrenz et al., 1999), where extremely low pCO$_2$ (<100 μatm) and high pH (>8.5) can be found in nearshore river plume surface waters, particularly in spring

and summer (Huang et al., 2015b; Guo et al., 2012; Kealoha et al. 2020a). Surface-produced organic matter sinks to the bottom, where aerobic respiration depletes oxygen (Turner and Rabalais, 2008) and gives rise to low-oxygen and elevated pCO_2 (~1500 μatm) in bottom waters (Hu et al., 2017). Elevated pCO_2 leads to low pH and Ω in bottom waters (Hu et al., 2017), with the extreme values exceeding end of century predictions based on atmospheric CO_2 uptake alone (Cai et al., 2011). Cai et al. (2011) also predicted long-term intensification of this seasonal acidification effect due to further atmospheric CO_2 uptake by offshore waters that enter this shelf region. In addition, benthic anaerobic respiration in combination with oxidation of reduced minerals, iron sulfide burial, and possible carbonate dissolution leads to a low TA/DIC ratio (<1) (Wang et al., 2020). This low TA and high DIC benthic flux causes further acidification within bottom waters. Climate projections indicate intensifying eutrophication could cause geographic expansion of hypoxic areas and greater benthic anaerobic respiration with prolonged duration (Laurent et al., 2018).

4. GOM ecosystem and marine species sensitivity to OA

The GOM is home to a range of marine habitats including salt marshes, seagrass beds, mangroves, and coral reefs (Fig. 5) that host economically, ecologically, and recreationally important marine species that are vulnerable to OA. While numerous studies have examined biological responses to OA, studies that are specific to the GOM have been limited to date. This section describes the existing scientific literature on GOM ecosystems that provide essential services (Table 2) and the sensitivity of regional economically important species and ecologically important lower trophic species (Table 3).

4.1. Salt marshes

Found at the land-sea interface (Fig. 5), salt marshes are one of the most productive and heterogeneous ecosystems in the coastal GOM region. They have been described as "CO_2 pumps" (marshes behave as strong CO_2 pumps taking up atmospheric CO_2 and in return growing marsh primary production; Wang and Cai, 2004; Wang et al., 2016; Wallace et al., 2014), as a sink for atmospheric CO_2, and as a source of

DIC to the coastal water (Wang and Cai, 2004). Salt marshes can affect tidal water pH by injecting DIC and generating TA, a process that may also be decoupled due to differential effects of marsh aerobic and anaerobic respiration on DIC and TA (Wang et al., 2016). There are limited studies on OA and salt marshes in the GOM, however other North America regions of salt marsh typically show net heterotrophy, elevated levels of microbial communities, and eutrophication, all of which result in coastal acidification (Wallace et al., 2014). Salt marsh studies outside the GOM have found neutral to positive impacts of OA on salt marsh productivity in relation to the "Marsh CO2 Pump" concept. However, the sensitivity of GOM salt marshes to atmospherically-driven and coastal acidification is largely unknown.

4.2. Seagrass beds

Seagrass beds make up an important coastal habitat throughout the GOM and serve as an extensive blue carbon sink (Thorhaug et al., 2017) (Fig. 5). Significant fluctuations of seawater carbonate chemistry occur in GOM seagrass beds primarily due to photosynthesis and respiration, but riverine influx, nutrient delivery, and organic-matter degradation also cause variability (Manzello et al., 2012; Challener et al., 2015). Studies of diurnal fluctuation indicate that Florida's Tampa Bay seagrass beds experience average diurnal pH fluctuations of 0.22 units (Yates et al., 2007), with pH up to 0.5 pH units higher in seagrass beds than surrounding habitats (Yates et al., 2016). Similarly, Florida's St. Joseph Bay, which is dominated by shallow seagrass beds, experiences diurnal pH fluctuations of 0.36 (Challener et al., 2015). The ability of seagrass to utilize large amounts of DIC lends the possibility of these ecosystems locally elevating pH and Ω. Models, based on published water chemistry data, indicate the potential for increase in pH of up to 0.38 units, and $Ω_{ar}$ increases of 2.9 in the vicinity of seagrass meadows (Manzello et al., 2012; Unsworth et al., 2012). In fact, seagrass meadows in the Florida Reef Tract have been shown to be net autotrophic on an annual scale, with $Ω_{ar}$ increase in spring and summer, greater than $Ω_{ar}$ depression in autumn and winter (Manzello et al., 2012). This in turn may benefit marine calcifiers, such as corals, suggesting seagrass could potentially be used for conservation and OA relief efforts if elevation of pH and Ω are persistent over long (multiple years) time scales (Koch et al., 2013; Yates et al., 2016).
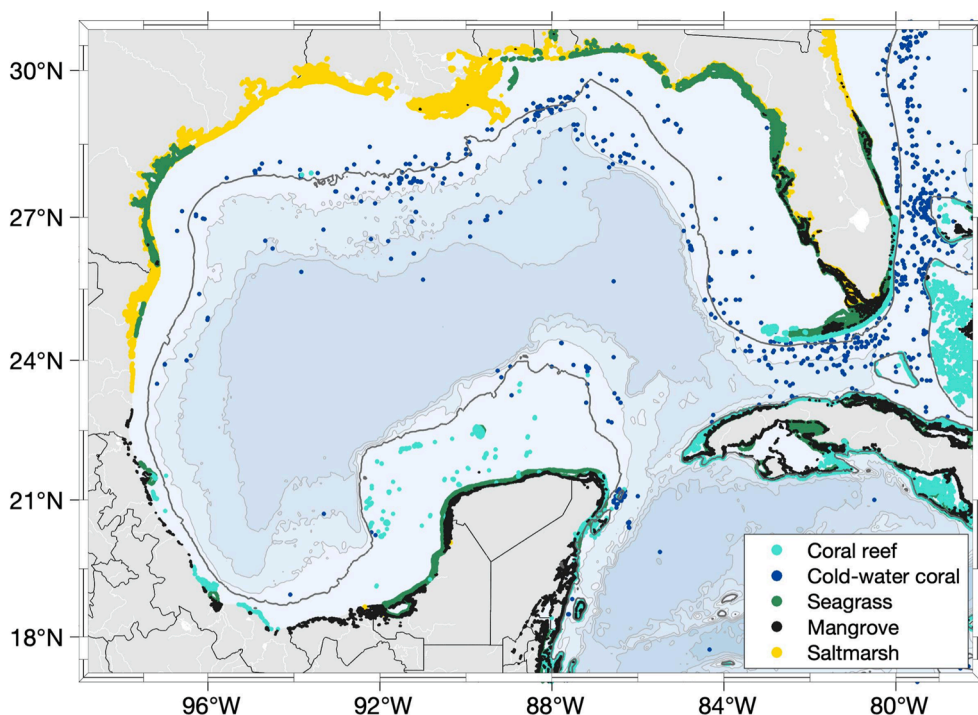

Fig. 5. Distribution of salt marsh (yellow), seagrass (green), mangroves (black), shallow coral reefs (cyan) and cold water corals (blue) in the Gulf of Mexico. Habitat data are from the UN Environment Programme World Conservation Monitoring Centre (https://data.unep-wcmc.org/, (UNEP-WCMC and Short 2020, Freiwald et al. 2017, UNEP-WCMC et al. 2010, Spalding et al. 2010, McCowen et al. 2017). The dark gray bathymetry contour represents the 200 m isobath and light grey bathymetry lines represent 1000, 2000, and 3000 m depths, respectively.

