RAPID VULNERABILITY ASSESSMENT FOR GRAY'S REEF NATIONAL MARINE SANCTUARY

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Abstract

Gray's Reef National Marine Sanctuary (GRNMS) is a 22 sq. mile (5700 ha) marine protected area approximately 17 nautical miles (31 km) east of the Georgia coast, and is part of the National Marine Sanctuary System. It is home to one of the largest "live bottom" reef systems in the southeast United States. Gray's Reef is currently experiencing changing environmental conditions, and climate projections to 2100 suggest that these changes will continue and likely accelerate. The sensitivity of marine species at Gray's Reef 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 November 2017, GRNMS convened an expert workshop to assess the climate vulnerability of nine key species that occur within the sanctuary, with participants identifying two additional species for post-workshop assessments. Participants were provided information about the current and projected climate conditions of the sanctuary and applied this to their knowledge of each species and its capacity to adapt to changing conditions. They used a modified version of the Commission for Environmental Cooperation's North American Marine Protected Area Rapid Vulnerability Assessment tool to transform this knowledge into a vulnerability score for each species. Once climate vulnerabilities were established, participants discussed possible adaptation strategies which, if implemented, might reduce vulnerability.

This report summarizes the outcomes of the Gray's Reef Rapid Vulnerability Assessment workshop. Key findings were that top climate concerns included changes such as storm frequency and intensity, increasing water temperature, and ocean acidification. Top non-climate stressors were identified as well, such as invasive lionfish, sedimentation, coastal development, and marine debris/anchor damage. Initial adaptation strategies that participants felt could be widely applicable, low cost, and efficacious included lionfish reduction efforts (e.g., traps, derbies), and establishing a rapid, post-storm damage assessment protocol.

Key Words

1. Habitat, Climate, and Climate Change of Gray's Reef National Marine Sanctuary

1.1 Overview of Gray's Reef National Marine Sanctuary

Gray's Reef National Marine Sanctuary (GRNMS) off the coast of Georgia is one of the largest near-shore "live-bottom" reefs of the southeastern United States. It is just one of 14 (with two more in designation at present time) marine protected areas that make up the National Marine Sanctuary System and is governed by the National Marine Sanctuaries Act.

The approximately 22 square mile (about 14,000 acres or 5700 ha) marine protected area is situated roughly 17 nautical miles (31.5 km) east-southeast of Sapelo Island, Georgia (Fig. 1.1). GRNMS is currently the only protected natural reef area on the continental shelf off the Georgia coast and one of only a few natural marine protected areas in the ocean between Cape Hatteras, North Carolina and Cape Canaveral, Florida. Gray's Reef is just a small part of the U.S. territorial Atlantic Ocean, yet its value as a natural marine habitat is recognized nationally and internationally.
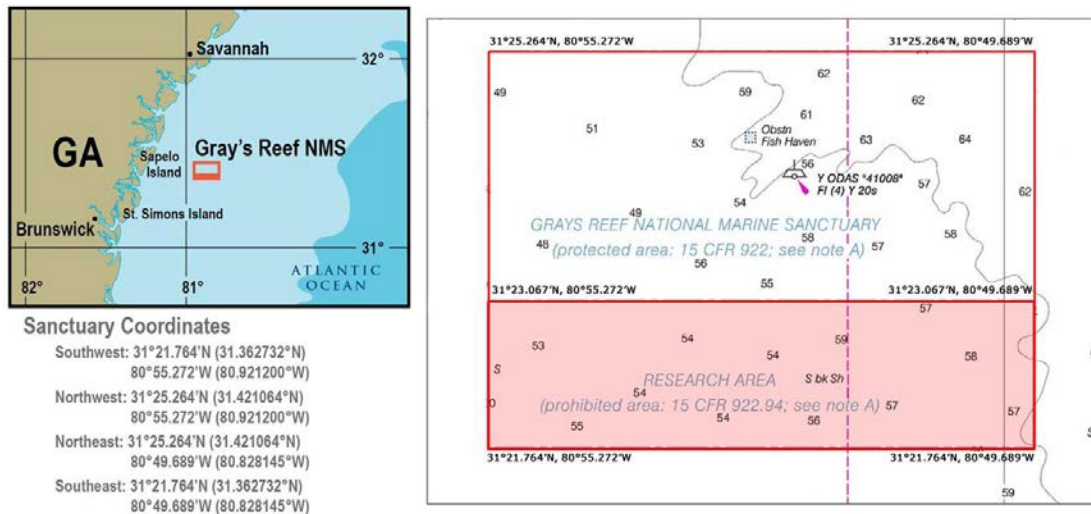
Figure 1.1 Location and spatial extent of GRNMS off the Georgia coast. (Image: NOAA)

"Live bottom" is a term used to refer to hard or rocky seafloor that typically supports high numbers of large invertebrates such as sponges, corals, and sea squirts. These spineless creatures thrive in rocky areas, as many are able to attach themselves more firmly to the hard substrate, as compared to sandy or muddy "soft" bottom habitats. Within GRNMS

there are rocky ledges with sponge and coral live bottom communities, as well as sandy bottom areas that are more typical of the seafloor off the southeastern U.S. coast.

1.2 Habitat Characteristics

Gray's Reef is a submerged hard bottom (carbonate-cemented sandstone) area that, as compared to surrounding areas, contains extensive but scattered rock outcroppings. The rocky ledges can be as tall as six feet and lie under 60 to 70 feet of ocean water. The rocky ledges are complex: they have nooks, crannies and bumps, and plenty of places for invertebrates to latch on to and for fish to hide in. Some of the rocky ledges are large enough to accommodate resting sea turtles. The rocky places provide a firm base for a variety of invertebrates that live their lives permanently attached to the rock. These animals include bryozoans (moss fauna), ascidians or tunicates (sea squirts), sponges, barnacles, and hard-tubed worms. The complex structure provides shelter for mobile invertebrates such as worms, shrimps, and crabs. Many fish shelter in the reef or hover in the water column above.

Algae (marine plants) and invertebrates grow on the exposed rock surfaces. Dominant invertebrates include sponges, barnacles, fan corals and other soft corals, hard corals, sea stars, crabs, lobsters, snails, and shrimps. The reef attracts numerous species of fish that live on or near the substrate (benthic) or that swim in the water above (pelagic). These include black sea bass, snappers, groupers, and mackerels. Since Gray's Reef lies in a transition area between temperate and tropical waters, fish population composition changes seasonally. Loggerhead sea turtles, a threatened species, use Gray's Reef year-round for foraging and resting and the reef is near the only known winter calving ground for the highly endangered North Atlantic right whale.

Gray's Reef is a consolidation of marine and terrestrial sediments (sand, shell, and mud) which was laid down as loose aggregate between six and two million years ago. Some of these sediments were deposited by coastal rivers draining into the Atlantic and others were brought in by currents from other areas (Harding and Henry 1990). These sediments accumulated until a dramatic change began to take place on Earth during the Pleistocene Epoch, between 1.8 million and 10,000 years ago. It was during this time that the area which is now Gray's Reef was, at times, exposed land and the shoreline was as much as 80 miles east of its present location. As a result of this exposure, the sediments solidified into porous carbonate-cemented sandstone rock. As the glacial ice melted, the water returned to the sea, filling the ocean basins back to their earlier levels.

1.3 Climate of Gray's Reef

The climate of GRNMS is characterized by both atmospheric and oceanographic components. Chief among them are air and water temperature, precipitation, currents, salinity, pH (acidity), winds, waves, and storms. The region sees a warm summer and cool winter, with a summertime precipitation maximum and late fall minimum. Although

climate classifications are not generally assigned to offshore geographies, based on the criteria defined by the Köppen-Geiger climate classification system (Köppen 1918; Geiger 1961), the region in which Gray's Reef resides is considered humid subtropical (Cfa). This means that the coldest month averages 0°C (32°F), at least one month's average temperature exceeds 22°C (71.6°F), and no fewer than four months average above 10°C (50°F). In Cfa climates there is no significant precipitation difference between seasons.

Like the atmosphere, the water temperature also experiences significant seasonality. The sanctuary sits on the continental shelf at a depth of between 18 and 21 meters (60 to 70 feet). As such, the sanctuary is entirely within the mixed surface layer of the ocean and is influenced by diurnal and seasonal heating cycles, tidal currents, and both tropical and extratropical storm systems. Gray's Reef sits inshore of the major ocean current in the region, the Florida Current/Gulf Stream, but is occasionally affected by eddies that shear from the main current channel. The Labrador Current also extends into the region periodically (inshore of the Florida Current), transporting colder, denser water. While longshore currents tend to be less prevalent than tidal processes in the coastal zone (Dean and Walton 1973; Watson 1980), there is a weak and ephemeral longshore component that produces a net southward sediment transport, but with frequent reversals (Wang et al. 1998). In one or two locations along the coast, the transport is predominantly northerly (e.g., Cumberland Island, Georgia, Griffin and Henry 1984; Tybee Island, Oertel et al. 1985).

1.3.1 Environmental Observations

Given the importance of weather to seafaring, atmospheric and oceanographic data collection has taken place in the region since the 1700s, when passing vessels (primarily those of the British Navy) would record environmental observations (e.g., air temperature, sea surface temperature, winds, sky condition, general character of the weather). In many cases, these data have been transcribed from historical ships' logs and included in the International Comprehensive Ocean-Atmosphere Data Set (ICOADS; Freeman 2017). These historical data, averaged over 2°x2° grid boxes (1°x1° since 1960) provide for monthly average water temperature (among other parameters) in the region dating back to 1824.

NOAA's National Data Buoy Center (NDBC) operates a moored buoy (41008) within the GRNMS boundary. It is a 3-meter discus buoy with the Advanced Modular Payload System (AMPS), which is the latest NDBC payload and incorporates sensors that satisfy the growing need for climatological information (NDBC 2009). Buoy 41008 observes the variables listed in Table 1.1 on an hourly basis, and has done so since 1988, with a gap in observations from 1992 to 1997.

Table 1.1. NDBC buoy 41008 measured variables.

Wind direction	Dominant Wave Period	Atmospheric Pressure	Water Temperature
Wind speed	Average Period	Pressure Tendency	Dew Point
Wind Gust	Mean Wave Direction	Air Temperature	Heat Index
Wave height	Source: National Data Buoy Center (NDBC 2009)		

The NDBC buoy also serves as the framework for a series of additional instruments installed by academic researchers as part of the Ocean Acidification Data Stewardship (OADS) project (Jiang et al. 2016). These instruments, installed by researchers from the University of Georgia, monitor elements such as pH, partial pressure of CO_2, dissolved oxygen, and seabed temperature (Sabine et al. 2011). Observations from this suite of instruments extend from 2006 to the present.

Sea level is monitored by tide gauges located along the Atlantic coast, including the nearest at Ft. Pulaski, and another at Fernandina Beach, Florida (tidesandcurrents.noaa.gov). The gauge at Ft. Pulaski has a record of water level extending back to 1935, and the one at Fernandina Beach extends to 1897. Both are part of the National Water Level Observing Network (NWLON) and are instrumental in evaluating the change in water level along the Georgia coast over that time period.

Satellite observations of sea surface temperature (SST), altimetry, cloud cover, outgoing longwave radiation, and ocean color (e.g., chlorophyll concentration), and other parameters are incorporated into several datasets available to the public. In many cases these satellite datasets extend back in time at least 30 years and are available at resolutions finer than five kilometers. A number of these satellite observation datasets relevant to Gray's Reef are available as Climate Data Records (e.g., Banzon et al 2016) from the National Centers for Environmental Information (NCEI; www.ncei.noaa.gov).

Two U.S. National Weather Service Doppler radars (WSR-88D) positioned at Jacksonville, Florida and Charleston, South Carolina provide continuous monitoring of hydrometeorological (e.g., rain, snow) and to some extent winds over Gray's Reef, and have been doing so since their installation in the 1990s (though non-Doppler [WSR-57 and WSR-74] radars have existed at these locations since the 1950s). Observations from these radars are archived by and accessible from NCEI (Ansari et al. 2017).

Lastly, a number of research activities within and around the GRNMS have produced a suite of *ad hoc* data sets of a variety of environmental variables (e.g., Watson 1980; Hyland et al. 2001; Hare et al. 2003; Balthis et al. 2007). However, in general such data sets are of insufficient length to reconcile changes in climate over time.

1.3.2 Past and Present Climate

Geologic evidence suggests that the substrate of Gray's Reef formed during the Pleistocene Epoch (Harding and Henry 1990; Garrison et al. 2016). During the Pleistocene Epoch (~2.59 million to 11,700 years ago) the climate was characterized by several major ice ages, which oscillated between glacial and interglacial periods. As a result, sea level fluctuated dramatically, falling as glacial ice expanded and rising as the glaciers melted (Hansen et al. 2013). At times, Gray's Reef was dry land, with the shoreline as much as 80 miles east of where it is today.

Analyses by Hansen et al. (2013) suggest that the prehistoric period since the formation of Gray's Reef has been one of substantial variability in both temperature and sea level. Average sea level between 2 million and 10,000 years ago was generally below that of today, falling to between 50-120 meters below present sea level during glacial periods (Fig. 1.2). Globally averaged surface temperature during the Pleistocene was approximately 2-3°C cooler than at present, with annual fluctuations ranging from 0°C to approximately 6°C cooler than the 2016 global average temperature (Fig. 1.3).
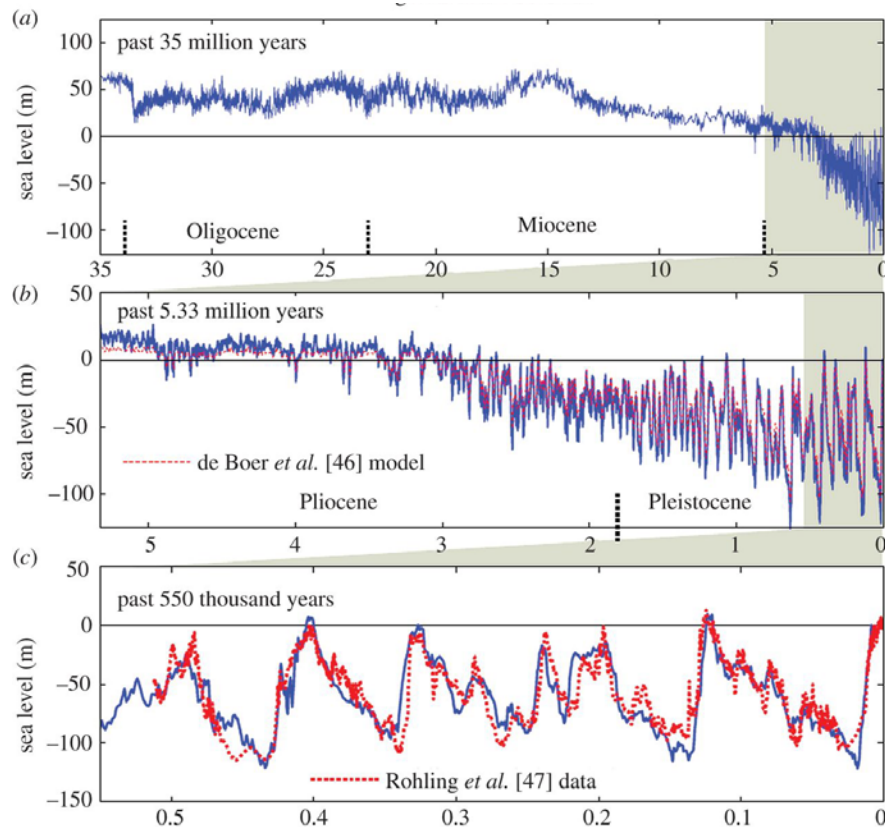
Figure 1.2. Global mean sea level reconstructions based on paleoclimate proxy data. Figure from Hansen et al. (2013).
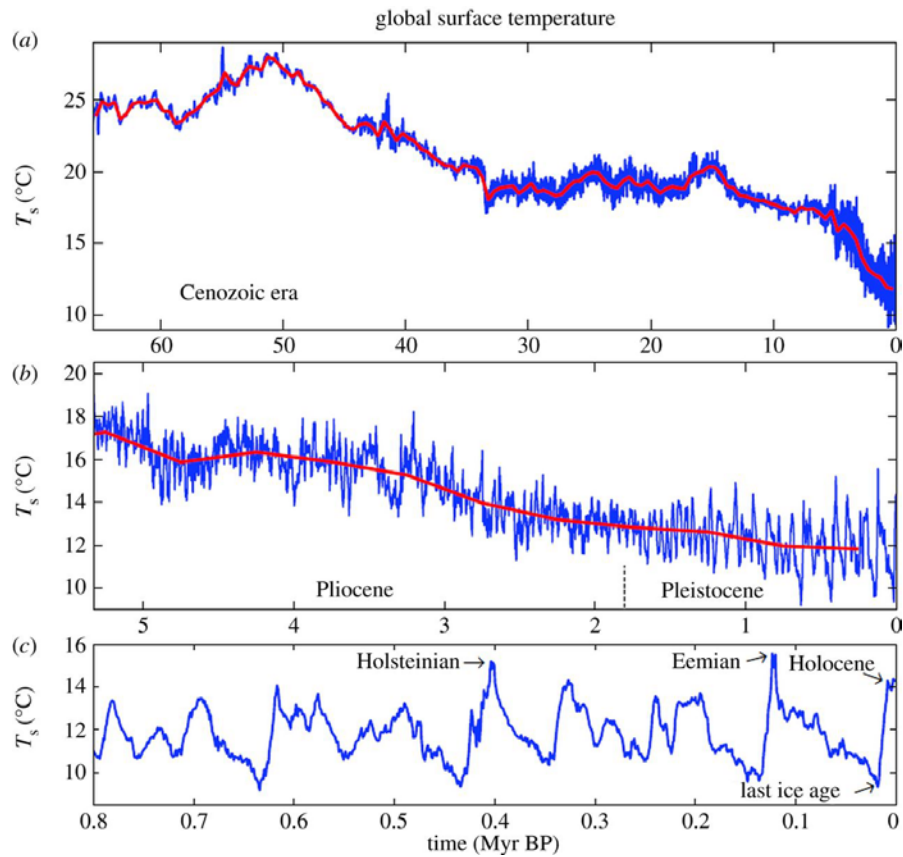
Figure 1.3. Global surface temperature reconstructions (blue) and moving averages (red) based on paleoclimate proxy data by Hansen et al (2013).

Since the mid-1800s, globally averaged surface air temperature has been on an upward trajectory (Fig. 1.4), rising at a rate of 0.07°C per decade, resulting in an overall increase of 0.94°C between 1880 and 2016 (Blunden and Arndt 2017). This increase in surface temperature is joined by a corresponding but delayed increase in sea surface temperature (SST; Fig. 1.5). Monthly averaged data from NOAA suggest that, after initially continuing to cool, modern-era SST began to increase around 1908 at a rate of 0.08°C per decade for a 1909-2016 increase of 0.92°C.

While globally- and annually-averaged data are useful for understanding large-scale trends in variables of interest, they mask local and regional scale variability that can be critical to addressing issues of species or habitat vulnerability. These local to regional scale variables include air and water temperature, water chemistry, storm conditions, and currents.
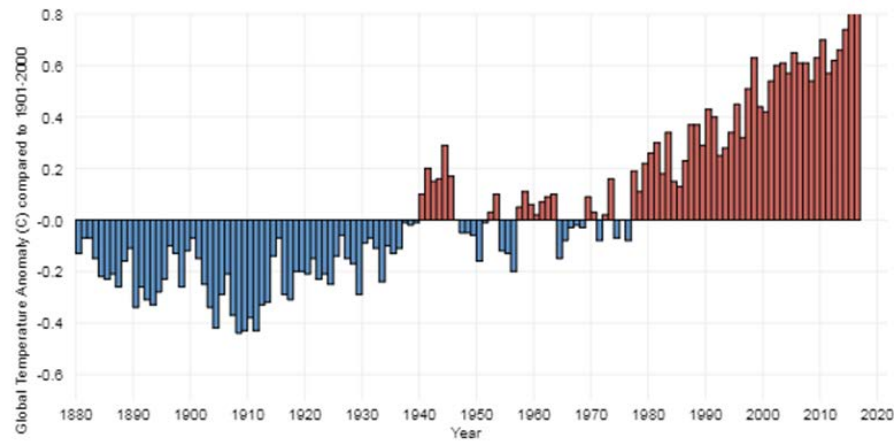
Figure 1.4. Globally averaged annual surface air temperature anomaly 1880-2016 (from Blunden and Arndt 2017). Anomalies are based on the 1901-2000 average.

