Office of National Marine Sanctuaries
National Oceanic and Atmospheric Administration

NATIONAL MARINE SANCTUARIES CONSERVATION SERIES

Rapid Climate Vulnerability Assessment for Flower Garden Banks National Marine Sanctuary

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Cover photo: A scuba diver swims over coral and sponges at Flower Garden Banks National Marine Sanctuary. Photo: Schmahl/NOAA.

About the National Marine Sanctuary System

The Office of National Marine Sanctuaries, part of the National Oceanic and Atmospheric Administration, serves as the trustee for a system of underwater parks encompassing more than 1,600,000 km^2 of ocean and Great Lakes waters. The 15 national marine sanctuaries and two marine national monuments within the National Marine Sanctuary System represent areas of America's ocean and Great Lakes environment that are of special national significance. Within their waters, giant humpback whales breed and calve their young, coral colonies flourish, and shipwrecks tell stories of our nation's maritime history. Habitats include beautiful coral reefs, lush kelp forests, whale migration corridors, spectacular deep-sea canyons, and underwater archaeological sites. These special places also provide homes to thousands of unique or endangered species and are important to America's cultural heritage. Sites range in size from less than 2 to over 1,500,000 km^2. They serve as natural classrooms and cherished recreational spots and are home to valuable commercial industries.

Disclaimer

Report Availability

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Abstract

Flower Garden Banks National Marine Sanctuary (FGBNMS, or "sanctuary") is a group of 17 reefs and banks situated 129 to 201 km off the coasts of Texas and Louisiana in the northwestern Gulf of Mexico. A part of the National Marine Sanctuary System, FGBNMS is home to thriving high and low relief coral reef habitat, algal-sponge communities, and deeper mesophotic reefs. The sanctuary is impacted by climate changes (such as increasing seawater temperatures, bleaching, and possible acidification), and climate projections for the next 50 years suggest these changes will accelerate. The sensitivity of marine species at FGBNMS to these changes (i.e., vulnerability) and their ability to acclimate to these changes (i.e., resilience) will define the sustainability of the sanctuary as a viable marine habitat in coming decades.

In July of 2022, FGBNMS convened an expert workshop to assess the climate vulnerability of two habitat types, the coral reef cap (18–50 m) and mesophotic reef habitat (>50 m), as well as 23 key species or groups of species occurring within the sanctuary. Participants were supplied with information about the current and projected climate conditions of the sanctuary and used this information to apply their knowledge of each species and the species' adaptability. Using a modified version of the Commission for Environmental Cooperation's North American Marine Protected Area Rapid Vulnerability Assessment tool (CEC, 2017; see Appendix C), participants' knowledge was transformed into a vulnerability score for each species. Once climate vulnerabilities were established, participants discussed possible adaptation strategies for each habitat type, which, if implemented, might reduce vulnerability.

This report summarizes the outcomes of the Flower Garden Banks Climate Vulnerability Assessment workshop. A key finding suggests increasing seawater temperatures, ocean acidification, and increasing storm intensity and precipitation will interact with non-climate stressors to impact many species within the sanctuary. Both coral reef cap and mesophotic habitats were ranked as moderately to highly vulnerable to increasing seawater temperatures and ocean acidification and less vulnerable (low vulnerability score) to storm and precipitation changes. Temperature increases may exacerbate coral bleaching and stress fish and invertebrate species, potentially resulting in trophic cascades and habitat alterations. Ocean acidification will make it more difficult for scleractinian corals, crustose coralline algae, and other calcifying organisms to undergo calcification, and may also negatively impact fish and invertebrates through metabolic expenditure. Importantly, habitat loss or degradation (e.g., enhancement of bioerosion, loss of framework habitat) can result from ocean acidification. Increasing storm severity and frequency may cause physical damage to reefs and sponges and the increased sediments and nutrients from precipitation will likely stimulate algae overgrowth and clog the pores of filter feeders. Other various impacts of storm and precipitation changes were noted, and all these climate stressors may be exacerbated by pressures from land-based pollution, invasive species, disease, harvest, and mining and oil and gas extraction in the region.

Workshop participants identified increasing research on knowledge gaps to improve future management, including comprehensive monitoring, as essential first steps that would allow early identification of impacts of climate change on the FGBNMS and rapid responses of Sanctuary personnel to these impacts. Other major adaptation strategies suggested in the workshop included encouragement of invasive lionfish harvest, disease management, and

strengthening existing or forging new collaborative partnerships with stakeholders, zoos, aquariums, and management entities.

Keywords

Flower Garden Banks, climate change, vulnerability, adaptation strategies, coral reefs

Chapter 1: Habitat, Climate, and Climate Change at Flower Garden Banks National Marine Sanctuary

Climate change is impacting marine systems worldwide, causing environmental, social, and economic harm (Moretzsohn et al., 2012; USGCRP, 2018). Some of these impacts include rising seawater temperatures, sea level rise, acidification of seawater, lowered water oxygen levels, alterations of species ranges and interactions, and changing weather and storms (Moretzsohn et al., 2012; USGCRP, 2018). Flower Garden Banks National Marine Sanctuary (FGBNMS or "sanctuary") and other national marine sanctuaries and monuments must contend with these climate changes and plan for future possibilities.

1.1 Overview of Flower Garden Banks National Marine Sanctuary

The 414.4 km^2 (160 mi^2) FGBNMS is located 129 to 201 km (80 to 125 mi) off the coasts of Texas and Louisiana in the northwestern Gulf of Mexico (nwGOM) (Fig. 1.1). One of 15 national marine sanctuaries and two marine national monuments protected by the National Marine Sanctuary System, which encompasses 1,553,993 km^2 of ocean and Great Lakes waters and is administered by the National Oceanic and Atmospheric Administration's (NOAA) Office of National Marine Sanctuaries (ONMS), FGBNMS consists of high and low relief coral reef habitat (18–50 m), and deeper mesophotic areas (>50 m) consisting of algal nodule, coralline algae reef, deep reef, and soft bottom habitat. Portions of 17 individual reefs and banks, composed of small underwater mountains, ridges, troughs, and hard bottom patches along the continental shelf, primarily created by underlying salt domes, are encompassed within FGBNMS (Fig. 1.1).

Discovered by fishers in the early 1900s, FGBNMS was designated by NOAA in 1992, and originally consisted of East and West Flower Garden Banks (EFGB and WFGB, respectively). Stetson Bank was added in 1996, and portions of 14 more reefs and banks (Horseshoe, MacNeil, Rankin, 28 Fathom, Bright, Geyer, Elvers, McGrail, Bouma, Sonnier, Rezak, Sidner, Parker, and Alderdice Banks, hereafter, referred to as the sanctuary expansion area) were included in 2021 (Fig. 1.1; ONMS, 2020). Some of these banks are surface expressions of underlying salt domes, which push overlying sediments upward and provide a chain of habitats for ecologically and economically important species such as snapper, grouper, and jacks across the nwGOM. Other reefs may occur on exposed bedrock. Healthy high and low relief coral reef habitat, algal-sponge communities, and deep reef habitat consisting of black coral and octocoral all reside within FGBNMS (ONMS, 2020).

The disconnected banks of reefs found within FGBNMS are the northernmost limit of the geographic range of many coral species found there, and are geographically isolated from other similar communities found in the Caribbean. This creates a unique series of habitats with an original community structure in an otherwise dissimilar region of ocean. Habitat and species recovery of this isolated area from alterations due to climate and non-climate stressors will likely be difficult due to lack of proximity to similar habitats and species. It is therefore vital to effectively manage the FGBNMS and prevent future harm to the Sanctuary, which may be irreversible.

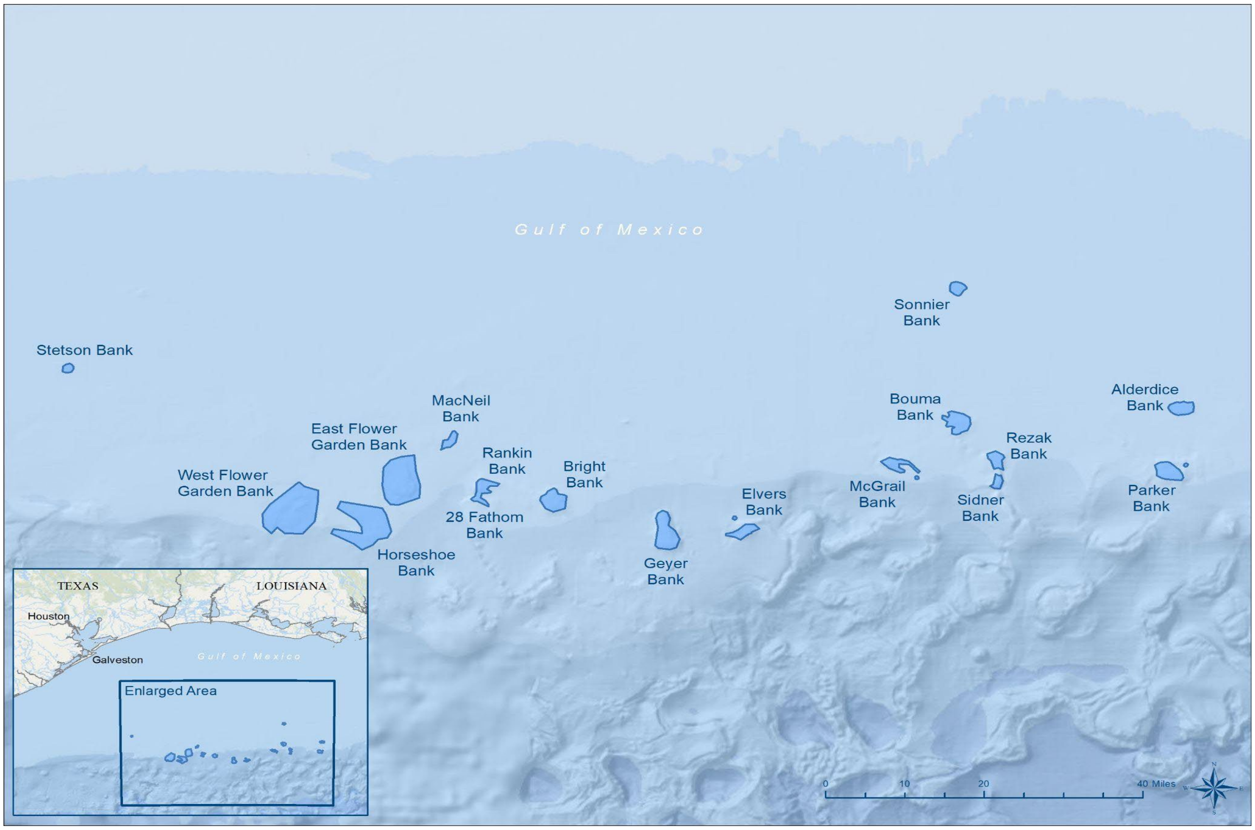

Figure 1.1 Location and spatial extent of FGBNMS in the nwGOM (Image: NOAA).

1.2 Habitat Characteristics

The characteristic salt domes of FGBNMS began to form about 190 million years ago, when the Gulf of Mexico (GOM) sea level was shallower and high temperatures resulted in evaporative deposition of salt on the seafloor (Bright et al., 1985). Over time, riverine allochthonous material (mud, sand, and slit) deposited over the salts. Once pressures from the overlying sediments became great enough, the salt layers pushed upward, forming the banks. During this process, faults and cracks are frequently formed in the overlying and surrounding rock, trapping oil and gas. Salt deposits vary in depth from 1 to >3000 m below the sea floor sediments. Shallow salt deposits may result in seepage of hypersaline waters (>200) into the water and formation of brine seep ponds; several of these underwater brine ponds are documented in FGBNMS (Bright et al., 1985; Boland et al., 1983).

The sanctuary consists of shallow-water (<50 m) high and low relief tropical coral reef communities and deeper mesophotic (50–221 m) non-reef building algal nodule, coralline algae reef, deep reef, and soft bottom habitats and their associated communities (ONMS, 2020). The shallow waters provide habitat for many species of algae, invertebrates, fishes, and other marine organisms. Notably, stony corals such as brain coral species (*Pseudodiploria strigosa* and *Colpophyllia natans*) and several species of threatened *Orbicella* sp. corals and sponges provide substrate for other organisms within the shallower depths of the sanctuary. These corals have shown remarkable resiliency, maintaining 40–70% live coral cover, which is higher than most reefs in the Caribbean region (Moretzsohn et al., 2012; Johnston et al., 2019). FGBNMS may provide a refuge for Caribbean corals and a source of corals in the future, when other reef systems have been severely damaged (Moretzsohn et al., 2012). Snapper, grouper, wrasse, parrotfish, and jack species, and threatened manta rays (*Manta birostris*) are known to inhabit these areas and provide economic and ecological benefits to the region.

The mesophotic habitats of FGBNMS are less accessible and lesser known than the shallow areas of the sanctuary. On the deeper edges of coral reef zones (40–50m), mesophotic coral ecosystems consist of deeper communities of the shallow habitat forming corals. These ecosystems connect shallower coral reefs with deep-water coral assemblages and provide habitat for a variety of species. Below the coral reefs and mesophotic coral ecosystems are areas dominated by crustose forms of algae (coralline algae or CCA). Coralline algae contains a calcified structure, creating biogenic substrate on which coral larvae can settle and is inhabited by sponges, crinoids, fishes, and a variety of other marine species. In deeper waters, mesophotic reefs support structurally complex coral forests of black corals and octocorals, providing habitat for fish, brittle stars, crinoids, basket stars, shrimp, squat lobsters, and other marine organisms.

1.3 Climate of Flower Garden Banks

Although climate classifications are not assigned to offshore regions, based on the Köppen-Geiger climate classification system, FGBNMS resides in a warm, temperate, humid zone with hot summers (Cfa; Fig. 1.2; Rubel and Kottek, 2010). Atmospheric temperatures recorded at buoy 42035 (LLNR, 1200), located at 29.232^{0}N, 94.413^{0}W at 3.7 m above sea level, accessed from NOAA's National Buoy Data Center (National Weather Service, n.d.) averaged 22.04 ^{0}C (71.6 7^{0}F) and ranged from -6.30–31.81 ^{0}C (20.66–89.26 ^{0}F) in 2021 (Table 1.1). The coldest month was February, which averaged 11.1 ^{0}C (52.0^{0}F), and six months (May–October) had average temperatures above 22 ^{0}C (71.6 ^{0}F; Table 1.1; National Weather Service, n.d.).

Sea surface temperature (SST) at FGBNMS exhibits mild seasonality, averaging 25.1 ^{0}C (77.18 ^{0}F; Fig. 1.2) with a range of 17.9–31.0 ^{0}C (64.2–87.8 ^{0}F) between 1985 and 2001 (from SeaBird and hobos LTM data for reefs collected by the FGBNMS, along with regional data from NOAA ERDAPP data portal CoastWatch CoralTemp V3.1 from NOAA, National Environmental Satellite Data Information Service, STAR Coral Reef Watch Program for expanded areas). February had the lowest mean SST (20.6 ^{0}C or 69.1 ^{0}F), whereas August had the highest (29.9 ^{0}C or 85.8 ^{0}F; Table 1.1), and distinct seasonality was observed in water samples (Fig. 1.3). Most of the sanctuary resides within the upper 221 m of the ocean and may be influenced by diurnal and seasonal temperature variations, currents, and storm events. These averages should be considered with the caveat that mean SST at some of the banks may not be representative of temperatures at depth or within all 17 banks which extend 322 km (200 mi) of longitude.

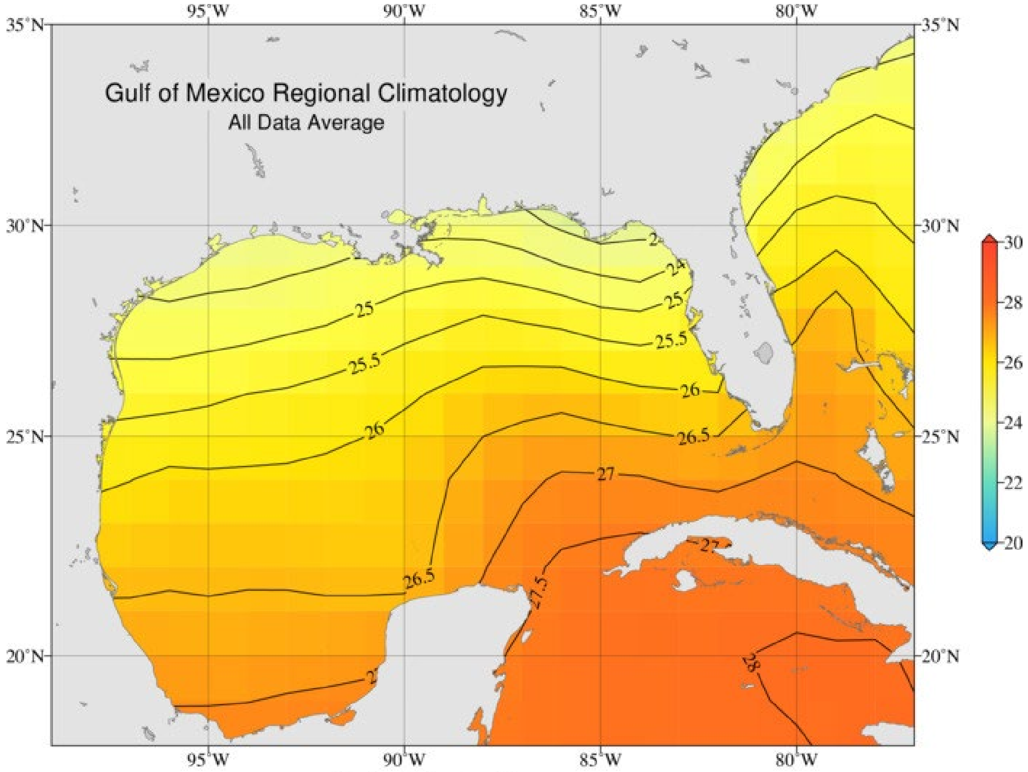

Figure 1.2 Annual average mean SST (ºC) at the surface (one-degree grid) for the GOM from 2005–2017 (Image: Seidov et al., 2020).

Table 1.1 Range and mean temperatures (°C) for average data from FGBNMS between 1985 and 2001 for SST and for 2021 for air temperature (Seidov et al., 2020).

Month	SST Range	SST Mean	Air Temp. Range	Air Temp. Mean
Jan	18.5 – 23.2	21.2	4.0 – 18.0	13.1
Feb	17.9 – 22.3	20.6	-6.3 – 19.0	11.1
Mar	17.9 – 22.8	21.0	10.1 – 22.6	17.1
Apr	19.5 – 24.5	22.4	12.2 – 25.4	20.4
May	23.4 – 26.4	25.3	19.0 – 27.1	24.2
Jun	26.4 – 29.4	28.2	22.5 – 31.1	28.1
Jul	28.3 – 30.6	29.5	23.2 – 30.2	28.7
Aug	28.7 – 31.0	29.9	23.3 – 31.8	29.4
Sep	27.6 – 30.3	29.1	22.3 – 30.7	27.4
Oct	25.6 – 28.8	27.2	18.2 – 28.0	25.1
Nov	22.7 – 26.3	24.8	11.1 – 23.3	19.0
Dec	20.9 – 24.8	22.8	9.2 – 22.5	19.1
Annual	17.9 – 31.0	25.1	-6.3 – 31.8	22.0

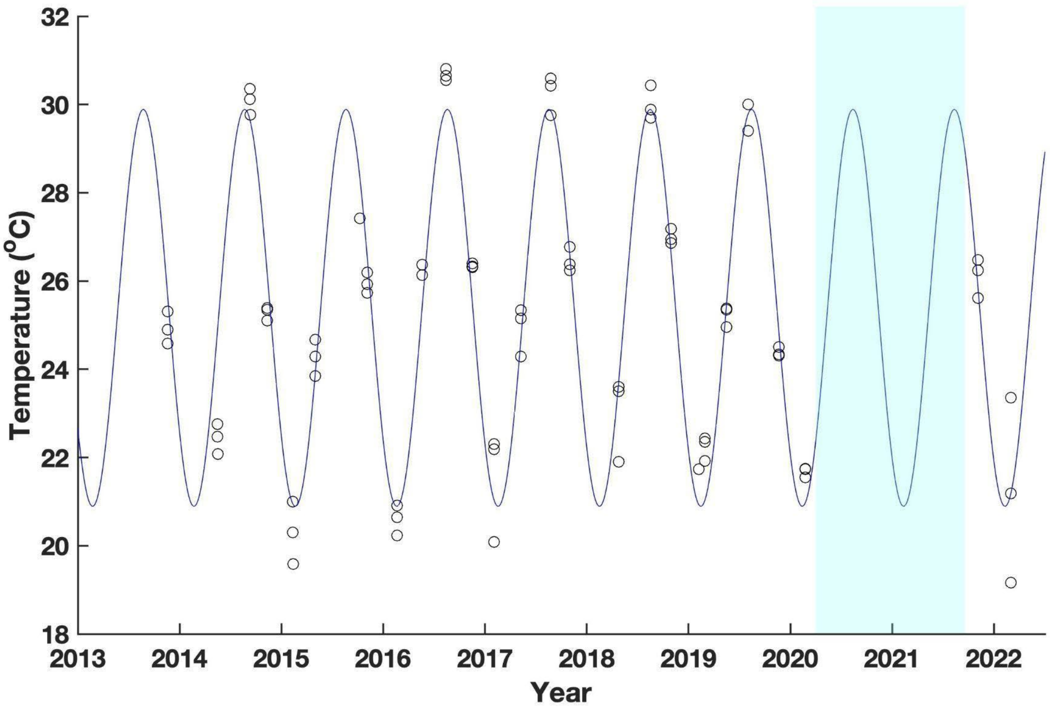

Figure 1.3 Seasonal SST (ºC) oscillations observed in FGBNMS since 2013. Blue shading represents the period of time where no *in-situ* samples were collected due to restrictions during the COVID-19 pandemic (Image: NOAA).

1.3.1 Environmental Observations

NOAA has ongoing cruises to assess environmental conditions at FGBNMS and elsewhere, with the aim of assessing current climate changes and providing sanctuary managers information to prepare for future changes. Sanctuary managers are working with NOAA's Ocean Acidification Program and researchers at Texas A&M University and Texas A&M University-Corpus Christi to study ocean acidification (OA) in the sanctuary, including monitoring of key ocean chemistry measurements.

Data on temperature in FGBNMS was collected in situ for long-term monitoring by SeaBird Instruments and Onset HOBO Temperature Loggers and used alongside regional data from NOAA ERDAPP data portal (CoastWatch CoralTemp V3.1 from NOAA, National Environmental Satellite Data Information Service, STAR Coral Reef Watch Program). Forecasts for future temperature were based on the Intergovernmental Panel on Climate Change (IPCC) fifth phase of the Coupled Model Interpolation Project (CMIP5), model averages under Representative Concentration Pathway for 8.5 watts m^{-2} warming across the planet (RCP8.5, a possible climate emissions scenario whereby 8.5 Watts per meter squared will be emitted in 2100 without ever exceeding that value[1]), and predictions from Alexander et al. (2018) and Lawman et al. (2022).

Since 2013, the Ecosystem Science and Modeling research group at Texas A&M University-Corpus Christi's Harte Research Institute (led by Dr. Xinping Hu) has collected discrete water

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[1] See van Vuuren et al. (2011) for more information on the representative concentration pathways.

samples from the surface (1 m), mid-water (10 m), and bottom waters (20 m) at East, West, and Stetson Bank. These samples were collected with Niskin bottles and were analyzed in the laboratory for pH, total alkalinity (TA), and dissolved inorganic carbon (DIC) according to standard protocol for carbonate system analyses (Dickson et al., 2007). Total pH values were adjusted for standard temperature, and saturation state of aragonite (Ω_{Ar}) and partial pressure of carbon dioxide ($p\mathrm{CO}_2$) of seawater were calculated using the program CO2SYS for Excel®.

1.3.2 Past and Present Climate

During the Jurassic period (201–145 mya), extensive salt was deposited on the continental crust in the northern GOM salt basin, part of which is now the region of FGBNMS (Holmes, 2021). At the time, this region was a very shallow sea and subject to evaporation (Holmes, 2021). Fluvial (stream and river) transport provided terrigenous sediments to the area following the salt depositional period as the GOM deepened (Ward, 2017). The subterranean salt domes eventually pushed the overlying sediments upwards, forming mountains, ridges, and troughs (Goedicke, 1955).

Many millions of years after the formation of salt diapirs, FGBNMS was likely colonized by species from coral reefs off Mexico, which were brought to the area via currents. FGBNMS currently lies 16–221 m deep, with historical SSTs in the GOM averaging 22–26 °C (Poore et al., 2009). More recently, average SSTs are rising globally (Fig. 1.4).

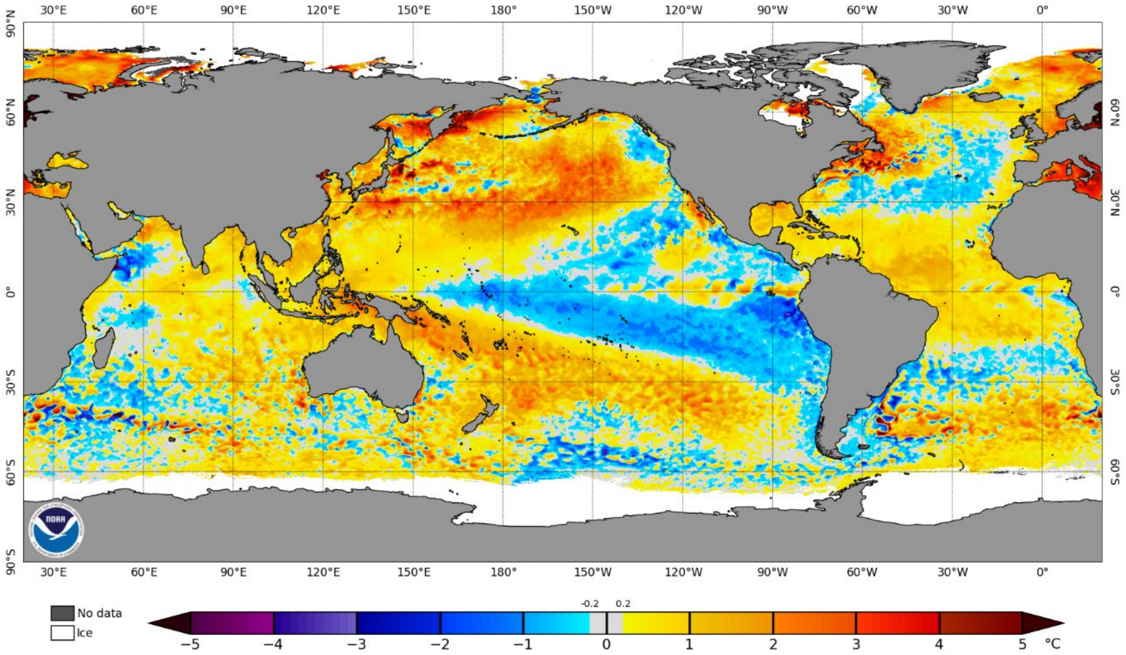


Figure 1.4 Global SST anomalies (ºC), which subtracts the long-term mean (seasonal cycle removed, from 1984) from the current value (Image: Office of Satellite and Product Operations, n.d.).

Air and Water Temperature and Bleaching

SeaBird and hobo long-term monitoring data for reefs (collected by FGBNMS), along with regional data from the NOAA ERDAPP data portal for the sanctuary expansion area was used to estimate water temperature trends in FGBNMS from January of 1985 through March of 2021 (for mean and seasonal temperatures see "Section 1.3: Climate of the Flower Garden Banks"). Data on air temperature collected from a NOAA buoy (National Weather Service, n.d.) supports the SST observations of warm summers and mild winters in FGBNMS.

As global atmospheric temperatures rise, the ocean absorbs some of this heat and seawater temperatures rise (USGCRP, 2018). Surface and coral cap-depth water temperatures in EFGB and WFGB have been increasing since 1990 (Johnston et al., 2018). A modified Mann Kendall statistical test was run in R (R Core Team, 2021) on all banks to determine a trend in SST over time (1985–2021) for average monthly data. Statistically significant ($p<0.05$) positive (increasing) trends for SST were detected for all banks individually and for the entirety of FGBNMS grouped together, with an average increase of 0.35 °C per decade (Fig. 1.5). Significantly increasing seawater temperatures were also observed at coral reef cap depths (23–27 m) at EFGB, WFGB, and Stetson Bank (Fig. 1.6) (DeLong et al., 2023). For the time frame of this assessment, seawater temperatures are anticipated to rise by 1.25–3.5 °C in the GOM by 2072.

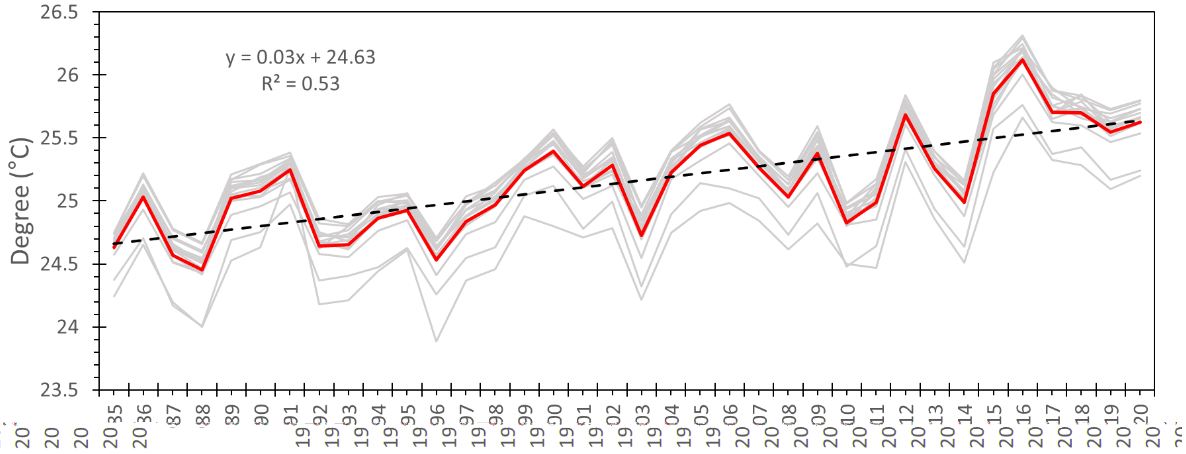
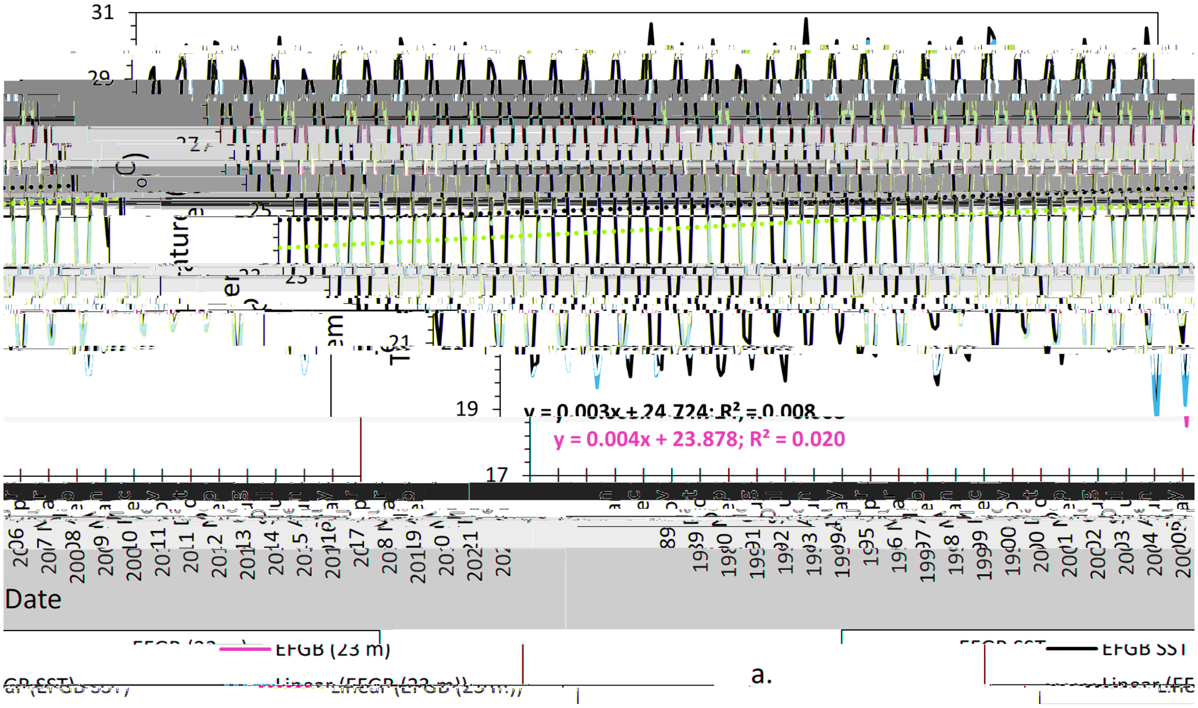
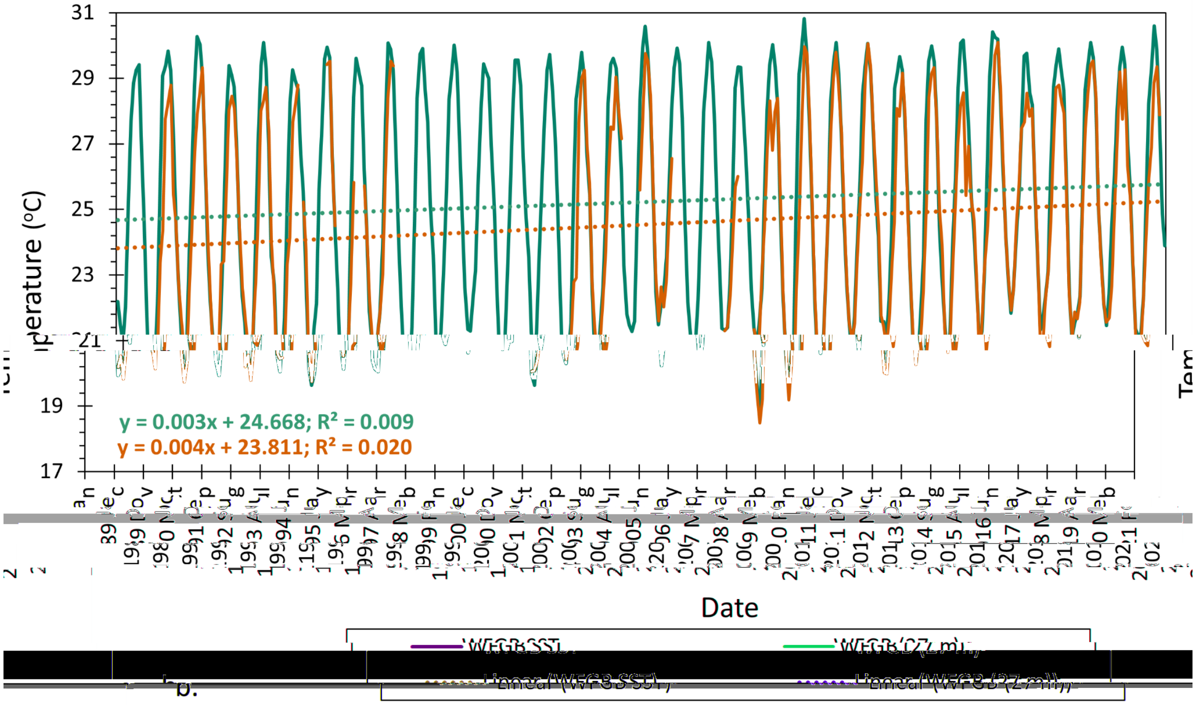


Figure 1.5 Average annual SST (ºC) for individual banks (gray lines), overall annual average SST (red line), and linear trend (dotted black line) for FGBNMS from January 1985–March 2021 (Image: NOAA).


31
29
27
25
23
21
19
17
Temperature (°C)
y = 0.003x + 24.724; R² = 0.008
y = 0.004x + 23.878; R² = 0.020
Date
EFGB SST
EFGB (23 m)
Linear (EFGB SST)
Linear (EFGB (23 m))
a.


31
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17
Temperature (°C)
y = 0.003x + 24.668; R² = 0.009
y = 0.004x + 23.811; R² = 0.020
Date
WFGB SST
WFGB (27 m)
Linear (WFGB SST)
Linear (WFGB (27 m))
b.

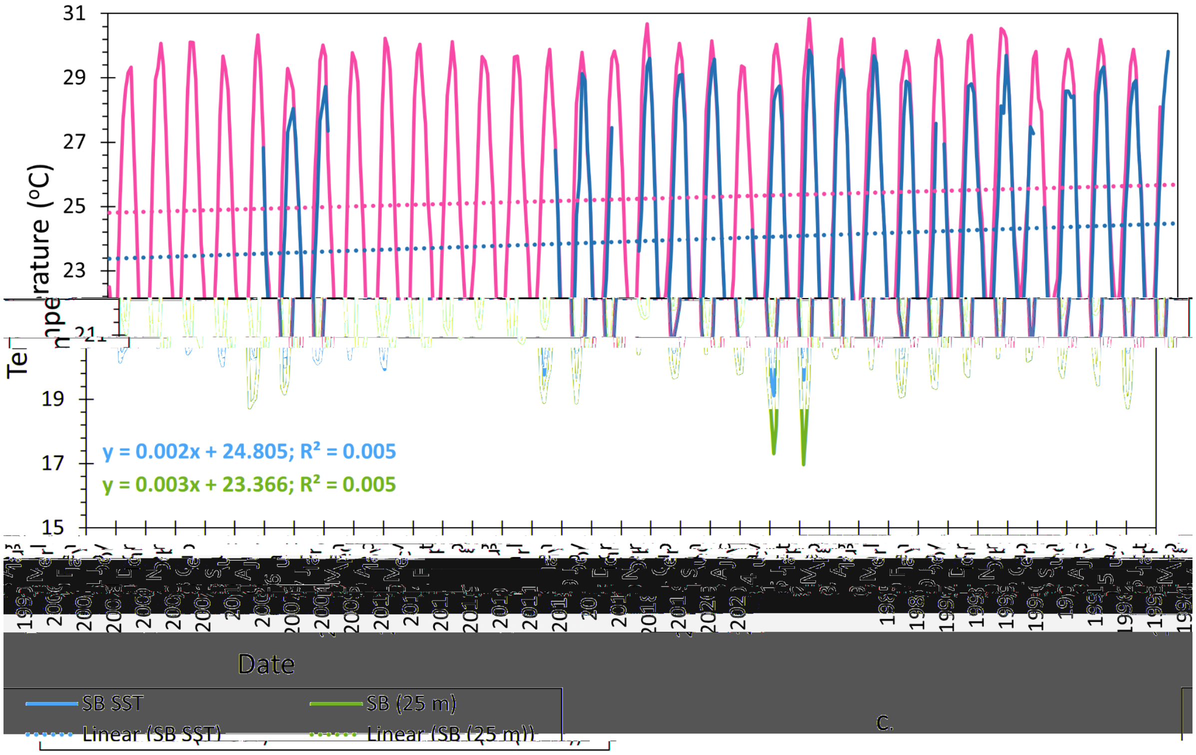


Figure 1.6 Long-term temperature trends (ºC) with linear fit (dotted lines) at surface and at depth at East (a), West (b), and Stetson (c) banks from 1989 to 2021 (Image: NOAA).

EFGB and WFGB are home to tropical reefs that support >50% living coral cover (Johnston et al., 2019). Some corals contain symbiotic algae that provide food and help the coral animal with waste processing. When thermally stressed, these corals can expel the algae, which is known as "bleaching" and can lead to coral death. Multiple incidents of coral bleaching have been observed in FGBNMS since 1990, with moderate and severe bleaching events in 1995, 2005, 2010, and 2016, following known exposure to thermal stress (Fig. 1.7; Johnston et al., 2019). During the most recent severe bleaching event in October 2016, 67% of the coral cover within EFGB long-term monitoring stations and 25% within WFGB monitoring stations exhibited signs of bleaching or paling stress (Johnston et al., 2019). By the end of January 2017, seawater temperatures surrounding the banks had cooled and signs of coral paling and bleaching had subsided with minimal mortality (<1%). Calculated bleaching threshold curves for EFGB and WFGB suggest that more than 50 days above 29.5 ºC would initiate a bleaching year. Climate model projections suggest that frequency of bleaching will continue to increase in the future (Ateweberhan et al., 2013; Heron et al., 2016; von Hooidonk et al., 2016; Hughes et al., 2018), and specific projections for FGBNMS suggest that the reef will be exposed to severe thermal stress (eight-degree heating weeks) every year by 2040 under emissions scenario RCP8.5, which is a high emissions scenario constructed to simulate possible worst-case climate conditions (Maynard, 2018).