Table 2

Synthesis of OA impacts to GOM ecosystems that provide essential services based on existing scientific literature.

Habitat		Impact	References
Salt marshes	↑⊥	Positive/Neutral Impact - CO_2 sinks; buffer regions, though could decrease with increased acidification	Wang and Cai, 2011; Wang et al., 2016; Wallace et al., 2014
Seagrass beds	↑⊥	Positive/Neutral Impact - refugia to OA; stimulated growth and primary productivity; seagrass bed composition changes	Thorhaug et al., 2017; Manzello et al., 2012; Challener et al., 2016; Yates et al., 2007, 2016; Sunday et al., 2016; Guerrero-Meseguer et al., 2020; Beer and Koch 1996; Beer and Rehnberg 1997; Bjork et al. 1997; Alcoverro et al. 1999; Invers et al. 2001; Hall-Spencer et al. 2008; Jiang et al. 2010; Cyronak et al. 2018; Koweek et al. 2018; Unsworth et al. 2012; Koch et al. 2013; Sale et al. 2014
Mangroves	↑⊥	Positive/Neutral Impact - elevated mangrove productivity, expansion of mangrove habitats, and increased productivity of some mangrove species	Camp et al., 2016; Kellogg et al., 2020; Yates et al., 2014; Bianci et al., 2013; Ellison and Farnsworth, 1996; Gilman et al, 2008; Raddabaugh et al., 2020; Ball and Munns, 1992; Field, 1995; Ball et al., 1997; Comeaux et al., 2012, Komiyama et al. 2020; Bouillon, 2011; Breithaupt et al., 2012; Thorhaug et al., 2018
Coral reefs	↓	Negative Impact - already declining; net dissolution in upper keys; phase shift from hard corals to macroalgae and soft corals	Ruzicka et al. 2013; Toth et al, 2019; Somerfied et al., 2008; Sebens, 1994; Manzello, 2015; Rippe et al., 2018; Lapointe et al., 2019; Muehllehner et al, 2016; Yates et al., 2017; Somerfield et al, 2008; Johnson et al., 2011; Melendez et al., 2020; Dee et al., 2019; Kealoha et al., 2020a; Hu et al., 2018
Oyster reefs	⊤↓	Neutral/Negative Impact - most stable remaining reefs in GOM; evidence of decline however	Beck et al., 2011; Seavey et al., 2011

Table 3

Synthesis of regional economically important species and ecologically important lower trophic species responses to OA in the GOM based on existing scientific literature.

Species		Response	References
Oysters (*Crassostrea virginica*)	↓	Negative - declines in calcification and growth; shell weakening; delayed metamorphosis; increased mortality. decreased acute thermal and salinity tolerance; varying responses depending on species though	Gazeau et al., 2007, 2013; Miller et al., 2009; Talmage and Gobler, 2009, 2011; Beniash et al, 2010; Dickinson et al, 2012; Hettinger et al., 2012
Bay scallop (*Argopecten irradians*)	↓	Negative - larval growth reduction; soft body protusion; reduced larval survivorship	White et al., 2013; Gobler et al., 2014
Hard clam (*Mercenaria spp*)	↓	Negative - larval growth reduction; soft body protusion; reduced larval survivorship; no effect on adults individually, but when combined with other stressors, growth rates reduced; reduced calcification rates	Gobler et al., 2014; Waldbusser et al., 2010
Queen conch (*Strombus gigas*)	↓	Negative - decreased net calcification and increased net dissolution	Ries et al., 2009
Gulf shrimp	⊢⊢↓	Unknown/Negative - outside of GOM: delayed larval growth; decrease in transparency; more calcium in exoskeletons; reduced snapping behavior	Bechmann et al., 2011; Taylor et al., 2015; Rossi et al., 2016
Stone crab	⊤↓	Neutral/Negative - larvae had delayed metamorphosis, reduced embryonic development, and increased mortality; adults generally considered resilient to acidificaiton	Gravinese, 2018; Gravinese et al., 2018; Gravinese et al., 2020
Blue Crab	↓	Negative - larvae smaller in size and reduction in survival	Glitz and Caz, 2017
Spiny lobser	↓	Negative - impaired ability to locate settlement habitats	Gravinese et al., 2020
Finfish	⊤↓	Neutral/Negative - growth, survival, fertilization, embryonic and larval development reduced; hyperactivity; robust; smaller size; depends on species	MacFarlane and Livingston, 1983; Bignami et al., 2012; Hurst et al., 2016, Clements and Hunt, 2018; Williams et al., 2019
Corals	↓	Negative - reduced skeletal formation; reduced calcification; reduced wound recovery; depends on species	Albright et al., 2010; Enochs et al., 2014; Hall et al., 2015; Manzello et al., 2021
Deep-sea corals	⊤↓	Neutral/Negative - can adapt to low pH environments; reduced calcification rates and skeletal mineral properties	Farfan et al., 2018; Form and Reibesell, 2011; Hennige et al., 2015; Georgian et al., 2016a; Kurman et al., 2017; Farfan et al., 2018;

OA has the potential to benefit seagrass beds because high CO_2 conditions can stimulate the growth and primary productivity of seagrass (Beer and Koch, 1996; Beer and Rehnberg, 1997; Bjork et al., 1997; Alcoverro et al., 1999; Invers et al., 2001; Hall-Spencer et al., 2008; Jiang et al., 2010; Cyronak et al., 2018; Koweek et al., 2018; Zimmerman, 2021), as they can utilize DIC produced from anthropogenic CO_2 uptake by the oceans (Unsworth et al. 2012), due to carbon-limited photosynthesis in many seagrass species (Borum et al., 2016; Touchette and Burkholder, 2000). However, seagrass bed composition could be altered under elevated pCO$_2$ if some species respond more positively to high CO2 conditions than others, potentially changing the dominant species or recovery rates of re-vegetation (Sunday et al., 2017). Two seagrass species that coexist in heterospecific beds on the northern GOM shelf, *Halodule wrightii* and *Rupia maritima*, showed no difference in morphology,