Air and water temperature

Based on monthly averaged air and sea surface temperatures obtained for the ICOADS grid box enclosing GRNMS, the sanctuary experiences hot summers and mild to cool winters (Table 1.2).
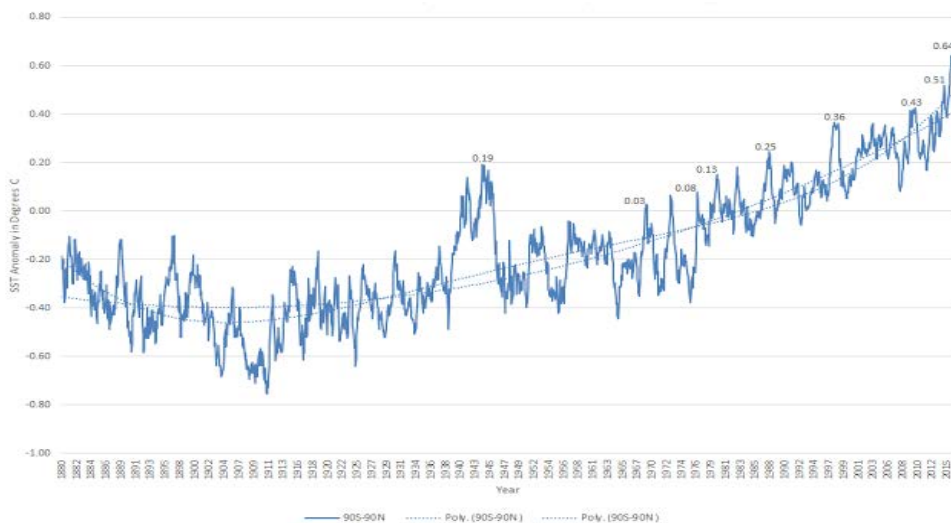
Figure 1.5. Globally averaged monthly SST 1880-2016 from NOAA. Anomalies are based on the 1971-2000 average. (Image: NOAA)

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Table 1.2. Monthly and annual sea surface (1824 -2016) and air temperature (1849 - 2016) observed in the vicinity of GRNMS. (Source: ICOADS)

Temp. (°C)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
SST Min	8.0	6.9	7.5	15.6	18.3	21.2	24.4	25.6	24.2	20.0	14.7	9.8	11.1
SST Mean	14.9	14.5	16.3	19.3	23.0	26.1	27.9	28.3	27.3	24.3	20.4	17.0	21.2
SST Max	24.2	24.4	26.7	26.7	29.0	29.8	30.8	31.4	30.5	30.6	26.7	24.7	27.9
Air Min	1.4	0.0	1.9	12.6	18.2	22.5	21.2	22.2	22.0	14.4	11.2	4.0	6.7
Air Mean	12.7	13.2	15.6	19.5	22.9	26.0	27.4	27.3	26.1	22.5	18.0	14.5	20.4
Air Max	23.0	22.3	25.6	24.9	29.0	33.3	31.1	30.4	30.0	28.5	25.1	25.0	28.9

Using these data obtained from ICOADS for the region surrounding GRNMS, and integrating *in situ* buoy data from the sanctuary since 1988, annually averaged SST has increased since 1824 by 1.15°C (0.006°C/yr), and in 2016 averaged 22.30°C. Annual average air temperature has similarly increased by 1.20°C (0.0072°C/yr) since 1849, with a 2016 average of 21.16°C.

Large-scale weather patterns

The region is subjected to the occasional intrusion of strong cold fronts that push offshore from the continent and may raise significant swells from the west and northwest ahead of and during passage. These fronts are most pronounced from late fall through early spring and are frequently associated with developing "Nor'easters" (extratropical cyclones) that form along the Gulf Coast or in the vicinity of the sanctuary itself. Wintertime cold fronts may drop air temperatures to below freezing for several days and allow for substantial but temporary chilling of the ocean's surface layer. The surface low driving these fronts may also pass over the region, dropping the central pressure and creating gale conditions. The so-called "Storm of the Century" in March 1993 was one example of this (Fig. 1.6).
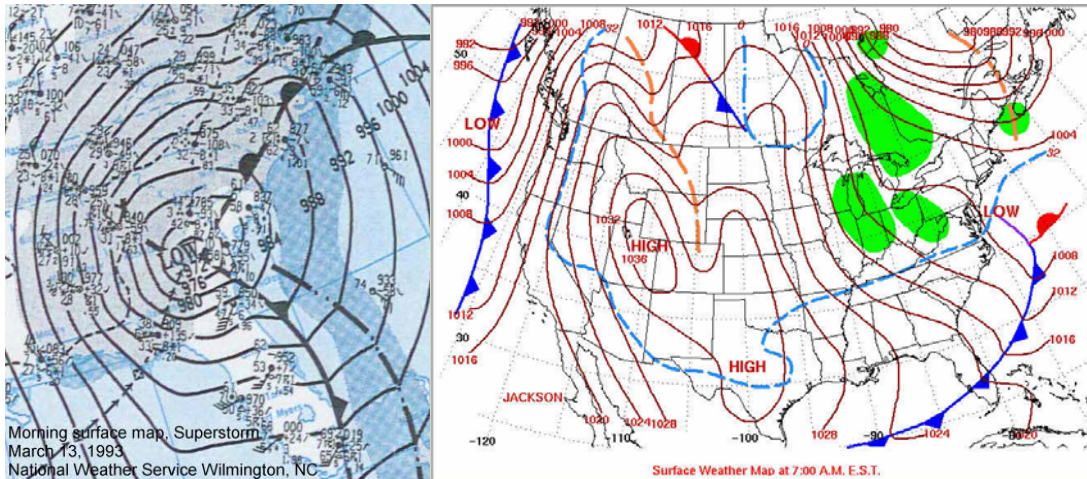
Figure 1.6. Surface weather maps showing (L) the March 1993 "Storm of the Century," and (R) a typical cold front that pushed past GRNMS and out to sea. (Source: NOAA)

Both the position and strength of the Bermuda High, especially during the summer months, will have a significant effect on the day-to-day weather, and thus the seasonal climate at GRNMS (Fig. 1.7). The proximity of the high produces an average annual sea level pressure at Gray's Reef of 1018.0 hPa, approximately 5 hPa greater than the global mean sea level pressure of 1013.25 hPa. The clockwise rotation of the high, which is, on average, centered east of GRNMS, produces a predominant inflow of warm and humid air into the region from the east. This high also influences the steering of tropical cyclones in the vicinity. A strong, inshore extent of the high will inhibit tropical system impacts to the sanctuary, while a weaker or more offshore high may direct storms over the region.

Figure 1.7. Idealized representation of the pressure and wind patterns associated with the Bermuda High (not to scale). Clockwise airflow advects warm air over GNRMS and higher pressure can steer hurricanes toward the area. (Image: Karsten Shein/NOAA).

Tropical cyclones

Tropical cyclones impact Gray's Reef and surrounding waters from time to time. The International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al. 2010) identifies 47 tropical cyclone systems that have passed within 25 NM of the sanctuary since 1853, including three in 2016

(Fig. 1.8). Given the relatively shallow depth of the sanctuary, conditions associated with strong storm systems may damage the sanctuary habitat.

Ocean currents

A major factor in the ocean climate of Gray's Reef is its proximity to the Florida Current (Fig. 1.9). This current moves north-northeast along the U.S. coast from southern Florida, eventually becoming the Gulf Stream. The current has a mean transport of around 31 Sverdrup (Sv)[1], but is far higher and more variable at the sanctuary latitude (perhaps as much as 50 Sv; e.g., Leaman et al. 1989). There is a

Figure 1.8. Tracks of known tropical storm and hurricanes that have passed within 25 nautical miles of Gray's Reef, 1853-2016. (source: https://coast.noaa.gov/hurricanes/).

strong seasonal component to the transport, and its position relative to the sanctuary can greatly affect temperature, current, and nutrient loading. The current also often sheds eddies anywhere from tens to hundreds of kilometers in diameter, and can affect the sanctuary even though the main current channel may be some distance away.

In addition to the Florida Current and Gulf Stream transporting warmer water northward, the Labrador Current transports cooler water equatorward along the coast, inshore of the Gulf Stream. The Labrador Current generally crosses southeasterly beneath the Gulf Stream at around Cape Hatteras, North Carolina (Richardson 1977), but may on occasion influence inshore waters south of the cape (Talley and McCartney 1982).

Ocean Chemistry

Ocean chemistry can play an important role in the health of the GRNMS ecosystem. The ocean is a major sink for atmospheric carbon dioxide (CO_2), and changes in the quantity of dissolved CO_2 in ocean water alter the pH of the water and affect the availability of carbonates upon which many marine organisms rely for shell and skeletal growth. Global, annually averaged partial pressure of CO_2 in the atmosphere in 2016 was 404.21 µAtm (404.21 parts per million [ppm]) and, measured since 1959, has been increasing at an average rate of +1.55 ppm/yr, increasing to a rate of +2.43 ppm since 2010 (Fig. 1.10).

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[1] http://oceancurrents.rsmas.miami.edu/atlantic/florida.html

Figure 1.9. MODIS SST from NOAA-18 satellite on March 21, 2017, showing the position of the Florida Current/Gulf Stream just east of Gray's Reef (yellow square, not to scale). Heat transport of the current is substantial, as is the rate of flow. Cooler conditions prevail inshore, partly due to transport of Labrador sea water around Cape Hatteras. (Image: Rutgers University Department of Marine and Coastal Sciences)
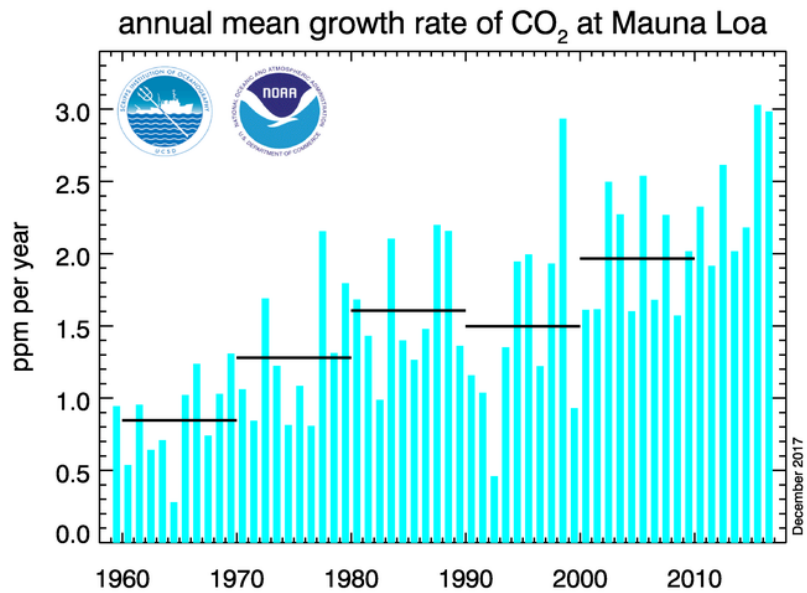
Figure 1.10. Annual mean growth rate of CO_2 at Mauna Loa Observatory. Black lines are decadal averages. (Image: NOAA)

Measurements of atmospheric pCO_2 levels at the GRNMS data buoy closely mirror the global average, with a 2006 level around 380 ppm, rising to a 2016 level of around 400 ppm (Fig. 1.11). More critical to the underwater habitat of GRNMS is the dissolution of CO_2 into the water column.

As a sink for CO_2, the ocean accounts for the uptake and storage of roughly 26 percent of the CO_2 that has been released by anthropogenic activities (Le Quéré et al. 2012). However, the continued absorption of CO_2 by the ocean also reduces the available capacity to continue absorbing CO_2 at those rates (the Revelle factor), while increases in water temperature have the opposite effect (Sabine et al. 2004). Globally, average seawater pH has seen a decrease of around 0.11 to 8.08 since preindustrial times (PMEL 2017). Observations at GRNMS between 2006 and 2014 reveal that ocean pCO_2 levels have a pronounced seasonal signal (Fig. 1.11), ranging between around 250 ppm in summer and over 600 ppm in winter. The trend between 2006 (~370 ppm) and 2013 (~450 ppm) was around +10 ppm/yr.
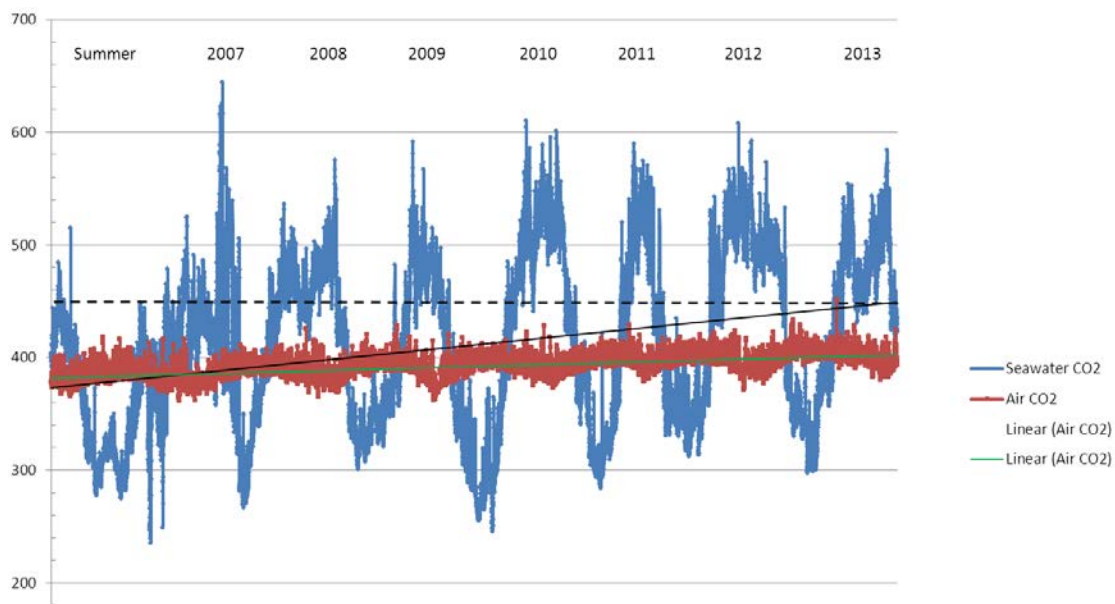
Figure 1.11. Partial pressure of CO_2 (ppm) for air and seawater, measured at GRNMS between 2006 and 2014. (Image: Scott Noakes/University of Georgia)

Precipitation and river discharge

Lastly, an important climatological consideration for Gray's Reef is precipitation, especially terrestrial precipitation between the Georgia coast and inland to the Appalachian foothills. The amount and timing of precipitation falling here affects the discharge of the Altamaha and other rivers. High discharge/flow will reduce surface salinity levels in the region, may temporarily reduce water temperature at GRNMS, and
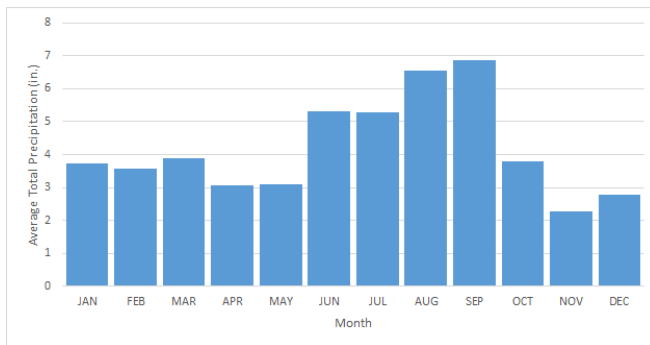
Figure 1.12. Monthly average total precipitation observed at Sapelo Island, GA between 1957 and 2017. (Image: xmacis).

can inhibit upwelling from the shelf edge to the east. The timing of droughts and rainfall may also affect sediment and nutrient discharge onto the reef from land-based sources.

Precipitation is measured at several coastal locations, including the nearest observing station at Sapelo Island, GA. Daily precipitation totals, available from Sapelo Island since 1957, suggest that there is a summer (Aug-Sep) peak, with a September average total of 6.88 in (175 mm), and a minimum of 2.27 in (58 mm) in November (Fig 1.12). Annual total precipitation has been declining at a rate of -0.0892 inches/year, or -5.26 in over the 1957-2017 period of record (Fig 1.13).

Global climate projections suggest that precipitation in many locations will become more variable and experience more frequent extreme events. Data from Sapelo Island demonstrate that the number of days per year in which 1.0 inch (25 mm) of precipitation was observed has increased at a rate of 0.0619 days/yr (3.65 days over the period of record; Fig. 1.14). Simultaneously, the number of multi-day periods (or runs) of days where no precipitation fell showed only a slight decline of -0.0065 runs/yr (Fig 1.14).

One potential driver of precipitation over Gray's Reef is the North Atlantic Oscillation (NAO). This teleconnection is defined by the pressure difference between the Icelandic Low and the Azores High (Fig. 1.15). Not only does the NAO control the strength and pattern of westerly atmospheric flow across the North Atlantic, but associated storm events as well, especially in winter (Fig. 1.16). The positive phase of the NAO that has been in place for much of the past 40 years is partly associated with warming water temperatures and increased rainfall along the U.S. East Coast (Hurrell and Deser 2010).
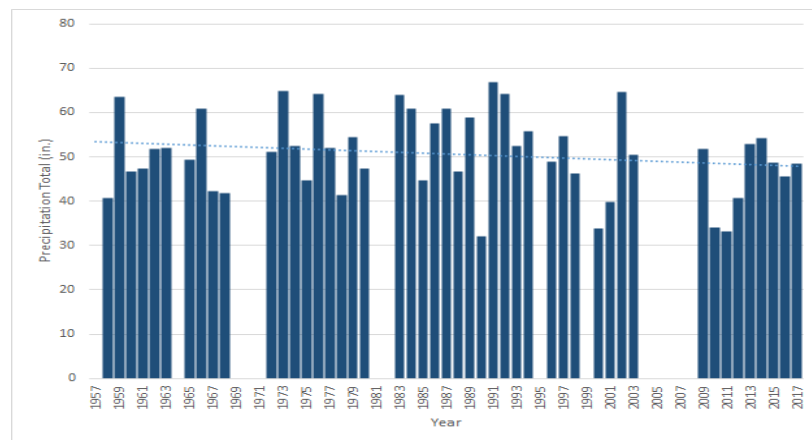
Figure 1.13. Annual total precipitation observed at Sapelo Island, GA, 1958-2017. Blue dotted line is a linear trend applied to the data. (Source: xmacis)

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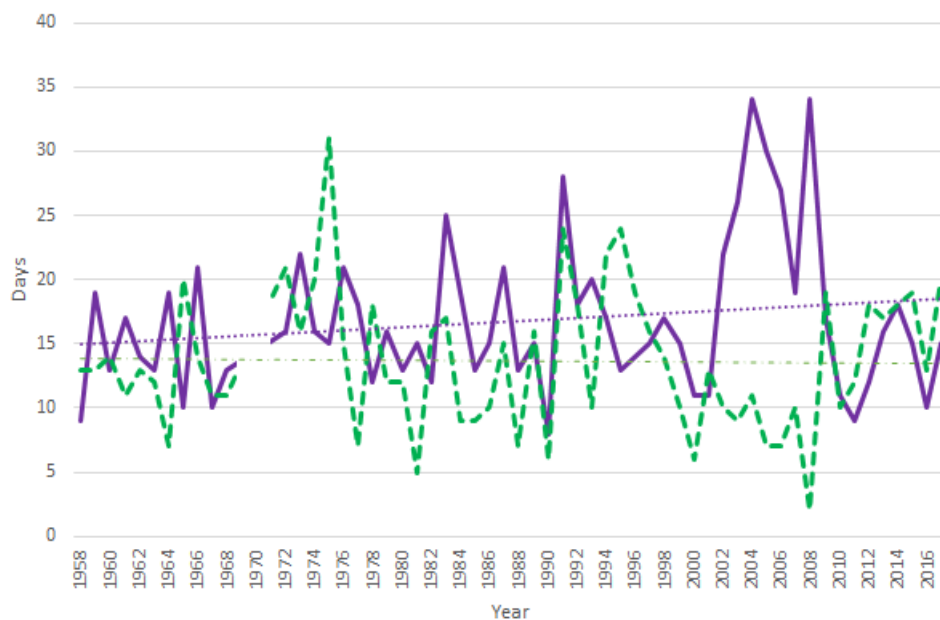
Figure 1.14. Number of days of heavy (≥1.0 in.) precipitation (solid purple line), number of multi-day periods of zero precipitation (dashed green line), and associated linear trend lines (dotted similar color) observed at Sapelo Island, Georgia. (Source: xmacis)

North Atlantic Oscillation (NAO) winter index
Lisbon - Stykkishólmur/Reykjavík, December to March