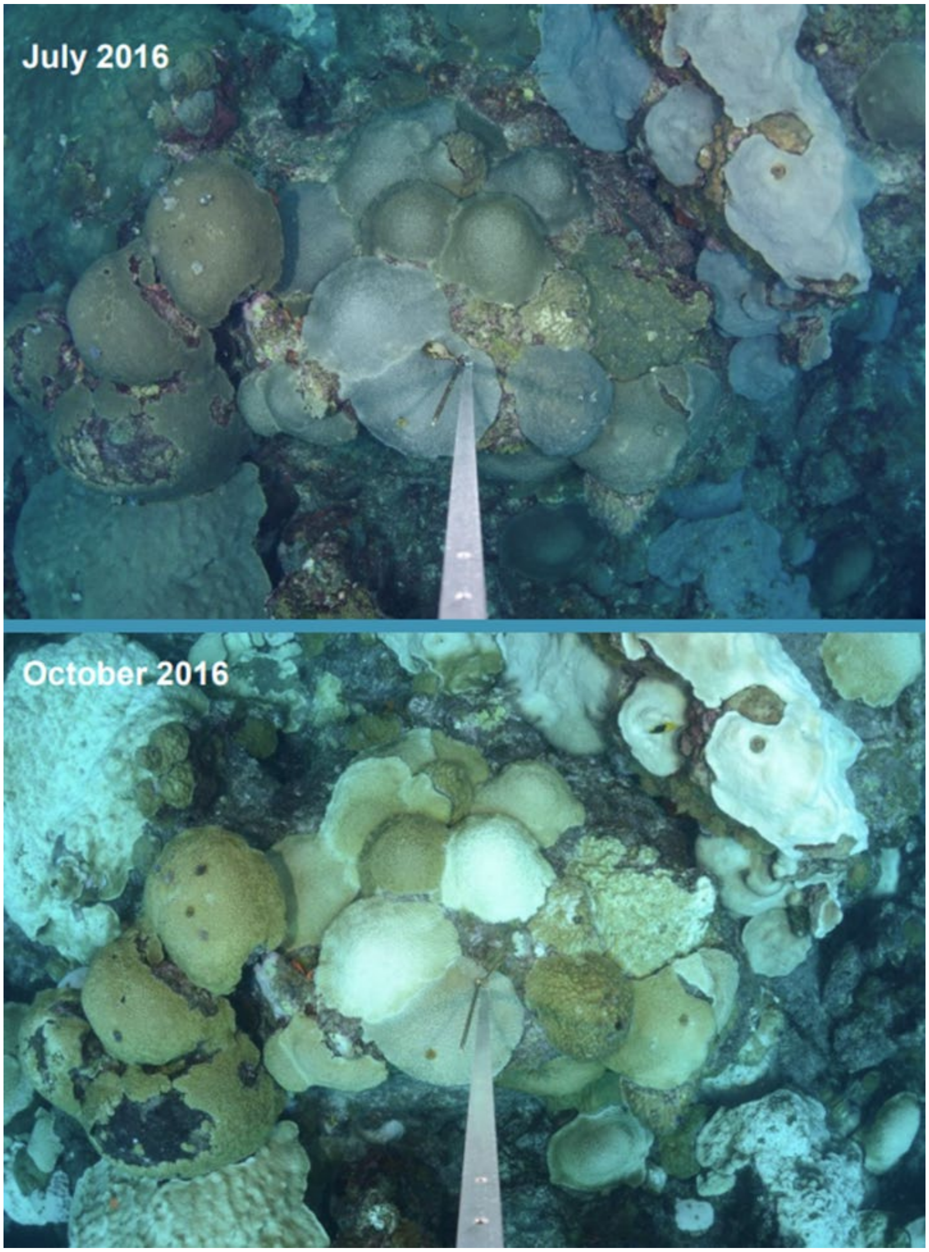
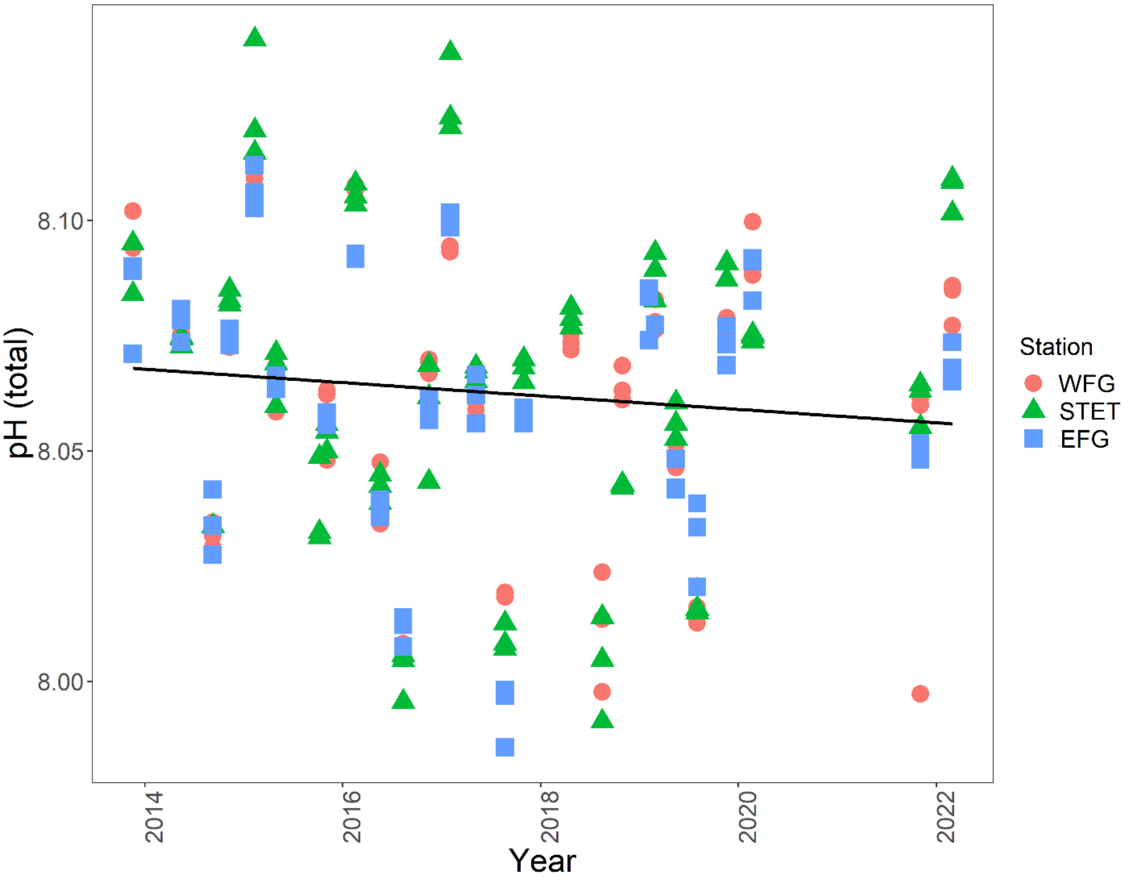


Figure 1.7 In September 2016, following exposure to thermal stress, coral reefs in FGBNMS experienced an extreme bleaching event (Image: Johnston et al., 2019).

Ocean Acidification

The world's oceans help lessen some of the effects of anthropogenic CO_2 emissions on climate change by serving as a net sink for atmospheric CO_2, and have thus far absorbed about 30% of anthropogenic CO_2 (Feely et al., 2010; Sabine and Tanhua, 2010; Humphreys et al., 2018; Le Quéré et al., 2018; Gruber et al., 2019;). Carbon dioxide enters into and interacts with seawater, resulting in lowered pH and alteration to the carbonate system. This process is termed acidification, although ocean water is not becoming technically acidic (Zeebe and Wolf-Gladrow, 2001), and surface ocean pH has dropped by 0.1 units (from 8.21–8.10) since the beginning of the industrial revolution (~1800; Sabine et al., 2004; Doney et al., 2009; Moretzsohn et al., 2012). OA, along with other climate stressors, may severely impact marine organisms, ecosystems, and economies and threatens the ecosystem services (e.g., fisheries, shoreline protection, recreation, tourism, aquaculture, etc.) provided by the ocean (Doney et al., 2020).

The waters of FGBNMS have acidified faster than the open ocean, especially since 2007 (Moretzsohn et al., 2012; Hu et al., 2018). Waters from the Mississippi and Atchafalaya Rivers and throughout the Texas coast input freshwater, which is typically more acidic than saltwater, into the sanctuary on a regular basis (Moretzsohn et al., 2012). Since 2013, mean pH (including surface, bottom, and mid-depth waters) at EFGB, WFGB, and Stetson Banks has been 8.063±0.03 (range 7.98–8.11), and pH values can primarily be explained by temperature alone (Fig. 1.8). This linear relationship between pH and temperature is due to thermodynamic shifts in the carbonate system towards greater CO_2 concentration and lower CO_3^{2-} (carbonate ion) concentration at higher temperatures, which lowers pH (Zeebe and Wolf-Gladrow, 2001). pH was similar between banks and sampling depths, but highest values were recorded in winter and lowest values were recorded in summer (Tables 1.2, 1.3, and 1.4). Waters in the FGBNMS region are experiencing declining pH (by -0.004 per year total pH since November 2013) in subsurface waters (~100–250 m; Hu et al., 2018).



a.

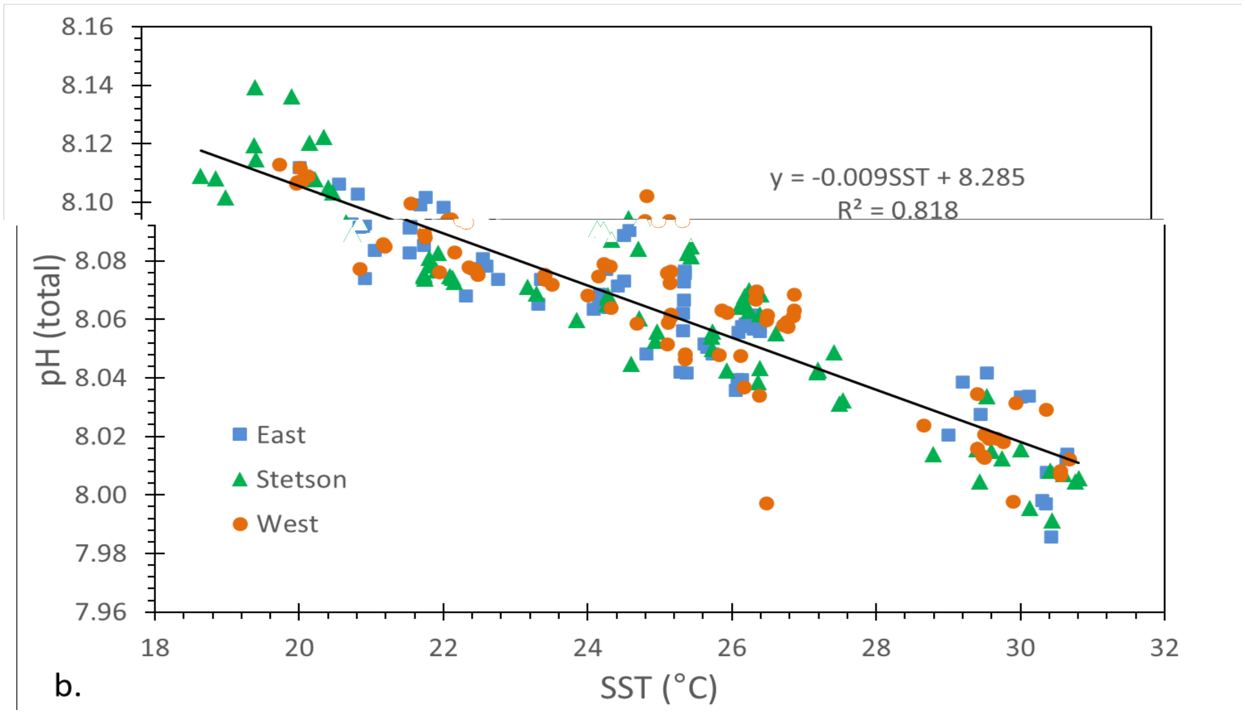


Figure 1.8 Total surface, middle, and bottom-depth pH values from East (EFG), Stetson (STET), and West (WFG) banks of FGBNMS since 2013. Linear fit of total data is shown by the black line (a.). pH versus temperature (ºC) for all data (surface, middle, and bottom-depths) collected at East, West, and Stetson banks of FGBNMS since 2013 (b.) (Image: NOAA).

Table 1.2 Mean values for all years since 2013 for carbonate parameters by season and sampling depth for East Flower Garden Bank (n=64) (Source: NOAA).

	pH	**Ω_{Ar}**	***p*CO₂ (µatm)**	**DIC (µmol kg^{-1})**	**TA (µmol kg^{-1})**	**Salinity**
Spring	8.08	3.58	375.4	2071	2392	36.07
Summer	8.01	3.91	452.0	2024	2344	33.92
Fall	8.07	3.85	389.9	2054	2391	36.20
Winter	8.10	3.59	353.7	2089	2403	36.40
Surface	8.06	3.74	390.8	2061	2385	35.77
Middle	8.06	3.71	392.5	2061	2386	35.81
Bottom	8.07	3.75	386.7	2062	2390	36.03
Overall Mean	8.06	3.73	390.0	2061	2387	35.87

Table 1.3 Mean values for all years since 2013 for carbonate parameters by season and sampling depth for West Flower Garden Bank (n=72) (Source: NOAA).

	pH	**Ω_{Ar}**	***p*CO₂ (µatm)**	**DIC (µmol kg^{-1})**	**TA (µmol kg^{-1})**	**Salinity**
Spring	8.07	3.57	376.0	2076	2398	36.15
Summer	8.01	3.95	458.0	2056	2393	35.79
Fall	8.06	3.88	389.9	2058	2398	36.35
Winter	8.09	3.54	366.4	2088	2404	36.39
Surface	8.06	3.75	395.8	2069	2400	36.09
Middle	8.06	3.75	393.7	2067	2397	36.19
Bottom	8.06	3.76	389.0	2067	2400	36.30
Overall Mean	8.06	3.75	392.8	2068	2398	36.20

Table 1.4 Mean values for all years since 2013 for carbonate parameters by season and sampling depth for Stetson Bank (n=73) (Source: NOAA).

	pH	**Ω_{Ar}**	**pCO$_2$ (µatm)**	**DIC (µmol kg^{-1})**	**TA (µmol kg^{-1})**	**Salinity**
Spring	8.08	3.50	376.2	2081	2396	35.89
Summer	8.02	3.93	450.3	2048	2379	34.99
Fall	8.06	3.86	388.7	2056	2396	36.11
Winter	8.12	3.50	338.4	2096	2406	36.13
Surface	8.06	3.69	390.6	2066	2392	35.73
Middle	8.06	3.72	393.1	2068	2394	35.83
Bottom	8.06	3.72	390.1	2071	2397	36.00
Overall Mean	8.06	3.71	391.3	2068	2395	35.86

Aragonite saturation is commonly used to track OA because it is a measure of the ratio of carbonate ion (in the form of aragonite, the building block of coral skeletons) concentration and calcium ion concentration and the stoichiometric solubility constant, which determines the favorability of waters towards aragonite precipitation or dissolution (Zeebe and Wolf-Gladrow, 2001). Aragonite precipitation is increasingly facilitated as Ω_{Ar} increases above one, and coral reefs are restricted to regions in which Ω_{Ar} is greater than ~3.3 (Chan et al., 2013) In general, coral calcification rate is positively correlated to Ω_{Ar} (Chan et al., 2013). Currently, most tropical, subtropical, and temperate oceanic regions have average Ω_{Ar} above three, but polar and deeper waters may fall below this range and seasonal and regional variability may render some reef areas vulnerable to low Ω_{Ar} (Hoegh-Guldberg et al., 2007). Ω_{Ar} at FGBNMS had a mean of 3.7±0.2 (range 3.4–4.1) since 2013 (Fig. 1.9). Ω_{Ar} was slightly higher in summer and fall than other seasons but displayed little variation between sampling depth and banks (Tables 1.2, 1.3, and 1.4). Unlike many minerals, aragonite is more soluble at low (rather than high) temperatures, and Ω_{Ar} at FGBNMS appeared to primarily be explained by temperature alone (Fig. 1.9), indicative of oligotrophic (nutrient poor) areas. The natural oligotrophy at FGBNMS allows corals to thrive in deep waters without excess light obstruction by algal blooms in the overlying waters. At high temperatures, there was higher variability in Ω_{Ar} due to high-temperature freshwater input with low calcium ion (Ca^{2+}) concentration (Fig. 1.9), because Ω_{Ar} is controlled by both calcium and carbonate ion concentrations in seawater, as well as a solubility product K_{sp}, which is determined by temperature, pressure, and salinity (Eq. 1; Zeebe and Wolf-Gladrow, 2001).

$$\Omega = \frac{[Ca^{2+}]_{SW} \times [CO_3^{2-}]_{SW}}{K_{sp}^*} \tag{1}$$

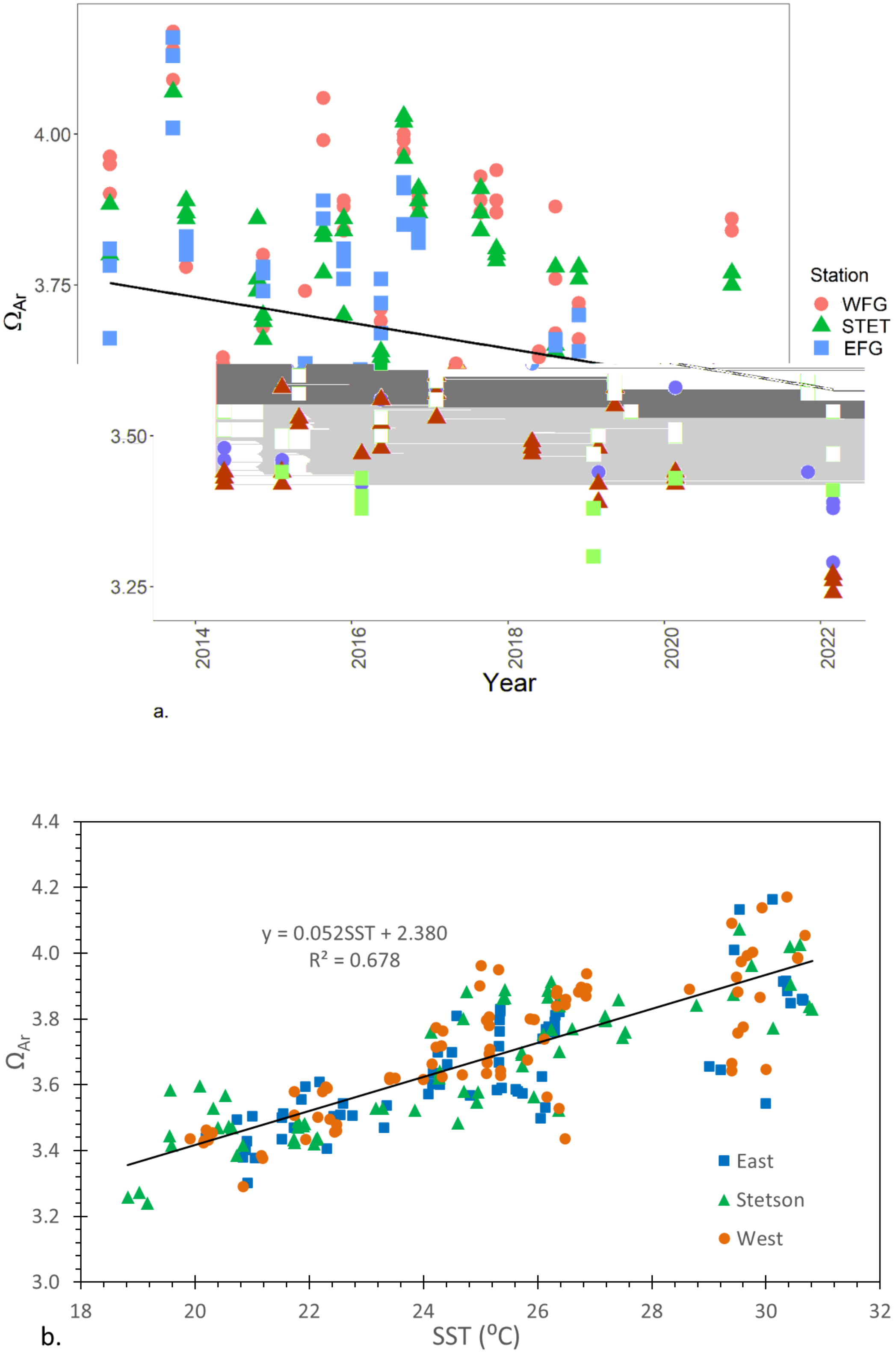
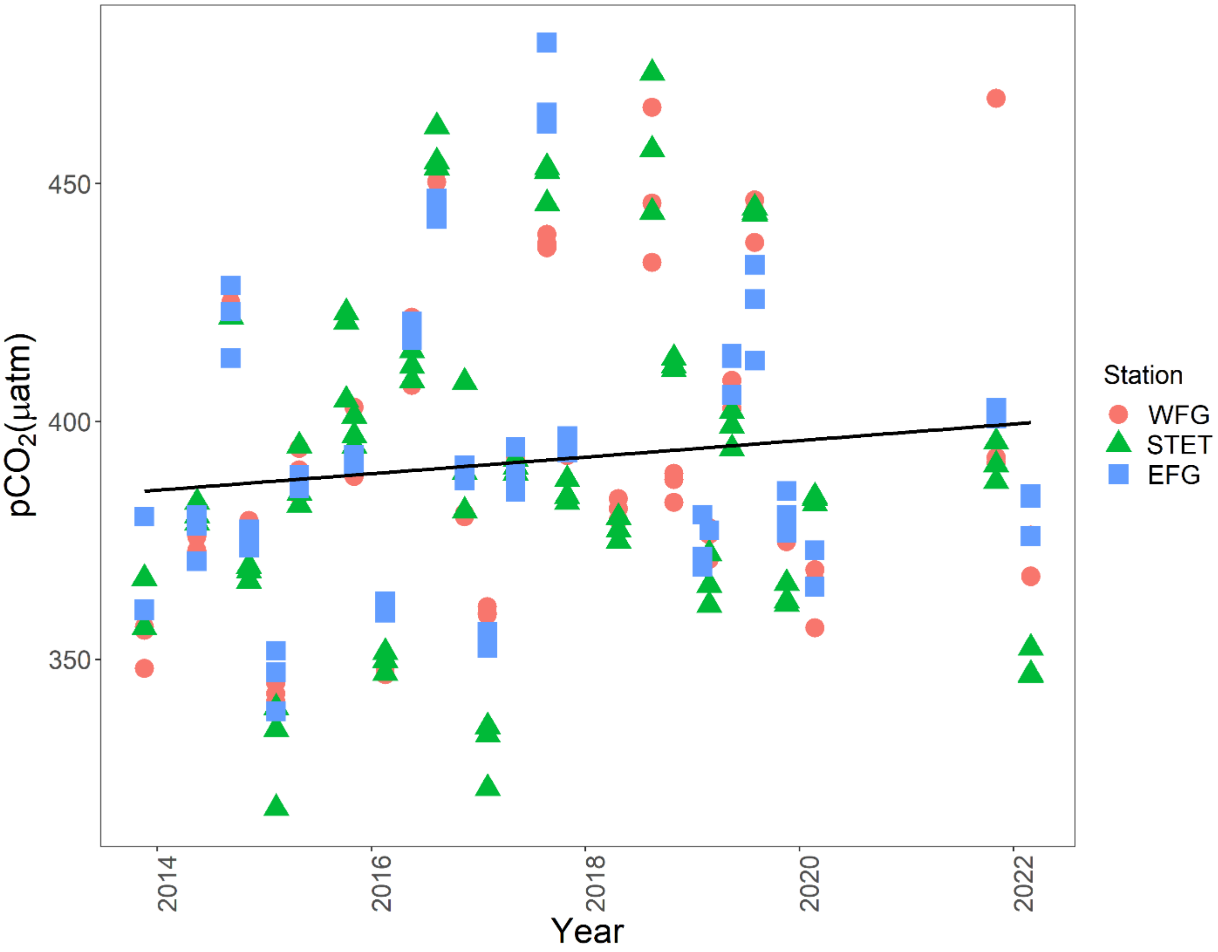


Figure 1.9 Ω_{Ar} values from East (EFG), Stetson (STET), and West (WFG) banks of FGBNMS since 2013, with linear regression fit shown in black (a.). Ω_{Ar} versus temperature for all data collected at East, West, and Stetson banks of FGBNMS since 2013 (b.) (Image: NOAA).

Partial pressure of CO_2 (pCO_2) refers to the fraction of the total gas pressure exerted by CO_2. The mean of pCO2 for seawater at FGBNMS was 391.6 µatm and appeared to follow atmospheric levels closely (Fig. 1.10). Seawater pCO2 was highest in the summer and lowest in the winter for all three banks yet showed little difference between banks and sampling depths (Table 1.2, 1.3, and 1.4). As with pH and ΩAr, pCO2 was primarily thermally regulated in this oligotrophic system (Fig. 1.10). FGBNMS likely has an approximately neutral CO2 flux (the amount of CO2 moving from atmosphere to seawater equals the amount moving from seawater to atmosphere) due to the similarities of pCO2 with atmospheric levels, although further studies are needed to verify this flux estimate. These trends require long time spans to be detectable, and more data are needed for trend detection of carbonate parameters in FGBNMS.



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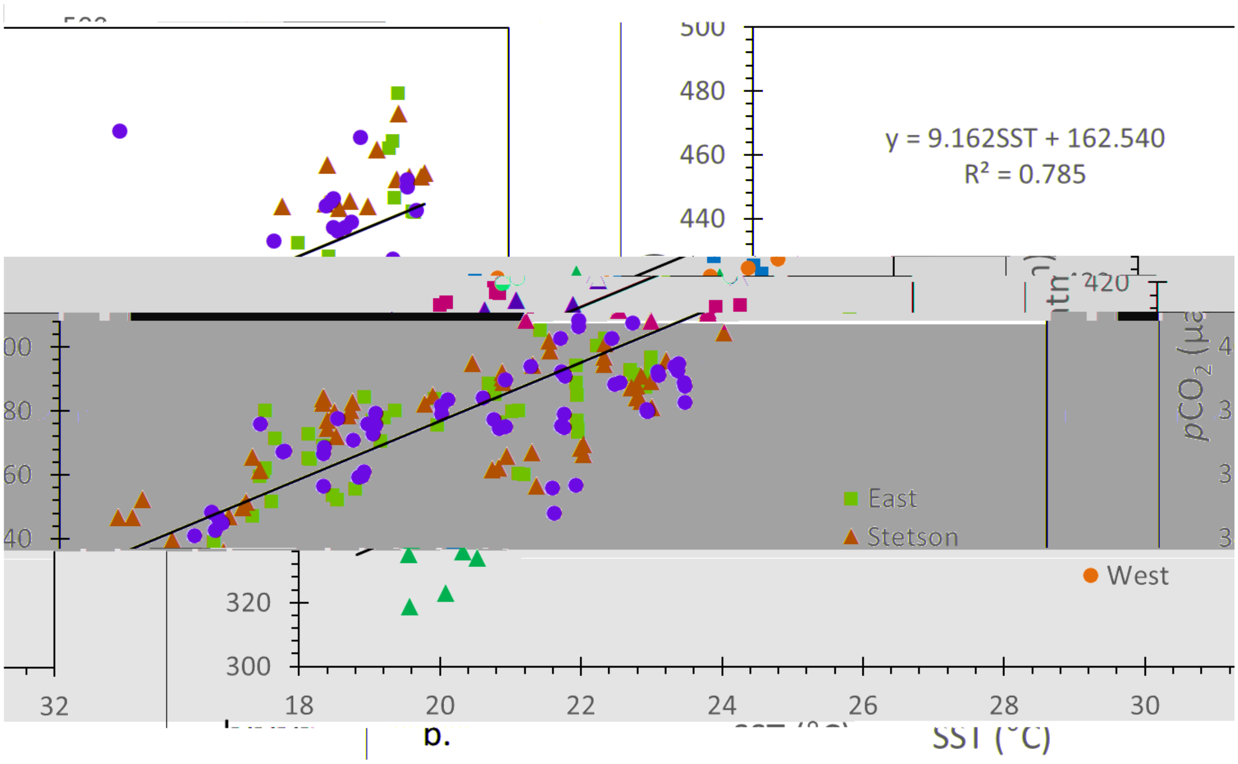


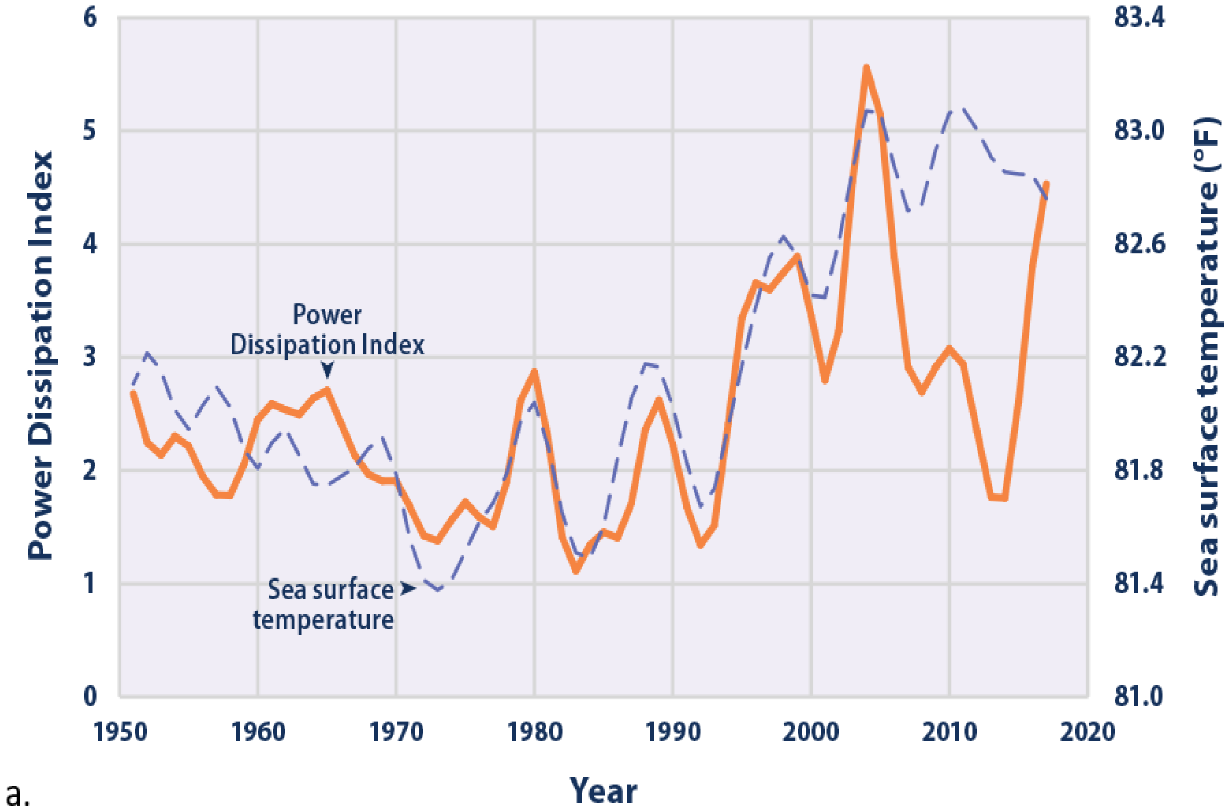
Figure 1.10 Seawater *p*CO2 (µatm) values from East (EFG), Stetson (STET), and West (WFG) banks of FGBNMS since 2013, with a linear regression line shown in black (a.). Seawater *p*CO2 versus temperature for all data collected at East, West, and Stetson Banks since 2013 (b.) (Image: NOAA).

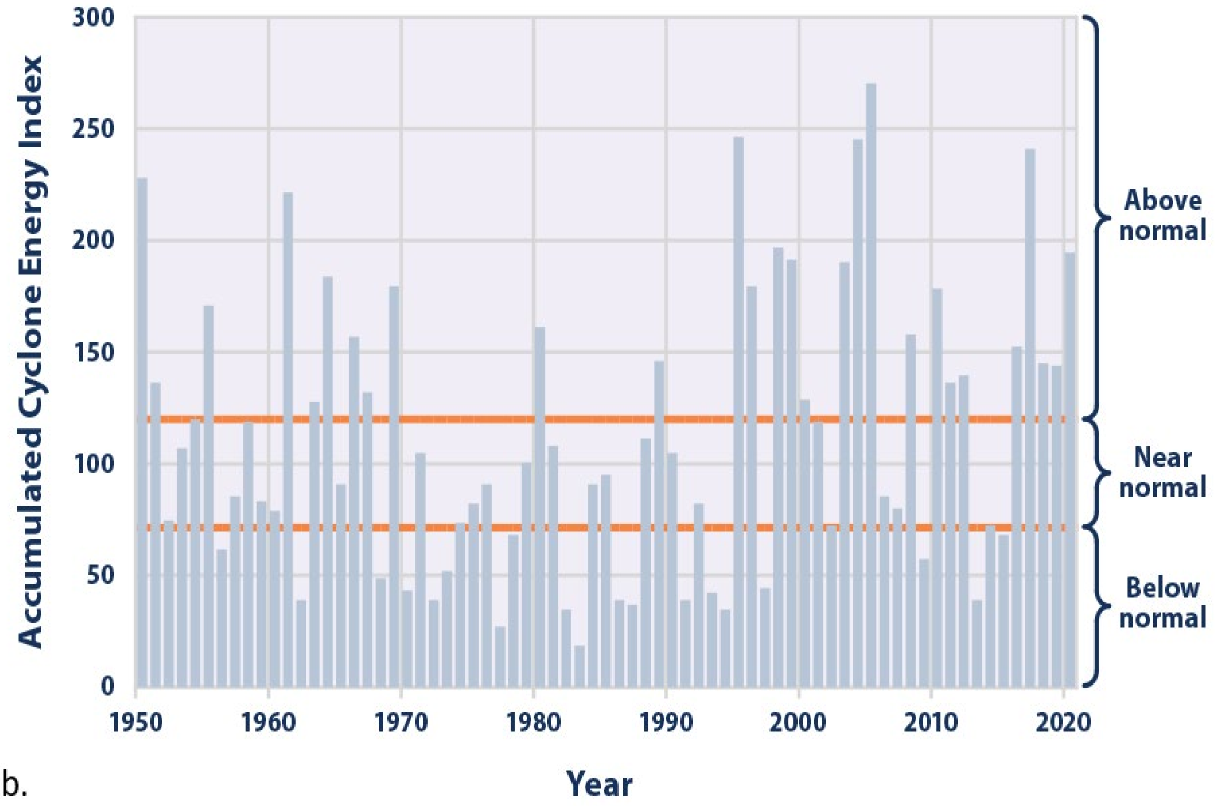
Mean DIC, or dissolved inorganic carbon (sum of CO_2, carbonate, and bicarbonate ions in water) was 2066.6±21.4 µmol kg^{-1} for all sampling locations. DIC did not vary consistently between sampling depths but was slightly lower at EFGB than at WFGB and Stetson Bank (Tables 1.2, 1.3, and 1.4). There was a consistent trend in season, with highest DIC in winter and lowest in summer (Tables 1.2, 1.3, and 1.4). Mean TA (total alkalinity, the buffering capacity of seawater) was 2393.7±21.6 µmol kg^{-1} for all sampling locations. TA did not vary consistently between sampling depths but was slightly lower at EFGB than WFGB and Stetson Bank (Tables 1.2, 1.3, and 1.4). TA was consistently highest in winter and lowest in summer (Tables 1.2, 1.3, and 1.4). Very small increases in salinity were observed at depth, and salinity covaried with TA and DIC measurements in seasonality, with highest salinities in winter and lowest in summer (Tables 1.2, 1.3, and 1.4), suggesting that freshwater from rainfall or river input may have caused the trends instead of OA.

Storm Severity and Frequency and Precipitation

On average, there is a 52% incidence rate of a tropical storm passing within 200 km of FGBNMS annually (Lugo-Fernández and Gravois, 2010; Nuttall et al., 2019). The heaviest rainfall from tropical storms and hurricanes in the GOM is currently 5–7% higher than it was a century ago (Fig. 1. 11; Bruyère et al., 2017; Emanuel, 2017; Knutson et al., 2019; Rendfrey et al., 2021; Knutson et al., 2022). Cyclone intensity has risen noticeably over the past 20 years, and eight of the ten most active years since 1950 have occurred since the mid-1990s (Fig. 1.11; EPA, 2022). Relatively high levels of cyclone activity were also seen during the 1950s and 1960s, but there is uncertainty regarding historic records of cyclone activity due to changes in observation methods over time (EPA, 2022). Complexity in understanding patterns in storm frequency and severity in the GOM are also due to the multiple controlling factors such as SST variations, wind shear, upper tropospheric temperatures, the Loop Current, Atlantic Multidecadal Oscillation, and El Niño-Southern Oscillation (Goldenberg et al., 2001; Rodysill et al., 2020).

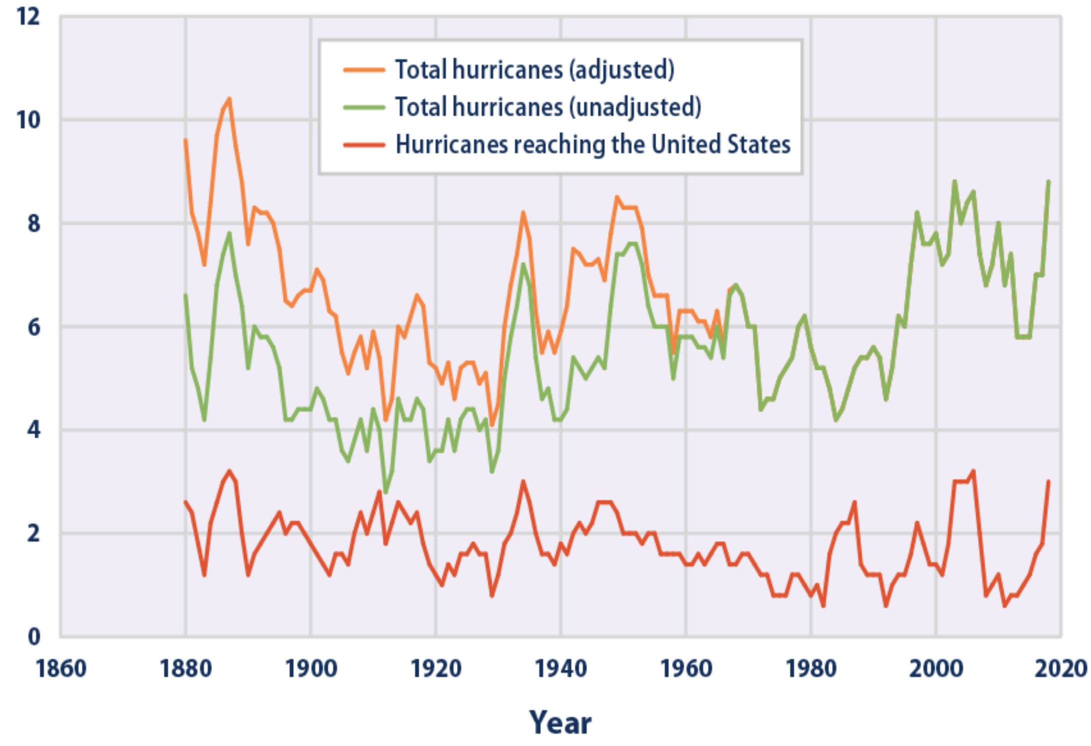
Despite the increasing storm severity, there has been no overall trend in the number of hurricanes in the North Atlantic since 1878 (Fig. 1.12; Bruyère et al., 2017; Rendfrey et al., 2021; Knutson et al., 2022). Extreme rainfall events and river discharge are increasing with runoff in the northeastern GOM region in association with intensifying precipitation, reduced lag times, and increasing flood frequency (Dykstra and Dzwonkowski, 2021). The watershed feeding into the FGBNMS region of the GOM is large, with two-thirds of the continental U.S., all of eastern Mexico, and part of Canada draining into the Mississippi River Basin and other nearby river systems.





b.

Figure 1.11 Power dissipation index for the North Atlantic region relative to SST from 1949–2019 (ºF; a; Image: Emanuel, 2021), and accumulated cyclone energy index for the North Atlantic region from 1950–2020 (b.; Image: Atlantic Oceanographic and Meteorological Laboratory, 2021).



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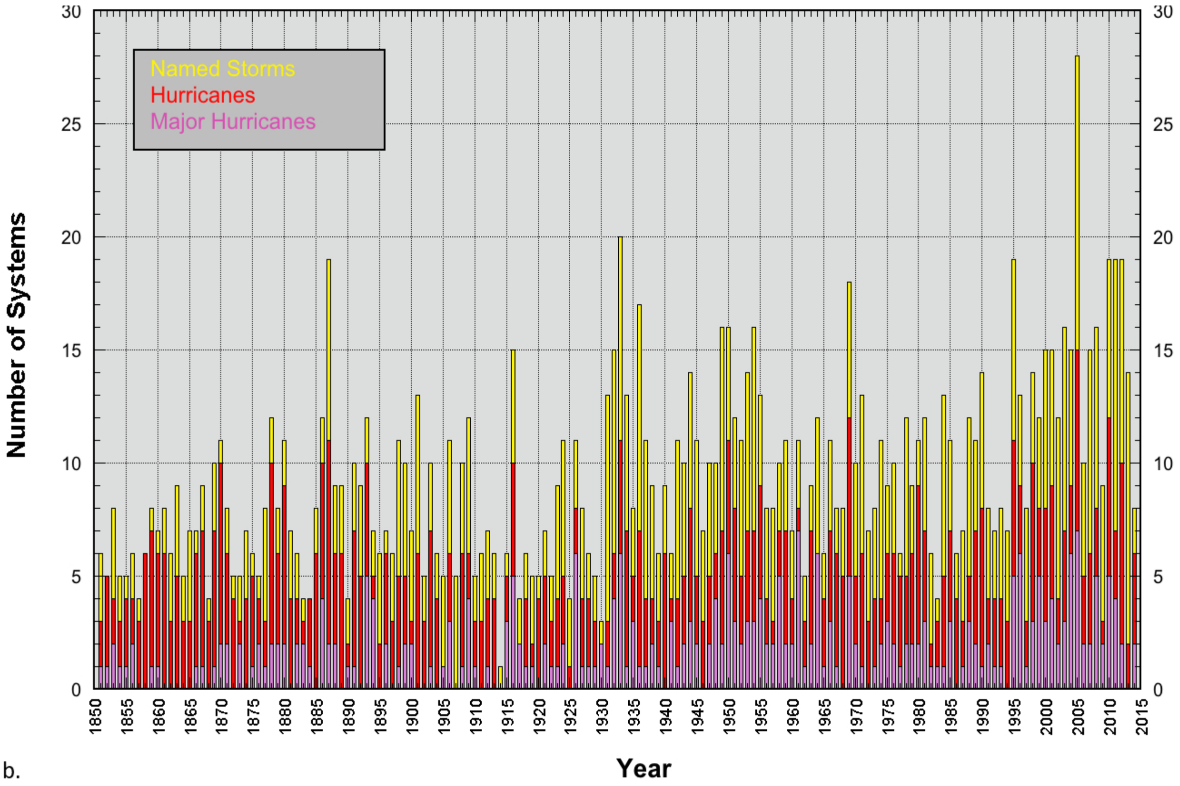

Figure 1.12 Number of adjusted and non-adjusted hurricanes in the North Atlantic and hurricanes reaching the United States (a.; Image: Atlantic Oceanographic and Meteorological Laboratory, 2021; Vecchi and Knutson, 2011), and total storm count (including tropical cyclones) for the Atlantic Basin since 1878 (b.; NHC, 2022).

Ocean Currents

A current of warm water from the Caribbean enters the GOM from the south between the Yucatan Peninsula of Mexico and Cuba. The Loop Current flows northward before making a U-turn and heading south along Florida's west coast and exiting through the Florida Straits, later becoming the Gulf Stream which runs alongside the eastern U.S. coast (Alvera-Azcarate et al., 2009; Sturgis and Evans, 1983; Fig. 1. 13).