Table 3 (*continued*)

Species	Response	References
Sea urchins ↓	Negative - fertilization, larval development, gene expression, immune response, juvenile growth all negative under acidificaiton; possible that they can adapt (not studied in GoM)	Georgian et al., 2016b; Albright et al., 2012; Bogner, 2016; Figueiredo et al., 2016; Byrne et al., 2014
Sponges ↑	Positive/Neutral - winners under acidification; increased bioerosion rates	Lesser et al., 2016; Bennet et al., 2017; Bell et al., 2018; Enochs et al., 2015; Webb et al., 2017; Page et al., 2021

biomass, photo-physiology, metabolism, or carbon and nitrogen uptake when exposed to elevated pCO$_2$ conditions (mean pH 7.7)(Guerrero-Meseguer et al., 2020). Global declines in sea grass bed coverage have been observed as a result of anthropogenic stressors (e.g., Waycott et al., 2009); further research is needed to understand trends within the GOM region and the regional contribution of sea grasses to GOM buffering capacity and ameliorating the impacts of OA to local ecosystems.

4.3. Mangroves

Mangroves are extensive in the southern (Mexican) GOM and along the Gulf Coast of south Florida, covering >650,000 ha collectively across the entire Gulf region (Fig. 5; Thorhaug et al., 2019. Similar to salt marshes, mangroves are extremely productive marine ecosystems and are one of the largest stores of coastal blue carbon (Bouillon, 2011; Breithaupt et al., 2012). Pore waters of mangrove habitats have higher pCO$_2$, DIC, and TA than in surrounding waters (Sippo et al., 2016) and may be able to locally buffer pH, potentially providing refugia for organisms such as corals (Yates et al. 2014, Camp et al., 2016; Kellogg et al., 2020). However, mangroves can also be a source of carbon exported to the coastal ocean. A GOM case study within the largest contiguous mangrove forest in North America concluded that estimates of carbon fluxes in mangrove-dominated estuaries might underrepresent systems that export large amount of carbon to the coastal ocean (Volta et al., 2020).

While anthropogenic and natural impacts have altered mangrove habitats throughout the GOM (Comeaux et al., 2012), it is predicted that climate change and elevated pCO$_2$ may increase productivity for some mangrove species (Ball and Munns, 1992; Field, 1995; Ball et al., 1997; Comeaux et al., 2012; Komiyama et al., 2020), potentially expanding some mangrove habitats (Comeaux et al., 2012). Warming, which has driven mangrove expansion into salt marsh regions in southern Texas over the last 100 years (Armitage et al., 2015; Comeaux et al., 2012), could result in greater carbon sequestration, since mangroves have been shown to store more carbon relative to salt marshes in the GOM (Thorhaug et al., 2019; Comeaux et al., 2012; Vaughn et al., 2020). This habitat transition could also support the stabilization of carbon turnover rates in the northwestern GOM (Bianchi et al., 2013). It is unclear if increased productivity and habitat expansion will be enough to compensate for losses from future sea-level rise and severe storms (Gilman et al., 2008; Raddabaugh et al., 2020; Ellison and Farnsworth, 1996).

4.4. Coral reefs

In the GOM, coral reefs (shallow and mesophotic) occupy ~2,640 km^2, with approximately 85% of these reefs existing along the Florida coastline and throughout the Cuba archipelago (Gil-Agudelo et al., 2020). Cold-water corals are also found throughout the GOM, including

in the East and West Flower Garden Banks off the coast of Texas and Louisiana. GOM coral reefs provide coastal protection from storms, habitat and nurseries for many commercially important species, and support high levels of biodiversity. However, coral reefs are particularly vulnerable to OA (Kleypas and Yates, 2009; Andersson and Gledhill, 2013; Hoegh-Guldberg et al., 2017; Lemasson et al., 2017). Reef structures are formed when scleractinian corals deposit calcium carbonate (aragonitic) skeletons through the process of calcification. This process is energetically costly, and while the mechanism between pH and calcification is not fully understood (e.g., Cohen & Holcomb 2009, Jokiel 2011a, Jokiel 2011b, Venn et al. 2011, Cyronak et al., 2016; Cai et al. 2016) it is clear that OA ultimately slows calcification, increases dissolution and erosion and, thus, decreases reef accretion (e.g., Cohen & Holcomb 2009; Jokiel 2011a; Schoepf et al., 2013; Leclercq et al., 2000, Albright et al., 2018). As previously mentioned, seagrass beds and mangrove habitats located in and around the Florida Keys may provide refugia from OA for some coral species (Manzello et al., 2012; Kellogg et al., 2020). Other studies suggest that an increase in heterotrophic feeding can mitigate the negative effect of OA by maintaining coral reef calcification to some extent (e.g., Cohen & Holcomb, 2009; Holcomb et al. 2010, Chauvin et al. 2011; Towle et al., 2015; Kealoha et al. 2020b). Under future ocean conditions, however, corals will be exposed to multiple stressors (i.e., OA *and* increasing sea surface temperature) likely decreasing calcification further (e.g., Langdon & Atkinson 2005, Edmunds et al. 2012, Schoepf et al., 2013, Van der Zande et al., 2020).

Within the Florida Reef Tract, coral cover has decreased from >50% to barely 5% in most areas (Somerfield et al., 2007; Somerfield et al., 2008) with scleractinian corals being gradually replaced with Alcyonacea (i.e., soft corals and gorgonians), macroalgae, and sponges (Somerfield et al., 2008; Ruzicka et al., 2013, Toth et al., 2019). This dramatic decline is due to local and global stressors, including OA, increasing sea surface temperatures, disease, and eutrophication (Sebens, 1994; Manzello, 2015; Rippe et al., 2018; Lapointe et al., 2019). While the Florida Reef Tract continues to show net carbonate production overall, reef calcification is only 10% of historical rates and the northernmost reefs are now experiencing net dissolution (Muehllehner et al., 2016). Seafloor elevation change measurements throughout the Florida Reef Tract show significant erosion, indicating that carbonate production is insufficient to keep pace with sea level rise (Yates et al., 2017). Coastal hazards like storms, waves, and flood inundation also increase as these natural reef barriers degrade. Furthermore, wound recovery, reproduction, and recruitment in scleractinian corals are also impacted by OA and will negatively affect reefs of the Florida Reef Tract and throughout the GOM (Albright et al., 2010; Enochs et al., 2014; Hall et al., 2015).