NAO Index Data provided by the Climate Analysis Section, NCAR, Boulder, USA, Hurrell (2003)
Updated regularly. Accessed 2017-10-08
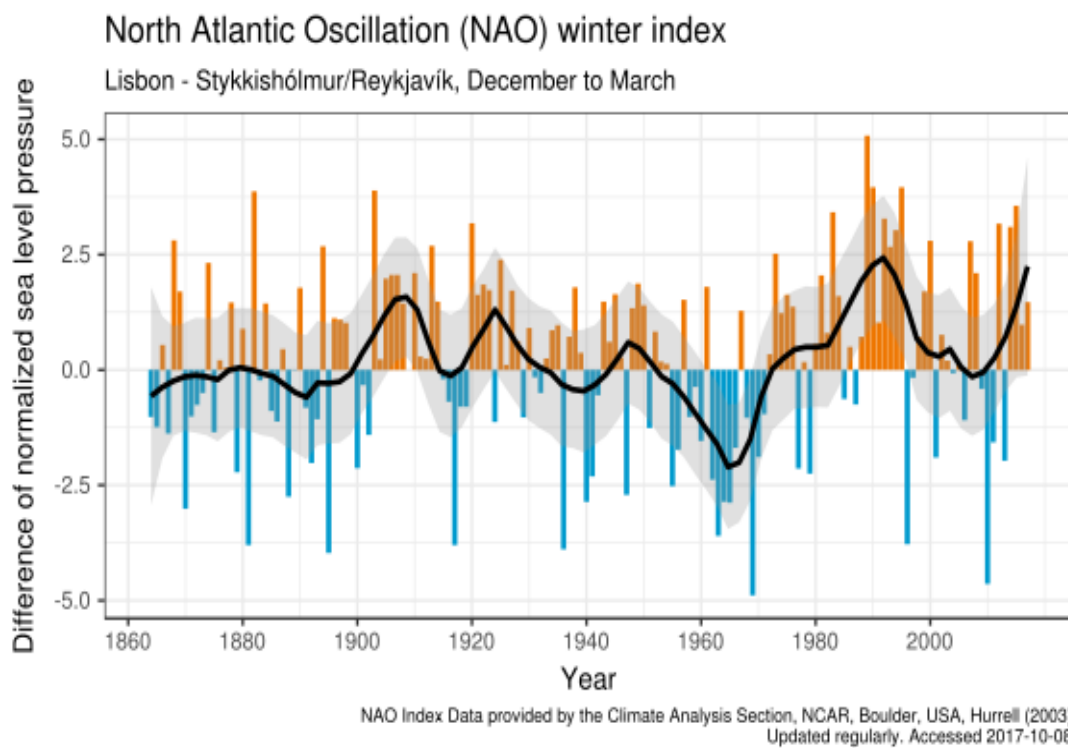
Figure 1.15. NAO Index since 1864. (Source: National Center for Atmospheric Research)
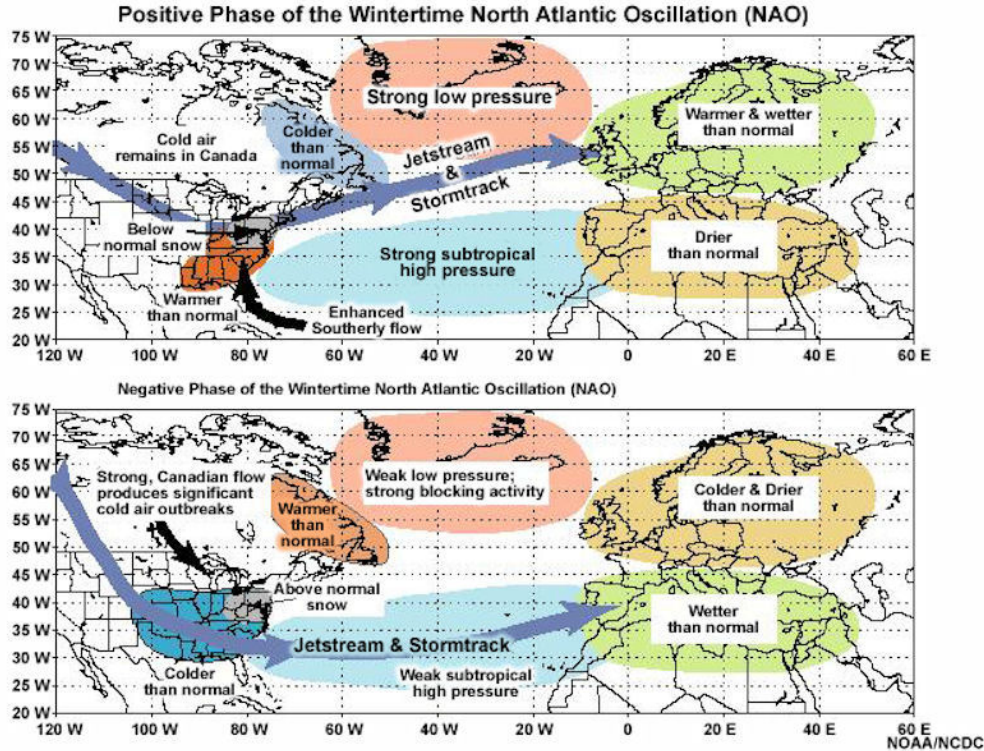
Figure 1.16. Northern Hemisphere weather patterns consistent with the positive and negative phases of the North Atlantic Oscillation teleconnection. (Image: NOAA)

1.3.3 Future Climate Projections

Data in this section are derived from several sources as indicated but come primarily from the Coupled Model Intercomparison Project Phase 5 (CMIP5), a suite of approximately 62 coupled ocean-atmosphere climate models (Taylor et al. 2012). CMIP5 is an ensemble of climate models that together produce a suite of possible future climates when run under several different assumptions about greenhouse gas concentrations in the atmosphere and their resulting radiative influence. CMIP5 data are used by the Intergovernmental Panel for Climate Change (IPCC) in their 5th Assessment Report on Climate Change (IPCC 2013), from which this section draws heavily. Though these assessments have focused almost entirely on terrestrial climate change (with the exception of sea level rise), the climate models on which these reports are based have in most cases included coverage of the ocean. Additional sources of relevant climate change information are the Fourth U.S. National Climate Assessment (USGCRP 2017) and, for the Southeast U.S., the NOAA NESDIS Tech Report 142-2 "Climate of the Southeast U.S." (Kunkel et al. 2013).

Sea surface temperature

Of importance to Gray's Reef is sea surface temperature (SST). The CMIP5 models use several Relative Concentration Pathways (RCPs): RCP 2.6 (low emissions scenario), RCP4.5, RCP6, and RCP8.5 (high emissions scenario). The numbers represent the change in radiative forcing (Wm^{-2}) of the atmosphere by 2100 AD, relative to preindustrial conditions.

For Gray's Reef, the RCP2.6 (low emissions) outlook is for an increase in SST of 0.8°C (relative to the 1981-2010 average) by 2050, with a leveling off thereafter, through 2100. Alternatively, RCP8.5 suggests a steady increase in SST through 2100, reaching 1.4°C above the 1981-2010 average by 2050 and over 3°C by 2100 (Fig. 1.17).

Sea level change

Sea Level along the coast of Georgia is expected to rise between 152 mm (6 in) and 330 mm (13 in) within the next 50 years, and between 0.5 to 1.2 m (20 to 39 in) by 2100 (e.g., IPCC 2013; Keating and Habeeb 2012; Climate Central 2012; cf. http://gacoast.uga.edu/research/major-projects/sea-level-rise/). Significance for the
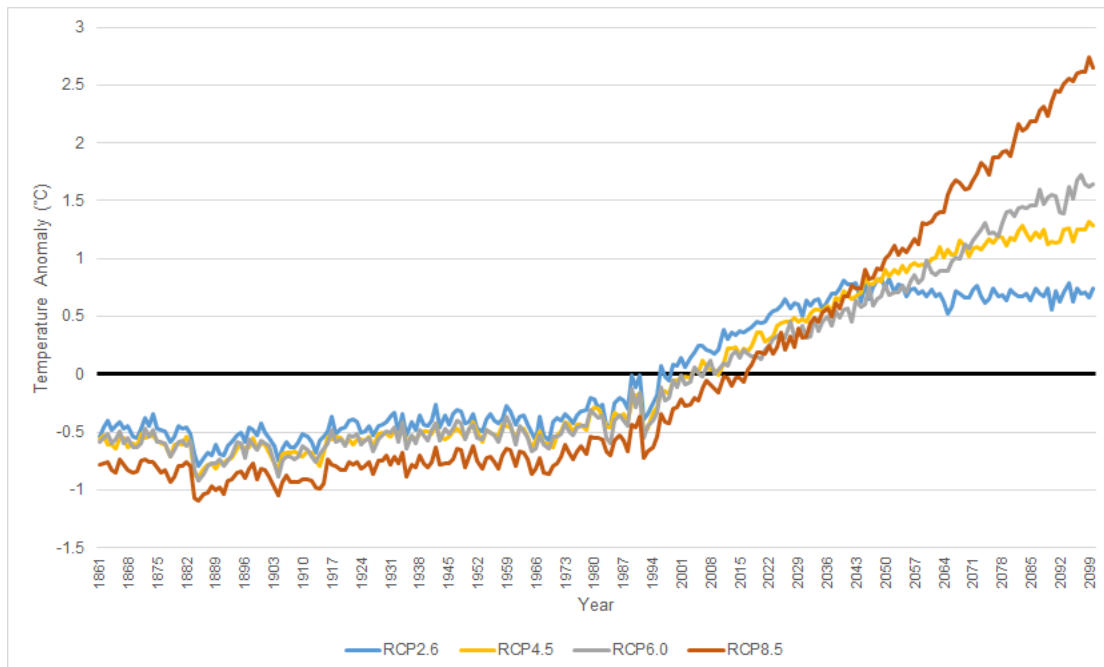
Figure 1.17. Annual average SST anomalies (1981-2010 mean) for GRNMS through 2100 derived from the four relative concentration pathways (RCPs) of the CMIP5 ensemble. (Source: KNMI; http://climexp.knmi.nl/)

Gray's Reef ecosystem is that rising sea levels support more frequent and extensive coastal inundation, especially when tides and periodic storm surges are factored in. The result of inundation events is the potential to mobilize significant quantities of terrestrial sediments and pollutants that were deposited on the land prior to inundation. Drainage from such events has the potential to transport these pollutants to Gray's Reef. This situation may be exacerbated as well should rising sea levels and other factors, both climatic and non-climatic, reduce the extent and effectiveness of living shorelines (i.e., salt marshes and wetlands).

Pressure patterns and tropical cyclones

In addition, research is suggesting that the position of the center of the Bermuda High is gradually expanding westward and intensifying under warmer climates (Li et al. 2012). A summary of this research can be found at http://www.climatecentral.org/news/global-warming-may-shift-summer-weather-patterns-study-finds-15100. Additionally, the poleward expansion of the Hadley Cell, the planetary circulation pattern governing atmospheric flow in the tropics, as well as the increasing size of the cold pool of water in the North Atlantic due to glacial melt from the arctic and Greenland, may result in a net north to northeast shift of the high's center. As it migrates, the high will no longer regulate conditions at Gray's Reef as significantly as it has in the past.

The shift in the Bermuda High also affects the steering of North Atlantic tropical cyclones. Though they do not indicate an increase in the frequency of tropical cyclones, IPCC future climate scenarios suggest those storms are likely to increase in intensity by between 2 and 11 percent by 2100, and in that same time period the number of "very intense" storms (Category 4 or 5) is expected to increase by an even larger percentage (90 percent). A summary of these findings (with references) are at https://www.gfdl.noaa.gov/global-warming-and-hurricanes/.

Ocean acidification

All future climate scenarios are run under an assumption of a continued increase, to some degree, in atmospheric CO_2 and other greenhouse gases. Such an increase will likely continue to produce a corresponding increase in the quantity of dissolved CO_2 taken up by the ocean, and therefore a corresponding decrease in pH. Atmospheric CO_2 is expected to reach levels near 800 ppm by 2100 (IPCC 2013), and seawater pH is expected to decrease an additional 0.1 during that period, to around 7.8 (Fig. 1.18; Feely et al 2009).

This decrease is expected to result in aragonite undersaturation throughout the global ocean, beginning in the Arctic by 2020 and gradually extending to the area of GRNMS. Aragonite is an important form of calcium carbonate ($CaCO_3$) and occurs naturally in
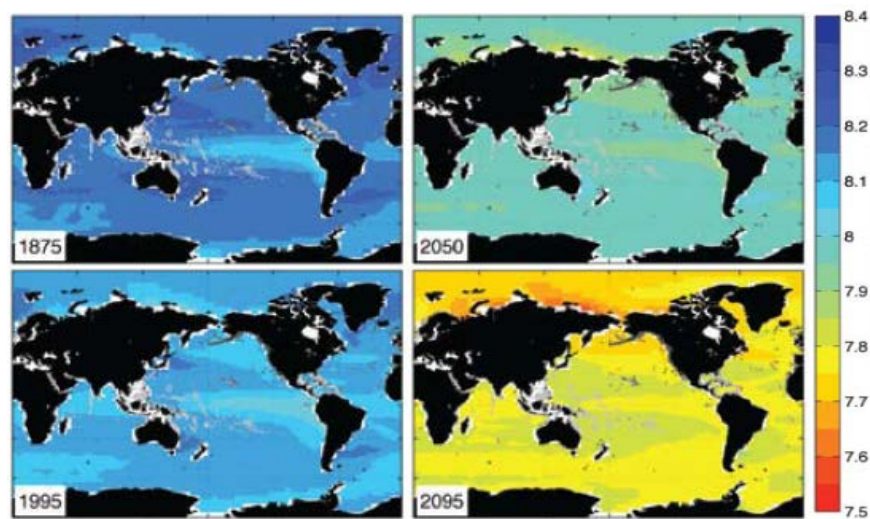
Figure 1.18. Historical and projected seawater pH for the world ocean. (Image: Feely et al. 2009)

many marine animal shells and coral skeletons. A saturated state for aragonite supports shell and skeletal growth among these animals. Undersaturation can promote difficulty in uptake and even dissolution of those calcareous frameworks. Feely et al. (2009) estimate a 21 to 40 percent decrease in aragonite saturation for GRNMS by 2100. The Labrador Current may also accelerate this process by directly transporting undersaturated water to the region from the Arctic.

Other changes

Numerical models of the ocean suggest that between now and 2050, GRNMS should expect a decrease in transport rates of the Florida current as well as a shift in the median track of the Gulf Stream. Additionally, atmospheric warming has been connected to the intensity and extent of the Bermuda High (Li et al. 2010; Li et al. 2012). Future climate scenarios suggest that between now and 2050, the Bermuda High will continue to strengthen and expand. This is likely to increase the frequency and severity of droughts over the Southeast. Coupled with the expected increase in the occurrence of extreme rainfall events, this change increases the likelihood of increased sediment/nutrient discharge and mobilization events for GRNMS.

Changes in the Bermuda High are also likely to influence the strength and extent of the subtropical oceanic gyre that rests beneath it and may also play a role in the expected decrease in transport rates of the Florida Current. Similarly, an increase in the extent of the gyre is likely to push both the Gulf Stream and southern extent of the Labrador Current northward, reducing the likelihood of cool water intrusions into the GRNMS.

Dissolved oxygen has been steadily declining in the global ocean, and is expected to continue that decline, by between 1 and 7 percent by 2100 (Schmidtko et al. 2017). At

GRNMS, dissolved oxygen may decline by around 0.004 mol m^{-3} (1%) by 2050. However, this decline may be enhanced by a combination of increased water temperature and a greater concentration of nutrient/sediment levels resulting from more erratic and intense river discharge along the Georgia coast.

Other long-term changes in the characteristics of the Atlantic Ocean, such as the Atlantic Thermohaline Circulation and the Atlantic Multidecadal Oscillation (AMO) are receiving attention but remain poorly understood.

1.4 Potential Climate Impacts

All ecological systems are to some degree or another adapted to and influenced by the environmental conditions to which they are exposed. A variable and changing climate has the potential to expose species and habitats to conditions outside their evolutionary tolerance, resulting in adverse responses, such as increased stress and morbidity, forced migration, lowered fecundity, competition from invasive species, susceptibility to pathogens, and even behavioral stress and physical injury. Mobile species may or may not alter their range to take advantage of changing conditions, as has been seen in the general poleward migration of a variety of fish populations (e.g., Nye et al. 2009; Mills et al. 2013), but often they either do not find support from a suitable habitat during forced migrations or are out-competed by native species. Even when mobile species are able to migrate quickly in response to climate stressors, their migration may not synchronize with prey species that also may be migrating in response to the same climate-induced pressures. Sessile species, on the other hand, are more limited in their ability to mobilize in response to threats because their life histories are dependent on larval stages (both motile and sessile) to shift their distribution. Therefore, sessile species often must quickly adapt to changing environmental conditions or suffer widespread mortality (e.g., Hoegh-Guldberg et al. 2007; Sorte et al. 2011). The accelerated time frame of climate stressors may exceed the resiliency of many mobile and sessile species to adapt quickly enough to successfully relocate (mobile species) or survive where they currently exist (sessile species). Migratory/range shifts for species in response to climate-induced stressors can also cause complex non-linear changes in biotic interactions between species leading to trophic cascades.

Presented with a summary of potential changes in climate (atmospheric and oceanographic) conditions that may affect GRNMS, and the list of species for which this rapid vulnerability assessment was to be conducted (RVA species), workshop participants identified a few primary changes that likely pose the greatest challenges to those species' health and vitality over the next 50-year time frame. The climate changes of greatest concern were changes in the characteristics (e.g., frequency, intensity, track) of severe tropical (and in some cases extratropical) cyclones, increase in water temperature, ocean acidification, changes in currents, changes in precipitation patterns over sediment/nutrient contributing river basins, turbidity, diminished dissolved oxygen, and changes in upwelling/mixing. Nearly all RVA species appear likely to be affected by

changes in storms and increasing water temperature by 2050, although these factors also play a role in modifying other climate change stressors, such as increased turbidity and decreasing seawater pH.

Some potential effects of warming seawater in GRNMS include the northward shift of species range and disruption of reproductive cycles. Impacts from stronger tropical and extratropical cyclones are led by potential physical damage to the GRNMS habitat as well as scouring/smothering of sessile species and food sources. Additionally, warming water and increased nutrients may produce more frequent and long-lasting hypoxic events and harmful algae blooms in the region. It is uncertain to what extent such events would affect GRNMS directly.

2. Vulnerability Assessment: Methods and Workshop Activities

In November 2017, GRNMS and the National Marine Protected Areas Center convened a rapid vulnerability workshop at the GRNMS offices adjacent to the University of Georgia Skidaway Institute for Oceanography (SkIO) on Skidaway Island, Georgia. The workshop tasked an invited group of topical experts (see Appendix B) with the objective of summarizing exposure and response of nine keystone marine species to projected changes in environmental conditions at GRNMS and standardize those summaries using the North American Marine Protected Area Rapid Vulnerability Assessment Tool[2] (Fig. 2.1), developed by the Commission for Environmental Cooperation (CEC 2017; see Appendix C). The nine species assessed were initially identified by GRNMS staff. Workshop participants subsequently modified that list (as described further on) and suggested adding two species via post-workshop assessments (following the same protocols).
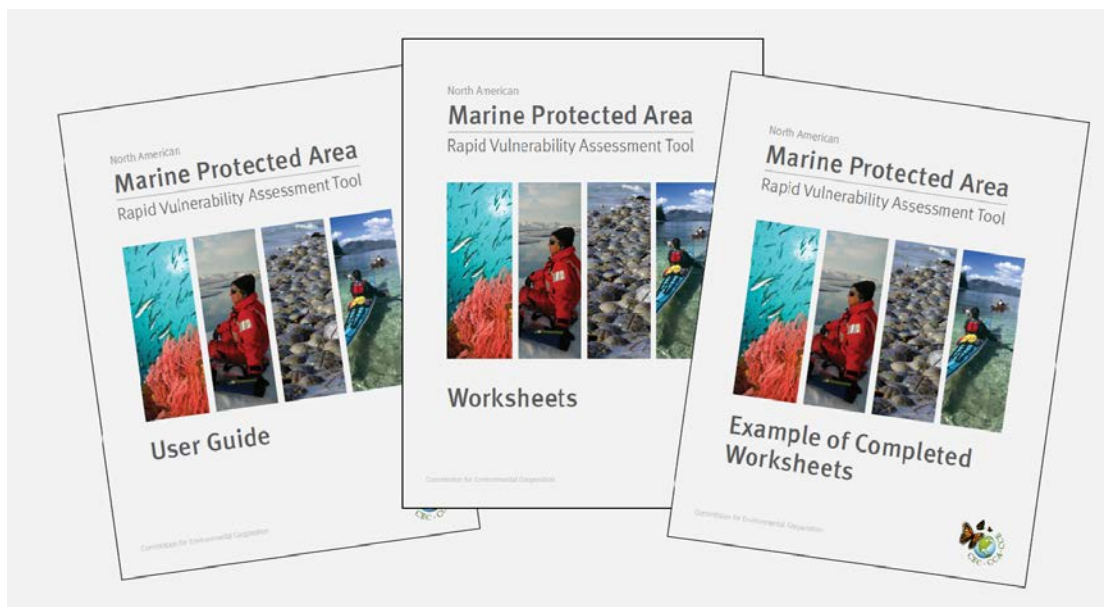
Figure 2.1. North American Marine Protected Area Rapid Vulnerability Assessment Tool from the Commission for Environmental Cooperation (CEC). Image: Commission for Environmental Cooperation

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[2]www3.cec.org/islandora/en/item/11739-north-american-marine-protected-area-rapid-vulnerability-assessment-tool

2.1 Workshop Preparation

The most critical component of a vulnerability assessment is ensuring that the needed expertise and partnerships will be represented by the right combination of participants. Months in advance of the workshop, sanctuary staff and organizers identified individuals with expertise regarding (1) biological and ecological information specific to the species of interest, (2) regional climate science, and/or (3) management, partnerships, and implementation. It was important to include representation from all levels of government (federal, state, local), academic institutions, and non-governmental organizations to ensure a well-balanced perspective throughout the assessment.

Given that this effort is considered a "rapid" vulnerability assessment, the workshop was time limited (1.5 days) and much of the participant orientation took place in advance of the workshop opening. The project team compiled and distributed the following materials to participants to ensure they would be well-informed with consistent data and trends, methodology, and expectations for the workshop:

- Instructions for use of the RVA tool.
- Read-ahead document that presented climate trends and data, species data, and geographical overview.
- Collection of literature to support the assessment.