Many shallow and wind-driven currents also circulate in the GOM. Some run opposite and landward of the Loop Current (counterclockwise), beginning near the Yucatan peninsula and contributing to Caribbean influences on FGBNMS. Based on present knowledge of current patterns, the coral reefs of FGBNMS most likely originated from the coral reefs off Mexico.

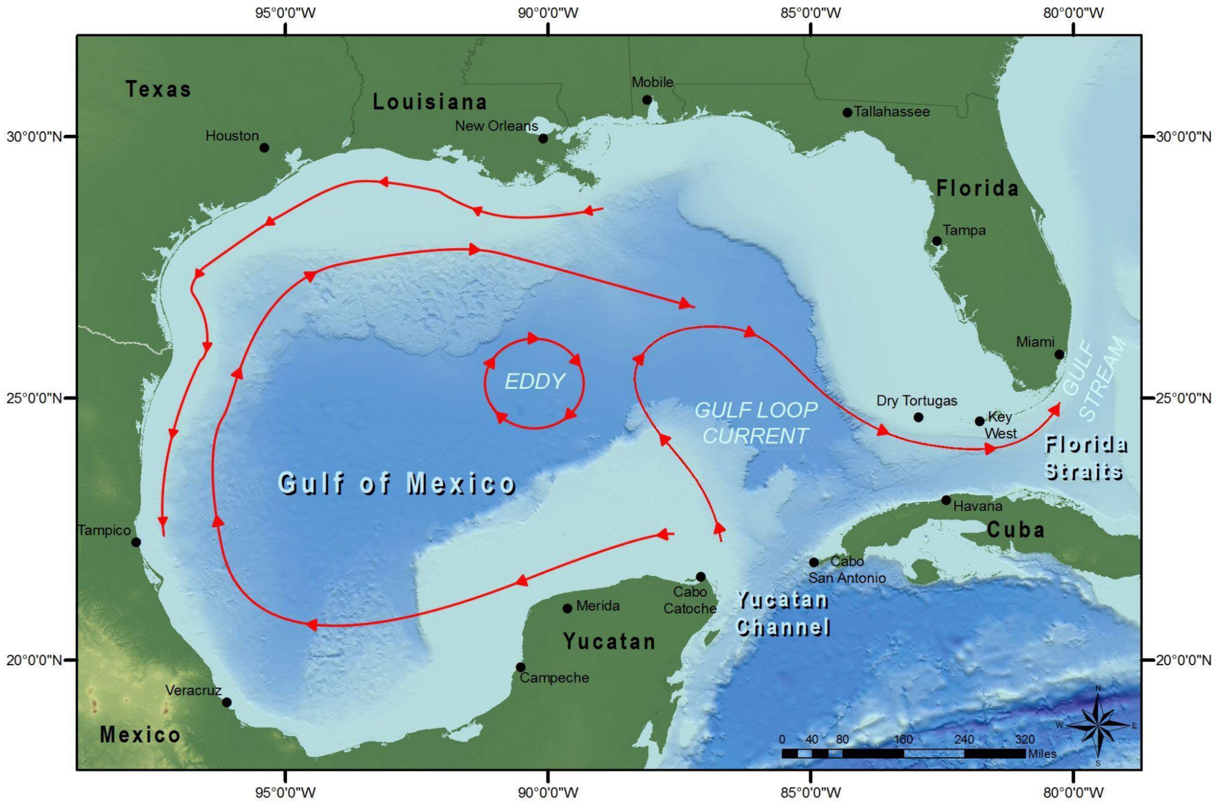

Figure 1.13. Map of the predominant ocean currents in the Gulf of Mexico (Image: NOAA).

1.3.3 Future Climate Projections

Sea Surface Temperature and Bleaching

By 2100, some climate projections predict that the yearly average water temperature in the GOM will be higher than the warmest year currently on record (Alexander et al., 2018). In the GOM, SST is projected to increase by 2.2 to 2.8°C over the next century under RCP8.5 (Lawman et al., 2022), with more frequent and more extreme temperature events (IPCC, 2014; Alexander et al., 2018; Johnston et al., 2018; USGCRP, 2018; National Centers for Environmental Information, 2022). The largest heating is forecasted along the northern GOM coast in some model projections (Lawman et al., 2022). Although there is high confidence in the directionality of this trend (increasing), there is low confidence on the magnitude, which depends on greenhouse gas emissions scenarios (IPCC, 2014; Alexander et al., 2018).

Coral mortality after bleaching is more likely following prolonged exposure to higher seawater temperatures above the species' thermal tolerances (Lawman et al., 2022). This thermal stress will be exacerbated by OA as the increasing acidity of seawater will likely cause corals to struggle to build stony aragonite skeletons, which will inhibit growth and render them vulnerable to storm damage (Kleypas et al., 2006; Doney et al., 2009, 2012; Moretzsohn et al., 2012; Ricke et al., 2013). Increasing average water temperatures and ocean "heat waves" will likely stress corals, resulting in more frequent bleaching at FGBNMS (Maynard, 2018; USGCRP, 2018).

More than 50 days at greater than 29.5 °C would likely cause a bleaching year at EFGB and WFGB (Johnston et al., 2019). Current climate forecasts suggest the coral reefs of FGBNMS will be exposed to severe thermal stress (eight-degree heating weeks) by 2040 under RCP8.5 ("business as usual") or by 2055–2060 under Representative Concentration Pathway Scenario, 4.5 watts m^{-2} Global Warming (RCP4.5) (Van Hooidonk et al., 2014, 2016; Heron et al., 2016; Maynard, 2018). The number of degree heating months, whereby a location's monthly SST exceeds 1 °C of the warmest monthly SST during a climatological base period, is forecasted to increase in the nwGOM by the end of the century regardless of the climate scenario (Lawman et al., 2022). Additionally, corals of higher latitudes may be more susceptible to bleaching than equatorial corals due to lack of regular exposure to thermal stress (Lawman et al., 2022).

Ocean Acidification

Mean global ocean pH is already 0.1 below preindustrial levels and is predicted to decline in oceanic waters 0.035–0.155 pH units over the next 50 years under the two climate scenarios Representative Concentration Pathway Scenario, 2.6 watts m-2 Global Warming (RCP2.6) and RCP8.5 respectively (Fig. 1.14; IPCC, 2014). In the GOM, pH is predicted to decline by approximately 0.2 between 2040 and the end of the century (Lawman et al., 2022). Globally, Ω_{Ar} has decreased by 0.1 per decade in seawater less than 100m in depth (Jiang et al., 2015). In the GOM, Ω_{Ar} is forecast to remain above 3 until 2065–2090, and the northern GOM is projected to experience faster declines in Ω_{Ar} than other regions of the GOM (Lawman et al., 2022). Corals exhibit a 15% decline in calcification (densification) for every 1 unit decrease in Ω_{Ar} ($2< \Omega_{Ar}<4$), which is predicted to occur by the end of the century (Jiang et al., 2015), and most shallow water scleractinian corals are found in $\Omega_{Ar}>3$ conditions (Lawman et al., 2022). As atmospheric CO_2 levels continue to rise, increasing the dissolved CO_2 in seawater, the carbonate system will shift towards greater CO_2 and lesser carbonate ion concentrations (see Eq. 1; Feely et al., 2009). Global atmospheric pCO_2 is rising and may reach up to 560 µatm in the next 50 years (Feely et al., 2009), and surface water pCO_2 in the nwGOM open ocean (including FGBNMS) is increasing at a rate comparable to those measured at long-term ocean time-series stations (Kealoha et al., 2020).

Mean global ocean DIC is projected to increase from the current mean of 2026–2090 µmol kg^{-1} with a doubling of atmospheric CO_2 under the IPCC IS92a emissions scenario (Feely et al., 2009). Mean global ocean TA is stable at 2287 µmol kg^{-1} (Feely et al., 2009). However, carbon cycles are difficult to model, and regional biases and downscaling challenges exist in current models, creating large uncertainty in the forecasts, although there is high confidence in direction of trends (IPCC, 2014).

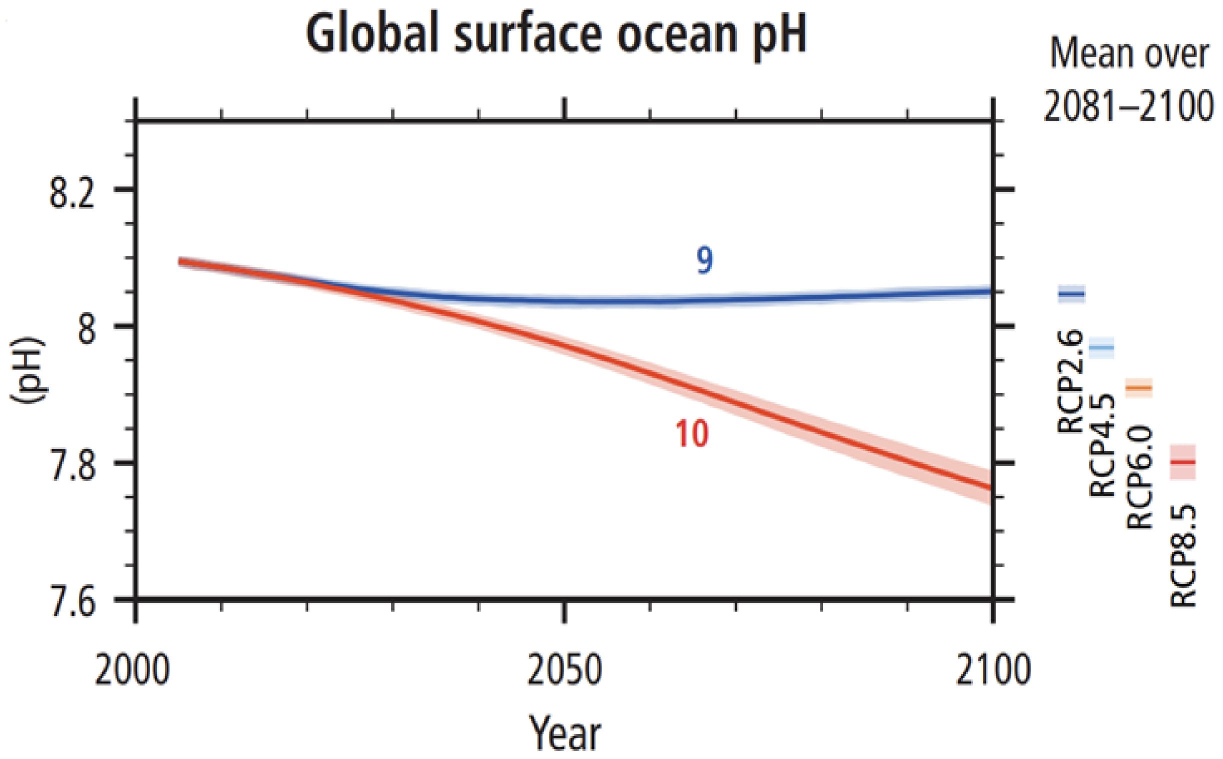

Figure 1.14 Forecast global surface ocean pH and the 5 to 95% range across the distribution of individual models (shaded area) until 2100 under the least (RCP2.6) and most (RCP8.5) extreme emissions scenarios. The number of models used to calculate the multi-model mean is indicated next to each line (Image: IPCC, 2014).

Storm Severity and Frequency and Precipitation

Climate change is altering global weather patterns (USGCRP, 2018). Intense hurricanes and reduced wind shear, accompanied by increased radiative forcing, have been observed, but predictions are difficult to accurately quantify due to the high variability in the variables controlling forecast (Rodysill et al., 2020). The heaviest rainfall from tropical storms and hurricanes is presently 5–7% higher than a century ago, and could increase an additional 30–40% (Moretzsohn et al., 2012; Bruyère et al., 2017). Future storms are also forecast to be more powerful and intensify more rapidly (Moretzsohn et al., 2012; Emanuel, 2017; Knutson et al., 2019) with the GOM experiencing the largest increase in rapidly intensifying hurricanes in the North Atlantic (Benedetto and Trepanier, 2020). These more intense storms could produce waves that scour and move corals, damaging reefs, as was seen during hurricanes Rita (2005) and Ike (2008) (Moretzsohn et al., 2012). Storm frequency is projected to decrease in the GOM region, but is highly dependent on regional variability in winds, currents, atmospheric circulation, and El Niño-Southern Oscillation (ENSO), and demonstrates high inter-annual variability (Bruyère et al., 2017; Knutson et al., 2015; Mann & Emanuel, 2006; Oouchi et al., 2006; Rendfrey et al., 2021; Knutson et al., 2022; Webster, 2005). Reduced water absorption by soil in coastal areas from expansion of impermeable surfaces (such as concrete and pavement) and changing extreme storm patterns (slower hurricanes with heavier precipitation) are increasing the frequency and intensity of floodwater influx into marine environments (Shore et al., 2021). Extreme rainfall events are projected to become more common in the GOM watershed (Christian et al., 2015; Hayhoe et al., 2018; USGCRP, 2018), which will result in higher river discharge reaching the FGBNMS, carrying with it more acidic water with higher nutrient loads (Moretzsohn et al., 2012).

Dissolved Oxygen

Hypoxia is increasing in the nwGOM and has occurred in FGBNMS (Bianchi et al., 2010; Moretzsohn et al., 2012; Johnston et al., 2019; Kealoha et al., 2020). Rising temperatures and increased river input reduce the ability of the water to hold oxygen, add nutrients (primarily from anthropogenic sources) to the water, and increase stratification of the water column, preventing mixing with oxygen-rich surface waters (Moretzsohn et al., 2012; Fennel et al., 2016; USGCRP, 2018). Worldwide, dissolved oxygen (DO) is diminishing and oxygen minimum zones are expanding as temperatures rise and nutrient input from rivers continues to increase (Cai et al., 2011). The interacting influences of seawater temperature, stratification, and biogeochemistry cause high uncertainties in forecasts of future DO, although the directionality of the trend (declining DO) is well-established (Cai et al., 2011).

Sea Level Rise

Between 1901 and 2010, global mean sea level rose by 0.17–0.21 m, and this trend is predicted to continue, with total sea level rise of 0.24–0.30 m by 2046–2065 (IPCC, 2014; Van Hooidonk et al., 2014, 2016; Heron et al., 2016). In FGBNMS, the total rise by the end of the century is forecast at 0.8 m (IPCC, 2014; Van Hooidonk et al., 2014, 2016; Heron et al., 2016).

Invasive and Non-Native Species

Invasive species have entered FGBNMS and are known to cause changes that negatively alter ecosystems (Moretzsohn et al., 2012; Salvaterra et al., 2013). Climate changes can provide advantages to invasive species and allow for range-expansion and invasion of new areas (Stachowicz et al., 2002; Byers et al., 2013; Crickenberger & Moran, 2013; Whitfield et al., 2014; Grieve et al., 2016). Lionfish (*Pterois volitans* and *P. miles*) have been documented in both shallow and mesophotic habitat at FGBNMS since 2011, and subsequently are now established (Nuttall et al., 2014; Johnston et al., 2019).Lionfish have the potential to cause ecological harm by preying on native species and competing with native predators, such as grouper and snapper (Moretzsohn et al., 2012; Whitfield et al., 2014; Grieve et al., 2016). Lionfish are expected to benefit from increasing seawater temperatures (Moretzsohn et al., 2012). The non-native regal demoiselle (*Neopomacentrus cyanomos*) has been sighted in FGBNMS since 2018 and may outcompete similar small, schooling fish such as brown chromis (*Azurina multilineata*) (Moretzsohn et al., 2012). Orange cup coral (*Tubastraea coccinea*), a non-native, non-reef building coral, has been present in FGBNMS since 2002 and competes for space with native sessile invertebrates (Fenner & Banks, 2004; Moretzsohn et al., 2012). Orange cup coral may also be more resistant to acidification than native corals (Margolin, 2012; Moretzsohn et al., 2012; Precht et al., 2014).

1.4 Potential Climate Impacts

Marine organisms experience stress when environmental conditions extend beyond their optimal ranges (Shein et al., 2019). This stress may manifest as increased mortality, forced migration, lowered fecundity, competition from invasive species, susceptibility to pathogens, behavioral stress, and physical injury (Shein et al., 2019). Mobile species, such as some species of fish, are sometimes able to adapt to changing environmental conditions by extending their ranges or relocating (Mills et al., 2013; Nye et al., 2009). For example, many species in the northern hemisphere are moving northward or deeper to cooler water with rising seawater temperatures (Poloczanska et al., 2013). When forced to move, motile species may also be unable to find suitable habitat and food, may compete with native species, or may alter native food webs (Shein et al., 2019). Relocating is more difficult for sessile species such as corals, which often depend on larval motile phases as well as availability of suitable substrates for settling (Shein et al., 2019). Sessile species are more vulnerable to changes in climate because they cannot quickly alter their distribution and may experience widespread mortality (Hoegh-Guldberg et al., 2007; Sorte et al., 2011; Shein et al., 2019). The rapidity of climate changes often exceeds the abilities of both motile and sessile species to relocate or adapt (Shein et al., 2019)

Prior to the FGBNMS climate vulnerability assessment (CVA) workshop, facilitators and organizers with FGBNMS, ONMS, and other NOAA offices identified the three major climate stressors most likely to impact organisms at FGBNMS within a 50-year time frame: increasing water temperature, OA (with a focus on pH, $p\mathrm{CO}_2$, and Ω_{Ar}), and alterations in storm and precipitation patterns (storm frequency and intensity, and precipitation). Elevated seawater temperatures were followed by a bleaching event at FGBNMS in 2016 (Johnston et al., 2019), and rising seawater temperatures have also been associated with increases in and benefits to non-native and invasive species (e.g., cup coral and lionfish; Stachowicz et al., 2002; Crickenberger & Moran, 2013; Whitfield et al., 2014; Grieve et al., 2016; Bruyère et al., 2017) as well as larger and longer-lasting harmful algal blooms, which can cause illness or mortality in fish, birds, marine mammals, and people (Jöhnk et al., 2008; Moore et al., 2008; Moretzsohn et al., 2012; Gobler et al., 2017). Higher water temperatures also increase water column stratification and lead to low DO in FGBNMS (Moretzsohn et al., 2012). With rising seawater temperatures, temperate species like Spanish mackerel could become less abundant in FGBNMS (Morley et al., 2018) while tropical species such as elkhorn coral could become more common (Zimmer et al., 2006; Moretzsohn et al., 2012; Precht et al., 2014). This tropicalization could alter the ecosystem functioning of the sanctuary (Moretzsohn et al., 2012; Vergés et al., 2014). Corals, which are the foundational species that support much of the life at FGBNMS, are particularly vulnerable to rising temperatures and may bleach annually by 2040 (Moretzsohn et al., 2012; Van Hooidonk et al., 2016; Maynard, 2018).

Respiration-induced acidification has been observed near FGBNMS (McCutcheon et al., 2021), and declining pH and Ω_{Ar} (due to anthropogenic CO_2 and elevated respiration) have been observed in subsurface waters of FGBNMS (Hu et al., 2018). Slowed mesophotic coral growth, reduced fish larval growth, survival, and recruitment, and reduced growth and survival of crustose coralline algae (CCA) may all occur in FGBNMS due to ocean acidification (Moretzsohn et al., 2012). Loss of shallow or mesophotic corals or CCA would cause severe degradation of the ecosystems in FGBNMS.

Hurricane Harvey, which made landfall along the southern and central Texas coast in 2017, was one of the most severe hurricanes to hit the U.S. in recent history (Du et al., 2019). Following this storm, low salinity surface water (15 PSU) was observed near FGBNMS (Du et al., 2019). Low salinities lasting longer than five days have the potential to cause coral mortality (Du et al., 2019; Jokiel et al., 1993), and in 2016 and 2017, following severe storm events, corals, sponges, and other benthic invertebrates at EFGB experienced mortality or sub-lethal stress (Shore et al., 2021). In 2005, runoff from Hurricane Rita, combined with a bleaching event, caused a community alteration at Stetson Bank from fire coral and sponge-domination to algae-domination (Moretzsohn et al., 2012; DeBose et al., 2013). Higher acidity and nutrient loads of river water can increase coral disease, cause bleaching, fuel algae blooms, and produce low-oxygen conditions in FGBNMS, and storms can damage coral reefs by scouring and moving coral (Moretzsohn et al., 2012).

Chapter 2: Climate Vulnerability Assessments: Methods and Workshop Activities

In July 2022, FGBNMS hosted a virtual climate vulnerability assessment (CVA) workshop (see Appendix A for workshop agenda). During the workshop, an invited group of topical experts (see Appendix B) were asked to summarize the exposure and response of two habitat types and 23 species or groups of organisms (Table 2.1) to projected changes in environmental conditions at FGBNMS, and to standardize those summaries using the North American Marine Protected Area Rapid Vulnerability Assessment Tool (RVA), developed by the Commission for Environmental Cooperation (CEC, 2017; see Appendix C). The species and habitats assessed were initially identified by FGBNMS staff.

Table 2.1 List of species or groups of organisms selected for CVA at FGBNMS.

Species	Common Name	Niche Group
Dermatolepis inermis (Valenciennes in Cuvier and Valenciennes, 1833)	Marbled grouper	Fish
Families Serranidae and Lutjanidae	Grouper and snapper complex	Fish
Pterois volitans (Linnaeus, 1758) and *Pterois miles* (Bennett, 1828)	Lionfish	Fish
Caranx latus (Agassiz in Spix and Agassiz, 1831)	Horse-eye jack	Fish
Pronotogrammus martinicensis (Guichenot, 1868)	Roughtongue bass	Fish
Azurina multilineata (Guichenot, 1853) and *Thalassoma bifasciatum* (Bloch, 1791)	Brown chromis and bluehead	Fish
Sparisoma viride (Bonnaterre, 1788)	Stoplight parrotfish	Fish
Acanthocybium solandri (Cuvier in Cuvier and Valenciennes, 1832)	Wahoo	Fish
Nicella sp. (Gray, 1870)	Octocorals	Mesophotic Invertebrates
Hypnogorgia (Duchassaing and Michelotti, 1864) and *Muricea* (Lamouroux, 1821) sp.	Octocorals	Mesophotic Invertebrates
Antipathes furcata (Gray, 1857)	Black coral	Mesophotic Invertebrates
Corallistes typus	Sponge	Mesophotic Invertebrates
Class Crinoidea (Miller, 1821)	Sea lilies and Feather Stars	Mesophotic Invertebrates
Montastraea cavernosa (Linnaeus, 1767)	Great star coral	Shallow Invertebrates
Porites astreoides (Lamarck, 1816)	Mustard hill coral	Shallow Invertebrates
Diadema antillarum (Philippi, 1845)	Long-spined sea urchin	Shallow Invertebrates
Xestospongia muta	Giant barrel sponge	Shallow Invertebrates
Dictyota (J.V. Lamour) sp.	Brown seaweed algae	Shallow Invertebrates
Orbicella franksi	Boulder star coral	Shallow Invertebrates
Pseudodiploria strigosa	Symmetrical brain coral	Shallow Invertebrates
Family Corallinaceae	Crustose coralline algae	Shallow Invertebrates
Agelas clathrodes	Orange elephant ear sponge	Shallow Invertebrates
Neofibularia nolitangere	Touch-me-not sponge	Shallow Invertebrates

2.1 Reasons for Conducting a CVA

CVAs are used to qualitatively describe and evaluate how climate and non-climate stressors impact a species, habitat, or area's vulnerability to climate change to improve management approaches for long-term success. The CVA provides a tool for managers to make informed decisions based on current and projected conditions, how they will affect resources, and why those resources are vulnerable. The goal of a CVA is to help managers prioritize resources for management actions, develop management strategies to address climate change by specifically targeting the mechanisms identified to be causing the vulnerability, and efficiently allocate resources. Resource managers conduct a CVA when they have an interest in learning how climate change is affecting their site, have some knowledge of the site being evaluated and a list of key resources to be assessed, and an awareness of relevant climate impacts and access to basic climate information to support the understanding.

2.2 CVA Process

A CVA measures how vulnerable a given resource (e.g., species, habitat, etc.) is to the cumulative impacts of climate change and non-climate stressors. It is a function of the consequence a resource experiences if it experiences climate changes, the likelihood the resource would experience those changes, and capacity to adapt to those changes (Fig. 2.1).

Consequence– whether and how a resource or community is likely to be affected by a given change in climate or another environmental factor.

Likelihood– how much change in climate or other environmental factor a resource is likely to experience.

Adaptive Capacity – ability of the resource or community to adapt to the effects or impacts of climate change.

The CVA process uses worksheets with specific questions, including rankings for each resource assessed. CVAs are typically conducted by protected area managers with participation from subject-matter experts. For NOAA's ONMS, each site conducts its own CVA, with help from ONMS staff and invited subject matter experts.

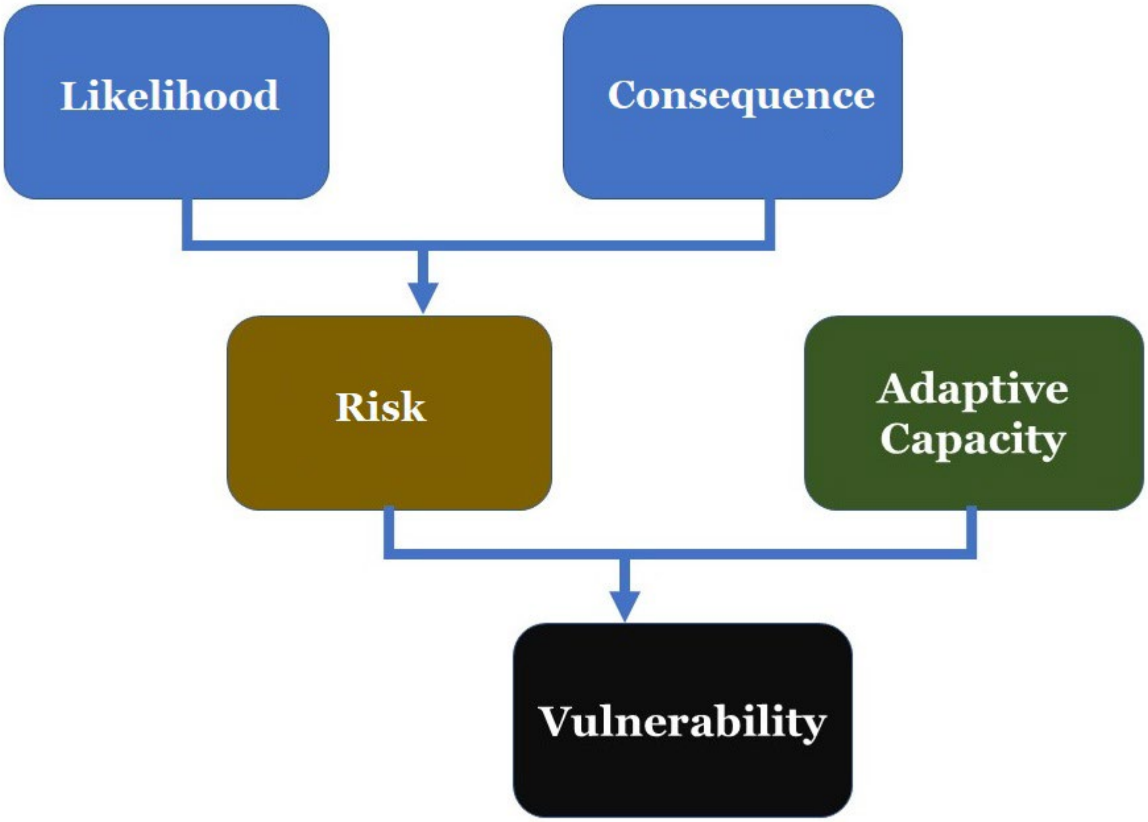

Figure 2.1 Flow diagram of the CVA process (Image: CEC, 2017).

2.2.1 RVA Tool

Many uncertainties and interacting factors make managing for climate change difficult; as a result, climate change often goes unaddressed in management actions. One simplified approach for beginning to manage for this complex issue is the Rapid Vulnerability Assessment (RVA), a series of worksheets and thought processes that allow for a rapid CVA that focuses on issues of primary concern (see Appendix C). The objectives of the RVA tool are as follows:

1. Allow managers to engage with the science of climate change as it pertains to their concerns.
2. Encourage the creation of adaptation strategies.
3. Empower managers to regularly consider the implications of climate change in the long-term by revisiting the tool and applying the thought process.

The RVA tool walks participants through a step-by-step process within a series of worksheets, allowing for individualization by habitat type or species. One timescale of concern (for forecasting possible climate impacts) is chosen, along with three climate stressors. Up to three non-climate stressors are chosen for each species or habitat that is assessed, which may interact with climate stressors during the assessment. The ultimate result is a vulnerability rating that is a product of the risk (likelihood *x* consequence) and adaptive capacity ratings for each climate stressor (Fig. 2.1; CEC, 2017).

Table 2.2 Ranking system for vulnerability ratings, from the RVA worksheets (CEC, 2017).

	Adaptive Capacity →		
Risk ↓	**Low**	**Moderate**	**High**
Low	**Low**	**Low**	**Low**
Moderate	**Moderate**	**Moderate**	**Low**
High	**High**	**Moderate**	**Moderate**
Extreme	**High**	**High**	**Moderate**

Resource managers involve stakeholders and experts in the RVA process, which is usually held as a workshop. The final step of the workshop is to develop adaptation strategies, which can later be modified or reassessed by resource managers. Following the workshop, a narrative report of findings (this report) is produced (CEC, 2017).

Steps 1 and 2

The first step guides the participant to define the scope and initial parameters of the assessment. This includes identifying the resources to be assessed (e.g., habitats, species, or groups of organisms), the timescale over which climate impacts are being considered (e.g., next 50 years), and which climate change variables (e.g., temperature, OA, sea level rise, etc.) are likely to have the greatest impacts on the selected resources. Because this is a rapid, rather than comprehensive, assessment, not all resources or variables can be assessed. Next, participants identify non-climate stressors the resources are currently experiencing, and transfer results of this step into the assessment tables.

Step 3

Step 3 of the RVA is to construct a series of assessment matrices that establish three parameters: consequence, adaptive capacity, and vulnerability. Vulnerability is defined by the RVA tool as a combination of risk (likelihood and consequence of climate change impact) and adaptive capacity. Likelihood is the degree of certainty that an identified climate impact will occur. Consequence is found by examining the non-climate stressors affecting the resource and determining whether climate change will impact that stress, and in what direction and magnitude. Adaptive capacity is a 1–5 (5 is superior) index of the resource's ability to adapt or cope with stress inputs, both climatic and non-climatic. It comprises ecological potential (e.g., factors intrinsic to the resource, such as plasticity or genetic diversity) and social potential (extrinsic factors). Social potential includes considerations such as the capacity of a conservation organization to manage the resource (e.g., stakeholder relationships, stability, policy, and science support). When risk and adaptive capacity tables have been completed, their results are added to the vulnerability table to derive a vulnerability score (Table 2.2).

Step 4

Step 4 in the RVA tool process is to generate and evaluate adaptation strategies and management responses that could potentially reduce the vulnerability of species with moderate or high vulnerability scores. In this part of the exercise, existing or achievable strategies that may lower the risk or increase adaptive capacity, or both, are considered in the context of both cost and efficacy. Often, such measures are based upon a “3R” approach.

- Resistance – bolstering a resource’s ability to withstand a stress event
- Resilience – improving a resource’s ability to recover from a stress event
- Response – aiding a resource in adapting to changed conditions

Once adaptation strategies and management actions have been identified, methods for implementation (e.g., determining leaders and partners, monitoring needs, timeline, and funding mechanisms) are considered.

It should be noted that due to the rapid nature of this assessment and the fact that most participants are experts in the natural sciences, the adaptation strategies are not meant to be detailed enough to be ready for implementation. Instead, they are intended to be further explored by FGBNMS staff as a follow-up to the RVA, in some cases with partners and stakeholders.

Step 5

Step 5 is to translate the RVA outcomes into a narrative vulnerability assessment report (this document). This is a means to provide a summary of results, identified strategies, and key messages in a format that is easily shared and understood by potential stakeholders, partners, and the public. The results of the RVA for each species are presented in the following chapter (Ch. 3), both as tabular summaries (e.g., Table 3.1) and a narrative. Color coded rankings in the summary tables follow Table 2.3.

Table 2.3 Summary rankings and their color coding for the RVA exercise conducted for each species (from the CEC RVA tool, see also Appendix C). Purple colored cells represent the most concerning vulnerability categories, followed by red, yellow, green, and blue (least concerning vulnerability category).

Likelihood	**Almost Certain**	**Likely**	**Possible**	**Unlikely**	**Rare**
Consequence	**Catastrophic**	**Major**	**Moderate**	**Minor**	**Negligible**
Risk	**Extreme**	**High**	**Moderate**	**Low**	
Adaptive Capacity	**Low**	**Moderate**	**High**		
Vulnerability	**High**	**Moderate**	**Low**		

2.3.1 Rapid CVA Workshop for FGBNMS

On July 27-28 2022, a virtual workshop was hosted by FGBNMS to conduct the CVA, following the RVA process (see Appendix C for workshop agenda). This workshop had three primary objectives.

1. Provide information about current and projected priority climate conditions for FGBNMS and apply this knowledge to key habitats and species to determine their vulnerability to changing conditions.
2. Use the RVA tool to generate a vulnerability score for key habitat and species.

3. Use workshop material to draft a FGBNMS CVA report, which will be an important resource to accompany the Condition Report and help guide the next FGBNMS Management Plan.

Workshop Preparations

Prior to the workshop, climate trends and projections were researched, with emphasis on studies proximal to FGBNMS, and a timeline of 50 years (the chosen timeline for the FGBNMS CVA). Participants were provided with a handout on these climate trends and future projections prior to the workshop. The three climate stressors most likely to impact FGBNMS and with sufficient data and research (identified by FGBNMS personnel) were identified as sea water temperature, OA, and storm frequency and severity and precipitation. All resources were assessed for their vulnerability to these three climate stressors. Prior to the workshop, two major habitat groups (shallow coral cap and mesophotic) and 23 species or groups of organisms (Table 2.1) were identified by FGBNMS staff on which to conduct RVAs. Experts were sorted into two breakout groups for assessing the habitat types, and five breakout groups for assessing species groups (two fish, one mesophotic invertebrate, and two shallow invertebrate groups), depending on their expertise.

Workshop

The RVA workshop began with introductory presentations, including an overview of the meeting objectives and methods, the RVA process, a basic summary of climate trends for the region, and breakout group introductions (Appendix A). Facilitators from NOAA led the breakout groups through the RVA process prior to reconvening a plenary discussion. Within each of the two habitat breakout groups (shallow coral cap and mesophotic), participants identified three non-climate stressors currently affecting the habitat, such as harvesting, pollution, or dredging. Following this, they assessed the climate and non-climate stressors' impacts on the habitat through the RVA worksheets, as well as adaptive capacity, ultimately resulting in vulnerability scores for each climate stressor and habitat combination. Participants were then split into five species breakout groups, each tasked with a subset of species (two fish, one mesophotic invertebrate, and two shallow invertebrate groups) to work through the RVA process. Later, fish groups and invertebrate groups reconvened to discuss results, followed by a wrap-up. On day 2 of the workshop, groups finished RVA assessments in the five species groups, then discussed as a full group in plenary. The last portion of the day was spent on adaptation planning for the two habitat types, followed by a group discussion of wrap-up and next steps. See Appendix A for the full workshop agenda.

Species were assessed according to expert knowledge that was available, and in some cases, expertise was needed for further understanding of the full impacts of climate on species. Given the limited time and information on some of the species, focus was primarily on species for which there was information at hand. Participants made the best reasonable estimate for each species or habitat, based on available knowledge of impacts of climate changes on that species or habitat. Additions beyond the findings and outcomes of the workshop may be necessary at a later time but would require further assessment activity beyond the scope of the workshop or this report. Additionally, time limitations constrained the discussion of adaptive strategies, which may require further consideration by FGBNMS personnel.

Chapter 3: Climate Vulnerability Assessment and Adaptation Planning Workshop Results

The vulnerability assessment results for the two habitats and 23 species or groups of organisms are summarized in this chapter. It is divided into two major sections (habitat assessments and species assessments), which are further divided according to shallow coral cap or mesophotic habitat, and fish, mesophotic invertebrate, or shallow invertebrate species groups. The shallow coral cap was defined as the high and low relief coral reefs that lie between 18–50 m depth. Dominant coral species include the scleractinian boulder star corals *Orbicella franksi* and symmetrical brain corals *Pseudodiploria strigosa*. Mesophotic habitat includes algal nodules, coralline algae reef, and deep reefs greater than 50 m depth, where black corals and octocorals are the dominant organisms.

Each section leads with a table listing the three major climate stressors, along with the index or level for each step of the RVA (likelihood, consequence, risk, adaptive capacity, and vulnerability). Each step is color-coded, with light blue and green being least concerning or likely, yellow as a moderately concerning or likely, red for a major concern or high likelihood, and purple for most concerning or likely (see Table 2.3; Shein et al., 2019).

3.1 Habitat Assessments

3.1.1 Shallow Coral Cap Habitat

Table 3.1 Influence of climate change on shallow coral cap habitat (18-50 m) from RVA scores.

Shallow Coral Reef Cap (18-50 m)	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Almost Certain**	**Likely**	**Likely**
Consequence	**Major**	**Moderate**	**Minor***
Risk	**Extreme**	**High**	**Moderate**
Adaptive Capacity	**Moderate**	**Moderate**	**Moderate**
Vulnerability	**High**	**Moderate**	**Moderate**

*There were disagreements in the expert panel on the extent of consequence of storm severity and frequency on shallow coral cap habitat.

Habitat Overview

The coral reef-capped EFGB and WFGB are approximately 20 km apart and within the photic zone in the GOM, where conditions are ideal for colonization by species of corals, algae, invertebrates, and fish that are also found in the Caribbean region (Bright et al., 1984; Clark et al., 2014; Johnston et al., 2016; Schmahl et al., 2008). The shallowest portions of each bank are topped by well-developed coral reefs in depths ranging from 18–50 m. Although the common coral species found on the reef caps of the banks are the same as those on Caribbean reefs (about 63% *Orbicella* complexes and 8% *P. strigosa*), the bank caps have low species diversity (22 coral species), octocorals are absent in shallow habitats, and scleractinian corals of the genus *Acropora* are exceedingly rare. These differences are likely due to depth and the latitude of the banks, as FGBNMS is near the northernmost limit of the warm-water coral distribution range and is distanced from source populations by several hundred kilometers (Aronson et al., 2005; Bright et al., 1985; CSA, 1989).

Since 1989, a federally supported, long-term coral reef monitoring program has focused on two one-hectare study sites on the reef caps at EFGB and WFGB. In over 30 years of nearly continuous monitoring, mean live coral cover has, on average, oscillated around 52% within the 0.01 km^2 (1 ha) study sites at both banks (Johnston et al., 2021). Despite global coral reef declines in recent decades, EFGB and WFGB have suffered minimally from hurricanes, recovered from coral bleaching events, and shown minimal signs of disease (until a recent disease outbreak in fall of 2022 following the CVA Workshop).

Vulnerability Assessment Results

Based on status and trend data reviewed in FGBNMS Condition Report workshops in April 2022, along with vetting from FGBNMS staff, climate experts, and Sanctuary Advisory Council members, the three climate change factors identified as most likely to adversely affect all habitats and species at FGBNMS over the next 50 years were seawater temperature, OA (pH, Ω_{Ar}, and pCO_2), and storm severity and frequency (including precipitation). The workshop participants decided the increased water temperature climate change stressor was almost certain to affect the shallow coral cap habitat within the 50-year timescale (2022–2072), while OA and changes in storm severity and frequency were likely to affect the habitat. There was considerable disagreement about the consequences of storm severity and frequency on shallow coral cap habitat at FGBNMS, due to the simultaneous impact of runoff, nutrients, sedimentation, and lowered salinities. The shallow coral cap habitat of FGBNMS ultimately had a high vulnerability to rising seawater temperatures, and moderate vulnerabilities to OA and storm alterations. Additionally, land-source nutrient pollution and sedimentation, disease such as Stony Coral Tissue Loss disease (SCTLD), and invasive species, were identified as the most likely and important non-climate stressors that could adversely affect the coral reef cap habitat within FGBNMS. At the time of the workshop, SCTLD had not yet been observed within FGBNMS, but SCTLD-like lesions were identified at EFGB and WFGB in September 2022 and prior to completion of this report.

Thermal stress associated with ocean warming can greatly impact scleractinian coral-dominated habitat through increased bleaching events resulting in mortality and loss of reef structure. Stress from bleaching events could also lead to increased susceptibility to disease and declines in coral growth. Increased temperatures may also reduce reproduction effort of corals and sponges or increase mortality of larval spawn.

Oceanic pH and Ω_{Ar} in the GOM are expected to decrease while pCO_2 is projected to increase during the next 50 years, potentially dipping below suitable conditions seasonally for shallow coral reef habitat at FGBNMS. These combined changes are likely to reduce growth and extension rates of corals, along with reduced calcification rates of coral species and CCA. A decline in CCA may result in habitat not suitable for coral recruits, which may in turn lead to less robust calcifiers, redacted reproduction, less structural complexity, and an ultimate shift in community structure. Lower pH will reduce the availability of planktonic food sources, and algal growth may increase, outcompeting corals for space (Morris et al., 2022).

Storm frequency in the GOM region is not expected to change greatly in the next 50 years, but storm severity is predicted to increase by 30–40%, producing extreme precipitation conditions leading to greater river discharge and runoff in the Mississippi River watershed. This shift toward stronger storms has the potential to increase physical toppling or dislodgement and breakage of the corals. Increased storm activity during annual spawning events could reduce successful fertilization. More concerning threats include decreased water quality and turbidity from increased run-off, causing increased pollution and excess nutrient runoff offshore to FGBNMS, increasing the potential for exposure to disease and bacteria. One benefit discussed among workshop participants is that colder upwelled waters during hurricanes can help reduce water temperatures, dropping water temperatures to a more suitable level for corals that are at risk of bleaching or are already bleached in the warmer summer months (Walker et al., 2005).

Non-climate stressors that may compound climate impacts (i.e., land-source nutrient pollution and sedimentation, disease, and invasive species) could lead to excess nutrients and turbidity which may lead to increased algal growth and space competition, or mortality events (Johnston et al., 2018). Increased lionfish predation on herbivores that control algal growth may impact habitat. Orange cup coral and algae may also compete for space with native coral. SCTLD-like lesions were observed in FGBNMS within one month of workshop completion, and the non-climate stressors discussed may increase the risk of disease, decrease immunity, or cause changes in coral and sponge microbiomes.

Finally, adaptive capacity was estimated for the shallow coral cap habitat, resulting in an overall moderate score for all climate stressors. The shallow coral cap communities of FGBNMS had fair to good ecological potential (a component of adaptive capacity), primarily due to high value and importance, ecologically and societally, of the habitat. This habitat also has populations of important species (protected, endangered, and ecologically critical). The social potential (a component of adaptive capacity) of shallow coral cap environments at FGBNMS was good due to strong stakeholder relationships, stability and longevity of planning horizons, existing mandates, and monitoring and evaluation capacity of the habitat.