Coral reefs in the Flower Garden Banks National Marine Sanctuary exist at the northern latitudinal limits for tropical coral reefs, but remain one of the healthiest coral ecosystems in the Caribbean and GOM with > 50% coral cover (Schutte et al., 2010; Kealoha et al., 2020b). However, in 2016, the East Bank coral reef within the Flower Garden Banks experienced a localized mortality event, potentially due to an intersection of three stressors: a turbid river-derived surface layer that blocked light, deep water upwelled onto the reef that enhanced bottom water stratification, and net respiration resulting in low oxygen and acidification of reef bottom waters (Kealoha et al., 2020b; Hu et al., 2018). While coral mortality associated with this event was high (up to 82%), it affected only a localized area on East Bank (2.6% of the coral reef) and did not impact overall coral cover of the Flower Garden Banks (Johnston et al. 2019a). A record generated from cores of the two most abundant coral species from the Flower Garden Banks Marine Sanctuary, *Pseudodiploria strigosa* 1957–2013 and *Orbicella faveolata* 1970–2014, show that calcification has significantly increased, likely due to warming temperatures; however, this temperature-growth relationship is anticipated to break down over time (Manzello et al., 2021). In fact, a widespread bleaching event occurred in the Flower Garden Banks from September to October 2016, following elevated seawater temperatures

on the reefs for over a month (Johnston et al. 2019b). Bleaching was most severe in the area where the East Bank mortality event occurred in July of the same year, highlighting the potential role of multiple stressors (Kealoha et al. 2020b). The Flower Garden Banks recovered from bleaching and remain healthy despite these events, but will continue to experience multiple stressors, including OA, in the future (Johnston et al. 2019a,b).

While some studies have shown that deep-sea corals in the GOM, such as *Lophelia pertusa,* are able to adapt to low pH, increased acidification can still affect their calcification rates and skeletal mineral properties (Form and Reibesell, 2012; Hennige et al., 2015; Georgian et al., 2016a; Kurman et al., 2017; Farfan et al., 2018). For example, a crystallographic shift observed in the skeletal aragonite of *L. pertusa* samples collected across a natural carbonate chemistry gradient in the GOM was weakly but distinctly correlated with changes in saturation state (Farfan et al., 2018). In addition, many GOM deep-sea coral studies have not accounted for the potential loss of framework from dissolution of exposed coral skeleton that may occur in response to OA (Hennige et al., 2015). Locally elevated TA that may be the result of carbonate dissolution has also been suggested to occur above *L. pertusa* mounds in the GOM (Georgian et al., 2016b). While increased alkalinity may provide more favorable conditions for living coral and partially mitigate the effects of OA, dissolution could undermine the structural integrity of the reef framework over time.

There are ongoing efforts to restore GOM coral reefs (Johnson et al., 2011), although there is still much to understand about impacts of OA on the reef ecosystem as a whole. It is crucial to determine if carbonate production of GOM coral reefs, and other GOM carbonate sediment dominated environments, can keep up with dissolution from OA. Forward projections suggest that the joint impacts of increasing sea surface temperatures and ocean acidification will severely degrade GOM reef systems by the end of the 21st century (Dee et al., 2019). Currently, coastal hazards risk and vulnerability assessments do not account for impacts of acidification on reduced rates of calcification and increased rates of carbonate dissolution on loss of seafloor elevation, structure, and associated acceleration of relative sea level rise.

Found throughout the GOM, crustose coralline algae (CCA) are a major calcifying algae and are especially important to coral reef ecosystems, acting to cement and stabilize the reef structure. CCA may be even more sensitive to acidification than corals because of the high-magnesium calcite used in their skeletons (McCoy and Kamenos, 2015). Recruitment rate and growth of CCA are severely inhibited under OA scenarios (Kuffner et al., 2008). CCA is often found in habitats where diel cycles in pH can surpass OA projections and cause intensified negative effects (reduced calcification rates) on CCA over time (Johnson et al., 2019). Additional research is needed to better understand the impacts of OA on CCA in the GOM, especially within coral reef ecosystems.

4.5. Shellfish

Shellfish (i.e., Eastern oysters, Bay scallops, Hard clams, Queen conch, Gulf shrimp, and Florida stone crab) have received considerable attention in the GOM, where they make up the majority of commercial fisheries based on landings (Tunnell, 2017). Similar to corals, shellfish are particularly vulnerable to low pH, Ω_{ar}, and Ω_{ca} (a result of OA), which hinder the formation of calcium carbonate shells. Further, aragonite and calcite under-saturation can lead to reduced calcification and/or dissolution (Gazeau et al., 2013). However, shellfish response to OA has been shown to vary both between species (Parker et al., 2010) and within the same species (Parker et al., 2011), and can be affected by the presence of additional stressors such as changes in temperature or salinity (Dickinson et al., 2012; Ginger et al., 2014; Parker et al., 2017).

Oyster reefs offer many of the same critical ecosystem services as coral reefs throughout the GOM, including protecting coastlines from storms, and providing habitat and nurseries for many commercially important fisheries. However, importantly, they also filter coastal water (Beck et al., 2011), and are a valuable fishery species. Threats to these

reefs include overharvesting, pollution, eutrophication, changes in freshwater input, oil spills, hurricane events, salinity intrusions from river diversions, disease, and climate change trends, including OA (Seavey et al., 2011; Beseres Pollack et al., 2012). While approximately 85% of oyster reefs have been lost worldwide (Beck et al., 2011), the GOM harbors some of the most stable remaining oyster reefs (Beck et al., 2011) which are typically dominated by *Crassostrea virginica* (Eastern oysters). As of 2010, over 50% of the US commercial oyster harvest came from the GOM, but there is evidence of decline in oyster reefs across the GOM, e.g., Big Bend, FL (Beck et al., 2011; Seavey et al. 2011) and Galveston Bay, TX (Beseres Pollack et al., 2012; Du et al., 2021). While juvenile and adult oysters form calcite shells, larval oysters bio-calcify aragonite, which is less stable than calcite, making larval oysters particularly sensitive to OA (Hettinger et al., 2012). Under predicted future OA conditions, studies have found *Crassostrea virginica* to exhibit decreased calcification, shell weakening, delayed metamorphosis, increased mortality, and reduced acute thermal and salinity tolerance (Gazeau et al., 2007; Miller et al., 2009; Talmage and Gobler, 2009, 2011; Beniash et al., 2010; Dickinson et al., 2012). By comparison, *trans*-generational exposure to future OA conditions has been found to increase larval resilience to OA in Sydney rock-oysters (*Saccostrea glomerata:* Parker et al., 2012; Parker et al., 2015) and Hong Kong oysters (*Crassostrea hongkongensis:* Lim et al., 2021).