Confirmed participants (Appendix B) were asked to join in a pre-workshop webinar in which organizers briefed them on workshop logistics (see Appendix A) and how to apply the RVA Tool (Appendix C), and provided a chance for the participants to have their questions regarding the workshop or read ahead materials addressed. This webinar proved valuable both to organizers and participants, and helped the workshop to run more quickly and smoothly.

The RVA tool used in the GRNMS workshop produces a metric for habitat vulnerability to climate change. However, given the small size and complex nature of the GRNMS habitat, sanctuary staff concluded it would be more effective to focus the assessment on individual species occupying the habitat. Originally, twelve species were selected by GRNMS staff, but workshop time limitations and a discussion among participants during preliminary phases of the workshop regarding availability of information for certain species (e.g., Caribbean lancelet, fan coral) modified the list of species to nine in four niche groups, with two additional species selected for post-workshop assessment (Table 2.1).

Table 2.1 List of species selected for rapid vulnerability assessment.

Species	Common Name	Niche Group
Ircinia campana (Lamarck 1816)	Stinking vase sponge	Sessile Macrofauna
Oculina arbuscula (Agassiz, 1864)	Ivory bush coral	Sessile Macrofauna
Arbacia punctulata (Lamarck 1816)	Atlantic purple sea urchin	Sessile Macrofauna
Centropristis striata (Linnaeus 1758)	Black sea bass	Reef-Associated Predator
Haemulon aurolineatum (Cuvier 1830)	Tomtate	Reef-Associated Predator
Lutjanus campechanus (Poey 1860)	Red snapper	Reef-Associated Predator
Scomberomorus cavalla (Cuvier 1829)	King mackerel	Migratory Pelagic Predator
Decapterus punctatus (Cuvier 1829)	Round scad	Forage Fish
Hypanus americana (Hildebrand & Schroeder 1928)	Southern stingray	Reef-Associated Predator
Caretta caretta* (Linnaeus 1758)	Loggerhead sea turtle*	Migratory Pelagic Predator
Acipenser oxyrhynchus* (Mitchill 1815)	Atlantic sturgeon*	Anadromous Forage Fish

* Included via post-workshop assessments

Fortunately, although the RVA tool was developed for habitat assessment, with a few critical modifications to the worksheets, the tool can be adapted to other resources of interest, including species. One of the authors of this report was also a developer of the CEC RVA tool that was adapted for use by GRNMS, and facilitated the use of the tool in the workshop. She also consulted with the other tool developer (EcoAdapt) to ensure the protocol was appropriately adapted for assessing species vulnerability rather than habitat. Following consultation with the tool developers, the worksheets were modified as follows:

Step 1
● Box 1: Habitat list replaced with list of species (identified in Table 2.1 above)

Steps 2 & 3

- "Habitat" changed to "Species" throughout all worksheets
- Table 3 (Ecological Potential):
  - "Past evidence of recovery" changed to "dispersal"
  - "Physical diversity" changed to "phenotypic and behavioral plasticity"
  - "Biodiversity" changed to "genetic diversity"
  - "Keystone/indicator species" changed to "generalist/specialist ranking"

2.2 Overview of the RVA Tool

This section provides a brief summary of the RVA tool. Internet links to the full tool and instruction on its use are provided in Appendix C of this document, or can be found at the web address www3.cec.org/islandora/en/item/11739-north-american-marine-protected-area-rapid-vulnerability-assessment-tool.

Steps 1 and 2

The RVA Tool determines the climate change vulnerability of a particular resource by guiding the participant through a series of thought steps. The first step guides the participant to define the scope and initial parameters of the assessment. This includes identifying the resource(s) to be assessed (e.g., habitats, species), the timescale over which climate impacts are being considered (e.g., next 50 years), and which climate change variables are likely to most greatly affect the resource(s). Because this is a rapid, rather than comprehensive assessment, not all resources or variables could be assessed.

Using an initial list provided by GRNMS staff, workshop participants identified 11 species for assessment. This list was based on existing knowledge of how the species responds to changes in its environment. The assessment focused on likely changes over the next 50 years, and participants identified three climate variables that would likely have a consequential effect on a particular species. In general, the climate variables that were considered were supported by ample data and research. Some potential variables include sea level rise, turbidity, or increasing water temperature. Lastly in Step 1, participants are asked to consider what non-climate stressors currently affect the resource(s), such as harvesting, pollution, or dredging. The second step instructs the participant to transfer their input from the Step 1 boxes into the Step 3 (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 or not climate change will

mitigate/exacerbate that stress. 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 is comprised of 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).

Table 2.2 Vulnerability (Risk x Adaptive Capacity) matrix (from Figure 3, RVA worksheets)

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

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 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, Step 4 prompts the participant to identify considerations for implementation, such as determining leaders and partners, monitoring needs, timeline, and funding mechanisms.

It should be noted that due to the rapid nature of this assessment and the fact that the majority of the participants were 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 GRNMS staff as a follow-on to the RVA, in some cases with partners and stakeholders.

Step 5

Finally, Step 5 is to translate the RVA outcomes into a narrative vulnerability assessment report. 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 rapid vulnerability assessment exercise conducted for each species (from the CEC RVA tool, see also Appendix C).

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 GRNMS RVA Workshop

The RVA workshop began with introductory presentations, including an overview of the goals/objectives of the meeting and the methods (detailed methods were provided in the pre-workshop webinar), as well as a basic summary of climate trends for the region (see Appendix A for workshop agenda). Because sanctuary staff identified species of interest for the assessment in advance of the workshop, time on the agenda was allowed for discussion and modification of this list by all participants. The final list of species assessed appears in Table 2.1. Based on these species identified for assessment, participants were allocated to one of three assessment break-out groups based on expertise and interest: invertebrates, reef fish, and pelagic fish.

Similarly, workshop participants were provided with a GRNMS climate summary and briefing from a NOAA climatologist (similar to Chapter 1 of this report) that helped inform their selection of climate factors of importance to the target species. Though there may be many climate stressors that affect a particular species, the rapid nature of the RVA tool promotes limiting the number of climate stressors to no more than three. Therefore, for each target species, workshop participants identified the three climate stressors they deemed most impactful to the species.

The bulk of the workshop was spent in these smaller assessment groups, and each group completed three species assessment during this time. Species were assessed in these groups in order of information availability and interest from the participants, so the species assessed in this report do not necessarily reflect sanctuary species-related management or conservation priorities. Participants identified needed expertise in order to complete assessments for additional species of interest. The final hour of the workshop was spent summarizing the assessment results and discussing opportunities for collaboration regarding adaptation responses by management and scientific entities.

Given the limited time and targeted scope of the workshop, participants were instructed to focus solely on the selected species and provide assessment based on the information at hand and their expert knowledge. As such, this document, which is a workshop report, does not expand beyond the findings and outcomes of the workshop. While these findings may also apply to other species, habitats, or geographies, doing so would require further assessment activity beyond the scope of the workshop or this report.

Additionally, the adaptive strategies identified in this report are those that the workshop participants, in the limited time available to them, determined may reduce the vulnerability of the target species to climate change. These strategies are not recommendations for action to GRNMS, but rather identify some possible approaches, among others, that GRNMS staff may select for further consideration.

3. Vulnerability Assessment and Adaptation Planning Results

This chapter presents the summary of vulnerability assessments of the 11 species examined by RVA workshop participants. It is divided into three sections: Invertebrates/Sessile Macrofauna, Reef Species, and Pelagic Species. The distinction between reef and pelagic species in the context of this report is that reef species are restricted to those that spend their full life cycle on or near the reef, while species considered pelagic are either migratory or are otherwise not fully dependent on the reef habitat.

Each section leads with a table that identifies the top three climate stressors identified for the species by workshop participants. For each stressor, the index/level of each step in the RVA is provided using the RVA worksheet terminology (e.g., high, medium, low) and color coded for reference to its likelihood or contributory impact, with green being most positive or least concerning, yellow as possible or moderate, red for likely or major concern, and purple for most likely, extreme or negative (see Table 2.3).

3.1 Invertebrates/Sessile Macrofauna

3.1.1   Stinking Vase Sponge (*Ircinia campana*)

Table 3.1. Influence of climate change on stinking vase sponge from rapid vulnerability assessment scores.

Stinking Vase Sponge	Increased Water Temperature	Turbidity	Storm Severity/Frequency
Likelihood	Almost Certain	Almost Certain	Almost Certain
Consequence	Major	Major	Major
Risk	Extreme	Extreme	Extreme
Adaptive Capacity	High	High	High
Vulnerability	Moderate	Moderate	Moderate

Species overview

Benthic coverage of live-bottom ledge areas in Gray's Reef is dominated by various species of sponges in the genera *Ircinia* and *Chondrilla*. The stinking vase sponge (*Ircinia campana*) is a vase-shaped sponge, typically reddish-brown on the outside and tan inside (Fig. 3.1). The species ranges from the United States mid-Atlantic coast as far

south as Brazil, and is also found throughout the Caribbean and Gulf of Mexico. This species also occurs in the Mediterranean Sea. They occur at depths ranging from 3 to 30 meters deep and are found on shallow hard-bottom areas, seagrass beds, and inshore reefs. Within GRNMS, they are almost exclusively associated with the rocky ledges. The species is hermaphroditic and zygotes develop into free-swimming larvae before settling down onto a substrate to grow into sponges.

Figure 3.1. Stinking vase sponge (*Ircinia campana*). (Image: Greg McFall, NOAA)

The stinking vase sponge is the dominant sponge species within Gray's Reef and plays an important ecological function in the benthic community. They are filter feeders, collecting food (phytoplankton, zooplankton, bacteria, etc.) while whipping seawater in through pores in their central body cavities. Sponges such as this species provide a variety of microhabitats for many invertebrate species (e.g., polychaetes are a dominant associated species off Georgia coast) by serving as refuge from predation, a food source, and an attachment site – all of which contribute to the stinking vase sponge providing an important ecological function on Gray's Reef. The stinking vase sponge also provides an important maintenance (structural) function on the ledges within Gray's Reef. As filter feeders, these sponges also provide a critical benthic-pelagic trophic coupling.

Vulnerability assessment results

Workshop participants determined the climate change factors most likely to adversely affect the stinking vase sponge at GRNMS to be increased water temperature, turbidity, and changes in storm severity/frequency. The workshop participants decided these climate change stressors were all almost certain to occur in GRNMS. Additionally, tourism, disease (e.g., wasting disease), and altered sediment transport were identified as the most likely and important non-climate stressors that could adversely affect stinking vase sponges on Gray's Reef.

Seawater temperatures are anticipated to rise by 0.8 to 1.4°C by 2050. Thermal stress associated with ocean warming can greatly impact sponge assemblages through the induction of diseases and mortality by decreasing the efficacy of sponge defense mechanisms allowing for the development of pathogens. The threat from wasting disease to the stinking vase sponge may be exacerbated by climate change factors such as increased seawater temperatures, ocean acidification, and altered sediment transport

(urban/agricultural runoff). Thermal stress can limit reproductive capacity, limiting dispersal by causing reabsorption of spermatic cysts and oocytes and can even prevent the release altogether of asexual propagules. Thermal stress may impact sponge feeding by increasing filtration rates (warming temperatures) and decreasing choanocyte chamber density and size, causing shifts in microbial communities of the host sponge. Seawater temperature increases could lower the availability/concentrations of planktonic food washing through Gray's Reef. This could lower sponge growth rates and reproductive capacity. Increased water temperatures, seasonally and/or year-round may impact plankton species composition as well that could also reduce sponge growth rates. The workshop group discussed that stinking vase sponge has a high adaptive capacity that drives down their vulnerability somewhat. The species has a wide dispersal distance but their habitat within Gray's Reef is also patchy and largely limited to the rocky-ledge habitat within the sanctuary. As sessile invertebrates, changes in their prey species composition and distribution that result from seawater temperature increases, for instance, make the stinking vase sponge moderately vulnerable to climate change.

Turbidity can cause a huge impact to sponges on Gray's Reef by clogging sponge pores and reducing pumping/filtration capacity. Increased turbidity is anticipated as a result of increased storm severity in the area and from large-scale dredging projects (e.g., Savannah River). More intense storms may change wave height over Gray's Reef in addition to changing wave period. These changes will increase turbidity during acute events and extend the time period before suspended materials settle after storms, especially if storm frequency increases as well. More extreme turbidity from storms may resettle benthic materials onto sponges, inundating them and inhibiting filtration feeding.

Little change has occurred in the overall number of large storm events annually in recent years, hovering at about ten events per year. However, there has been a decrease in the number of weak storms with a greater percentage of annual storms being large storm events. Post-storm survey events have documented substantial scouring from recent Category 1 and 2 hurricanes. Projecting ahead, larger storms will likely increase sponge mortality in GRNMS and impede recovery of damaged sponges, especially if there is less of an interval between storm events. More intense storms may increase scouring of sponge habitat, increase sedimentation, either covering and/or clogging sponges, or displacing/upending sponges from their substrate.

Potential adaptation strategies

The breakout group discussed one potential management response for the stinking vase sponge.

Develop a rapid response monitoring and assessment team
The most achievable option was to develop a rapid response monitoring and assessment team to assess damages from severe storm events (e.g., document damages from Hurricane Irma). The group suggested that such an assessment team approach be coupled

to overlapping long-term monitoring and assessment sites within GRNMS. The success of such an approach is also dependent on the availability or establishment of species baseline data against which changes could be detected and assessed.

Cost: Low

Efficacy: High

3.1.2   Ivory Bush Coral (*Oculina arbuscula*)

Table 3.2. Influence of climate change on compact ivory bush coral based on rapid vulnerability assessment scores.

Compact Ivory Bush Coral	Increased water temperature	Ocean Acidification	Storm severity/frequency
Likelihood	Almost certain	Likely	Almost certain
Consequence	Moderate	Moderate	Major
Risk	High	High	Extreme
Adaptive Capacity	High	High	High
Vulnerability	Moderate	Moderate	Moderate

Species overview

Compact ivory bush coral (*Oculina arbuscula*), also known as ivory tree coral, is a shallow water (< 100m) ahermatypic (non-reef building) scleractinia, or stony/hard coral (Fig. 3.2). With its tangled, branching skeleton, ivory bush coral crudely resembles a small bush or tree (hence its common name). Unlike their larger, deep water variant (*O. varicosa*), these colonizing corals appear brownish to yellowish as a result of the presence of zooxanthellae in the tissue. Ivory bush coral colonies reach approximately 60 cm (24 in) in diameter/height, with individual skeletal branches having a diameter of about 1.5 to 2.5 cm (0.5 to 1.0 in) and closely spaced corallites (Reed 1980). The polyps are facultatively symbiotic, fed both by their symbiotic zooxanthellae as well as suspension-feeding on planktonic microorganisms in the water column.

Figure 3.2. Compact ivory bush coral (*O. arbuscula*) on a ledge top in GRNMS (Photo: Greg McFall/NOAA).

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Ivory bush coral is primarily found on the west coast of Florida, and on the Atlantic coast from Florida to South Carolina at depths between 3 and 30 m (10-33 ft). In GRNMS, it is relatively abundant, growing primarily on the tops of the rocky ledges at depths of around 15 to 20 m (50 to 66 ft). This coral reproduces via annual broadcast spawning, usually in July or August. Miller (1995) demonstrated that ivory bush coral has a relatively broad temperature tolerance and that growth is significantly greater in warm water than cold water, though other studies (e.g., Shenkar et al. 2005) suggest that sustained temperature above 31°C produces bleaching in ivory bush coral colonies.

Owing to the limited light at depth (only around 6 percent of surface irradiance is available at 65 feet), many of the colonies found on vertical surfaces and beneath overhangs in Georgia waters exhibit permanent bleaching, but are nonetheless healthy (D. Gleason, 2018 pers. comm.).

Due partly to the protection its tangled structure provides as well as forming thickets on the substrate, ivory bush coral offers shelter to a wide variety of reef fish and invertebrates, and thus is an important keystone species and habitat. Like most zooxanthellae corals, ivory bush coral is susceptible to bleaching when stressed. Bleaching is the process by which zooxanthellae are expelled from the stressed coral's tissue. Such stress has been associated with elevated (and suppressed) water temperatures.

The deep-water species of ivory bush coral (*O. varicosa*) is listed as threatened on the IUCN Red List as a result of substantial decline in abundance in a primary part of its range (Oculina Banks off Florida), where extensive removal has been attributed to bottom trawling (Reed et al 2007). There is insufficient information on shallow water ivory bush coral (*O. arbuscula*) to support an IUCN listing for the species. It is however included with *O. varicosa* by NOAA as a "Species of Concern" (see http://www.nmfs.noaa.gov/pr/pdfs/species/ivorybushcoral_detailed.pdf), primarily because its morphology makes it equally susceptible to damage from fishing activities (i.e., line entanglement, bottom trawling). Bottom trawling on hard bottom is now prohibited throughout the region, and part of GRNMS is closed to all fishing. Dredging, anchoring, and other bottom disturbance (including invertebrate collecting) is prohibited at GRNMS. However, other factors, such as scour or from passing storms may detach ivory bush coral from the substrate and sedimentation (burial) from storms also may adversely affect the species.

Vulnerability assessment results

The most likely climate change factors workshop participants concluded would affect ivory bush coral at GRNMS were increased water temperature (e.g., SST), ocean acidification, and changes in storm behavior. The occurrence of these climate changes was deemed to be almost certain (increased temperature and storm behavior) and likely

(ocean acidification) within GRNMS. Non-climatic stressors that may compound impacts were development/population growth, tourism/recreation (e.g., fishing, anchoring, marine debris), and altered sediment transport.

Thermally-induced bleaching of ivory bush coral has been observed within GRNMS, and the expected increase in water temperature of between 0.8°C and 1.4°C by 2050 may result in bleaching episodes of shallower colonies that have not experienced light-induced bleaching. Because ivory bush coral 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 of ivory bush coral.

Water pH at GRNMS 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 availability of carbonate that coral species can use to build their skeletons. Lower pH will also effectively reduce the availability of planktonic food sources. A laboratory experiment on Georgian ivory bush coral under elevated temperature and decreased pH is currently underway at Georgia Southern University (D. Gleason, 2018 pers. comm.).

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 potential to increase scouring and physical dislodgement/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 Georgia region through 2050 are expected to alter freshwater runoff and produce an increase in nutrient and pollutant loads for GRNMS. Similarly, increased human population pressures are coupled to increased tourism/recreational use of GRNMS, which include increases in fishing and diving – both of which have demonstrated potential to damage corals. While these factors will likely moderately reinforce the negative impacts of increasing water temperature and ocean acidification, they are expected to provide a major exacerbation of negative effects of storm impacts (e.g., increased mobilization of marine debris, interference with post-storm recovery). Altered sediment transport is expected also to provide a negative accompaniment to the three climate stressors by increasing smothering of sessile species in some areas while scouring the benthic habitat in other areas. The combined impacts of sediment transport and increased water temperature along with ocean acidification are expected to result in an overall major negative impact to ivory bush coral, while the combined effect of altered sediment transport and changes in storm behavior is anticipated to be catastrophic.

As with the other sessile invertebrate species assessed by workshop participants, compact ivory bush coral at GRNMS were identified as having a high adaptive capacity to offset

the potential impacts from climate change. The species is considered relatively abundant and fast-growing within GRNMS, and at least within the closed research area, any fishing or diving is prohibited. The species also is an ecologically-important species, but of little social/commercial value, limiting the likelihood of overharvesting (harvest is prohibited at GRNMS). Studies that have been done on ivory bush coral suggest limited larval dispersal (larvae tend to settle between one and three days). GRNMS may receive larval recruits from other habitats, and there has been demonstrated high recruitment on study tiles laid out on the ledges.

This high ecological potential for adaptation is somewhat offset by a lower social potential. While certain factors such as staff capability, monitoring ability, existing protections (e.g., CITES), scientific support, and stakeholder/partner relationships showed high adaptive capacity, other factors such as the capacity of existing staff (training/time) to engage in adaptation activities, responsiveness as a federal agency, and the overall societal value of ivory bush coral showed limited adaptation potential. The combination of ecological and social components set potential adaptive capacity for the species just above the moderate/high threshold.

Potential adaptation strategies

The high to extreme risk to ivory bush coral posed by climate change, coupled with a moderate (verging on high) vulnerability to that change, suggests the importance of planning and implementing adaptation strategies for this species. A number of potential strategies were discussed by workshop participants, and two were further explored.

Among the strategies identified as having high efficacy (but often at high cost) were establishing a lab-based *Oculina* nursery with water temperature controls to aid species adaptation to higher temperatures; installing artificial substrate (e.g., reef balls, artificial wrecks) to increase recruitment; outplanting to increase population densities; better education and enforcement for compliance in GRNMS public use to reduce marine debris and anchor damage; rapid restoration of damaged corals; removal of marine debris; installation of permanent boat moorings; and transitioning monitoring instruments and activities from soft to hard funding to ensure longevity and consistency.

Three strategies that exhibited low cost and high efficacy were discussed: installing artificial substrate to promote recruitment and recovery; repairing anchor damage/removing marine debris; and increasing enforcement for compliance to reduce marine debris and anchor damage.