Rising seawater temperatures

To address the impacts of rising seawater temperatures on the shallow coral cap habitats of FGBNMS, workshop participants first suggested artificial upwelling of cooler, deeper waters using renewable energy from a proposed offshore wind farm. Prior to implementation of this strategy, depth, temperature, nutrient composition, and water quality of upwelled waters will need to be quantified. This strategy has not been implemented in the nwGOM region and may be difficult due to cost and lack of areas suitable for wind farms near the FGBNMS. Alternately, following bleaching events, restoration or transplantation with warm water-resistant coral or zooxanthellae species, subspecies, or genotypes could be conducted, given information on resistance to rising SST in genotypes. Shading corals (as implemented in the Great Barrier Reef) may be another possibility for mitigating rising temperatures at FGBNMS. Public relations should be emphasized to help people make connections between greenhouse gas emissions and marine resources, and Sanctuary-aquaria and zoo partnerships should be enhanced to incorporate climate messages into outreach, with a focus on locations with preexisting FGBNMS exhibits. Future research should involve permanent markers with deeper monitoring to identify deeper refugia and population or coral changes. These strategies, however, have high cost and unknown efficacy.

Ocean acidification

To adapt to OA at FGBNMS, workshop participants discussed the use of local buffer materials that could be added using various proposed techniques (e.g., carbonate or biorock addition through electrically mediated calcium carbonate deposition on submerged metal structures, and seawater electrolysis; see Berger et al., 2013); however, participants recognized these discussions were theoretical and “out of the box,” as this is preliminary technology that would need to be adapted to offshore reef environments and further researched before implementation. It was also proposed to keep up with current research on OA mitigation, which is actively evolving, and to continue public relations efforts on OA, with an emphasis on the lag time between greenhouse gas emissions and repercussions of acidification that may be observed by the community.

Storm exposure

If needed in the future, storm exposure can be mitigated by coral restoration using larval propagation for recruitment-limited species (collected locally) and asexual propagation (e.g., microfragmentation) could be implemented. Damage assessments following hurricanes should be conducted to better understand natural and heightened impacts of storms on coral reef systems.

Disease

In late August and early September of 2022 (following the CVA workshop), SCTLD-like lesions were observed at both EFGB and WFGB (Johnston et al., 2023). This was after adaptation strategies had already been proposed. Immediately (less than a week) following these disease observations, the SCTLD Preparedness Plan (Johnston, 2021) was implemented whereby research partners joined FGBNMS divers to assist with initial disease responses (including photo documentation and application of antibiotics) and training sanctuary personnel in treatment techniques. Prior to these observations, workshop participants recommended disease prevention measures (best management practices such as cleaning diving gear before water entry), and these practices could still be implemented for other disease-free banks of the Sanctuary. Disease intervention actions should be maintained and updated as new knowledge becomes available. Genetic material from SCTLD-susceptible species could be preserved through genetic banking, and dynamic management could be implemented (e.g., closing off access to some of the reefs).

Land-based runoff

To manage land-based runoff, herbivores such as long-spined sea urchins (*Diadema antillarum*) that control benthic algae could be restored or enhanced. Similarly, removal of parrotfish and other herbivorous fishes could be prohibited. Methods to enhance the capability of FGBNMS researchers to detect anomalous conditions to better understand the risk of extreme events (e.g., instruments to detect conditions leading to localized mortality) could be employed.

Invasive species

Immediately following the CVA workshop, a permit was issued to help remove invasive lionfish (*Pterois volitans*) from FGBNMS, following the workshop's recommendation to promote the catching of lionfish by divemasters on the recreational dive charter *MV Fling*. Permits could also be issued to recreational divers, and culinary lionfish events could be conducted if lionfish is deemed safe to eat, since there is currently a Food and Drug Administration advisory against ciguatera toxin. Participants also suggested more frequent (quarterly) lionfish removal cruises and implementing lionfish strategies used in other locations. Additional lionfish cruises could be conducted to all banks, with the possibility of opening lionfish harvest to the public and encouragement of private vessels to get involved in lionfish derbies. This method is low cost, but high efficacy.

Opening a lionfish fishery (such as spearfishing) would likely have low cost and high efficacy, with potential partnerships in American Academy of Underwater Sciences, Wounded American Veterans Experience Scuba (WAVES) Project, Association of Dive Program Administrators, sport and spearfishing dive clubs, the National Marine Fisheries Service, law enforcement (NOAA's Office of Law Enforcement and others), Texas and Louisiana Sea Grants, Texas A&M University, and vendors (to get harvested lionfish out to consumers). Baseline surveys and monitoring would need to be conducted to see if the fishery is effective. Reports on catch and length would need to be required. Some organizations would need funding but others can likely operate without help. However, there may not be much actual cost in terms of changing the regulation. Some data assimilation costs would be possible. Partnerships with the National Marine Fisheries Service and Sea Grant could help cover these costs, as well as assist with the commercialization of the resource. The sanctuary would need to change its regulations or issue permits for this strategy to be implemented, and a vendor connecting the lionfish fishery to consumers would need to be identified. Likely this process could be completed in less than three years, in time for the review of the management plan.

To address invasive cup corals (*Tubastraea* sp.), dive masters could be trained for removal, and local aquaria and zoos could be issued permits for collection, or harvest for at-home sale could be permitted (cup coral is a valued at-home aquarium coral species).

3.1.2 Mesophotic Habitat

Table 3.2 Influence of climate change on mesophotic habitat (>50 m) from RVA scores.

Mesophotic Habitat (50-220 m)	Increased Water Temperature	Ocean Acidification	Storm Severity/Frequency
Likelihood	Unlikely	Possible	Unlikely
Consequence	Moderate	Moderate	Minor
Risk	Moderate	Moderate	Low
Adaptive Capacity	Moderate	Moderate	Moderate
Vulnerability	Moderate	Moderate	Low

Habitat Overview

While the sanctuary is best known for the coral reef cap habitat perched atop EFGB and WFGB, the majority of FGBNMS habitats are within the mesophotic zone (50–221 m). This mid- to low-light zone at FGBNMS contains several different habitat types, including algal nodules, coralline algae reef, and deep reef (where black corals and octocorals predominate) (ONMS, 2020). The dominant communities providing structural habitat in the mesophotic zone are corals, sponges, and algae, which is utilized by a variety of species, including commercially and recreationally valuable fish such as grouper and snapper (Boland et al., 2016).

Coralline algal reef and algal nodule habitats are found in between the shallower coral reef and deep reef habitat, and are dominated by crustose forms of algae, creating biogenic substrates, serving as biodiversity hotspots and important foundational habitat for corals and juvenile fish (Fredericq et al., 2019; Moura, 2021). Some species of corals, sponges, and leafy algae that are found in deep reef habitat also occupy these habitats, showing the transitional nature of this zone. In deep reef habitat (or lower mesophotic zone: the deepest part of the sanctuary's mesophotic habitat), there are very few light-dependent stony corals. Black corals and octocorals, which are structurally different from reef-building corals, build coral forests that provide vertical relief and habitat for many other species including brittle stars, crinoids, and deep reef fish species (Boland et al., 2016). Black corals (Antipatharians) are made of flexible chitin and move with water currents. They vary in shape and pigmentation (named for the color of their spiny, internal skeletons), but most are the shape of trees or bushes. Like the rigid stony coral species found on the coral reef cap habitat, black corals have polyps with tentacles in multiples of six. Octocorals (Alcyonarians), also known as gorgonians, are named for their polyps with eight pinnate (branching, feather-like) tentacles. Their skeletons are made of a combination of flexible protein and calcium carbonate aggregates. Octocorals grow in a variety of shapes, but sea fans are probably the most recognizable. Many kinds of gorgonians can be found on shallow coral reefs around the world, but at FGBNMS, they are only found at mesophotic depths. Along with habitat for invertebrates, mesophotic coral ecosystems also serve as essential fish habitat for some economically and ecologically important fish species, which use these areas for spawning, breeding, feeding, and growing to maturity (Etnoyer & Cairns, 2017).

Vulnerability Assessment Results

Like shallow coral cap habitats, the climate change factors most likely to adversely affect the mesophotic habitat over the next 50 years at FGBNMS are seawater temperature, OA (pH, Ω_{Ar}, and $p\mathrm{CO}_2$), and storm severity and frequency (including precipitation). Mesophotic habitats at FGBNMS are unlikely to be impacted by rising seawater temperatures or storm alterations but had possible impacts from OA. Ultimately, mesophotic habitats had moderate vulnerabilities to rising seawater temperatures and OA, and low vulnerability to storm alterations. Additionally, harvest, extraction (oil and gas), and invasive species, were identified as the most likely and important non-climate stressors that could adversely affect mesophotic habitat within FGBNMS.

Increasing SST will likely not have a significant effect on this deeper habitat. However, thermal stress in upper mesophotic habitats may result in some habitat loss, depending on temperature ranges. Thermal stress in shallower habitats may result in range shifts of all types of species (both native and invasive) into deeper mesophotic depths. The degree and extent this threat poses to this habitat are unknown and need to be evaluated.

Changing OA parameters (pH, Ω_{Ar}, mean $p\mathrm{CO}_2$) will most likely have minimal impact on mesophotic habitats within the next 50 years, as the region is well mixed with high buffering capacity. However, changes in food export may occur alongside altered surface chemical cues, which are important for the reproduction of mesophotic species, resulting in other behavioral changes in mesophotic organisms.

The shift toward stronger storms in the nwGOM has the potential to cause fish to move to deeper habitat as a form of storm avoidance. More concerning threats include decreased water quality and turbidity from increased run-off, as anything that limits light penetration can be disruptive to the already low-light conditions at these depths. Increased turbidity would prevent sunlight from reaching this ecosystem, thus impacting photosynthesizing organisms, and increased nutrients may also create unwanted bacterial or algal growth.

Non-climatic stressors that may compound impacts (i.e., harvest, extraction, and invasive species) could lead to: trophic cascades and directly impact grazers, damage to habitat from fishing gear and oil and gas infrastructure, and a direct reduction of the fish population from invasive species if not carefully managed.

Finally, adaptive capacity for the mesophotic habitat was estimated as moderate for all climate stressors. Mesophotic habitats of FGBNMS had good ecological potential, driven by high biodiversity and presence of keystone and other indicator species. Fair social potential was increased by the sanctuary’s proactive management capabilities and strong partner relationships, but limited by staff capacity, responsiveness (ability to adjust and change organizational structure), and monitoring and evaluation capacity at this depth.

Adaptation Planning Results

Warming sea water temperatures

To adapt to warming sea water temperatures, artificial upwelling could be orchestrated for mesophotic habitats in addition to shallower environments. Additionally, depth distribution and life histories of corals on the banks needs to be explored so that possible highly adaptive "super corals" can be investigated as a way to enhance restoration outcomes on the coral cap (e.g., *M. cavernosa* and others).

Likelihood and Consequence of ocean acidification

To address increasing OA in the mesophotic habitats of FGBNMS, ideas such as alkalinity enhancement or addition of large blocks of calcium carbonate were discussed in the workshop, yet these ideas are highly speculative and might not be feasible in the near future. Calcium carbonate-based alternatives to concrete may be considered when creating artificial reefs and other infrastructure. The cost of materials for this method is low, but deployment may be costly depending on whether the timing can be simultaneous with existing field work.

Invasive species

To mitigate the impacts of invasive species on mesophotic habitats of FGBNMS, it was proposed to outfit ROVs to capture and kill or survey mesophotic lionfish, a strategy assessed as having medium to high cost and low efficacy. Expanding partnerships with occupational and zoo and aquarium technical diver programs to allow mesophotic lionfish derbies, or allowing for spearfishing for lionfish only outside of lionfish invitationals, would also have low cost and high efficacy. Alternative methods could be to deploy lionfish traps, which would have low cost and high efficacy.

Harvest

To address fishing pressure in the mesophotic habitat, harvest could be reduced by creation of fishery closure areas, since no no-fishing areas exist at FGBNMS. The cost of this method would be low for the sanctuaries, but this may also be difficult to implement due to political pressures. Seasonal closures may be more feasible but less effective than year-round closures. A better understanding of actual fishing use (e.g., what organizations or persons are fishing and how often) at FGBNMS is needed.

Monitoring and evaluation capacity

Monitoring and evaluation capacity at mesophotic habitats of FGBNMS can be enhanced through partnerships, which can help managers leverage to work towards fishery closures. Managers could work collaboratively with fishers (commercial, recreational for-hire, and reef fish) to conduct or support science from their vessels, which would enhance stakeholder relationships and buy-in. Partnerships with divers (Wounded American Veterans Experience Scuba, technical zoo and aquarium dive programs, and citizen science groups) could be forged to aid in mooring buoy installation, maintenance, and upkeep. Participants emphasized the importance of zoos and aquariums as conveyors of information. Additionally, zoos and aquariums may be looking for ways to enhance their own conservation efforts, and partnerships with these organizations may be mutually beneficial. Leveraging partnerships and experience of retired military veterans should also be considered. Monitoring equipment could be deployed on artificial reefs. Researchers at Texas A&M University can also be collaborated with, and partnerships with the GOM Fishery Management Council (FMC) can be enhanced.

Collaboration with the oil and gas industry could lead to determination of impacts of geological processes on the ecology of areas where oil and gas development takes place.

A second research vessel of larger size class could be acquired. A crewed underwater habitat in the mesophotic zone (like Florida International University's undersea laboratory Aquarius) could help with studies. Funding could be obtained through cooperative research proposals that include numerous partners such as fishers, researchers, and FMCs. Funding could also be leveraged from oil and gas, particularly to explore physical, geological, and chemical processes, which will promote the aspects of the sanctuary beyond ecology and biology. Leveraging such funding would require changing regulations and establishing cooperative agreements, particularly for organizations with which FGBNMS has not previously partnered. Collaboration with the FMC, and a grant writer, development coordinator, or operator at the site, are needed. This can be started immediately but would take 2–5 years for full execution. Sanctuary Advisory Council members could take ownership of this task.

Snapper-grouper complex

To address conservation of the snapper-grouper complex, spawning aggregations need to be found, so they can be protected through fishery closures. Education outreach campaigns about not removing fish at spawning aggregations can be conducted, and agencies can be encouraged to regulate this fishery. More robust catch reporting programs need to be created, and a climate working group that can collaborate with the FMC can be established. Additionally, tracking the number of publications on spawning as well as spawning aggregations and spawning behavior will help better manage fisheries at FGBNMS' mesophotic habitats.

Impact of OA on crustose coralline algae (CCA)

To address the knowledge gap on impact of OA on CCA, water chemistry requires further study with focus on sites in CCA areas.

Deepwater corals

Deepwater corals can be protected by aquarium experimentation to understand adaptation and response to climate change, for which there is a knowledge gap. Harvest and growth of corals for replanting and restoration should be considered alongside in situ coral propagation in the mesophotic zone. The depth distribution of corals on banks and life history as possible adaptive "super corals" that can be used to enhance restoration outcomes on the coral cap warrants further investigation.

3.2 Species Assessments

3.2.1 Fish Species

Grouper and Snapper Complex

Table 3.4 Influence of climate change on the grouper and snapper complex from RVA scores.

Grouper and Snapper Complex Serranidae/Lutjanidae Families	Increased Water Temperature	Ocean Acidification	Storm Severity/Frequency
Likelihood	Almost Certain	Unlikely	Likely
Consequence	Major	Negligible	Moderate
Risk	Extreme	Low	High
Adaptive Capacity	Moderate	Moderate	Moderate
Vulnerability	High	Low	Moderate

Species overview

The grouper and snapper complex (not including marbled grouper, see next species description) contains many fish species in the Serranidae (grouper) and Lutjanidae (snapper) families, some of which have no market interest (e.g., soapfish and other small serranids). However, market interest is high for some groupers and snappers, making them important fishery resources with high commercial value (Amorim & Westmeyer, 2016). Red snapper (*Lutjanus campechanus*) dominate harvest in the GOM.

The geographic range for these fish is wide in the Western Atlantic, with some extending well beyond the U.S. South Atlantic. The grouper and snapper complex also varies in depth from shallow reef caps to mesophotic habitat. Within and around the boundaries of FGBNMS, the GOM FMC manages the fishery for most of the grouper species (excluding small serranid species) and almost all the snapper species recorded in the sanctuary. The following fish species are those most often recorded in the sanctuary's long-term monitoring program for the grouper and snapper complex: dog snapper (*Lutjanis jocu*), gray snapper (*L. griseus*), yellowtail snapper (*Ocyurus chrysurus*), rock hind (*Epinephelus adscensionis*), scamp (*Mycteroperca phenax*), graysby (*Cephalopholis cruentata*), tiger grouper (*M. tigris*), and yellowmouth grouper (*M. interstitialis*). However, other species in the grouper and snapper complex (40 species of groupers and 12 species of snappers; FGBNMS, 2023l) have been documented in FGBNMS, but due to behavior, distribution, or depth, are not regularly observed during monitoring dives on the sanctuary's reef caps.

Most species within the grouper and snapper complex are bottom dwellers, living close to the reef or substrate. Information exists on life histories for some, not all (e.g., marbled grouper) of these species. Expected life spans are long in the grouper and snapper complex, with some grouper species reaching ages over a century (Luckhurst & Dead, 2019). In addition to slow development and long lives, many species in the grouper and snapper complex swim to the same place each year at the same time to reproduce. During reproduction, separate sexes release gametes which are externally fertilized in the water column. Information on these fish spawning aggregations is incomplete for the GOM (Heyman et al., 2019). When fishers know when and where these aggregations exist, these special places can be overfished quickly and with less effort. Observations of marbled grouper displaying courtship or spawning coloration and behavior likely indicates a fish spawning aggregation within the sanctuary. This aggregation may be under considerable threat from fishing pressure. With continued exploration and research in the GOM, discovery of additional fish spawning aggregations and their use by numerous fish species is likely, by fishers and funded researchers alike.

Grouper and snapper are important fishery resources with high commercial value domestically and internationally. During 2011–2014, the U.S. snapper harvest averaged 4,849 tons (whole weight) worth $35.4 million, and the U.S. grouper harvest averaged 4,105 tons (whole weight) worth $28.7 million (Amorim & Westmeyer, 2016; referencing NMFS reports in 2013 and 2015). The U.S. also imported snappers and groupers to meet demand, though the demand for snappers far outweighed the demand for groupers (14,860 tones and 4,849 tons, respectively) (Amorim & Westmeyer, 2016). Northern red snapper and red grouper dominate harvest in the Gulf, followed distantly by vermilion and yellowtail snapper and gag grouper (Amorim & Westmeyer, 2016). Red snapper is the most caught snapper, representing almost 50% of the total catch.

Several species within the grouper and snapper complex are considered vulnerable to overfishing by the International Union for the Conservation of Nature (IUCN) Red List. Many of the grouper species are protogynous hermaphrodites (females change sex to male), develop slowly over years before reaching maturity, and migrate annually during specific time periods to fish aggregation sites to reproduce. Snappers are also slow-growing and migrate during specific time periods to fish aggregation sites to reproduce. Overfishing has greatly reduced or eliminated fish spawning aggregations and skewed adult sex ratios. Different management measures exist for the grouper and snapper complex including size limits, recreational bag limits and commercial fishing quotas, gear and seasonal controls, and marine protected areas.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\mathrm{CO}_2$), and storm severity and frequency (including precipitation), all of which had possible likelihoods of impacting grouper and snapper in FGBNMS. Grouper and snapper were ranked as almost certain to be impacted by rising seawater temperatures, and likely to be impacted by storm alterations in the FGBNMS over the next 50 years. Workshop participants evaluated the grouper and snapper complex in FGBNMS to have a high vulnerability to increased water temperature and a moderate vulnerability to storm severity and frequency. A low vulnerability to OA was assessed by the group, though participants noted uncertainty about OA impacts on fish with potential to underestimate vulnerability. The participants estimated major to moderate consequences to climate and non-climate stressors and likely to almost certain likelihood of future climate changes, with final vulnerability scores of moderate to high, in part due to the grouper and snapper complex’s low adaptive capacity and vulnerability to overfishing. For OA, consequences were scored as negligible, likelihood as unlikely, and vulnerability as low. The group noted low confidence in the certainty of assessments of OA as a climate stressor, and its impacts on the grouper and snapper complex beyond disruptions in the food web.

The projected rise in seawater temperature at FGBNMS may result in changes to the reproductive season and operational sex ratio (ratio of fertilizable females to sexually mature males), or may shorten larval stages, which could create mismatches with available food sources (trophic-level disruptions). Shifts in direction and intensity of currents are expected, partly because of the increased SST. Changes in current could affect larval recruitment and, again, create mismatches with available food sources.

OA may result in decrease in habitat, altered reproductive behavior, lowered prey abundance, lowered recruitment, and otolith abnormalities in grouper and snapper complex species. Storms can have direct effects on the species' preferred habitat such as physical destruction or smothering of the reefs as well as changes in salinity near the coast where larval transport occurs. Increasing intensity of storms may coincidentally reduce the recovery period between major storm events for fish species in the grouper and snapper complex.

The three most significant non-climate stressors were identified as harvest, invasive species, and land-source nutrient pollution. Fishing is limited to conventional hook and line gear within FGBNMS. Bandit rigs (multiple hooks near the seafloor originating from one line) are allowed and remove multiple individuals with each effort. Some but not all species in the grouper and snapper complex are included in U.S. fishery management plans. Marbled grouper, discussed above, are not managed and in 2006, a significant number of this rare species was harvested at a bank now within sanctuary borders. Invasive species such as lionfish may present potential habitat and prey competition, as well as potential for direct predation of young groupers and snappers. Land source pollution is likely to increase with more intense storm events due to climate change. Land-source nutrient pollution will increase with more runoff from heavy rain events. Land source pollution, both nutrient and non-nutrient, is likely to result in lower salinity and impact water quality in other ways (e.g., nitrogen and phosphorous flux increases, decreasing DO, etc.), which could increase mortality of larval and juvenile stages in nearshore brackish and estuarine habitats. At the same time, increased nutrient loads could benefit plankton productivity, which would be beneficial to juveniles, depending on the nutrient input and plankton species affected.

Finally, adaptive capacity for grouper and snapper was estimated as moderate for all climate stressors. The ecological potential of the grouper and snapper complex is high due to their distribution, connectivity, value, and genetic diversity. The social potential is moderate because of the difficulty in identifying fish spawning aggregations and monitoring them. Participants noted a significant need for collaboration with the GOM FMC to ensure proper management of snapper and grouper species at FGBNMS.

Marbled Grouper (Dermatolepis inermis)

Table 3.3 Influence of climate change on marbled grouper from RVA scores.

Marbled Grouper ***D. inermis***	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Almost Certain**	**Unlikely**	**Likely**
Consequence	**Major**	**Negligible**	**Moderate**
Risk	**Extreme**	**Low**	**High**
Adaptive Capacity	**Low**	**Low**	**Low**
Vulnerability	**High**	**Low**	**High**

Species overview

Marbled grouper (*Dermatolepis inermis;* family Serranidae [sea bass]) was assessed separately from the grouper snapper complex due to their deeper habitat range and rarity within FGBNMS. The marbled grouper is a subtropical marine fish species found in the Western Atlantic from Bermuda and North Carolina to Brazil, including the GOM and Caribbean. Known as a deeper reef fish, its depth range extends from 3–250 m. Rarely seen, marbled grouper are normally solitary. Banks in the western GOM currently appear to have the highest abundance of marbled grouper; although marbled grouper is a rare species, it is more likely to be seen in FGBNMS than elsewhere in its range (Ferreira and Bertoncini, 2018). Found on reef-associated deep ledges, marbled grouper are usually secretive, darting away into caves or deep crevices when approached or frightened. These serranids have an angular head (i.e., steeply sloped area between eyes and dorsal fin) and are mottled olive to brown and black in coloration. Marbled grouper typically have small black dots and may have large white blotches over the body. Very little is known about their life history, including the age and length for when this species matures. Common adult size is 50 cm total length (TL), though the record is 91 cm TL. Juveniles have been seen on the seafloor in association with sea urchins, taking refuge in and around spines (Ferreira and Bertoncini, 2018). Maximum published weight is 10 kg. No food-habit studies have been conducted on this species.

Marbled grouper are thought to change sex during their lifespans, like most, if not all, other groupers. During reproduction, separate sexes release gametes which are externally fertilized in the water column, though spawning frequencies in the U.S. are currently unknown. Also, like others in the Serranid family, coloration and behavior changes occur in marbled grouper during reproduction. Within the sanctuary, marbled grouper have been observed in the upper mesophotic reaches in small groups of 3 or 4, and have more white blotches on the face, body, and tail fin than other observed populations of this species. Although normally solitary, this congregating behavior along with the different color phases described above indicate a spawning aggregation, located within FGBNMS. This aggregation may be under considerable threat from fishing pressure. In 2006, a head boat based in Freeport, Texas confirmed harvest of 67 gravid marbled grouper over several days at an unpublished location within FGBNMS (Campbell et al., 2019).

Marbled grouper were assessed for the IUCN Red List of Threatened Species in 2018, and were listed as "data deficient" due to the lack of population information and generation length data. A project funded by the National Centers for Coastal Ocean Science in 2022 is underway to help address some of the data deficiencies surrounding spawning aggregations of this species (National Centers for Coastal Ocean Science, n.d.). Fishing was identified as a major threat to this species, especially where spawning aggregations are targeted. The IUCN's recommendations for marbled grouper includes improved monitoring of exploited populations, protection of spawning aggregations, and advancement in research on its life history and reproductive biology. Its previous status in 1996 was categorized as "threatened - vulnerable" (Baillie & Groombridge, 1996). Suspected declines in marbled grouper populations in the U.S. GOM and Brazil were attributed to fishing pressure and possible depletion of spawning aggregations. Rarely seen or sold in markets, marbled grouper are infrequently reported in commercial and recreational catch records, mostly from Louisiana. In the Florida Keys, this fish species is no longer or infrequently captured (Ferreira and Bertoncini, 2018). This species is not included in any U.S. fishery management plans. Many grouper species develop slowly, are long-lived, and swim to the same place each year at the same time to reproduce. When fishers know when and where these aggregations exist, these special places can be overfished quickly and with less effort.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and pCO_2), and storm severity and frequency (including precipitation), all of which were determined to have the possibility of impacting marbled grouper in FGBNMS. Rising seawater temperatures were almost certain and storm alterations were likely to impact marbled grouper in the FGBNMS over the next 50 years. Workshop participants evaluated marbled grouper in FGBNMS to have a high vulnerability to increased water temperature and storm severity and frequency. The participants estimated major to moderate consequences to climate and non-climate stressors and likely to almost certain likelihood of future climate changes, with final vulnerability scores of high, in part due to the marbled grouper's low adaptive capacity and vulnerability to overfishing. For OA, consequences were scored as negligible, likelihood as unlikely, and vulnerability as low. The group noted low confidence in the certainty of assessments of OA as a climate stressor, and its impacts on marbled grouper beyond disruptions in the food web. Participants noted the potential to underestimate vulnerability of this species to OA.

Increasing temperatures in FGBNMS may result in changes in the reproductive season and operational sex ratio (ratio of fertilizable females to sexually mature males) as well as shorter larval stages, which could create mismatches with available food sources (trophic-level disruptions). Shifts in direction and intensity of currents are expected, partly because of the increased SST. Changes in currents could affect larval recruitment and, again, create mismatches with available food sources.

OA may decrease habitat, alter reproductive behavior and recruitment, and change shape and growth of otoliths in marbled grouper. Storms can have direct effects on marbled groupers' preferred habitat such as physical destruction or smothering of the reefs as well as changes in salinity. Increasing intensity of storms may coincidentally reduce the recovery period for marbled grouper between major storm events.

The three most significant non-climate stressors were identified as harvest, invasive species, and noise. Fishing is limited to conventional hook and line gear within FGBNMS. However, bandit rigs (multiple hooks near the seafloor originating from one line) are allowed and if used, could remove multiple individuals with each effort. Invasive species, such as lionfish, may present potential habitat and prey competition, as well as potential for direct predation of juvenile marbled groupers. Noise (from shipping fairways over banks, fishing vessels, or oil and gas activities) was also identified as a non-climate stressor on marbled grouper, especially during its reproductive season.

Finally, adaptive capacity for marbled grouper was estimated as low for all climate stressors. For ecological potential, distribution and connectivity, dispersal, phenotypic and behavior plasticity, genetic diversity, and generalist ability were ranked as critical due to its rarity and spawning behavior, among other factors. Value and importance were ranked as good due to their value as a recreational species. The social potential is also low, because of the difficulty in monitoring this deeper water and shy reef fish species and the lack of catch reports from most of its geographic range.

Lionfish (Pterois volitans/miles)

Table 3.5 Influence of climate change on lionfish from RVA scores.

Lionfish ***P. volitans/miles***	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Possible**	**Possible**	**Unlikely**
Consequence	**Minor**	**Negligible**	**Minor**
Risk	**Moderate**	**Low**	**Low**
Adaptive Capacity	**Moderate**	**Moderate**	**Moderate**
Vulnerability	**Moderate**	**Low**	**Low**

Species overview

Lionfish (*Pterois volitans* or *P. miles*, family Scorpaenoidae (scorpionfishes)) is a venomous fish with a voracious appetite. Variable in color, lionfish have numerous, alternating bands of white and reddish brown to black. Their fins, including their long, feather-like pectoral fin rays, are also banded with alternating colors. Lionfish often have large tentacles above the eyes. Venomous spines are in the dorsal, pelvic, and anal fins. Usually solitary, lionfish inhabit waters 2–55 m deep. Feeding during the day and at night, lionfish hunt small fishes, shrimps, and crabs. Lionfish are fecund, with mature females (>1 year old) releasing 50,000 eggs every three days.

Native to the Pacific Ocean, lionfish have invaded more areas outside of their home range than any other invasive fish species and were thought to have originally invaded from aquarium releases. First recorded in Florida in 1985, lionfish were initially sighted within sanctuary boundaries in the GOM in 2011. By the end of 2015, over 2,600 lionfish were observed within the sanctuary. Lionfish grow rapidly, develop quickly to sexual maturity, frequently spawn, are opportunistic generalist feeders, and appear to be resistant to disease and parasites. Lionfish also have no known predators in their invasive range (local predators don't recognize them as prey), the animals they eat don't recognize the threat (prey doesn't recognize them as a predator), and they are tolerant of a wide range of temperatures, habitat types, and depths. These characteristics facilitated the rapid expansion of lionfish in their invasive range, in which they are growing faster and larger than in their native range.

Although consistent physical removal within the sanctuary is not practical, lionfish removal efforts began in 2015 and are ongoing through Lionfish Invitationals, multi-day, science-based research expeditions. Densities within the sanctuary appear to be significantly lower than in some of the other regions invaded by lionfish, potentially signaling a functional incorporation into the existing ecosystem processes (Blakeway et al., 2022). This idea is supported by not seeing any measurable decreases or negative effects on prey fish communities. Within the sanctuary, the maximum age of lionfish was 10 years and maximum size was 44.5 cm TL (Blakeway et al., 2021).

Lionfish occurs within the aquarium trade and is a popular table fish in some Gulf states. Lionfish pose a threat to recreational divers and other marine organisms and have a powerful sting which can result in tachycardia, hypertension, hypotension, seizures, chest pain, abdominal pain, swelling, pain, subdermal necrosis at the sting site, and even temporary paralysis to all extremities, although long term health impacts of repeated envenomation are unknown.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\text{CO}_2$), and storm severity and frequency (including precipitation). Lionfish have a possible likelihood of being impacted by increasing temperatures and OA and are unlikely to be impacted by storm alterations. Workshop participants evaluated lionfish in FGBNMS to have a low vulnerability to OA and increased storm severity and moderate vulnerability to rising SST. Although workshop participants noted low confidence in the likelihood of lionfish being directly impacted by climate stressors, this species is highly adaptable and has a competitive advantage over native fish species. It should be noted that lionfish are an invasive species with damaging effects on the native ecosystem of FGBNMS, and therefore high vulnerability scores whereby lionfish are likely to be harmed are more desirable than low vulnerability scores whereby lionfish are unharmed or benefit.

Rising seawater temperatures in FGBNMS may result in enhanced reproduction and wider distribution of lionfish, both resulting in negative impacts on native fish species. Shifts in direction and intensity of currents are expected, partly because of the increased SST. Changes in currents could affect larval recruitment and distribute lionfish into new areas and habitats.

OA may provide lionfish with a competitive advantage; however, decreased structure and habitat and potential decreases in prey due to OA could still negatively impact lionfish. Storms can have direct effects on lionfish preferred habitat such as physical destruction or smothering of the reefs as well as changes in salinity near the coast where larval transport occurs.

Participants identified harvest, overwater and underwater structures, and disease as non-climate stressors on lionfish. Workshop participants noted harvest of lionfish, as an invasive species through Lionfish Invitationals, is can have a positive impact for the ecosystem. However, the harvest of predators that might prey on lionfish was discussed as a negative impact to the ecosystem. Across the GOM, oil and gas platforms have provided structure and connectivity for lionfish. Workshop participants noted that platform removals and placement in permanent reefing areas could increase lionfish populations. Finally, workshop participants discussed disease in lionfish, noting this disease could potentially impact native fish species.

Finally, adaptive capacity for lionfish was estimated as moderate for all climate stressors. The ecological potential of lionfish is high due to its distribution and connectivity and its life history of frequent reproduction. The social potential is moderate due to the knowledge and proactive management (removals, stomach contents, acoustic tagging) conducted by FGBNMS staff, research partners, and citizen scientists.

Horse-Eye Jack (Caranx latus)

Table 3.6 Influence of climate change on horse-eye jack from RVA scores.

Horse-Eye Jack ***C. latus***	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Almost Certain**	**Unlikely**	**Possible**
Consequence	**Minor**	**Negligible**	**Minor**
Risk	**Moderate**	**Low**	**Moderate**
Adaptive Capacity	**High**	**High**	**High**
Vulnerability	**Low**	**Low**	**Low**

Species overview

Horse-eye jack (*Caranx latus;* family Carangidae) is a pelagic schooling species with a wide distribution across the western Atlantic basin, found from New Jersey, Bermuda, and northern GOM to central Brazil. This silvery fish sometimes has an indistinct spot on the corner of the operculum but can be distinguished from the similar-sized crevalle jack (*Caranx hippos*) by its less steep forehead and because horse-eye jack usually lacks a dark blotch on the pectoral fin bases. Horse-eye jack attains lengths up to 101 cm and weighs up to 13.4 kg. Found on reefs and soft or seagrass bottoms, this species is tolerant of salinity shifts, even entering freshwater. This pelagic species has a depth range down to 151 m. Juvenile horse-eye jacks are found along beach shorelines and over muddy bottoms. Adults feed on fishes, shrimps, and other invertebrates, providing flexibility in prey consumption from the water column and the substrate. During reproduction, separate sexes release gametes which are externally fertilized in the water column, though spawning frequencies in the U.S. are currently unknown.

Although minor in catch, horse-eye jack is a game fish and food fish, targeted by both commercial and recreational fishers. This species is commonly used as bait for larger species of pelagic game fish. This species has been identified as a carrier of the ciguatera toxin. Horse-eye jack was assessed for The IUCN Red List of Threatened Species in 2018, and was listed as “least concern”, with a stable population trend (Smith-Vaniz et al., 2019). It has been observed spawning at fish spawning aggregations in the Cayman Islands and Belize (Whaylen et al., 2004, 2006; Heyman & Kjerfve, 2008). Aggregate spawning behavior was identified by the IUCN as a potential heightened risk of exploitation for horse-eye jack.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\text{CO}_2$), and storm severity and frequency (including precipitation). Increasing temperatures were almost certainly likely to impact horse-eye jack, while storm alterations were possible at FGBNMS in the 50-year timespan. Workshop participants evaluated horse-eye jack in FGBNMS to have a low relative vulnerability to all three climate stressors. For OA, consequences were scored as negligible, likelihood as unlikely, and vulnerability as low. However, the group noted low confidence in the certainty of estimating impacts of OA as a climate stressor.

Rising seawater temperatures in FGBNMS may result in changes in the reproductive season and operational sex ratio (ratio of fertilizable females to sexually mature males) as well as shorter larval stage, which could create mismatches with available food sources (trophic-level disruptions). Shifts in direction and intensity of currents are expected, partly because of the increased SST. Changes in currents could affect larval recruitment and, again, create mismatches with available food sources.

OA may decrease habitat or alter reproductive behavior and prey availability for horse-eye jack in FGBNMS. Additionally, the shape and growth of otoliths may be altered under acidified conditions, although further research is needed to determine specific impacts on local horse-eye jack populations.

Storms can have direct effects on the species' preferred habitat such as physical destruction or smothering of the reefs as well as changes in salinity near the coast where larval transport occurs. Increasing intensity of storms may coincidentally reduce the recovery period for horse-eye jack between major storm events.

Harvest was identified by the participants as the most significant non-climate stressor on horse-eye jack. Fishing is limited to conventional hook and line gear within FGBNMS. However, bandit rigs (multiple hooks near the seafloor originating from one line) are allowed and if used, could remove multiple individuals with each effort. This species is not included in any U.S. fishery management plans. Participants noted a significant need for pelagic fish research and for collaboration with the GOM FMC. Additionally, horse-eye jack displays less skittish behavior than groupers and snappers, and thus might be easier to include in monitoring and evaluations.

Finally, adaptive capacity for horse-eye jack was estimated as high for all climate stressors. For ecological potential, distribution and connectivity, dispersal, and genetic diversity were ranked superior, and phenotypic and behavior plasticity and generalist ability were ranked as good, due to their wide distribution. Value and importance were ranked as fair based on their stability and value as a recreational species. The social potential was moderate, as there is a need for pelagic fish research and greater collaboration with the GOM FMC.

Roughtongue Bass (Pronotogrammus martincensis)

Table 3.7 Influence of climate change on roughtongue bass from RVA scores.

Roughtongue Bass ***P. martincensis***	**Increased water temperature**	**Ocean acidification**	**Storm Severity/Frequency**
Likelihood	**Unlikely**	**Unlikely**	**Unlikely**
Consequence	**Minor**	**Negligible**	**Minor**
Risk	**Low**	**Low**	**Low**
Adaptive Capacity	**High**	**High**	**High**
Vulnerability	**Low**	**Low**	**Low**

Species overview

Roughtongue bass (*Pronotogrammus martincensis*; family Serranidae (sea bass)) is a small but relatively fast-growing fish with a wide distribution across the western Atlantic basin, found from New Jersey, Bermuda, and northern GOM to central Brazil. Brightly colored, roughtongue bass has a peach to pink body, with yellow to orange spots and blotches on the front half of the body, just behind the operculum. A bright smudge, deeper orange in coloration, sometimes extends downward from the dorsal fin to mid-body. Like other Anthias (subfamily Anthiinae), roughtongue bass have elongated bodies, though they are deeper bodied than the similar-sized threadnose bass (*Choranthias tenuis*), another Anthias observed often among roughtongue bass. Common adult size is 16 cm TL, with a maximum of 20 cm TL (Anderson et al., 2015). With a depth range of 65–230 m, roughtongue bass is abundant on mesophotic reefs in the GOM (Bierman & Szedlmayer, 2021). They are demersal, remaining close to the substrate but darting short distances to feed on zooplankton. Its diet also consists of crustaceans, ostracods, copepods, and pteropods (Heemstra et al., 2002). This species has been found around soft corals in association with the stony corals *Oculina* or *Madrepora*. Roughtongue bass are a food source for larger predators like groupers and snappers, and for invasive lionfish, making them an important trophic link for energy transfer in the mesophotic systems.

Roughtongue bass are protogynous hermaphrodites, with half of females changing sex to males within the first year, and spawning occurring primarily from February to July (McBride et al., 2009). With a lifespan of 15 years, this species lives longer than other small serranids which may contribute to its high abundance and wide distribution (McBride et al., 2009). Relatively long life and early maturation enhances the species persistence. Roughtongue bass was last assessed for The IUCN Red List of Threatened Species in 2012 and was listed as “least concern” (Anderson et al., 2015). This species is of no interest to fisheries, although it has occasionally occurred in the aquarium trade.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\text{CO}_2$), and storm severity and frequency (including precipitation). Roughtongue bass was unlikely to be impacted by all three climate stressors. Workshop participants also evaluated roughtongue bass in FGBNMS to have a low relative vulnerability to all three climate stressors, as this species would be unlikely to be directly impacted by climate stressors, unless its habitat experienced significant degradation. However, the group noted low confidence in the certainty of estimating impacts of OA as a climate stressor.

Increasing seawater temperatures at FGBNMS may result in changes in the reproductive season and operational sex ratio (ratio of fertilizable females to sexually mature males) for roughtongue bass, as well as shorten their larval stage, which could create mismatches with available food sources (trophic-level disruptions). Shifts in direction and intensity of currents are expected, partly because of the increased SST. Changes in current could affect larval recruitment and, again, create mismatches with available food sources for roughtongue bass.

Storms can have direct effects on the species' preferred habitat such as physical destruction or smothering of the reefs as well as changes in salinity near the coast where larval transport occurs. Increasing intensity of storms may coincidentally reduce the recovery period for roughtongue bass between major storm events. However, participants noted this species occurs in deeper habitats, far from the impact of storms on the shallower water systems.

Participants identified invasive lionfish preying upon roughtongue bass as the most significant non-climate stressor. Increasing SST may expand habitat lionfish find suitable and more intense storms may increase dispersal of lionfish, which may lead to increased predation of roughtoungue bass.

Finally, adaptive capacity for roughtongue bass was estimated as high for all climate stressors. The ecological potential of roughtongue bass is high due to its distribution and connectivity and its life history of fast growth and early maturation. The social potential is also high, mainly due to this species' stability, and the potential to learn more about the species and change monitoring protocols.

Brown Chromis (Azurina multilineata) and Bluehead Wrasse (Thalassoma bifasciatum)

Table 3.8 Influence of climate change on blue chromis and bluehead from RVA scores.

Blue Chromis/Bluehead ***A. multilineata/ T. bifasciatum***	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Unlikely**	**Unlikely**	**Possible**
Consequence	**Minor**	**Minor**	**Minor**
Risk	**Low**	**Low**	**Moderate**
Adaptive Capacity	**High**	**High**	**High**
Vulnerability	**Low**	**Low**	**Low**

Species overview

Brown chromis (Azurina multilineata)

The brown chromis (*Azurina multilineata*) is a tropical marine fish widely distributed throughout reefs in the tropical Atlantic. Its range extends from Florida and Texas throughout the Caribbean Sea to Brazil in the Western Atlantic and from St. Helena and Ascension Islands to Principe and Cape Verde Islands in the Eastern Atlantic (Kells & Carpenter, 2011). Brown chromis occur over steep slopes and patch reefs ranging in depth from 0–40m.