Bay scallops (*Argopecten irradians*) have been used as a food source since at least 900 CE, though populations are declining due to overfishing and habitat loss, and therefore, fishery managers are imposing stricter regulations to help with recovery (Arnold, 2009). Studies have shown that under OA conditions, larval *A. irradians* experience reduced shell growth, inhibited development (White et al., 2013; Gobler et al. 2014), and reduced survivorship (Gobler et al. 2014). Similarly, studies of Hard clams (*Mercenaria* spp.) under OA conditions have found significantly reduced growth (Waldbusser et al., 2010). The queen conch (*Strombus gigas*), found predominantly throughout south Florida and the Caribbean, has historically been an important food and shell source, though is now considered a specialty food due to heavy exploitation and overfishing (Posada et al., 2007). Under OA conditions, *Strombus* spp. exhibit decreased calcification and increased dissolution (Ries et al., 2009).

Generally, adult crustaceans are considered to be resilient to reduced pH (Gravinese et al., 2020), but frequent molting and the presence of calcium carbonate in the carapace increases the possibility that at some point during their life cycle, some species will respond negatively to OA (Tunnell, 2017). Although there are relatively few studies on the impacts of OA on GOM crustaceans, current research demonstrates that several iconic regional species are vulnerable. In the 1950 s-1970 s, southern GOM gulf shrimp (*Farfantepenaeus duorarum*) fisheries had yields of approximately 24,000 metric tons which have since collapsed to approximately 1,200 metric tons (Arreguin-Sanchez et al., 2015). Originally thought to be due to overfishing practices, additional recent evidence suggests this collapse was strongly related to climate change (Arreguin-Sanchez et al., 2015). Studies of non-GOM shrimp species under OA conditions have found increased calcium in shrimp exoskeletons resulting in decreased transparency that reduces predator avoidance (Taylor et al., 2015), delayed larval growth (Bechmann et al., 2011), and reduced snapping behavior (loudness and frequency) in snapping shrimp (*Alpheus novaezelandiae*) (Rossi et al., 2016). Laboratory studies have shown that larvae of Florida stone crabs (*Menippe mercenaria*) reared in elevated pCO$_2$ exhibited delayed metamorphosis, reduced embryonic development, and increased mortality (Gravinese, 2018; Gravinese et al., 2018). Larval Blue crabs (*Callinectes sapidus*) reared at a reduced pH (7.8) were 10% smaller and had a 24% reduction in survival compared to larvae reared in ambient pH (8.2) conditions (Giltz and Taylor, 2017). Spiny lobster (*Panulirus argus*) larvae exhibited an impaired ability to locate settlement habitats in reduced pH environments (Gravinese et al., 2020). Thus, OA represents a threat to valuable shellfish species throughout the GOM that merits further research to better quantify this threat and develop adaptation and potential mitigation strategies.

4.6. Finfish

The GOM provides unique oceanographic and coastal habitats for finfish, with over 1,443 species characterized (Tunnel et al., 2017). Although limited, several laboratory studies have shown that physiological processes of finfish can be sensitive to OA conditions, in some cases impacting growth, survival, fertilization, embryonic and larval development, and behavior (e.g., Hurst et al., 2016; Williams et al., 2019). In one study, Gulf killifish were exposed to different pH levels (using less-accepted methods of addition of sulfuric acid to seawater), and those exposed to low pH water became hyperactive (MacFarlane and Livingston, 1983). In contrast, Cobia (*Rachycentron canadum*), a widely distributed pelagic-spawning species found in the GOM, was robust under OA conditions. Larval Cobia raised in elevated pCO$_2$ environments showed no differences in swimming ability and activity; however, these larval Cobia were 25% smaller, showed a 2–3 day developmental delay, and exhibited significantly larger otoliths under OA (Bignami et al., 2013). However, uncertainty remains regarding how many GOM finfish will be affected by OA.

4.7. Sea urchins

Sea urchins are important algal-grazers on coral reefs, seagrass beds, and rocky regions. Studies suggest sea urchins may be particularly vulnerable to acidification, especially early life stages. Fertilization, larval development, gene expression, immune response, and juvenile growth are negatively affected by exposure to elevated pCO$_2$ (Albright et al., 2012; Bogner, 2016; Figueiredo et al., 2016). Urchins build their skeletal structure with high-magnesium calcite that is less stable than calcite or aragonite, making them susceptible to dissolution under OA, which can leave them vulnerable to predation or being crushed (Byrne et al., 2014). Some species have the ability to adapt to acidic environments due to changes in gene expression (e.g., *Strongylocentrotus purpuratus;* Pespeni et al., 2013), but this has not been thoroughly studied in GOM urchin populations.

4.8. Sponges

With over 300 species in the GOM, sponges are one of the most abundant invertebrates in the region (Rutzler et al., 2002). Some studies show that sponges are generally tolerant of acidification, but species-specific differences in tolerance could shift sponge assemblage compositions in different regions of the GOM (Bell et al., 2018). For example, there may be a shift from heterotrophs to phototrophs due to reduced resiliency to OA and warming (Bennet et al., 2017). Acidification and warming stress could also destabilize sponge microbiomes (Lesser et al., 2016). Some boring sponge species play an important role in coral-reef bioerosion and acidification is likely to increase bioerosion rates (Enochs et al., 2015; Webb et al., 2017). Coral reef communities may switch to sponge dominated communities because sponges tend to grow more volumetrically and outcompete corals under acidification (Page et al., 2021).

4.9. Phytoplankton and harmful algal blooms (HABs)

OA is predicted to influence planktonic systems where the pH dependent changes in the marine carbonate system have broad implications for carbon acquisition. Phytoplankton dynamics help determine how depressed pH and elevated pCO$_2$ will affect biogeochemical cycling because of their innate ability to produce O$_2$ and sequester CO$_2$. Changes in phytoplankton communities can indicate changes in ability to cycle nutrients and sequester carbon. In the GOM, natural estuarine phytoplankton communities were collected from two biogeochemically distinct Louisiana estuaries and cultured in ambient (400 ppm) and elevated (1000 ppm) pCO$_2$ levels (Mallozzi et al., 2019). Results suggested that elevated pCO$_2$ does not necessarily cause an increase in phytoplankton biomass. There was a loss in species diversity within each major taxonomic class by the end of the exposure, however most of the cultures showed community adaptation.