Installing artificial substrate
GRNMS has permitting mechanisms already in place but funding is needed (perhaps from partner sportfishing clubs, diving groups, etc.). The anticipated 50-year time frame of this strategy includes a five-year installation plan, five-year evaluation period, and long-term monitoring. Complex substrate would increase *Oculina* recruitment and

population density. However, while this strategy may be considered for the region outside of sanctuary boundaries, GRNMS has communicated to stakeholders that placing artificial substrate within sanctuary boundaries is unlikely.
Cost: Low
Efficacy: High

Reattaching dislodged ivory bush coral and removal of marine debris
While anchorage within GRNMS has been prohibited since 2007, dislodging of coral by illegal anchoring and other causes does occur occasionally. Adding this restoration component to existing in-water missions would be feasible without great additional costs to GRNMS or its partners. In most cases, individual corals can be reattached and smaller marine debris (e.g., cans, bags) can be removed by mission divers.
Cost: Low
Efficacy: High

Increasing compliance and enforcement
The latter strategy has immediate need with an indefinite time horizon. Awareness of and compliance with regulations at GRNMS can be enhanced through targeted education and outreach efforts by GRNMS staff and partners. NOAA or GRNMS partners would need to identify funds to support enforcement efforts. Lack of staff capacity to provide enforcement necessitates reliance on other agencies (e.g., Georgia DNR, U.S. Coast Guard, local law enforcement), and even private citizens (e.g., self-enforcement) to achieve results.
Cost: Low (if costs borne by other agencies)
Efficacy: High

An adaptation strategy that has already been adopted and is applied to GRNMS is the prohibition on bottom trawling, which Reed et al (2007) identified as a primary cause of damage to these corals. In addition, the research area of GRNMS is closed to all recreational and commercial water activities and vessel anchoring. With no plans to alter these restrictions, this strategy can continue at little to no cost but high efficacy.

3.1.3   Purple-Spined Sea Urchin (*Arbacia punctulata*)

Species overview

Arbacia punctulata (Fig. 3.3) is a shallow-water urchin (echinoid) found along the western Atlantic coast from Massachusetts south to Cuba, in the Gulf of Mexico along the Yucatan peninsula from Texas to Florida, throughout many locations in the Caribbean Sea, and along the coast of Panama to French Guiana. This species is usually found along shallow, sandy, rocky, shell-detritus bottom habitat, often found in association with turtle grass (*Thalassia testudinum*). Their depth range is from 0 to 225 meters (0 to 738 feet). The purple-spined sea urchin is a benthic forager on sessile invertebrates and algae and shifts its diets over different substrates (e.g., rubble, sand). They are generalist feeders

Table 3.3. Influence of climate change on purple-spined sea urchin from rapid vulnerability assessment scores.

Purple-Spined Sea Urchin	Increased Water Temperature	Ocean Acidification	Storm Severity/Frequency
Likelihood	Almost Certain	Almost Certain	Likely
Consequence	Moderate	Major	Moderate
Risk	High	Extreme	High
Adaptive Capacity	High	High	High
Vulnerability	Moderate	Low	Moderate

with food availability being the primary factor controlling their diets. This species is ubiquitous within Gray's Reef, in particular on or near the ledge habitat. Three years of urchin species/habitat data have been collected to date within and outside of the research-only area on Gray's Reef.

Vulnerability assessment results

The most likely climate change factors by which workshop participants felt sea urchins at GRNMS might be affected were increased water temperature, ocean acidification, and changes in storm severity/frequency (Table 3.3). The workshop participants decided these climate change stressors ranged from possible to likely to occur in GRNMS.

Additionally, development and population growth (e.g., runoff), tourism/recreation (increased use of GRNMS from fishing, diving, etc.), and altered sediment transport were identified as the most likely non-climate stressors to occur and important stressors that could adversely affect purple-spined sea urchins.

Seawater temperatures are anticipated to rise by 0.8 to 1.4°C by 2050. This temperature increase may affect the distribution and abundance of sea urchins throughout Gray's Reef by altering their prey distribution in addition to altering their developmental and reproductive capacity. Over the next 50 years,

Figure 3.3. Purple-spined sea urchin (*Arbacia punctulata*). (Photo: NOAA)

seawater temperature increases could exceed thermal preference or tolerance for urchins on Gray's Reef. The rates of such changes within GRNMS may exceed the species' (or its prey's) ability to adapt. Elevated seawater temperatures in the range of 28°C to 32°C have been demonstrated to impact important neuromuscular-mediated behaviors in urchins that could negatively impact population and community dynamics. Important behaviors such as covering (camouflage) used during the day, Aristotle's lantern reflex (feed intake), and righting behavior may all be negatively affected by elevated seawater temperatures. This may cause urchins to migrate northward (outside of Gray's Reef) seasonally or altogether if temperature tolerances are exceeded. This migratory shift would affect trophic dynamics within GRNMS. Increases in seawater temperature may also cause a shift from a diet currently dominated by invertebrate prey to a more algal-dominated diet for resident urchins. Elevated seawater temperatures will likely reduce efficient use of resources in urchins, reducing their feeding efficiency and reproductive capacity.

Ocean acidification is increasing both globally and locally (Gray's Reef) with a seasonal pH fluctuation from 8.2 to 7.8. Projections are that pH will shift downward (greater acidity) another 0.1 by 2050 (seasonal variation from 7.7 to 8.1). The seasonal low pH is decreasing at a faster rate than the seasonal high. Greater variability between seasonal lows and highs in pH are anticipated. Increasingly acidified seawater with decreased available carbonate material would negatively affect both urchin prey and urchins themselves. Urchin larvae exposed to acidified seawater have reduced growth rates, delayed development, and overall stunted growth. Urchins exposed to increased ocean acidification reduce their mean body size and experience reduction in arm growth and supporting skeletal rods. Decreases in aragonite saturation levels also will lower availability of planktonic food, further impacting urchin foraging.

Recent changes in the severity of storms could impact urchins on Gray's Reef. The annual number of storms has changed little in recent years, hovering at about 10 storms per year. However, there has been an increase in the number of major (category 4/5) storms annually. More intense hurricanes will increase mortality (e.g., cracked open when slammed into rocks) and increase scouring of available habitat and prey species as evidenced by recent storms in 2017 (e.g., Hurricane Irma).

Potential adaptation strategies

Develop a rapid response monitoring and assessment team
As with ivory bush coral, develop a rapid response monitoring and assessment team to assess damages from severe storm events (e.g., document damages from Hurricane Irma). Probably pair this with overlapping long-term monitoring and assessment sites within GRNMS.
Cost: Low
Efficacy: High

Continue ongoing urchin research
Continue ongoing urchin research inside/outside the research-only area. Some of this research should continue to focus on correlations between climate change stressors and urchin population size, habitat use, dietary shifts, and short- and long-term recovery after storm events.
Cost: Low
Efficacy: High

3.2 Reef Species

3.2.1 Black Sea Bass (*Centropristis striata*)

Table 3.4. Influence of climate change on black sea bass from rapid vulnerability assessment scores.

Black Sea Bass	Increased water temperature	Altered Currents	Storm Severity/Frequency
Likelihood	Almost certain	Possible	Likely
Consequence	Major	Moderate	Moderate
Risk	Extreme	Moderate	High
Adaptive Capacity	High	High	High
Vulnerability	Moderate	Low	Moderate

Species overview

The black sea bass (*Centropristis striata*) is a temperate marine species that inhabits irregular hard-bottom areas, such as wrecks or reefs. Its range extends along the U.S. Atlantic coast from Cape Cod to the Florida Keys and in the Gulf of Mexico. Those found in the South Atlantic Bight usually occur inshore with tropical reef fish such as snappers, groupers, porgies, and grunts. They are often found in bays and sounds, and offshore to a depth of around 130 m (430 ft). They tend to avoid the open water column, instead spending a large proportion of time near the sea bed, often gathering around protruding formations such as rocks, artificial reefs, wrecks, pilings, and piers.

These fish are grey to black in color (juveniles may be a dusky brown), with a long dorsal fin transitioning from spiny to soft ray appearance (Fig. 3.4). They can attain a maximum size of 50 cm (20 in) and weight of 4.6 kg (10 lb.). Black sea bass are protogynous hermaphrodites; that is, they change sex with size, all starting out as females. Large individuals are males, and smaller individuals are female, with the transition occurring at a length between 24 and 33 cm (Provost et al. 2017). They spawn once mature, which occurs roughly at a size of around 19 cm (7.5 in.). The spawning season is February

through May in the South Atlantic Bight. Their eggs are buoyant and develop in one to two days. Black sea bass may live up to 20 years, although fish older than nine years are rare. Black sea bass are opportunistic feeders that will generally eat any available food, preferring crabs, shrimp, worms, small fish, and clams.

Black sea bass are a commercially- and recreationally-valued species for fishers, and as such have the potential to be overfished. Quotas, seasons, and

Figure 3.4. Black sea bass (*Centropristis striata*). (Photo: Karsten Shein/NOAA)

management actions are in place for the species in the South Atlantic Bight. According to the South Atlantic Fisheries Management Council[3], for commercial operations there is minimum size limit of 279 mm (11 in.) and a pot fishing prohibition in the vicinity of GRNMS that extends from November 1 to April 30. Recreational fishers may take up to seven fish per person per day, with no closed season and minimum fish length of 330 mm (13 in.). Total annual catch limit is 822,817 kg (1,814,000 lbs.), with a commercial limit of 353,811 kg (780,020 lbs.), and a recreational limit of 469,005 kg (1,033,980 lbs.) across their managed geography.

Vulnerability assessment results

Workshop participants evaluated black sea bass in Gray's Reef to have a low to moderate relative vulnerability to climate change. While the participants estimated major to moderate consequences to climate and non-climate stressors and high likelihood of future climate changes, the final vulnerability score was lowered due to the black sea bass' expected high adaptive capacity.

Workshop participants identified the most significant climate stressors and non-climate stressors on black sea bass population in Gray's Reef. The three most significant climate stressors were increased water temperature, altered currents, and increased storm severity and frequency.

Sea surface temperatures are expected to increase by 0.8 to 1.4°C by 2050. This temperature change may result in a northward distribution shift for black sea bass, and

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[3] Information from: http://safmc.net/regulations/regulations-by-species/black-sea-bass/

thus a corresponding decrease in population at Gray's Reef as water temperature there warms. It may also result in changes in their reproductive season and operational sex ratio (ratio of fertilizable females to sexually mature males) 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 as a result of the increased sea surface temperature. This would include the Florida Current/Gulf Stream, which could potentially shift eastward. Changes in current could affect larval recruitment and, again, create mismatches with available food sources.

Storm severity and frequency is expected to change with fewer but more intense storms; however, it is difficult to estimate what impacts that may have on such a small area as Gray's Reef. 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 frequency of storms may coincidentally reduce the recovery period for black sea bass between major storm events.

The three most significant non-climate stressors were identified as land source pollution, harvest, and altered sediment transport (which could smother preferred habitats). 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 dissolved oxygen, etc.), which could increase mortality of larval and juvenile stages in nearshore brackish and estuarine habitat. At the same time, increased nutrient loads could benefit plankton productivity, which would be beneficial to both juvenile and adult black sea bass depending on the nutrient input and plankton species affected. Land source pollution is likely to increase with more intense storm events due to climate change.

Fishing is limited to recreational captures in GRNMS; however, the overall population is dependent on commercial and recreational fishery management in the region. Current management measures may become less effective with a northward distribution shift resulting in a smaller population in the southern portion of their range. The ecological potential of black sea bass is high, due to its wide distribution, large population, high dispersal potential, early maturation, and generalist feeding nature. The social potential is also high, because it is a valuable fishery with high investment in monitoring and management.

Potential adaptation strategies

Workshop participants identified a number of strategies which if implemented could reduce the vulnerability of black sea bass to climate change. These strategies were as follows.

Promoting awareness: Black sea bass as climate change ambassador
Because GRNMS is at the southern edge of the black sea bass range, the species may not persist in the sanctuary as temperatures warm and the species' range shifts northward. However, this provides an opportunity to use black sea bass as a climate change outreach tool, targeting a sector generally disengaged from discussing the impacts of climate change. Black sea bass is the most popular recreational fishing target species in GRNMS. Successful outreach could alter the public's perception and behavior with respect to CO_2 emissions reduction or other climate stressors, as well as result in higher public engagement (e.g., influence elected officials).
Cost: Low.
Efficacy: Low (it may not prevent a northward shift of black sea bass, but may have long-term beneficial effects by increasing awareness on climate change and mobilizing people to take action).

Reducing threat of lionfish invasion: Trapping lionfish
One of the central roles of a marine reserve is to enhance native biotic resistance to threats such as the climate and non-climate threats outlined above. Invasive lionfish settling within GRNMS is a major potential threat to black sea bass. As the population of black sea bass declines due to increasing temperatures, more invasive lionfish might move into GRNMS to fill the black sea bass ecological niche. The increased presence of lionfish, also opportunistic feeders, could result in black sea bass having increased competition for food sources such as tomtate (Ballew et al. 2016), reducing species carrying capacity, changing size distributions, and even reducing fecundity. If lionfish populations increase substantially in GRNMS, it stands to reason that juvenile/smaller black sea bass would be preyed upon by adult lionfish, further tipping the population numbers in favor of lionfish at the expense of black sea bass. As potential prevention of this, GRNMS could deploy lionfish traps, such as those designed by Gittings et al. (2017), to mitigate a lionfish invasion. Knowing that lionfish are likely to colonize from the deep-water areas offshore from GRNMS, the sanctuary could focus on deploying traps between GRNMS and the deep-water aggregation areas in a few source locations from where lionfish are likely to migrate into GRNMS. While this would not help the decline of black sea bass population due to climate change stressors, it would help maintain biodiversity at GRNMS and not add another stressor (lionfish) that might accelerate black sea bass decline.
Cost: High.
Efficacy: Medium (it may be very effective for GRNMS but of a low spatial scale overall; hopefully, only a few source locations offshore seed GRNMS with lionfish, probably related to inshore current flow).

Reducing threat of lionfish invasion: Encouraging lionfish fishery
Similar to what has been done at Flower Garden Banks National Marine Sanctuary, GRNMS could develop a public outreach to encourage a recreational fishery for lionfish, introducing the concept of lionfish as a good food source. Lionfish can be caught by hook and line, usually by divers and spearfishers. Currently, the number of lionfish in GRNMS

is low but it is likely to grow over time. Initially, GRNMS could suggest adding a lionfish catching contest as part of an existing fishing derby (with a special prize for lionfish catch in addition to the regular derby prizes). The ongoing lionfish derbies in the Florida Keys that were organized initially by the Reef Environmental Education Foundation would provide a good template to start at GRNMS. When lionfish becomes more abundant on GRNMS, a stand-alone lionfish contest could be created.
Cost: Medium.
Efficacy: Medium.

Monitoring for climate change: Using GRNMS as ecological reference point
Using GRNMS as an ecological reference point (ERP) for black sea bass (and other species) would provide a logical, efficient place to monitor the effects of climate change with respect to distributional shift (northward) and arrival of more southern species. By using GRNMS as an ERP, NOAA would capitalize on the presence of the research area to distinguish between the effect of fishing and climate change. This may require an increase in the research area size to more effectively capture influence of fishing vs. climate change impact. Ideally, the research area size should be several times the home range of targeted species. The information gathered as part of this ERP would benefit fisheries management (states, commission, and council) as well.
Cost: High.
Efficacy: High (it may not prevent northward shift of black sea bass but may provide tangible, significant monitoring information about climate change effects on regional species composition).

3.2.2   Tomtate (*Haemulon aurolineatum*)

Table 3.5. Influence of climate change on tomtate based on rapid vulnerability assessment scores.

Tomtate	Increased Water Temperature	Turbidity	Storm Severity/Frequency
Likelihood	Almost certain	Likely	Likely
Consequence	Negligible	Negligible	Minor
Risk	Low	Low	Moderate
Adaptive Capacity	Moderate	Moderate	Moderate
Vulnerability	Low	Low	Moderate

Species overview

The tomtate (*Haemulon aurolineatum*) is a relatively small grunt. This schooling fish is silver-white with a brownish-yellow stripe that runs the length of its body from the eye to a black spot at the base of the caudal fin (Fig. 3.5). The inside of their mouth is bright

red, giving rise to colloquial names of red mouth or blood mouth grunt. Tomtate range from Cape Hatteras to northern Brazil, and are prevalent in southeast U.S. waters. Tomtate spawn in spring, and reach sexual maturity within five years and a mature size between 14 and 16.5 cm (5.5-6.5 in.). They may attain a maximum size of around 30

Figure 3.5. Tomtate (*Haemulon aurolineatum*). (Photo: NOAA)

cm (12 in.) and a weight of 0.5 kg (1.1 lbs.). Tomtate preferred habitats are the rough bottom areas (e.g., reefs and live-bottom such as GRNMS) found along the continental shelf throughout their range. These fish are rarely seen in waters cooler than 12°C (54°F). Tomtate generally feed on bottom-dwelling invertebrates and are in turn an important prey species for many piscivore reef species such as barracuda and king mackerel. Tomtate are not heavily fished and do not regard divers as a threat. Because they are not prized by sport or commercial fisheries, tomtate fisheries are not heavily regulated, with no size or trip/bag limits, but general grunt landings in the South Atlantic (U.S.) are managed under NOAA annual catch limits (ACL).

Vulnerability assessment results

The most likely climate change factors to which workshop participants felt tomtate at GRNMS might be affected were increased water temperature (e.g., SST), increased turbidity, and changes in storm behavior. The occurrence of these climate changes was deemed to be likely to almost certain for GRNMS. Additionally, harvest (i.e., incidental bycatch in non-target fisheries), noise, and altered sediment transport were identified as the primary non-climatic stressors currently affecting tomtate, but the impact of these on tomtate were determined to be ephemeral and largely negligible.

Water temperatures at GRNMS are expected to increase by 0.8 to 1.4°C by 2050. As with other species, this will likely facilitate a northward expansion of the tomtate range. However, because GRNMS is not at the southerly extent of the range, increased water temperature and northerly range extension is unlikely to produce a population decline at GRNMS. It is possible, however, that an earlier warm up in spring may affect spawning times and reduce larval duration. Overall, the effect of warming water on tomtate was considered neutral

The increase in water temperature, coupled with more frequent intense rain events and more intense storm systems, may result in increased sediment load, algal blooms, and turbidity. These changes could potentially reduce visibility, which may benefit a

schooling species such as tomtate, as schooling fish are normally preyed upon by visual predators. The net effect may be a decrease in natural mortality from predation. Conversely, tomtate may have more difficulty foraging for prey given reduced visibility in their environment.

A shift to fewer but more intense storms affecting GRNMS is likely to produce habitat disturbance via physical damage and sediment smothering. These effects may impact tomtate food sources by scouring the sea bed and increasing mortality of their invertebrate food sources.

Tomtate at GRNMS were identified by workshop participants as having moderate adaptive capacity to offset the impacts of climate change. The species is widely distributed, with GRNMS at the northern edge of its range. High genetic diversity is thought likely, given the population size, and tomtate exhibit high phenotypic/behavioral plasticity and are of high value to the ecosystem. However, while their ecological adaptive capacity is high, their social potential is moderate. There is no accepted stock assessment of the species, their socioeconomic value is low, they are not individually managed (all grunt species are managed in aggregate), and there is limited scientific research on the species. These limitations are offset by relatively good monitoring capacity and a proactive conservation management approach by GRNMS staff and stakeholders.

Potential adaptation strategies

Given the relatively low vulnerability of tomtate to climate change, potential adaptation strategies were not discussed during the workshop. However, as part of this RVA, GRNMS has identified tomtate as a species of ecological importance to the habitat. Such an identification promotes monitoring for changes in the species that correspond to changing environmental conditions. At present, GRNMS in conjunction with partners monitors species such as tomtate within its boundaries and has set aside a research area in which public access is prohibited. GRNMS also maintains a strong outreach and educational focus which has the capacity to inform the public and key stakeholders about any observed or forecast changes in tomtate as a result of climate change.

3.2.3   Northern Red Snapper (*Lutjanus campechanus*)

Species overview

The northern red snapper (*Lutjanus campechanus*) is a species of snapper native to the western Atlantic Ocean including the U.S. Atlantic coastal waters and the Gulf of Mexico, where it commonly inhabits reef environments. The northern extent of its range in U.S. waters is currently around Cape Cod, Massachusetts. Red snapper occupy water between nine and 90 m (30 to 300 ft) and favor reefs, rocky bottom, ledges, ridges, wrecks, and other habitats with vertical relief. They often gather in large schools of

Table 3.6. Influence of climate change on red snapper from rapid vulnerability assessment scores.

Red Snapper	Increased water temperature	Altered Currents	Storm Severity/Frequency
Likelihood	Likely	Possible	Almost Certain
Consequence	Moderate	Minor	Moderate
Risk	High	Moderate	High
Adaptive Capacity	Moderate/High	Moderate/High	High
Vulnerability	Moderate	Low	Moderate

relatively uniform-sized individuals. Like black sea bass and other reef-based fish, red snapper normally remain close to the sea bottom.

Northern red snapper are pink to red in color and have a typical snapper profile, with a sloped head, medium-sized scales, and spiny dorsal fin (Fig. 3.6). Unlike other snapper, red snapper have short, needle-like teeth. At maturity, red snapper are around 39 cm (15 in.) total length, and adults commonly attain a size of around 60 cm (24 in.). The maximum recorded size and weight is 1 m (39 in.) and 38 kg (84 lbs.). Red snapper can live many decades, with specimens living beyond 100 years. A northern red snapper attains sexual maturity at two to five years old. However, fecundity is correlated to age and size with larger/older females producing greater numbers of better-quality eggs. The spawning season is April through August in the South Atlantic Bight.