These fish are brownish-gray or olive-brown in color with a dark spot at the base of the pectoral fins and a white spot at the rear of the dorsal fin; however, this white spot may be absent. The border of the dorsal fin and tips of the caudal fin are yellow. Brown chromis can grow to a maximum length of 20 cm with average lengths between 7–12 cm. They feed on plankton, primarily copepods, forming feeding aggregations above the reef tops. These fish often form moderate-sized schools, however there may be solitary fish throughout the reef habitat (Myrberg et al., 1967). Brown chromis are generalists in terms of depth, exposure, and substrate level (Krajewski & Floeter, 2011). Brown chromis are one of the most abundant fish in FGBNMS (Hickerson et al., 2008) and one of the most common prey species of the invasive lionfish (*Pterois volitans*) (Johnston et al., 2019). Other predators of this fish include other larger fish species such as snappers and groupers.

Bluehead Wrasse (Thalassoma bifasciatum)

The bluehead wrasse (*Thalassoma bifasciatum*) is found widespread throughout the tropical northwestern Atlantic in Bermuda, Florida, the GOM, and Caribbean Sea to Venezuela (Kells & Carpenter, 2011) and are one of the most common fish found in FGBNMS (Hickerson et al., 2008; Johnston et al., 2019). This fish is associated with coral reefs, having high residency and site fidelity after settlement on the reefs (Warner & Schultz, 1992).

Bluehead wrasse are protogynous hermaphrodites with three main stages: juvenile, initial, and terminal (Munday et al., 2006; Warner & Schultz, 1992). The initial and juvenile phase fish are yellow dorsally and white ventrally with purple or pale red bands across the head. They have a black spot at the front of the dorsal fin and may have a dark lateral stripe along the body. The initial phase fish may be male or female. Terminal blueheads have a blue head and green body with two broad black vertical bars forming a V-shape with white in between. Terminal phase blueheads are all male with the largest of the species growing up to 25 cm in length (Warner & Swearer, 1991). Blueheads are generalist feeders preying on zooplankton, small benthic invertebrates, and ectoparasites found on other fish. They are prey to the invasive lionfish as well as to morays, groupers, and other large predatory fish.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\text{CO}_2$), and storm severity and frequency (including precipitation). Brown chromis and bluehead wrasse were combined in one assessment by the workshop participants as the two species fill similar niches on the reef and are not likely to have different responses to climate change in the 50-year timeframe of this assessment. The likelihood of the evaluated climate stressors impacting brown chromis and bluehead wrasse were deemed to be unlikely for rising temperatures and OA, and possible for storm alterations. Brown chromis and bluehead wrasse were evaluated to have low vulnerability to all three climate stressors with minor consequences of climate and non-climate stressors. Participants agreed these species have high adaptive capacity and therefore climate change will not have significant impacts on these fish in the next 50 years. Invasive species were selected as the only significant non-climate stressor to these species in FGBNMS.

Increased SST will likely have no direct effect on brown chromis and bluehead wrasse populations in FGBNMS but may impact the species via impacts on their habitat. These species are found in much warmer climates than FGBNMS and therefore increased temperature will most likely have negligible impacts on these two species due to their high thermal tolerance. Significant loss of structure due to increasing temperatures may cause declines in populations; however, this is unlikely to happen in the next 50 years.

OA effects, such as changes in oceanic pH and Ω_{Ar} levels are also likely to have minimal effects on brown chromis and bluehead wrasse. Indirectly, OA will impact these species via reef structure loss, however this may take longer than 50 years to affect these fish populations. There may be some effects of OA on sensory and olfactory abilities as well as otolith growth, however more knowledge in this area of research is needed for a more confident assessment.

Most impacts of storms on brown chromis and bluehead wrasse are likely to be from habitat damage. While fish may be dispersed during storms, they are likely to return to the reefs, and therefore storms will not have a lasting impact on these populations.

Invasive lionfish are the largest threat to brown chromis and bluehead wrasse in FGBNMS. These two fish species are the most common prey items found in the stomachs of lionfish caught in the sanctuary. Increasing SST may expand the suitable habitat for lionfish causing a growth in population in the area, leading to decreases in their prey. Similarly, storms may increase the dispersal of lionfish across the reefs expanding their presence within the sanctuary, again potentially leading to decreases in their prey. Higher density of lionfish will result in increased predation of brown chromis and bluehead wrasse. Additionally, a similar-looking species to brown chromis, the non-native regal demoiselle (*Neopomacentrus cyanomos*) has been sighted in FGBNMS since 2018 and may outcompete similar small, schooling fish such as brown chromis (Moretzsohn et al., 2012).

Finally, adaptive capacity for brown chromis and bluehead wrasse was estimated as high for all climate stressors. The ecological potential of brown chromis and bluehead wrasse ranged from good to superior due to high value and importance, phenotypic and behavioral plasticity, and role as generalists. The social potential ranged from fair to superior, mainly due to the stability of these species.

Stoplight Parrotfish (Sparisoma viride)

Table 3.9 Influence of climate change on stoplight parrotfish from RVA scores.

Stoplight Parrotfish *S. viride*	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Unlikely**	**Unlikely**	**Possible**
Consequence	**Minor**	**Minor**	**Minor**
Risk	**Low**	**Low**	**Moderate**
Adaptive Capacity	**High**	**High**	**High**
Vulnerability	**Low**	**Low**	**Low**

Species overview

Stoplight parrotfish (*Sparisoma viride*) are protogynous hermaphrodites with three phases: juvenile, initial, and terminal (Loera-Padilla et al., 2022). Juvenile stoplight parrotfish are reddish-brown with three rows of evenly spaced white spots along the side and usually a white band on the caudal fin. Initial phase fish have a mottled black and white head with pale white scales outlined in a dark color on the upper body and bright red on the belly and fins. Initial phase fish can be either male or female. Terminal adults are always male and colorful with a blue to green body with pinkish bands across the head, a bright yellow spot on the upper operculum, and a yellow blotch at the base of the caudal fin. Stoplight parrotfish are found in the tropical western Atlantic from Florida to Brazil including Bermuda, the GOM, and throughout the Caribbean. They are very common throughout their range, often found on coral reefs and seagrass beds at depths from 1–50 m (Hawkins & Roberts, 2004).

This species is mainly herbivorous, feeding on soft algae associated with dead coral substrates (Bruggemann et al., 1994). Stoplight parrotfish may also graze occasionally on live corals (Rotjan and Lewis, 2005; Burkepile et al., 2019). This fish along with other parrotfish species are extremely important for producing sediment via bioerosion as well as controlling algae growth (Comeros-Raynal et al., 2012). Terminal males can grow to a maximum length of 64 cm with average length of initial and terminal adults ranging from 30–40 cm. This fish is frequently solitary but may form small groups as juveniles and young adults. While some Caribbean nations, such as Jamaica and Dominica, have commercial and artisanal fisheries for stoplight parrotfish, contributing to decreasing abundance in those areas (Hawkins & Roberts, 2004), there is no known fishery for this species in FGBNMS.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\mathrm{CO}_2$), and storm severity and frequency (including precipitation). Temperature and OA changes are unlikely to impact stoplight parrotfish, while storm alterations was found to have a possible likelihood. The stoplight parrotfish was also given a low vulnerability to climate change. The participants agreed climate change in the next 50 years will not have major impacts on this species due to its ubiquitous nature. Very drastic changes would need to happen to influence this species. Therefore, only one non-climate stressor, invasive species, was chosen and evaluated as other non-climate stressors did not have a major or direct impact on stoplight parrotfish in FGBNMS.

Increasing sea water temperature at FGBNMS is not likely to have any direct impacts on the stoplight parrotfish in the sanctuary. As a primarily herbivorous species, increased algal cover due to higher temperature may even be beneficial towards population growth. Structural damage may influence this species, however there would have to be significant degradation to the reef to impact this fish, which most likely will take longer than 50 years to occur.

Effects on the reef structure due to OA such as loss of coral skeleton could impact stoplight parrotfish; however, there would need to be critical damage to the reef structure to make a significant change to stoplight parrotfish populations of FGBNMS. This species has been observed on low rugosity and dying reefs consisting mainly of coral rubble and therefore it will most likely survive substantial loss to reef structure. The direct effect of OA on stoplight parrotfish is mostly unknown and not well documented. Some effects of lower pH and Ω_{Ar} may include impacts on olfactory and other sensory capabilities as well as otolith growth.

Stronger storms may temporarily displace stoplight parrotfish, making them more susceptible to pelagic predators. However, this will not likely be a lasting effect as the fish will most likely return to the reefs. There would need to be significant structural damage to the reef to impact these parrotfish.

Invasive lionfish are opportunistic feeders and may feed on juvenile and small individual stoplight parrotfish. Climate change is most likely to increase lionfish populations at the sanctuary and therefore predation on stoplight parrotfish may also increase.

Overall, stoplight parrotfish had a high adaptive capacity score, yielding good ecological potential with high value and importance, and good overall social potential.

Finally, adaptive capacity for stoplight parrotfish was estimated as high for all climate stressors. The ecological potential of parrotfish ranged from fair to superior due to its value as a key herbivorous fish. The social potential is ranged from fair to superior due to the knowledge of this species by staff, research partners, and citizen scientists, as well as their stability.

Wahoo (Acanthocybium solandri)

Table 3.10 Influence of climate change on wahoo from RVA scores.

Wahoo ***A. solandri***	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Almost certain**	**Possible**	**Unlikely**
Consequence	**Major**	**Minor**	**Minor**
Risk	**Extreme**	**Moderate**	**Low**
Adaptive Capacity	**Moderate**	**Moderate**	**Moderate**
Vulnerability	**High**	**Moderate**	**Low**

Species overview

Wahoo (*Acanthocybium solandri*) are an epipelagic species found globally in tropical and subtropical waters in the Pacific, Indian, and Atlantic oceans including the Caribbean and Mediterranean seas. In the western Atlantic, they can be found from North Carolina through the Caribbean and GOM, down to Northern Brazil (Oxenford et al., 2003). While they are present year-round through the Caribbean and GOM, wahoo have seasonally high abundance in these areas from winter to late spring, aggregating around EFGB, WFGB, Geyer Bank, Sonnier Bank, and Bright Bank (personal communication, Capt. Scott Hickman, 2023). This species prefers warm waters between 20–30 ^{0}C but has been observed in waters as cool as 11 ^{0}C (Sepulveda et al., 2011).

Part of the mackerel family, wahoo have an elongated body shape with irregular iridescent blue vertical bars across the body and a long, pointed snout. They are fast growing and early maturing, reaching a maximum fork length of 210 cm with an average length between 90–130 cm and sexually maturing around 1 year (Oxenford et al., 2003; Gao et al., 2020;). Larval and juvenile stages are found around drifting objects including sargassum; however, adults may also congregate in the vicinity of floating objects. There are commercial, artisanal, and recreational fisheries for wahoo throughout its global range with a steady increase in landings over the past 30 years (Oxenford et al., 2003).

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\mathrm{CO}_2$), and storm severity and frequency (including precipitation), all of which had possible likelihoods of impacting wahoo in FGBNMS. Wahoo are almost certain to be impacted by rising temperatures, may possibly be affected by OA, and are unlikely to be impacted by storm alterations in the next 50 years. The workshop participants evaluated wahoo to have a high vulnerability to temperature, moderate vulnerability to OA, and low vulnerability to alterations in storm patterns. As a pelagic species, wahoo are susceptible to some stressors while resilient to others. One of the major threats to this fish is harvest, which was chosen as one of the non-climate stressors. It is difficult to determine whether changes to this species, specifically population declines, are due to climate change or fishing pressures and further research and information would be required to make those distinctions.

Increasing SST will have the biggest impact on wahoo and potentially other pelagic species. With a narrow temperature tolerance, it is unlikely that wahoo would continue to be present at FGBNMS if temperatures reach above wahoo upper tolerance limit of 30 °C. It is predicted there will be an increase of 1.25–3.5 °C over the next 50 years in the GOM, and with the current sanctuary temperature range between 18.8–30.8 °C, this may impact the already decreasing abundance of wahoo in FGBNMS.

OA may have impacts on Wahoo prey species, such as cephalopods and crustaceans, or floating habitat structure such as sargassum. Floating habitat is critical for larval and juvenile stages of wahoo and adults are likely to present near these habitats as well. Very low pH may impact the growth and shape of otoliths as well as larval development of wahoo.

The workshop participants agreed wahoo will be least affected by storm severity. As a pelagic species, these fish can swim great distances and easily travel away from storms. Storm alterations may temporarily displace wahoo out of the sanctuary, but they will remain within their natural range. Storms may also reduce fishing pressures as fishers are less likely to go out in storms.

The largest threat to wahoo is harvest. There has been a rapid increase in wahoo landings over the past 30 years in the western Atlantic. Increased boat registrations, technological advancements, and increased number of anglers have tremendously increased fishing effort in the northern GOM. Local anglers have noticed a steady decline in wahoo abundance in FGBNMS over the past 10 years and with little to no management of wahoo, this is unlikely to change. Land-sourced nutrient and non-nutrient pollution were listed as additional non-climate stressors on wahoo.

Finally, adaptive capacity for wahoo was estimated as high for all climate stressors. For ecological potential, distribution and connectivity (wahoo are well distributed), value (prized tournament fish), phenotypic and behavior plasticity, and generalist abilities were ranked as good, while dispersal (they are highly mobile) was ranked as superior. Although FGBNMS is a well-managed organization with strong partnerships, considering the societal potential adaptive capacity only in relation to its impact on climate stressors, variable rankings ranged from critical to good, as the sanctuary program does not manage fish and there is no fishery management plan for wahoo in the GOM.

3.2.2 Shallow Invertebrate Species

Great Star Coral (Montastraea cavernosa)

Table 3.11 Influence of climate change on *M. cavernosa* from RVA scores.

Great Star Coral M. cavernosa	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Almost certain**	**Likely**	**Possible**
Consequence	**Major**	**Moderate**	**Minor**
Risk	**Extreme**	**High**	**Moderate**
Adaptive Capacity	**Moderate**	**Moderate**	**Moderate**
Vulnerability	**High**	**Moderate**	**Low**

Species overview

Montastraea cavernosa, also known as great star coral, is a species of the genus *Montastraea*, which are colonial stony corals ranging across the Atlantic Ocean, occurring in the Caribbean Sea, GOM, Bahamas, Bermuda, Brazil, and some parts of West Africa (Vaughan, 2015). *M. cavernosa* can appear a red, green, or brown coloration and is dome-shaped, usually forming massive boulders. *M. cavernosa* is usually found at depths of 0.5–5 m and observed from 16–55 m at FGBNMS (FGBNMS 2008; Johnston et al., 2021). *M. cavernosa* exhibits two types of activity: nocturnal, where polyp expansion occurs at night, and diurnal, where polyp expansion occurs both night and day. The species may exhibit both autotrophic and heterotrophic feeding strategies; they use their tentacles to feed on suspended zooplankton.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\text{CO}_2$), and storm severity and frequency (including precipitation), all of which had possible likelihoods of impacting *M. cavernosa* in FGBNMS. Rising temperatures were almost certain to impact *M. cavernosa*, while OA was likely and storm alterations were possible to impact this species. *M. cavernosa* had a high vulnerability to temperature, moderate vulnerability to OA, and low vulnerability to alterations in storm patterns. Workshop participants determined that the non-climate stressors currently affecting *M. cavernosa* in FGBNMS are land-source nutrient pollution or sedimentation and disease.

Some anticipated effects of increased temperature, both direct and indirect, on this species are increased bleaching, increased susceptibility to some diseases, reduced reproduction, increased mortality of spawning products, reduced calcification, decreased immunity, possible changes in microbiomes, and increased mortality.

Some anticipated effects of lowered pH on *M. cavernosa* are reduced calcification, reduced growth, increased bioerosion or compromised structure, damage or decrease in skeleton density, increased susceptibility to other impacts, and a possible metabolic trade-off where *M. cavernosa* may prioritize growth over spawning or vice versa.

Some anticipated effects of increased storm severity are increased run-off and increased pollution or sedimentation, increased potential for disease and bacteria, increased turbidity, possible cooling of water temperatures, and impacts on larvae survival.

Land-source nutrient pollution and sedimentation could cause algal blooms, increasing competition and decreasing light availability for *M. cavernosa*. This could result in low oxygen events as were observed in 2016, when *M. cavernosa* was more highly impacted than many other species. Decreased light penetration due to turbidity will decrease photosynthesis and calcification, with interactions with temperature, OA, and storms resulting in possible impacts on spawning and increased bio-erosion. Disease could cause coral mortality and spread quickly, decreasing coral overall immunity, and altering the natural microbiome. Storms could exacerbate the spread of disease.

Finally, adaptive capacity for *M. cavernosa* was estimated as moderate for all climate stressors. For ecological potential, distribution, connectivity, and dispersal were ranked as poor, due to the relative isolation of FGBNMS. Phenotypic and behavior plasticity and genetic diversity were ranked as fair, as this species is sensitive to bleaching. Value and generalist abilities were ranked as good, due to the value of this species as a dominant reef building coral. For societal potential, all variables were ranked as good due to the long-term monitoring and knowledge of this species.

Mustard Hill Coral (Porites astreoides)

Table 3.12 Influence of climate change on *P. astreoides* from RVA scores.

Mustard Hill Coral P. astreoides	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Likely**	**Likely**	**Unlikely**
Consequence	**Moderate**	**Moderate**	**Minor**
Risk	**High**	**High**	**Low**
Adaptive Capacity	**High**	**High**	**High**
Vulnerability	**Moderate**	**Moderate**	**Low**

Species overview

Porites astreoides, also known as mustard hill coral, is a stony coral species in the family Poritidae (Rowland & Wood, 2022). The species is found in the Bahamas, Caribbean, Bermuda, GOM, and Florida. *P. astreoides* is a flat coral with a hemispherical shape; it is typically a yellow to brown color covered with small bumps. *P. astreoides* usually grow in depths ranging from 0.5–15 m and can be found in both shallow and deep waters; its shape varies with depth. In the FGBNMS, *P. astreoides* can be found in the shallowest zone, the coral reef zone, which occurs at depths between 16–44 m. *P. astreoides* is typically flat and encrusting in shallow waters and dome shaped in deeper waters. *P. astreoides* use suspension feeding via tentacles to capture prey, primarily feeding at night when there is a decreased chance of predation. Zooplankton and bacteria are the main prey of *P. astreoides*.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\text{CO}_2$), and storm severity and frequency (including precipitation). Temperature and OA are likely, and storm alterations are unlikely, to impact *P. astreoides*. *P. astreoides* were determined to have a moderate vulnerability to rising temperatures and OA, and a low vulnerability to storm pattern alterations. Workshop participants determined that the non-climate stressors currently affecting *P. astreoides* in FGBNMS are land-source nutrient pollution or sedimentation and disease.

Some anticipated effects of increased temperature, both direct and indirect, on this species are increased paling or bleaching, increased mortality risk, reduced reproduction, increased mortality of spawning products, reduced calcification, and possibly decreased immunity or changes in microbiomes.

For OA, as pH and Ω_{Ar} continue to decline over the next 50 years, and mean $p\text{CO}_2$ continues to rise with atmospheric levels, some anticipated effects on *P. astreoides* are reduced calcification and lack of suitable habitat for *P. astreoides* recruits, reduction in growth, metabolic trade-offs (prioritizing growth over spawning or vice versa), increased bio-erosion or compromised structure, increased susceptibility to other impacts or damage or decrease to skeleton density, and decrease in reproductive output.

For storm severity and frequency, if storm severity increases and extreme precipitation events become more common in the GOM, there will be increased local sedimentation and increased turbidity, which can cause cooling of water temperatures. It should be noted that *P. astreoides* is likely to be smothered due to sedimentation; however, *P. astreoides* is hardy with respect to the physical impact of storms.

Land-source nutrient pollution and sedimentation (runoff) could cause algal blooms, increasing competition and decreasing light availability for *P. astreoides*. This non-climate stressor could also lead to low-oxygen events as was observed in FGBNMS in 2016. Turbidity could exacerbate the low light penetration, further lowering photosynthesis and calcification for *P. astreoides*. Disease is another factor which is likely to impact *P. astreoides* in the FGBNMS.

Finally, adaptive capacity for *P. astreoides* was estimated as high score for all climate stressors. For ecological potential, dispersal and genetic diversity was ranked as poor due to the relative isolation of FGBNMS. Distribution and connectivity were ranked as fair. Value and phenotypic and behavior plasticity were ranked as good due to their dominance as a high coral cover species at FGBNMS. The generalist abilities were ranked as superior, due to their ability to withstand disease and bleaching. For societal potential, all variables were ranked as good or superior due to the long-term monitoring and knowledge of this species.

Boulder Star Coral (Orbicella franksi)

Table 3.13 Influence of climate change on *O. franksi* from RVA scores.

Boulder Star Coral *O. franksi*	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Almost Certain**	**Likely**	**Likely**
Consequence	**Major**	**Moderate**	**Minor**
Risk	**Extreme**	**High**	**Moderate**
Adaptive Capacity	**Moderate**	**Moderate**	**Moderate**
Vulnerability	**High**	**Moderate**	**Moderate**

Species overview

The *Orbicella* sp. complex are the predominant hermatypic (i.e., reef building) corals of the Caribbean region (Goreau, 1959), with *O. franksi* (boulder star coral) the predominant species found in FGBNMS. All three species of the *Orbicella* sp. complex are listed as threatened in the Endangered Species Act, though they are found in larger numbers within the sanctuary. *O. franksi* grows in irregular colonies that encrust or form plates over its substrate (Weil & Knowton, 1994), eventually forming large coral mounds that are generally green to brown in color. Its coralites are 2.4–3.4 mm in diameter and grow irregularly (Weil & Knowton, 1994). The species is known for its irregular, warty shape which can cause paling within the tissues and Christmas tree tube worms often embed into the coral's skeleton.

O. franksi, as well as the rest of its family, is a well-studied species due to its large range within the Atlantic and the species predominance (Weil & Knowton, 1994). Studies on comparative thermal performance relative to its latitudinal range limits found the species can thermally adapt or acclimate to thermal metrics within its range (Silbiger et al., 2019). The same study found that at thermal limits, calcification is the most sensitive function before photosynthesis and respiration (Silbiger et al., 2019). Increasing temperatures have in the past found to aid *O. franksi*, along with *Pseudodiploria strigosa*, in its calcification within FGBNMS, but is likely to be at the tipping point where thermal stressors are setting in (Manzello et al., 2021). Thermal stressors have also been found to have a negative effect on the coral's ability to spawn in the long term (Levitan et al., 2014) leading to increasing SST to be a large concern for *O. franksi* and its greater *Orbicella spp*. complex.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\text{CO}_2$), and storm severity and frequency (including precipitation), all of which had possible likelihoods of impacting *O. franksi* in FGBNMS. *O. franksi* had almost certain likelihood of impact from rising temperatures and OA, and likely impact from storm alterations, with overall high vulnerability to temperature changes and moderate vulnerabilities to OA and storm alterations at FGBNMS. Non-climate stressors impacting *O. franksi* were identified by workshop participants as land-source nutrient and non-nutrient pollution, invasive species (orange cup coral), and disease.

Increased SSTs were forecast to cause large amounts of bleaching and coral mortality over the next 50 years. As *O. franksi* is the largest FGBNMS reef builder, increased bleaching and mortality would result in loss to reef structure (FGBNMS, 2019). Increasing SST may increase the growth rates of algae. These algae would grow over where the corals used to be and would impact their recovery potential, as well as decreasing the space in which the corals could colonize through spawning. Thermal stressors will decrease the ability for the coral to spawn, while also increasing the mortality of spawning products, leading to an overall decrease of spawning success (Levitan et al., 2014). While some past studies have shown increasing temperatures could aid in calcification, the same study shows FGBNMS could be at a tipping point where bleaching events will reduce any benefits (Manzello et al., 2021).

Decreasing Ω_{Ar} could cause reduced calcification of *O. franksi* corals putting them at risk of a reduction of structural complexity. These effects could make *O. franksi* subject to excessive bioerosion. Due to lower skeletal densities, the coral would be more susceptible to damage from impacts or other events.

Changes in storm severity and frequency are likely to increase toppling events of *O. franksi* coral heads within the sanctuary, especially at shallower or more exposed parts of the reef. While these toppling events already occur within the sanctuary, it is thought these events will become more common and will increase physical damage to the *O. franksi* coral heads. The resulting runoff from these storms will increase run-off pollution and sedimentation within the sanctuary. The chemical stress from run-off pollution and the increased turbidity from sedimentation could reduce the growth potential of the *O. franksi* corals. Run-off holds the potential as a vector for disease and bacteria to enter the sanctuary that is not already present.

In addition to the three climate stressors evaluated in the assessment, land-source nutrient and non-nutrient pollution (as a combined nutrient and non-nutrient stressor), invasive species, and disease were picked as non-climate stressors to *O. franksi*. Excess nutrients from land-source nutrient pollution could negatively impact *O. franksi* zooxanthellae, depending on the kinds and concentrations. Increased turbidity from land-source pollution could limit photosynthesis and calcification leading to decreased coral health. Nutrients that benefit algae in combination with increasing SST could increase their growth, reducing coral recruitment area and promoting overgrowth. Increasing severity of tropical storms in the GOM would act as pulse events for rapid land-source pollution. Overall, the effects of land-source nutrient and non-nutrient pollution is expected to become worse with climate change. The invasive orange cup coral (*Tubastraea sp.*) can act as a space competitor to many coral species, including *O. franksi.* Orange cup coral may be more resilient to increasing SST due to its lack of zooxanthellae and is believed to fare better than *O. franksi* at lower Ω_{Ar}. Its ability to thrive in disturbed areas could benefit the orange cup coral in areas affected by tropical storms, increasing its overall coverage and aiding its distribution. The last non-climate stressor selected was disease (due to SCTLD concerns). Increased stress with increased SST and changes to OA will likely exacerbate the effects of coral diseases. Meanwhile, changes to storm frequency and severity could help the dispersal of diseases. Climate change could make the effects of disease worse, but there is more to learn about how the effects interact.

O. franksi had a moderate adaptive capacity score, with fair to good ecological potential but critical to poor social potential. Participants noted that social potential scores were low not because of poor interest or efforts of FGBNMS staff, but, rather, due to limited abilities to assist this species when faced with severe and global impacts of climate change.

Finally, adaptive capacity for *O. franksi* was estimated as high for all climate stressors. For ecological potential, distribution and connectivity and genetic diversity was ranked as poor, due to the relative isolation of FGBNMS. Dispersal and phenotypic and behavior plasticity were ranked as fair, and value and generalist abilities were ranked good due to the dominance of *O. franksi* as a high coral cover species at FGBNMS. For societal potential, all variables were ranked as critical or poor due to limitations in abilities to address climate changes for this species in general (i.e. sensitivity of this species to disease and bleaching and the limited capacity of FGBNMS to respond).

Symmetrical Brain Coral (Pseudodiploria strigosa)

Table 3.14 Influence of climate change on *P. strigosa* from RVA scores.

Symmetrical Brain Coral *P. strigosa*	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Almost Certain**	**Likely**	**Likely**
Consequence	**Major**	**Moderate**	**Minor**
Risk	**Extreme**	**High**	**Moderate**
Adaptive Capacity	**Moderate**	**Moderate**	**Moderate**
Vulnerability	**High**	**Moderate**	**Moderate**

Species overview

Pseudodiploria strigosa, commonly known as the symmetrical brain coral, is a hermatypic coral that can be found throughout the Caribbean region and can grow near the surface and down to approximately 40 m (Kluijver et al., 2022). Much like other brain coral species, *P. strigosa* grows in a hemispherical dome in convoluted valleys with a smooth ridge made of the costa (Kluijver et al., 2022). The ridges tend to straighten out as they approach the edge of the coral head and do not connect, or form a skirt, like *Colpophyllia natans*. *P. strigosa* can be green to brown in color but can occasionally be found as blue or green-gray (Kluijver et al., 2022).

P. strigosa populations have been found to be growing, alongside *P. astroties*, outside of the sanctuary and are projected to continue to grow within and outside of FGBNMS in the next 100 years (Edmunds, 2010). However, increasing SST that have benefited the calcification of *P. strigosa* in the past are believed to be at a tipping point where thermal stressors are setting in, like *O. franksi* (Manzello et al., 2021). Increasing SSTs are also of concern for fertilization and embryogenesis as extended periods of high temperatures will dramatically affect embryonic development and larval viability (Bassim et al., 2001).

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\text{CO}_2$), and storm severity and frequency (including precipitation), all of which had possible likelihoods of impacting *P. strigosa* in FGBNMS. The vulnerability assessment for *P. strigosa* was found overall to be like *O. franksi*'s assessment due to their similar niches within FGBNMS, with temperature and OA having almost certain likelihoods and storm alterations having likely impacts on the species. *P. strigosa* had high vulnerability to rising temperatures and moderate vulnerabilities to OA and storm alterations. Non-climate stressors were identified as land-source nutrient and non-nutrient pollution, invasive species (cup coral), and disease.

Increasing SSTs are predicted to cause large amounts of bleaching and coral mortality over the coming 50 years. With *P. strigosa* being the second largest reef builder in FGBNMS, increasing bleaching and mortality would result in a major loss to the reef structure (FGBNMS, 2019). Increasing SST may increase the growth of algae which would grow over areas lost to the dying corals and would impact recovery potential, and decrease the space in which the corals could colonize through spawning. Thermal stressors will decrease the ability for the coral to spawn, while also increasing the morality of the spawning products, leading to an overall decrease of spawning success (Levitan et al., 2014). Increased SST issues were found to be almost certain in the next 50 years and would have a major consequence, putting *P. Strigosa* at an extreme risk.

Decreasing Ω_{Ar} could cause reduced calcification of *P. strigosa* corals, putting them at risk of reduced structural complexity. These effects could make *P. strigosa* susceptible to excessive bioerosion or other compromised structure. Due to lower skeletal densities, the *P. strigosa* would be more susceptible to damages from impacts or other events. The effects of the decreased Ω_{Ar} were likely to happen in the next 50 years with a moderate consequence, putting *P. strigosa* corals at a high risk.

Changes in storm severity and frequency are likely to increase toppling events of *P. strigosa* coral heads within the sanctuary, especially at shallower or more exposed parts of the reef. While these toppling events already occur within the sanctuary, these events will become more common and increase physical damage to the *P. strigosa* coral heads. The resulting runoff from these storms will increase the run-off pollution and sedimentation within the sanctuary. The chemical stress from run-off pollution and the increased turbidity from sedimentation could reduce the growth potential of the *P. strigosa* corals. Run-off has the potential as a vector for disease and bacteria to enter the sanctuary that is not already present. The effects of changes in store severity and frequency were likely to happen but with only minor effects, putting *P. strigosa* corals at a moderate risk.

In addition to the three climate stressors evaluated in the assessment, land-source nutrient and non-nutrient pollution (as a combined nutrient and non-nutrient stressor), invasive species, and disease were picked as non-climate stressors to the *P. strigosa*. Excess nutrients from land-source nutrient pollution could negatively affect *P. strigosa* zooxanthellae, depending on the kinds and concentrations. Increased turbidity from land-source pollution could limit photosynthesis and calcification leading to decreased coral health. Nutrients that benefit algae in combination with increasing SST could increase their growth, reducing coral recruitment area and promoting overgrowth. Increasing severity of tropical storms, in the GOM, would act as pulse events for rapid land-source pollution. Overall, the effects of land-source nutrient and non-nutrient pollution is expected to become worse with climate change. The invasive orange cup coral (*Tubastraea* sp.) can act as a space competitor to many coral species, including *P. strigosa*. The cup coral may be more resilient to increasing SST due to its lack of zooxanthellae and is believed to fare better than *P. strigosa* at lower Ω_{Ar}. Its ability to thrive in disturbed areas could benefit orange cup coral in areas affected by tropical storms, increasing its overall coverage and aiding its distribution. While the effects of the orange cup coral are forecast to worsen with climate change, it will be less impactful than land-source pollution and disease. The last non-climate stressor assessed was disease, with SCTLD noted as a particular concern. Increased stress with increased SST and changes to OA will likely exacerbate the effects of SCTLD and any other diseases. Meanwhile, changes to storm frequency and severity could help the dispersal of diseases. Climate change could make the effects of disease worse but there is more to learn about how the effects interact.

Finally, adaptive capacity *P. strigosa* was estimated as moderate for all climate stressors. For ecological potential, distribution and connectivity and genetic diversity was ranked as poor, due to the relative isolation of FGBNMS. Dispersal and phenotypic and behavior plasticity were ranked as fair, and value and generalist abilities were ranked good due to the dominance of *P. strigosa* as a high coral cover species at FGBNMS. For societal potential, all variables were ranked as critical or poor due to limitations in abilities to address climate changes for this species in general (i.e. sensitivity of this species to disease and bleaching and the limited capacity of FGBNMS to respond).

Giant Barrel Sponge (Xestospongia muta)

Table 3.15 Influence of climate change on X. muta from RVA scores.

Giant Barrel Sponge X. muta	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Almost certain**	**Unlikely**	**Almost certain**
Consequence	**Moderate**	**Negligible**	**Minor**
Risk	**High**	**Low**	**Moderate**
Adaptive Capacity	**Moderate**	**Moderate**	**Moderate**
Vulnerability	**Moderate**	**Low**	**Moderate**

Species overview

Xestospongia muta, also known as the giant barrel sponge, is a marine sponge in the family Petrosiidae. They are found in their highest concentrations near coral reefs off the coasts of Florida, Central America, and the Caribbean (Jorde, 2022). *X. muta* are benthic animals, living at depths from 10–30 m, and they are the largest sponge species found on Caribbean coral reefs. They are usually large and typically barrel-shaped, with a cone-shaped cavity at the apex known as the osculum. However, some individuals may be low and wide or tall and thin. The surface of the sponge can range from smooth to rough, and the color of the species is brownish-red to brownish-gray. Giant barrel sponges play an important ecological role, filtering large quantities of water which increases water clarity, controlling algae contributing to coral binding to substrate, and aiding in reef regeneration. These sponges provide a habitat for other invertebrates, benthic fish, bacteria, and cyanobacteria, which play an important role in carbon and nitrogen fixation; fixation of nitrogen by bacteria and cyanobacteria in giant barrel sponges can lead to the release of large amounts of dissolved inorganic nitrogen, providing a nutrient rich environment for algae.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\mathrm{CO}_2$), and storm severity and frequency (including precipitation). *X. muta* was moderately vulnerable to temperature and storm changes and had low vulnerability to OA. Workshop participants determined that the non-climate stressors currently affecting *X. muta* in FGBNMS are land-source nutrient pollution or sedimentation and disease.

As SST in the GOM increases over the next 50 years, some anticipated direct and indirect effects on this species are sponge bleaching and mortality, microbiome changes, or possible induction of disease or mortality by decreasing efficacy of sponge defense mechanisms allowing for development of pathogens. In addition, thermal stress can limit reproductive capacity by limiting dispersal and thermal stress may impact sponge feeding by changing filtration rates (in warm temperatures) and decreasing choanocyte chamber density and size, causing shifts in microbial communities of the host sponge. Seawater temperature increases could lower the availability or concentrations of planktonic food, lowering sponge growth rates and reproductive capacity.

For OA, as pH and Ω_{Ar} continue to decline over the next 50 years, and mean surface seawater $p\text{CO}_2$ continues to rise with atmospheric levels, some anticipated effects on *X. muta* are decreased growth, increased susceptibility to disease, and reduced stability of sponge microbiomes and their predicted functions.

For storm severity and frequency, if storm severity increases and extreme precipitation events become more common in the GOM, it could lead to physical disturbance resulting in a loss of sponges and impeded recovery of damaged sponges. More intense storms may also increase the scouring of sponge habitat, increased sedimentation (covering or clogging sponges), or displacing and upending sponges from their substrate.

Land-source nutrient pollution and sedimentation (runoff) could cause algal blooms which will increase competition and decrease light availability. This could lead to localized low-oxygen events such as was observed in 2016, where sponges were negatively impacted. However, land-sourced materials may benefit sponges by increasing food availability for these filter-feeding organisms. Diseases could cause mortality and spread quickly throughout FGBNMS, resulting in decreased immunity and changes in microbiomes in *X. muta*.

Finally, adaptive capacity for *X. muta*. was estimated as moderate for all climate stressors. For ecological potential, all values were ranked as fair (important filter feeder, provides habitat for fish, can be sensitive to temperature changes and disease) relative to impacts on this species in relation to climate stressors. Although FGBNMS is a well-managed organization with strong partnerships, considering the societal potential adaptive capacity only in relation to its impact on climate stressors, all social potential variables were ranked as good due to the long-term monitoring and knowledge of this species.

Orange Elephant Ear Sponge (Agelas clathrodes)

Table 3.16 Influence of climate change on *A. clathrodes* from RVA scores.

Orange Elephant Ear Sponge *A. chathrodes*	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Possible**	**Unlikely**	**Likely**
Consequence	**Minor**	**Negligible**	**Moderate**
Risk	**Moderate**	**Low**	**High**
Adaptive Capacity	**Low**	**Low**	**Low**
Vulnerability	**Moderate**	**Low**	**High**

Species overview

The orange elephant ear sponge *Agelas clathrodes* (Schmidt, 1870) has variable morphology, but typically is fan or ridge-shaped with multiple round and elongated holes. Larger specimens may have massive and tube-like areas, while smaller specimens can be encrusting. The surface is rough to verrucose, with membrane-bearing oscula (Smithsonian Tropical Research Institute, 2022). *A. clathrodes* resides deeper than 10 m (33 ft) below the sea surface, typically where currents are strong (Smithsonian Tropical Research Institute, 2022). Its distribution includes the Caribbean and parts of the Atlantic Ocean bordering the northern portion of the South American continent (World Register of Marine Species, 2022)

As a member of the class Demospongia, *A. clathrodes* is a filter-feeder that relies on choanocytes (flagellated cells) to generate currents through its canals and chambers (Van Soest et al., 2012). Microscopic food particles and oxygen are removed from the circulating water while waste products flow out of the larger holes with water currents (Van Soest et al., 2012). These hermaphroditic sponges (producing both gametes associated with male and female sexes) are known to participate in mass spawning events, whereby eggs and sperm are released into the water column in a synchronized manner (Hoppe, 1988b). *A. clathrodes* can also reproduce asexually through fragmentation (Hoppe, 1998b; Van Soest et al., 2012).

Sponges are increasing in abundance and in ecological importance on Caribbean reefs (Bell et al., 2013; Pawlik & McMurray, 2020; Shore et al., 2021). Sponge symbionts aid with the nitrogen cycle and contribute to organic matter production in oligotrophic habitats such as within FGBNMS (Van Soest et al., 2012). Sponges also may compete with other sessile organisms such as corals (Van Soest et al., 2012). *A. clathrodes* has high microbial abundance in its tissues, which can be disrupted following flood events (Shore et al., 2021). Wastewater contamination following severe storms may be one cause of the altered bacterial communities of *A. clathrodes* following floods (Shore et al., 2021). *A. clathrodes* is also known to contain anti-predation organic compounds (secondary metabolites) which may have unknown medicinal or ecological functions (Chanas et al., 1996).

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\text{CO}_2$), and storm severity and frequency (including precipitation). Temperature was thought to possibly impact *A. clathrodes*, while OA was unlikely and storm alterations were likely to impact the species. *A. clathrodes* had moderate vulnerability to rising temperature, low vulnerability to OA, and high vulnerability to storm alterations. For *A. clathrodes*, land-sourced non-nutrient pollution (including sediments) and disease were identified as the non-climate stressors.

Rising water temperatures in FGBNMS were thought to possibly alter spawning cues, exacerbate sponge disease, and increase disease susceptibility for *A. clathrodes* in the next 50 years. However, since *A. clathrodes* is a tropical and subtropical species and increased temperature may allow for greater plankton presence, there may be unknown benefits of rising water temperatures at the FGBNMS.

Sponges are known to be hardier relative to OA than corals due to the composition of their hard parts, which are made of siliceous spicules rather than aragonite and are less soluble in acidified seawater. Participants proposed OA will cause reduced recruitment of sponges due to increased algal overgrowth (less refugia).

Storm severity and precipitation increases may cause increased toppling (physical damage) to sponges (more severe at shallower depths) and increased run-off, pollution, sedimentation, and turbidity, which could reduce sponge growth due to smothering. Disease and bacterial community alterations (Shore et al., 2021) could also occur due to freshwater inflow, and storm activity during spawning could reduce successful fertilization.

Land-source non-nutrient pollution may cause occasional sedimentation over sponges that would not be fatal but would have unknown interactions with rising temperature and OA and would be exacerbated by increased storm severity (greater pulse events). Alternately, storm events interact with land-source pollution to benefit sponges by washing out heavy metals and other pollutants. Little is known about sponge disease in FGBNMS, but a die-off in 2016 at EFGB may have been associated with stress-induced disease (Shore et al., 2021). Higher temperatures will likely cause sponges to be more susceptible to disease, as disease vectors typically fare better at warmer temperatures. Storms may additionally spread disease, but the impacts of OA on sponge diseases is unknown.

Finally, adaptive capacity *A. clathrodes was estimated as* low for all climate stressors. For ecological potential, the distribution and connectivity and specialist ranking were ranked as poor, whereas this species had fair dispersal abilities, phenotypic and behavioral plasticity, and genetic diversity, and good value and importance (ecologically or societally), relative to impacts on this species in relation to climate stressors. It was noted that little is known about the phenotypic and behavioral plasticity or genetic diversity of *A. clathrodes*. Although FGBNMS is a well-managed organization with strong partnerships, considering the societal potential adaptive capacity only in relation to its impact on climate stressors, all social potential variables were ranked as critical.

Touch-Me-Not-Sponge (Neofibularia nolitangere)

Table 3.17 Influence of climate change on *N. nolitangere* from RVA scores.

Touch-Me-Not Sponge *N. nolitangere*	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Likely**	**Unlikely**	**Likely**
Consequence	**Moderate**	**Negligible**	**Moderate**
Risk	**High**	**Low**	**High**
Adaptive Capacity	**Low**	**Low**	**Low**
Vulnerability	**High**	**Low**	**High**

Species overview

The touch-me-not sponge *Neofibularia nolitangere* (Duchassaing and Michelotti, 1864) occurs as thick and encrusting (0.4–3.0 cm) or as massive to large vases (up to 80 cm wide and high) with cup-shaped cloaca on the apex, in morphology, and has been observed to be firm but fragile (Colin, 1978; Smithsonian Tropical Research Institute, 2022). The surface ranges from smooth and porous to corrugated and microhispid with a velvety texture, with oscules dispersed throughout (Smithsonian Tropical Research Institute, 2022), and it is deep brown to dark red (Colin, 1978). *N. nolitangere* typically resides 3-46 m below the sea surface on reef habitats (Colin, 1978; Smithsonian Tropical Research Institute, 2022) and is also commonly found in disturbed areas, where it may be considered a member of the fouling community. Its distribution includes much of the Caribbean and parts of the north Atlantic Ocean bordering the eastern U.S. (World Register of Marine Species, 2022). This sponge can cause pain or numbness to the skin when handled and a possibly severe allergic reaction (Colin, 1978).