The most widespread HAB species in the GOM is *Karenia brevis* (Florida Red Tide), although other taxa are found consistently throughout coastal zones (e.g., *Pseudo-nitzschia, Gambierdiscus, Dinophysis, Pyrodinium bahamense*, and *Aureoumbra lagunensis*) (Anderson et al., 2021). Modes of harmful action from these taxa consist of ingestion of toxin-containing fish/shellfish (*Gambierdiscus, Dinophysis, P. bahamense,* and *Pseudo-nitzschia*), ecosystem disruptors (*Aureoumbra lagunensis* and *Pyrodinium bahamense*), and direct toxin production (*K. brevis*) (Heil and Muni-Morgan, 2021). Errera et al. (2014) showed that *K. brevis* brevetoxin production remained the same under elevated pCO$_2$, yet algal growth rates significantly increased. There are strong dependencies on CO$_2$ in HAB species, and *K. brevis* has mechanisms that could also increase resiliency to elevated pCO$_2$ (Bercel and Kranz, 2019). OA could favor initiation and maintenance of HABs (Wells et al., 2015), however further research is needed to understand the interaction of OA and HAB dynamics, particularly with respect to their occurrence in the GOM (Riebesell et al., 2018; Wells et al., 2020).

4.10. Calcifying plankton

Planktonic foraminifera produce calcite shells contributing to an estimated ~ 32–80% of the total deep-marine calcite budget (Schiebel, 2002). Planktonic foraminifera became prominent as producers of calcareous sediments during the Cretaceous, when atmospheric CO$_2$ levels were several times higher than today (e.g., Wei et al., 2021). Nevertheless, evidence for 20th century reduction in planktonic foraminiferal calcification has been reported in the California Current Ecosystem (Osborne et al., 2020) and the Equatorial Pacific (Fox et al., 2020). Studies examining OA impacts to planktonic foraminiferal calcification and trends over time have yet to be conducted in the GOM. Benthic forams, which are much more diverse, are well studied in the GOM (e.g., Poag, 2015). Among the benthic foraminifera, the porcelaneous taxa of the Order Miliolida are the most susceptible to OA because they produce high-Mg calcite shells susceptible to dissolution. These forams are most abundant in carbonate-shelf environments throughout much of the GOM, where they are important producers of carbonate sediments. Porcelaneous forams are especially prevalent where salinities, pH and carbonate saturation are somewhat elevated, including the Florida reef tract, Florida Bay, Cuba, and southern Mexico (Poag, 2015). Coccolithophores and pteropods are also found throughout the Gulf of Mexico, are major producers of CaCO$_3$, yet have been understudied in this region in reference to acidification (Guinotte and Fabry, 2008). Most studies in other regions show decreased calcification, growth malformations, and dissolution of coccolithophore and pteropod CaCO$_3$ under OA (reviewed in Guinotte and Fabry, 2008).

4.11. Microbes

There are few studies observing the direct effect of OA on microbes. Bacteria, Archaea, viruses, and protists can be affected directly or indirectly by changes in seawater chemistry, but have also been shown to adapt quickly to these changes (Liu et al., 2010). Cyanobacteria play a crucial role in biogeochemical cycles throughout the GOM where nitrogen is often limiting. Some cyanobacteria are even considered precursors to HABs such as *K. brevis* (Lenes and Heil, 2010). Shi et al. (2012) found that the rate of iron uptake in *Trichodesmium* declines as pH decreases. Blue holes throughout the GOM are natural laboratories where unique carbonate chemistry profiles exist (e.g., low pH, elevated DIC). The microbial community in one of these holes showed previously undocumented levels of phyla Woesearchaeota and Candidate Phyla Radiation, although this may be due to a combination of OA and a redox-stratified environment (Patin et al., 2021). Ecosystem pH can also change as a result of microbial activity, as microbes respire, pCO$_2$ is elevated, thus increasing acidification (Cai et al., 2011).

5. GOM OA monitoring gaps

The GOM lacks sustained observing assets in the open ocean, coastal zones, and estuaries needed to fill major data gaps that are critical for tracking the progression and understanding the dynamics of acidification. Observations need to include, at minimum, two of the four carbonate system variables (pH, pCO_2, DIC, TA) to enable calculation of the full carbonate system. Although current off the shelf sensors are predominantly for pH and pCO_2 monitoring, supporting variables (e.g., temperature, salinity, dissolved oxygen), and sustained operation to ensure long-term time-series measurements needed to identify time of emergence (the time at which the signal of carbonate chemistry change emerges from the noise of its natural variability) of acidification. These data are critical for understanding causes, controls, impacts and consequences of ocean and coastal acidification.

5.1. Open ocean observing

Open ocean GOM OA time-series and basin-scale spatial transects used for monitoring and improving models of the progression of OA, climate-scale modulation, and time of emergence are limited. Use of existing and new platform and buoy infrastructure is needed to fill key data gaps in sustained time-series monitoring. For example, time-series monitoring at key GOM deep water coral locations such as Flower Garden Banks National Marine Sanctuary are needed to understand the impact of acidification on deep reefs. Autonomous observing systems such as biogeochemical-Argo floats and gliders could expand full water-column, deep, and basin-scale spatial measurements of carbonate-system and related variables currently collected during ship cruises. Additional ship-based measurements could be leveraged (including shelf-wide cruises for hypoxia studies and NOAA surveys) to increase spatial coverage of both surface and subsurface carbonate parameters.

5.2. Coastal zone observing

Coastal OA time-series data are needed to characterize sub-regional variability in OA due to differences in physical and environmental conditions (for example bathymetry, freshwater inputs, groundwater discharge, hydrodynamics, habitat composition, etc.). Key locations that are representative of broader GOM environmental conditions but where there are currently no sustained OA time-series moorings include, for example, the West Florida Shelf; offshore of Corpus Christi, Texas; offshore of Tampico, Veracruz, and Mérida-Cancún, Mexico; and offshore of Havana and the west coast of Cuba.

5.3. Estuarine observing

Estuarine carbonate and related chemistry is much more variable than in the open GOM. Sustained long-term observing is required to characterize variability, identify acidification drivers and environmental influences, and determine time of emergence for OA signals. Currently only three (Tampa Bay, Florida, Aransas Bay, Texas, and Mobile Bay, Alabama) of over 200 GOM estuaries have sustained time-series observation programs. Expansion of existing general monitoring programs and developing new programs for carbonate chemistry dynamics is needed, particularly in estuaries that have experienced declining commercial shellfish production over the last several decades (e.g., Galveston Bay). Potential collaborators for expansion of existing monitoring programs include, for example, state-level environmental monitoring programs, EPA's National Estuary Program, NOAA's National Estuarine Research Reserve System, and Gulf of Mexico Coastal Ocean Observing System. Monitoring programs should also consider including river flow (e.g., from USGS), submarine-groundwater discharge, and associated carbonate chemistry data to better understand the effects of freshwater input on acidification.