Northern red snapper move to different types of habitats during their growth and development. When they are newly spawned, red snapper settle over large areas of open benthic habitat, often congregating around oyster beds. They gradually move to high-relief reefs such as GRNMS at about two years of age. Red snapper tend to have high site fidelity, only moving about a mile or so from their adult settling location (Szedlmayer and Shipp 1994).

Figure 3.6. Northern red snapper in GRNMS. (Photo: Greg McFall/NOAA)

Northern red snapper are a prized food fish historically and today, caught commercially as well as recreationally. Red snapper is the most commonly caught snapper in the continental U.S. (almost 50 percent of the total catch), with similar species being more common elsewhere.

To address population decline, both recreational and commercial bag limits have been established since the 1980s, with recent years seeing a closure of both commercial and recreational landings for the South Atlantic region. However, short commercial and recreational fishing seasons were reinstated in 2018 (http://safmc.net/regulations/regulations-by-species/red-snapper/). Commercial fishing for snapper in federal waters requires a federal permit. Open seasons in 2019 remain uncertain.

Vulnerability assessment results

Workshop participants evaluated red snapper in Gray's Reef to have moderate relative vulnerability to climate change. According to estimates from the participants, the consequences of climate and non-climate stressors were minor to moderate and the likelihood of future climate changes varied from possible to almost certain, with an overall risk estimated to be moderate to high. The final vulnerability score was influenced by the red snapper moderate to high adaptive capacity.

Workshop participants identified the most significant climate stressors and non-climate stressors on red snapper population in Gray's Reef. The three most significant climate stressors were increased water temperature, altered currents, and increased storm severity and frequency. Sea surface temperatures are expected to increase by 0.8 to 1.4°C by 2050. This temperature change may result in a northward distribution shift for red snapper, with Gray's Reef potentially gaining in population size. It may also result in changes in their reproductive season as well as shorten their larval stage, which could create mismatches with available food sources. Warmer sea surface temperature might result in increased growth rate; however, this species already exhibits rapid growth rate so this is not expected to result in significant changes.

Shifts in direction and intensity of currents are expected, partly as a result of the increased sea surface temperature. This would include the Florida Current/Gulf Stream, which could potentially shift eastward. Changes in current could affect larval recruitment and, again, create mismatches with available food sources.

Storm severity and frequency is expected to change with fewer but more intense storms; however, it is difficult to estimate what impacts that may have on such a small area as Gray's Reef. 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 and coastal discharge and nutrient load near the coast where larval transport occurs. We would also anticipate impacts to red snapper prey and prey habitat from increasingly intensified storms that could indirectly impact red snapper populations within GRNMS.

The three most significant non-climate stressors were identified as harvest, invasive species, and altered sediment transport (which could smother preferred habitats). Harvest is limited to recreational fishing in GRNMS; however, the overall population is

dependent on commercial and recreational fishery management in the region. Fishing pressure may increase with an increasing population size due to warmer waters moving north; however, it is unclear whether the fishery management would be precise enough to avoid overfishing. Without intervention, the invasive species red lionfish (*Pterois volitans*) is likely to become more established at Gray's Reef with increasing water temperatures, and they are excellent competitors with red snapper, which may have negative effects on the red snapper population. Lionfish have high reproductive rates, low parasite load, defensive venomous spines, and are habitat generalists and efficient predators. These factors all make red lionfish a dangerously well-suited competitor to red snapper should they establish themselves on Gray's Reef.

Although red snapper experienced overfishing in the second half of the 20th century, its ecological potential is high due to its wide distribution, large population, high dispersal potential, early maturation, and generalist nature. The social potential is moderate. Even though red snapper is a highly managed fish species, there is a lack of information on climate impacts to red snapper and the current management framework is not yet suited to monitor those impacts.

Potential adaptation strategies

Reducing threat of lionfish invasion: Trapping lionfish
As movement of invasive lionfish into GRNMS is likely enhanced due to increasing water temperature, lionfish are likely to outcompete red snapper and to fill the ecological niche red snapper currently occupy, resulting in a declining population of red snapper. GRNMS could deploy lionfish traps (e.g., Gittings et al. 2017) to mitigate lionfish invasion. Knowing lionfish are likely to colonize from the deep-water areas offshore GRNMS, the sanctuary could focus on deploying traps between GRNMS and deeper water. This would help prevent the displacement of red snapper population and maintain biodiversity at GRNMS.
Cost: High.
Efficacy: Medium. It may be very effective for GRNMS (local extirpation with sustained efforts) but of a low spatial scale overall.

Reducing threat of lionfish invasion: Encouraging lionfish fishery
Similar to what has been done at Flower Garden Banks and Florida Keys national marine sanctuaries, GRNMS could develop a public outreach to encourage a recreational fishery for lionfish, introducing the concept of lionfish as a good food source. Currently, the number of lionfish in GRNMS is low but is expected to grow. Some possibilities to involve fishers in lionfish extirpation may include sponsoring lionfish derbies in adjacent waters, or holding controlled culls within the sanctuary (excluding the research area). Such methods, initiated in tandem with offshore fishing traps, may provide an effective one-two punch to hold lionfish in check in GRNMS.
Cost: Medium.
Efficacy: Medium.

Monitoring for climate change: Using GRNMS as an ecological reference point
Using GRNMS as an ecological reference point (ERP) for red snapper (and other species)
would provide a logical, efficient way to monitor the effect of climate change with
respect to distributional shift (northward) and arrival of more southern species. By using
GRNMS as an ERP, NOAA would capitalize on the presence of the research area to
distinguish between the effect of fishing and climate change. This may require an
increase in the research area size to more effectively capture the influence of fishing vs.
climate change impact, especially as red snapper biomass appears higher outside the
current research area due to the greater abundance of tall ledges outside the research area
(R. Muñoz, SEFSC, pers. comm.). Ideally, the research area size should be several times
the home range of targeted species. The information gathered as part of this ERP would
benefit fisheries management (states, commission, and council) as well.
Cost: High.
Efficacy: High (it may not prevent effects of a changing climate but may provide
tangible, significant monitoring information about climate change effects on regional
species composition).

3.3   Pelagic Species

3.3.1   King Mackerel (*Scomberomorus cavalla*)

Table 3.7. Influence of climate change on king mackerel based on rapid vulnerability assessment scores.

King Mackerel	Increased Water Temperature	Altered Currents	Altered Upwelling/Mixing
Likelihood	Almost Certain	Likely	Likely
Consequence	Major	Minimum	Minimum
Risk	Extreme	Moderate	Moderate
Adaptive Capacity	High	High	High
Vulnerability	Moderate	Low	Low

Species overview

The king mackerel (Fig. 3.7) is a fast-swimming piscivore. It is found in both the
nearshore and offshore waters throughout its range in the Western Atlantic, from Canada
down through South America, including the Caribbean Sea and Gulf of Mexico. King
mackerel prefer water temperatures above 20°C (68°F) and migrate to warmer waters in
the fall of the year. They are oceanadromous, often found on outer reef areas. Their depth
range is between five to 140 m (~16 to 460 ft) deep but they are most often found
between five to 15 m (~16 to 50 ft) depth. They primarily feed on schooling bait fish

Figure 3.7. King mackerel (*Scomberomorus cavalla*). (Photo: Stephen Ewen)

(e.g., round scad, also found on Gray's Reef, see section 3.3.2), penaeid shrimp, and squid (Saloman and Naughton 1983). Large schools of king mackerel have been documented to migrate over great distances along the Atlantic U.S. coast and they are mostly limited by cooler water temperatures (Sutherland and Fable 1980).

King mackerel are highly sought after as game fish. There are regulated commercial and recreational fisheries for king mackerel in addition to artisanal fisheries throughout their range. Common length is about 70 cm (28 in) and their maximum lifespan is reported to be approximately 13 years (Beaumariage 1973). In the southeastern U.S., king mackerel spawn spring through summer. Approximately 50 percent of both males and females mature at about two years. The species is currently not over-exploited and is managed as two separate stocks, the Western Atlantic stock and the Gulf of Mexico stock, which mix in winter off south Florida.

Vulnerability assessment results

The three most likely climate change factors by which workshop participants felt king mackerel at GRNMS might be affected were increased water temperature, altered currents, and altered upwelling/mixing. The most impactful non-climate stressors identified were harvesting (commercial and recreational), aquaculture, and underwater/overwater structures.

Water temperatures at GRNMS are expected to increase by 0.8 to 1.4°C by 2050. This increasing water temperature may coerce king mackerel into a northerly range extension but it is questionable whether this shift would mean a commensurate decline within GRNMS. It may however, affect the timing of occurrence of king mackerel within and near GRNMS, which could have economic repercussions for the region (e.g., fishing tournaments). Regional increases in water temperature may also incline congener species such as Spanish mackerel (*Scomberomorus maculatus*) to move into the region with unknown ecological and economic ramifications.

Similarly, altered currents resulting from projected changes in the eddies shed from the Gulf Stream could change king mackerel seasonal distribution and stock mixing. These shifts in aggregations of king mackerel may also impact spawning and occurrence of eggs/larvae and cause trophic level shifts.

Altered upwelling/mixing may result from prevailing wind changes, changes to the Bermuda High, wave period, and changes in eddies/currents. Some changes in upwelling/mixing could benefit prey such as round scad, creating more food for them in addition to benefiting larval stages of king mackerel. Overall for all climate change stressors identified, these are anticipated to possibly change the seasonal distribution and abundance of king mackerel within GRNMS but mackerel have a low to moderate vulnerability to these stressors and a high adaptive capacity.

Potential adaptation strategies

The three adaptive management strategies for king mackerel and round scad (see Sec. 3.3.2) are identical.

Develop a regional response network
Develop a regional response network that will respond to climate stressors impacting king mackerel. This strategy carries over for all pelagic species assessed and the idea is to work with the South Atlantic Fishery Management Council (SAFMC) to adjust management strategies for fully protected MPAs that recognize the relationship between pelagic and benthic species based on research from GRNMS. This would establish a network of MPAs across the southeast U.S. that builds resilience to climate change.
Cost: Low
Efficacy: Moderate

Develop a rapid response monitoring and assessment team
Develop a rapid response monitoring and assessment team to assess damages from severe storm events (e.g., document damages from Hurricane Irma). This should be paired with overlapping long-term monitoring sites within GRNMS.
Cost: Low
Efficacy: High

Identify source areas for lionfish
Lionfish recruitment and localized control is an active area of research throughout the Southeast U.S. and Caribbean, and GRNMS has habitat topography conducive to explosive proliferation of the species if not addressed. This strategy would identify source areas for red lionfish recruitment onto Gray's Reef and develop collaborations to extirpate lionfish at these source areas. GRNMS could develop a strategic plan that fosters collaboration among diving groups, harvesters, and universities. Tying lionfish harvesting into active research could enhance results. If lionfish source areas are diver/trap accessible (e.g., manageable depths and distance from shore), this strategy could help in other lionfish hotspot areas (e.g., Florida Keys National Marine Sanctuary). Consider pathways for any scientific harvesting to provide harvested lionfish samples to NOAA and other agencies/universities conducting studies on this invasive species.
Cost: Moderate
Efficacy: High

3.3.2 Round Scad (*Decapterus punctatus*)

Table 3.8. Influence of climate change on round scad based on rapid vulnerability assessment scores.

Round Scad	Ocean Acidification	Altered Upwelling/Mixing	Storm Severity/Frequency
Likelihood	Likely	Possible	Possible
Consequence	Moderate	Negligible	Moderate
Risk	High	Low	Moderate
Adaptive Capacity	High	High	High
Vulnerability	Moderate	Low	Low

Species overview

The round scad (Fig. 3.8) is a shoaling fish species inhabiting neritic waters, often near sandy bottom. The Western Atlantic population ranges from Nova Scotia southward through the Gulf of Mexico and Caribbean to Brazil. The maximum length for this species is about 30 cm (12 in) total

Figure 3.8. Round scad (*Decapterus punctatus*). (Photo: NOAA)

length but typically adults usually reach about 18 cm (7 in) length. They are a macrofauna predator, feeding primarily on planktonic invertebrates, usually copepods, but also on gastropod larvae, pteropods, and ostracods. They are resilient with a high population doubling time of 15 months. Round scad are generalists, feeding in the water column. They are fished heavily in Georgia, mostly as a bait fish, and there is not a managed fishery for them.

Vulnerability assessment results

The most likely climate change factors to which workshop participants felt round scad at GRNMS might be affected were ocean acidification, altered upwelling/mixing, and changes in storm severity/frequency. The workshop participants decided these climate change stressors were possible to likely to occur within GRNMS. Additionally, invasive

species (e.g., red lionfish), altered sediment transport, and harvesting were identified as the most likely and important non-climate stressors to adversely affect round scad.

Ocean acidification has the potential to decrease pH to 7.8 over the timeframe assessed. Ocean acidification will impact invertebrate communities on which round scad feed, but which invertebrate prey species will be most affected remains unknown. It is anticipated that structural invertebrates (benthic ledge invertebrate species in particular) as well as copepods will be adversely impacted, disrupting round scad foraging patterns and maybe precluding them from feeding inside GRNMS if threshold pH levels are exceeded for key prey species. Vulnerability was assessed at moderate for the ocean acidification threat because of the impacts to scad invertebrate prey.

Altered upwelling/mixing was identified as an important climate-influenced risk to scad although there are not a lot of data to anticipate the magnitude and type of changes in store. Wind force, flow, changes in the Bermuda High, and wave period/intensity all will influence upwelling/mixing over GRNMS. Changes in upwelling could impact prey distribution, reproductive capacity, and temperature thresholds of both scad and its prey species. Seawater temperatures above 15°C (59°F) could impact spawning. However, round scad are believed to use GRNMS primarily for foraging so impacts to prey distribution may be the greatest threat from changes in upwelling/mixing. Overall, the pelagic group assessed the vulnerability to scad as low from upwelling/mixing because they could forage elsewhere following changes in prey distribution and abundance.

Storm severity/frequency was also assessed as an important climate stressor that could impact round scad. There is considerable uncertainty in predictive models for this threat, although any changes in storm intensity and frequency are bound to impact prey distribution of invertebrate species that inhabit both the benthos and water column. More severe storms are already occurring in the region and as they continue these storms may impact CO_2 concentrations, pulling CO_2 from the sediment with lower pH. More intense storms may scour the available hardbottom ledge habitat and inundate other areas with sediment – both of which would impact scad prey abundance and distribution. The group found that scad have a low vulnerability to this threat because their foraging habits are flexible and presumably they would move to other areas where prey are abundant during recovery periods after storm events. The duration and frequency of storms over time may lead to long-term impacts on prey availability.

Potential adaptation strategies

Overall, vulnerability of round scad to climate change was deemed low to moderate. Three adaptation strategies were discussed, which are identical to those identified for king mackerel (see sec. 3.3.1).

Develop a regional response network that will respond to climate stressors
Develop a regional response network that will respond to climate stressors affecting GRNMS. This strategy carries over for all pelagic species assessed. The idea is to influence the SAFMC to alter management strategies for fully protected MPAs that recognize the relationship between pelagic and benthic species based on research from GRNMS. This would establish a network of MPAs across the southeast U.S. that builds resilience to climate change.
Cost: Low
Efficacy: Moderate

Develop a rapid response monitoring and assessment team
Develop a rapid response monitoring and assessment team to assess damages from severe storm events (e.g., document damages from Hurricane Irma). Probably pair this with overlapping long-term monitoring and assessment sites within GRNMS.
Cost: Low
Efficacy: High

Identify source areas for lionfish
Round scad have been identified as a prey species of red lionfish, *P. volitans* (Peake et al. 2018; Dahl and Patterson 2014). Thus, a strategy could be to identify source areas for lionfish that are recruiting onto Gray's Reef and develop collaborations to extirpate lionfish at these source areas before they can recruit into GRNMS. Develop a strategic plan that fosters collaboration among different diving groups, harvesters, universities. Best would be to tie the lionfish harvesting into active research on this invasive species. If the lionfish source areas are diver/trap accessible (i.e., suitable depths, distance from shore), this extirpation method could help in other lionfish hotspot areas (e.g., Florida Keys National Marine Sanctuary).
Cost: Moderate
Efficacy: High

3.3.3   Southern Stingray (*Dasyatis americana*)

Table 3.9. Influence of climate change on southern stingray based on rapid vulnerability assessment scores.

Southern Stingray	Diminished Dissolved Oxygen	Ocean Acidification
Likelihood	Unlikely	Possible
Consequence	Minimum	Moderate
Risk	Low	Moderate
Adaptive Capacity	High	High
Vulnerability	Low	Low

Species overview

The southern stingray (Fig. 3.9) is a coastal marine and estuarine species with a wide distribution in the Western Atlantic from New Jersey south through the Gulf of Mexico and into the Caribbean Sea south to Brazil. It is a commonly sighted species in GRNMS, although the species has declined throughout its range mostly due to bycatch in various commercial fisheries. There are targeted fisheries in some countries (e.g., Brazil, Venezuela) but none in the United States. The species is listed as threatened on the IUCN Red List (worldwide distribution) and also as a species of concern for NOAA/NMFS; however, populations in the U.S. are generally abundant (e.g., west coast of Florida in Gulf of Mexico, coastal areas along the southeastern U.S.). Southern stingrays are most often associated with sand flats, seagrass beds, and coral reefs, at depths from 0 to 53 m (0 to 174 ft). Their diet consists of benthic and infaunal invertebrates and demersal teleosts. Common prey are decapod crustaceans such as alphaeid, penaeid and calliansid shrimp and brachyuran crabs. Southern stingrays usually bury themselves partially in the sand during the day and forage at night. They feed by creating depressions in the sand, exposing invertebrates and small fishes. Southern stingrays are ovoviviparous and after a gestation period of four to five months, they typically have three to four pups per litter.

Figure 3.9. Southern stingray (*Hypanus americanus*). (Photo: Karsten Shein/NOAA)

Vulnerability assessment results

The most likely climate change factors to which workshop participants felt southern stingray at GRNMS might be affected were diminished dissolved oxygen and ocean acidification. We discussed that only these two climate threats warranted consideration given the offshore location of GRNMS location and the life history and habitat use of this species. The consensus of the group discussion was that rising seawater temperature would not be a concern for the southern stingray given the projected increase in temperature from 0.8 to 1.4°C by 2050 and the thermal tolerance of this species. Similarly, with non-climate stressors, the workgroup identified just development/population growth (impacts to estuarine habitat) as a potential non-climate stressor for the species. Invasive species (i.e., red lionfish) and electric fields (e.g., underwater telecommunications cabling) were discussed but not a significant threat to

consider further. Harvest as indirect bycatch in fisheries may be regionally relevant but the group felt this threat was not specific to Gray's Reef.

As seawater temperatures rise, dissolved oxygen levels may drop appreciably that in turn may change the abundance and distribution of invertebrate prey for the southern stingray. Lower available dissolved oxygen at or near to the benthos, while unlikely to reach biologically harmful levels as it has elsewhere (e.g., northern Gulf of Mexico), will likely reduce the abundance and possibly also the diversity of prey species available to southern stingrays inside GRNMS. Depending on levels of dissolved oxygen, rays may not be able to tolerate bottom habitat and would move to more amenable areas with higher dissolved oxygen levels for foraging/resting/pupping.

Ocean acidification has the potential to decrease pH to 7.8 over the timeframe assessed. Ocean acidification will impact the benthic invertebrate community that the southern stingray, a benthic forager, feeds upon, in the extreme case causing trophic cascades. It is anticipated that structural invertebrates (benthic ledge invertebrates but also borrowing and motile invertebrates in sandy areas) will be adversely impacted by ocean acidification, disrupting southern stingray foraging patterns and maybe precluding them from feeding inside GRNMS if threshold pH levels are exceeded for key prey species. Vulnerability was assessed as low for both ocean acidification and diminished dissolved oxygen, largely because of the adaptive capacity of southern stingrays to move into areas less impacted by climate change stressors.

Potential adaptation strategies

Overall, vulnerability of southern stingrays to climate change was deemed low because they are common throughout Gray's Reef and the region, they have a wide-variety of prey selection (opportunistic generalists), and GRNMS provides ample suitable habitat to this species. Some adaptation strategies were discussed, but ultimately, only one was selected as feasible from a cost/efficacy standpoint.

Increase monitoring of dissolved oxygen levels within GRNMS
The adaptation strategy advanced by the workshop was to increase monitoring of dissolved oxygen levels within GRNMS and assess the effects of diminished dissolved oxygen levels on benthic prey species for southern stingrays. The same should be done for increased pH levels within GRNMS. Monitor pH levels and look for shifts in benthic prey communities in terms of abundance and species richness. Perhaps sediment core sampling could be added to existing monitoring/sampling regimes in and out of the research-only area.
Cost: Moderate
Efficacy: High

3.3.4 Loggerhead Sea Turtle (*Caretta caretta*) [Northwest Atlantic (NWA) Distinct Population Segment (DPS)]

Table 3.10. Influence of climate change on NWA DPS loggerhead sea turtles based on rapid vulnerability assessment scores (not conducted during workshop).