As a member of the class Demospongia, *N. nolitangere* is a filter-feeder that relies on choanocytes (flagellated cells) to generate currents through its canals and chambers (Van Soest et al., 2012; World Register of Marine Species, 2022). Microscopic food particles and oxygen are removed from the circulating water while waste products flow out of the larger holes with water currents (Van Soest et al., 2012). A parasitic polychaete worm *Syllis spongicola* is often observed protruding from the cloacal walls of *N. nolitangere* (Colin, 1978). These sponges are known to orchestrate massive spawning events (Colin, 1978), but can also reproduce asexually through fragmentation (Van Soest et al., 2012).

Sponges are increasing in abundance and in ecological importance on Caribbean reefs (Bell et al., 2013; Pawlik & McMurray, 2020; Shore et al., 2021). Sponge symbionts aid with the nitrogen cycle and contribute to organic matter production in oligotrophic habitats such as FGBNMS (Van Soest et al., 2012). Sponges also may compete with other sessile organisms such as corals (Van Soest et al., 2012). *N. nolitangere* has anti-predatory mechanisms and rapid regeneration capacity and is well adapted to reef habitats (Hoppe, 1988a).

Vulnerability assessment results

The three climate stressors that were evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\mathrm{CO}_2$), and storm severity and frequency (including precipitation), with likely impacts from temperature and storm alterations, and unlikely impacts from OA on the species. *N. nolitangere* had high vulnerability scores for rising temperatures and storm severities, and a low vulnerability score for the OA climate stressor. For *N. nolitangere*, land-sourced non-nutrient pollution (including sediments) and disease were identified as the non-climate stressors.

Rising water temperatures in FGBNMS were thought to possibly alter spawning cues, exacerbate sponge disease, and increase disease susceptibility of *N. nolitangere* in the next 50 years. Since *N. nolitangere* resides in deeper waters (temperature range 22–28 °C) than *A. clathrodes*, increased temperature could have negative implications on this species. Alternately, increased temperature may allow for greater plankton presence, benefitting sponges.

Sponges are known to be more resilient to OA impacts than corals due to the composition of their hard parts, which are made of siliceous spicules rather than aragonite and are less soluble in acidified seawater. It is believed that OA will cause reduced recruitment of sponges due to increased algal overgrowth (less refugia), but the likelihood was ranked as unlikely with low confidence and high uncertainty. Storm severity and precipitation increases may cause increased toppling (physical damage) to sponges but will be less severe for *N. nolitangere* than *A. clathrodes* due to the increased water depth at which *N. nolitangere* resides. Increased run-off, pollution, sedimentation, and turbidity could reduce sponge growth due to smothering. Disease and bacterial community alterations (Shore et al., 2021) could also result from increased run-off, and storm activity during spawning could reduce successful fertilization.

Land-source non-nutrient pollution may cause occasional sedimentation of sponges that would not be fatal but would have unknown interactions with OA. Temperature stress combined with sedimentation may cause reduced sediment removal capacity. Stress from sedimentation would be exacerbated by increased storm severity (greater pulse events). Bacteria may be brought in with land-sourced non-nutrient pollution, but more research is needed, while storms could wash out pollutants such as heavy metals. The combination of sedimentation and storms may have impacts on the polychaetes and associated communities for *N. nolitangere*, but more research is necessary. Little is known about sponge disease in FGBNMS, but a die-off in 2016 at EFGB may have been associated with stress-induced disease (Shore et al., 2021). Higher temperatures will likely cause sponges to be more susceptible to disease, as disease vectors typically fare better at warmer temperatures. Storms may additionally spread disease and reduce host resistance, but the impacts of OA on sponge diseases is unknown; sometimes OA inhibits the pathogen but at other times it stresses the host and allows for disease progression.

Finally, adaptive capacity for *N. nolitangere* was estimated as low for all climate stressors. For ecological potential, the distribution and connectivity and specialist ranking were ranked as poor, whereas this species had fair dispersal abilities, phenotypic and behavioral plasticity, and genetic diversity, and good value and importance (ecologically or societally). It was noted little is known about the phenotypic and behavioral plasticity or genetic diversity of *N. nolitangere*. Although FGBNMS is a well-managed organization with strong partnerships, considering the societal potential adaptive capacity only in relation to its impact on climate stressors, all social potential variables were ranked as critical.

Long-Spined Urchin (Diadema antillarum)

Table 3.18 Influence of climate change on *D. antillarum* from RVA scores.

Long-Spined Urchin D. antillarum	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Possible**	**Possible**	**Rare**
Consequence	**Minor**	**Moderate**	**Negligible**
Risk	**Moderate**	**Moderate**	**Low**
Adaptive Capacity	**Moderate**	**Moderate**	**Moderate**
Vulnerability	**Moderate**	**Moderate**	**Low**

Species overview

Diadema antillarum, also known as the long-spined urchin, is an herbivore of the family Diadematidae. Long-spined urchins are a keystone species, playing a significant role in removing macroalgae which promotes stony coral colony growth and facilitates juvenile coral recruit settlement (Lin, 2020). *D. antillarum* is a round urchin with thin, often black, spines that range from 300–400 mm in length (Puckett, 2022). These urchins are found in the shallow waters of the Atlantic Ocean, in the Bahamas, and the Western Atlantic from eastern Florida to Brazil. *D. antillarum* are usually found near coral reefs but can also be found near turtle grass beds and rock bottoms. At the base of the urchin are branched tentacles called tube feet, which help in gathering food, respiration, locomotion, and mucous production. *D. antillarum* grazes on the algal turf of coral reefs primarily during the night but may also feed on young corals and zoanthids.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and pCO_2), and storm severity and frequency (including precipitation). Temperature and OA changes may possibly have an impact on *D. antillarum,* but the likelihood of storm alterations impacting this species is rare. *D. antillarum* was moderately vulnerable to temperature and OA changes and had low vulnerability to storm severity alterations. Workshop participants determined the non-climate stressors currently affecting *D. antillarum* in the FGBNMS are land source nutrient pollution or sedimentation and disease.

As SST in the GOM increases over the next 50 years, some anticipated negative direct and indirect effects to *D. antillarum* are on important behaviors such as covering (camouflage) used during the day, Aristotle's lantern reflex (for feed intake), and righting behavior. Elevated seawater temperatures will also likely reduce efficient use of resources in urchins, reducing their feeding efficiency and reproductive capacity. *D. antillarum* may be resilient to near-term (<2039) SST increases and periodic temperature stresses, but may struggle under long-term worst-case scenario conditions. Finally, increased temperatures may lead to changes in algae feeding patterns.

For OA, as pH and Ω_{Ar} continue to decline over the next 50 years, and mean surface seawater $p\text{CO}_2$ continues to rise with atmospheric levels, some anticipated effects on *D. antillarum* are reduced growth rates of urchin larvae, delayed development, and overall stunted growth. Urchins exposed to increased OA reduce their mean body size and experience reduction in growth. OA could interfere with the urchins' ability to transform calcium, magnesium, and other minerals from seawater into their “tests” (the white shell left when the animal dies), spines and teeth.

For storm severity and frequency, if storm severity increases and extreme precipitation events become more common in the GOM, it could lead to decreases in mean *D. antillarum* density following the storms. There is a correlation between density of *D. antillarum* and the magnitude of sediment deposition on reefs, suggesting that abrasion or burial from sediment transport may contribute to *D. antillarum* mortality. Some studies show the possibility of urchins being buried by increased sedimentation from extreme storms, but that has a rare potential in FGBNMS.

Land-source nutrient pollution and sedimentation (runoff) could cause algal blooms, increasing competition and decreasing light availability for reefs. This would likely lead to low-oxygen events like the 2016 mortality observed at FGBNMS, in which urchins were highly impacted. Disease could result in mortality of *D. antillarum* and is likely to spread quickly once established. This would result in decreased immunity and reduced density and grazing capacity of *D. antillarum* at FGBNMS.

Finally, adaptive capacity for *D. antillarum* was estimated as moderate for all climate stressors. For ecological potential, distribution and connectivity and dispersal were ranked as poor, due to the relative isolation of FGBNMS and previous urchin die-offs. Phenotypic and behavior plasticity, generalist abilities, and genetic diversity were ranked as fair, as this species is sensitive to changes in salinity and DO levels, and value was ranked as good, due to the value of this species as a dominant herbivore. For societal potential, all variables were ranked as fair or good due to the long-term monitoring and knowledge of this species.

Crustose Coralline Algae (CCA)

Table 3.19 Influence of climate change on crustose coralline algae from RVA scores.

Crustose Coralline Algae	Increased Water Temperature	Ocean Acidification	Storm Severity/Frequency
Likelihood	Possible	Possible	Possible
Consequence	Minor	Minor	Minor
Risk	Moderate	Moderate	Moderate
Adaptive Capacity	Low	Low	Low
Vulnerability	Moderate	Moderate	Moderate

Species overview

Crustose forms of algae, or crustose coralline algae (CCA) are algae that create a calcified structure (FGBNMS, n.d). At FGBNMS, they reside between the shallow coral reefs and deeper coral zones (FGBNMS, n.d.). CCA come in a variety of morphologies: some are leafy, some form rhodoliths (algal nodules), and others are encrusting (FGBNMS, n.n). The encrusting CCA help cement the reef together, provide solid substrate, and emit chemical cues for coral larval settlement (FGBNMS, n.d). Algal rhodoliths provide habitat for many other species including black corals (antipatharians), octocorals, sponges, and leafy algae (FGBNMS, n.d).

CCA have honeycomb-structured, magnesium-calcite lining individual algae cells, which stack together to form the hard "crust" (Johnson, 2014), although additional calcifications can be found both extracellularly and intracellularly (Johansen, 2018). CCA are known to have a slow calcification rate (10–30 mm yr^{-1}) relative to corals and are vulnerable to smothering by fleshy seaweeds (Belliveau & Paul, 2002; Kuffner 2013; Johnson 2014;). Grazing by fish helps to clear seaweeds from the surface, preventing this smothering and allowing for larval coral settlement on a smooth CCA surface (Belliveau & Paul, 2002; Johnson, 2014).

CCA are red photosynthetic autotrophic algae of the Phylum Rhodophyta and are found globally in marine habitats ranging from polar areas to the tropics, although they are more common in warmer regions (Bosence, 1983; Johansen, 2018). CCA are thought to have been instrumental in formation of modern-day (beginning in the Paleozoic Era) coral reefs and are major contributors to the earth's carbon cycle (Aguirre et al., 2010). CCA are asexual and reproduce by emitting spores, which develop into male and female gametophyes or bispores (Bosence, 1983; Johansen, 2018). In a carpogonium (the female reproductive organ), fertilization produces diploid offspring that grow into asexual organisms (Bosence, 1983; Johansen, 2018).

Vulnerability assessment results

The three climate stressors valuated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and pCO_2), and storm severity and frequency (including precipitation), all of which may possibly impact CCA in FGBNMS. CCA is moderately vulnerable to all three climate stressors. Land-sourced nutrient and non-nutrient pollution (including sediments) and invasive species (primarily orange cup coral *Tubastraea* sp.) were identified as the non-climate stressors for CCA.

Rising water temperatures in FGBNMS could cause paling (color loss) for CCA and allow leafy algae from warmer climates to cover the substrate (i.e., out-compete CCA) in the next 50 years. The likelihood of rising seawater temperature causing these impacts on CCA was ranked as possible, with high uncertainty.

CCA could experience reduced calcification due to OA because of their high magnesium (Mg) calcite composition. Mg calcite may be impacted faster by OA than aragonite of corals. This could result in a reduction in growth and nodule extension (Kuffner et al., 2008), which would subject CCA at FGBNMS to bio-erosion or compromised structure, increasing susceptibility to other impacts and damage, and decreasing structural density. The likelihood of this was ranked as possible with high uncertainty, although some workshop participants suggested a literature review may increase this likelihood rating.

Storm severity and precipitation increases may cause increased degradation of CCA through physical damage, and increased runoff, pollution, sedimentation, and turbidity could reduce CCA growth. However, CCA may benefit from storms because they produce areas for recruitment.

Land-source nutrient and non-nutrient pollution may cause decreased light penetration, resulting in lowered photosynthesis and calcification. Nutrient input could stimulate leafy algae over CCA, which will compete for substrate. This land-source pollution will interact with SST by exacerbating calcification reductions and further increasing leafy algal growth into the recruitment area. OA will interact with increased land-based pollution by stimulating productivity and respiration, resulting in carbon dioxide increases. Lower growth rates from OA combined with smothering from sedimentation could have cumulative impacts. Increasing storm severity would further increase runoff, with greater pulse events. CCA are not as susceptible to damage as coral and sponge species but could be smothered by sand. Orange cup corals compete with CCA for space (which are limited to 30 m). Decreased herbivory due to lionfish community interactions could decrease algal coverage, possibly resulting in fewer recruitable spaces. Invasive and non-native species have unknown interactions with temperature, but orange cup corals have decreased potential overgrowth with lower pH. Orange cup coral is hardy and thrives in disturbed areas more than CCA, so this species may benefit from greater magnitude storm events. Storm events could also aid with dispersal of invasives.

Finally, adaptive capacity for CCA was estimated as moderate for all climate stressors. For ecological potential, distribution and connectivity (CCA thrive in deeper waters and on oil platforms and reproduce well), phenotypic and behavior plasticity, and genetic diversity were ranked as fair. Dispersal and generalist abilities were ranked as good, and value and importance (CCA is a dominant species) were ranked as superior in relation to climate stressors, although there is uncertainty regarding the plasticity and genetic diversity aspects of this rating. Although FGBNMS is a well-managed organization with strong partnerships, considering the societal potential adaptive capacity only in relation to its impact on climate stressors, all social potential variables were ranked as critical.

***Dictyota* sp. (Brown Algae)**

Table 3.20 Influence of climate change on algae *Dictyota* sp. from RVA scores.

***Dictyota* sp.**	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Likely**	**Likely**	**Likely**
Consequence	**Negligible**	**Negligible**	**Negligible**
Risk	**Low**	**Low**	**Low**
Adaptive Capacity	**High**	**High**	**High**
Vulnerability	**Low**	**Low**	**Low**

Species overview

Dictyota is a genus of brown seaweed algae in the family Dictyotaceae that is found in tropical to warm temperate environments (Lopes-Filho et al., 2017). *Dictyota* are long, branched, flattened, and brown in color. *Dictyota* is an important food source, shelter, and substrate to several species of invertebrates and other algae. In FGBNMS, *Dictyota* is found within the coral cap region of the sanctuary (0–40 m depth) (FGBNMS, 2021).

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and pCO_2), and storm severity and frequency (including precipitation), all of which had possible likelihoods of impacting *Dictyota sp.* in FGBNMS. However, *Dictyota* sp. ultimately had low vulnerability to all three climate stressors. Workshop participants determined the only non-climate stressor currently affecting *Dictyota* sp. in FGBNMS is land-source nutrient pollution or sedimentation.

As SST in the GOM increases over the next 50 years, an anticipated effect of increased temperature on this genus is potential for increased growth and more available space for colonization (shift toward algal dominated state), which are positive impacts on *Dictyota*. There may also be a negative impact on the fertility of *Dictyota* by ocean warming, potential for reduced reproductive performance, and potential for phenological shifts in seaweeds in response to ocean warming.

For OA, as pH and Ω_{Ar} continue to decline over the next 50 years, and mean surface seawater pCO_2 continues to rise with atmospheric levels, some anticipated effects on *Dictyota* sp. are enhanced growth caused by higher CO_2 levels. Workshop participants noted that *Dictyota sp.* is likely to be a winner under this scenario, relative to slower growing calcifying organisms. OA may benefit algae that are able to capitalize on increased carbon availability for photosynthesis.

If storm severity increases and extreme precipitation events become more common in the GOM, it could lead to some overall positive effects on *Dictyota* identified by workshop participants. Damage from storms may lead to available substrate for colonization of algae, which grows faster than coral; under this scenario, algae benefits. Furthermore, nutrient enrichment due to increased storms benefits *Dictyota* sp. by stimulating growth.

Land-source nutrient pollution and sedimentation could benefit *Dictyota* sp. through nutrient enrichment and stimulated growth. However, land-source input could also stimulate blooms of algal species in competition with *Dictyota*, decreasing light availability and leading to low-oxygen events. In 2016, a similar event resulted in *Dictyota* mortality at FGBNMS. Decreased light penetration due to higher turbidity may also decrease photosynthesis in *Dictyota* sp.

Overall, the adaptive capacity for *Dictyota* sp. was high, with an ecological potential rating of fair and a social potential rating of good.

Finally, adaptive capacity for *Dictyota* sp. was estimated as high for all climate stressors. For ecological potential, all values were ranked as fair (important algae on the reef, provides habitat and food, for fish and invertebrates, can be sensitive to temperature changes) relative to impacts on this species in relation to climate stressors. Although FGBNMS is a well-managed organization with strong partnerships, considering the societal potential adaptive capacity only in relation to its impact on climate stressors, all social potential variables were ranked as good due to the long-term monitoring and knowledge of this species.

3.2.3 Mesophotic Invertebrate Species

Octocorals (Nicella sp.)

Table 3.21 Influence of climate change on *Nicella sp.* from RVA scores.

Octocorals *Nicella* sp.	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Unlikely**	**Possible**	**Unlikely**
Consequence	**Negligible**	**Minor**	**Minor**
Risk	**Low**	**Moderate**	**Low**
Adaptive Capacity	**Moderate**	**Moderate**	**Moderate**
Vulnerability	**Low**	**Moderate**	**Low**

Species overview

Nicella is a genus of mesophotic, ahermatypic (non-reef building) corals. They are often red or pale-orange in color. Most colonies range up to 20 cm in height but can be found as large as 60 cm. The genus has been identified globally in both areas of the Atlantic and Pacific (Shuler, 2020).

Nicella sp. has been found across the GOM at depths of 45–274 m (Etnoyer, 2017). In FGBNMS, *Nicella* sp. has been collected for classification purposes up to a depth of 117 m (352 ft). In FGBNMS, it is a widely distributed and moderately abundant octocoral growing on rocky outcroppings both exposed and partially covered by mud or silt. Little is still known about *Nicella* sp. as researchers continue to collect samples and identify new species through genetic testing. Species of *Nicella* are indistinguishable from each other in situ. For the purposes of this workshop, it was advisable to identify them only to the genus level (Schuler, 2020).

Vulnerability assessment results

The three climate stressors that were evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\text{CO}_2$), and storm severity and frequency (including precipitation), which were ranked as unlikely, possible, and unlikely, respectively, to impact *Nicella* sp. *Nicella* sp. had low vulnerability to increasing temperature and storm alterations, and moderate vulnerability to OA. Non-climatic stressors that may compound impacts include extraction, marine debris, and altered sediment transport.

Thermally induced bleaching of *Nicella* sp. has not been observed within FGBNMS, but the expected increase in water temperature of between 1.25–3.5 °C by 2050 may result in bleaching episodes. Because *Nicella* sp. can sustain itself on plankton, thermal bleaching alone may not increase its mortality. It may however reduce photosynthesis and lower available planktonic food, thus reducing growth and fecundity.

Water pH at FGBNMS is expected to decrease by another 0.1 by 2050 to a seasonal range of 7.7 to 8.1, with the seasonal low pH decreasing at a higher rate than the seasonal high pH. This change is likely to reduce the availability of carbonate that octocoral species can use to build their sclerites which are the structural base of their skeleton and can lead to weakening structure and eventually breakage. Lower pH will also effectively reduce the availability of planktonic food sources.

The number of storms (both tropical and extratropical) is not expected to change greatly, but a larger number of those storms are expected to produce extreme conditions in the GOM. This shift toward stronger storms has the potential to increase scouring and physical dislodgement or breakage of the corals. Remaining corals could be smothered with mobilized sediment. An expected decrease in the interval between major storms would exacerbate the problem and is likely to impede coral recovery.

Increased human population pressures are coupled to increased tourism and recreational use of FGBNMS. However, as these corals are found at around 160 km offshore and at depths beyond the typical recreational diver, we find these impacts to be negligible. Rather, participants thought marine debris and extraction (mining, oil, and gas) would have a larger impact on the species. These activities can cause direct mortality to colonies near areas of activity and can have secondary impacts such as smothering of corals or destruction of habitat. While workshop participants feel these factors will likely negligibly reinforce the negative impacts of increasing water temperature, they are expected to provide a minor exacerbation of negative effects of storm impacts (e.g., increased mobilization of marine debris, interference with post-storm recovery, increased sedimentation) and OA (weakened skeletal structure would lead to more severe physical damage). Altered sediment transport is predicted to provide a negative accompaniment to increased temperature and storm severity by increasing smothering and burial of *Nicella sp*. in some areas while scouring the benthic habitat in other areas. However, this is regarded to be unlikely amongst workshop participants who feel *Nicella* sp. is too far offshore and too deep to be heavily impacted. Some benefit can be found to increased altered sediment transport, which could increase the food source for coral colonies more reliant on filter feeding. The combined impacts of sediment transport and increased water temperature, along with OA, are expected to result in an overall negligible impact to *Nicella* sp. The .e combined effect of altered sediment transport and changes in storm behavior (more storms would bring more sediment), is anticipated to be minor.

Finally, adaptive capacity for *Nicella* sp. was estimated as moderate for all climate stressors. For ecological potential, distribution and connectivity (Nicella sp. thrive in deeper waters and are found globally), phenotypic and behavior plasticity, and genetic diversity were ranked as moderate. The species is relatively abundant within FGBNMS (Opresko, 2016) and is ecologically important, providing habitat and shelter for other invertebrates and prey species; however, its social and commercial value is moderate. This moderate ecological potential for adaptation is balanced by a moderate social potential. Factors such as sanctuary stability and longevity, scientific support, and stakeholder or partner relationships showed high adaptive capacity, other factors such as the capacity of existing staff (training and time) to engage in adaptation activities, responsiveness as a federal agency, and the monitoring and evaluation capacity of Nicella sp. showed limited adaptation potential. The combination of ecological and social components set potential adaptive capacity for the species as moderate.

Octocorals (<u>Hypnogorgia</u> and <u>Muricea</u> sp.)

Table 3.22 Influence of climate change on *Hypnogorgia* and *Muricea* sp. from RVA scores.

Octocorals *Hypnogorgia and Muricea* sp.	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Unlikely**	**Possible**	**Unlikely**
Consequence	**Negligible**	**Minor**	**Minor**
Risk	**Low**	**Moderate**	**Low**
Adaptive Capacity	**Moderate**	**Moderate**	**Moderate**
Vulnerability	**Low**	**Moderate**	**Low**

Species overview

Hypnogorgia and *Muricea* sp. have been found across the GOM at depths of 60–128 m (Etnoyer, 2017). *Muricea* (specifically *M. pendula*) has been historically identified as *Hypnogorgia pendula* in the GOM (Shuler, 2020). *Hypnogorgia* and *Muricea* can come in a variety of colors from white, pink, orange and red with tissue of branches possibly being a pale yellow.

In FGBNMS, *Hypnogorgia* and *Muricea* sp. have been collected for classification purposes up to a depth of 117 m (352 ft). These octocorals are widely distributed and moderately abundant in FGBNMS, growing on rocky outcroppings both exposed or partially covered by mud or silt. *Hypnogorgia* and *Muricea* sp. have been collected for classification purposes up to a depth of 353 and 176 m (1059 and 528 ft.), respectively.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\text{CO}_2$), and storm severity and frequency (including precipitation), all of which had possible likelihoods of impacting *Hypnogorgia* and *Muricea* sp. at FGBNMS. The occurrence of these climate changes was deemed to be unlikely (increased temperature and storm severity or frequency) but possible relative to OA (driving impact on sclerite formation) within FGBNMS. *Hypnogorgia sp*. and *Muricea sp*. had low vulnerabilities to rising temperatures and storm alterations, and moderate vulnerability to OA. Non-climatic stressors that may compound impacts include extraction (mining, oil & gas), marine debris, and altered sediment transport.

Thermally induced bleaching of *Hypnogorgia* sp. and *Muricea* sp. has not been observed within FGBNMS, the expected increase in water temperature of between 1.25–3.5 °C by 2050 may result in bleaching episodes. Because *Hypnogorgia* sp. and *Muricea* sp. can sustain themselves on plankton, thermal bleaching alone may not increase their mortality. It may however reduce possible photosynthesis mechanisms and lower available planktonic food, thus reducing growth and fecundity.

Water pH at FGBNMS is expected to decrease by another 0.1 by 2050 to a seasonal range of 7.7 to 8.1, with the seasonal low pH decreasing at a higher rate than the seasonal high pH. This change is likely to reduce the availability of carbonate that coral species can use to build their skeletons. Lower pH will also effectively reduce the availability of planktonic food sources.

The number of storms (both tropical and extratropical) is not expected to change greatly, but a larger number of those storms are expected to produce extreme conditions. This shift toward stronger storms has the potential to increase scouring and physical dislodgement or breakage of the corals. Remaining corals could be smothered with mobilized sediment. An expected decrease in the interval between major storms would exacerbate the problem and is likely to impede coral recovery.

Increased human population pressures are coupled to increased tourism and recreational use of FGBNMS along with commercial energy and fishing use in the nearby areas may impose secondary effects on the sanctuary; however, as these corals are found at around 160 km offshore and at depths beyond most human activity, participants believed these impacts will be negligible. Rather, participants thought marine debris and extraction (mining, oil, and gas) would have a larger impact on the species. These activities can cause direct mortality to colonies near areas of activity and can have secondary impacts such as smothering of corals or destruction of habitat. While these factors will likely insignificantly reinforce the negative impacts of increasing water temperature, they are expected to provide a minor exacerbation of negative effects of OA (e.g., weakened skeletal strength and inhibited rate of recovery) and storm impacts (e.g., increased mobilization of marine debris, interference with post-storm recovery, increased sedimentation). Altered sediment transport is predicted to provide a negative accompaniment to the three climate stressors by increasing smothering and burial of *Hypnogorgia* sp. and *Muricea* sp. in some areas while scouring the benthic habitat in other areas. However, this is regarded to be unlikely amongst workshop participants that feel *Hypnogorgia* sp. and *Muricea* sp. are too far offshore and too deep to be heavily impacted. Altered sediment transport could benefit these species by increasing the food source, since these corals are heavily reliant on filter feeding. The combined impacts of sediment transport and increased water temperature are expected to result in an overall negligible impact to *Hypnogorgia* sp. and *Muricea* sp., while the combined effect of altered sediment transport and changes in storm behavior along with OA is anticipated to be minor.

Finally, adaptive capacity for *Hypnogorgia* sp. and *Muricea sp.* was estimated as moderate for all climate stressors. For ecological potential, distribution and connectivity, phenotypic and behavior plasticity, and genetic diversity were ranked as moderate. The species was ranked as good as being moderate for being relatively abundant within FGBNMS (Opresko, 2016), and are ecologically important. Its social or commercial value is tied to its use as jewelry and potential to be an important species for researchers (harvest has been allowed by permitted researchers at FGBNMS) in the future, making it moderate. Dispersal and generalist abilities are moderate but little is known, no studies have been done on *Hypnogorgia* sp. and *Muricea* sp. in FGBNMS addressing larval dispersal. This low to moderate ecological potential for adaptation is somewhat balanced by a moderate social potential. Sanctuary stability and longevity, scientific support, and stakeholder and partner relationships showed high adaptive capacity. Factors such as a lower value and importance, the capacity of existing staff (training and time) to engage in adaptation activities, responsiveness as a federal agency, and the monitoring and evaluation capacity of *Hypnogorgia* sp. and *Muricea sp.* showed limited adaptation potential. The combination of ecological and social components set potential adaptive capacity for the species is moderate.

Black coral (Antipathes furcata)

Table 3.23 Influence of climate change on *A. furcata* from RVA scores.

Black coral **_A. furcata_**	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Unlikely**	**Rare**	**Rare**
Consequence	**Negligible**	**Negligible**	**Minor**
Risk	**Low**	**Low**	**Low**
Adaptive Capacity	**Moderate**	**Moderate**	**Moderate**
Vulnerability	**Low**	**Low**	**Low**

Species overview

Antipathes furcata is a mesophotic (50–221 m), ahermatypic (non-reef building) coral. Colonies are bushy to broom-like in shape with long, pseudodichotomous branches extending vertically and away from the stem and reducing the thickness down to 0.1–0.2 mm. Colonies will begin branching in a two-dimensional plane but will expand to three dimensions over time. Colonies can grow up to 40 cm in height, coloration can be white to grayish in color and the black skeleton can be seen through the tissue. Polyps are arranged in a single series along one side of a branch with 6–8 polyps in one centimeter (Opresko 2106). The polyps are obligate feeders, relying heavily on their ability as suspension-feeders to catch planktonic microorganisms in the water column.

A. furcata has been found across the Atlantic, as far East as the African coast, throughout the Caribbean, and in the nwGOM at depths of 30–100 m (Cairns, 1993), but has been reported deeper (135 m) in FGBNMS (Opresko, 2016). In FGBNMS, *A. furcata* has been collected for genetic connectivity studies up to a depth of 123 m (370 ft). In FGBNMS, it is a widely distributed and moderately abundant black coral growing on rocky outcroppings both exposed or partially covered by mud or silt.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\text{CO}_2$), and storm severity and frequency (including precipitation), and *A. furcata* had low vulnerability to all three climate stressors. The likelihood of these climate changes impacting *A. furcata* was deemed to be unlikely (increased temperature) and rare (OA and storm severity or frequency) within FGBNMS. Non-climatic stressors that may compound impacts include extraction, research disturbance, and altered sediment transport.

Thermally induced bleaching of *A. furcata* has not been observed within FGBNMS, but the expected increase in water temperature of between 1.25–3.5 °C by 2050 may result in bleaching episodes. Because *A. furcata* can sustain itself on plankton, thermal bleaching alone may not increase its mortality. It may however reduce photosynthesis and lower available planktonic food, thus reducing growth and fecundity.

Water pH at FGBNMS is expected to decrease by another 0.1 by 2050 to a seasonal range of 7.7 to 8.1, with the seasonal low pH decreasing at a higher rate than the seasonal high pH. This change is likely to reduce the availability of carbonate that coral species can use to build their skeletons. Lower pH could also reduce the availability of planktonic food sources.

The number of storms (both tropical and extratropical) is not expected to change greatly, but a larger number of those storms are expected to produce extreme conditions. This shift toward stronger storms has the potential to increase scouring and physical dislodgement or breakage of the corals. Remaining corals could be smothered with mobilized sediment. An expected decrease in the interval between major storms would exacerbate the problem and is likely to impede coral recovery.

Development and population growth in the coastal GOM region through 2050 are expected to alter freshwater runoff and produce an increase in nutrient and pollutant loads for FGBNMS. Similarly, increased human population pressures are coupled to increased tourism and recreational use of FGBNMS; however, as these corals are found at around 160 km offshore and at depths beyond the typical recreational diver, these impacts were determined to be negligible. Rather, participants thought research disturbance and extraction (mining, oil, and gas) would have a greater impact on the species. These activities can cause direct mortality to colonies near areas of activity and can have secondary impacts such as smothering of corals or destruction of habitat. While these factors will likely insignificantly reinforce the negative impacts of increasing water temperature and OA, they are expected to provide a minor exacerbation of negative effects of storm impacts (e.g., increased mobilization of marine debris, interference with post-storm recovery, increased sedimentation). Altered sediment transport is predicted to provide a negative accompaniment to the three climate stressors by increasing smothering and burial of *A. furcata* in some areas while scouring the benthic habitat in other areas. However, this is regarded to be unlikely amongst workshop participants that feel *A. furcata* is too far offshore and too deep to be heavily impacted. Increased sediment transport could benefit *A. furcata* by increasing the food source since the coral is more reliant on filter feeding. The combined impacts of sediment transport and increased water temperature along with OA are expected to result in an overall negligible impact to *A. furcata*, while the combined effect of altered sediment transport and changes in storm behavior is anticipated to be minor.

Finally, adaptive capacity for *A. furcata* was estimated as moderate for all climate stressors. For ecological potential, distribution and connectivity, phenotypic and behavior plasticity, and genetic diversity were identified as moderate. Species dispersal and generalist abilities are moderate and relatively abundant within FGBNMS (Opresko, 2016). Its ecological and social importance are moderate in relation to climate stressors. Dispersal and generalist abilities were ranked as moderate although no studies have been done on *A. furcata* in FGBNMS addressing larval dispersal, and FGBNMS may receive larval recruits from other habitats, as it is moderately abundant across the banks. However, *A. furcata* can be found across the Atlantic and the Caribbean. This high ecological potential for adaptation is offset by a moderate social potential. Factors such as sanctuary stability and longevity, scientific support, and stakeholder and partner relationships showed high adaptive capacity, alongside a high value and importance, other factors such as the capacity of existing staff (training and time) to engage in adaptation activities, responsiveness as a federal agency, and the monitoring showed limited adaptation potential. The combination of ecological and social components set potential adaptive capacity for the species as moderate.

Sponge (Corallistes typus)

Table 3.24 Influence of climate change on *C. typus* from RVA scores.

Sponge **_C. typus_**	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Unlikely**	**Likely**	**Unlikely**
Consequence	**Negligible**	**Major**	**Minor**
Risk	**Low**	**High**	**Low**
Adaptive Capacity	**Moderate**	**Moderate**	**Moderate**
Vulnerability	**Low**	**Moderate**	**Low**

Species overview

Corallistes typus is a mesophotic (50–221 m) sponge that forms shallow or flattened cups with undulating rims, sometimes covered in sediment. This species grows up to 20 cm in diameter, with a smooth surface, and the walls approximately 1–3 cm thick. The oscules of *C. typus* are not visible. The coloration of *C. typus* is pale brown with a rosy tinge.

C. typus is typically found at depths of 61–914 m, with abundances increasing from 150–900 m (Pomponi et al., 2001). *C. typus* is common in Southern, Eastern and Northern regions of the Caribbean, and in Florida and the Bahamas (Van Soest & Stentoft, 1988). In FGBNMS, the species occurs widespread at 17 sites from low to medium abundances (2–100 individuals). *C. typus* is most common to coralline algae reefs and deep reef systems.

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\mathrm{CO}_2$), and storm severity and frequency (including precipitation). The likelihoods of these climate changes impacting *C. typus* were deemed to be unlikely (increased temperature and storm severity and frequency) and unlikely (OA) within FGBNMS. *C. typus* had low vulnerabilities to changing seawater temperatures and storm patterns, and moderate vulnerability to OA. Additionally, extraction from mining, oil, and gas, and altered sediment transport were identified as the most likely and important non-climate stressors that could affect *C. typus* in FGBNMS.

The impacts of rising SST on *C. typus* are very uncertain. SST is expected to increase 1.25–3.5 °C in FGBNMS by 2050; however, workshop participants deemed the likelihood of increased SST to impact *C. typus* as unlikely. Thermal stress associated with ocean warming can greatly impact sponge assemblages through disease and alteration of regeneration rates. However, there may also be unknown benefits to increased temperature which may allow for increased abundance of plankton. Increased SST may not have the same effect on the mesophotic zone as it does in shallower regions.

Water pH at FGBNMS is expected to decrease by another 0.1 by 2050 to a seasonal range of 7.7–8.1, with the seasonal low pH decreasing at a higher rate than the seasonal high pH. Workshop participants deemed the likelihood of OA to impact *C. typus* as likely. While siliceous sponges have survived prehistoric mass extinction events caused by OA (Liu et al., 2008), OA has also been shown to impact larval mortality, increase development abnormalities, and decrease settlement of sponges (Dupont et al., 2008), resulting in changes to sponge abundance and community structure at shallower depths (Goodwin et al., 2014). It is possible CO_2 affects silica formation, compromising or weakening the spicules and consequently preventing sponge skeletons from colonizing. Additionally, workshop participants acknowledged changes in pH could affect symbiotic bacterial relationships.

The number of storms (both tropical and extratropical) is not expected to change greatly, but a larger number of those storms are expected to produce extreme conditions. This shift toward stronger storms has the potential to increase scouring and physical dislodgement of *C. typus*, and an expected decrease in the interval between major storms is likely to impede sponge recovery. However, *C. typus* may be able to handle increased turbidity and possible scouring, because of its low profile. Storms may also benefit *C. typus* by increasing dispersal of clonal bodies.

Workshop participants identified sediment transport and extraction (mining, oil, and gas) as non-climate stressors on the species. These events can cause direct mortality to colonies and can have secondary impacts such as smothering of sponges or destruction of habitat. Altered sediment transport can adversely impact *C. typus* by clogging sponge pores and reducing pumping and filtration capacity. Altered sediment transport may resettle benthic materials onto sponges, inundating them, inhibiting filtration feeding, and altering ability to regenerate or disperse. Increased sediment transport is anticipated because of increased storm severity and frequency in the area, and from extraction projects (e.g., mining, oil and gas). Extraction will insignificantly reinforce the negative impacts of increasing sea water temperature and OA; however, it is expected to provide a minor exacerbation of negative effects of storm impacts (e.g., increased scouring from breaking infrastructure, increased spills).

Finally, adaptive capacity for *C. typus* was estimated as moderate for all climate stressors. For ecological potential, distribution and connectivity, dispersal, and value were ranked as poor, phenotypic and behavior plasticity were ranked as fair, and generalist abilities were ranked as good, in relation to climate stressors. Genetic diversity was not ranked at this time due to uncertainty regarding the genetic diversity of this species. Although FGBNMS is a well-managed organization with strong partnerships, considering the societal potential adaptive capacity only in relation to its impact on climate stressors, all social potential variables were ranked as fair.

Crinoids

Table 3.25 Influence of climate change on crinoids from RVA scores.

Crinoids	**Increased Water Temperature**	**Ocean Acidification**	**Storm Severity/Frequency**
Likelihood	**Unlikely**	**Likely**	**Unlikely**
Consequence	**Negligible**	**Major**	**Minor**
Risk	**Low**	**High**	**Low**
Adaptive Capacity	**Moderate**	**Moderate**	**Moderate**
Vulnerability	**Low**	**Moderate**	**Low**

Species overview

Crinoids are marine animals belonging to the phylum Echinodermata and the class Crinoidea. They are an ancient group of organisms that first appeared in the seas of the mid Cambrian, about 300 million years before dinosaurs. Crinoids vaguely resemble flowering plants, with a body structure that includes an array of branching arms, arranged on top of a spherical structure. The skeleton is made of the mineral calcite and consists of hundreds of individual plates of different shapes and sizes.

There are approximately 700 known species today, typically existing in two forms: ‘stalked’ crinoids, or sea-lilies, and ‘unstalked’ crinoids, also known as comatulids or feather stars. (Ruppert et al., 2004; Karleskint et al., 2012). Sea lilies are sessile and usually live at depths greater than 100 m, where they attach themselves to rocks and grow up to a length of 1 m. Feather stars are commonly encountered from the intertidal zone and coral reefs to the deep ocean (Karleskint et al., 2012). Feather stars are free-moving and can swim or crawl short distances (Ruppert et al., 2004). Within FGBNMS, crinoids are most common in the mesophotic zone (Voss et al., 2014).

Vulnerability assessment results

The three climate stressors evaluated in FGBNMS were seawater temperature, OA (pH, Ω_{Ar}, and $p\mathrm{CO}_2$), and storm severity and frequency (including precipitation). The likelihoods of these climate changes impacting crinoids were deemed to be unlikely (increased temperature) and rare (OA and storm severity and frequency) within FGBNMS. Crinoids were thought to have moderate vulnerability to OA and low vulnerabilities to rising seawater temperatures and storm alterations. Additionally, extraction from mining, oil, and gas, and altered sediment transport were identified as the most likely and important non-climate stressors that could affect crinoids in FGBNMS.

The impacts of rising SST on crinoids are very uncertain. SST is expected to increase 1.25–3.5 °C in the FGBNMS by 2050; however, workshop participants deemed the likelihood of increased SST to impact crinoids as unlikely. Thermal stress associated with ocean warming can greatly impact crinoid assemblages through increased stress and possible expansion of predators into their range. However, some crinoids may find refuge from increased predation by seeking deeper depths. Additionally, there may be unknown benefits to increased temperature which may allow for increased abundance of small organisms (algae, diatoms, larvae, etc.), which crinoids feed on (Ruppert et al., 2004). Increased SST may not have the same effect on the mesophotic zone as it does in shallower regions.

Water pH at FGBNMS is expected to decrease by another 0.1 by 2050 to a seasonal range of 7.7–8.1, with the seasonal low pH decreasing at a higher rate than the seasonal high pH. Workshop participants deemed the likelihood of OA to impact crinoids as likely, with major consequence. While crinoids in the mesophotic zone of FGBNMS have not been specifically studied, available data concludes OA decreases availability of carbonate material, which would negatively affect the skeletal structure of crinoids and other echinoderms. This will likely result in significant consequences at the ecosystem level (Dupont et al., 2010). Echinoderm larvae exposed to acidified seawater also have reduced growth rates, delayed development, and overall stunted growth.

The number of storms (both tropical and extratropical) is not expected to change greatly, but a larger number of those storms are expected to produce extreme conditions. This shift toward stronger storms has the potential to increase scouring and physical dislodgement of crinoids, and an expected decrease in the interval between major storms is likely to impede crinoid recovery. However, crinoids are capable of regenerating lost limbs, which helps them survive predation and physical damage (Dupont et al., 2010). Storms may also benefit crinoids by increasing dispersal of larvae.

Workshop participants thought altered sediment transport and extraction (mining, oil, and gas) would have major impacts on crinoids. These events can cause direct mortality to crinoids and can have secondary impacts such as smothering of crinoids or destruction of habitat. Altered sediment transport can adversely impact crinoids by reducing filtration capacity. Altered sediment transport may resettle benthic materials onto crinoids, inundating them, inhibiting filtration feeding, and altering ability to regenerate or disperse. Increased sediment transport is anticipated because of increased storm severity and frequency in the area, and from extraction projects. Extraction will likely insignificantly reinforce the negative impacts of increasing sea water temperature and OA; however, it is expected to provide a minor exacerbation of negative effects of storm impacts (e.g., increased scouring from breaking infrastructure, increased spills).