5.3.1. GOM OA research gaps

There are considerable knowledge gaps with respect to the dynamics, regional, and sub-regional impacts of OA in the GOM. Regionally-focused, hypothesis-driven research on GOM marine ecosystems, physical–chemical dynamics, and multi-stressor interactions is central to building a more robust scientific understanding of OA within the GOM. Filling these knowledge gaps is essential for guiding resource management, restoration and mitigation strategies, and coastal resilience and hazards planning for ocean and coastal acidification. Topical areas of research include: data synthesis and analysis, improved projection modeling, research to increase observation capabilities, improve monitoring technologies, and extend the observational record, understanding acidification drivers and environmental influences, impacts to species, impacts to ecosystems and their services, and socioeconomic impacts.

5.4. Synthesizing existing OA-relevant data for new analyses

Ensuring that all OA-relevant chemical, physical, biological, and biogeochemical data collected in the GOM are submitted to appropriate data centers, formatted, and documented using Findability, Accessibility, Interoperability, and Reuse (FAIR) principles and appropriate quality flagging will maximize the utility of existing OA-related GOM datasets. Examining synthesized GOM OA data using climatological approaches for 'time of emergence' and 'time of detection' analysis will aid investment decision making for monitoring critical areas of interest and informing restoration and mitigation strategies. Using innovative methods, such as artificial intelligence, to extrapolate sparse data in space and time will be particularly useful for improving ocean biogeochemical models that can also inform sampling strategies and observing system design (e.g., Carter et al., 2019) through Observing System Experiments. Collaboration among the GOM states and nations is needed to enhance data sharing and collaborative modeling activities. Coastal and estuarine historical water quality data sets need to be identified and examined for their utility in modeling past changes in OA-related variables to aid in projecting future changes. A repository of consistently formatted biological data is needed for understanding OA on the GOM ecosystem.

5.5. Improving near- and long-term regional and sub-regional projections

Further modeling studies are required to improve the representation of carbon system dynamics and gain further insights on the carbonate system variability. Within the model improvements that could be considered in future modeling efforts are (i) increasing horizontal resolution to better resolve coastal circulation and biogeochemical processes at sub-regional or local scales (e.g., estuaries, bays); (ii) realistic representation of land–ocean fluxes of nutrients, DIC, and alkalinity, including time evolving river chemistry, to evaluate the potential role of river runoff as modulator of coastal acidification patterns; and (iii) enhanced representations of remineralization processes to simulate realistic bottom acidification and carbon export patterns. Refinement and expansion of GOM carbonate chemistry models, along with the downscaling of CMIP6 scenarios, will contribute to describing and attributing observed long-term changes in the carbonate system and predicting future conditions. Models will provide critical system-wide understanding of acidification within the Gulf region, which can help to identify observational gaps, and inform monitoring, management, and conservation plans. Higher-resolution models (at spatial and temporal scales appropriate for location-specific resource management guidance) are needed for high-priority sub-regions and estuaries. Coupling existing physical models (hydrodynamics, seafloor elevation change, sea level rise, etc.) with water column and seafloor biogeochemistry models are needed to improve characterization of current and prediction of future acidification impacts.

5.6. Advancing acidification observing technologies

Advancements toward incorporating carbonate system sensors in combination with other sensor packages on gliders are needed to increase efficiency and improve spatial coverage of observations throughout the GOM. Coordination among technology development research groups is needed to expedite sensor development, integration into observing platforms, field testing, and establishment of best practices for use in diverse GOM environments. Efficient expansion and improvement of GOM OA spatial and time-series observations will benefit from development of new surface and profiling sensor capabilities for OA observing and build-out of an integrated network of gliders, floats, moorings, autonomous surface vehicles (ASVs), and other autonomous platforms (Bushinsky et al., 2019). Inclusion of sensors on observing platforms for measurement of additional OA-related variables (such as TA, DIC, nutrients, $[CO_3^{2-}]$, chlorophyll, and others) is important for better characterization of GOM water that is highly influenced by terrestrial and riverine inputs.

5.7. Generating paleo-records to extend the observational record

Understanding historical and prehistoric changes in carbon dynamics and environmental conditions is essential for tracking progression and improving projections of acidification within the region. Records developed for the Anthropocene are particularly helpful for tracking the human-induced changes in the marine carbonate system and pairing with the relatively short modern observational record of OA. The preservation of calcium carbonate fossil remains of planktonic foraminifera, corals, and other calcifying benthic species have been broadly used to reconstruct past ocean conditions. For example, studies demonstrated that fossil foraminiferal shell geochemistry and physical characteristics can be used to estimate surface ocean pH of the past (e.g., Hönisch et al., 2012; Osborne et al., 2019). Coral cores have also been used to study past environmental conditions and rates of carbonate production, and existing coral core archives could be utilized to expand studies of past carbonate chemistry and calcification conditions (Wall et al., 2019; Tarique et al., 2021).

5.8. Understanding drivers and environmental influences

The GOM is characterized by numerous physical, environmental processes and characteristics that drive and/or influence ocean and coastal acidification. While many of these processes have been identified (reference sections above), there are major gaps in our understanding of the complex interactions among them, their relative influence, and spatial and temporal variability at regional, sub-regional, and individual estuary scales. Specific areas of research that represent major knowledge gaps particularly important in the GOM include: hypoxia and HAB interactions, surface and deep hydrodynamic circulation and input of anthropogenic CO_2, sea level rise and coastal inundation, freshwater inflow and episodic storm events, interactions with carbonate lithology, and effects from oil seeps and spills.

5.8.1. Interactions among acidification, HABs, and hypoxia

The occurrence and duration of HABs and hypoxia in the GOM Region has increased in recent years and is a major environmental and resource management challenge. Interactions among HABs (including their duration, frequency, and toxicity), acidification, hypoxia, and other environmental conditions are not well-understood, limiting prediction capabilities for future HAB occurrences, hypoxia and acidification events. A synthesis of information from existing studies and development of focused research that co-examines these processes is needed to develop a better understanding of linkages among them. Given the close correlation between bottom water dissolved oxygen concentration and the extent of acidification along the Louisiana shelf (Cai et al., 2011), it is expected that bottom waters along the Texas shelf,

Mobile Bay and its adjacent shelf are also subject to episodic, seasonal declines in pH. Increased frequency of occurrence in bottom-water hypoxia to the east of the Mississippi River delta (e.g., Mississippi Sound) is also a concern related to acidification and local fishery resources. Benthic-pelagic coupling studies are needed to further investigate sediment respiration on OA as well as the effect of long-term accumulation of organic matter (due to potentially increasing surface production as a result of eutrophication) in areas prone to hypoxia, including other coastal zones and estuaries.