NWA DPS Loggerhead Sea Turtle	Storm Severity/Frequency	Ocean Acidification	Diminished Dissolved Oxygen
Likelihood	Likely	Almost Certain	Likely
Consequence	Major	Catastrophic	Catastrophic
Risk	High	Extreme	Extreme
Adaptive Capacity	High	High	High
Vulnerability	Moderate	Moderate	Moderate

Species overview

The loggerhead sea turtle (Fig. 3.10) is one of seven extant sea turtle species in the world and was listed as threatened under the Endangered Species Act (ESA) throughout its global range in 1978. NOAA Fisheries and the U.S. Fish and Wildlife Service (USFWS) published a final rule designating nine DPSs for loggerhead sea turtles on September 22, 2011. Critical Habitat under the ESA was established for the NWA DPS of loggerheads in August 2014 for marine areas. Specific areas for designation include 38 occupied marine areas within the range of the Northwest Atlantic Ocean DPS. These areas contain one or more of the following habitat types: nearshore reproductive habitat, winter area, breeding areas, constricted migratory corridors,

Figure 3.10. Loggerhead sea turtle (*Caretta caretta*). (Photo: NOAA)

and/or *Sargassum* habitat. USFWS issued a final rule for critical habitat for terrestrial areas (nesting beaches) separately from NOAA Fisheries designation.

The NWA DPS of loggerhead sea turtles is the DPS that associates with Gray's Reef National Marine Sanctuary. Loggerheads are large sea turtles with relatively large heads, which support powerful jaws that enable them to feed on hard-shelled prey such as whelks and conch. Adults in the southeastern United States average about 3 feet (92 cm) long, measured as a straight carapace length, and weigh approximately 255 pounds (116 kilograms). Within the NWA DPS, most loggerhead sea turtles nest from North Carolina to Florida and along the Gulf Coast of Florida. The majority of loggerhead nesting in the southeastern U.S. (~80 percent) occurs in six Florida counties. The Archie Carr National Wildlife Refuge in Brevard and Indian River counties accounts for about 25 percent of all loggerhead nesting in the United States. Loggerheads are long-lived animals. They reach sexual maturity between 20 and 38 years of age, although age at maturity varies widely among populations.

The annual mating season occurs from late March to early June, and female turtles lay eggs throughout the summer months. Females deposit an average of 4.1 nests within a nesting season, but an individual female only nests every 3.7 years on average. Each nest contains an average of 100 to 126 eggs which incubate for 42 to 75 days before hatching. Loggerhead hatchlings are 1.5 to 2.0 inches long and weigh about 0.7 ounces (20 grams). As post-hatchlings, loggerheads hatched on U.S. beaches enter the "oceanic juvenile" life stage, migrating offshore and becoming associated with *Sargassum* habitats, driftlines, and other convergence zones. The Northwest Atlantic Loggerhead Recovery Team defined the following eight life stages for the loggerhead life cycle, which include the ecosystems those stages generally use: (1) egg (terrestrial zone), (2) hatchling stage (terrestrial zone), (3) hatchling swim frenzy and transitional stage (neritic zone[4]), (4) juvenile stage (oceanic zone), (5) juvenile stage (neritic zone), (6) adult stage (oceanic zone), (7) adult stage (neritic zone), and (8) nesting female (terrestrial zone). It is primarily in the adult stage (neritic zone) that loggerheads inhabit Gray's Reef NMS.

Adult loggerheads forage on a wide variety of invertebrate species including bryozoans, crabs, urchins, and other sessile and motile organisms. Within Gray's Reef, loggerheads primarily forage and take refuge on and near the limestone ledges. This preferred habitat makes up less than 5 percent of the overall habitat within the sanctuary.

Vulnerability assessment results

The workshop participants did not complete a vulnerability assessment for loggerheads, but rather, it was agreed upon by participants that an RVA was needed for this species and the RVA was completed directly after the workshop by Joe Cavanaugh. Cavanaugh

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[4] Neritic refers to the nearshore marine environment from the surface to the sea floor where water depths do not exceed 200 meters.

used the information about Gray's Reef ecology, climatology, staffing capacity, partnerships, etc., in consultation with sea turtle experts Mark Dodd (Georgia DNR), Dennis Klemm (NOAA Fisheries) and others to assess potential impacts to loggerheads at Gray's Reef from projected climate and non-climate stressors.

Loggerhead sea turtles (NWA DPS) have a moderate relative vulnerability to climate change considering their marine life history stages apart from nesting/hatching stages (e.g., beach/sand temperature/moisture affecting sex ratio of hatchlings in nests leading to bias in females; Sifuentes-Romero et al. 2017). Although generally quite vulnerable to climate change impacts, regionally in Gray's Reef loggerheads are less vulnerable given their use of Gray's Reef as foraging adults. Climate change stressors will likely have a greater impact on nesting habitat, for instance, than on the offshore sanctuary.

Loggerhead vulnerability is still moderate because of projected adverse impacts to loggerhead prey within the sanctuary. It is likely that both prey abundance and species richness will be adversely impacted by climate change stressors. The most significant climate stressors affecting loggerhead sea turtles are: (1) storm severity/frequency; (2) ocean acidification; and, (3) diminished dissolved oxygen – all three of which are anticipated to adversely impact the invertebrate prey community that attracts loggerheads into the sanctuary, especially around the ledge habitat that provides preferable foraging and resting habitat for loggerheads.

Increased storm intensity/frequency may impact loggerhead prey (e.g., urchins, bryozoans, crabs, etc.) in both the short-term (acute events) and long-term (sedimentation, scouring) of important invertebrate habitat. Shifts in prey distribution and abundance may reduce loggerhead use of habitat within Gray's Reef, making them seek alternative, possibly lesser-quality foraging and resting habitat outside of the sanctuary. These shifts in foraging patterns may reduce loggerhead fitness, forcing them to expend more energy foraging in lesser-quality habitat than exists presently in Gray's Reef. This also may reduce their reproductive fitness.

Diminished dissolved oxygen levels in GRNMS are anticipated over the next 50-year period. As dissolved oxygen levels are reduced seasonally and possibly year-round in GRNMS, monitoring of the benthic invertebrate community may reveal changes in distribution and abundance that would in turn impact loggerhead foraging. The ledge habitat within Gray's Reef currently provides good quality foraging habitat in addition to important vertical relief habitat (< 5 percent of Gray's Reef habitat) where loggerheads prefer to rest.

Increased ocean acidification is also anticipated at Gray's Reef and would be expected to adversely impact the benthic invertebrate community on the ledges on which loggerhead sea turtles depend. Increased ocean acidification will impact some species at first more than others, but as thresholds for different species are exceeded, there will likely be wholesale community shifts in the communities occupying the more vulnerable ledge

habitat possibly leading to trophic cascades and the disappearance of some important prey species within Gray's Reef.

Potential Adaptation Strategies

Rapid response team to assess storm damage
Develop a rapid response team to assess damage to benthic habitat both in terms of sand deposition and damaged benthic community in and around ledges where not just loggerheads but most of the important biomass is concentrated. Focus on post-storm assessments as soon after the events as possible. Compare results to baseline monitoring (transects, roving diver, belt transects – whatever methodologies best suited to those ledge habitats), and link to broader loggerhead habitat monitoring and assessment efforts where available. Also assess changes in salinity, temperature, and dissolved oxygen after storm events to compare with baseline data. Near to real-time damage assessments on Gray's Reef could be correlated to storm intensity, track, seasonality, etc. These data would help management prepare long-term strategic planning and aid species/habitat vulnerability reassessments. This strategy would help sanctuary managers secure funding targeted to protect species most at risk from climate change impacts. And based on RVAs, GRNMS could target funding to those most vulnerable species that also have the highest adaptive capacities.
Cost: Moderate to High.
Efficacy: High.

Climate and loggerhead prey monitoring
Establish long-term (e.g., 50 years) monitoring of climate variables (abiotic factors such as salinity, temperature, dissolved oxygen, beyond existing NOAA buoy data) and loggerhead prey species affected (benthic invertebrates). This strategy would also include the addition of a sea turtle expert to the GRNMS Sanctuary Advisory Council. Also, this strategy would add sea turtles to any fish assemblage/invertebrate monitoring plans (if not already included).
Cost: Moderate.
Efficacy: High.

3.3.5 Atlantic Sturgeon (*Acipenser oxyrhynchus oxyrhynchus*)

Table 3.11. Influence of climate change on Atlantic sturgeon based on rapid vulnerability assessment scores (not conducted during workshop).

Atlantic Sturgeon	Diminished Dissolved Oxygen	Altered Precipitation Patterns	Storm Severity/Frequency
Likelihood	Almost Certain	Almost Certain	Likely
Consequence	Catastrophic	Major	Major
Risk	Extreme	High	High
Adaptive Capacity	Moderate	Moderate	Moderate
Vulnerability	High	Moderate	Moderate

The Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) is an anadromous species (spawns in freshwater in spring/early summer, then migrates into estuarine/marine habitats where it spends the majority of its life). Atlantic sturgeon attain lengths up to 14 feet (425 cm) and weights up to 800 lbs. (363 kg). They are bluish black or olive brown dorsally with paler sides and a white ventral surface, and have five major rows of dermal scutes (Fig. 3.11). They are long-lived (60 years) and age at maturation shows latitudinal variation with faster growth and earlier age at maturation in more southern systems, probably around five to 19 years of age in Georgia. Regional upriver spawning begins in February or March in Georgia. Atlantic sturgeon do not spawn every year. Instead, spawning intervals range from one to five years for males and two to five years for females. Fecundity of Atlantic sturgeon is correlated with age and body size (ranging from 400,000 to 8 million eggs). Females typically exit rivers within four to six weeks after spawning, whereas males may remain in rivers/low estuaries until the fall.

The species range is along the Atlantic coast of the U.S. from Maine to northern Florida (Fig. 3.12), with the nearest spawning site to GRNMS being the Altamaha River. Historically, Atlantic sturgeon were harvested in the Altamaha River in a commercial

Figure 3.11. Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*). (Photo: USFWS)

fishery until 1997, when it was closed due to severe overfishing. Recent genetic analysis showed that the Altamaha River population is distinct from neighboring populations in Ogeechee and Savannah rivers. Overall, genetic diversity for species is surprisingly low. There are only two rivers with enough Atlantic sturgeon for population size estimates, the Altamaha and Hudson Rivers. There are five Distinct Population Segments (DPSs) of Atlantic sturgeon, all of which are designated either as threatened or endangered under the Endangered Species Act: the Chesapeake Bay, New York Bight, Carolina, South Atlantic, and Gulf of Maine populations. All five DPSs are currently utilizing GRNMS. Species recovery time is estimated to require the next 40 years at least. Currently the species is in the early stages of recovery after 10+ years of federal protection. In Georgia, Atlantic sturgeon has a skewed young-age structure (oldest 17 years old from recent 2011 study) from previous overharvesting.

Demographic and genetic diversity concerns led to their listing under the Endangered Species Act in 2012 and then designation of critical habitat in 2016. Many of the major rivers in Georgia are listed as critical habitat for the species that include the Savannah, Ogeechee, and Altamaha rivers. The Altamaha River is nearest to Gray's Reef and is listed as critical habitat for the South Atlantic DPS of Atlantic sturgeon (Figs. 3.12 and 3.13).

Atlantic sturgeon utilize GRNMS for foraging (adults) and nearshore estuarine and river habitats for migration, spawning, and juvenile development. The Altamaha River is the nearest spawning site to GRNMS for this species (~ 21 mi from SW corner of the sanctuary). Atlantic sturgeon foraging on GRNMS are primarily consuming benthic invertebrates in the sand and mud with their protrusible mouths, suctioning benthic prey such as amphipods, polychaetes, and mussels and shrimp off the substrate.
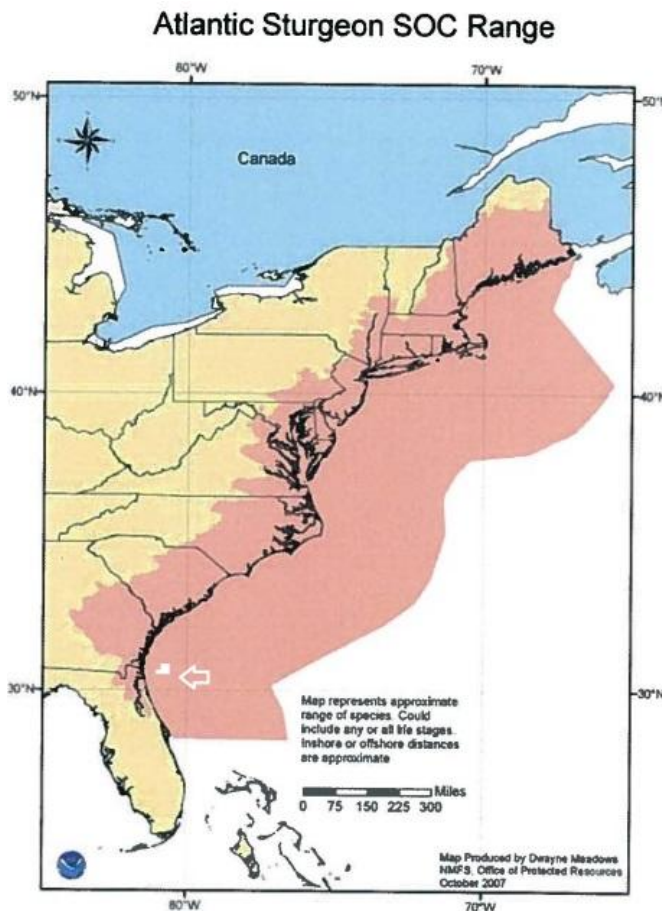
Figure 3.12. Image showing Atlantic Sturgeon range and approximate location of Gray's Reef (white arrow). (Image: Rich and Tursi, 2012)
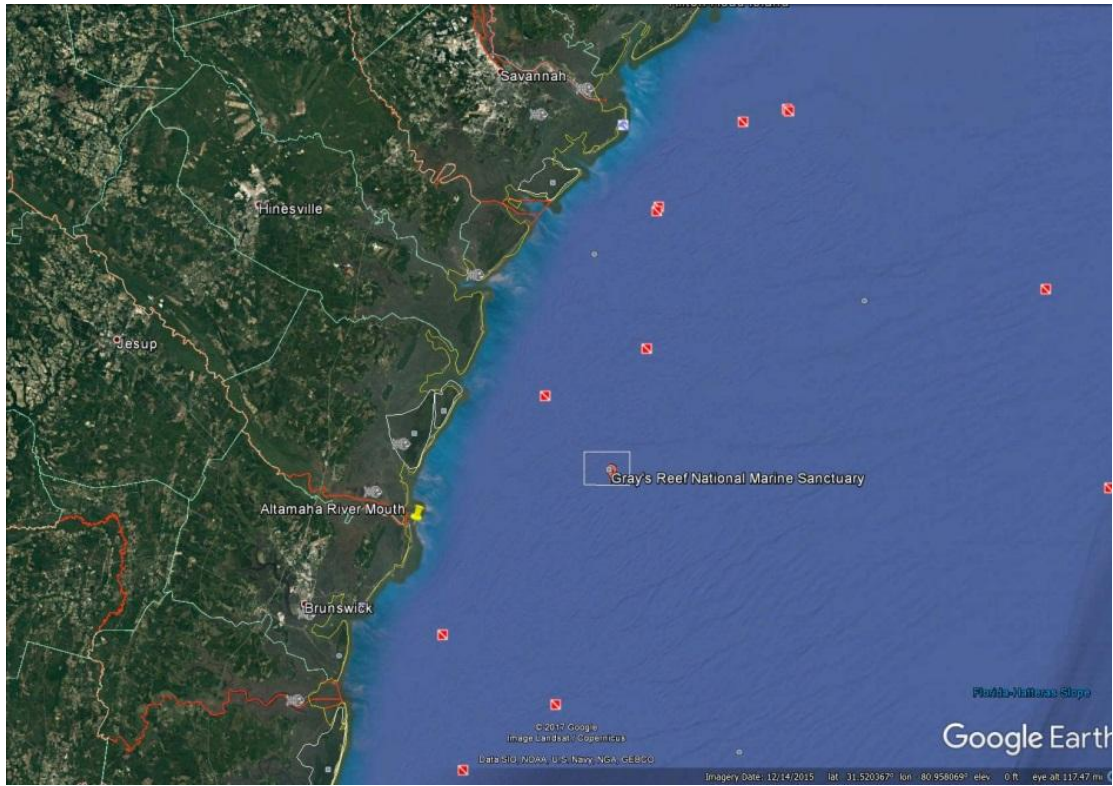
Figure 3.13. Gray's Reef in relation to Atlantic Sturgeon critical habitat (rivers in red). Yellow pin identifies the mouth of the Altamaha River. (Source: 2017 Google)

The species faces numerous threats, including habitat destruction/alteration, harvesting (direct fisheries until the 1990s), and indirect bycatch in current fisheries targeting other species. There is also concern over non-indigenous pathogens being introduced from aquaculture. Furthermore, water flow, river/seawater temperature, dissolved oxygen, salinity, hard-bottom substrate (necessary for eggs to stick), and pollutant concentrations are all important factors in successful spawning and larval development. NOAA Fisheries estimates that Atlantic sturgeon are present in 35 rivers ranging from St. Croix, Maine, to the Saint Johns River, Florida, but are spawning in only about 20 of these rivers.

For purposes of this RVA, our action area is Gray's Reef and the nearby rivers such as the Altamaha and Savannah rivers. Climate and non-climate stressors that impact the nearby rivers and estuaries will also influence sturgeon use of Gray's Reef. For instance, a climate stressor (e.g., altered precipitation patterns) may have more of an adverse impact on sturgeon in the nearby Altamaha River where spawning occurs than on Gray's Reef because of elevated risk to successful spawning. A non-climate stressor such as land-source nutrient and non-nutrient pollution would also likely impact sturgeon in the Altamaha River more heavily than offshore at Gray's Reef because the pollution would

impact a more vulnerable life-stage in-river (spawning females and progeny) than offshore (foraging adults).

Vulnerability assessment results

The workshop participants did not complete a vulnerability assessment for Atlantic sturgeon, but rather, participants agreed that an RVA was needed for this species and the RVA was completed directly after the workshop. Workshop participant Joe Cavanaugh led this assessment, using information about Gray's Reef ecology, climatology, staffing capacity, and partnerships that were identified during the workshop. Consulting on this assessment were Atlantic sturgeon experts such as Andrew Herndon, NOAA Fisheries Atlantic Sturgeon Coordinator, and others to assess potential impacts to Atlantic sturgeon on Gray's Reef and nearshore habitat including spawning rivers from projected climate and non-climate stressors.

Atlantic sturgeon has a moderate to high relative vulnerability to climate change. Their vulnerability is elevated due to life history stages spent in estuaries and rivers where the identified climate and non-climate stressors will be magnified in both relative scale to those habitats and because rivers in particular are weighted more heavily in terms of habitat usage for sturgeon than Gray's Reef habitat. In other words, stressors that adversely affect rivers will affect vulnerable life history phases of sturgeon that occur while they occupy those rivers (e.g. spawning adults, egg, embryo, and young-of-the-year survival) more than life stages spent as adults on Gray's Reef (foraging habitat). However, GRNMS staff will presumably also have less direct influence over decision making for those most vulnerable areas outside of the sanctuary borders. Yet there are opportunities for GRNMS staff to become more involved in coastal management decision making – especially given the identified interconnectivity for sturgeon between nearby river and nearshore coastal habitats and Gray's Reef.

The most significant climate stressors and non-climate stressors on Atlantic sturgeon population in Gray's Reef were assessed. The three most significant climate stressors were diminished dissolved oxygen, altered precipitation patterns, and storm severity and frequency. A fourth climate stressor, salinity, was also assessed because salinity is such an important factor in the diadromous life cycle of the species, outside of Gray's Reef in the estuaries and rivers where they spawn and early embryonic and juvenile survival depends. The non-climate stressors assessed were land-source nutrient and non-nutrient pollution, harvesting (bycatch in fisheries), and dredging.

Although non-climate stressors are not addressed in this summary, dredging bears mentioning. The Savannah Harbor Expansion Project began in 2017 and this dredging project is impacting Atlantic sturgeon that may visit Gray's Reef. This project to date (NOAA Fisheries Incidental Take Data) has relocated 120 live sturgeon through relocation trawls as of January 10, 2018, and killed six to eight sturgeon between the project's four hopper dredges in service. One live sturgeon was also found on a hopper

dredge in December 2017. The captures in this project to date indicate that this estuary is being heavily used by Atlantic sturgeon because they are aggregating seasonally possibly in higher numbers than previously anticipated. Projects like this may have a more immediate impact than climate change stressors on sturgeon use of Gray's Reef by possibly disrupting reproductive behaviors leading to diminished returns of adults foraging on Gray's Reef.

Very low dissolved oxygen levels may impact sturgeon prey abundance on Gray's Reef but more immediately affect Atlantic sturgeon in their coastal estuarine and riverine habitats. Even slightly diminished dissolved oxygen levels can have a much greater impact at spawning sites within river habitats than would be expected with similar diminished dissolved oxygen levels on Gray's Reef, for instance, where adults forage over very large areas.