Finally, adaptive capacity for crinoids was estimated as moderate for all climate stressors. For ecological potential, value and importance were ranked as poor, phenotypic and behavior plasticity were ranked as fair, and distribution and connectivity, dispersal, and generalist abilities were ranked as good. Although FGBNMS is a well-managed organization with strong partnerships, considering the societal potential adaptive capacity only in relation to its impact on climate stressors, all social potential variables were ranked as fair.

Chapter 4: Conclusions and Next Steps

Flower Garden Banks National Marine Sanctuary is a network of 17 reefs and banks which provide a chain of habitats for ecologically and economically important species such as snapper, grouper, and jacks across the nwGOM. Thriving shallow water coral reefs, algal-sponge communities, and deep mesophotic reefs of black coral, octocoral, and algal nodule habitats all reside within FGBNMS. FGBNMS is currently experiencing climate changes (such as increasing seawater temperatures, bleaching, and OA), and climate projections for the next 50 years suggest these changes will accelerate. This report aims to summarize results of a Climate Vulnerability Assessment Workshop in which a panel of experts used information on current and projected climate conditions to evaluate vulnerability of two habitat types and 23 key species or groups of organisms and brainstorm adaptation strategies. The aim was to better understand, and manage for, climate change impacts and the effects it may have on FGBNMS.

Environmental conditions at FGBNMS are expected to continue to change between now and 2072 (50-year forecast). SST is projected to increase by 3.5 °C over the next 50 years, with more frequent and more extreme temperature events. Current climate forecasts suggest the coral reefs of FGBNMS will be exposed to severe thermal stress by 2040 under RCP8.5 (“business as usual”) or by 2055–2060 under RCP4.5, a more modest climate projection. Mean global ocean pH is already 0.1 below preindustrial levels and is predicted to decline in oceanic waters by 0.035–0.155 over the next 50 years under the two climate scenarios RCP2.6 and RCP8.5. Ω_{Ar} has decreased by 0.1 per decade in <100 m depth seawater. Corals exhibit a 15% decline in calcification (densification) for every 1 unit decrease in Ω_{Ar} ($2 < \Omega_{Ar} < 4$), which is predicted to occur by the end of the century. Global atmospheric $p\mathrm{CO}_2$ is rising and may reach up to 560 µatm in the next 50 years, and $p\mathrm{CO}_2$ of seawater in FGBNMS will rise along with these atmospheric levels. Mean global ocean DIC is forecasted to increase from the current mean of 2026–2090 µmol kg^{-1} with a doubling of atmospheric CO_2 under IPCC IS92a emissions scenario. Mean global ocean TA is stable at 2287 µmol kg^{-1}.

The heaviest rainfall from tropical storms and hurricanes is presently 5–7% higher than a century ago, and could increase an additional 30–40%. Future storms are also forecast to be more powerful and intensify more rapidly. Storm frequency is projected to decrease in the GOM region, but extreme rainfall events are projected to become more common in the GOM watershed. Hypoxia is increasing in the northwestern GOM and has occurred in FGBNMS. Between 1901 and 2010, global mean sea level rose by 0.17–0.21 m, and this trend is predicted to continue, with total sea level rise of 0.24–0.30 m by 2046–2065. Non-native species have entered FGBNMS and are known to cause changes that negatively alter ecosystems. Climate changes can provide advantages to invasive species and allow for range-expansion and invasion of new areas.

This CVA focused on three climate impacts thought to have the greatest potential harmful impacts at FGBNMS: increasing seawater temperature, OA, and storm frequency and intensity and precipitation. Of these, increased water temperature was identified as having moderate to high vulnerability for both habitats and most species assessed (Table 4.1). A trend toward increasing water temperatures was thought to have moderate to high impacts on fish and shallow invertebrate species, resulting in moderate median vulnerability ratings overall for these groups of species. Specifically, rising seawater temperatures are likely to cause thermal stress on scleractinian corals, resulting in bleaching, mortality, and loss of reef structure. Corals could experience increased susceptibility to disease, decreased growth, altered microbiome, and reduced reproduction. Corals and sponges may need to exert greater metabolic effort and experience increased larval mortality. Deep water corals such as octocorals may also experience decreased photosynthesis, disease, and altered regeneration rates. Crinoids may exhibit increased stress and expansion of predators, but could also benefit from increased plankton abundance. Other invertebrates may have altered feeding and other behaviors, while some sponges may also benefit from warmer temperatures. The above impacts on invertebrates could ultimately lead to habitat loss and possible range shifts of many species into deeper waters. Fishes will possibly experience altered reproductive seasons and/or locations, operational sex ratios, shorter larval stages, trophic-level disruptions, and shifts in larval recruitment. Some, such as the wahoo, have a narrow optimal temperature range, while others such as stoplight parrotfish may benefit from increased algae abundance. CCA may experience paling and increased competition from leafy algae.

OA resulted in moderate to high vulnerability of both habitats and in 11 of 23 assessed species (Table 4.1). Acidifying seawater may have moderate to high impacts on shallow and mesophotic invertebrate species, resulting in moderate median vulnerability ratings. Corals will likely experience reduced growth and extension rates, increased bioerosion, compromised structure, reduced skeletal density, increased susceptibility to other impacts, and reduced reproductive output. CCA and corals may have reduced calcification rates, leading to lower available recruitment habitat and less robust calcifiers, reduced reproduction, less structural complexity, and a shift in community structure. CCA, which uses the more soluble magnesium calcite to build its skeleton, could additionally experience reduced calcification, growth, nodule extension, increased bioerosion, compromised structure, susceptibility to damage, and decreased structural density. Reductions in planktonic food and increased algal growth, which compete for space with corals, may also have habitat-level repercussions because of OA. Mesophotic habitats are well-mixed with good buffering capacity but may still experience altered food export and surface chemical cues, which may impact reproduction and result in other behavioral changes of mesophotic invertebrates. Sponges may experience decreased growth, increased disease, reduced recruitment, weaker structure, increased breakage, reduced planktonic food availability, and decreased stability of microbiomes. Crinoids could suffer from reduced carbonate materials and skeletal structure, altered ecosystems, reduced growth of larvae, delayed development, and stunted growth. Fish species may experience reduced olfaction, changes to otoliths, and altered larval development as well as impacts from changed habitat and prey species.

Storm severity and frequency resulted in low vulnerability for both habitats but moderate to high vulnerability in 8 of 23 species assessed (Table 4.1). Storm severity and frequency was predicted to have the greatest impact on shallow invertebrates, resulting in moderate median vulnerability overall for these species. Increased precipitation could notably cause greater river discharge and runoff in the Mississippi river and other watersheds entering the nwGOM, leading to decreased water quality, increased turbidity, increased pollution, and increased disease and bacteria input. This precipitation could possibly benefit organisms by flushing out heavy metals and pollutants. Increased sediment loads from higher runoff will have a variety of impacts such as lower light penetration and photosynthesis, and covering, clogging, and smothering of sponges. Storms may increase physical toppling or dislodgement and breakage of corals but may also help mitigate temperature increases by causing upwelling. Storms that occur during spawning events may reduce successful fertilization of corals, sponges, and some fish species. Corals and sponges may also experience toppling, community alterations, physical dislodging, and increased dispersal (benefit) from storms. *D. antillarum* will likely experience reduced density, while CCA may experience physical damage, degradation, increased recruitment (benefit), and negative effects of sedimentation, runoff, pollution, and increased turbidity. Fish may move deeper to avoid storms, experience habitat alterations, altered larval transport, temporary displacement, increased predation in open waters, and altered recovery time from major storms. Alternatively, wahoo may benefit from reduced fishing pressure during storms.

Other non-climate impacts on species that were identified frequently included land-source nutrient and non-nutrient pollution, which could stimulate algal growth (competition), harm zooxanthellae, and decrease photosynthesis. Disease (especially SCTLD) is currently impacting FGBNMS and may be exacerbated by climate stressors. Invasive species such as lionfish and orange cup corals compete with native organisms and reduce fish populations, alter food webs and habitats, promote algal growth, and cause trophic cascades. Harvest and extraction activities (such as oil and gas) may also damage habitat and organisms.

Throughout the assessment, adaptive capacities of habitats and organisms were ranked as moderate to low because, although the sanctuary is taking considerable actions to protect FGBNMS against climate stressors, some of the stressors would require global mitigation strategies and may occur regardless of human actions within the sanctuary. Some participants noted they ranked adaptive capacities lower than they otherwise would have due to considering the impacts that the measured value had on species rather than the actual actions taken by sanctuary personnel. Some suggested giving less weight to adaptive capacity in future RVAs.

It should be noted that lionfish (*Pterois volitans*) were assessed as a species despite being an invasive, undesirable species in FGBNMS, and any negative impacts of climate on lionfish are likely to positively impact native species of the FGBNMS. Some participants questioned whether assessing this species is of value, although it was noted it is important to understand potential climate-driven changes to this species as such changes could result in further negative impacts on the FGBNMS ecosystem. NOAA is working to curb the success of invasive species through removal events such as Lionfish Invitationals. While some teams of divers remove as many lionfish as possible during these events, others gather data on populations of both native competitors and lionfish. The removal of invasive species like lionfish can reduce biological stresses on the local ecosystem and make it more resilient to climate impacts.

Table 4.1. Median rankings for the three most identified climate impacts on the 23 species or groups of organisms assessed in the FGBNMS RVA. Note that workshop participants only assessed the top three climate stressors; thus, other lesser climate stressors may affect a given species but were not considered.

FGBNMS Workshop Results	Increased Water Temperature	Ocean Acidification	Storm Severity/Frequency
Trend to 2072	Increase by 3.5ºC (annual average). Greater seasonal variability. Increased frequency of coral bleaching.	Decrease in pH by 0.035 to 0.155. Ω_{Ar} will decline by 0.5, $p\text{CO}_2$ will reach up to 560 µatm and DIC may reach 2090 µmol kg^{-1}.	Storm severity will increase but frequency may decrease. Precipitation is increasing in the watershed.
RVA Habitats Affected (Moderate – High Vulnerability)	2 of 2	2 of 2	0 of 2
RVA Species Affected (Moderate – High Vulnerability)	13 of 23	11 of 23	8 of 23
Habitats			
Median Likelihood	Possible – Likely	Possible – Likely	Possible
Median Consequence	Moderate – Major	Moderate	Minor
Median Risk	High	Moderate – High	Low – Moderate
Median Adaptive Capacity	Moderate	Moderate	Low – Moderate
Median Vulnerability	Moderate – High	Moderate	Low
Species			
Median Likelihood	Possible	Possible	Possible
Fish	Likely	Unlikely	Possible
Shallow Invertebrates	Likely	Possible	Likely
Mesophotic Invertebrates	Unlikely	Possible	Unlikely
Median Consequence	Minor	Minor	Minor
Fish	Moderate	Negligible	Minor
Shallow Invertebrates	Moderate	Minor	Minor
Mesophotic Invertebrates	Negligible	Moderate	Minor
Median Risk	Moderate	Moderate	Moderate
Fish	Moderate	Low	Moderate
Shallow Invertebrates	High	Moderate	Moderate
Mesophotic Invertebrates	Low	Moderate	Low
Median Adaptive Capacity	Moderate	Moderate	Moderate
Fish	Moderate	Moderate	Moderate
Shallow Invertebrates	Moderate	Moderate	Moderate
Mesophotic Invertebrates	Moderate	Moderate	Moderate
Median Vulnerability	Moderate	Low – Moderate	Low
Fish	Moderate	Low	Low
Shallow Invertebrates	Moderate	Moderate	Moderate
Mesophotic Invertebrates	Low	Moderate	Low

Participants noted many unknowns exist in our knowledge of impacts of climate stressors on organisms in FGBNMS, and the results of this assessment should be complemented by additional research to fully inform proactive management. It is imperative that managers ask questions and communicate with scientists, who should work together with managers to address knowledge gaps. They also emphasized that management for commercially important fish species needs to be further considered as many highly sought-after fish are declining in population in and around the sanctuary. The remoteness of the Sanctuary may also make it difficult for species to find alternative habitat if parts of FGBNMS are no longer habitable in the future.

4.1 Next Steps

Rather than serve as a direct instruction for action, this report summarizes the CVA workshop results and suggests adaptation strategies that FGBNMS may consider in future management planning. It is not intended to be comprehensive or to recommend one course of action over another. The nature of the RVA tool and workshop encouraged participants to reach conclusions in a limited amount of time and often with incomplete information, with an intent that the outcomes would reveal what is known, where information gaps exist, and what may require a more comprehensive investigation. Information from CVA reports will inform a new FGBNMS management plan.

There are immediate next steps that FGBNMS can take to begin preparing for climate changes. There was a heavy emphasis on partnerships, building on existing relationships, and resources that can be used to explore science, technology, and innovation. Sanctuary staff and managers actively participate in outreach and education with students, teachers, and the public throughout the region. The sanctuary also works with local partners on outreach activities such as workshops to help teachers and community members learn to effectively communicate about climate change and how it is affecting FGBNMS (Moretzsohn et al., 2012). These types of collaborations can help Sanctuary officials better address both climate and non-climate stressors. Additional monitoring is also needed in order to fully understand the impacts of climate change on species at FGBNMS and managers must work closely with climate researchers to fully address the possible changes that may occur.

To strengthen vulnerable coral species and help them withstand future changes, the FGBNMS can develop coral restoration capacity by collecting, growing, and releasing larvae collected locally, and limiting coral bioeroders. Sea urchin and other herbivore populations can be managed more carefully to encourage benthic algae control. Moorings can be maintained to prevent physical damage to reefs from boats, and underwater platforms that provide habitat can be maintained. Site-specific restoration of reefs can be implemented.

Fish populations at FGBNMS may be enhanced by further fishing regulations that protect spawning aggregations of select species (e.g., marbled grouper), or regional or seasonal fishing closures, if allowable. More robust catch reporting programs are also needed.

Planning and preparing for more long-term mitigation strategies for future climate changes could begin immediately. Artificial upwelling was a notable recommendation to address rising seawater temperature in the region. Warm water-resistant species could additionally be used to restore local species if they are negatively impacted by seawater warming in the region; similarly, heat-tolerant zooxanthellae could be used to repopulate bleached corals.

Invasive lionfish management strategies such as issuing permits for divers and fishing vessels to remove lionfish, deploying traps, outfitting ROVs to kill lionfish, increased frequency of lionfish removal cruises, promoting consumption of lionfish (with FDA approval), enhancing partnerships with zoo and aquarium diver programs to allow lionfish derbies, and tracking management strategies used elsewhere may all help control this invasive species. Similarly, if needed in the future, invasive cup coral collection permits can be issued to aquaria and zoos, a commercial enterprise for harvest of cup coral for private ownership can be encouraged, and dive masters can be trained to remove the invasive cup corals.

Although coral disease may be present in FGBNMS, the Sanctuary can still prevent spread and introduction of new diseases by continued enforcement of “best management practice” coral disease prevention measures such as cleaning dive gear prior to water entry. Immediate measures such as widespread antibiotic application can be taken to control SCTLD and other diseases upon arrival within the FGBNMS, and adherence to the SCTLD preparedness plan should take place. SCTLD-susceptible species should undergo genetic banking, while the Sanctuary practices dynamic management as it may be required to undergo drastic measures (e.g., closing one bank) to control disease after an outbreak at FGBNMS. Additional discussion regarding adaptation actions occurred as the last item on the workshop agenda, and habitat-specific discussion centered on the themes from Section 3.1, “Habitat Assessment”.

4.1.1 Future Research Directions

A commonly discussed knowledge gap was the influence of OA on many of the species assessed. Impacts of OA on fish otolith growth, and its repercussions, are not well known. In general, there is high uncertainty on OA impacts on mesophotic habitats and invertebrates.

4.1.2 Invasive Species

Continued strategies for removal and control of invasive lionfish were identified as important by all workshop groups. Lionfish removal could pair with orange cup coral collections, or a relationship with the aquarium trade could be established to hand over these corals for aquarium trade. There is a concern of ciguatera advisory for lionfish from the Food and Drug Administration, but more study is needed on whether this issue pertains to lionfish from FGBNMS.

4.1.3 Fishery Management

Possible seasonal or spatial closures of fisheries may help stressed species increase in population. However, dive closures may interfere with outreach.

4.1.4 Partnerships and Collaborations

All workshop groups emphasized building on existing relationships and forging new relationships to promote outreach, facilitate research, and for management actions such as lionfish control. In particular, most participants agreed having a more formal relationship with the GOM FMC would be beneficial for addressing a variety of concerns. Zoos and aquariums are trusted by the public and information disseminated by these organizations could also serve to promote conservation efforts in the Sanctuary; collaboration with these organizations was also suggested multiple times during the workshop. Additionally, the U.S. Geological Survey genomics researchers, NOAA Fisheries, and Sea Grant would provide useful collaborations for future work.

4.1.5 Disease

Proactive measures are being taken to address the new occurrence of SCTLD-like observations in FGBNMS, but managers need to stay on top of current research and methodology for addressing this and other potential diseases. Proactive measures should continue to be taken to prevent further spread of disease in the sanctuary.

4.1.6 Genetics

eDNA and use of Clustered Regularly Interspaced Short Palindromic Repeats for coral species may warrant further investigation. Gene banking of corals and hearty stony corals for future restoration of mesophotic regions may also be useful if future populations become scarce.

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Glossary of Acronyms

Ω_{Ar}	Saturation state of aragonite
CCA	Crustose coralline algae
CVA	Climate Vulnerability Assessment
DIC	Dissolved inorganic carbon
DO	Dissolved oxygen
EFGB	East Flower Garden Bank
FGBNMS	Flower Garden Banks National Marine Sanctuary
FMC	Fishery Management Council
GOM	Gulf of Mexico
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for the Conservation of Nature
NOAA	National Oceanic and Atmospheric Administration
nwGOM	Northwestern Gulf of Mexico
OA	Ocean acidification
ONMS	Office of National Marine Sanctuaries
$p\mathrm{CO}_2$	Partial pressure of carbon dioxide
SCTLD	Stony coral tissue loss disease
SST	Sea surface temperature
TA	Total alkalinity
TL	Total length
RCP2.6	Representative Concentration Pathway Scenario, 2.6 watts m^{-2} Global Warming
RCP4.5	Representative Concentration Pathway Scenario, 4.5 watts m^{-2} Global Warming
RCP8.5	Representative Concentration Pathway Scenario, 8.5 watts m^{-2} Global Warming
RVA	Rapid Vulnerability Assessment
WFGB	West Flower Garden Bank

References

Aguirre, J., Perfectti, F., & Braga, J. C. (2010). Integrating phylogeny, molecular clocks, and the fossil record in the evolution of coralline algae (Corallinales and Sporolithales, Rhodophyta). *Paleobiology, 36*(4), 519–533. https://doi.org/10.1666/09041.1

Atlantic Oceanographic and Meteorological Laboratory. (2021). *North Atlantic Hurricane Basin (1851-2022) Comparison of Original and Revised HURDAT* . National Oceanic and Atmospheric Administration. Retrieved October 21, 2022, from www.aoml.noaa.gov/hrd/hurdat/comparison_table.html.

Alexander, M. A., Scott, J. D., Friedland, K. D., Mills, K. E., Nye, J. A., Pershing, A. J., & Thomas, A. C. (2018). Projected sea surface temperatures over the 21st century: Changes in the mean, variability and extremes for large marine ecosystem regions of Northern Oceans. *Elementa: Science of the Anthropocene, 6*(9). https://doi.org/10.1525/elementa.191

Alvera-Azcarate, A., Barth, A., & Weisberg, R. H. (2009). The surface circulation of the Caribbean Sea and the Gulf of Mexico as inferred from satellite altimetry. *Journal of Physical Oceanography, 39(3),* 640–657. https://doi.org/10.1175/2008JPO3765.1

Amorim, P. & Westmeyer, M. (2016). *Snapper and Grouper: SFP Fisheries Sustainability Overview 2015*. Sustainable Fisheries Partnership Foundation. 18 pp. https://www.fishsource.com

Aronson, R.B., Precht, W. F., Murdoch, T. J. T., & Robbart, M. L. (2005). Long-term persistence of coral assemblages on the Flower Garden Banks, Northwestern Gulf of Mexico: Implications for science and management. *Gulf of Mexico Science, 23*(1), 6. https://doi.org/10.18785/goms.2301.06

Ateweberhan, M., Feary, D. A., Keshavmurthy, S., Chen, A., Schleyer, M. H., & Sheppard, C. R. (2013). Climate change impacts on coral reefs: synergies with local effects, possibilities for acclimation, and management implications. *Marine Pollution Bulletin, 74*(2), 526–539. https://doi.org/10.1016/j.marpolbul.2013.06.011

Baillie, J.E.M., & Groombridge, Bt (Eds). (1996). *1996 IUCN Red List of Threatened Animals*. IUCN. https://www.iucnredlist.org/resources/baillie1996

Bassim, K., Sammarco, P., & Snell, T. (2002). Effects of temperature on success of (self and non-self) fertilization and embryogenesis in *Diploria strigosa* (Cnidaria, Scleractinia). *Marine Biology, 140,* 479–488. https://doi.org/10.1007/s00227-001-0722-4

Bell, J. J., Davy, S. K., Jones, T., Taylor, M. W., & Webster, N. S. (2013). Could some coral reefs become sponge reefs as our climate changes? *Global Change Biology 19*(9), 2613–2624. https://doi.org/10.1111/gcb.12212

Belliveau, S.A., & Paul, V. J. (2002). Effects of herbivory and nutrients on the early colonization of crustose coralline and fleshy algae. *Marine Ecology Progress Series, 232,* 105–114. https://doi.org/10.3354/meps232105

Bianchi, T. S., DiMarco, S. F., Cowan, J. H., Hetland, R. D., Chapman, P., Day, J. W., & Allison, M. A. (2010). The science of hypoxia in the northern Gulf of Mexico: A review. *Science of the Total Environment, 408*(7), 1471–1484. https://doi.org/10.1016/j.scitotenv.2009.11.047

Benedetto, K. M., & Trepanier, J. C. (2020). Climatology and spatiotemporal analysis of North Atlantic rapidly intensifying hurricanes (1851–2017). *Atmosphere, 11*(3), 291. https://doi.org/10.3390/atmos11030291

Berger, N., Haseltine, M. G., Boehm, J. T., & Goreau, T. J. (2013). Increased oyster growth and survival using biorock technology. In Goreau, T. J. & R. K. Trench (eds.), Innovative Methods of Marine Ecosystem Restoration. CRC Press, Boca Raton, LA, pp. 157–166.

Blakeway, R. D., Fogg, A. Q., & Jones, G. A. (2021). Oldest Indo-Pacific lionfish (*Pterois volitans/P. miles*) recorded from the northwestern Gulf of Mexico. *Gulf and Caribbean Research, 32*(1), GCFI1-GCFI4. https://doi.org/10.18785/gcr.3201.01

Blakeway, R. D., Fogg, A. Q., Johnston, M. A., Rooker, J. R., & Jones, G. A. (2022). Key life history attributes and removal efforts of invasive lionfish (*Pterois volitans*) in the Flower Garden Banks National Marine Sanctuary, Northwestern Gulf of Mexico. *Frontiers in Marine Science, 9*, 774407. https://doi.org/10.3389/fmars.2022.774407

Boland, G.S., Gallaway, B. J., Baker, J. S., & Lewbel, G. S. (1983). Ecological effects of energy development on reef fish of the Flower Garden Banks. National Marine Fisheries, Galveston, Texas. Contract No. NA80-GA-C-00057. 466 pp.

Boland, G.S., Etnoyer, P. J., Fisher, C. R., & Hickerson, E. L. (2016). State of Deep-Sea Coral and Sponge Ecosystems of the Gulf of Mexico Region: Texas to the Florida Straits. In Hourigan, T.F., P.J. Etnoyer, and S.D. Cairns (eds.), The State of Deep-Sea Coral and Sponge Ecosystems of the United States. NOAA Technical Memorandum X. NOAA, Silver Spring, pp 11-1 – 11-59.

Bosence, D. W. J. (1983). Coralline algal reef frameworks. *Journal of the Geological Society 140*(3), 365–376. https://doi.org/10.1144/gsjgs.140.3.0365

Bright, T. J., Kraemer, G. P., Minnery, G. A., & Viada, S. T. (1984). Hermatypes of the Flower Garden Banks, northwestern Gulf of Mexico: A comparison to other Western Atlantic reefs. *Bulletin of Marine Science, 34*(3), 461–476.

Bright, T. J., McGrail, D. W., Rezak, R., Boland, G. S., & Trippett, A. R. (1985). The Flower Gardens: A compendium of information. OCS Study MMS 85-0024. U.S. Department of the Interior Minerals Management Service, Gulf of Mexico Outer Continental Shelf Regulations. New Orleans, Louisiana, 103 pp. https://espis.boem.gov/final%20reports/3815.pdf

Bruggemann, J. H., Van Oppen, M. J., & Breeman, A. M. (1994). Foraging by the stoplight parrotfish *Sparisoma viride*. I. Food selection in different, socially determined habitats. *Marine Ecology Progress Series, 106,* 41–41. https://doi.org/10.3354/meps106041

Bruyère, C. L., Rasmussen, R., Gutman, E., Done, J., Tye, M., Jaye, A., Prein, A., Mooney, P., Ge, M., Fredrick, S., Friis-Hansen, P., Garrè, L., Veldore, V. & Niesel, J. (2017). Impact of Climate Change on Gulf of Mexico Hurricanes. *NCAR Technical Notes*, 535(STR), 165 pp. http://dx.doi.org/10.5065/D6RN36J3

Burkepile, D. E., Adam, T. C., Roycroft, M., Ladd, M. C., Munsterman, K. S. & Ruttenberg, B. I. (2019). Species-specific patterns in corallivory and spongivory among Caribbean parrotfishes. *Coral Reefs, 38*(3), 417–423. https://doi.org/10.1007/s00338-019-01808-6

Byers, J. E., Hampshire, N., & Road, C. (2002). Impact of non-indigenous species on natives enhanced by anthropogenic alteration of selection regimes. *OIKOS, 97*(3), 449–458. https://doi.org/10.1034/j.1600-0706.2002.970316.x

Cai, W. J., Hu, X., Huang, W. J., Murrell, M. C., Lehrter, J. C., Lohrenz, S. E., Chou, W. C., Zhai, W., Hollibaugh, J. T., Wang, Y., Zhao, P., Guo, X., Gundersen, K., Dai, M., & Gong G. C. (2011). Acidification of subsurface coastal waters enhanced by eutrophication. *Nature Geoscience, 4*(11), 766–770. https://doi.org/10.1038/ngeo1297

Cairns, S. D., Opresko, D. M., Hopkins, T. S., & Schroeder, W. W. (1993). New records of deep-water Cnidaria (Scleractinia & Antipatharia) from the Gulf of Mexico. *Gulf of Mexico Science, 13*(1), 1. https://doi.org/10.18785/negs.1301.01

Campbell, M. D., Rademacher, K. R., Noble, B., Salisbury, J., Felts, P., Moser, J., Caillouet, R., Herndon, M., & Driggers, W. B. (2019). Status and Trends of Marbled Grouper in the North-Central Gulf of Mexico. *Marine and Coastal Fisheries, 11(*2), 114–124. https://doi.org/10.1002/mcf2.10066

Commission for Environmental Cooperation. (2017). *North American Marine Protected Area Rapid Vulnerability Assessment Tool. Commission for Environmental Cooperation*. 18 pp. http://www3.cec.org/islandora/en/item/11739-north-american-marine-protected-area-rapid-vulnerability-assessment-tool

Chan, N.C. (2013). Sensitivity of coral calcification to ocean acidification: A meta-analysis. *Global Change Biology, 19*(1)*,* 282–290. https://doi.org/10.1111/gcb.12011

Chanas, B., Pawlik, J. R., Lindel, T., & Fenical, W. (1996). Chemical defense of the Caribbean sponge *Agelas clathrodes* (Schmidt). *Journal of Experimental Marine Biology and Ecology, 208(1-2),* 185–196. https://doi.org/10.1016/S0022-0981(96)02653-6

Christian, J., Christian, K., & Basara, J. B. (2015). Drought and pluvial dipole events within the great plains of the United States. *Journal of Applied Meteorology and Climatology, 54*(9), 1886–1898. https://doi.org/10.1175/JAMC-D-15-0002.1

Clark, R., Kracker, L. M., Taylor, J. C., & Buckel, C. A. (eds). 2014. Fish and benthic communities of the Flower Garden Banks National Marine Sanctuary: Science to Support Sanctuary Management. *NOAA Technical Memorandum NOS NCCOS 179*. Silver Spring, Maryland. 317 pp.

Colin, P.L. (1978). Marine Invertebrates and Plants of the Living Reef. *TFH Publications*, pp. 110–111.

Comeros-Raynal, M. T., Choat, J. H., Polidoro, B. A., Clements, K. D., Abesamis, R., Craig, M. T., Lazuardi, M. E., McIlwain, J., Muljadi, A., Myers, R. F., Nañola Jr., C. L., Pardede, S., Rocha, L. A., Russell, B., Sanciangco, J. C., Stockwell, B., Harwell, H., & Carpenter, K. E. (2012). The likelihood of extinction of iconic and dominant herbivores and detritivores of coral reefs: The parrotfishes and surgeonfishes. *PLoS One, 7*(7), e39825. https://doi.org/10.1371/journal.pone.0039825

Crickenberger, S., & Moran, A. (2013). Rapid range shift in an introduced tropical marine invertebrate. *PLoS ONE, 8*(10), 1–8. https://doi.org/10.1371/journal.pone.0078008

DeBose, J. L., Nuttall, M. F., Hickerson, E. L., & Schmahl, G. P. (2013). A high-latitude coral community with an uncertain future: Stetson Bank, northwestern Gulf of Mexico. *Coral Reefs, 32*(1), 255–267. https://doi.org/10.1007/s00338-012-0971-3

De Kluijver, M., Gijswijt, G., de Leon R., & da Cunda, I. Marine Species Identification Portal. Retrieved August 19, 2022 from http://species-identification.org/species.php?species_group=caribbean_diving_guide&id=310

DeLong, K., Palmer, K., Wagner, A. J., Weerabaddana, M. M., Slowey, N., Herrmann, A. C., Duprey, N., Martinez-Garcia, A., Jung, J., Hadjas, I., Rose, N. L., Roberts, S. L., Roberts, L. R., Cundy, A. B., Gaca, P., Milton, J. A., Yang, H., Turner, S. D., Huang, C. Y., Shen, C. C., & Zinke, J. (2023). The flower garden banks *Siderastrea siderea* coral as a candidate global boundary stratotype section and point for the Anthropocene series. *The Anthropocene Review, 10*(1), 1–26. https://doi.org/10.1177/20530196221147616

Dickson, A. G., Sabine, C. L., & Christian, J. R. (eds) (2007). *Guide to best practices for ocean CO2 measurements*. Sidney, British Columbia, North Pacific Marine Science Organization, 191pp. (PICES Special Publication 3; IOCCP Report 8). https://doi.org/10.25607/OBP-1342

Doney, S. C., Busch, D. S., Cooley, S. R., & Kroeker, K. J. (2020). The impacts of ocean acidification on marine ecosystems and reliant human communities. *Annual Review of Environment and Resources, 45,* 83–112. https://doi.org/10.1146/annurev-environ-012320-083019

Doney, S. C., Fabry, V. J., Feely, R. A., & Kleypas, J. A. (2009). Ocean acidification: The other CO_2 problem. *Annual Review of Marine Science, 1*, 169–192. https://doi.org/10.1146/annurev.marine.010908.163834

Doney, S. C., Ruckelshaus, M., Emmett Duffy, J., Barry, J. P., Chan, F., English, C. A., Galindo, H. M., Grebmeier, J. M., Hollowed, A. B., Knowlton, N., Polovina, J., Rabalais, N. N., Sydeman,W. J., & Talley, L. D. (2012). Climate change impacts on marine ecosystems. *Annual Review of Marine Science, 4,* 11–37. https://doi.org/10.1146/annurev-marine-041911-111611

Du, J., Park, K., Dellapenna, T. M., & Clay, J. M. (2019). Dramatic hydrodynamic and sedimentary responses in Galveston Bay and adjacent inner shelf to Hurricane Harvey. *Science of the Total Environment, 653,* 554–564. https://doi.org/10.1016/j.scitotenv.2018.10.403

Dupont, S., Ortega-Martínez, O., & Thorndyke, M. (2010). Impact of near-future ocean acidification on echinoderms. *Ecotoxicology, 19*(3), 449–462.

Dykstra, S. L., & Dzwonkowski, B. (2021). The role of intensifying precipitation on coastal river flooding and compound river-storm surge events, northeast Gulf of Mexico. *Water Resources Research, 57*(11), 1–17. https://doi.org/10.1029/2020WR029363

Edmunds, P. J. (2010). Population biology of *Porites astreoides* and *Diploria strigosa* on a shallow Caribbean reef. *Marine Ecology Progress Series, 418,* 87–104. https://doi.org/10.3354/meps08823

Emanuel, K.A. (2017). Will global warming make hurricane forecasting more difficult? *Bulletin of the American Meteorological Society, 98*(3), 495–501. https://doi.org/10.1175/BAMS-D-16-0134.1

Emanuel, K.A. (2021). 2021 update to data originally published in: Emanuel, K.A. 2007. Environmental factors affecting tropical cyclone power dissipation. *Journal of the Climate, 20*(22), 5497–5509.

Environmental Protection Agency (2022). Climate Change Indicators: Tropical Cyclone Activity. https://www.epa.gov/climate-indicators/climate-change-indicators-tropical-cyclone-activity

Erisman B, Heyman, W., Kobara, S., Ezer, T., Pittman, S., Aburto-Oropeza, O., & Nemeth, R. S. (2017). Fish spawning aggregations: Where well-placed management actions can yield big benefits for fisheries and conservation. *Fish and Fisheries, 18*(1), 128–144. https://doi.org/10.1111/faf.12132

Etnoyer, P. J., & Cairns, S. D. (2017). Deep-Sea Coral Taxa in the U.S. Gulf of Mexico: Depth and Geographical Distribution. NOAA Center for Coastal Monitoring and Assessment, National Centers for Coastal Ocean Science, Charleston, SC. National Museum of Natural History, Smithsonian Institution, Washington, DC. https://repository.si.edu/bitstream/handle/10088/34996/NOAA_DSC-Species-List_GulfofMexico_Etnoyer-Cairns_2017.pdf?sequence=1&isAllowed=y

Feely, R. A., Alin, S. R., Newton, J., Sabine, C. L., Warner, M., Devol, A., Krembs, C., & Maloy, C. (2010). The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. *Estuarine, Coastal and Shelf Science, 88*(4), 442–449. https://doi.org/10.1016/j.ecss.2010.05.004

Feely, R. A., Orr, J., Fabry, V. J., Kleypas, J. A., Sabine, C. L., & Langdon, C. (2009). Present and future changes in seawater chemistry due to ocean acidification. In: McPherson, B.J. & E. T. Sundquist (eds.), *Carbon Sequestration and its Role in the Global Carbon Cycle*. pp. 175–188. USGS Publications Warehouse. https://doi.org/10.1029/GM183

Fennel, K., Laurent, A., Hetland, R., Justic, D., Ko, D. S., Lehrter, J., Murrell, M., Wang, L., Yu, L., & Zhang, W. (2016). Effects of model physics on hypoxia simulations for the northern Gulf of Mexico: A model intercomparison. *Journal of Geophysical Research: Oceans, 121*(5), 5731–5750. https://doi.org/10.1002/2015JC011577

Fenner, D., & Banks, K. (2004). Orange cup coral *Tubastraea coccinea* invades Florida and the Flower Garden Banks, northwestern Gulf of Mexico. *Coral Reefs, 23,* 505–507. https://doi.org/10.1007/s00338-004-0422-x

Ferreira, B., & Bertoncini, A. A. (2018). *Dermatolepis inermis*. The IUCN Red List of

Threatened Species 2018: e.T39303A46914065. http://dx.doi.org/10.2305/IUCN.UK.2018-2.RLTS.T39303A46914065.en

Flower Garden Banks National Marine Sanctuary. (2021). Brown Alga List. *National Oceanic and Atmospheric Administration*. https://flowergarden.noaa.gov/about/algaelist.html

Flower Garden Banks National Marine Sanctuary. (n.d). *Flower Garden Banks National Marine Sanctuary*. *National Oceanic and Atmospheric Administration*. Retrieved August 11, 2022, from https://flowergarden.noaa.gov

Flower Garden Banks National Marine Sanctuary. (2023). Bony Fish Species. *National Oceanic and Atmospheric Administration*. Retrieved August 25, 2022, from https://flowergarden.noaa.gov/about/fishlist.html

Fleurence, J. & Levine, I. (2016). Seaweed. In: *Health and Disease Prevention. Elsevier Inc.*

Fredericq, S., Krayesky-Self, S., Sauvage, T., Richards, J., Kittle, R., Arakaki, N., Hickerson, E., & Schmidt, W. E. (2019). The Critical Importance of Rhodoliths in the Life Cycle Completion of both Macro- and Microalgae, and as Holobionts for the Establishment and Maintenance of Marine Biodiversity. *Frontiers in Marine Science, 5,* 502. https://doi.org/10.3389/fmars.2018.00502

Gao, C., Tian, S., Kindong, R., & Dai, X. (2020). Biology and Environmental Preferences of Wahoo, *Acanthocybium solandri* (Cuvier, 1832), in the Western and Central Pacific Ocean (WCPO). *Journal of Marine Science and Engineering, 8*(3), 184. https://doi.org/10.3390/jmse8030184

Gobler, C. J., Doherty, O. M., Hattenrath-Lehmann, T. K., Griffith, A. W., Kang, Y., & Litaker, R. W. (2017). Ocean Warming since 1982 has Expanded the Niche of Toxic Algal Blooms in the North Atlantic and North Pacific Oceans. *Proceedings of the National Academy of Sciences of the United States of America, 114*(19), 4975–4980. https://doi.org/10.1073/pnas.1619575114

Goedicke, T. R. (1955). Origin of the Pinnacles on the Continental Shelf and Slope of the Gulf of Mexico. *The Texas Journal of Science, 7*(2), 149–159. http://hdl.handle.net/1969.3/18933

Goldenberg, S.B., Landsea, C. W., Mestas-Nunez, A. M., Gray, W. M. (2001). The recent increase in Atlantic hurricane activity: Causes and implications. *Science, 293*(5529), 474–479. https://doi.org/10.1126/science.1060040

Goreau, Thomas F. 1959. The ecology of Jamaican coral reefs I. Species composition and zonation. Ecology, 40(1), 67-90.

Goreau, T. F. (1959). The ecology of Jamaican coral reefs I. Species composition and zonation. *Ecology, 40*(1), 67–90. https://doi.org/10.2307/1929924

Grieve, B. D., Curchitser, E. N., & Rykaczewski, R. R. (2016). Range expansion of the invasive lionfish in the Northwest Atlantic with climate change. *Marine Ecology Progress Series, 546*, 225–237. https://doi.org/10.3354/meps11638

Gruber, N., Clement, D., Carter, B. R., Feely, R. A., Heuven, S., Van Hoppema, M., Ishii, M., & Key, R. M. (2019). The oceanic sink for anthropogenic CO_2 from 1994 to 2007. *Science, 363*(6432)*,* 1193–1199. https://doi.org/10.1126/science.aau5153

Hawkins, J. P., & Roberts, C. M. (2004). Effects of fishing on sex-changing Caribbean parrotfishes. *Biological Conservation, 115*(2), 213–226. https://doi.org/10.1016/S0006-3207(03)00119-8

Hayhoe, K., Wuebbles, D. J., Easterling, D. R., Fahey, D. F., Doherty, S., Kossin, J., Sweet, W., Vose, R., & Wehner, M. (2018). Our changing climate. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. pp. 59–76. https://doi.org/10.5822/978-1-61091-885-5

Heron, S. F., Maynard, J. A., Van Hooidonk, R., & Eakin, C. M. (2016). Warming trends and bleaching stress of the world's coral reefs 1985-2012. *Scientific Reports, 6*(1)*,* 38402. https://doi.org/10.1038/srep38402

Heyman, W.D., Grüss, A., Biggs, C. R., Kobara, S. I., Farmer, N. A., Karnauskas, M., Lowerre-Barbieri, S., Erisman, B. (2019). Cooperative monitoring, assessment, and management of fish spawning aggregations and associated fisheries in the U.S. Gulf of Mexico. *Marine Policy, 109,* 103689. https://doi.org/10.1016/j.marpol.2019.103689

Hickerson, E. L., Schmahl, G. P., Robbart, M., Precht, W. F., & Caldow, C. (2008). The state of coral reef ecosystems of the Flower Garden Banks, Stetson Bank, and other banks in the northwestern Gulf of Mexico. *The state of coral reef ecosystems of the United States and Pacific Freely Associated States*, 189–217.

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., Harvell, C. D., Sale, P. F., Edwards, A. J., Caldeira, K., Knowlton, N., Eakin, C. M. Iglesias-Prieto, R., Muthiga, N., Bradbury, R. H., Dubi, A., & Hatziolos, M.E. (2007). Coral reefs under rapid climate change and ocean acidification. *Science, 318*(5857), 1737–1742. https://doi.org/10.1126/science.1152509

Holmes, C. W. 2021. *Geologic History of the Gulf of Mexico.*

Hoppe, W.F. (1988a). Growth, regeneration and predation in three species of large coral reef sponges. *Marine Ecology Progress Series, 50*, 117–125.

Hoppe, W.F. (1988b). Reproductive patterns in three species of large coral reef sponges. *Coral Reefs, 7,* 45–50.

Hu, X., Nuttall, M. F., Wang, H., Yao, H., Staryk, C. J., McCutcheon, M. R., Eckert, R. J., Embesi J. A., Johnston, M. A., Hickerson, E. L., Schmahl, G. P., Manzello, D., Enochs, I. C., DiMarco, S., & Barbero, L. (2018). Seasonal variability of carbonate chemistry and decadal changes in waters of a marine sanctuary in the northwestern Gulf of Mexico. *Marine Chemistry, 205,* 16–28. https://doi.org/10.1016/j.marchem.2018.07.006

Hughes, T. P., Kerry, J. T., Baird, A. H., Connolly, S. R., Dietzel, A., Eakin, C. M., Heron, S. F., Hoey, A. S., Hoogenboom, M. O., Liu, G., McWilliam, M. J., Pears, R. J., Pratchett, M. S., Skirving, W. J., Stella, J.

S., & Torda, G. 2018. Global warming transforms coral reef assemblages. Nature 556, 492–496. https://doi.org/10.1038/s41586-018-0041-2

Humphreys, M. P., Daniels, C. J., Wolf-Gladrow, D. A., Tyrrell, T., & Achterberg, E. P. (2018). On the influence of marine biogeochemical processes over CO_2 exchange between the atmosphere and ocean. *Marine Chemistry, 199,* 1–11. https://doi.org/10.1016/j.marchem.2017.12.006

Intergovernmental Panel on Climate Change. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.). IPCC, Geneva, Switzerland, 151 pp.