5.8.2. Impact of surface and deep water circulation

Water flow into and out of the GOM from surface to bottom influences the residence time and accumulation of respiratory and anthropogenic CO_2. A better understanding of basin-wide circulation combined with carbon tracer studies is needed to understand and explain sources, (e.g., atmosphere, adjacent ocean basins, terrestrial/coastal), transport, and rates of anthropogenic CO_2 increase. Results from National Academy of Science GOM Circulation Studies focus on understanding Loop Current dynamics (including eddy shedding) and deep-circulation, and may provide the foundation for additional OA focused studies. International collaboration is needed to improve understanding of carbon dynamics along the Mexican coast (e.g., near the Usumacinta River) and associated with upwelling along the Yucatán shelf.

5.8.3. Sea level rise and coastal inundation

Coastal wetlands such as salt marshes and mangrove habitats are known to "outwell" both inorganic and organic carbon to the coastal ocean. Coastal inundation due to sea level rise could facilitate transport of this carbon and disturb and oxidize buried blue carbon and reduced compounds in sediments that may also contribute to enhanced acidification in the coastal zone. Focused experiments, long-term monitoring, and modelling of these sensitive areas are needed to study the impact of coastal inundation, particularly since the GOM has greater coastal subsidence rates than many parts of North America.

5.8.4. Freshwater inflow and episodic storm events

River flow, terrestrial run-off, and groundwater inflow can contribute substantial inorganic and organic carbon and nutrients, and can dramatically alter carbon, calcium concentrations, and carbonate chemistry dynamics. However, the impacts of episodic storm events on open GOM and coastal acidification as the frequency and magnitude of storms increases, groundwater discharge and spring fed surface flow (particularly in carbonate environments), and human alteration of freshwater flow (e.g., controlled release of flood water) on open GOM and coastal acidification are not well understood. Key aspects of research needed to address these gaps include rapid post-storm investigations on impacts to acidification related variables, better understanding of the influence of coastal currents on impacts from freshwater inflow, and characterization of variations in calcium concentrations in coastal waters (particularly in the northwest GOM and along the Springs Coast of Florida). Much of Florida and the West Florida Shelf as well as the Yucatán Shelf are carbonate platforms with karst topography and seafloor sediments characterized by high carbonate content. Few studies (e.g., Beckwith et al. 2019) have characterized the effect of subsurface or surface carbonate dissolution on altering calcium concentrations, alkalinity, and carbonate mineral saturation states in water flowing into these GOM coastal zones.

5.8.5. Oil seeps and spills

An abundance of petroleum carbon enters Gulf waters, however, monitoring of carbonate chemistry dynamics in association with oil spills and oil and gas seeps has been limited. Monitoring of both petroleum itself and water chemistry (carbonate parameters, stable carbon isotopes, and dissolved oxygen) along with isotopic tracer studies are needed to better assess the influence of this carbon source on the marine environment.

5.9. Response of ecologically and economically important marine species

The impacts of OA on ecologically and economically important GOM marine species have not been well studied. Focused OA exposure studies in both the laboratory and field setting using GOM species are needed to close this gap, ideally using a framework that also examines multi-stressor interactions including OA, warming, hypoxia, HABs, and others. Focused studies are especially needed to examine impacts to key GOM species including crustaceans (shrimp, lobster, crabs), bivalves (clams, oysters, scallops), conch, urchins, coral, finfish, and pelagic calcifiers (coccolithophores, pteropods, foraminifera) and for life stages of these species.

5.10. Impacts to ecosystems and ecosystem services

Estuarine, coastal, and open marine habitats of the GOM provide a variety of ecosystem services that support food security, recreation, tourism, industry, coastal resilience, and coastal hazards protection (Section 4.0). Focused long-term studies on salt marsh, seagrass, mangrove, oyster reef, coral reef, and other carbonate ecosystems are needed to understand OA impacts on ecosystem resources and services that provide benefits to coastal communities. This includes focused field and laboratory studies as well as model studies that can estimate ecosystem range shifts of salt marshes, seagrass, mangroves, and changes in seafloor structure and habitats under future elevated $p\mathrm{CO_2}$ and sea level rise. Additional key knowledge gaps include the impacts of carbonate dissolution on seafloor chemical erosion, elevation loss, and associated coastal hazards; identification of resilient ecosystems; research to inform potential mitigation strategies for acidification; and downstream consequences of multi-stressor species impacts to ecosystem function.

5.11. Socioeconomic impacts

Acidification in GOM ecosystems has been documented, and laboratory investigations indicate several ecologically and commercially important species can be impacted. However, gaps in our understanding of OA dynamics, species and ecosystem impacts, and lack of field investigations that directly link species response to OA in the GOM make it difficult to produce accurate assessments of socioeconomic impacts. Information in this synthesis provides the context for examining potential regional and sub-regional socioeconomic impacts and identifying uncertainties related to science and monitoring gaps. Synthesis of socioeconomic data on potentially impacted species, ecosystems, industries, resources, dependencies, and adaptability is needed to begin developing risk and vulnerability assessments at the regional to sub-regional scales, and associated with specific socioeconomic sectors that can be improved as understanding of OA in the GOM advances.

6. Conclusions and next steps

The GOM region spans temperate, subtropical, and tropical climate zones across three nations; a broad variety of ecosystems, habitats, species, and environmental conditions; and highly complex interactions among chemical, physical and biological processes that drive or are influenced by acidification. The challenges of understanding acidification processes and environmental impacts mirror the intricacies of assessing related socioeconomic risks and vulnerabilities in this region. The GOM region's geographic scale, substantial connectivity among sub-regions, and the breadth and diversity of natural and socioeconomic science needed to advance research and monitoring requires international partnerships, engagement of regional networks such as GCAN and other Coastal Acidification Networks (CANs), and a transdisciplinary approach to achieve a system-wide understanding of OA.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No new scientific data are presented in this review article, rather we provide an inventory of published and known unpublished datasets and have identified data sources (DOIs, databases, POCs).

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pocean.2022.102882.

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