As with diminished dissolved oxygen, altered precipitation pattern will have less of an impact on Gray's Reef than in nearby estuary and river habitat sturgeon utilize during their most vulnerable life stages. Altered precipitation patterns cause increases/decreases in rainfall distribution that can dramatically impact river habitat (flow, bottom habitat, predator/prey interactions, habitat niche partitioning, nutrient flow, pollutant dispersal, and important abiotic factors). The seasonal timing and precipitation pattern changes (e.g., summer flooding) for anadromous fish like sturgeon may undermine successful spawning or embryo survival for that spawning season. Female Atlantic sturgeon may spawn every two to five years, so the potential loss of an entire reproductive effort can profoundly impact species recovery.

Storm severity and frequency changes would likely impact estuary and river habitat more immediately and acutely than at Gray's Reef. Also, within Gray's Reef, the sand/mud bottom would probably not be as adversely impacted as the productive ledges within the sanctuary. Sturgeon are primarily feeding in the soft sand sediment that account for over 95 percent of the Gray's Reef habitat. Sturgeon benthic prey also have relatively fast recovery rates, such as four to six weeks for amphipods and polychaetes, that would allow a quicker recovery time for sturgeon foraging than if they were foraging the ledges themselves. Outside of very large storms/hurricanes, we expect less disruption to Atlantic sturgeon on Gray's Reef than to nearshore and upriver where these habitats may suffer greater impacts from storm events coincident with the most vulnerable life-stages for sturgeon.

Sturgeon life history as an anadromous species reveals that its vulnerability and adaptive capacity is inextricably tied to the species use of both marine and freshwater habitats. In this case, sturgeon are more vulnerable to climate change stressors when they occupy the rivers and nearshore estuarine habitats. However, it is unknown what threshold levels exist whereby climate change stressors would make Atlantic sturgeon not use habitat within Gray's Reef.

Potential adaptation strategies

Developing rapid post-storm response team
Develop a rapid response assessment SCUBA diving team that could visit storm impacted areas of Gray's Reef as soon as possible after large storm events (e.g., Hurricane Irma, 2017). Team would complete standardized assessments to storm-affected areas but likely have longer-term control sites for monitoring as well. Metrics to monitor would include species composition, sand deposition, and damage to ledge habitat. If acoustic arrays are set up eventually, they could determine how quickly sturgeon come back into affected area post-storm events. Acoustic arrays would also give data on temporal/spatial usage patterns of Gray's Reef and these data could be interrelated to other nearshore sturgeon datasets. Sturgeon habitat use/movement data would help management prepare long-term strategic planning and assist in re-assessing species/habitat vulnerability for the sanctuary.
Cost: Moderate to high.
Efficacy: High.

Add acoustic tagging array to Gray's Reef for Atlantic sturgeon
Possibly piggyback on existing acoustical arrays that are set up inshore for sturgeon by university and Georgia state researchers. This would establish sturgeon usage patterns for Gray's Reef, seasonality, size-class of individuals, and connectivity between GRNMS and estuary and river use (nearshore acoustical arrays already in place) would provide important data largely absent for determining extent that Atlantic sturgeon uses GRNMS. It is possible that GRNMS could leverage Federal Section 10 funds to purchase arrays at a cost of around $2,000 apiece. Areal coverage of GRNMS would need to be established to determine the number of arrays needed.
Cost: Moderate.
Efficacy: High.

4. Conclusions and Next Steps

Gray's Reef is one of the largest near-shore "live-bottom" reefs of the southeastern United States. Its ledges and outcroppings provide habitat to many marine species and attract pelagic predators. Gray's Reef is protected and managed by Gray's Reef National Marine Sanctuary, which undertook a rapid vulnerability assessment in order to better understand and manage for climate change and the effects it may have on the reef and its denizens.

Environmental conditions at GRNMS are expected to continue to change between now and 2050. The temperature of the water is expected to increase, on average, between 0.8 and 1.4°C, relative to the 1999 annual average. The pH of the water is anticipated to decrease by an additional 0.1 to around 7.8 over that same period. Climate models also suggest shifts in atmospheric pressure and precipitation. Pressure shifts are expected to alter the position of the Bermuda High, which influences both the atmospheric circulation over GRNMS as well as the behavior and positioning of the subtropical gyre, Florida Current, and Gulf Stream. These changes are connected to anomalous warm and cool water incursions to GRNMS, though there is insufficient information to determine trends in such events. Precipitation totals are unlikely to change greatly in the Southeast, but the frequency, duration, and geographic pattern of regional precipitation favor a trend toward higher variability, producing more extremes. Droughts are likely to become longer lasting and more widespread, while precipitation events are likely to be more intense. This has the potential to concentrate river discharge and sediment/nutrient flows into GRNMS at greater concentrations than at present. Similarly, although little change is predicted in the number of cyclonic storm systems (both tropical and extratropical) affecting the area, atmospheric changes are anticipated to produce an increase in the number of those storms that reach major categorization. Thus, there is an increased likelihood of storm-related damage to GRNMS over the next 30 years or so.

Of the several aforementioned climate change factors, storm severity/frequency, increased water temperature, ocean acidification, altered currents, and diminished dissolved oxygen were identified as influencing the climate vulnerability of the most species assessed (Table 4.1).

A trend toward more major tropical and extratropical storms impacting GRNMS was identified as a major impact to many species, particularly sessile invertebrates that would suffer from physical damage/detachment and possible sediment smothering as a result of passage of a major storm system. Participants deemed this impact as likely, which when coupled by non-climate stressors (RVA Consequences) produced a high risk of impact.

The second most identified climate stressor was increased water temperature. This factor was likely to shift mobile populations northward, possibly away from GRNMS; reduce fecundity; and facilitate competition by invasive species (e.g., red lionfish). Occurrence

Table 4.1. Median rankings for the five most identified climate impacts on the 11 species assessed in the GRNMS RVA. Note that workshop participants only identified the top three climate stressors, thus, other lesser climate stressors may affect a given species but were not considered.

GRNMS Workshop Results	Storm Severity/ Frequency	Increased Water Temperature	Ocean Acidification	Altered Currents	Diminished Dissolved Oxygen
Trend to 2050	Little change in total number of tropical cyclones. Increase in percentage of major cyclones. Increase in strength of extratropical cyclones.	Increase of between 0.8 and 1.4˚C (annual avg.). Greater seasonal variability.	Decrease in pH by an additional 0.1. Aragonite under-saturation expected in temperate water by 2050.	Decreased transport rates in Florida Current. Shift in median track of Gulf Stream. Southerly limit of Labrador Current shifts northward. Shift in gyre positions.	Decreased dissolved oxygen. -0.004 mol m^{-3} by 2050 (~1.0%). Greater likelihood of hypoxia.
RVA Species Affected (top 3 climate impact)	8 of 11	7 of 11	5 of 11	3 of 11	3 of 11
Median Likelihood	Likely	Almost Certain	Likely	Possible	Likely
Median Consequence	Moderate	Moderate	Moderate	Low	Catastrophic
Median Risk	High	High	High	Moderate	Extreme
Median Adaptive Capacity	High	High	High	High	High
Median Vulnerability	Moderate	Moderate	Moderate	Low	Moderate

of this stressor was deemed "Almost Certain," and when coupled with a moderate non-climate consequence produced a high risk of impact.

Ocean acidification was identified as a major climate stressor for about half of the assessed species, with a likely chance of occurrence. As with storms and temperature, a moderate level of consequence yielded an overall high risk of impact.

Altered currents and associated declining dissolved oxygen were identified as primary climate stressors for three of the species assessed. Effects included diminished and shifted larval recruitment, reduced fecundity, and food source mismatches. Dissolved oxygen reduction was deemed likely, while altered currents were possible. Altered currents had a moderate risk due to low non-climate consequences, but declining dissolved oxygen would be greatly exacerbated by catastrophic level non-climate stressors on the affected species, resulting in extreme risk.

Throughout the assessments, the adaptive capacity, or the ability of the species to mitigate or adapt to the climate stress combined with the stewardship capacity of GRNMS and its partners that can be applied to manage species impacts, was identified as high. As a result, otherwise high vulnerability scores were lowered to moderate.

However, it should be noted that in nearly all instances, the final vulnerability scores were on the upper limit of the moderate range, and workshop participants felt that the three-tier ranking (low, moderate, high) somewhat underrepresented the true vulnerability of the species to the identified climate stressors. Participants suggested that future applications of this particular RVA tool would benefit from expanding the vulnerability index to five tiers (e.g., negligible, low, moderate, high, extreme) to more accurately convey assessment results.

One species that received attention in the workshop but was not individually assessed was the red lionfish (*Pterois volitans*). This species, invasive to Atlantic coastal waters since the 1990s, has been documented at GRNMS since at least 2003. Workshop participants identified lionfish as a non-climate stressor for many of the assessed species, as it is an opportunistic feeder that competes with many of the native foragers and predators for food, and reduces survivorship of native juveniles.

As a result, lionfish reduction efforts (e.g., traps, derbies) were frequently listed as potential adaptation strategies to lower species risk and vulnerability to climate change. While costs would likely be low, efficacy is uncertain as lionfish are prolific reproducers, have no well-established predators in the Atlantic, and are extremely adaptable to different habitats. Also, little is known about lionfish spawning locations/behaviors in the region. Additionally, although some success has been gained in local population reduction (e.g., culling, trapping, and removal from source locations outside MPA boundaries), evidence from removal efforts elsewhere (e.g., Florida, Cayman Islands) suggests that complete eradication may be impossible, advancing the questions of

whether lionfish are likely to become a permanent fixture in the GRNMS habitat, and when (if ever) they should no longer be considered "invasive."

Other frequently identified adaptation strategies to reduce species risk and vulnerability to climate changes were primarily centered about monitoring efforts. With the high number of species likely impacted by major storms, participants noted the lack of a post-storm assessment process for GRNMS. They suggested GRNMS could establish a protocol for visiting the sanctuary and surveying storm damage soon after the storm passed. This would be a low cost, high efficacy way to create a recovery baseline, monitor recovery progress, and target management efforts to those species that exhibited difficulty in rebounding. Additionally, a number of species adaptation strategies suggested improving long-term ecological and climate monitoring, either by increasing surveys or by establishing additional monitoring instrumentation. Increasing and pairing long-term monitoring and assessment surveys currently underway in GRNMS with post-storm event monitoring may help tease out species and habitat vulnerabilities from storm events.

Next steps

This report should not be considered as a "roadmap" to action. Rather it summarizes the workshop outcomes and provides a variety of possible adaptation strategies that GRNMS may consider in future management planning. The report is not intended to be a comprehensive source of information or a recommendation for advancing a particular course of action over others. The nature of the workshop encouraged participants to reach determinations 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 examination.

The Rapid Vulnerability Assessment workshop at Gray's Reef National Marine Sanctuary was the first full implementation of the CEC Rapid Vulnerability Assessment tool, and a pilot application for the Office of National Marine Sanctuaries to test the efficacy of the method. Workshop participants provided feedback to sanctuary staff following the workshop that will be incorporated for future application at additional national marine sanctuaries, but the overall response from participants was that the workshop was a good use of time and an effective way to approach climate-informed planning at the sanctuary. It is the hope of this assessment report that the conversation regarding climate vulnerability at Gray's Reef will continue, and as resources, expertise, and information become available, additional species should be assessed and included in future editions of this report. To that end, participants identified the following species for future assessments:

1. Algal species (e.g., *Sargassum*)
2. Invasive lionfish
3. Polychaetes (soft-bottom infaunal)

        a. Nereid worm
        b. Glycerid worm
4. Belted sandfish (prey species that is tied to the reefs)
5. Tunicate (information lacking)
6. Lancelet (information lacking)

Immediate next steps identified for the sanctuary include engaging with the Sanctuary Advisory Council, including the Connectivity Working Group, around the results of this workshop and next steps for climate adaptation at the sanctuary; investing time and resources in completing a storm response plan for GRNMS resources to document damage following large, destructive storms; and prioritizing the gathering and analysis of visitation and use of the sanctuary to inform enforcement and education actions.

Additional discussion regarding collaborative adaptation actions occurred as the last item on the workshop agenda, and discussion centered on the following themes:

Education/outreach
Due to its importance to the recreational fishing community, there may be an opportunity to use the declining black sea bass population as a bellwether for climate change. These efforts could reach a constituency that has not traditionally been receptive to the concept of climate change. From an ecological standpoint, there are potential replacements, but many people, particularly recreational fishers, care about sea bass in particular. Climate impacts to sea bass distribution could provide a tangible, real-time example of climate change.

Lionfish
Pursue proactive management of lionfish. There are not many out there right now, but workshop participants agreed that it is a good idea to get ahead of the problem by introducing lionfish fishing (derbies) and trapping while local extirpation from with GRNMS may still be tenable.

MPA connectivity
Consider increasing the size of Gray's Reef research area and of the sanctuary itself, with connected units within the region. For pelagic species, GRNMS may be too small to effect change. A network of connected MPAs is needed to effectively manage these species for climate change. The following ideas were presented to that effect:
- Connect first with the South Atlantic Fishery Management Council (SAFMC) to discuss the expansion of the system of MPAs in the South Atlantic region.
- Identify deeper environments that serve as refuges to species for temperature and consider adding them to GRNMS.
- SAFMC MPAs and GRNMS are not showing much impact to building the fisheries, so it may be time to talk about what is needed in the region (may be due to remote location and less fishing effort than other MPAs). Seasonal changes make it more complicated as well.

- Currently SAFMC does not protect pelagic predators (only bottom species, by restricting bottom trawling). FMC MPAs should be based on the relationship between pelagic and benthic species based on research.

Post-storm analysis
GRNMS has a hurricane plan for the office, but not for the sanctuary to evaluate damage on sanctuary resources.

Enhanced collaboration
With king mackerel moving into other areas, enhancing collaboration with Stellwagen Bank National Marine Sanctuary and the Mid-Atlantic/New England FMCs on management of the species may be judicious.

Sanctuary visitation/use
Data have shown no difference between the research area (where no fishing is allowed) and the public-use area of the sanctuary; this could be due to regulations not being followed (in which case, increased enforcement of existing regulations is critical to mitigate local, non-climate effects such as anchor damage), or that the sanctuary is not being fished enough to detect a difference. Fishing activity within the research area has been documented (i.e., marine debris and boats with gear in the water). Data on visitation and use of the sanctuary are critical to understand if enforcement is needed. The remoteness of the site has to date precluded systematic monitoring of usage. Workshop participants had suggested possible technological solutions to capture sanctuary visitations. Some ideas include:
- Partnership with university to analyze satellite imagery data to do boat counts – images still need to be processed.
- Citizen science project.
- Tech program to analyze images for boats automatically.
- Buoy hotspot that can be used to track boats.

The GRNMS Rapid Vulnerability Assessment workshop and report provided preliminary insight into the potential impact of select climate-driven and non-climate stressors on several key species present in the sanctuary. Inherent to a more "rapid" assessment approach, many factors and variables were not considered, but as the original RVA methodology states, the longer-term goal of applying this approach is to empower managers to "regularly consider the implications of climate change in their work, either by revisiting and reapplying the tool, or by applying the thought process it provides." This has been a positive first step toward identifying dominant climate and non-climate stressors affecting the sustainability of the sanctuary, and has promoted discussion about existing and potential measures to reduce exposure or enhance adaptation and resilience. In nearly all adaptation strategies, a regional approach in which the GRNMS is used as a sentinel site or in an evaluation role may provide more effectual solutions to addressing species and habitat vulnerability and adaptation. However, much more work is required to determine whether such measures are feasible or can be effective strategies for the sanctuary.

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Acknowledgements

Glossary of Acronyms

ACL   Annual Catch Limit
AMO   Atlantic Multidecadal Oscillation
AMPS   Advanced Modular Payload System
AR5   Fifth IPCC Assessment Report
CaCO3   Calcium Carbonate
CEC   Commission for Environmental Cooperation
CITES   Convention on International Trade in Endangered Species of Wild Fauna and Flora
CMIP5   Fifth Coupled Model Intercomparison Project
CO2   Carbon Dioxide
DNR   Department of Natural Resources
DO   Dissolved Oxygen
DPS   Distinct Population Segment
ERP   Ecological Reference Point
FKNMS   Florida Keys National Marine Sanctuary
FL   Florida
GA   Georgia
GRNMS   Gray's Reef National Marine Sanctuary
IBTrACS   International Best Track Archive for Climate Stewardship
ICOADS   International Comprehensive Ocean Atmosphere Data Set
IPCC   Intergovernmental Panel on Climate Change
KNMI   Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)
MPA   Marine Protected Area
NC   North Carolina
NCEI   National Centers for Environmental Information (NOAA)
NMFS   National Marine Fisheries Service (NOAA)
NOAA   National Oceanic and Atmospheric Administration
NWA   Northwest Atlantic
NWLON   National Water level Observing Network
OADS   Ocean Acidification Data Stewardship
RCP   Relative Concentration Pathway
RVA   Rapid Vulnerability Assessment
SAFMC   South Atlantic Fishery Management Council
SEFSC   Southeast Fisheries Science Center
SkIO   Skidaway Institute of Oceanography
USFWS   United States Fish and Wildlife Service

Appendix A. Workshop Agenda

Gray's Reef National Marine Sanctuary
Vulnerability Assessment Workshop

November 7-8, 2017

10 Ocean Science Circle
Savannah GA 31411

Thank you for participating in this 2-day workshop to assess the vulnerability of select Sanctuary resources to the impacts of climate change.

The objectives of this workshop are to:
1.   Apply a rapid vulnerability assessment tool to selected species of GRNMS;
2.   Allow managers and partners to engage with the science of climate change as it pertains to their climate concerns;
3.   Encourage the creation of adaptation strategies to reduce the vulnerabilities that are identified through the assessment process; and
4.   Provide education and networking opportunities to partners and stakeholders to increase knowledge and awareness of climate science and to enhance outreach related to climate change and its impacts in GRNMS.

Tuesday November 7	
9:00 – 9:30	Sign-in and breakfast (provided by the National Marine Sanctuaries Foundation)
9:30 – 9:35	Welcome *George Sedberry, GRNMS*
9:35 – 9:45	Participant Introductions
9:45 – 10:15	Introduction to Agenda and Workshop Objectives *Sara Hutto, GFNMS and Helene Scalliet, ONMS*
10:15–10:30	Presentation: Climate Trends in the Region *Karsten Shein, NOAA*

Tuesday November 7 (continued)	
10:30–11:00	Presentation and Discussion: Tool Overview and Defining the Scope of the Assessments *Sara Hutto, GFNMS and George Sedberry, GRNMS*
11:00 – 11:15	Break and re-assemble into break-out groups
11:15–12:30	Activity**:** Construct matrices and begin assessments for selected species
12:30–1:30	Lunch (provided by the National Marine Sanctuaries Foundation)
1:30–4:00	Activity**:** Complete assessments for selected species
4:00–5:00	Wrap-up Discussion**:** What did we learn? What issues did we encounter? Planning Day Two
No-host group dinner – gather and depart at 6:00 for Savannah	

Wednesday November 8	
8:00-8:30	Breakfast (provided by the National Marine Sanctuaries Foundation)
8:30–8:45	Introduction to Day Two - goals and agenda *Sara Hutto, GFNMS*
8:45–10:15	Activity: Complete assessments
10:15 – 10:30	Break
10:30 – 10:45	Presentation: Introduction to Adaptation Planning *Sara Hutto, GFNMS*
10:45 – 12:15	Activity: Adaptation Strategy Development

Wednesday November 8 (continued)	
12:15 – 1:00	Lunch (provided by the National Marine Sanctuaries Foundation)
1:00 – 2:00	Large group discussion: adaptation strategies
2:00 – 2:30	Wrap-up, Next Steps, Feedback
2:30	Workshop Adjournment

Appendix B. Participant List

Joseph Cavanaugh
Fisheries Ecology
NOAA National Marine Fisheries Service

Mary Conley
Marine Conservation
The Nature Conservancy

Pat Geer
Marine Fisheries
Georgia Dept. of Natural Resources

Danny Gleason
Invertebrate taxonomy/ecology
Georgia Southern University

Justin Grubich
Marine Ecology
Pew Charitable Trusts

Chris Hines
Deputy Superintendent
Gray's Reef National Marine Sanctuary

Sara Hutto
Climate Program Coordinator
Greater Farallones National Marine Sanctuary

David Lawrence
Ecologist
U.S. National Parks Service

Roldan Muñoz
Fisheries Ecology
NOAA National Marine Fisheries Service

Scott Noakes
Ocean Chemistry
University of Georgia

Marcel Reichert
Fisheries
South Carolina Dept. of Natural Resources

Kim Roberson
Research Coordinator
Gray's Reef National Marine Sanctuary

Hélène Scalliet
Program Specialist
NOAA Office of National Marine Sanctuaries

George Sedberry
Superintendent
Gray's Reef National Marine Sanctuary

Karsten Shein
Climatologist
National Centers for Environmental Information

Becky Shortland
Resource Protection / Facilitator
Gray's Reef National Marine Sanctuary

Tracy Ziegler
Marine Ecology
U.S. National Parks Service

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: http://www3.cec.org/islandora/en/item/11733-north-american-marine-protected-area-rapid-vulnerability-assessment-tool-en.pdf

WORKSHEETS:
http://www3.cec.org/islandora/en/item/11739-north-american-marine-protected-area-rapid-vulnerability-assessment-tool-en.pdf

NATIONAL MARINE
SANCTUARIES

AMERICA'S UNDERWATER TREASURES