Jiang, L. Q., Feely, R. A., Carter, B. R., Greeley, D. J., Gledhill, D. K., & Arzayus, K. M. (2015). Climatological distribution of aragonite saturation state in the global oceans. *Global Biogeochemical Cycles, 29*(10), 1656–1673. https://doi.org/10.1002/2015GB005198

Johansen, H.W. (1981). *Coralline Algae, A First Synthesis*. CRC Press.

Jöhnk, K. D., Huisman, J., Sharples, J., Sommeijer, B., Visser, P. M., & Stroom, J. M. (2008). Summer heatwaves promote blooms of harmful cyanobacteria. *Global Change Biology, 14*(3), 495–512. https://doi.org/10.1111/j.1365-2486.2007.01510.x

Johnson, M.D. (2014). Coralline algae: The unsung architects of coral reefs. *Smithsonian Ocean: Find Your Blue*.Retrieved August 11, 2022, from https://ocean.si.edu/ocean-life/plants-algae/coralline-algae-unsung-architects-coral-reefs

Johnston, M. A., Embesi, J. A., Eckert, R. J., Nuttall, M. F., Hickerson, E. L., & Schmahl, G. P. (2016). Persistence of coral assemblages at East and West Flower Garden Banks, Gulf of Mexico. *Coral Reefs, 35,* 821–826. https://doi.org/10.1007/s00338-016-1452-x

Johnston, M. A., Nuttall, M. F., Eckert, R. J., Blakeway, R. D., Sterne, T. K., Hickerson, E. L., Schmahl, G. P., Lee, M. T., MacMillan, J., & Embesi, J. A. (2018). Localized coral reef mortality event at East Flower Garden Bank, Gulf of Mexico. *Bulletin of Marine Science, 95*(2)*,* 239–250. https://doi.org/10.5343/bms.2018.0057

Johnston, M. A., Nuttall, M. F., Eckert, R. J., Embesi, J. A., Hickerson, E. L., & Schmahl, G. P. (2018). Long-term Monitoring at East and West Flower Garden Banks: 2017 Annual Report. *Marine Sanctuaries Conservation Series ONMS-18-02*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Flower Garden Banks National Marine Sanctuary, Galveston, TX. 124 pp.

Johnston, M. A., Hickerson, E. L, Nuttall, M. F., Blakeway, R. D., Sterne, T. K., Eckert, R. J., , & Schmahl, G. P. (2019). Coral bleaching and recovery from 2016 to 2017 at East and West Flower Garden Banks, Gulf of Mexico. *Coral Reefs, 38*(4), 787–799. https://doi.org/10.1007/s00338-019-01788-7

Johnston, M.A., O'Connell, K., Blakeway, R. D., MacMillan, J., Nuttall, M. F., Hu, X., Embesi, J. A., Hickerson, E. L., & Schmahl, G. P. (2021). Long-Term Monitoring at East and West Flower Garden Banks: 2019 Annual Report. *National Marine Sanctuaries Conservation Series ONMS-21-02*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Flower Garden Banks National Marine Sanctuary, Galveston, TX. 88 pp.

Johnston, M. A. (2021). Strategy for Stony Coral Tissue Loss Disease Prevention and Response at Flower Garden Banks National Marine Sanctuary. National Marine Sanctuaries Conservation Series ONMS-21-06. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Flower Garden Banks National Marine Sanctuary, Galveston, TX. 30 pp.

Johnston, M.A., Studivan, M.S., Enochs, I.C., Correa, A.M.S., Besemer, N., Eckert, R.J., Edwards, K., Hannum, R., Hu, X., Nuttall, M., O'Connell, K., Palacio-Castro, A.M., Schmahl, G.P., Sturm, A.B., Ushijima, B., and Voss. J.D. 2023. Coral disease outbreak at the remote Flower Garden Banks, Gulf of Mexico. *Front. Mar. Sci., 10,* 100. https://doi.org/10.3389/fmars.2023.1111749

Jorde, A. (2022). *Xestospongia muta*. *Animal Diversity Web*. Retrieved August, 2022, from https://animaldiversity.org/accounts/Xestospongia_muta/ 25

Karleskint, G., Turner, R., & Small, J. (2012). *Introduction to Marine Biology*. Cengage Learning. Belmont, CA.

Kealoha, A. K., Shamberger, K. E. F., DiMarco, S. F., Thyng, K. M., Hetland, R. D., Manzello, D. P., Slowey, N. C., & Enochs, I. C. (2020). Surface Water CO2 variability in the Gulf of Mexico (1996–2017). *Scientific Reports, 10*(1), 12279. https://doi.org/10.1038/s41598-020-68924-0

Kealoha, A. K., Doyle, S. M., Shamberger, K. E. F., Sylvan, J. B., Hetland, R. D., & DiMarco, S. F. (2020). Localized hypoxia may have caused coral reef mortality at the Flower Garden Banks. *Coral Reefs, 39*(1), 119–132. https://doi.org/10.1007/s00338-019-01883-9

Kells, V. A., & Carpenter, K. E. (2011). *A field guide to coastal fishes: from Maine to Texas*. Johns Hopkins University Press.

Kleypas, J., Feely, R., Fabry, V., Langdon, C., Sabine, C., & Robbins, L. (2006). *Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research, report of a workshop held 18-20 April 2005,* St. Petersburg, FL, sponsored by NSF, NOAA, and the U.S. Geological Survey, 88 pp.

Knutson, T. R., Sirutis, J. J., Zhao, M., Tuleya, R. E., Bender, M., Vecchi, G. A., Villarini, G., & Chavas, D. (2015). Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios. *Journal of Climate 28*(18)*,* 7203–7224. https://doi.org/10.1175/JCLI-D-15-0129.1

Knutson, T. R., Camargo, S. J., Chan, J. C. L., Emanuel, K., Ho, C. H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., & Wu, L. (2019). Tropical Cyclones and Climate Change Assessment. *Bulletin of the American Meteorological Society, 100*(10), 1987–2007. https://doi.org/10.1175/BAMS-D-18-0189.1

Knutson, T. R., Sirutis, J. J., Bender, M. A., Tuleya, R. E., & Schenkel, B. A. (2022). Dynamical downscaling projections of late twenty-first-century U.S. landfalling hurricane activity. *Climatic Change, 171*(3–4), 28. https://doi.org/10.1007/s10584-022-03346-7

Krajewski, J. P. & Floeter, S. R. (2011). Reef fish community structure of the Fernando de Noronha Archipelago (Equatorial Western Atlantic): The influence of exposure and benthic composition. *Environmental Biology of Fishes, 92*(1), 25–40. https://doi.org/10.1007/s10641-011-9813-3

Kuffner, I.B., Andersson, A. J., Jokiel, P. L., Rodgers, K. S., & MacKenzie, F. T. (2008). Decreased abundance of crustose coralline algae due to ocean acidification. *Nature Geoscience, 1*(2), 114–117. https://doi.org/10.1038/ngeo100

Kuffner, I. B., Hickey, T. C., Morrison, J. M. (2013). Calcification rates of the massive coral *Siderastrea siserea* and crustose coralline algae along the Florida Keys (USA) outer-reef tract. *Coral Reefs, 32,* 987–997. https://doi.org/10.1007/s00338-013-1047-8

Lawman, A. E., Dee, S., DeLong, K. L., Correa, A. M. S. (2022). Rates of future climate change in the Gulf of Mexico and the Caribbean Sea: Implications for coral reef ecosystems. *Journal of Geophysical Research: Biogeosciences, 127*(9)*,* e2022JG006999. https://doi.org/10.1029/2022JG006999

Le Quéré, C., R.M. Andrew, P. Friedlingstein, S. Sitch, J. Pongratz, A.C. Manning, J. Ivar Korsbakken, G.P. Peters, J.G. Canadell, R.B. Jackson, T.A. Boden, P.P. Tans, O. Andrews, V.K. Arora, D.C.E. Bakker, L. Barbero, M. Becker, R.A. Betts, L. Bopp, Chevallier, F., Chini, L. P., Ciais, P., Cosca, C. E., Cross, J., Currie, K., Gasser, T., Harris, I., Hauck, J., Haverd, V., Houghton, R. A., Hunt, C. W., Hurtt, G., Ilyina, T., Jain, A. K., Kato, E., Kautz, M., Keeling, R. F., Goldewijk, K. K., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lima, I., Lombardozzi, D., Metzl, N., Millero, F., Monteiro, P. M. S., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S., Nojiri, Y., Padin, X. A., Peregon, A., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Reimer, J., Rödenbeck, C., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B. D., Tian, H., Tilbrook, B., Tubiello, F. N., van der Laan-Luijkx, I. T., van der Werf, G. R., van Heuven, S., Viovy, N., Vuichard, N., Walker, A. P., Watson, A. J., Wiltshire, A. J., Zaehle, S., & Zhu, D. (2018). Global Carbon Budget 2017. *Earth System Science Data, 10*(1), 405–448. https://doi.org/10.5194/essd-10-405-2018

Levitan, D.R., Boudreau, W., Jara, J., & Knowlton, N. (2014). Long-term reduced spawning in *Orbicella* coral species due to temperature stress. *Marine Ecology Progress Series, 515,* 1–10. https://doi.org/10.3354/meps11063

Lin, M. & Tarnita, C. (2020). The Ecological Role of Keystone Herbivore *Diadema antillarum* in Promoting Indices of Caribbean Coral Reef Health. Dataspace.

https://dataspace.princeton.edu/handle/88435/dsp014m90dz52v

Liu, G., Feng, Q., & Gu, S. (2008). Extinction pattern and process of siliceous sponge spicules in deep-water during the latest Permian in South China. *Science in China Series D: Earth Sciences, 51*(11), 1623–1632. https://doi.org/10.1007/s11430-008-0124-2

Loera-Padilla, F. J., Pineros, V. J., Baldwin, C. C., Cox, C. E., Simoes, N., Ribeiro, E., Lasso-Alcala, O. M., Dominguez-Dominguez, O. (2021). Phylogeography, population connectivity and demographic history of the Stoplight parrotfish, *Sparisoma viride* (Teleostei: Labridae), in the Greater Caribbean. *Coral Reefs, 41,* 753–765. https://doi.org/10.1007/s00338-020-02036-z

Lopes-Filho, E. A. P., Salgueiro, F., Nascimento, S. M., Gauna, M. C., Parodi, E. R., & Campos De Paula, J. (2017). Molecular evidence of the presence of *Dictyota dichotoma* (Dictyotales: Phaeophyceae) in Argentina based on sequences from mtDNA and cpDNA and a discussion of its possible origin. *New Zealand Journal of Botany*, *55*(3), 293-305. https://doi.org/10.1080/0028825X.2017.1326387

Luckhrst, B.E., & Dean, J. M. (2009). Age estimates of two large misty grouper, *Epinephelus mystacinus* (Serranidae) from Bermuda with a comparison of the age of tropical groupers in the Western Atlantic. *Gulf and Caribbean Research, 21*(1), 73–77. https://doi.org/10.18785/gcr.2101.09

Lugo-Fernandez, A., & Gravois, M. (2010). Understanding impacts of tropical storms and hurricanes on submerged bank reefs and coral communities in the northwestern Gulf of Mexico. *Continental Shelf Research, 30*(10-11), 1226–1240. https://doi.org/10.1016/j.csr.2010.03.014

Oouchi, K., Yoshimura, J., Yoshimura, H., Mizuta, R., Kusunoki, S., & Noda, A. (2006). Tropical cyclone climatology in a global-warming climate as simulated in a 20 km mesh global atmospheric model: Frequency and wind intensity analyses. *Journal of the Meteorological Society of Japan, 84*(2), 259–276. https://doi.org/10.2151/jmsj.84.259

Mann, M.E., & Emanuel, K. A. (2006). Atlantic hurricane trends linked to climate change. *EOS, Transactions American Geophysical Union, 87*(24), 233–244. https://doi.org/10.1029/2006EO240001

Manzello, D. P., Kolodziej, G., Kirkland, A., Besemer, N., & Enochs, I. C. (2021). Increasing coral calcification in *Orbicella faveolata* and *Pseudodiploria strigosa* at Flower Garden Banks, Gulf of Mexico. *Coral Reefs, 40*(4), 1097–1111. https://doi.org/10.1007/s00338-021-02108-8

Margolin, C. L. (2012). *Interactive Effects of Water Flow and Light Levels with Decreasing pH on the Growth and Survival of Tropical Cnidarians*. Dissertation, University of Miami.

Maynard, J. (2018). Past and projected future climate impacts to coral reefs in the Flower Garden Banks. https://www.coris.noaa.gov/activities/projects/climate/docs/fgbnms_climate_impacts_summary.pdf

McCutcheon, M. R., Yao, H., Staryk, C. J., & Hu, X. (2021). Temporal variability and driving factors of the carbonate system in the Aransas Ship Channel, TX: A time-series study. *Biogeosciences*, *18*(15), 4571–4586. https://doi.org/10.5194/bg-18-4571-2021

Mills, K. E., Pershing, A. J., Brown, C. J., Chen, Y., Chiang, F. S., Holland, D. S., Lehuta, S., Nye, J. A., Sun, J. C., Thomas, A. C., & Wahle, R. A. (2013). Fisheries management in a changing climate: Lessons from the 2012 ocean heat wave in the Northwest Atlantic. *Oceanography, 26*(2), 191–195. https://doi.org/10.5670/oceanog.2013.27

Moore, S. K., Trainer, V. L., Mantua, N. J., Parker, M. S., Laws, E. A., Backer, L. C., & Fleming, L. E. (2008). Impacts of climate variability and future climate change on harmful algal blooms and human health. *Environmental Health, 7*(2), 1–12. https://doi.org/10.1186/1476-069X-7-S2-S4

Morris, J. T., Enochs, I. C., Besemer, N., Viehman, T. S., Groves, S. H., Blondeau, J., Ames, C., Towle, E. K., Grove, L. J. W., Manzello, D. P. (2022). Low net carbonate accretion characterizes Florida's coral reef. *Scientific Reports, 12*(1), 19582. https://doi.org/10.1038/s41598-022-23394-4

Moretzsohn, F., Chávez, J. A. S., & Tunnell, J. W. (2012). *Flower Garden Banks*. https://web.archive.org/web/20120125120635/http://www.gulfbase.org/reef/view.php?rid=fgb1

Morley, J. W., R.L. Selden, R.J. Latour, T.L. Frölicher, R.J. Seagraves, & M.L. Pinsky. 2018. Projecting shifts in thermal habitat for 686 species on the North American continental shelf. PLoS ONE, 13(5), 1–28. https://doi.org/10.1371/journal.pone.0196127

Motomura, H., & Matsuura, K. (2016). *Pterois volitans*. The IUCN Red List of Threatened Species 2016: e.T190468A78940195. https://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T190468A78940195.en

Moura, R. L., Abieri, M. L., Castro, G. M., Carlos-Junior, L. A., Chiroque-Solano, P. M., Fernandes, N. C., Teixeira, C. D., Ribeiro, F. V., Salomon, P. S., Freitas, M. O., Goncalves, J. T., Neves, L. M., Hackradt, C. W., Felix-Hackradt, F., Rolim, F. A., Motta, F. S., Gadig, O. B. F., Pereira-Filho, G. H., & Bastos, A. C. (2021). Tropical rhodolith beds are a major and belittled reef fish habitat. *Science Reports, 11*(1), 794. https://doi.org/10.1038/s41598-020-80574-w

Munday, P. L., Wilson White, J., & Warner, R. R. (2006). A social basis for the development of primary males in a sex-changing fish. *Proceedings of the Royal Society B: Biological Sciences, 273*(1603), 2845–2851. https://doi.org/10.1098/rspb.2006.3666

Myrberg, A. A., Brahy, B. D., & Emery, A. R. (1967). Field observations on reproduction of the damselfish, *Chromis multilineata* (Pomacentridae), with additional notes on general behavior. *Copeia, 1967*(4), 819–827. https://doi.org/10.2307/1441893

National Centers for Coastal Ocean Science. (n.d.). *Determining Habitat Requirements and Connectivity for Reef Fishes in the Gulf of Mexico*. National Oceanic and Atmospheric Administration. Retrieved October 13, 2023, from https://coastalscience.noaa.gov/project/determining-habitat-requirements-and-connectivity-for-reef-fishes-in-the-gulf-of-mexico/

National Centers for Environmental Information. (2022). *Gulf of Mexico Climatology Data*. National Oceanic and Atmospheric Administration. Retrieved August 15, 2023, from https://www.ncei.noaa.gov/access/gulf-of-mexico-climate/gulf-data.html

National Hurricane Center (2022). *National Hurricane Center Data Archive*. National Oceanic and Atmospheric Administration. Retrieved October 21, 2022, from https://www.nhc.noaa.gov/climo/.

National Weather Service (n.d.). *National Oceanic and Atmospheric Administration's National Data Buoy Center*. Retrieved October 13, 2023, https://www.ndbc.noaa.gov

Nuttall, M. F., Somerfield, P. J., Sterne, T. K., MacMillan, J. T., Embesi, J. A., Hickerson, E. L., Johnston, M. A., Schmahl, G. P., Sinclair, J. (2020). Stetson Bank Long-Term Monitoring: 1993-2015. *National Marine Sanctuaries Conservation Series ONMS-20-06*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Flower Garden Banks National Marine Sanctuary, Galveston, TX. 156 pp.

Nuttall, M.F., Johnston, M. A., Eckert, R. J., Embesi, J. A., Hickerson, E. L., Schmahl, G. P. (2014). Lionfish (*Pterois volitans/miles*) records within mesophotic depth ranges on natural banks in the northwestern Gulf of Mexico. *BioInvasions Records 3(*2), 111–115. https://doi.org/10.3391/bir.2014.3.2.09

Nye, J. A., Link, J. S., Hare, J. A., and Overholtz, W. J. (2009). Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. *Marine Ecology Progress Series, 393,* 111–129. https://doi.org/10.3354/meps08220

Office of National Marine Sanctuaries (2008). *Flower Garden Banks National Marine Sanctuary Condition Report 2008*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 49 pp.

Office of National Marine Sanctuaries (2020). *Flower Garden Banks National Marine Sanctuary Expansion Final Environmental Impact Statement*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 154 p.

Office of Satellite and Product Operations. (n.d.). *Operational 5km SST Anomaly Charts*. National Oceanic and Atmospheric Administration. Retrieved August 25, 2022, from https://www.ospo.noaa.gov/Products/ocean/sst/anomaly/

Opresko, D. M., Nuttall, M. F., & Hickerson, E. L. (2016). Black corals of the Flower Garden Banks National Marine Sanctuary. *Gulf of Mexico Science, 33*(1), 5. https://doi.org/10.18785/goms.3301.05

Oxenford, H. A., Murray, P. A., & Luckhurst, B. E. (2003). The biology of wahoo (*Acanthocybium solandri*) in the western central Atlantic. *Gulf and Caribbean Research, 15*(1), 33–49. https://doi.org/10.18785/gcr.1501.06

Pawlik, J.R. &McMurray, S. E. (2020). The emerging ecological and biogeochemical importance of sponges on coral reefs. *Annual Review of Marine Science, 12*, 315–337. https://doi.org/10.1146/annurev-marine-010419-010807

Poloczanska, E. S., Brown, C. J., Sydeman, W. J., Kiessling, W., Schoeman, D. S., Moore, P. J., Brander, K., Bruno, J. F., Buckley, L. B., Burrows, M. T., Duarte, C. M., Halpern, B. S., Holding, J., Kappel, C. V., O'Connor, M. I., Pandolfi, J. M., Parmesan, C., Schwing, F., Thompson, S. A., & Richardson, A. J. (2013). Global imprint of climate change on marine life. *Nature Climate Change, 3*(10), 919–925. https://doi.org/10.1038/nclimate1958

Pomponi, S. A., Kelly, M., Reed, J. K., & Wright, A. E. (2001). Diversity and bathymetric distribution of lithistid sponges in the tropical western Atlantic region. *Bulletin of the Biological Society of Washington, 10,* 344–353.

Poore, R. Z., DeLong, K. L., Richey, J. N., & Quinn, T. M. (2009). Evidence of multidecadal climate variability and the Atlantic Multidecadal Oscillation from a Gulf of Mexico sea-surface temperature-proxy record. *Geo-Marine Letters, 29,* 477–484. https://doi.org/10.1007/s00367-009-0154-6

Precht, W. F., Deslarzes, K. J. P., Hickerson, E. L, Schmahl, G. P., Nuttall, M. F., and Aronson, R. B. (2014). Back to the future: The history of acroporid corals at the Flower Garden Banks, Gulf of Mexico, USA. *Marine Geology, 349,* 152–161. https://doi.org/10.1016/j.margeo.2013.12.012

Precht, W. F., Hickerson, E. L., Schmahl, G. P., & Aronson, R. B. (2014). The invasive coral *Tubastraea coccinea* (Lesson, 1829): Implications for natural habitats in the Gulf of Mexico and the Florida keys. *Gulf of Mexico Science, 32*(1–2), 55–59. https://doi.org/10.18785/goms.3201.05

Puckett, E. (2022). *Diadema antillarum* long-spined sea urchin. Animal Diversity Web. Retrieved August 25, 2022, from https://animaldiversity.org/accounts/Diadema_antillarum/

Rendfrey, T. S., Bukovsky, M. S., McCrary, R. R., & Fuentes-Franco, R. (2021). An assessment of tropical cyclones in North American CORDEX WRF simulations. *Weather and Climate Extremes, 34,* 100382. https://doi.org/10.1016/j.wace.2021.100382

Ricke, K. L., Orr, J. C., Schneider, K., & Caldeira, K. (2013). Risks to coral reefs from ocean carbonate chemistry changes in recent earth system model projections. *Environmental Research Letters, 8*(3), 034003. https://doi.org/10.1088/1748-9326/8/3/034003

Rodriguez, R., Easton, E. E., Shirley, T. C., Tunnell, J. W., & Hicks, D. (2018). Preliminary multivariate comparison of coral assemblages on carbonate banks in the western Gulf of Mexico. *Gulf and Caribbean Research, 29*(1), 23–33. https://doi.org/10.18785/gcr.2901.11

Rodysill, J. R., Donnelly, J. P., Sullivan, R., Lane, P. D., Toomey, M., Woodruff, J. D., Hawkes, A. D., MacDonald, D., d'Entremont, N., McKeon, K., Wallace, E., & van Hengstum, P. J. (2020). Historically unprecedented northern Gulf of Mexico hurricane activity from 650 to 1250 CE. *Scientific Reports, 10*(1), 1–17. https://doi.org/10.1038/s41598-020-75874-0

Rotjan, R.D., & Lewis, S.M. (2005). Selective predation by parrotfishes on the reef coral *Porites astreoides*. *Marine Ecology Progress Series, 305*, 193–201. https://doi.org/10.3354/meps305193

Rowland, A., & Wood, J. B. (2022). Marine invertebrates of Bermuda: Mustard Hill Coral (*Porites astreoides*). Retrieved August 25, 2022, from http://www.thecephalopodpage.org/MarineInvertebrateZoology/Poritesatreoides.html

Rubel, F. & Kottek, M. (2010). Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification. *Meteorologische Zeitschrift, 19*(2), 135–141. https://doi.org/10.1127/0941-2948/2010/0430

Ruppert, E. E., Fox, R. S., & Barnes, R. D. (2004). *Invertebrate Zoology: A Functional Evolutionary Approach*. Brooks/Cole Publishing Company.

Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., Wanninkhof, R., Wong, C. S., Wallace, D. W. R., Tilbrook, B., Millero, F. J., Peng, T. H., Kozyr, A., Ono, T., Rios, A. F. (2004). The oceanic sink for anthropogenic CO_2. *Science, 305*(5682), 367–371. https://doi.org/10.1126/science.1097403

Sabine, C. L. & Tanhua, T. (2010). Estimation of anthropogenic CO_2 inventories in the ocean. *Annual Review of Marine Science, 2*(1), 175–198. https://doi.org/10.1146/annurev-marine-120308-080947

Salvaterra, T., Green, D. S., Crowe, T. P., & O'Gorman, E. J. (2013). Impacts of the invasive alga *Sargassum muticum* on ecosystem functioning and food web structure. *Biological Invasions, 15*(11), 2563–2576. https://doi.org/10.1007/s10530-013-0473-4

Sammarco, P. W., Nuttall, M. F., Beltz, D., Hickerson, E. L., & Schmahl, G. P. (2016). Patterns of mesophotic benthic community structure on banks off vs inside the continental shelf edge, Gulf of Mexico. *Gulf of Mexico Science, 33*(1), 7. https://doi.org/10.18785/goms.3301.07

Schmahl, G. P., Hickerson, E. L., & Precht, W. F. (2008). *Biology and ecology of coral reefs and coral communities in the Flower Garden Banks region, northwestern Gulf of Mexico*. In Riegl, B. & R. Dodge (eds), Coral Reefs of the USA. Springer, Netherlands, pp 221–261.

Seidov, D., A.V. Mishonov, T.P. Boyer, O.K. Baranova, E. Nyadjro, S.L. Cross, A.R. Parsons, & K.W. Weathers. (2020). *Gulf of Mexico Regional Climatology Version 2*. National Centers for Environmental Information, National Oceanic and Atmospheric Administration. Retrieved August 2, 2022, from https://doi.org/10.25921/4sxe-ay54

Shein, K. J., Cavanaugh, J., Scalliet, H., Hutto, S., Roberson, K., Shortland, B., & Wenzel, L. (2019). Rapid vulnerability assessment for Gray's Reef National Marine Sanctuary. *National Marine Sanctuaries Conservation Series ONMS-19-01*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 84 pp.

Shuler, A. J. & Etnoyer, P. J. (2020). *Alcyonacean* octocorals of the Pinnacle Trend: A photo-identification guide. *NOAA Technical Memorandum NOS NCCOS 282*. 56 pp. https://doi.org/10.25923/xzd1-z382

Shore, A., Sims, J. A., Grimes, M., Howe-Kerr, L. I., Grupstra, C. G. B., Doyle, S. M., Stadler, L., Sylvan, J. B., Shamberger, K. E. F., Davies, S. W., Santiago-Vázquez, L. Z., & Correa, A. M. S. (2021). On a reef far, far away: Anthropogenic impacts following extreme storms affect sponge health and bacterial communities. *Frontiers in Marine Science, 8,* 1–16. https://doi.org/10.3389/fmars.2021.608036

Silbiger, N. J., Goodbody-Gringley, G., Bruno, J. F., Putnam, H. M. (2019). Comparative thermal performance of the reef-building coral *Orbicella franksi* at its latitudinal range limits. *Marine Biology, 166*(10), 1–14. https://doi.org/10.1007/s00227-019-3573-6

Sepulveda, C. A., Aalbers, S. A., Ortega-Garcia, S., Wegner, N. C., & Bernal, D. (2011). Depth distribution and temperature preferences of wahoo (*Acanthocybium solandri*) off Baja California Sur, Mexico. *Marine Biology, 158*(4), 917–926. https://doi.org/10.1007/s00227-010-1618-y

Smithsonian Tropical Research Institute. (2022). *Agelas clathrodes Schmidt, 1869.* https://panamabiota.org

Smith-Vaniz, W.F., Williams, J. T., Pina Amargos, F., Curtis, M., & Brown, J. (2019). *Caranx latus*. The IUCN Red List of Threatened Species 2019: e.T191829A86346808. https://dx.doi.org/10.2305/IUCN.UK.2019-2.RLTS.T191829A86346808.en

Sorte, C. J. B., Jones, S. J., & Miller, L. P. (2011). Geographic variation in temperature tolerance as an indicator of potential population responses to climate change. *Journal of Experimental Marine Biology and Ecology, 400*(1–2), 209–217. https://doi.org/10.1016/j.jembe.2011.02.009

Stachowicz, J. J., Terwin, J. R., Whitlatch, R. B., & Osman, R. W. (2002). Linking climate change and biological invasions: Ocean warming facilitates nonindigenous species invasions. *Proceedings of the National Academy of Sciences of the United States of America, 99*(24), 15497–15500. https://doi.org/10.1073/pnas.242437499

Sturges, W., & Evans, J. C. (1983). On the variability of the Loop Current in the Gulf of Mexico. *Journal of Marine Research, 41,* 639–653.https://doi.org/10.1357/002224083788520487

R Core Team. (2021). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.r-project.org

U. S. Global Climate Research Program .(2018). *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II:* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, & B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. https://doi.org/10.7930/NCA4.2018

Van Hooidonk, R., Maynard, J. A., Manzello, D., & Planes, S. (2014). Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs. *Global Change Biology, 20*(1), 103–112. https://doi.org/10.1111/gcb.12394

Van Hooidonk, R., Maynard, J., Tamelander, J., Gove, J., Ahmadia, G., Raymundo, L., Williams, G., Heron, S. F., & Planes, S. (2016). Local-scale projections of coral reef futures and implications of the Paris Agreement. *Scientific Reports, 6,* 1–8. https://doi.org/10.1038/srep39666

Van Soest, R. W. M., Boury-Esnault, N., Vacelet, J., Dohrmann, M., Erpenbeck, D., De Voogd, N. J., Santodomingo, N., Vanhoorne, B., Kelly, M., Hooper, J. N. A. (2012). Global diversity of sponges (Porifera). *PLoS ONE, 7,* e35105. https://doi.org/10.1371/journal.pone.0035105

van Soest, R.W.M. & Stentoft, N. (1988). Barbados deep-water sponges: Studies on the fauna of Curacao and other Caribbean Islands. *Amsterdam, Foundation for Scientific Research in Surinam and the Netherlands Antilles, 70,* 175.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Laarque, J. F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., Rose, S. K. (2011). The representative concentration pathways: An overview. *Climatic Change, 109,* 5–31. https://doi.org/10.1007/s10584-011-0148-z

Vaughan, N. (2015). *The Online Guide to the Animals of Trinidad and Tobago: Montastrea cavernosa (Great Star Coral).* University of the West Indies.

https://sta.uwi.edu/fst/lifesciences/sites/default/files/lifesciences/documents/ogatt/Montastrea_cavernosa%20-%20Great%20Star%20Coral.pdf

Vecchi, G.A., & Knutson, T. R. (2011). Estimating annual numbers of Atlantic hurricanes missing from the HURDAT database (1878-1965) using ship track density. *Journal of the Climate, 24*(6), 1736–1746. https://doi.org/10.1175/2010JCLI3810.1

Vergés, A., Steinberg, P. D., Hay, M. E., Poore, A. G. B., Campbell, A. H., Ballesteros, E., Heck, K. L., Booth, D. J., Coleman, M. A., Feary, O. A., Figueira, W., Langlois, T., Marzinelli, E. M., Mizerek, T., Mumby, P. J., Nakamura, Y., Roughan, M., van Sebille, E., Gupta, A. S., Smale, D. A., Tomas, F., Wernberg, T., & Wilson, S. K. (2014). The tropicalization of temperate marine ecosystems: Climate-mediated changes in herbivory and community phase shifts. *Proceedings of the Royal Society B: Biological Sciences, 281,* 1–10. https://doi.org/10.1098/rspb.2014.0846

Voss, J. D., Williams, M. A., Reed, J. K., & Clark, R. (2014). Benthic and fish communities in the mid and lower mesophotic zone of the sanctuary. *Fish and Benthic Communities of the Flower Garden Banks National Marine Sanctuary: Science to Support Sanctuary Management, 179,* 200.

Walker, N.D., Leben, R. R., Balasubramanian, S. (2005). Hurricane-forced upwelling and chlorophyll *a* enhancement within cold-core cyclones in the Gulf of Mexico. *Geophysical Research Letters, 32*(18). https://doi.org/10.1029/2005GL023716

Ward, C. H. (2017). *Habitats and biota of the Gulf of Mexico: Before the deepwater horizon oil spill. Volume 2: Fish Resources, Fisheries, Sea Turtles, Avian Resources, Marine Mammals, Diseases and Mortalities. In Habitats and Biota of the Gulf of Mexico: Before the Deepwater Horizon Oil Spill (Vol. 1)*. Springer.http://link.springer.com/10.1007/978-1-4939-3447-8

Warner, R. R., & Schultz, E. T. (1992). Sexual selection and male characteristics in the bluehead wrasse, *Thalassoma bifasciatum*: Mating site acquisition, mating site defense, and female choice. *Evolution, 46*(5), 1421–1442. https://doi.org/10.1111/j.1558-5646.1992.tb01134.x

Warner, R. R., & Swearer, S. E. (1991). Social control of sex change in the bluehead wrasse, *Thalassoma bifasciatum* (Pisces: Labridae). *The Biological Bulletin, 181*(2), 199–204. https://doi.org/10.2307/1542090

Webster, P. J., Holland, G. J., Curry, J. A., & Chang, H. R. (2005). Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science, 309*(5742), 1844-1846. https://doi.org/10.1126/science.1116448

Whaylen, L., Pattengill-Semmens, C. V., Semmens, B. X., Bush, P. G., & Boardman, M. R. (2004). Observations of a Nassau grouper, *Epinephelus striatus*, spawning aggregation site in Little Cayman, Cayman Islands, including multispecies spawning information. *Environmental Biology of Fishes 70*(3), 305–313. https://doi.org/10.1023/B:EBFI.0000033341.57920.a8

Whaylen, L., Bush, P., Johnson, B., Luke, K., McCoy, C., Heppell, S., Semmens, B., & Boardman, M. (2006). Aggregation dynamics and lessons learned from five years of monitoring at a Nassau grouper (*Epinephelus striatus*) spawning aggregation in Little Cayman, Cayman Islands, BWI, *Proceedings of the 59th Annual Gulf and Caribbean Fisheries Institute*, 2006 (pp. 479-487).

Weil, E., & Knowton, N. (1994). A multi-character analysis of the Caribbean coral *Montastraea annularis* (Ellis and Solander, 1786) and its two sibling species, *M. faveolata* (Ellis and Solander, 1786) and *M. franksi* (Gregory, 1895). *Bulletin of Marine Science, 55*(1), 151–175.

Whitfield, P.E., Muñoz, R. C., Buckel, C. A., Degan, B. P., Freshwater, D. W., & Hare, J. A. (2014). Native fish community structure and Indo-Pacific lionfish *Pterois volitans* densities along a depth-temperature gradient in Onslow Bay, North Carolina, USA. *Marine Ecology Progress Series, 509,* 241–254. https://doi.org/10.3354/meps10882

World Register of Marine Species. (2023). World Porifera Database. Retrieved August 11, 2022, from https://www.marinespecies.org/porifera/

Zeebe, R. E., & Wolf-Gladrow, D. A. (2001). *CO_2 in Seawater: Equilibrium, Kinetics, Isotopes*. Elsevier Science B.V., Amsterdam, The Netherlands. 360 pp.

Zimmer, B., Precht, W., Hickerson, E., and Sinclair, J. (2006). Discovery of *Acropora palmata* at the Flower Garden Banks National Marine Sanctuary, northwestern Gulf of Mexico. *Coral Reefs, 25*(2), 192. https://doi.org/10.1007/s00338-005-0054-9

Zischke, M. T. (2012). A review of the biology, stock structure, fisheries and status of wahoo (*Acanthocybium solandri*), with reference to the Pacific Ocean. *Fisheries Research, 119*, 13–22. https://doi.org/10.1016/j.fishres.2011.11.026

Appendix A: Workshop Agenda

Flower Garden Banks National Marine Sanctuary

Climate Vulnerability Assessment Workshop

July 27 - 28, 2022

Google Meet (Virtual)

Workshop Objectives:

1. Provide participants with information about current and projected priority climate conditions of Flower Garden Banks National Marine Sanctuary (FGBNMS) and then apply this knowledge to key habitats and species to determine their vulnerability to changing conditions.
2. Use a modified version of the Commission for Environmental Cooperation's North American Marine Protected Area Rapid Vulnerability Assessment tool to generate a vulnerability score for key habitats and species.
3. Use workshop material to draft a FGBNMS Climate Vulnerability Assessment, which will be an important resource to accompany our Condition Report and help guide the next FGBNMS Management Plan.

Wednesday July 27	
8:45 – 9:00	Sign in and microphone check
9:00 – 9:05	Welcome *Michelle Johnston, FGBNMS*
9:05 – 9:45	Introduction to Agenda and Workshop Objectives Presentation and Discussion: Tool Overview and Defining the Scope of the Assessments *Sara Hutto, Greater Farallones National Marine Sanctuary*
9:45 – 10:05	Presentation: Climate Trends in the Gulf of Mexico Region *Larissa Dias, Texas A&M University-Corpus Christi*
10:05 – 10:15	Break and re-assemble into break-out groups
10:15 – 11:30	Activity: Conduct assessments for habitats (two breakout groups) • Shallow Coral Cap Group – Facilitator: *Zac Cannizzo* • Mesophotic Group – Facilitator: *Sara Hutto* •
11:30 – 12:00	Plenary group discussion of habitat assessment
12:00 – 12:50	Lunch Break

12:50 – 2:50	Activity: Complete assessments for selected species (2 hrs, five breakout groups, 2-3 species/species groups per group) • Fish Group 1 – Facilitator: *Leslie Clift* • Fish Group 2 – Facilitator: *Sara Hutto* • Mesophotic Invertebrate Group – Facilitator: *Zac Cannizzo* • Shallow Invertebrate Group 1 – Facilitator: *Michelle Johnston* • Shallow Invertebrate Group 2 – Facilitator: *Larissa Dias*
2:50 – 3:00	Break and reconvene in two groups (fish and invert groups) • All Fish Groups – Facilitator: *Sara Hutto* • All Invertebrate Groups – Facilitator: *Zac Cannizzo*
3:00 – 3:45	Reconvene in two groups (fish and invert groups) and review findings, opportunity for feedback • All Fish Groups – Facilitator: *Sara Hutto* • All Invertebrate Groups – Facilitator: *Zac Cannizzo*
3:45 – 4:00	Wrap-up plenary discussion: • 5 minutes from each group: What did we learn? What issues did we encounter? • 5 minutes overview of Day Two

Thursday July 28	
8:45 – 9:00	Sign in and microphone check
9:00 – 9:10	Introduction to Day Two – goals and agenda *Sara Hutto, Greater Farallones National Marine Sanctuary*
9:10 – 11:00	Activity: Complete species assessments (five breakout groups, 2-3 species per group) ● Fish Group 1 – Facilitator: *Leslie Clift* ● Fish Group 2 – Facilitator: *Sara Hutto* ● Mesophotic Invertebrate Group – Facilitator: *Zac Cannizzo* ● Shallow Invertebrate Group 1 – Facilitator: *Michelle Johnston* ● Shallow Invertebrate Group 2 – Facilitator: *Larissa Dias*
11:00 – 11:10	Break and reconvene in plenary group
11:10 – 12:00	Plenary group discussion of species assessments
12:00 – 1:00	Lunch Break
1:00 – 1:15	Presentation: Introduction to Adaptation Planning *Sara Hutto, Greater Farallones National Marine Sanctuary*
1:15 – 2:30	Activity: Adaptation strategy development (two habitat breakout groups)

	- Shallow Coral Cap Group – Facilitator: *Zac Cannizzo* - Mesophotic Group – Facilitator: *Sara Hutto*
2:30 – 2:45	Break and reconvene in plenary group
2:45 – 3:45	Wrap-up and next steps

Appendix B: Participant List

Alicia Caporaso
Benthic Ecology Lead
Bureau of Ocean Energy Management, New Orleans Office

Jake Emmert
Dive Safety Officer
FGB Advisory Council Chair
Moody Gardens

Holden Harris
Marine Ecology
University of Florida

Will Heyman
Fisheries Science; Former Council Member
LGL

Lauren Wenzel
Marine Management; Climate
NOAA National Marine Protected Areas Center

Diego Gil Agudelo
Marine Ecology and Biology
Texas A&M University Galveston

Mike Dance
Fisheries Science
FGB Advisory Council Member
Louisiana State University

Laura Jay Grove
Fisheries Science
NOAA Southeast Fisheries Science Center

Jeremiah Blondeau
Marine Ecology
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Scott Hickman
Fishing Guide
FGB Advisory Council Member
Fishing Guide

Andy Lewis
Diving Operations
FGB Advisory Council Member
FLING

Katie Lohr
Coral Reefs and Restoration
NOAA Office of National Marine Sanctuaries

Sepp Haukebo
Dive Operations; Fish; Climate
FGB Advisory Council Vice Chair
Environmental Defense Fund

Mercer Brugler
Marine Invertebrates
City University of New York

Erin Easton
Marine Invertebrates; Benthic Ecology
University of Texas Rio Grande Valley

David Hicks
Marine Invertebrates and Reefs
University of Texas Rio Grande Valley

Kristopher Benson
Marine Ecology
NOAA Restoration Center

Tom Bright
Marine Biology
Texas A&M University (retired)

Steve Gittings
Coral Reefs; Benthos; Marine Protected Areas
NOAA Office of National Marine Sanctuaries

Jorge Brenner
Mapping; Benthos; Marine Conservation
Executive Director, GCOOS
GCOOS

Samantha Coy
Marine Microbiology
Rice University

Ian Enochs
Coral Reefs; Benthos; Ocean Acidification
NOAA AOML

Xinping Hu
Water Quality; Ocean Acidification
Texas A&M University-Corpus Christi

Kelly Montenero
Climate; Water Quality
NOAA AOML

Jacque Emmert
Corals
NOAA Flower Garden Banks National
Marine Sanctuary

Derek Manzello
Coral Reef Ecology
Coordinator, NOAA Coral Reef Watch
NOAA STAR

Lory Z. Santiago-Vázquez
Microbiology; Genomics; Sponges
University of Houston-Clear Lake

Greg Boland
Coral Reefs; Benthos
Bureau of Ocean Energy Management
(retired)

Jason Sylvan
Water Quality
Texas A&M University

Erica Towle
Climate and Corals
National Coral Reef Monitoring Program
(NCRMP) Coordinator
NOAA Coral Reef Conservation Program

Kristine DeLong
Corals; Climatology
Louisiana State University

Donavon French
Reef Biology; Notetaker
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Prati Rosen
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NOAA Office of National Marine
Sanctuaries

Kayla Williams
Knauss Fellow; Notetaker
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Ryan Hannum
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Larissa Dias
Ocean Acidification
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Texas A&M University-Corpus Chris

Appendix C: CEC North American Marine Protected Area Rapid Vulnerability Assessment Tool: Worksheets and Instructions

Instructions and worksheet PDFs can be viewed at:

USER GUIDE: 11733-north-american-marine-protected-area-rapid-vulnerability-assessment-tool-en.pdf (cec.org)

WORKSHEETS: 11739-north-american-marine-protected-area-rapid-vulnerability-assessment-tool-en.pdf (cec.org)

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